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OPTICAL FIBRE COMMUNICATION

(14 - 25 March 1988)

FIBRE TRANSMISSION SYSTEMS - II

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SIP
ROME, ITALY

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" Second Workshop on Optical Fibre Communications "

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Part one of three parts

Lightwave system design

Lightwave transmission systems have moved to center stage in the telecommunications industry. This, the first part of a three-part article on lightwave system design, will discuss important lightwave design questions telecommunications engineers and managers must answer

K.H. LEWIS and D.M. BUCK

UNDERSTANDING LIGHTWAVE systems is rapidly becoming a fundamental requirement for every telecommunications engineer and manager.

This new technology is being widely used today and will be even more widely used in the future. This dictates the need to understand lightwave systems and to be comfortable with the transmission design considerations applicable to their use. What are the necessary steps to determine repeater spacings and specify fiber performance for both multimode and single-mode technology?

Multimode system considerations will include fiber spectral attenuation and dispersion characteristics, equipment gain parameters, splice intervals and losses, wavelength division multiplex (WDM) and an example calculation. Consideration of single-mode technology will follow a similar outline.

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Design parameters

Economical design of a practical lightwave system involves many considerations to achieve the lowest total system cost. These considerations include, at a minimum, operating wavelength, bit rate, splicing philoso-

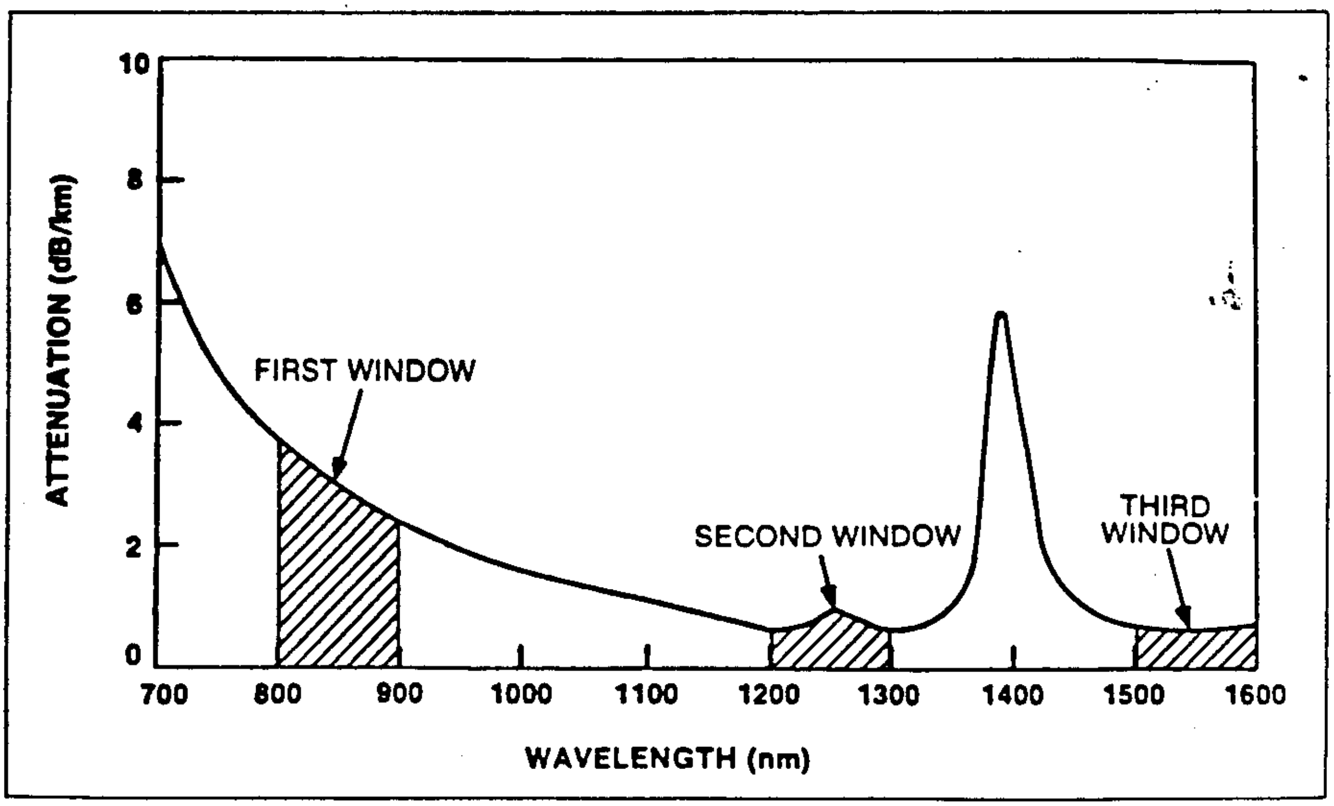


FIG. 1 *Typical multimode fiber spectral attenuation.*

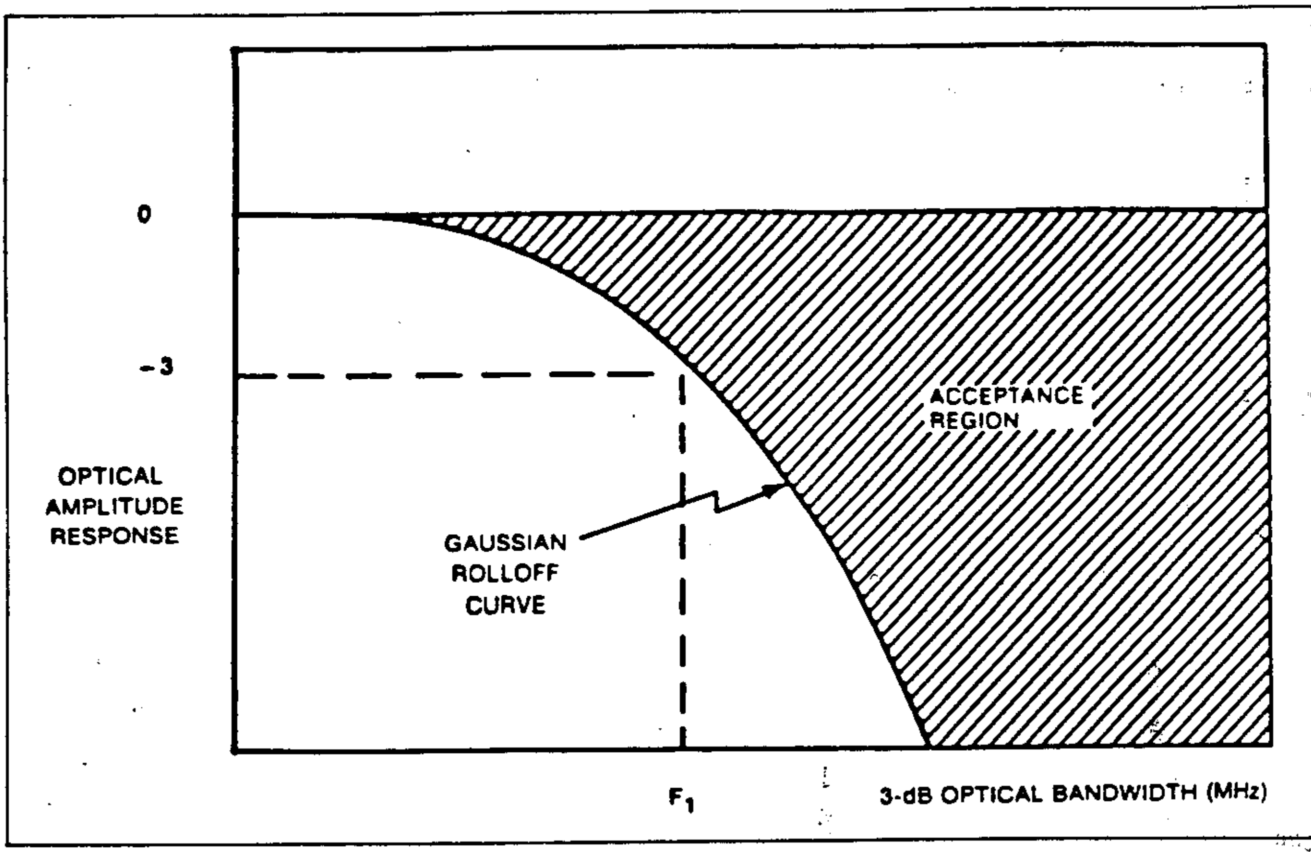
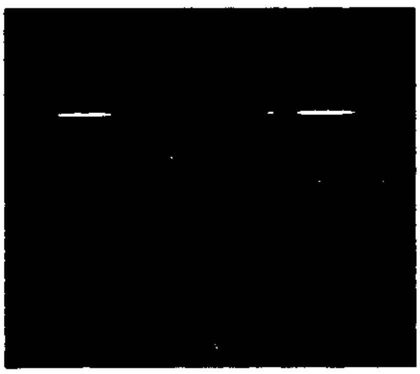


FIG. 2 *Minimum Gaussian 3 dB optical bandwidth mask.*

phy, wavelength division multiplexing, optimum repeater spacing and system safety margins. However, in the initial planning stages of a lightwave project, one of the key decisions to be made by the system engineer is whether the network will be configured with multimode optical cable, single-mode cable or a combination of both.

In the recent past, this decision was driven almost entirely by economic considerations. To their advantage, multimode fibers were readily available, relatively inexpensive, and compatible with a wide variety of lightwave electronic hardware. The disadvantages associated with multimode cable related primarily to bandwidth restrictions (and, hence, lower bit rates) and comparatively high basic fiber loss. The combination of these factors had the effect of limiting the achievable span distance in multimode systems to approximately 25 km, or 15.5 miles. Conversely, single-mode fibers provided much larger bandwidths (and higher bit rates), as well as significantly lower loss. This allowed unrepeatered span lengths of up to 50 km in conjunction with transmission rates of 405 Mb/s or higher.

However, single-mode fibers were as much as two to three times as expensive as their multimode counterparts. Therefore, the decision which had to be made by the design engineer was whether to trade overall cable cost for repeater electronics cost. Unfortunately, widely fluctuating cable and equipment prices made this trade-off difficult to calculate and precluded the establishment of rigid engineering rules for lightwave system design. This also made system engineering more complex, time consuming and costly.



Cover photo by Collins Transmission Systems.

Lightwave technology presents the telecommunications industry with new images of itself.

Beginning in early 1983, increased demand for single-mode cable and a corresponding increase in production reduced the price of single-mode fibers to values equal to or less than the price of multimode fibers. The lightwave system engineer now can realize all the advantages of single-mode transmission without paying a significant cost penalty. The effect has been to make single-mode systems much more prevalent and to push multimode technology toward rapid obsolescence. However, there are still a large number of multimode systems being installed, and multimode fiber will probably be used for years to come.

What are the transmission design characteristics of both single-mode and multimode systems? What are the primary differences between the two?

Multimode considerations

The two key parameters in the design of a multimode lightwave system are the allowable link loss and the end-to-end bandwidth requirements. These two parameters drastically affect repeater spacing and cable pricing, which in turn have a significant impact on the total system cost. Therefore, it is important to define these parameters and to understand how they are used in the system design process.

However, first an explanation of the spectral attenuation and dispersion characteristics of multimode fibers is appropriate.

Figure 1 illustrates the attenuation (dB/km) versus operating wavelength (nm) for a typical multimode optical fiber. The attenuation decreases rather uniformly ($1/\lambda^4$) from approximately 7 dB/km at 700 nm to less than 0.8 dB/km at 1300 nm. The slight increase at around 1260 nm and the large increase at approximately 1400 nm are due to the presence of hydroxyl (OH-) ions in the glass. The attenuation approaches a minimum (less than 0.6 dB/km) at approximately 1550 nm.

Obviously, as can be seen in Figure 1, the ideal operating wavelength would be in the 1500 to 1600 nm range because of the lower attenuation values. At this time, however, lightwave system designer to study the life cost of an intermediate repeater on long, aggressively spaced spans versus the premium paid for the low-loss fibers. Unless repeater prices are low and physical facilities for the repeater installation exist, the premium fibers usually prove to be the economic winners. However, each system is unique, a fact which dictates that this cost study be performed for each.

Fiber dispersion

Although multimode fibers offer very large bandwidths compared with conventional copper cables, they certainly do not provide infinite (typically 1 km) basis.

Unfortunately, the conversion between the time domain and the frequency domain is complex in practical systems because measured fiber bandwidth performance does not conform to rolloff curves which can be expressed by simple mathematical formulas.

The required operating bandwidth, the proper specification of this bandwidth and how this bandwidth varies as a function of length are the subjects of much discussion within the industry. Standards are evolving, but no firm specifications exist at this time. At this point, most fiber cable

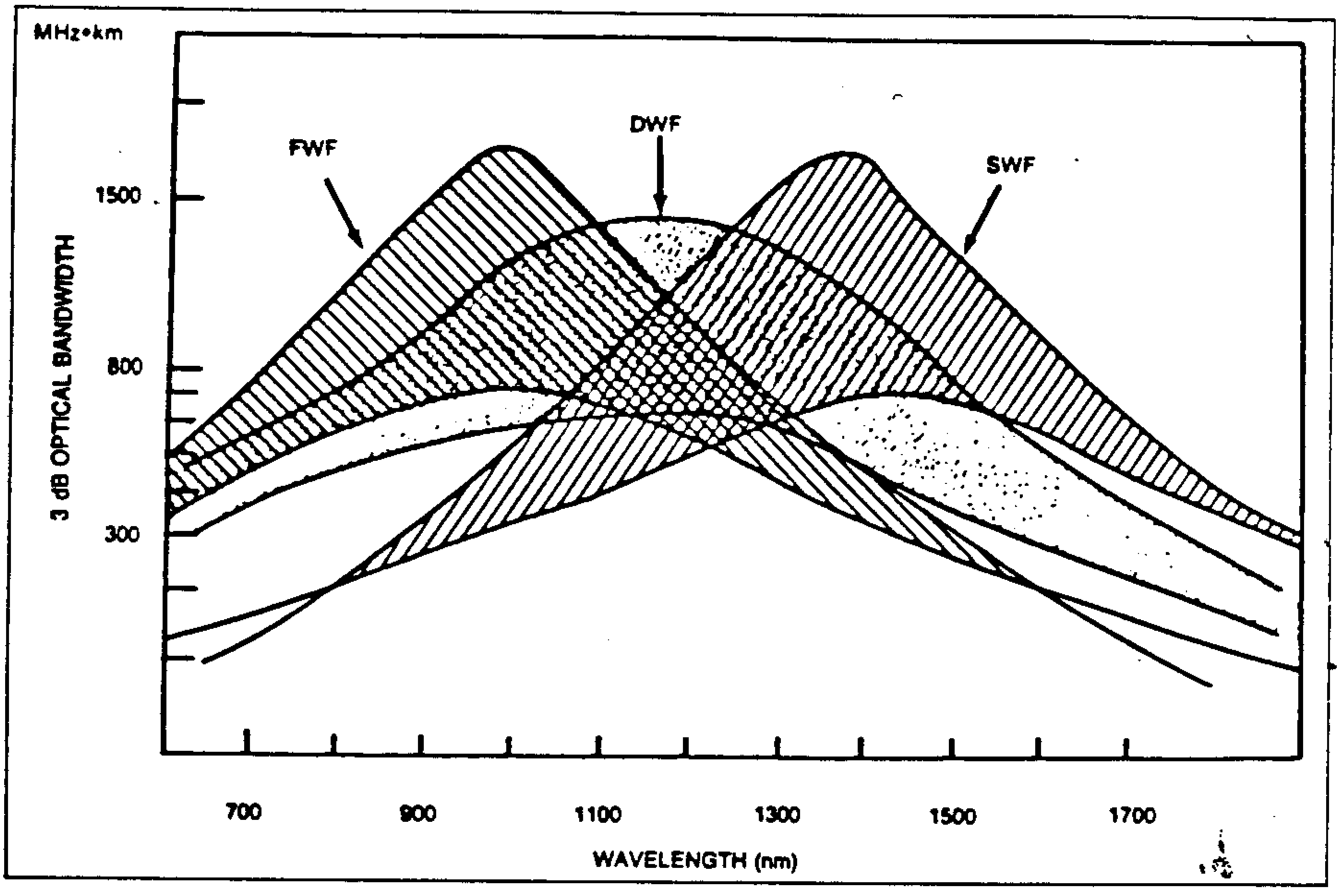


FIG. 3 *Typical 3 dB optical bandwidths for first, second and double-window multimode fibers.*

sources that operate in this region are not commercially available at a competitive price. Fortunately, devices with proven reliability and economical prices in the 1200 to 1300 nm range are available. In fact, long wavelength (1200 to 1300 nm) devices are now priced competitively with their short wavelength (800 to 900 nm) counterparts for medium to long haul applications.

When trying to minimize the total system lifecycle cost, it is important to note that a large premium is sometimes charged for fibers with less than 0.8 to 0.9 dB/km attenuation at 1300 nm. This factor should prompt the transmission capacity. The pulse spreading caused by this finite bandwidth is due to several mechanisms—modal dispersion, material dispersion and waveguide dispersion—with modal dispersion substantially dominating the combined effects of the other two.

As with conventional electrical circuits, bandwidth can be expressed in the time domain as a full-width, half-maximum dispersion or in the frequency domain in units of megahertz. Because the effects of modal dispersion are distributed over the length of the fiber, it is usually necessary to express this bandwidth on a per-unit bandwidths are specified as a bandwidth-distance product and are expressed in units of megahertz multiplied by kilometers. The parameter typically specified is 3 dB optical bandwidth. From the standpoint of optoelectronic equipment, this parameter only specifies amplitude information and provides no data about the shape of the fiber bandpass characteristic or the accompanying phase response.

Most lightwave systems are digital and thus require that the expected pulse spreading (or dispersion) be characterized. However, determining

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dispersion from a fiber's 3 dB optical bandwidth is difficult, if not impossible. Depending on rolloff shape, fibers with the same 3 dB optical bandwidth can cause drastically different amounts of pulse dispersion. Additionally, the one/zero decision is made by an electrical threshold detector at the output of the optical device.

As a result, it is the fiber's 3 dB electrical (1.5 dB optical) bandwidth that determines the amount of pulse dispersion and accompanying intersymbol interference. Because end-to-end electrical bandwidth and rolloff shape are never available on fibers before they are installed, it is necessary to make certain assumptions about the fiber's bandpass characteristic. The assumption typically made is that the fibers will have a Gaussian amplitude response. A Gaussian rolloff, however, rarely exists in the real world when fibers are spliced together to form long spans.

To ensure a properly specified cable bandwidth, it becomes necessary to define an optical response mask such that the actual fiber rolloff response falls in an acceptance region of this mask. The mask represents the minimum Gaussian rolloff curve with a 3 dB optical bandwidth of F1 MHz, which can be fitted under the actual measured rolloff. This concept is shown in Figure 2.

Figure 3 shows a range of typical 3dB optical bandwidths for first, second and double-window fibers. Bandwidth, like attenuation, is wavelength dependent, because fiber index profiles are optimized to provide maximum bandwidth at a particular operating window. Fibers whose profiles are compromised for operation at both short and long wavelengths (double-window fibers) provide less bandwidth, sometimes at a premium price, and are no longer recommended. Notice that multimode fiber, over a 1 km length, can provide bandwidths between 700 and 1800 MHz. This is extremely important in today's long wavelength, high data rate systems, where greater per-unit bandwidths are required because of increased repeater spacing.

Splicing fiber reels in the field to form long spans makes it necessary to understand the effect of distance on concatenated fiber bandwidth. Unfortunately, the prediction of a long concatenated fiber's bandwidth is a complex process and the subject of much investigation. Theory suggests that this length dependence is somewhere between a linear and a square root reduction. The equation for the prediction of the effective (or end-to-end) bandwidth for a long string of shorter concatenated fibers is given by equation (1):

$$BW_{EFF} = \left(\sum_{j=1}^{n} BW_j^{\frac{-1}{\gamma}} \right)^{-\gamma}$$

where:

BW_{EFF} = end-to-end bandwidth
n = number of concatenated reels in the span
BW_j = bandwidth of each reel
γ = length dependence exponent (scaling factor).

Current empirical data suggests the expected range of γ is 0.7 to 1.0; value of 0.8 to 0.9 is the generally accepted value. Notice that this makes the length dependence close to linear (γ = 1). Assuming each reel of cable has the same per-unit bandwidth and that γ = 0.9, equation (1) simplifies to equation (2):

$$BW_{EFF} = \frac{BW_{per\ unit}}{L^{0.9}}$$

where:

$BW_{per\ unit}$ = MHz x km specification of each 1 km section
L = total span length in km.

Equation (2) can be solved for $BW_{per\ unit}$ such that the result is equation (3):

$$BW_{per\ unit} = BW_{EFF} \times L^{0.9}$$

Equation (3) can be used as a general guide to predict the grade of fibers required to achieve an expected end-to-end bandwidth. This bandwidth then should ensure that

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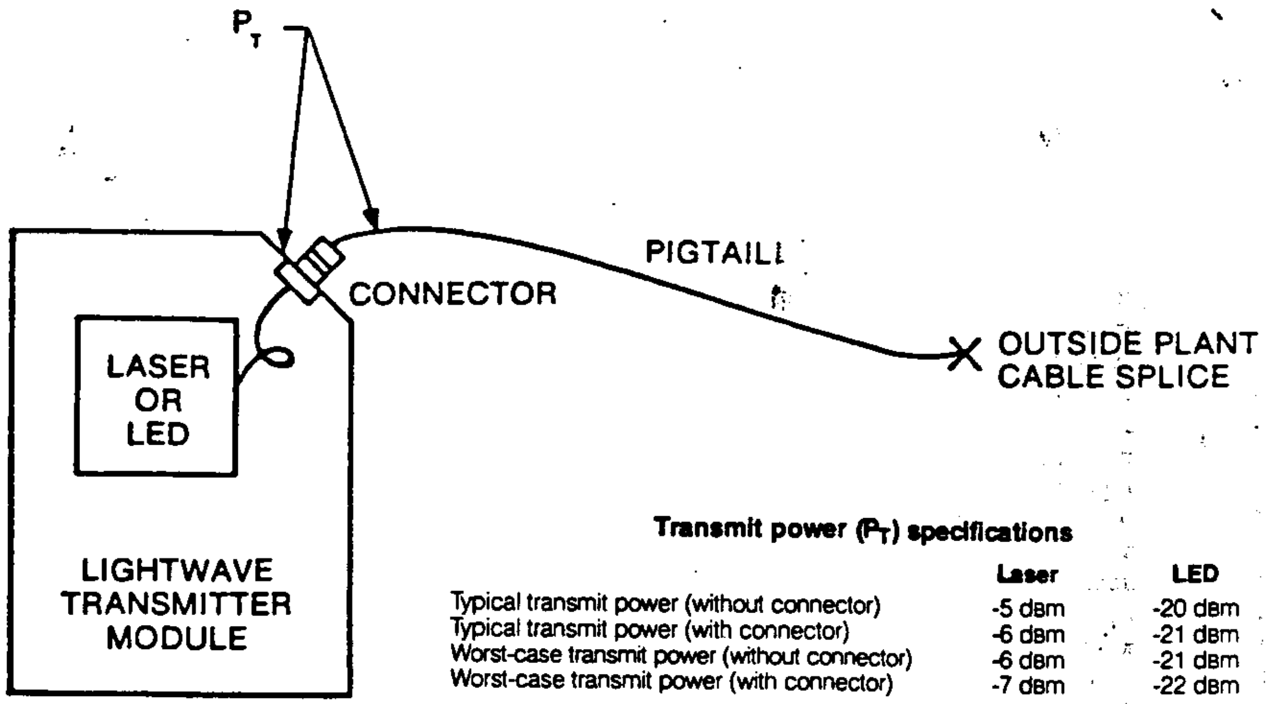
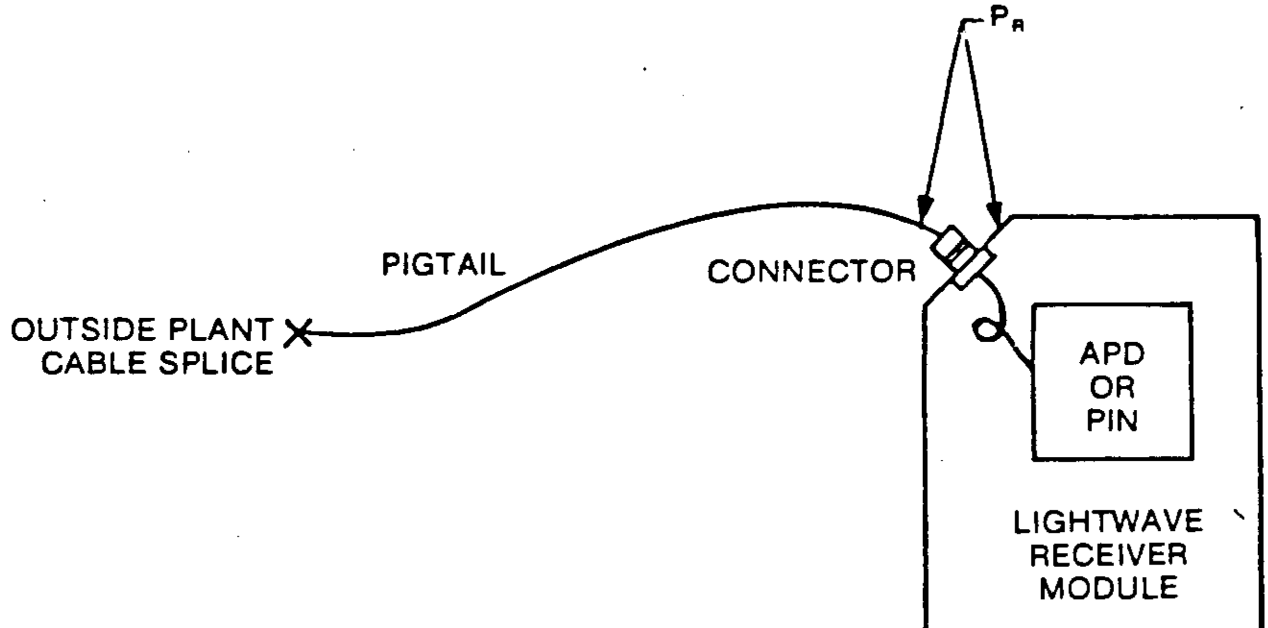


Transmit power (P_T) specifications

	Laser	LED
Typical transmit power (without connector)	-5 dBm	-20 dBm
Typical transmit power (with connector)	-6 dBm	-21 dBm
Worst-case transmit power (without connector)	-6 dBm	-21 dBm
Worst-case transmit power (with connector)	-7 dBm	-22 dBm

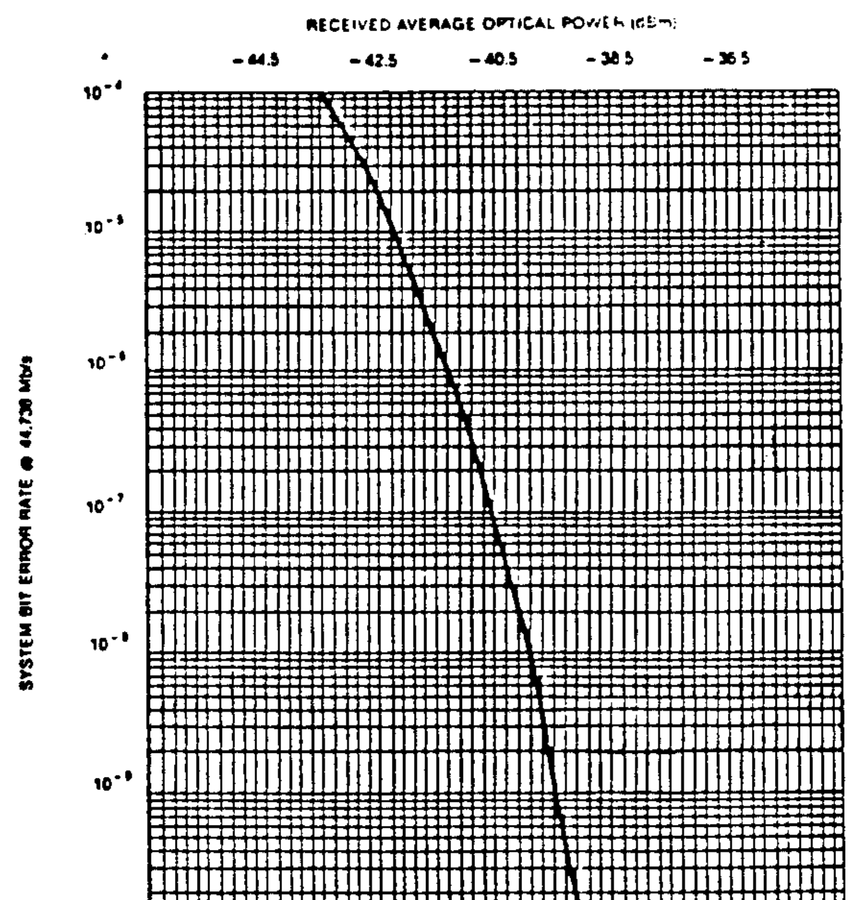
FIG. 4 *Transmitter power specifications.*



Receiver sensitivity (P_R) specifications (1 x 10^{-9} BER)

	APD	PIN
Typical receive threshold (without connector)	-41.0 dBm	-34.0 dBm
Typical receive threshold (with connector)	-40.0 dBm	-33.0 dBm
Worst-case threshold (without connector)	-39.5 dBm	-32.5 dBm
Worst-case threshold (with connector)	-38.5 dBm	-31.5 dBm

FIG. 5 *(above) Receiver sensitivity specifications.* **FIG. 6** *(right) Typical BER versus receiver signal level.*



the lightwave electronics will function properly.

As in the case of low attenuation, per unit bandwidth values that are very large increase the per-fiber-meter price of the cable. The sensitivity of fiber price to bandwidth is nonlinear, with prices typically rising very sharply for bandwidth which exceeds 1000 to 1200 MHz x km. This forces the system designer to study the cost of intermediate repeaters against the cost of premium bandwidth fibers on longer spans to determine the impact on total system cost.

Prices for 1400 MHz x km fiber are often twice as much as those for 800 to 900 MHz x km fiber. One tool the system designer can use to reduce cable costs, especially for systems with data rates above 90 Mb/s is to lower the required end-to-end bandwidth as much as possible.

Equipment system gain

Equipment system gain, simply stated, is the difference between transmit power and receiver sensitivity. Stated differently, it is the amount of allowable loss the cable can contribute over the span under

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consideration, with no operating margin. Unfortunately, no standards are in effect to dictate how a particular vendor specifies system gain. Consequently, there is room for ambiguity when comparing equipment parameters of several vendors. What are these ambiguities? What are the effects of bit rate and wavelength on system gain for multimode operation?

Early lightwave systems operated in the 800 to 900 nm range and used gallium-aluminum-arsenide (GaAlAs) laser sources and silicon (Si) detectors. The detectors were either ordinary PIN photodiodes or avalanche photodiode (APD) detectors, which have a gain approximately 7 to 10 dB greater than PIN detectors. Although long wavelength systems have less system gain than their short wavelength counterparts, longer repeater spacings are possible because of the lower fiber attenuation. In fact, now that long wavelength devices (1200 to 1300 nm window) are available, the demand for the earlier short wavelength devices has been reduced drastically.

The reduced system gain at longer wavelengths is due to several reasons. The indium-gallium-arsenide-phosphide (InGaAsP) lasers used in the long wavelength range typically have 1 to 3 dB lower power output than GaAlAs devices. The primary detector at long wavelength is the InGaAsP PIN; no InGaAsP APD is commercially available. These detectors have approximately 6 to 10 dB less sensitivity than short wavelength Si detectors. Germanium (Ge) APD are available in the 1200 to 1300 nm range and exhibit approximately 3 to 5 dB better sensitivity than InGaAsP PIN photodiodes. They are more expensive, however, and require thermoelectric cooling for stability.

The InGaAsP technology will also be used for 1500 to 1600 nm operation in the near future. The Ge APDs, however, are less sensitive at this window and are not recommended. As previously noted, even with this decrease in system gain, long wavelength operation permits much longer repeater spacings (approximately twice as great) than short wavelength operation, thereby reducing repeater requirements and significantly reducing total system cost.

Receiver sensitivity decreases with increasing bit rates in a lightwave system just as it does in other transmission systems, such as microwave radio. As the low-pass noise filter in front of the threshold detector widens to accommodate the higher bit rates, the sensitivity is reduced proportionately. The reduction of sensitivity, expressed in decibels, is approximated by the equation: sensitivity reduction = $10 \log (BR_1/BR_2)$.

Doubling the bit rate thus reduces system gain by 3 dB, shortening the repeater spacing somewhat. However, the significant savings realized by reductions in lightwave transmitter/receiver and fiber count typically more than offset the increases due to shorter spans. For large transmission requirements, higher data rate systems are the most economical.

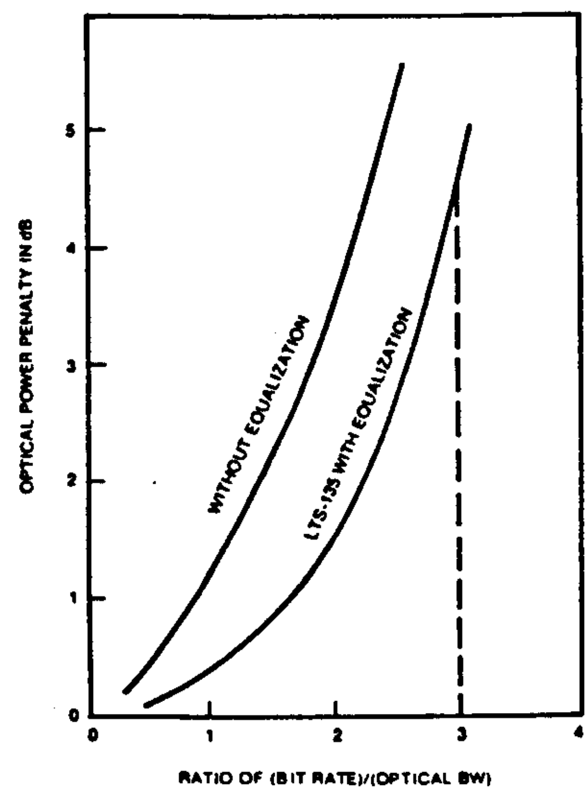

FIG. 7 *Optical power penalty versus bandwidth.*

Definition of parameters

Before the system gain for particular equipment can be calculated, each of the operating parameters must be precisely defined. Again, there are no industry standards; consequently, there are wide variations from vendor to vendor. Some of these variations include specifying typical instead of worst-case values, specifying transmit power for an all-ones pattern instead of alternating ones and zeroes, specifying receiver sensitivity at various bit error rates (BER) and neglecting to specify whether module connector losses are included in the transmitter power and receive sensitivity values. These inconsistencies can lead to widely varying values, as shown in Figure 4 for transmitter power and in Figure 5 for receiver sensitivity. Further uncertainty can arise from the effect of BER on receiver threshold, as shown in Figure 6. The net effect is that the system designer must very carefully evaluate each of the lightwave equipment operating parameters before a decision is made about how the fiber loss will be specified.

The definitions of the parameters used by Rockwell in determining the system gains and link loss budgets for its lightwave equipment are:

P_T = Average effective transmitter power in decibels referred to one milliwatt (dBm) coupled into the single fiber cable that connects to the outside plant. This power includes the loss of the transmit module connector and assumes a 50% ones density modulating signal.

P_R = Receiver sensitivity in dBm for a 1×10^{-9} BER at the receiver module input connector; in other words, this value includes the receiver input connector loss. This sensitivity assumes no power penalty associated with fiber finite bandwidth or other system-related noise phenomena.

G = Equipment system gain with no external degradations—transmitter power minus receiver sensitivity.

A_E = Recommended margin for equipment in determining net system gain. This margin allows for con-

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nector tolerance/repeatability, temperature effects and measurement uncertainty. It is recommended that a value of 3 dB be used for A_E when typical equipment specifications are given, and 0 dB when worst-case, end-of-life specifications are given.

A_B = System gain reduction due to intersymbol interference caused by the finite bandwidth of the fiber optic cable.

A_C = Allowance for module connectors (if not included in the P_T and P_R values), as well as extra connectors used in optical patch or cross-connect facilities. The parameter A_C is typically 1 dB per series connector in multimode systems.

A_W = Allowance for future wavelength division multiplexing. This value is specified as 4 dB for two-wavelength multimode systems and 6 dB for three-wavelength systems.

Equation (4) is:

$$L = \text{link loss budget}$$
$$= P_T - P_R - A_E - A_B - A_C - A_W$$

The value L in equation (4) is the total end-to-end attenuation of the cable (installed and spliced) that is specified to the cable vendor. This value is normally given in conjunction with the required 3 dB bandwidth to define the overall performance requirements of the cable.

The P_T and P_R parameters thus defined assume back-to-back transmitter/receiver operation through an optical attenuator. This implies an infinite 3 dB optical bandwidth. Obviously, this never occurs in an operational system; as a result, most lightwave systems are specified to operate in an end-to-end 3 dB optical bandwidth approximately equal to the data rate.

Operating in an optical bandwidth equal to the data rate results in less than 1 dB degradation to threshold relative to operating back-to-back through optical attenuators with infinite bandwidth. In an actual system, it is possible to reduce the end-to-end bandwidth requirements at the expense of threshold degradation. In effect, the system designer chooses to reduce the allowed link loss budget in favor of reducing the end-to-end bandwidth requirements.

The Rockwell LTS-135 lightwave transmission system, which operates at a bit rate of 135 Mb/s, incorporates exclusive equalization circuitry to minimize the trade-off of link loss budget for bandwidth. Figure 7 shows a plot of this trade-off along with a plot of a NRZ (non-return to zero) modulation system without an equalizer. The equalization process is a nonlinear decision feedback design that is superior to conventional linear processes. Because of the equalization process, the receiver is much more forgiving of the fiber bandpass characteristic, making the trade-off less sensitive to the assumptions made about Gaussian or non-Gaussian passbands. The improvement that the equalizer provides is more dramatic as the bandwidth of the fiber is reduced.

The equalizer makes it possible to select fiber cable for the receiver typical of that required by most 90 Mb/s systems. In fact, it is possible to operate the receiver over fiber that is suitable for only 45 Mb/s operation. As previously mentioned, reduced end-to-end bandwidth requirements drastically reduce the cost of a fiber cable. □

The second part of this three-part article, which will appear in a coming issue of TELEPHONY, will discuss splicing loss and interval, WDM, example calculation and methods of specifying fiber performance.

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Part two of three parts

Lightwave system design

The design of lightwave systems is now of paramount concern to telecommunications engineers and managers. The first part of this article discussed design parameters, multimode considerations, and fiber dispersion and equipment system gain

K.H. LEWIS and D.M. BUCK

TODAY, cable suppliers routinely provide multimode fiber cable in nominal 2 km (1.2 mi.) or longer reel lengths.

This situation has many advantages over the shorter reels which are 1 km or less. The shorter reels were provided several years ago. Longer reel lengths mean greater intervals between splices. This has two dramatic effects: it reduces installation time, and reduces end-to-end attenuation due to splice loss.

Experience gained through installations indicates that installing fiber cable in longer reel lengths presents no major problems in most cases. Longer reel lengths also can be installed in crowded ducts in major metropolitan areas by forming figure eights with the cable for midspan pulls, or by providing pulling assistance in intermediate manholes. In most cases, it is worth the additional installation effort in placing the cable to avoid a splice location. The time and decibels saved in eliminating a splice point more than compensates for the midspan pull or other efforts used to reduce splice count.

For these reasons, it is recommended that at least 2 km splicing intervals be used in link loss budget calculations unless extenuating circumstances exist. Splice count can be determined by the method shown in Figure 8.

The losses encountered in splicing fibers have decreased substantially as the control of critical fiber parameters has improved. Making an assumption that there will be a splice loss of 0.35 dB is safe and conservative for multimode systems. The loss varies only slightly from one splicing approach to another; fusion or mechanical procedures produce little difference in mean splice loss.

WDM

Wavelength division multiplexing (WDM) permits combining the output from at least two transmitters operating at λ_1 and λ_2 onto a single fiber. A receiver WDM device separates the composite signal, sending each wavelength to individual receivers. The principle of operation

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K.H. Lewis is Lightwave Product Administrator and *D.M. Buck* is Systems Engineer, Telephone Systems, with the Collins Transmission Systems Div. of Rockwell International Corp., Dallas. Part one of this article appeared in TELEPHONY, Dec. 12, 1983, p. 34.

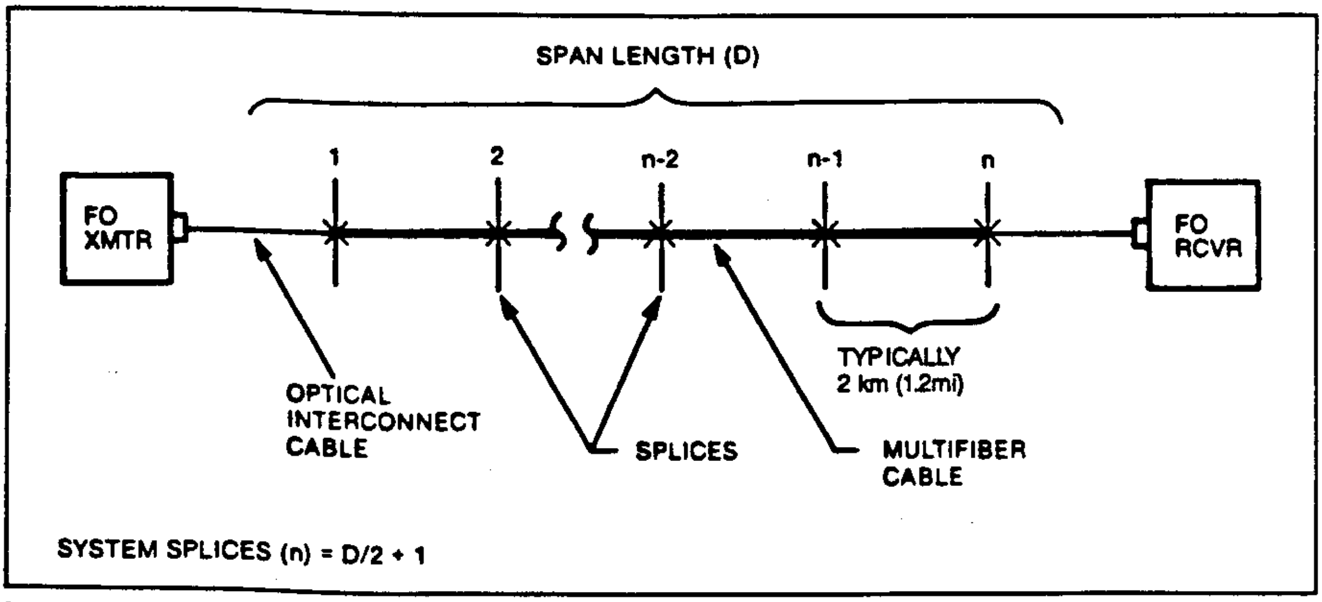

FIG. 8 *Method to determine splice count.*

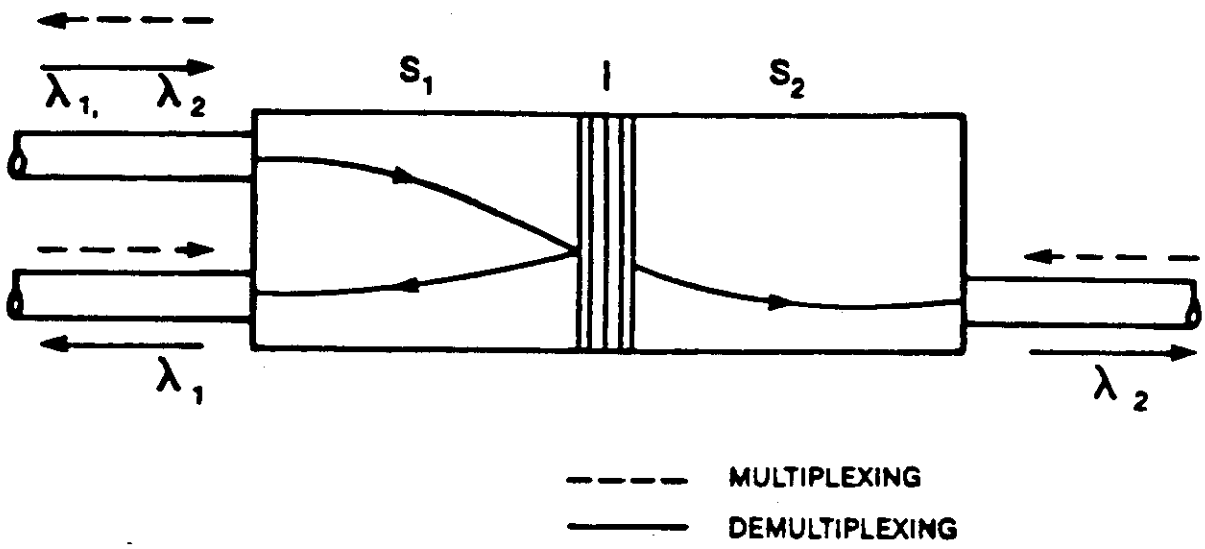

FIG. 9 *Schematic diagram of operation principle of the WDM device.*

behind the WDM device is shown in Figure 9. Figure 10 shows the typical implementation of the device for a 2-wavelength system.

There are several WDM alternatives on the market, with significant variance among vendors. One approach combines operating wavelengths in several different windows (800 to 900 nm, 1200 to 1300 nm, and in the future, 1500 to 1600 nm). Under this approach, with the current limitations in 1500 to 1600 nm technology, the two options are wavelengths in the first and second windows. This limits the repeater spacing to that of short wavelength, and severely reduces the potential for longer spacings with 1200 to 1300 nm wavelengths. For this reason, this approach is not recommended.

The preferred approach is to use WDM at two wavelengths in the 1200 to 1300 nm range. Rockwell currently does this at wavelengths of 1200 and 1300 nm. Adding a third wavelength in the near future in the 1500 to 1600 nm range is possible. Two-wavelength WDM effectively doubles the transmission capacity of each fiber pair, reducing the required fiber count by a factor of 2, while three-wavelength WDM reduces the required fiber count by a factor of 3. In planning the cable size for larger cross sections with out-year requirements, three-wavelength WDM should be considered.

The WDM devices are inserted in series with the fiber at the transmit and receive ends (Figure 10). If crosstalk isolation is sufficient, the only penalty for inserting these devices is the increased attenuation caused by the WDM devices and any additional connectors or splices required to install the devices. When implemented as shown in Figure 10, approximately 4 dB total insertion loss is added by the WDM transmit/receive pair for 2λ devices, while approximately 6 dB for 3λ devices should be planned. For users requiring an additional output/input connector for the mux/demux respectively, approximately 6 dB total insertion loss per transmit/receive pair is added for 2λ, and approximately 8 dB per 3λ WDM.

During the transmission design phase of a system, WDM should be planned on all spans. The cost savings inherent in reducing the required fiber count by 50% or 33% to meet traffic cross sectional requirements are tremendous; the cost of WDM devices is insignificant compared to the cost of the fiber saved. If the span length exceeds approximately 1.5 km, cutting fiber count in half more than pays for the WDM devices. The small increase in fiber performance required to compensate for the loss of the WDM devices only slightly affects fiber cost, not nearly offsetting the savings gained by reducing the required number of fibers. The timing of adding the third wavelength to meet growth requirements will dictate the viability of 3λ WDM. Avail-

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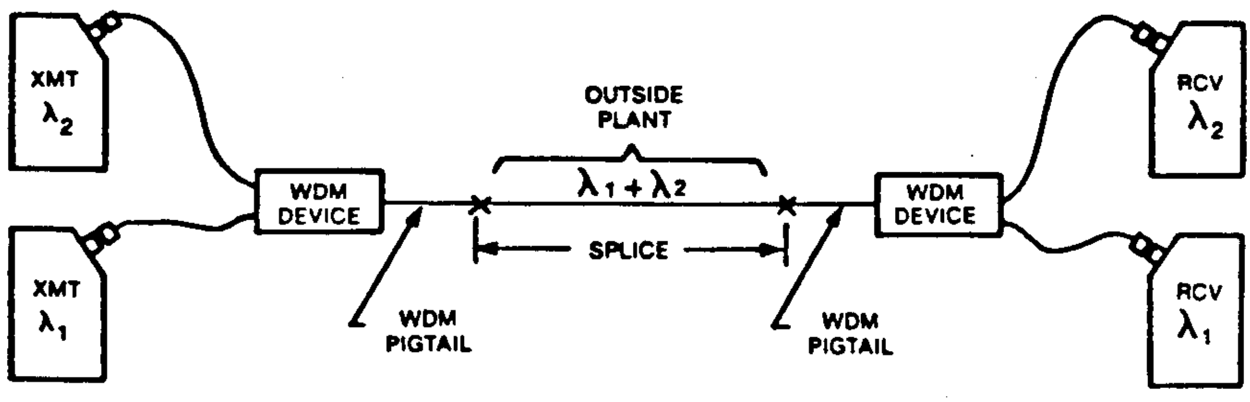

FIG. 10 *System implementation of WDM devices.*

ability before 1984 or 1985 is doubtful.

One potential system application of 2λ WDM devices is represented in Figure 11. In this figure, two parallel 135 megabits per second (Mb/s) systems, each with a fully equipped 1:11 cross section, are multiplexed onto the outside plant cable. These two systems provide a total traffic capacity of over 44,000 equivalent telephone circuits, or almost 4000 circuits per fiber pair. This high level of traffic density demonstrates the economic advantages of WDM, especially when compared to the conventional copper cables that would be required to handle the same load.

A model plan

A sample worksheet for multimode system gain is shown in Table 1. The parameters used in the table are from the Rockwell LTS-135 lightwave transmission system. The following assumptions were also made for this hypothetical system:

- The P_T and P_R parameters shown are typical rather than worst-case parameters. Therefore, a value of 3 dB for A_c was allowed.
- A 3 dB optical bandwidth of 68 MHz (megahertz), which is one-half of the bit rate, was used to minimize the required per-unit cable bandwidth. From Figure 7 (TELEPHONY. Dec. 12, 1983, p. 44), this results in a value for A_B of 1.7 dB.
- The Rockwell P_T and P_R parameters include the module connectors. Therefore, the parameter A_C was specified as O dB.
- An allowance of 4 dB was included for future two-wavelength WDM.

As shown in Table 1, the net value for L, the link loss budget, is 26.3 dB.

This value, along with the required end-to-end bandwidth of 68 MHz, typically would be specified to the cable vendor to aid selection of the appropriate grade of fiber.

The procedures discussed so far provide a means to obtain an allowable installed maximum span loss and minimum span end-to-end bandwidth. The system designer has two options: to specify these installed values to the cable vendor so the cable supplier selects fibers to meet these values, or to calculate the required per-unit values of the fibers and specify them to the cable supplier.

In the first approach, the cable vendor guarantees on a span-by-span basis that the installed and spliced cable will meet the maximum loss and minimum bandwidth requirements specified by the user. The cable vendor then selects fibers from his inventory with either statistical or worst-case attenuation and bandwidth specifications to meet the end-to-end criteria.

The estimated interval between splices and planned operating wavelengths must be specified to permit the cable supplier to select proper fiber performance. The underlying concept of this particular approach is that the cable supplier provides the per unit loss (dB/km) and bandwidth (MHz x km) performance specifications, and also guarantees that the end-to-end performance requirements will be met.

In the second approach, the span end-to-end values are not specified to the cable vendor. Instead, the user specifies the cable per-unit loss and bandwidth performance to the cable supplier as the controlling specification. The required per-unit values are derived by the user, based on the same methods normally used by the cable supplier. This approach, however, usually results

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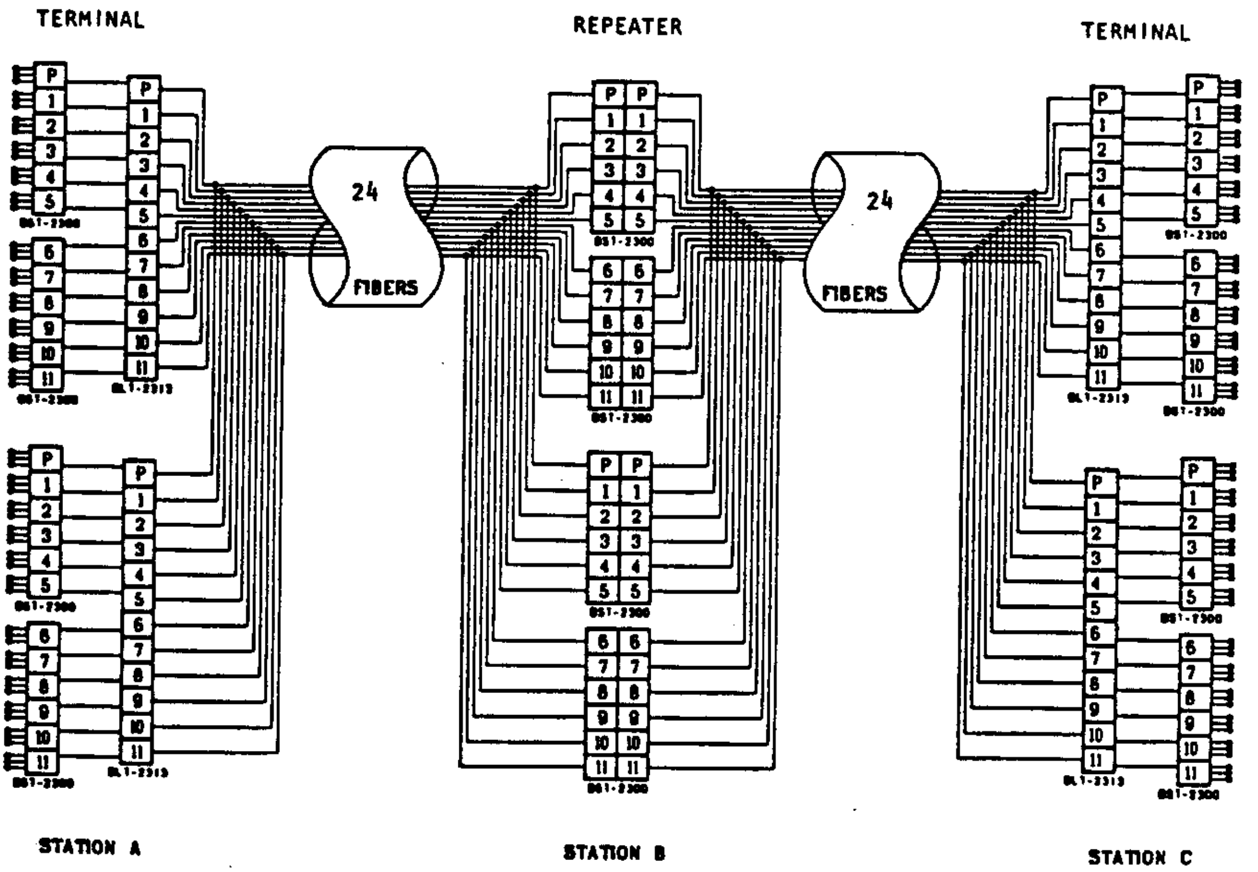


FIG. 11 *A potential WDM configuration for two parallel 1:11 systems.*

in higher fiber prices because every fiber of every reel is now controlled by the per-unit specification. Under the end-to-end approach, the per-unit values are often statistical, allowing the selection of fibers with average performance such that end-to-end values are met. In addition to higher fiber prices, the burden of risk in the second approach now falls on the user if the predicted end-to-end values are not met. Therefore, this method generally is not used.

When the cable vendor has selected the appropriate fiber grades for a system, the data will then be provided to either the lightwave electronics supplier, acting as the system integrator, or directly to the customer. As stated, bandwidth specifications normally are given on a per-unit-length basis, expressed in MHz x km. For example, consider a 20 km span with a required end-to-end bandwidth of 68 MHz. The per-unit specification would then be selected, according to equation 3 which gives us equation (5):

$$BW_{per\ unit} = BW_{eff} \times L^{0.9}$$
$$= 68 \times (20)^{0.9} = 1008$$

The per-unit specification in this case would be 1008 MHz x km. Therefore, the cable vendor would probably select a standard fiber grade with a value of 1000 MHz x km from the inventory.

The values for cable attenuation are generally specified in statistical terms, using methodology developed by the Bell System. The statistical approach requires that a number of cable coefficients be defined in terms of mean values and standard deviations of these values.

The coefficients used in this method are defined as:

μc = Mean fiber loss at 25°C (in dB/km) as measured after manufacture of the cable. This parameter assumes the cable is on the reel and not installed.

μct = Effect of temperature on mean fiber loss (in dB/km) over the specified operating range of the system. This range is typically -40°C to +70°C.

μd = Increase in mean fiber loss (in dB/km) due to laser transmitter drift over the specified stability range of the laser. Laser drift is specified by the equipment manufacturer and is typically ±20 nm.

μs = Mean splice loss (in dB/splice) at +25°C.

μst = Effect of temperature on mean splice loss (in dB/splice) over the specified operating range of the system (-40° to +70°C).

σc = Standard deviation in mean fiber loss (in dB/km) at +25°C.

σct = Effect of temperature on the standard deviation in mean fiber loss (in dB/km) over the specified operating range of the system (-40° to +70°C).

σf = Uncertainty in measurement of cable loss (in dB/km) at the factory due to test equipment tolerance, repeatability and other factors.

σs = Standard deviation in mean splice loss (in dB/splice) at +25°C.

σst = Effect of temperature on the standard deviation in mean splice loss (in dB/splice) over the specified operating range of the system (-40° to +70°C).

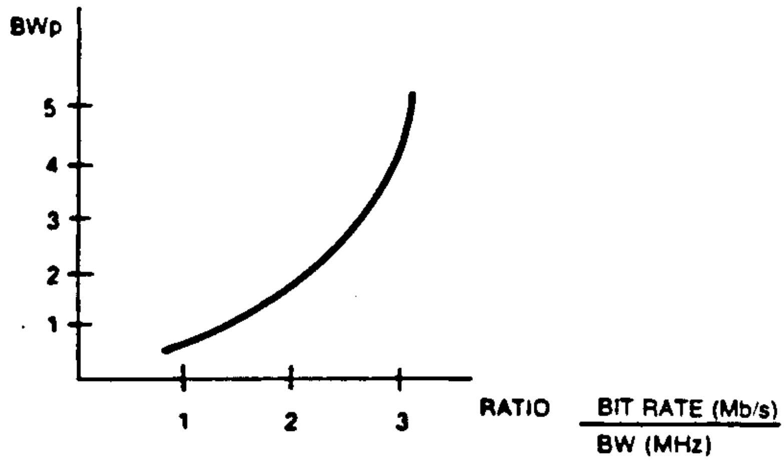
k = Measurement uncertainty in fiber length on the reel (expressed as decimal percent; for example, 10% = 0.1).

N_s+2 = Number of splices specified for the system plus two for future maintenance. The two extra

Table 1

Sample LTS-135 system gain worksheet

PARAMETERS	VALUE
P_T	-5.0 dBm
$-P_R$	-40.0 dBm
G	35.0 dB
$-A_E$	3.0 dB
$-A_B$	1.7 dB(1)
$-A_C$	0.0 dB(2)
$-A_W$	4.0 dB(3)
L	26.3 dB



Notes: (1)Assumed end-to-end optical bandwidth = 68 MHz.

(2)0 additional connectors added at 0 dB each.

(3)Future WDM loss of 4 dB ((2λ)/3λ) allowed.

λ (nm)	Cable Grade	Derived L_{max} (dB)	k	μ_c (dB/km)	μ_d (dB/km)	$\sigma_{c,max}$ (dB/km)	μ_{ct} (dB/km)	σ_{ct} (dB/km)	μ_s (dB)	σ_s (dB)	μ_{st} (dB)	σ_{st} (dB)	σ_f (dB)	Derived $\ell_{t,max}$ (km)	Option
1300	M24090	26.3	0.05	0.90	0.05	0.06	0.02	0.01	0.30	0.05	0.01	0.01	0.15	20.1	1
1520	M24090	26.3	0.05	0.90	0.05	0.06	0.02	0.01	0.30	0.05	0.01	0.01	0.15	20.1	2

* Underground/Buried
† Aerial

FIG. 12 *Cable attenuation values; coefficients can be displayed on a form such as this one.*

splices are reserved in the event the cable is inadvertently cut.

l_t = Derived maximum span length as a function of link loss budget (L).

These coefficients are typically displayed on a form, as shown in Figure 12. The coefficients are used in the following equation (6):

$$L = (1+k)(l_t+0.3)(\mu_c+\mu_{ct}+\mu_d) + (N_s+2)(\mu_s+\mu_{st}) + 2[(1+k)(l_t+0.3)(\sigma_c^2+\sigma_{ct}^2+\sigma_f^2) + (N_s+2)(\sigma_s^2+\sigma_{st}^2)]^{1/2}$$

Although this equation looks difficult to use, it is fairly straightforward. In most cases, the required span length (l_t) is known, as in the sample 20 km span. L also is known from the preceding system gain worksheets, and the required number of splices (N_s+2) are determined as shown in Figure 8. The remaining coefficients (except for μ_c) are essentially fixed and are well-defined by most cable vendors from their manufacturing and field experience. It only remains to select the basic fiber loss—μ_c—to satisfy the equation. In the example, the required span length was 20 km and the link loss budget was 26.3 dB. Rearranging and solving the equation would result in a μ_c of 0.9 dB/km,

Continued on page 49

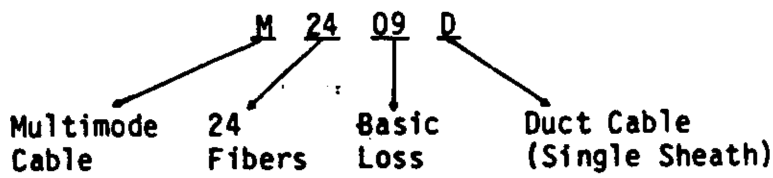


FIG. 13 *A typical designator for a sample cable.*

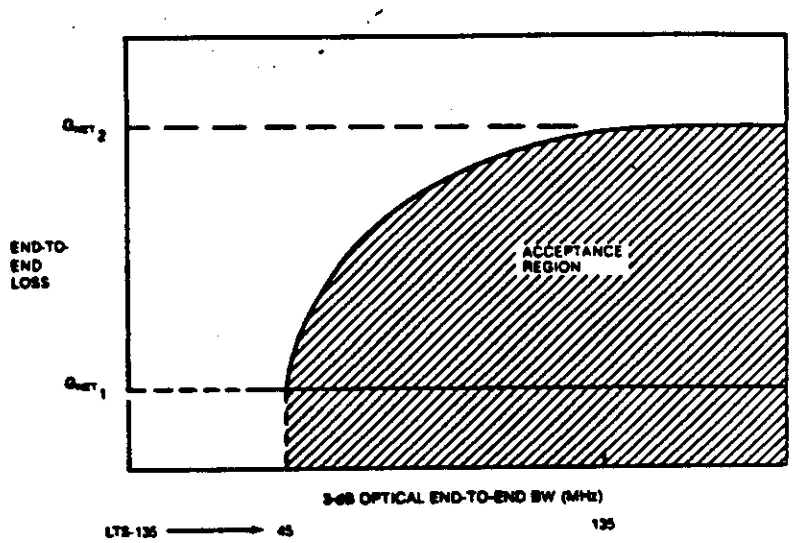


FIG. 14 *An alternate presentation of the required cable performance for the LTS-135 system. This diagram shows bounds on cable loss and bandwidth.*

which is readily achievable with today's multimode fibers. This would be the basic fiber grade selected by the cable vendor. A typical designator for this cable might be as shown in Figure 13.

Note that equation (6) can also be used in another way.

Consider a new system with no existing sites where the span lengths (l_t) have not been defined. In this example, the system designer can use predefined cable grades (or values of μ_c) to determine different repeater spacings. Cost trade-offs can then be made to evaluate the effects of lower cable loss (such as longer repeater spacing but higher cable price) against higher cable loss and more repeater stations. Using this method, the best compromise can be achieved to meet both the system transmission requirements and the lowest overall cost.

An alternate

The methods of specifying fiber performance which have been described often force the cable supplier to furnish cable that does not exceed a particular loss, and meets or exceeds a particular bandwidth. In other words, a single value of maximum loss and a single value of minimum bandwidth are specified. As described previously, the link loss allowed by the electronics is dependent on the bandwidth. In fact, one can be traded for the other.

An alternate presentation of the required cable performance is shown in Figure 14 for the LTS-135 system. Using this approach, a region of acceptable loss/bandwidth values is shown in the shaded region. Any combination of the two values that falls within the shaded region are permissible. Values within this region will result in proper operation of the electronic equipment and lower priced fiber due to increased latitude in cable selection by the fiber supplier.

This approach is not generally applied at this time, but is gaining acceptance as the effects of bandwidth on link loss budget are better understood. □

The third part of this three-part article, which will appear in a coming issue of TELEPHONY, *will discuss single-mode considerations, including fiber spectral attenuation characteristics, fiber dispersion characteristics, equipment system gain, splicing loss and interval, wavelength division multiplexing and specifying fiber performance.*

The Development of Single-Mode Fibre Transmission Systems at BTRL

Part 1—Early Developments

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In this first of two articles, the development of single-mode fibre systems at British Telecom Research Laboratories from 1979 to 1982 is charted with particular emphasis on the field-trial results and the impact upon the evolution of the trunk network. The second part of this article will describe the developments to date and discuss the future potential of single-mode fibre applications.

INTRODUCTION

The origins of single-mode (monomode) fibre as a transmission medium stretch back to the seminal ideas[1] of Kao and Hockham in the mid-1960s. The enormous bandwidth potential of light frequency ($\approx 10^{14}$ Hz) carriers was one of the main attractions of this medium and stimulated an intensive research programme at the British Telecom Research Laboratories (BTRL). It was recognised that, if solutions to the many practical difficulties could be found, then the communication engineers' dream of virtually unlimited bandwidth would be realised. The translation of this dream into reality has taken a more tortuous path than perhaps had first been imagined. However, over the past four years, as this realisation has taken shape, the long-term prospects have come more into focus to indicate areas of application not considered in the early days.

The practicalities of fabricating, splicing and coupling low-loss single-mode fibres, with core dimensions of only a few microns, were identified at an early stage as being among the major problems to be solved. The requirement in the early-1970s for a rapid evolution of fibre technology to the systems demonstration stage meant the temporary abandonment of single-mode fibre for multimode fibre. This fibre, with its large core diameter of several tens of microns, offered simpler splicing and coupling than single mode, albeit with low bandwidth due to the dispersion caused by the variation in the velocity of the many propagating modes. In consequence, a concentration of effort at low bit rates (8 Mbit/s) ensued and, in 1975, at the opening of BTRL at Martlesham Heath, an 8 Mbit/s system operating over a 6 km multimode fibre link was demonstrated.

In 1977, two significant field-trial systems using cabled multimode fibre installed in duct in the Martlesham area were demonstrated[2, 3]. Although originally planned as a step-index multimode experiment, graded-index fibre cable having superior bandwidth performance, due to its mode velocity equalisation property, became available and allowed experiments to be carried out at 140 Mbit/s as well as 8 Mbit/s. These experiments gave the first indications that fibre cables could be successfully installed in duct, spliced (jointed) and operated over repeater sections much longer than conventional copper-media based systems.

During the late-1970s, silica-based fibre, with losses of less than 5 dB/km in the 800–900 nm wavelength region, was beginning to dominate the fibre scene. Reliability performance of the opto-electronic devices (light-emitting diode (LED) or laser and photodiode) was improving and there was the growing prospect of operational systems being required by BT. However, in the mid to late-1970s, research establishments throughout the world were drawing attention to the possibility of lower-loss fibre, perhaps as low as 1 dB/km, at 1300 nm wavelength. Also, the chromatic dispersion, normally a significant bandwidth reducing factor at 800–900 nm with modulated LED and laser sources having wide optical spectra, is virtually zero in silica fibre at 1300 nm wavelength.

Opto-electronic device development for the 1300 nm wavelength region required new materials technology and, in the late-1970s, research programmes were gradually shifted to producing suitable semiconductor lasers and photo diode detectors.

The new wavelength region stimulated a re-awakening of single-mode technology since yet lower loss still, <0·5 dB/km, could be achieved, and work began in earnest at BTRL in 1978. Since modal dispersion disappears with single-mode propagation and chromatic dispersion had been virtually removed by the shift in wavelength, the fibre now offered almost limitless bandwidth. The development had come full circle, but with the prospect of repeater spacings at least of an order of magnitude greater than for equivalent copper-media systems.

In 1979, BT embarked on a major ordering programme for fibre systems for trunk and junction routes. These orders were for systems operating at 800–900 nm wavelength. Clearly, the future ordering programme would increasingly gravitate towards 1300 nm operation as confidence grew in the device technology for the longer wavelengths. The question then posed was should the network opt for a single-mode or multimode solution. The advantages of the single-mode solution were so attractive for the trunk network that BTRL stepped up the programme of research begun in 1978 to attempt to solve the practical problems that had remained since the early-1970s. In 1980, a demonstration of a 37 km unrepeatered system operating at 140 Mbit/s and 1300 nm during the first Martlesham Open Week indicated the potential of the single-mode approach. This experiment also demonstrated for the first time that the 30 km maximum separation of power feed stations in the UK trunk network could be bridged without a repeater. The components for this demonstration were all developed at BTRL initially for the inland network, but it had been realised that systems using single-mode fibre were well suited to undersea applications where maximising repeater spacing was a prime concern. In 1980, a 10 km link working at 140 Mbit/s and using identical components was demonstrated at Loch Fyne in collaboration with Standard Telecommunication Laboratories (STL). These and other demonstrations of single-mode capability encouraged the development of solutions to the cabling, splicing, coupling and systems problems.

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The culmination of the initial phase of research activity on single-mode fibre systems was the demonstration of field installed cables having low splice losses and carrying digital signals at up to 650 Mbit/s over links up to 60 km without intermediate repeaters. Several demonstrations of this type were undertaken during 1982, with further upgrading experiments performed subsequently, some of which took place in the lower-loss window at 1550 nm.

SINGLE-MODE FIBRE

The description of propagation in single-mode fibre has been dealt with elsewhere[4]; note that the ray-path approach used with multimode structures is no longer applicable and that electromagnetic (EM) field theory must be used. In single-mode fibre, the core diameter can be only 8 μm with a cladding diameter of about 125 μm.

Current single-mode fibres are based on silica, doped with other materials in order to produce the refractive index difference between core and cladding necessary to give guidance or propagation. Various materials-related loss mechanisms in these glasses produce absorption or scattering of the optical power in the propagating mode, and thus limit the available system repeater spacing. At shorter wavelengths, the ultra-violet absorption edge dominates, while at long wavelengths, the infra-red absorption from the oxides of the glass is the major loss effect. In between these two regions, Rayleigh scatter (due to particles of size comparable to the wavelength of the light transmitted) is, for the most part, the dominant loss mechanism. However, at wavelengths corresponding to the oxygen-hydrogen (O–H) bond overtone absorption lines (950 and 1370 nm) and at associated combination bands, absorption losses can be dominant. These effects result in two low-loss windows, at 1300 and 1550 nm. Attenuation in these windows is due to Rayleigh scatter, remnant O–H absorption and absorption from combination bands of the fibre dopants with O–H. Unfortunately, dopants added to the silica to produce the necessary fibre properties tend to increase the Rayleigh scatter. The need to keep processing temperatures as low as possible during fabrication militates against the use of pure silica for either the core or the cladding (in spite of the attraction of such structures on loss grounds). The necessary processing temperatures reduce with increasing dopant levels. These loss mechanisms and the best combination of dopants to use for the core and cladding for lowest loss have been the subjects of extensive study at BTRL[5,6]. The resulting solution uses a core region uniformly doped with germania (GeO). The cladding region uses both fluorine and phosphorus as dopants. These two dopants have opposite effects on the silica refractive index, allowing the cladding index to be matched to that of silica whilst enabling the processing temperature to be lower than that for pure silica. The dopant concentration in the cladding is arranged to be a maximum furthest from the core, reducing to nearly zero in the most loss-sensitive region near the core. In this way, losses can be reduced to minima of around 0·3 dB/km and 0·2 dB/km in the 1300 and 1550 nm windows, respectively.

Whilst the single-mode fibre eliminates modal dispersion, the small core region presents a challenge for splicing or jointing, since the cores must be accurately aligned, perhaps to within ±0·5 μm. The launching of light from a source such as a semiconductor laser, with its divergent asymmetric radiation pattern, into a small-core fibre is also more demanding in alignment accuracy. These factors were partly responsible for single mode being put to one side in the early to mid-1970s in favour of multimode technology.

In single-mode fibre, chromatic dispersion is the major bandwidth limiting effect. (Polarisation dispersion due to any slight ellipticity of the core also occurs, but this effect can usually be neglected.) Since most light sources, including lasers, do not always emit just a single wavelength, then the dependence of the fibre material refractive index (and hence velocity of propagation) on wavelength leads to dispersion effects. The semiconductor laser often emits a broad spectrum or 'comb' of wavelengths with each 'tooth' having a slightly different propagation velocity and, therefore, transit time along the fibre. The resulting dispersion, which produces intersymbol interference (ISI) in a digital system, can be obviated by reducing the spread of wavelengths (linewidth) emitted by the source and/or choosing the wavelength region of operation to be where the dispersivity is a minimum. Fortuitously, silica exhibits zero chromatic dispersion at 1300 nm, a wavelength at which the fibre loss is invitingly low (<0·5 dB/km).

A typical spectral-loss plot for single-mode fibre is shown in Fig. 1. The two low-loss windows are evident, one around 1300 nm and the other centered on 1550 nm. A large part of the loss is due to Rayleigh scatter in the silica. Since this loss reduces with the fourth power of wavelength, the fibre loss is lower at 1550 nm than at 1300 nm. However, the chromatic dispersion at 1550 nm is not zero and narrow linewidth laser sources will be needed to exploit effectively the lower loss.

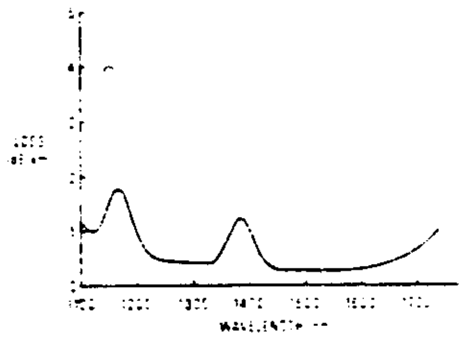

FIG. 1—Spectral loss of a single-mode fibre

Single-Mode Fibre Design and Specification

A more detailed investigation of the design of the single-mode fibre is necessary to assess properly the above properties. One of the main aims was to arrive at a fibre design that would work well in existing cable structures and allow 'standard' cabling techniques in manufacture and installation to be used for both multimode and single-mode fibre.

The need to minimise overall link loss produces several detailed constraints on the fibre design.

(*a*) *Cut-off wavelength* This is the wavelength which marks the transition between multi- and single-mode operation: above this wavelength the operation is single mode. In general, the cut-off wavelength must be below the operating wavelength.

(*b*) *Intrinsic fibre loss* This is the combination of Rayleigh scatter and losses due to dopants introduced into the silica to form the fibre core and/or to water (O–H ions) in the fibre.

(*c*) *Incremental cable loss due to microbending* This is superficially similar to the same phenomenon in multimode fibre, but here concerns minute bends in the fibre, coupling only one guided mode out of the core.

(*d*) *Splice loss* This is due to a combination of concentricity error, EM field mismatch and splicing techniques used.

Work at BTRL in the late-1970s was concerned with experimentally investigating these factors to arrive at the optimum design. The fibre design is specified in terms of the two measured parameters: the mode cut-off wavelength and

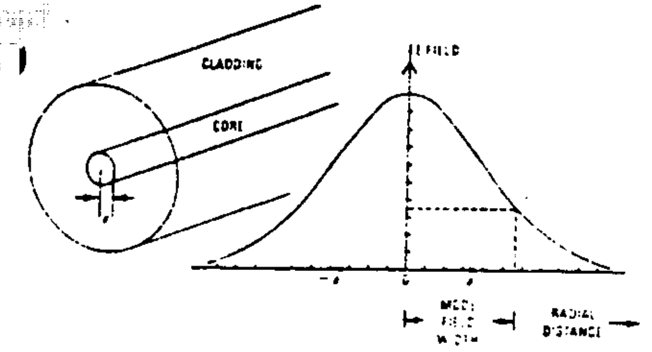

FIG. 2—Approximation to the electric field (mode field) distribution in a single-mode fibre

some measure of the mode field width (Fig. 2). Care must be taken to link these experimentally-determined quantities to the measurement technique used, an important technique being that of the offset joint[7].

If a plot with these two quantities as axes is produced, the fibre specification appears as an area on the plot, with the constraints as lines bordering the specification 'box', [illegible] is shown in Fig. 3. Taking each constraint in turn:

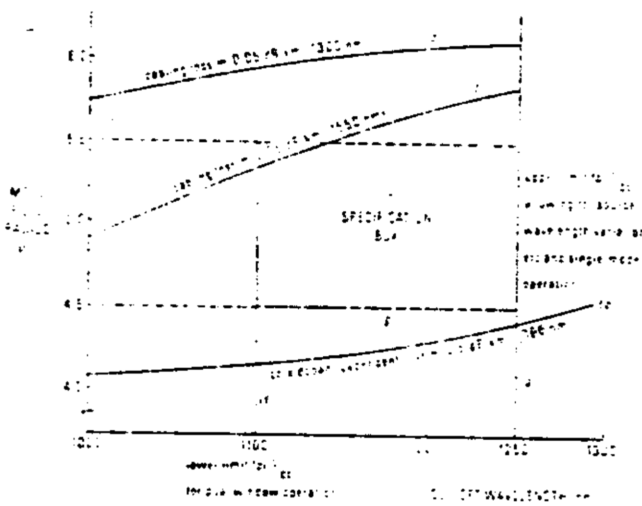

FIG. 3—Fibre design diagram

Cut-Off Wavelength

From a consideration of source wavelength variations, it is desirable to specify the fibre loss and to operate the systems over a wavelength range of 1275–1325 nm in the 1300 nm window. To avoid any possibility of bi-moded fibre at an operating wavelength, an upper value of 1250 nm is placed on the cut-off wavelength—this is line (a). A lower limit of 1100 nm has been adopted in order to minimise the effects of cabling loss and dispersion—this is line (e).

Intrinsic Fibre Loss

Fibre loss increases with doping level (germanium and fluorine are added to the fibre core to raise its refractive index above that of the cladding) and with O–H content. The dopant-level-dependent loss places an upper bound on the fibre refractive index difference, leading to a lower bound

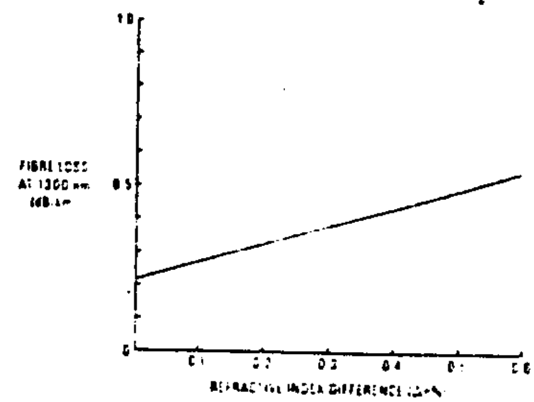

FIG. 4—Dopant level dependent loss as a function of index difference (Δn%)

on the field width for any particular cut-off wavelength. Fig. 4 shows empirical data for this loss at 1300 nm as a function of index difference, after the O–H contribution has been removed. If 0·5 dB/km is taken as a maximum for this loss, boundary line (b) in Fig. 3 is produced. The O–H contribution can be expected to add less than 0·05 dB/km to this figure.

Incremental Cabling Loss

In step-index single-mode fibre, the mode becomes less well guided as the wavelength is increased away from the cut-off, and eventually becomes susceptible to microbending loss from the cable structure. A fibre for operation in both windows must have the cut-off below 1300 nm and the microbending loss edge beyond 1550 nm. For any particular fibre core diameter, this places a lower limit on the fibre refractive index difference, corresponding to an upper limit on the mode field width. Since various types of cable are used by BT, it becomes a matter of some difficulty to determine the level of microbending to which any particular fibre will be subjected. Empirical data for a loose-tube coating is shown in Fig. 5. The worst-case situation for this cable type corresponds with the fibre left under some tension against the tube wall. Fig. 6 shows similar data for a tight secondary fibre coating. In spite of the very different cabling situation, a similar lower limit on index difference (Δn) is obtained in each case. Assuming a limit of 0·05 dB/km incremental loss from microbending, the loose-tube data is plotted in Fig. 3 as line (c). If operation at 1300 nm only is required, the data can be converted theoretically to show the same limit at 1300 nm as line (d). Fibre within the

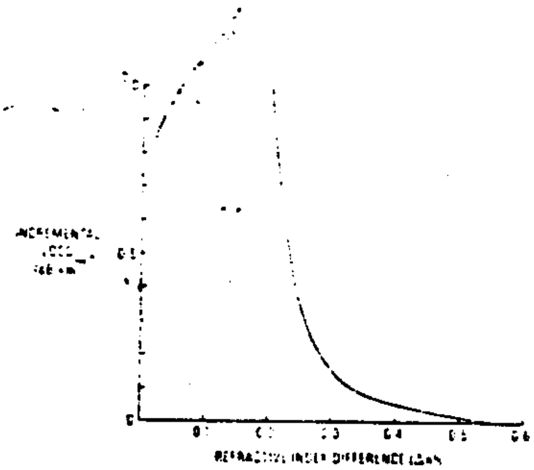

FIG. 5—Incremental loss at 1550 nm for a loose-tube fibre versus index difference (Δn%)

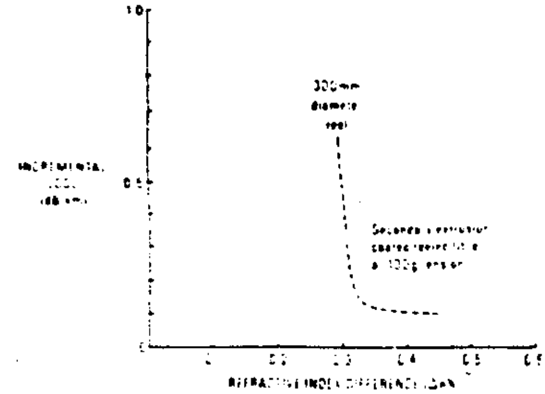

Fig. 6—Incremental loss at 1550 nm for a tight secondary coating versus fibre index difference (Δn%)

specification box could thus be expected to have average losses of around 0·45 dB/km at 1300 nm and 0·3 dB/km at 1550 nm, and could be cabled by using existing cable types with negligible loss increase at either wavelengths

Dispersion

The nominal step-index profile fibre design adopted by BT has a zero chromatic dispersion point around 1325 nm. Near the dispersion minimum, broad spectrum lasers can be used without incurring a serious penalty. As operation moves from the zero dispersion point, the penalty increases, and ultimately requires the use of narrow spectrum sources.

The dispersion characteristics of step-index fibre meeting the BT specification are shown in Fig. 7. Curve 1 is for a typical fibre with dispersion minimum at 1325 nm and the curves either side show the extremes that are expected for fibre falling within the specification box. Curve 2 corresponds to a fibre in the top-right-hand corner of the box and curve 3 to a fibre in the lower-left-hand corner. It is fibres in this region of the specification box that will first give rise to dispersion penalties and, therefore, is a further incentive to restrict the lower cut-off wavelength bound to 1100 nm.

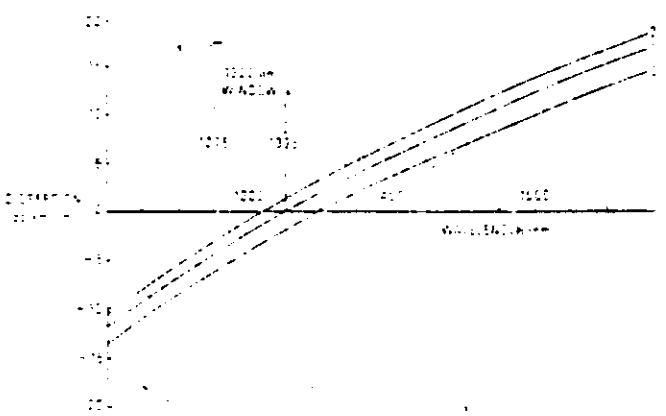

Fig. 7—Dispersion versus wavelength for single-mode fibres

Splice Loss

The main splicing technique for single-mode fibre is currently electric-arc fusion. Core concentricity and mode field width mismatch form the main fibre-related loss contributors. The effect of any given concentricity error on splice loss reduces as the field width is increased, making it desirable to operate towards the top of the area between the cabling (*c*) and cut-off (*a*) lines. Unfortunately, this reduces the available cut-off range, a good compromise is a field width centre of 5 μm. At this field width, a concentricity error of 0·5 μm in the two fibres could produce a maximum splice loss of around 0·2 dB due to this effect. Fibre production spreads and joint alignment statistics give an average splice loss considerably less than this figure. A field width range of ± 0·5 μm around the 5 μm centre (lines (*f*) and (*g*) in Fig. 3) gives a possible maximum splice loss due to field width mismatch of 0·17 dB. Again, an average value much less than this would be expected when the spread of fibre parameters and the statistical aspects of splicing are taken into account.

SPLICING TECHNIQUES

There are several well-documented techniques for the splicing of single-mode optical fibres and these can be generally classified on the following basis:

(*a*) fully-fused splices using cladding alignment only (optical power monitoring is not used);

(*b*) partially-fused splices using core alignment by optical power monitoring, to reduce losses due to core concentricity errors;

(*c*) fully-fused splices where core offset is minimised by using optical power monitoring and fibre rotation; and

(*d*) glued splices where core alignment by optical power monitoring is used to reduce core-concentricity errors, and core deformation is eliminated by avoiding the fusion process.

The fusion process involves butting together the two fibres to be spliced in the vicinity of some heating device, usually an electric arc. The fibres are then simply melted or fused together. In order to obtain low losses, however, this process has to be very carefully controlled, usually by a microprocessor. The glue technique bonds the fibres together by using some form of transparent adhesive.

The choice of technique to be used depends on the fibre specification, design and its application.

Splice Performance Comparison

The fundamental performance criterion is mean splice loss. In general, the mean splice loss in single-mode fibres can be considered to consist of three components:

(*a*) field width mismatch,

(*b*) core displacement due to core concentricity error, and

(*c*) core deformation due to the fusion technique.

Table 1 summarises the contributions from these components to the total splice loss for the four splicing classifications given above.

Field Width Mismatch

The loss contribution from field width variation is a fundamental splice loss limit. If Gaussian statistics for the distribution of field widths and the limits mentioned above (5 μm ± 0·5 μm) are assumed, then the mean loss introduced is less than 0·03 dB.

Core Concentricity Error

The question of which splicing technique to adopt hinges on the effect of core concentricity on splice loss. The allowable loss that can be allocated for concentricity effects will in turn determine the geometrical parameters in the fibre specification required for each of the splicing techniques discussed. The fibre specification will then determine fibre yields from given manufacturing processes and bear directly on the fibre's cost.

In order to assess the allowable allocation of splice loss arising from the effects of concentricity error alone, it is

TABLE 1

Splice Performance Comparisons

Loss Mechanism	Method (*a*) Fusion Cladding Alignment	Method (*b*) Fusion Core Alignment	Method (*c*) Fusion Fibre Rotation	Method (*d*) Glue Splicing
Field width mismatch	Same for all techniques			
Core displacement due to concentricity error	Depends critically on fibre specification	Does not depend significantly on fibre specification. Limit depends on alignment accuracy	Depends on fibre specification, but may be relaxed compared with method (*a*)	Independent of fibre specification. Limit given by alignment accuracy
Core deformation	Is minimised by machine parameters. <0·05 dB for standard system fibre	Additional deformation due to surface tension forces trying to align claddings. Minimised by short-duration fusion cycle	Same as for method (*a*)	None

necessary to examine system requirements and power budgets. A detailed statistical analysis was used to obtain a value for the mean system splice loss that can be tolerated for a 30 km 140 Mbit/s system. Then, by using the distributions of the component losses (field width mismatch, core deformation and concentricity error), values for the maximum tolerable concentricity error can be determined. (Less than 0·7 μm should give a mean loss below 0·08 dB, which is adequate for this purpose.)

Core Deformation

Splice loss due to core deformation occurs to some degree in all fusion-splicing processses and arises from three major causes.

(*a*) Surface-tension forces act to align the claddings of the fibre at the splice point. The effect, therefore, of any initial cladding misalignment is to introduce a shear force across the faces of the fibres during fusion.

(*b*) End-face angle on the fibres being fused also causes core deformation. When a single-mode fusion splicing machine is set up and operated correctly, end-angle effects are probably the dominant cause of core deformation.

(*c*) Contamination of the fibres by foreign material in the splice region, for example, dirt or primary coating material not being completely removed, is an often underestimated contribution to poor-quality fusion splicing.

Fusion-splicing techniques suffer from about the same amount of core deformation. Method (*b*) using power monitoring during core alignment will be prone to surface-tension forces increasing with core concentricity error. The effect of this may be mitigated by a short-duration heating cycle optimised for this method. On the other hand, method (*a*) uses these surface-tension forces for the final alignment of the fibre claddings. It is found that the initial visual cladding alignment under a low-power microscope is generally accurate to the order of 1 μm and that this residual misalignment produces insignificant core deformation. The glued-splice technique produces no core deformation and, in principle, could produce the lowest loss splices. Note, however, that there may be a small loss due to the refractive index mismatch (Fresnel loss) at the fibre/glue interfaces.

Splice Strength

High-strength fusion splices may be achieved with care and attention to absolute cleanliness in the preparation of the ends of the fibre. Post-etching in hydrofluoric acid increases the strength of the fusion splices dramatically. This high-strength splicing may be achieved with techniques (*a*) and (*c*). Splices made by using technique (*b*) are likely to be weaker because of the discontinuity in the outside diameter and because a full fusion does not take place. The strength of glued splices is likely to be lower than those achieved by using fusion techniques. In general, for land-based systems, strain relief for the fibres and splices is provided in the joint housing and very-high-strength splices are not essential. The major application for high-strength splices is in undersea systems, where production-line high-strength splicing is required in order to produce long cable lengths without full-joint housings.

Complexity of Splicing Technique

There are two distinct categories of splicing techniques described above: those where optical power monitoring is required and those where it is not. In technique (*a*), the splicing-machine operator visually aligns the fibre claddings to an accuracy in the order of 1 μm by using micromanipulators and a two-axis microscope. The fibres are butted together and automatic fusing takes place under the precise control of a microprocessor. Full fusion occurs, thus allowing the final very precise alignment of the fibres to be brought about by surface-tension forces.

The simplest power-monitoring system requires optical power to be launched into the remote end of the fibre to be spliced and either a distant or local receiver to feed back a signal related to the power coupled into the spliced fibre. The fibres are then aligned either by the operator or automatically so that the coupled power is maximised prior to splicing.

Power-monitoring systems can require an extra team at the launch site and possibly a further team at the receive site if local monitoring is not used. In addition, sequential splicing along a route may often be necessary. This could be disadvantageous since installation practices and local road traffic problems may restrict splicing to times outside normal working hours on difficult or busy sections of the route.

If a local injection/detection scheme is used to avoid the above problems, the length of stripped fibre at the splice could be fairly large, and this increases the risk of damage to the fibre and makes subsequent mechanical protection more difficult. However, injection/detection through the coatings can be used in order to avoid long lengths of uncoated fibre, but this is dependent on the choice of materials used for the primary and secondary coatings.

As a result of the detailed studies of splicing techniques undertaken at BTRL during the late-1970s and early-1980s, BT has adopted fusion splicing without power monitoring as the initial splicing technique for the trunk network modernisation programme The main reason for this is the simplicity of the technique for the field environment. As the use of single-mode fibre moves into the junction and local networks, the need for simple and low-cost splicing techniques increases. The fusion process adopted offers the greatest potential for simple low-cost, yet high-quality, splicing

SINGLE-MODE FIBRE SYSTEMS TRIALS

The production of quantities of experimental single-mode fibre at BTRL with loss less than 0·6 dB/km at 1300 nm wavelength led to a series of system tests beginning in 1980. The development of suitable transmitter and receiver modules at BTRL had been proceeding during the late-1970s, initially for graded-index multimode systems, but subsequently for single-mode fibre applications

Transmitter and Receiver Modules

The basic opto-electronic devices for operation at 1300 nm, that is, lasers and photodetectors, were incorporated into hybrid packages, usually in dual-in-line format, with integral fibre tails for connection to the main transmission fibres. A transmitter module typically comprised an optical source, often a semiconductor laser chip, and the necessary optical coupling components such as miniature lenses and a copper submount alignment jig to achieve an efficient launch of optical power into the single-mode fibre tail[9]. This package, shown in Fig 8, was also able to incorporate electronic

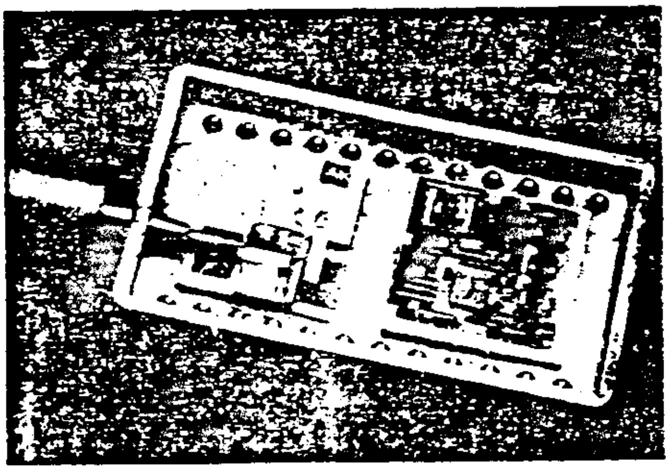

Fig. 8—Laser transmitter module showing fibre (left), submount, laser chip and feedback photodiodes (centre left) and IC controller chip (right)

interfaces in the form of drive and bias circuits The stabilisation of the laser operating point against temperature variations and ageing was of major importance since it was recognised that 1300 nm lasers were likely to be more temperature sensitive than their 850 nm counterparts. Successful operation at 140 Mbit/s and above in a practical systems environment depended on the effect of laser switch-on delay[10] being minimised without other performance criteria being compromised The development of the module therefore included a rear laser facet monitoring photodiode and specially developed BTRL integrated circuit for the control of the bias and drive signals[9].

The hybrid packaging concept became vitally important to the development of receivers at 1300 and 1550 nm. Fundamental changes to receiver design became necessary when the new wavelength region was adopted, since the silicon avalanche photodiode (APD) that had given such good performance at 850 nm could not be made to detect beyond about 1100 nm. The APD can be regarded as a device that detects incoming optical signals, and converts them to equivalent electrical current signals which undergo amplification within the device itself by a carrier avalanching effect, the gain is dependent upon the applied voltage. The effective noise figure of such a device is dependent in a complex fashion upon the gain and the level of the input signal The commercially available silicon APD could be operated with a noise figure much less than that of a conventional transistor amplifier. However, commercially available APD devices operating at 1300 and 1500 nm were germanium based with effective noise figures much higher than those for silicon and with a significant temperature dependency as well.

A number of research laboratories undertook development of APD devices in materials related to those being used for laser development; that is, gallium indium arsenide (GaInAs) and gallium indium arsenide phosphide (GaInAsP) III-V based semiconductor alloys. However, at BTRL, it was believed that any long-wavelength APD development would be on a long time-scale since these devices are structurally complex and therefore difficult to fabricate (true even in silicon, which is a well-characterised material). For this reason, the development of a simple non-avalanche GaInAs PIN structure photodiode was initiated by BTRL both internally and at Plessey Research. In order to achieve adequate sensitivity performance, it proved necessary to ensure that both the photodiode and following transistor preamplifier had low capacitance and that the input transistor was a low-noise device. Only by using hybrid integration techniques was it possible to achieve this first objective. The receiver, shown in Fig. 9, comprised a PIN

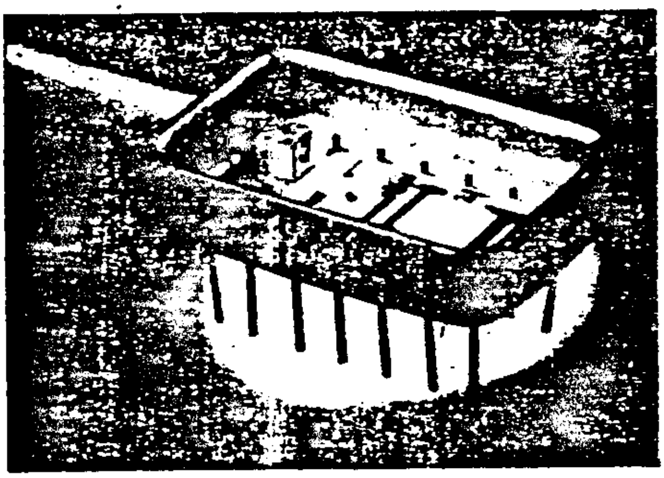

Fig. 9—PINFET receiver module showing fibre entry (left), quartz cube submount for photodiode (centre left) and preamplifier circuit (centre and right)

photodiode connected to a low-noise GaAs field-effect transistor (FET) device forming the first stage of amplification. Further amplification and buffering was also provided in the package by using additional bipolar transistor devices. The resulting module, known as a *PINFET* receiver, had sensitivity performance better than commercial germanium APDs in 1979[11]. More recently, both III-V and germanium-based APDs have been developed in the USA and Japan. These detectors have shown improved sensitivity so that performance is now comparable with PINFET receivers, which have also advanced in this period. Operational considerations are now, and in the future, likely to play a more dominant role in the choice of receiver technology.

…tial System Tests

The development of the transmitter and receiver modules at BTRL was undoubtedly a key factor in the successful demonstrations that took place during the 1980s over long lengths of single-mode fibre. In the first of these experiments, a prototype laser transmitter operating at 1275 nm was modulated with a 140 Mbit/s $2^{10}-1$ non-return-to-zero (NRZ) pseudo-random binary sequence (PRBS) test signal. The mean output power coupled from the laser into the fibre without lensing was 80 μW, or −11 dBm—an efficiency of about 10%. A continuous 37 km length of single-mode fibre coated, but not packaged or cabled, was butt connected to the fibre tail of the transmitter module. The loss of this fibre was about 0·7 dB/km at 1275 nm, slightly higher than the 1300 nm figure. The short multimode fibre tail of the receiver was connected to the main fibre via a lens connector. The sensitivity of the PINFET receiver was measured to be 50 nW, or −43 dBm, at 140 Mbit/s, with an error rate of 10^{-9}. The photodiode quantum efficiency, the proportion of incoming light that contributes to useful current flow, was 40%. The low-level output signal from a PINFET receiver, usually an integrated version of the received optical signal, was equalised by a differentiator and fed a regenerative repeater.

The repeater comprised linear and limiting wideband amplifiers, a clock extraction circuit and a bistable decision gate. The repeater also included an equaliser, which, in the … of single-mode fibre systems, is usually just a low-pass …er. The gain blocks and digital circuits were implemented by using integrated circuit components, no discrete devices …e used. The system block diagram is shown in Fig. 10. …is system was successfully operated over the full 37 km unrepeatered length with a system margin of 3 dB. A further experiment was undertaken in the 1550 nm low-loss window where the fibre attenuation averaged about 0·4 dB/km. The laser transmitter was changed for a prototype 1510 nm laser chip mounted on a package header. A BTRL photodiode capable of operating at both 1300 and 1550 nm had been used in the receiver module enabling the receiver/regenerator combination to remain unchanged. The reduced fibre loss enabled an extra 12 km of fibre to be added to the link to form a continuous 49 km length. This system again operated successfully with about a 3 dB system margin. However, some important differences were noted between the two experiments. At 1300 nm, the performance was loss limited, in other words the link length achievable was set only by the laser coupled power, the receiver sensitivity and the fibre loss. On the other hand, at 1510 nm, when the receiver sensitivity was measured through the 49 km length, an additional penalty of about 0·7 dB resulting from the …action of the broad spectrum of the laser and the fibre dispersion was discovered. The power budgets for these tests are given in Table 2.

TABLE 2

Power Budgets

Wavelength	1275 nm	1510 nm
Link length	37 km	49 km
Bit rate	140 Mbit/s	140 Mbit/s
Path loss	29 dB	24 dB
Transmitter coupled power	−11 dBm	−15·4 dBm
Received power	−40 dBm	−39·4 dBm
Receiver sensitivity	−43·5 dBm	−44·2 dBm
Laser extinction penalty	0 dB	1 dB
Dispersion penalty	0 dB	0·7 dB
System margin	3·5 dB	3·1 dB

Dispersion and Laser Spectrum

The dispersion of the fibre in the 1550 nm window was known to be in the region of 15 ps/nm/km; that is, after 1 km of fibre a launched impulse will have been transformed to a Gaussian pulse with 1/e full width of 15 ps for every nanometre of source linewidth, the linewidth being a measure of the spread of wavelengths emitted by the source. The 1510 nm laser was estimated to have an effective linewidth of 4 nm so that the dispersion amounted to about 3 ns, just under half the bit time for a 140 Mbit/s system. Since the transmitter launched full-width pulses, that is, 7·14 ns wide pulses, and not impulses, the dispersion of the fibre spreads these pulses into their adjacent time-slots, and causes ISI. About 1 dB of ISI penalty results when the dispersion is equivalent to half a time-slot and 5 dB when it is a full time-slot. This initial experiment at 1510 nm was nearing dispersion limited operation.

It was appreciated that if the 1550 nm window of this fibre was to be fully exploited with conventional single-mode fibre, then some measures to narrow the source linewidth needed to be taken. Subsequent 1550 nm source developments were aimed towards achieving this end (at 1300 nm the linewidth problems were of less concern). The spectrum of a semiconductor laser, as mentioned earlier, is often a comb of discrete wavelengths generated by the multiple cavity resonances. When modulated, this spectrum undergoes changes, with the first part of the pulse usually exhibiting the highest degree of instability of spectrum. Under DC conditions, or during the latter part of a long pulse, the spectrum stabilises and, in certain devices, can exhibit nearly single wavelength operation. A possible evolution of the wavelength spectrum of a semiconductor laser is shown in

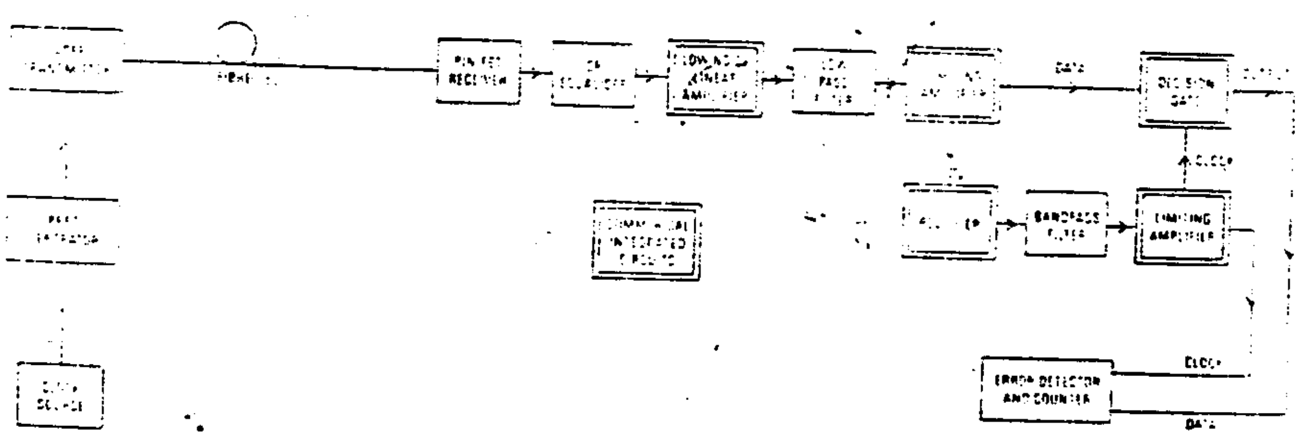

FIG. 10—Block diagram of fibre system under test, showing receiver regenerator configuration

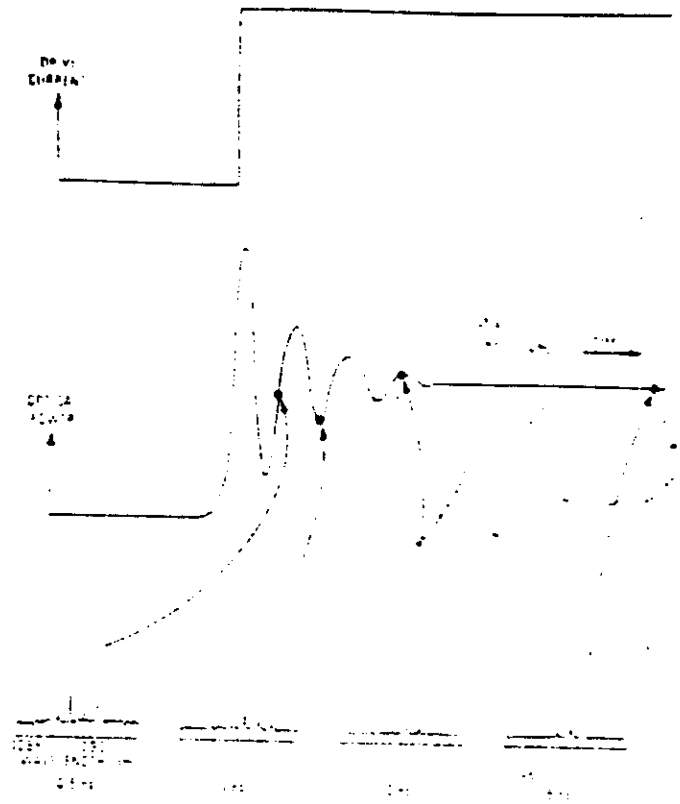

FIG. 11—Evolution of the mode spectrum of a nominal 1300 nm wavelength semiconductor laser

schematic form in Fig. 11. Note the transient ringing of the optical pulse, a distinctive feature of a pulsed semiconductor laser. A spectral line is referred to as a *longitudinal mode* and the presence of just one line referred to as a *single longitudinal mode* (SLM); the term *mode* here means cavity mode rather than propagating mode. The envelope of the comb of wavelengths bring about the dispersion penalty mentioned before, but additional effects were predicted even when an SLM was predominant.

During the life of a laser device, temperature and ageing effects may change the position of the SLM. It is possible that before this happens the device may hop between possible SLM positions. If this is coupled with the dispersion of the fibre, it is possible that with very long lengths, that is, many tens of kilometres, pulses may appear and disappear—a gross ISI effect. This effect leads to the error-rate performance becoming independent of input optical power above a certain threshold level and may result in the target system error rate being unachievable. These considerations led to the development of devices and techniques (external cavity control and distributed feedback (DFB) lasers) to produce more stable SLM operation under modulation for the 1550 nm wavelength region.

Laboratory-Based Cable Tests

Whilst the performance at 1550 nm clearly held out great potential, the development of a laser transmitter with the necessary spectral confinement and stability at 1550 nm was much further away than a suitable 1300 nm laser. The next stage of systems development was therefore centred on 1300 nm systems with the object of demonstrating a more realistic system using a laboratory-based cabled fibre link of about 30 km length. If a system at 140 Mbit/s could be operated over this length in the field without a repeater, then it would remove the need for dependent power-fed repeaters and metallic conductors in the cable for almost all routes in the national trunk network.

Towards the end of 1981, an experimental 31·6 km single-mode fibre link was set up in the laboratory in order to simulate as closely as possible an operational cable route[12]. In this experiment, 14 fibres, each 2·25 km long were cabled in three 2·25 km cables using a loose-tube technique[13]. All the fibres were fully characterised prior to splicing. The three cables were spliced together by using the fusion splicing technique without power monitoring to form a continuous fibre length of 31·6 km. Splice losses were determined by two methods: one was to use an optical time-domain reflectometer (OTDR)[14] to measure the individual splice losses, and the other was to measure the total link loss and then subtract the previously measured cabled-fibre losses to give a figure for the total splice loss. For this system there was good agreement between the two measurements, which indicated that the mean splice loss was between 0·18 and 0·23 dB at 1300 nm and approximately 0·12 dB at 1550 nm. The reduced loss at 1550 nm is due to the increasing field width with longer wavelengths; this helps to reduce the splice losses associated with concentricity error and core deformation. The total link loss for this experimental cable was 17·5 dB at 1300 nm, and permitted several system experiments to be performed in the 1300 nm window.

Transmitter and receiver modules at 1300 nm for operation over the cabled single-mode link were made available for a series of systems tests at 140, 280 and 565 Mbit/s. The transmitter module comprised a GaInAsP 10 μm oxide insulated stripe laser[10] with nominal operating wavelength of 1300 nm. The device was multi-longitudinal mode, with three main modes separated by 1 nm, to give an effective linewidth of about 2 nm. The optical power from the laser facet was launched into a single-mode fibre tail using simple butt coupling. The launched power was 80 μW (−11 dBm) mean when pulsed; no additional power could be coupled into the fibre by increasing the drive current since the main lobe of the laser output radiation saturated at this level and any additional power obtained was lost to uncoupled side lobes. The transmitter module was temperature controlled by a Peltier-effect thermoelectric cooler. This allowed stable transmitter operation to be achieved with these early 1300 nm devices. The threshold current at 16°C was 250 mA and a drive current of 50 mA was required for full modulation of the optical output power. It was envisaged that for most applications, reductions in threshold or bias current and improvements in module design might eventually enable the temperature controller to be dispensed with. Further development of the receiver, particularly with fibre coupling, had taken place. The PIN photodiode was now mounted on a quartz block with an alignment hole for the fibre inputs. The receiver sensitivity at 140 Mbit/s and 1300 nm was now −46 dBm. The principal results of the system tests are given in Table 3.

TABLE 3
Results of System Trials

Wavelength	1280 nm	1280 nm	1280 nm
Link length	31·6 km	31·6 km	31·6 km
Bit rate	140 Mbit/s	280 Mbit/s	565 Mbit/s
Total path loss†	20·5 dB	20·5 dB	20·5 dB
Transmitter power	−11 dBm	−11 dBm	−11 dBm
Received power	−31·5 dBm	−31·5 dBm	−31·5 dBm
Receiver sensitivity	−46 dBm	−41·5 dBm	−36·5 dBm
System margin	14·5 dB	10 dB	5 dB

† The increased loss over the 17·5 dB fibre and splice loss is mainly attributed to the two prototype lens connectors used at each end of the system

The system margin of 14·5 dB at 140 Mbit/s was very encouraging and was judged sufficient to cover the additional performance degradations usually experienced in transferring laboratory-based systems demonstrations to the working environment. At 565 Mbit/s, the system margin reduces to 5 dB because of the reduction in receiver sensitivity with bit rate. However, it was believed that additional system margin would be obtained by improvements to laser performance and transmitter design. For example, the use of a fibre tail with a specially designed lens[7] fabricated on its end face, as shown in Fig 12, was predicted to yield perhaps up to a factor of four improvement in coupling efficiency.

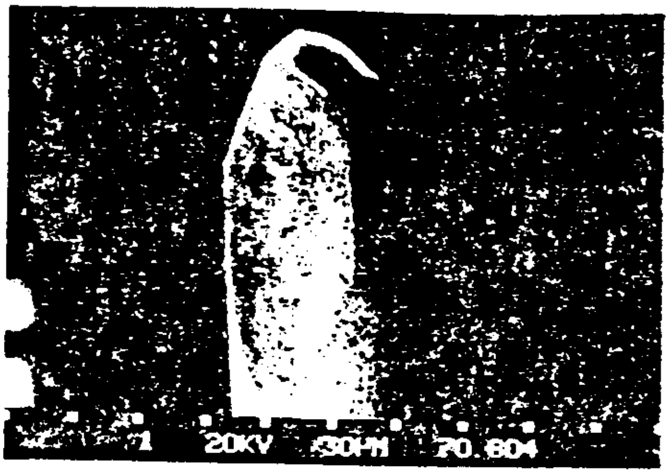

FIG. 12—Single-mode fibre with asymmetric hemispherical lens

The results signified that 140 Mbit/s systems without dependent repeaters were feasible and that such systems, once having been installed, could be upgraded to at least 565 Mbit/s at the same repeater spacing whenever necessary. Indeed, it was becoming evident that repeater spacings greater than 30 km were eventually going to be viable, and this realisation stimulated still further the development of single-mode fibre systems for undersea applications. Some initial tests at 140 Mbit/s using broad linewidth lasers were also undertaken in the 1550 nm window confirming that this wavelength option can be exploited. It remained to show the ultimate viability of single-mode technology by demonstrating systems over cables installed in the field.

The MIME and Woodbridge System Trials

During the early part of 1982, two major field trials of single-mode fibre technology were carried out. The first of these was a co-operative venture between BTRL and Telephone Cables Limited and involved the installation of a 30 km cable link between Martlesham and the nearby town of Woodbridge[7]. The other trial was in association with STL and involved the installation of a 15 km cable route between Martlesham and the town of Ipswich, this latter link being known as the *Martlesham Ipswich Monomode Experiment* (MIME)[8]. A map of the two routes is shown in Fig. 13.

The fibre for the Woodbridge trial was produced on an experimental basis by BTRL and GEC Optical Fibres Ltd (GECOF), and was not tightly toleranced. The fibre came from both BTRL and GECOF sources and derived from many different and varied experimental preforms. The fibre for the MIME trial was was tightly toleranced and was produced by STL/STC in a pilot manufacturing facility. As a consequence, the MIME fibre was more representative of

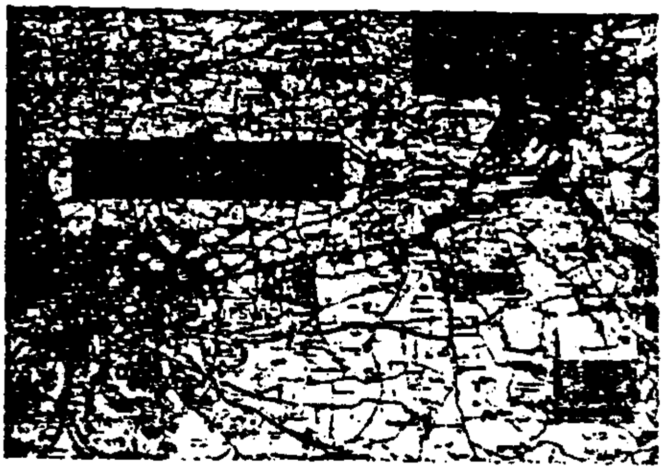

FIG. 13—MIME and Woodbridge single-mode fibre cable installations

the ultimate quality that could be expected from a dedicated production environment. The effect of fibre tolerances clearly manifested itself on the splicing results from the two links. Nevertheless, both links showed encouraging splicing performance.

The links were spliced by using the fusion-splicing technique without power monitoring. The Woodbridge link was spliced by BTRL, and the MIME link by STC field staff trained by STL. The splice-loss distributions from the two links are shown in Fig. 14. The mean splice loss of the Woodbridge link was 0·22 dB. The careful and extensive measurement programme associated with this link allowed calculations to be performed showing that this loss was made up of 0·08 dB due to core deformation, 0·07 dB due to concentricity error and a further 0·07 dB due to field width mismatch. The mean splice loss of the MIME link, however, was only 0·11 dB, indicating the possible level of splice loss that could be achieved with tightly toleranced fibre. Both of these cable installations were then used as test beds for many system experiments and, indeed, in 1985, they still form the major test beds for such experiments.

These cabled single-mode fibre installations gave the first opportunity to test, under field conditions, the operation of systems at 140 Mbit/s and above over repeater spacings of 30 km and greater. Laser transmitters with improved laser designs and lensed fibres were used in this series of experi-

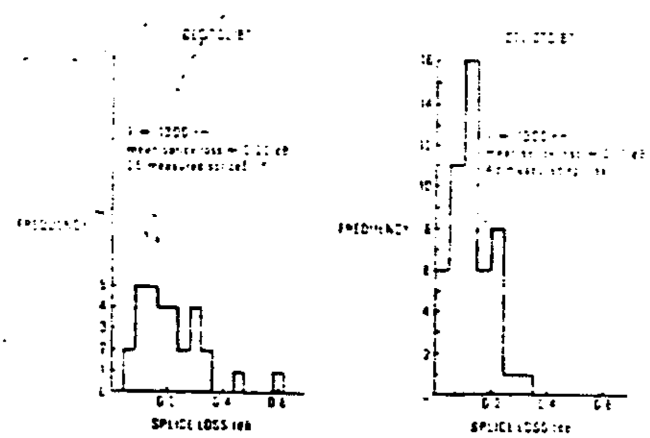

FIG. 14—Splice loss histograms for MIME and Woodbridge field installations

ments at 1300 nm. The transmitter and receiver were connected to the transmission fibres using shaped memory effect ferrule connectors[19]. The receiver and regenerator combination remained essentially the same as in previous experiments. The Woodbridge cable was operated at 140 Mbit/s initially and subsequently at 650 Mbit/s—the highest bit rate then available from test equipment. The MIME cable was operated over a range of bit rates with a final test at 565 Mbit/s over the full 61·3 km of the installation. The power budgets for the 1300 nm experiments are given in Table 4.

TABLE 4

Power Budgets for 1300 nm Experiments

Wavelength	1290 nm	1290 nm	1290 nm
Link length	31·5 km	31·5 km	61·3 km
Bit rate	140 Mbit/s	650 Mbit/s	565 Mbit/s
Path loss	21·9 dB	21·9 dB	30·5 dB
Transmitter power	−7 dBm	−6·7 dBm	−4·5 dBm
Received power	−28·9 dBm	−30·6 dBm	−35 dBm
Receiver sensitivity	−45 dBm	−34 dBm	−36 dBm
System margin	16·1 dB	3·4 dB	1 dB

The system margins achieved in this series of experiments were greater than in previous tests and were large enough to leave virtually no doubt about the eventual practicality of the 30 km spacing up to 650 Mbit/s. Fibre, cable and splicing data from these trials formed the basis for current BT single-mode fibre specifications. Research effort was then put into demonstrating the capabilities of systems operating at 1550 nm.

The 1550 nm System Tests

The initial attempts to stabilise laser devices for narrow line operation at 1550 nm utilised techniques involving external stabilising components. In the first of these experiments injection locking[20], see Fig. 15, was used wherein a laser was operated continuous wave to give a stabilised SLM. The output from this laser (LD1) feeds a second laser (LD2) forcing it to oscillate exclusively at this same wavelength. The second laser (LD2) was modulated in the conventional manner. The technique allowed the transmission of a 140 Mbit/s signal over a 102 km link of conventional fibre on reels without a repeater[20].

A second experiment using a transmitter module with an external cavity comprising a reflector placed at a controlled

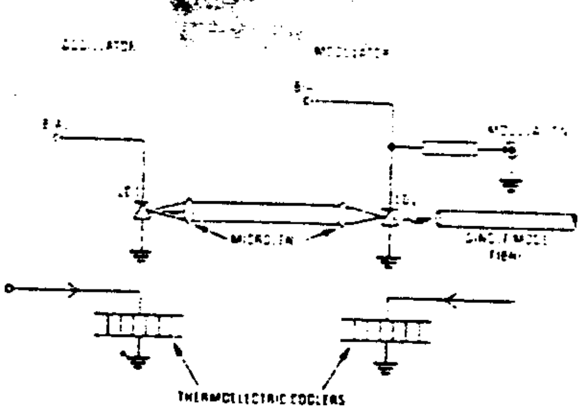

Fig. 15—Injection-locked laser transmitter arrangement

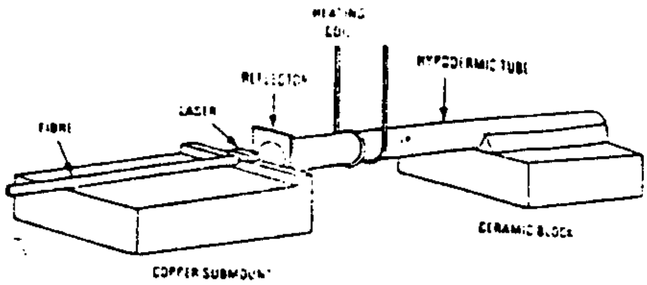

Fig. 16—External cavity laser transmitter arrangement

distance from the rear facet of the laser, see Fig. 16, allowed operation again at 140 Mbit/s and 102 km[21]. The SLM could be tuned in this case by altering the position of the reflector by applying heat via the heating coil to expand the metal tube on which the reflector is placed.

This latter transmitter module was employed in a further systems test in which all of the installed cable was linked together to form a 90·5 km length. Successful operation was achieved at 140 Mbit/s with a margin of about 2·5 dB. This feasibility demonstration, with a field-installed single-mode route, of a system operating over three times the then required unrepeatered span for the trunk network, set the scene for potentially very long unrepeatered systems at 1550 nm of great interest for submerged applications.

The power budgets for these systems tests are given in Table 5.

TABLE 5

1550 nm System Test Power Budgets

Wavelength	1520 nm	1520 nm	1520 nm
Link length	102 km†	102 km†	90·6 km‡
Bit rate	140 Mbit/s	140 Mbit/s	140 Mbit/s
Path loss	34 dB	36 dB	35·7 dB
Transmitter power	−8 dBm	−6 dBm	−7·8 dBm
Received power	−42 dBm	−42 dBm	−43·5 dBm
Receiver sensitivity	−45·7 dBm	−45·7 dBm	−46 dBm
Laser extinction	1 dB	0 dB	0 dB
System penalty*	1·6 dB	0·5 dB	0 dB
System margin	1·1 dB	3·2 dB	2·5 dB
	Note 1	Note 2	Note 2

† On reels
‡ MIME + Woodbridge installed fibre
* Miscellaneous impairments
Note 1 Injection-locked transmitter
Note 2 External-cavity transmitter

CONCLUSION

This article has described the development of single-mode fibre systems at BTRL up to about 1982 and indicated the significant aspects of fibre design, cabling, splicing and systems design that evolved during this period. These developments have had a profound effect upon the ensuing applications of the technology in the trunk and junction networks, and on undersea routes. In the second part of this article, some of the developments that have occurred since the MIME field trials will be described as well as an indication of what the implications are for the future exploitation of the growing single-mode fibre network.

[illegible]owledgement

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Biographies

Raymond Hooper joined the Post Office as a Trainee Technician Apprentice in London North Area. After graduating with an honours degree in Electrical Engineering from the Middlesex Polytechnic in 1970, he joined the optical-fibre communications project at the Research Department. He has been involved in all the major BTRL field demonstrations of optical-fibre transmission systems and was responsible for the field systems measurements with the installed single-mode fibre cables. He now heads a group working on advanced direct detection systems and receivers operating at gigabit/s information rates.

David Payne obtained a B.Sc. in Electrical Engineering from the University of Aston in Birmingham in 1971. He then joined the Post Office Research Department and worked on analogue and digital systems design with emphasis on interfacing problems. He was also involved in early work on microprocessor-controlled automatic test equipment. In 1979, he obtained an M.Sc. in Telecommunications Systems from the University of Essex. He then joined the optical-fibre communications project at BTRL and was responsible for single-mode fibre splicing and connectors. During this time, he was also involved in the establishment of the BT single-mode fibre specification. Since then, he has had responsibility for wavelength multiplexing components and is currently head of a group investigating the application of single-mode fibre technology for local networks.

Michael Reeve graduated from the University of Durham in 1973 with a degree in Applied Physics, and joined the Post Office Research Centre in the same year. He has worked on several aspects of optical-fibre communications, including modal properties, strength and cable design. Recently he has worked on the BT single-mode fibre specification and the design of a new type of optical cable—the blown-fibre cable. He is currently head of a group concerned with optical-cable and component design.

The Development of Single-Mode Fibre Transmission Systems at BTRL

Part 2—Recent Developments

R. C. HOOPER, B.SC., C.ENG., M.I.E.E., and D. W. SMITH, B.TECH.†

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In this, the second of two articles, recent developments in single-mode fibre transmission systems at British Telecommunications Research Laboratories are discussed. The article covers, firstly, improvements in system performance being achieved by enhancement of direct detection systems, and secondly, the further performance improvements becoming feasible by the adoption of coherent transmission technology.

INTRODUCTION

In the first of these articles*, the development of single-mode fibre transmission systems at British Telecom Research Laboratories (BTRL) from 1979 to 1982 was charted. In this second article, some of the developments that have occurred since 1982 are described.

A key development area has been the exploitation of the second low-loss window at 1550 nm allowing yet further increase in repeater spacing. However, it has been found that semiconductor laser sources with confined spectra need to be used in order to obviate the fibre chromatic dispersion of about 15–18 ps/nm/km at this wavelength.

Single-mode fibre cable will be the dominant fibre transmission technology in the UK national trunk network by the early-1990s. Systems technology under investigation in the laboratory is aimed towards the full exploitation of the potential of this medium. The developments are being carried out on two broad fronts.

The first of these is enhancement of direct-detection systems by direct upgrading at 1300 nm bringing information-carrying capacity into the gigabits per second range[1]. The use of the 1550 nm window with narrow linewidth sources is being investigated as a means of further increasing capacity and system range[2, 3]. Capacity may also be upgraded by using passive optical components to permit duplex[4, 5] and wavelength multiplex[6] systems.

The second area of development for future systems enhancement is coherent technology, where the carrier wave properties of semiconductor lasers are utilised to allow more sophisticated modulation and detection schemes to be used. Such systems[7] may exhibit up to 20 dB improvement in sensitivity over direct detection systems, allowing repeater spacings to be increased by possibly more than 100 km. It is becoming clear that this technology does not require fibre different from that being used in current direct detection systems[8].

DIRECT DETECTION SYSTEMS

Single-mode fibre typically exhibits two low-loss windows as shown in Fig. 1. The first appears at 1300 nm and the second at 1550 nm. The second window, however, exhibits chromatic dispersion requiring narrow line sources for operation at very high bit rates(gigabits per second) and long repeater spacings (>30 km).

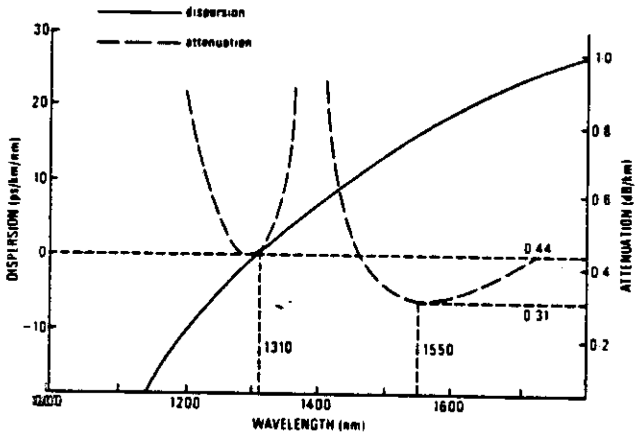

Fig. 1—Loss and dispersion of single-mode fibre

Gbit/s Systems

Systems based at 1300 nm are usually loss limited, that is, the repeater section length is set only by the transmitter coupled power, receiver sensitivity and fibre loss, whereas 1550 nm systems can be dispersion limited, without narrow line sources. However, in practice, it is unlikely that a precise match can be always attained between the laser operating wavelength and the chromatic-dispersion-zero wavelength. For 30 km repeater sections it is unlikely that a serious dispersion penalty will result until information rates of several gigabits per second are reached, although some tightening of the allowable spread of laser centre wavelengths may be necessary. In the case of much longer repeater sections, then the technology of line-narrowed sources developed for 1550 nm could be transferred to 1300 nm.

At BTRL, some experiments have been performed at 1·2 Gbit/s and 1300 nm over a 31 km length of installed single-mode fibre having a chromatic dispersion zero at 1300 nm. An InGaAsP/InP 1275 nm buried crescent laser[9]

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* HOOPER, R. C., PAYNE, D. B., and REEVE, M. H. The Development of Single-Mode Fibre Transmission Systems at BTRL, Part 1—Early Developments, *Br. Telecommun. Eng.*, Jul. 1985, 4, p. 74.

was modulated with a $2^{15}-1$ pseudo-random binary sequence test signal. The output from the laser was launched into the cabled (MIME†) fibre with a mean launch power of −5·5 dBm. At the far end, a PINFET receiver[10] was used for detection. This receiver comprised an InGaAs PIN photodiode having low capacitance and a GaAs MESFET preamplifier having both low capacitance and low noise. The PIN photodiode and GaAs MESFET were mounted on a thick-film circuit hybrid containing silicon bipolar transistors for buffering and amplification. The receiver sensitivity for a 10^{-9} bit error rate was −33·2 dBm. The detected electrical signal from the receiver was then regenerated in a regenerator utilising high-speed commercial integrated circuits[11]. The regenerator comprised linear and limiting wide-band amplification and a parallel processing decision gate as shown in Fig. 2.

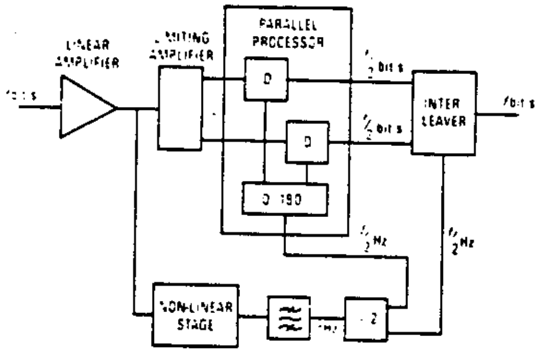

Fig. 2—Parallel processing regenerator

The decision gate comprised two emitter-coupled logic (ECL) D-type bistables operating in parallel at half the bit rate but 180° out of phase. The decisions then took place in each circuit on every other bit. The two streams at 600 Mbit/s were then interleaved to form the 1·2 Gbit/s signal in an integrated transistor array.

A further experiment was undertaken on a length of 54·7 km of reeled single-mode fibre using the same components. The results of the two experiments are given in Table 1, but in neither case was a dispersion penalty measured.

TABLE 1

1·2 Gbit/s 1300 nm Experiments

Link length	31 km	54·7 km
Laser transmitter power	−5·5 dBm	−5·5 dBm
Path loss	15 dB	23·5 dB
Received power	−20·5 dBm	−29 dBm
Receiver sensitivity	−33·2 dBm	−33·2 dBm
System margin	12·7 dB	4·2 dB

Duplex System

Whilst electronic multiplexing techniques have been the favoured method of achieving a direct upgrade of capacity in the past, optical-fibre systems offer a number of possible alternative approaches. Duplex use of the transmission path is possible by using fused tapered single-mode fibre couplers[12]. In these passive devices, generally having four ports, a proportion of the input optical power is transferred to an output port. These devices are reciprocal in that light may travel in either direction through the coupler with equivalent path losses. If two such couplers are inserted in a system at either end of the link, then it is possible to double the capacity of the system by using a single fibre for both directions of transmission simultaneously. If the couplers are arranged to divide the input power equally between the outputs, then an additional loss of 6 dB is incurred. Excess losses less than 0·1 dB have been measured[12]. Experiments were performed in which digital signals were transmitted bidirectionally at bit rates from 34–650 Mbit/s[4]. A schematic diagram of the system used for the experiments is shown in Fig. 3.

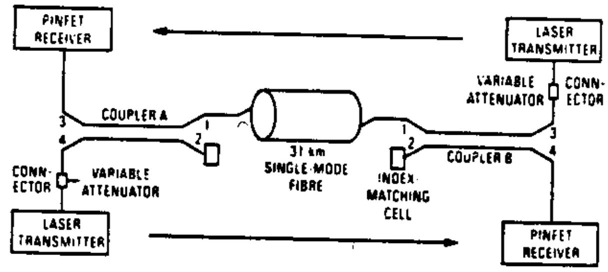

Fig. 3—Duplex transmission at 1300 nm

The two laser transmitters operated at the same nominal wavelength without interaction even when the wavelengths came to within about 1 nm separation. No crosstalk was found and the only additional penalty was due to the back-scatter from the fibre which, compared with receiver sensitivity at 34 and 140 Mbit/s, became significant. The high level of system margin obtained even at 650 Mbit/s makes this duplexing method very attractive. The detailed performance of the system is shown in Table 2.

TABLE 2

Duplex System Power Budget

Transmitter power (dBm)		−3·2	(−2·8)	
Total coupler loss (dB)		5·3	(7·6)	
Path loss (dB)		16·2		
Received power (dBm)		−24·7	(−26·6)	
Transmission rate (Mbit/s)	34	140	320	650
Receiver sensitivity (dBm)	−52·5	−46	−43·5	−35·5
Penalty (dB)	1·2	0·3	0	0
Margin (dB)	26·6 (24·7)	21 (19·1)	18·8 (16·9)	10·8 (8·9)

Note: Duplex power budget A–B (B–A shown in brackets)

1550 nm 1·2 Gbit/s System

Because of the very much lower losses available in the 1550 nm window, it is possible to achieve very much longer repeater separations at gigabits per second speeds. One method of achieving the necessary narrow linewidth of the laser source is to use a *distributed feedback* (DFB) laser[13]. Such a device operating at 1530 nm has been used at BTRL in a 1·2 Gbit/s 114 km experiment[14]. The DFB laser generates a *single longitudinal mode* (SLM) even when

† MIME—Martlesham Ipswich monomode experiment

modulated. The linewidth can be as narrow as a few tens of megahertz under continuous wave (CW) conditions. The DFB laser was modulated from the threshold by a $2^{15}-1$ pseudo-random binary sequence test signal at 1·2 Gbit/s with a peak-to-peak signal amplitude of 36 mA. The power launched into the single-mode fibre tail was −4 dBm. A PINFET receiver having a sensitivity of −35·6 dBm was used at the far end. Fibre links up to 114 km were configured for a series of tests which demonstrated that degradation of performance was incurred as the length increased.

Fig. 4 shows error-rate plots from 10–114 km indicating that penalties of about 3 dB at 114 km have occurred.

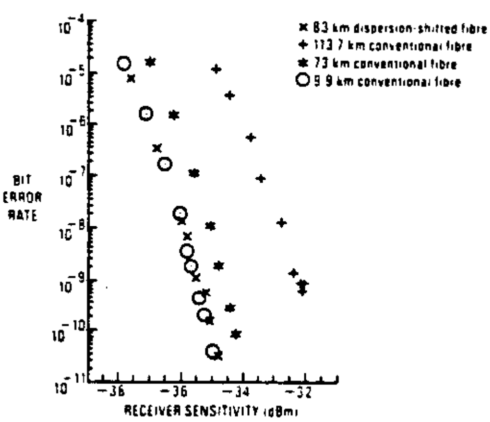

Fig. 4—Error-rate performance

However, by using dispersion-shifted fibre, with the chromatic dispersion zero at about 1560 nm, no such penalties are seen at 83 km. The penalty with conventional fibre must therefore be related to dispersion. Although the DFB laser is SLM, the mode shifts during the transient turn-on by about 0·24 nm. This shift appears as intersymbol interference which becomes measurable after about 50 km. It is possible to reduce the effect of this *chirp* by slowing the response of the device, in particular the relaxation oscillation or, alternatively, by using electrical compensation in the drive current waveform[15]. One method of overcoming chirp completely is to operate the device CW into an external modulator. However, such devices will have some loss associated with them which could be higher than the chirp penalty. Nevertheless, with higher output powers from laser sources, the external modulator is an attractive proposition.

Type T Fibre

The loss of conventional step-index 1300 nm based single-mode fibre can reach just under 0·2 dB/km at 1550 nm. It is possible to shift the dispersion zero to 1550 nm with the conventional design, but because a smaller core diameter and a higher refractive index difference are required, the loss at 1550 nm can be 0·35 dB/km or greater. The higher loss is associated with stress at the core/cladding interface, but this can be minimised by grading the refractive-index profile of the core. The triangular profile or *Type T* fibre[16] allows the zero-dispersion wavelength to be shifted from 1300 nm to 1550 nm without substantial change in loss at 1550 nm.

Some initial experimental studies using uncabled Type T fibre fabricated at BTRL were undertaken in late-1983. Transmission of 140 and 320 Mbit/s signals over 103·6 km of Type T single-mode fibre was achieved by using a BTRL 1550 nm laser chip. The link length was subsequently reduced to 83·3 km and a 650 Mbit/s signal successfully transmitted. The power budgets for these experiments are given in Table 3. The penalty of 0·5 dB for the 650 Mbit/s experiment arises from the mismatch of the laser centre wavelength and the fibre dispersion zero. However, these experiments have exhibited essentially loss-limited performance.

TABLE 3

Type T Fibre System

Bit rate (Mbit/s)	140	320	650
Link length (km)	103·6	103·6	83·3
Launch power (dBm)	−7·8	−7·8	−7·8
Loss (dB)	34·2	34·2	26·2
Received power (dBm)	−42	−42	−34
Receiver sensitivity (dBm)	−46·8	−42·2	−35·5
Margin (dB)	4·8	0·3	1·5
Penalty (dB)	0	0	0·5

COHERENT SYSTEMS

The maximum distance between repeaters in an optical-fibre transmission system could be further increased if coherent transmission instead of direct detection is used. With *coherent detection*, the weak input signal is combined with a strong local oscillator signal prior to photodetection. Because of the square law nature of photodetection, this mixing process results in conversion gain which effectively amplifies the detected signal photocurrent above the noise of the following electronic preamplifier. Since present-day direct-detection receivers are not quantum-noise limited, it is possible to achieve considerable improvements in receiver sensitivity, possibly by as much as 20 dB[7], by the use of coherent detection.

This theoretical benefit of coherent optical detection over direct detection has been widely appreciated since the invention of the laser and, in fact, some early line-of-site optical transmission experiments used heterodyne detection. Then, as interest developed in optical-fibre transmission using multimode fibre and broad linewidth semiconductor lasers, coherent techniques had to be temporarily abandoned. More recently, with the almost universal move to single-mode fibre for long-distance fibre transmission, the emergence of integrated optic technologies, and the tremendous progress in improving semiconductor laser spectral purity, laboratory demonstrations of coherent optical-fibre transmission are now possible. This second phase of research was initiated in laboratories in Europe and Japan, and is now carried out in all major telecommunication laboratories throughout the world.

Polarisation Stability

Polarisation stability of the transmission media was an initial worry because coherent detection is polarisation sensitive. Conventional circular symmetric single-mode fibre does not preserve the initial launched polarisation state throughout the transmission path. This is because any residual strain-induced birefringence left within the fibre after cable installation will be subject to environmental fluctuations and result in an output polarisation state which is in practice unpredictable. Although polarisation-holding fibres have been proposed and demonstrated[17], they currently have higher loss and are usually more complex than conventional fibres. Moreover, since much of the long-distance transmission network is already using or is planning to use standard single-mode fibre, there are great benefits if coherent detection schemes are fibre compatible with direct detection. Fortuitously, it has been found that although the polarisation state from standard fibre cannot be predicted in advance, its output state remains stable for long time periods, several hours for cabled fibre installed in ducts under the ground[8].

This slow polarisation fluctuation can be dealt with in the coherent receiver by using a polarisation control system that adjusts either the local oscillator polarisation or input signal polarisation. There are several techniques that can be used, including electromechanical, magneto-optic and electro-optic devices; the latter can be elegantly realised in integrated optic form[18]. However, for laboratory experiments, manual control has been sufficient.

Components for Coherent Transmission Systems

For coherent transmission, the sources used in the transmitter and for the receiver local oscillator must have spectral linewidths considerably narrower than those usually encountered in direct detection systems. The linewidth required depends upon the type of modulation and demodulation used. Homodyne detection with phase-shift keying (PSK) modulation offers the highest performance, but is most demanding on source spectral characteristics; for instance at 140 Mbit/s, linewidths of less than 100 kHz, or about 10^{-6} nm, are required. For these schemes, it has been necessary to reduce dramatically the spectral linewidth of semiconductor lasers. Two techniques that have been particularly successful to achieve this are injection locking, and the use of selective external cavities. The former is achieved in practice by coupling the output from a stable 1520 nm wavelength HeNe gas laser into a semiconductor laser[19]. However, the external cavity laser approach (see Fig. 5) offers a more versatile solid-state alternative which,

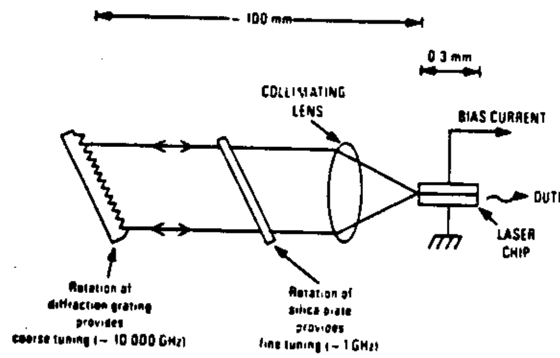

Fig. 5—External-cavity semiconductor laser

as well as having a linewidth of only a few kilohertz, can be tuned over a wide frequency range; a tuning range of about 10 000 GHz has been achieved for sources implemented by anti-reflection coated laser chips and diffraction-grating loaded external cavities of between 50 and 200 mm length[20]. Alternatively, for the less demanding applications requiring linewidths of a few tens of megahertz and limited tuning, the use of DFB lasers without external cavities has the attraction of small size, but is, however, extremely critical on the need for non-reciprocal optical isolation.

Coherent transmission requires a wide range of micro-optic, fibre optic and integrated optic devices. These include planar waveguide lithium niobate phase modulators for PSK systems, polarisation controllers, fibre directional couplers for signal combination and optical isolators. The optimum design of these transmission systems requires optical circuit design skills analogous to those of the traditional electrical circuit designer. Fig. 6 shows an example of an experimental PSK heterodyne transmission system indicating the range of optical, electro-optical and electronic components necessary.

First Demonstration of Improved Sensitivity

The first demonstration of an improvement in receiver sensitivity over a good direct-detection optical receiver by coherent detection was in an amplitude-shift keying (ASK) homodyne experiment at BTRL in 1982[21]. This rudimentary experiment used injection locking to line narrow a buried crescent semiconductor laser that was directly modulated. A single 1520 nm HeNe laser was used both as the input signal to the diode laser and as the local-oscillator laser. To overcome problems of wavefront matching, fibre-based components were used both for polarisation control and beam combination. To avoid the need for large local-oscillator powers and still achieve close to shot-noise-limited detection, a low-noise PINFET receiver was used in the experiment. This experiment with self homodyne detection and with ASK modulation was also repeated with PSK modulation; a combination that should give the ultimate in receiver sensitivity for a binary transmission system. The best ever sensitivity measurement achieved with a pseudo-random bit sequence[22] was −62 dB at 140Mbit/s, just 4 dB away from the quantum limit and 17 dB better than that which could be achieved with the same receiver in a direct-detection mode.

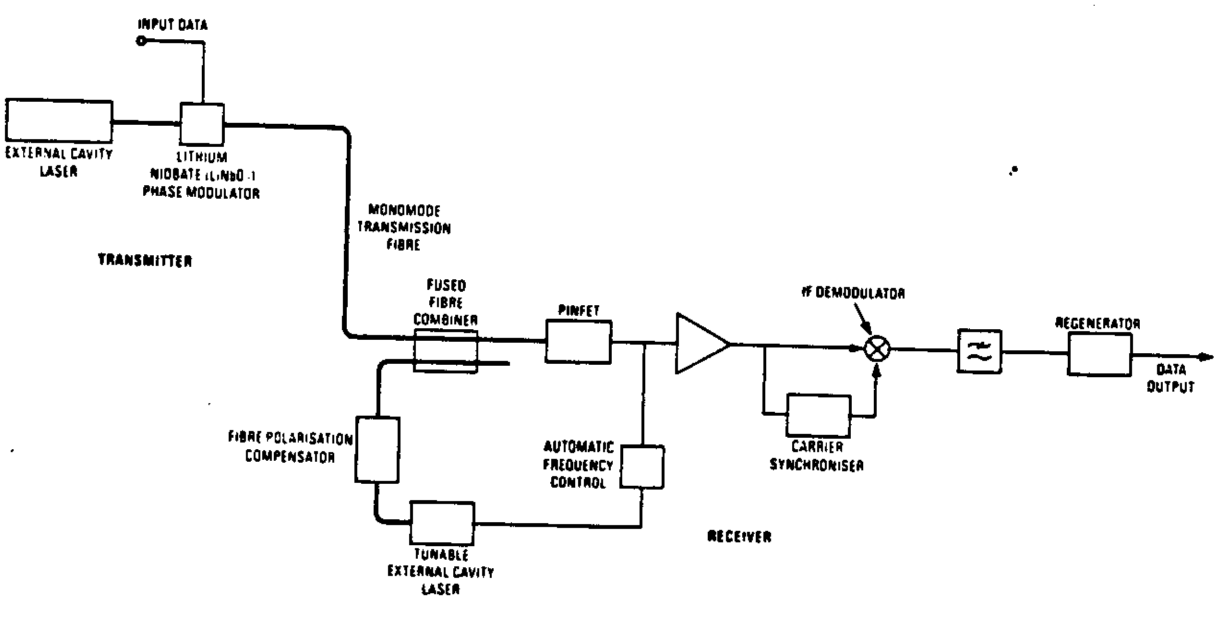

Fig. 6—Optical PSK transmission experiment

TABLE 4
Improved Sensitivity Receiver

Modulation	Transmitter	Receiver	Fibre Path	Sensitivity
ASK	HeNe	Self homodyne	1 m	−59 dBm
ASK	External cavity	Heterodyne external cavity	60 km	−53 dBm
FSK	External cavity	Heterodyne external cavity	200 km	−56 dBm
FSK	DFB	Heterodyne external cavity	1 m	−50 dBm
PSK	HeNe/$LiNbO_3$ modulator	Self homodyne	1 m	−63 dBm
PSK	HeNe/$LiNbO_3$ modulator	Optical PLL homodyne	30 km	−57 dBm
PSK	HeNe/$LiNbO_3$ modulator	Heterodyne external cavity	109 km	−59 dBm
DPSK	HeNe/$LiNbO_3$ modulator	Heterodyne external cavity	109 km	−57 dBm

System Results

Experiments have now been performed at BTRL on a range of coherent transmission configurations featuring either homodyne or heterodyne detection with either amplitude, phase or frequency modulation. In addition, both DFB and external-cavity laser sources have been considered, and transmission over fibre path lengths up to 200 km[23] achieved. Table 4 summarises results at 140Mbit/s data rate.

As expected, the best results in terms of receiver sensitivity have been achieved by using PSK modulation and homodyne detection over a short fibre path. Matching this performance over longer transmission paths will depend critically on the development of high-performance optical phase-lock loops[24]. Homodyne detection has one other significant advantage over heterodyne detection in that it is much more efficient in its use of the available receiver bandwidth, a factor of increasing importance as coherent transmission principles are applied to gigabits per second systems. Very recently, a homodyne receiver with bandwidth in excess of 1·5 GHz and featuring a local oscillator comprising a phased-locked semiconductor laser has been demonstrated[25], indicating that coherent transmission of several gigabits per second is now a realistic possibility in the laboratory. At the opposite extreme of complexity, experiments with DFB lasers[26] and large-deviation FSK that feature single-filter detection, although less demanding in terms of source characteristics, have been unable to produce, as yet, significant improvements over direct detection. As far as total system budget is concerned, the option of using narrow-deviation FSK has much to commend it, since direct frequency modulation by injection current eliminates losses in an external phase modulator. Performance approaching PSK could, in principle, be achieved by an optimised form of narrow-deviation FSK such as *minimum-shift keying.*

WIDEBAND NETWORKS

In addition to increasing unrepeatered transmission distance for intercity communication systems, coherent transmission could greatly increase the versatility of future optical wideband distribution networks and local area networks (see Fig. 7). For this application, the improvement in receiver sensitivity could be used to increase distribution losses and the selectivity of a tunable coherent receiver to isolate a single channel from an optical frequency multiplex. The basic principle of this has been demonstrated in a recent two-channel experiment where it was possible to select at

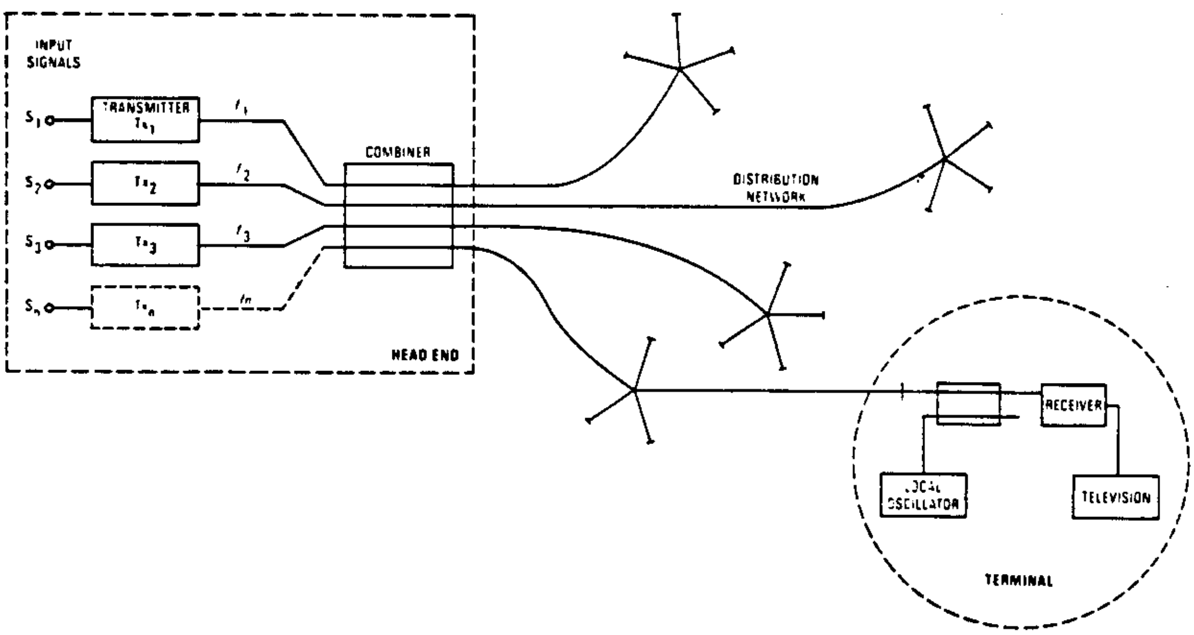

Fig. 7—Hypothetical future coherent wideband distribution system

the receiver between two PFM video channels spaced at optical frequencies just 1 GHz apart[27] (there is about 50 000 GHz bandwidth available between 1200 nm and 1600 nm).

The ultimate transmission capacity of a network built around coherent transmission principles is still a matter of speculation. Although, in fact, the future initial deployment of coherent transmission systems in the field, possibly in the early 1990s, will depend more on advances in the engineering of narrow linewidth lasers, improvements in the performance of DFB/DBR lasers and the commercial development of integrated optic components rather than on any fundamental physical constraints.

CONCLUSION

In the British Telecom national network, single-mode fibre is becoming a standard technology for cable transmission. It is now clear that this technology has enormous potential information carrying capacity. Upgrading systems from 140 Mbit/s to 1·2 Gbit/s at the same repeater spacing is viable at 1300 nm and 1550 nm ,with the latter wavelength giving some scope for increase in repeater spacing provided line-narrowed sources are employed. Alternative upgrading options exploiting duplex operation involving only passive optical components are feasible. An alternative low-loss fibre with dispersion zero at 1550 nm is emerging as a realistic long-term competitor to conventional step-index single-mode fibre. The single-mode fibre installed or being installed in the network now appears compatible with coherent systems allowing yet further upgrading potential. Whether the higher performance coherent systems will have more impact on traditional point-to-point links or on distribution and networking applications is a matter for speculation.

Acknowledgement

The authors wish to acknowledge the contributions made by their many colleagues throughout the optical project at BTRL and elsewhere.

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Biographies

Raymond Hooper joined the Post office as a Trainee Technical Apprentice in London North Area. After graduating with an honours degree in Electrical Engineering from Middlesex Polytechnic in 1970, he joined the optical-fibre communications project at the Research Department. He has been involved in all the major BTRL field demonstrations of optical-fibre transmission systems and was responsible for the field systems measurements with the installed single-mode fibre cables. He now heads a group working on advanced direct detection systems and receivers operating at gigabits per second information rates.

David Smith joined British Telecom in 1967 as an apprentice. In 1974, after graduating from Brunel University, he returned to the Martlesham Research Laboratories to work in the area of electronic switching. In 1977, he joined the optical communications division to become involved in the application of semiconductor lasers to optical transmission systems. Since 1981, he has been head of a group investigating coherent optical transmission.

data base. This technique reduces costs, both in terms of initial investment and subsequent logistic support. It also minimizes problems when expanding the telephone network and allows new features to be introduced more rapidly throughout the entire network.

Conclusion

Besides offering a wide range of features and a high level of performance and quality, an outstanding feature of a digital switching system is the flexibility with which it can be expanded and adapted to meet new exchange requirements with virtually no adverse effects on operation. An important precondition for this flexibility is a sound data base concept and effective support functions for modifying the data base. In the EWSD system this is achieved using a range of simple procedures. In applying these procedures, the operator is supported by operating manuals and consequently does not require the assistance of system specialists. Extensive automation of these procedures, together with a balanced number of on-line and off-line software tools, make it easier to modify the data base and enhance operating reliability.

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Ewald Braun and Baldur Stummer

Basic Equipment for Digital Transmission via Optical Waveguides

In the early 1980s, after the principles of optical transmission by means of optical waveguides (OWG) had been developed, attempts were made to construct and to use the first systems for practical operation. In addition to the satisfactory performance which had been given, the economic superiority over systems based on conventional transmission media (e.g. coaxial pairs) became evident at a very early stage. It was a major factor in convincing many telecommunications administrations and network carriers to plan to use exclusively optical waveguides for cable-based digital links which were to be set up as new installations. This, in turn, gave rise to a new wave of innovation, whereby systems have been and are being created, which are optimized for the various network levels. In addition to this, optical waveguide transmission offers entirely new possibilities of system technology, which are of great importance to the network designer and the maintenance personnel.

In the following article, the basic functions of optical transmission systems for use in regional and long-haul networks, for local interoffice lines and for relatively long digital feeder links in sparsely populated areas are described. Additions to the basic functions, such as in-service monitoring, service channel and other additional services and features, are presented in a separate article [1]. Optical transmission in the subscriber line network is discussed in [2, 3].

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The basic elements of an optical transmission route via optical waveguides are the line terminating units (LE) at the ends of the route, together with the interfaces (IF), which are in most cases standardized, for the signals to be transmitted (**Fig. 1a**). In order to span long distances, regenerative repeaters (ZWR) are included in the circuit (**Fig. 1b**). As will be shown later, the maximum repeater spacings (l) are calculated from the cable data on the basis of the optical power budget. Depending on the transmission rate and the conditions of use, e.g. whether connections are to be established with or exclusively without regenerative repeaters, the systems provided for this purpose can be optimally designed.

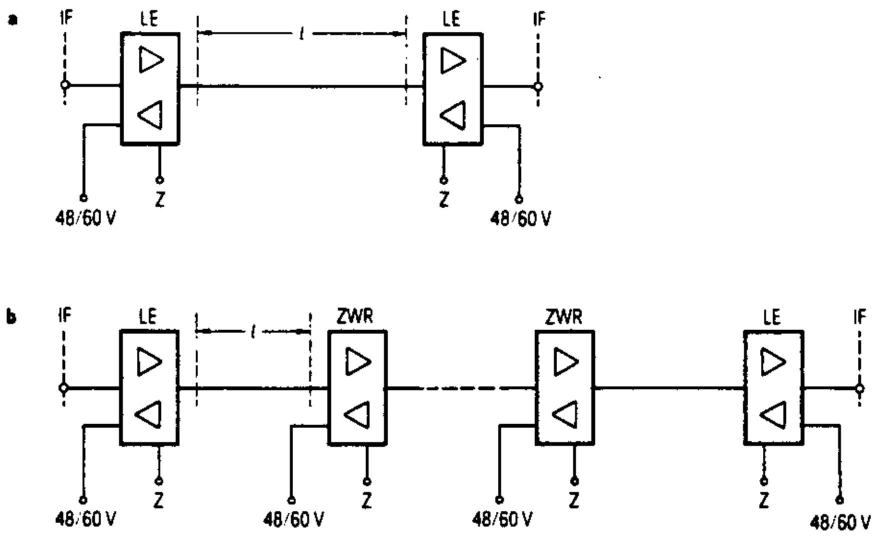
Thus, a variety of groups of systems is available for widespread and economic use, with which the future demands of digital transmission technology in a communication network can be met.

Long-haul and regional networks

Transmission capacity and range

In regional and especially in long-haul networks, medium and high bit rates must, as a rule, be transmitted over relatively long distances. The basic components of the group of systems suitable for this purpose are line terminating units (LE) and regenerative repeaters (ZWR).

With the technologies available today, it is possible to construct systems for up to 565 Mbit/s on an optical carrier; work is in progress on increasing this transmission capacity, e.g. for 2.4 Gbit/s. Whereas, a few years ago, 34 Mbit/s was



48/60 V	Interface for the 48- or 60-V power supply	LE	Line terminating unit
IF	Electrical standard interface for the digital signals	Z	Interface for additional functions or services
l	Regenerative repeater spacing	ZWR	Regenerative repeater

Fig. 1 Basic elements of an optical transmission route
a Without regenerative repeaters
b With regenerative repeaters

Transmission capacity	Mbit/s	34			140			565
Type of fiber		MM		SM	MM		SM	SM
Optical transmitter		LED*	LD		LED*	LD		LD
Optical power at 1300 nm in the fiber (behind the connector)	dBm	−21	− 5	− 6	−21	− 5	− 6	− 6
Spectral bandwidth Δλ	nm	150	10	5	90	10	5	4
Optical power received for bit error rate BER = 10^{-10} (in front of the connector)	dBm	−44	−45	−45	−38	−38	−39	−33
Optical attenuation which can theoretically be spanned	dB	23	40	39	17	33	33	27
System margin for dispersion, laser monitoring, additional services, temperature dependence, measurement tolerance, aging and other effects	dB	6	6	6	4	4	4	5
Maximum optical line loss which can in practice be spanned	dB	17	34	33	13	29	29	22
Dispersion for each repeater section	ps/nm	–	–	1200	–	–	300	120
Bandwidth for each repeater section	MHz	50	50	–	170	120	–	–

* Restrictions: a) Only for use without a regenerative repeater
b) Possible restriction of the maximum repeater spacing which can be spanned must be expected, as a result of dispersion and spectral width of transmitter

LD	Laser diode	MM	Multimode fiber
LED	Light-emitting diode	SM	Single-mode fiber

Table 1 Power budget for the optical digital transmission systems

defined as the lowest transmission rate, the increasing need for transmission capacity, the progressively increasing transmission bandwidth of the optical waveguides and the relatively small additional cost of a 140-Mbit/s system have caused the 34-Mbit/s system to recede to some extent into the background.

There are three different possibilities for the transmission of high bit rates: *fiber multiplex, optical wavelength multiplex* and *electrical multiplex*. As is shown by the detailed treatment given in [4], electrical multiplexing is superior, as regards economic operation, to the other two methods. For this reason, efforts are being made to increase the bit rate for each optical carrier, as far as the technology permits.

Optical waveguide systems with multimode (graded-index) fibers (MM multimode) and with single-mode fibers (SM single mode) are available for transmission rates of up to 140 Mbit/s. Suitable optical transmitters on MM fibers are light-emitting diodes (LED) or laser diodes (LD); at the present time, the former are more cost-effective, but require more regenerative repeaters in a given connection, as compared with laser diodes, because of the low transmitted power. As is shown by calculations, the economic optimum clearly lies with systems using laser diodes, and thus with the greatest possible spacing between regenerative repeaters. This trend is also continued in the selection of the optical waveguide. For example, at 1300 nm, SM fibers have a lower specific attenuation than MM fibers, and thus permit greater spacing between regenerative repeaters. In addition to this, in the case of SM fibers, the transmission capacity can be upgraded, more simply than in the case of MM fibers, by exchanging the first installed system, since the bandwidth of the SM fibers permits this. These are the reasons, in quite general terms, why in future almost exclusively SM fibers will be used in short-haul and long-haul networks.

A further reduction in the specific fiber attenuation is achieved by the change from the 1300 nm range (second optical window) to the range around 1550 nm (third window). For each of the windows dispersion-optimized fibers are available

Transmission capacity	Mbit/s	34			140			565
Type of fiber		MM		SM	MM		SM	SM
Optical transmitter		LED	LD		LED	LD		LD
Maximum optical line loss which can be spanned	dB	17	34	33	13	29	29	22
Fiber attenuation at 1300 nm	dB/km	1.0		0.4	1.0		0.4	
Average splice loss	dB per splice	0.2 to 0.1		0.1 to 0.05	0.2 to 0.1		0.1 to 0.05	
Installation length	km	1 to 4						
Specific splice loss	dB/km	0.2 to 0.025		0.1 to 0.0125	0.2 to 0.025		0.1 to 0.0125	
Specific repair reserve	dB/km	0.35 to 0		0.2 to 0	0.35 to 0		0.2 to 0	
Specific cable loss for route planning	dB/km	1.55 to 1.025		0.7 to 0.4125	1.55 to 1.025		0.7 to 0.4125	
Maximum repeater spacing which can be spanned	km	11 to 16.6	22 to 33	47 to 80	8.4 to 12.7*	18.7 to 28.3	41 to 70	31 to 53

* Possible restriction of the maximum repeater spacing that can be spanned must be expected, as a result of dispersion and spectral width of transmitter

LD Laser diode
LED Light-emitting diode
MM Multimode fiber
SM Single-mode fiber

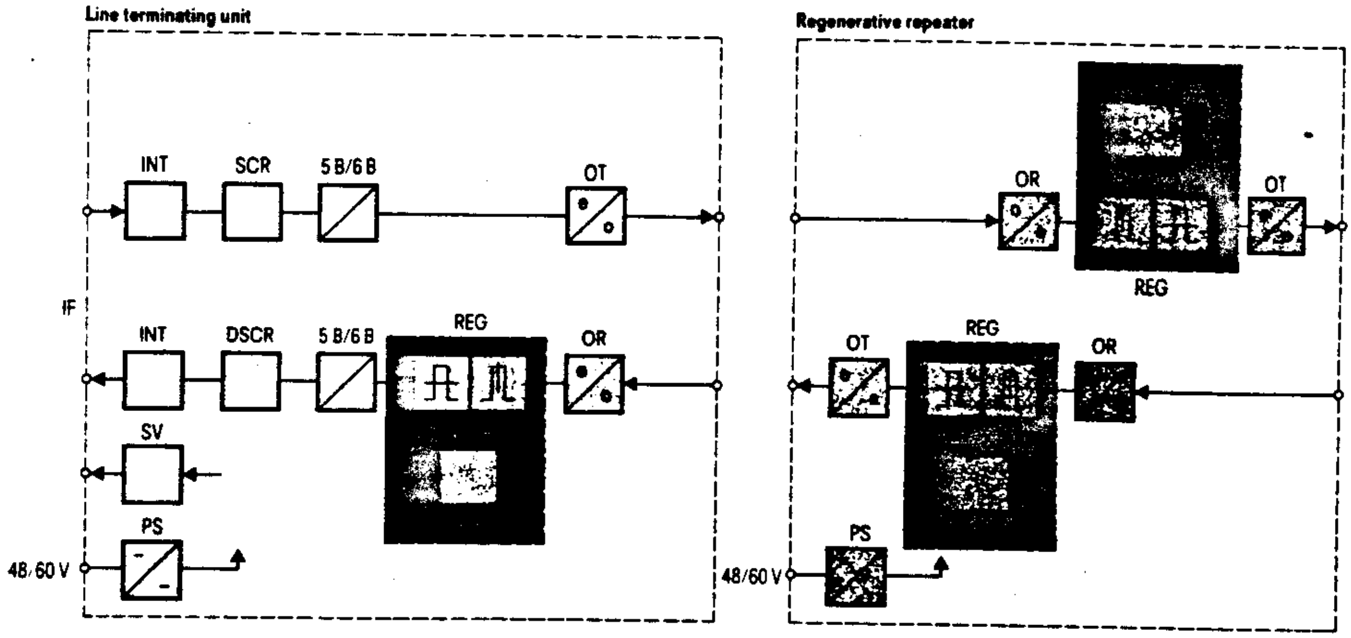
Table 2 Calculation of the maximum repeater spacings that can be spanned in optical transmission systems

nowadays. In this manner, the requirement for spectral purity of the optical transmitters for systems with high transmission capacity may be substantially lessened. Finally, optical transmitters operating at 1550 nm with a very narrow spectral width also permit the operation of systems with a high bit rate on normal fibers optimized for the second window.

The first steps have been made toward the production of fibers with low dispersion at both 1300 and 1550 nm ("dispersion-flattened fiber") [5].

Line coding

Line codes serve to convert signals into a format which is more suitable for transmission in a given channel. This line code must satisfy a series of requirements:



5B/6B 5B/6B codec
DSCR Descrambler
e/o Electro-optical conversion
IF Electrical standard interface for the digital base signals
INT Interface module
o/e Optoelectrical conversion
O/R Optical receiver
O/T Optical transmitter
REG Regenerative repeater
SCR Scrambler
PS Power supply
CkR Clock recovery
SV Supervision

Fig. 2 Functional diagram showing the basic functions of digital signal transmission for the line terminating unit and the regenerative repeater

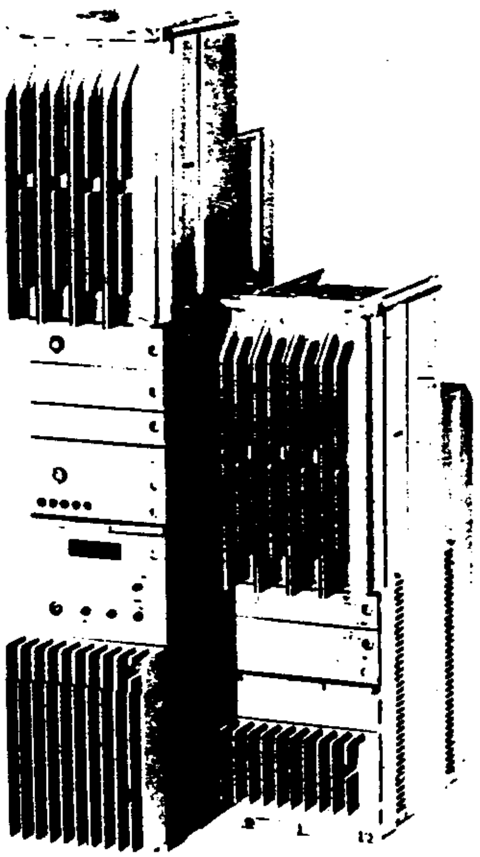


Fig. 3 Line terminating unit (left), with fault-locating unit and regenerative repeater (right) for the 34-Mbit/s system with optical waveguides

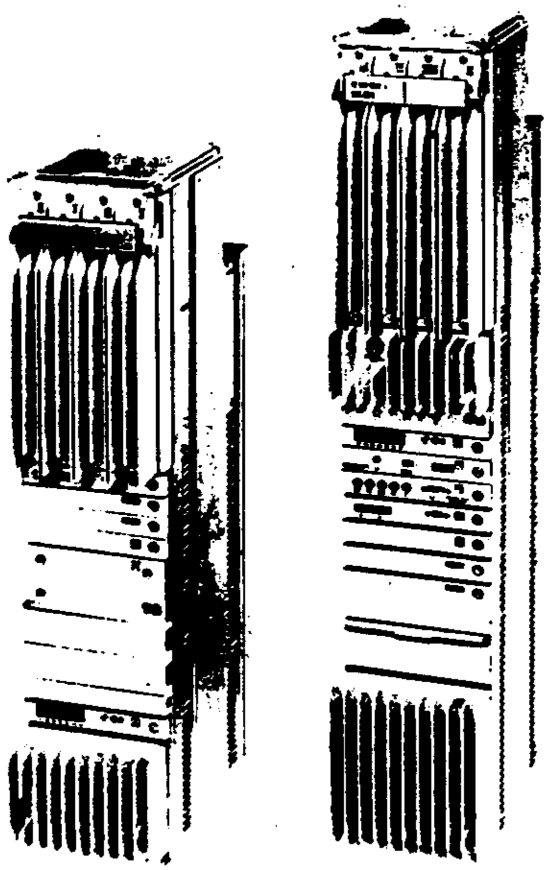


Fig. 4 Regenerative repeater (left) and line terminating unit (right) for the 140-Mbit/s system with optical waveguides

- adaptation of the signal spectrum to the properties of the channel (noise, bandwidth, etc.),
- assurance of bit-sequence independence, as well as facilitation of clock extraction and signal regeneration,
- provision of sufficient redundancy for the monitoring of bit errors on the transmission route and for the location of faulty units,
- restriction of redundancy to a minimum, in order to minimize the requirements regarding the bit rate of the circuit and the bandwidth of the transmission medium.

Having regard to these factors, the 5B/6B line code is very suitable for optical waveguide transmission systems of 34 to 565 Mbit/s in long-haul networks.

The following considerations were of importance in opting for this code:

- A two-level signal is most suitable as the transmission signal in optical waveguides.
- The low-frequency component of the signal spectrum is negligible, on account of the limited RDS (running digital sum $\leq \pm 3$).
- The density of signal transitions is high and very uniformly distributed, and the number of successive symbols of the same signal level is restricted to five. Accordingly, a reference clock may be obtained from the signal economically and reliably, with low jitter.
- The code permits constant monitoring of the bit error rate (BER) of regenerative repeaters by detecting overshoot of the RDS limits due to errors. In the range from very low to very high bit error rates, the relationship between actual errors and detected code violations is very close and to a large extent independent of the signal and error statistics.

Power budget

The basis for calculation of the maximum repeater spacing is the power budget. Proceeding from the minimum optical power launched into the fiber and the received optical power which is just sufficient for a defined bit error rate (**Table 1**), a margin is subtracted from the theoretical span loss for all influences to be considered in practice – whether these are capable of being calculated or whether they are estimated – until values for the maximum permissible cable loss assuring reliable transmission are obtained. From the data on the cable system, the relevant repeater spacings listed in **Table 2** are calculated.

System components

Fig. 2 shows, in the form of a block diagram, the functional units of the digital systems in the line terminating unit and in the regenerative repeater. In the line terminating unit, the signal to be transmitted passes through the interface module (INT) in the transmission direction. At this point, it is converted into a purely binary signal and, in the case of the 34-Mbit/s and 140-Mbit/s systems,

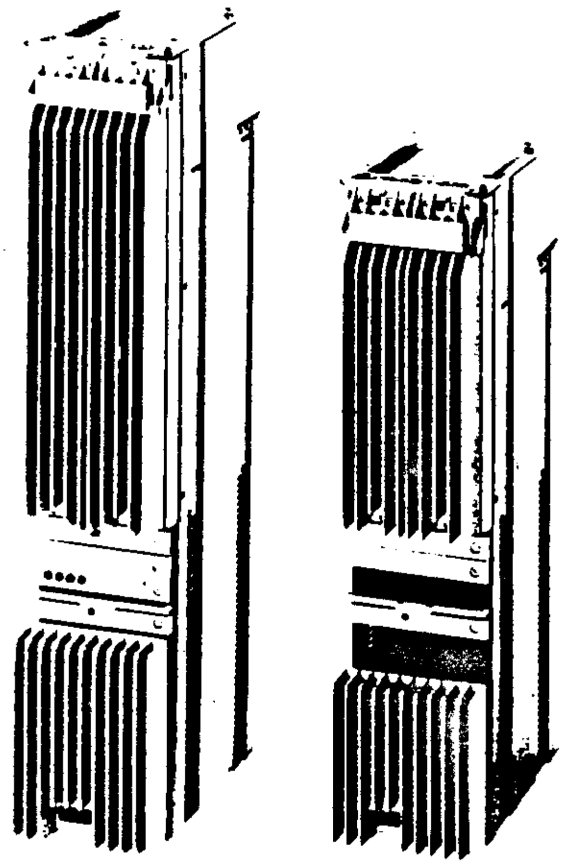


Fig. 5 Line terminating unit (left) and regenerative repeater (right) for the 565-Mbit/s system with optical waveguides

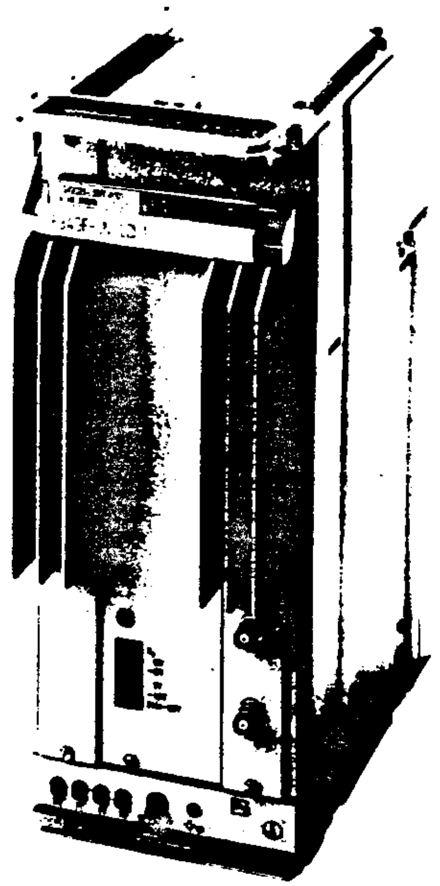


Fig. 6 Line terminating unit for 34 or 140 Mbit/s for local interoffice lines with optical waveguides

scrambled in the subsequent seven-stage scrambler (SCR); in the 565-Mbit/s system, scrambling already takes place in the DSMX 140/565 multiplexer. Line encoding (5B/6B) and electro-optical conversion (e/o) then follow.

In the receive direction, the optical signals are converted back into electrical signals in the optical receiver (OE), and subsequently they are regenerated in the regenerative repeater (REG) in amplitude and phase. The following operations include line decoding (5B/6B), possible descrambling (DSCR) and, in the interface (INT), output of the transmitted signals in accordance with the properties of the interface. The circuits processing the digital signals are designed in the form of bipolar integrated circuits.

For each direction of transmission, the regenerative repeater (ZWR) includes functional units as are also present in the line terminating unit. The units are supplied by a system power supply with the rated dc voltages of 48 or 60 V.

In order to satisfy with certainty the safety requirements, which have not yet been harmonized on a worldwide basis, with regard to eye damage due to laser light, automatic shut-off of the two lasers, adjacent to a point of interruption, is provided. For fault locating, this shut-off can be temporarily overridden by pressing a key at the regenerative repeaters. After restoration of the optical connection, the lasers which have been shut off can remotely be put into operation again from the line terminals.

Supervision and fault location

The transmission properties of the digital transmission route are monitored in the receiving line terminating unit; if predetermined threshold values are exceeded, optical and electrical alarms are actuated. Depending upon the particular requirements, the alarms can be made "urgent" or "non-urgent" and can be passed via an alarm signal panel to the main supervision facility of a station. In addition, there are separate and non-disconnectable signaling outputs (e.g. for central service observation equipment) associated with certain important criteria.

Disturbances and faults on the route are localized with the aid of the fault location system. In selecting the appropriate procedures, well-established principles of coaxial cable systems technology were adopted, such as in-system fault location, requiring no additional conductors in the cable. The last-mentioned point is of great importance specifically in the case of metal-free fiber-optic cables.

In a similar manner to digital systems using coaxial cables, in the 34-Mbit/s optical waveguide system fault location is carried out in accordance with the principle of *remote-controlled loop*; on the other hand, in the case of 140 and 565-Mbit/s systems *in-service monitoring* is used.

In the *loop fault-locating procedure*, the forward direction and the reverse direction in the regenerative repeaters of a transmission route are looped successively by remote control. By means of the loops connected in this manner, it is possible, proceeding from one terminal station, to localize faults accurately to within one section; during the time required for fault location, the actual signal transmission is interrupted.

The principle of fault location by means of *in-service monitoring* is described in detail in [1] within the context of additional services.

Mechanical design and housing

Line terminating units and regenerative repeaters are designed in the form of style 7R plug-in insets, having a width of 120 mm [6] (**Figs. 3** to **5**); the functional units are designed as slide-in units. Whereas it was necessary to provide a special mechanical construction for the remotely fed regenerative repeaters for coaxial cables for reasons of power feeding, lightning effects and the need to protect the personnel, in the case of optical systems it is possible to make optimum use of the same style for line terminating units as well as regenerative repeaters. This means it is possible to accommodate the units in narrow racks of different heights in conventional buildings of a telecommunications administration. Installation in underground containers is also possible, as shown in [7, 8].

The optical connectors which are employed are system-specific developments and products, which have been submitted to DIN for standardization [9].

Power supply

The line terminating units and regenerative repeaters receive the required power from the power supply via the 48/60-V interface (**Fig. 2**). Buffered by a battery, this power can be taken from the public mains or any other primary power source fed by the sun, wind etc. If such sources of power are not available locally on an economic basis, then an extremely attractive alternative is offered by a dc series power-feeding system using an additional copper cable parallel to the fiber-optic cable [10].

Local interoffice links

In larger local networks, digital local exchanges are situated at spacings of at most 10 to 20 km, and must be connected to one another by means of local interoffice links. As compared with conventional systems (PCM 30) using copper wire pairs and including a relatively large number of regenerative repeaters, optical transmission using optical waveguides permits connections without regenerative repeaters. Especially in

		2, 8 and 34-Mbit/s system									Local interoffice line systems				
Transmission capacity	Mbit/s	2			8			34			34			140	
Type of fiber		MM		SM	MM		SM	MM		SM	MM		SM	MM	SM
Optical transmitter		LED	LD		LED	LD		LED	LD		LED	LD		LD	
Optical power at 1300 nm in the fiber (behind the connector)															
Standard	dBm	−21	− 5	− 6	−21	− 5	− 6	−21	− 5	− 6	−20	− 4	− 6	− 5	− 6
with reduced transmitted power	dBm	–	–	–	–	–	–	–	–	–	–	–	–	− 9	− 9
Spectral bandwidth $\Delta\lambda$	nm	130	10	5	130	10	5	130	10	5	130	10	5	10	5
Received optical power for bit error rate BER = 10^{-10} in front of the connector															
without additional services	dBm	−51	−51	−51	−46	−46	−46	−40	−40	−40	−39	−39	−39	−32	−32
with additional services	dBm	−40	−40	−40	−40	−40	−40	−40	−40	−40	–	–	–	–	–
Optical attenuation which can theoretically be spanned															
without additional services	dB	30	46	45	25	41	40	19	35	34	19	35	33	27	27
with additional services	dB	19	35	34	19	35	34	19	35	34	–	–	–	–	–
with reduced optical power	dB	–	–	–	–	–	–	–	–	–	–	–	–	23	23
System margin	dB	6	6	6	6	6	6	6	6	6	6	4	4	4	4
Maximum optical line loss which can in practice be spanned															
without additional services	dB	24	40	39	19	35	34	13*	29	28	13*	31	29	23	23
with additional services	dB	13	29	28	23	29	28	13*	29	28	–	–	–	–	–
with reduced optical power	dB	–	–	–	–	–	–	–	–	–	–	–	–	19	19
Dispersion } for each repeater section	ps/nm	–	–	–	–	–	–	–	–	–	–	–	–	–	230
Bandwidth } for each repeater section	MHz	–	70	–	–	70	–	–	70	–	–	50	–	200	–

* Possible restriction of the maximum repeater spacing that can be spanned must be expected, as a result of dispersion and spectral width of transmitter

LD Laser diode
LED Light-emitting diode
MM Multimode fiber
SM Single-mode fiber

Table 3 Power budget for optical digital short-haul transmission systems

densely populated areas, this is particularly attractive. Consideration is given principally to 34 and 140-Mbit/s systems for the meshed network of local interoffice links. The line terminating units of the long-haul network systems as described in the previous section may, of course, also be used for this purpose. In order to save cost in this case too, line terminating units for 34 and 140 Mbit/s are available also with the more cost-effective light-emitting diode as the optical transmitting element.
However, if consideration is absolutely restricted to applications without regenerative repeaters, and if the line terminating unit is also optimized for shorter ranges, then the expenditure incurred in connection with the line terminating unit can be significantly reduced even further, as compared with the long-haul network version.

Line code and power budget

In place of the 5B/6B code, which is rather difficult to generate but saves bandwidth, in the case of the 34-Mbit/s system, a 1B/2B code – which can be derived in a very simple manner from the interface code – in the form of an MCMI code (MCMI modified coded mark inversion) is employed. In the case of the 140-Mbit/s system, the CMI interface code (CMI coded mark inversion) is also transmitted in unchanged form via the line. Instead of an increase amounting to only 20%, the clock rate on the line then increases by 100%. This does mean a slight reduction in the maximum range, but since it is possible at the same time to dispense with a scrambler, and since encoding back to the interface code and code error monitoring on the receive side can be carried out in a simple manner, the line terminating unit is simplified appreciably. Besides, in the case of relatively short connections, the laser can be replaced by a light-emitting diode, so that it is also possible to do without the laser safety shutdown arrangement, and the expenditure decreases even further. In order to manage without an optical attenuator (line build-out network), the optical receiver is designed for a full input dynamic range.

With the simplifications which have been mentioned above, the values shown in **Table 3** (right) for the maximum *optical losses* which can be spanned are obtained; having regard to the data of the cable system, the maximum *repeater spacings* are those shown in **Table 4** (right).

Properties of the fiber			
Type of fiber		MM	SM
Fiber loss at 1300 nm	dB/km	1.0	0.4
Average splice loss	dB per splice	0.2 to 0.1	0.1 to 0.05
Installation length	km	1 to 2	1 to 2
Specific splice loss	dB/km	0.2 to 0.05	0.1 to 0.025
Specific repair reserve	dB/km	0.35 to 0	0.2 to 0
Specific cable loss for route planning	dB/km	1.55 to 1.05	0.7 to 0.425

Maximum regenerative repeater section losses and spacings which can be spanned, with the fiber properties indicated above

		2, 8 and 34-Mbit/s system									Local interoffice line systems				
Transmission capacity	Mbit/s	2			8			34			34			140	
Type of fiber		MM		SM	MM		SM	MM		SM	MM		SM	MM	SM
Optical transmitter		LED	LD		LED	LD		LED*	LD		LED*	LD		LD	
Without additional services	dB	24	40	39	19	35	34	13	29	28	13	31	29	23	23
	km from	15.5	25.8	56	12.3	22.6	48	8.4	18.7	40	8.4	20	41	14.8	33
	km to	22.9	38	92	18.1	33	80	12.4	27.6	66	12.4	29.5	68	21.9	54
With additional services	dB	13	29	28	13	29	28	13	29	28	–	–	–	–	–
	km from	8.4	18.7	40	8.4	18.7	40	6.4	18.7	40	–	–	–	–	–
	km to	12.4	27.6	66	12.4	27.6	66	12.4	27.6	66	–	–	–	–	–
With reduced transmitter power	dB	–	–	–	–	–	–	–	–	–	–	–	–	19	20
	km from	–	–	–	–	–	–	–	–	–	–	–	–	12.3	28.6
	km to	–	–	–	–	–	–	–	–	–	–	–	–	18.1	4[illegible]

* Possible restriction of the maximum repeater spacing which can be spanned must be expected, as a result of dispersion and spectral width of transmitter

LD Laser diode
LED Light-emitting diode
MM Multimode fiber
SM Single-mode fiber

Table 4 Calculation of the maximum repeater spacings for regional transmission systems

Mechanical design

The functional units for a line terminating unit, including the associated power supply and monitoring units, are accommodated in an inset having a height of 30 cm (**Fig. 6**). If in a few exceptional cases the connection to be made is longer than indicated in **Table 4**, then two line terminating units (electrically back to back) take over the function of a regenerative repeater.

Long feeder links with low transmission capacity

For the connection of rather remote areas (e.g. to the nearest local exchange), optical transmission offers particularly economic solutions, even for bit rates of 2, 8 and 34 Mbit/s. Based on the design of the 34-Mbit/s system for local interoffice links, there is a system for 2, 8 or 34 Mbit/s for long ranges (in the first instance) without regenerative repeaters (**Fig. 7**). The same line terminating unit is employed for all three bit rates; operation at the respective bit rate is programmable. The left-hand part of **Tables 3** and **4** shows the power budget and the maximum repeater spacings which can be spanned using this equipment.

In order to develop the widest possible range of applications for the new system, modifications will be created for use on MM and SM fibers with laser diodes and light-emitting diodes as transmitting elements. In addition, this system offers a series of additional services, just like the long-haul system [1].

Conclusions and outlook

No more than ten years after the first industrial tests of optical transmission using optical waveguides, technically refined systems are available for widespread application at all levels of a telecommunications network, apart from the subscriber line network. Numerous routes have been installed and are in operation [7, 11, 12]. Already the 565-Mbit/s system on SM fibers [13] achieves cost levels, on newly installed routes, assessed per voice circuit and per kilometer, which are below those ever achieved by the most modern and most economic carrier frequency system V10800, using coaxial pairs. A further reduction of costs to be achieved by a wide variety of measures and principles is a prospect for the future.

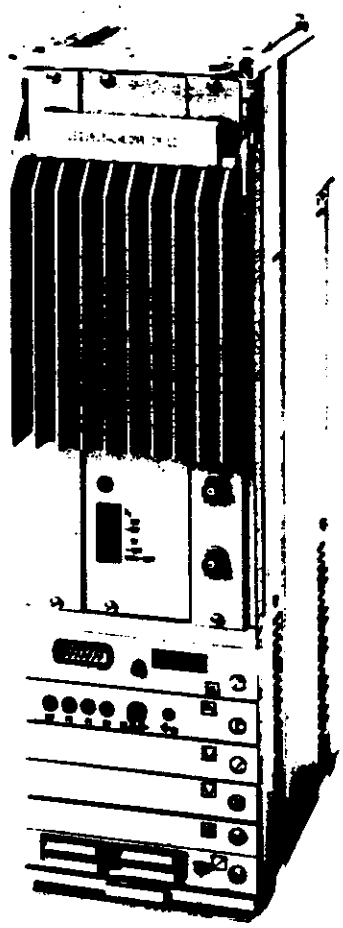


Fig. 7 Line terminating unit for 2, 8 or 34 Mbit/s via optical waveguide

The optical waveguide (OWG) transmission network is very well prepared for the coming era of broadband communication (ISDN-B); it is even to be expected that, in future, costly measures for reducing the bit rate in order to save transmission capacity will become superfluous.

The rapid progress in the development of systems for long-haul networks was possible because in the majority of cases the network carriers and thus the application profile were clearly associated, and because the pertinent standards of CCITT, CEPT and other bodies concerned with coaxial cable transmission, could be adopted directly.

In addition to the extremely favorable economics, optical waveguide transmission opens up entirely new possibilities for the network planner. Since the installation costs today represent a considerable proportion of the total costs, in case of coaxial cable technology the planning, construction and arrangement of a route represent a long-term project. In determining the number of coaxial pairs in the cable, and the number of underground containers which are laid as a precautionary measure, the future level of traffic must be estimated as accurately as possible and weighed against the initial capital expenditure.

The situation is different in the case of the relatively light and flexible fiber-optic cables. If in the first instance, one duct – or preferably two – are laid in the ground, and the first fiber-optic cable is subsequently pulled into such a duct, then any circumstances which may not have been considered at the outset may be corrected in a simple manner by subsequently pulling in a second fiber-optic cable or by replacing the first one, without any need for excavation work.

If in an existing fiber-optic cable route, the transmission capacity is to be increased without disturbance, one possibility is to install a system with the next-higher capacity. Since, in contrast to coaxial cable technology, the existing repeater spacings are not halved or reduced to one third, but must be reduced only slightly as compared with their previous dimensions, it is expedient to plan the repeater spacings already for the next-higher system. Finally, the subsequent incorporation of systems for optical wavelength multiplexing also permits a (subsequent) increase in the transmission capacity.

The extremely favorable economics of fiber-optic connections and a series of advantages, some of which have been presented here and of which others are described in [1], represent the driving force for the widespread use of this technology. Further improvements due to different wavelengths, lower-loss cables and other principles of modulation and transmission can be envisaged even today. Large investments in research and development were and continue to be necessary, in order to achieve further progress in this still very young technology. An essential prerequisite in this context is a broad and solid commercial basis.

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Ewald Braun and Erhard Steiner

Supervisory System and Additional Services for Digital Transmission via Optical Waveguides

Line terminating units, regenerative repeaters and the cable system with the repeater spacings *l* are the basic elements of a digital signal transmission route using optical waveguides (*Fig. 1*). It begins and ends at an electrical interface (IF), which is standardized to the CCITT Recommendation G.703. Operability and transmission properties are continuously monitored at the end of the route, and disturbances are reported. The entire route operates without maintenance; in most cases, the equipment is accommodated in unmanned stations.

With the object of rapidly detecting and localizing any possible disturbances from all stations, and, in addition, of supervising and optimally controlling an entire network with a greater or lesser degree of centralization, additional demands are made on the transmission system. In terms of their complexity they are scarcely subordinate to the primary function, namely that of transmitting digital signals at high bit rates.

Additional services

In order to ascertain the functional performance of a transmission route and to localize or locate faults on the route itself, in the cable system or in the units, an in-service monitoring system is incorporated. A 2.4-kbit/s transmission capacity is sufficient for this purpose; in addition, nine supervision alarm signals may be accommodated in this bit stream.

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For the requirements of the maintenance personnel, two data channels are provided, namely for 2.4 and 9.6 kbit/s. While access to the 2.4-kbit/s channel is provided at all points along the route, the 9.6-kbit/s channel as a rule connects the terminal stations (**Fig. 2**).

A further 32-kbit/s channel with access at all terminal and intermediate stations may be used to install a service telephone for the maintenance personnel. Collective or selective ringing is offered optionally.

If the bit streams of all services are combined, and 1.6 kbit/s is allowed for framing and alignment, this results in a digital signal of 48 kbit/s for all described auxiliary services in a system [1]. Normally, the above mentioned auxiliary services are needed only once or twice on a route with many parallel systems in the cable; only in-service monitoring is to be provided in every system.

Transmission channel for the signals of the auxiliary services

On routes using coaxial cables, if in fact all the auxiliary services are provided, the signals of these services are transmitted via system-specific copper pairs in the interstices between the coaxial pairs. Only the in-service monitoring signals pass via the coaxial pair specific to the system [2].

In most cases, fiber-optic cables do not contain conductive cores and shields, if all the advantages of this new transmission medium are to be fully utilized. It would indeed be possible for the signals of the auxiliary services to be transmitted centrally on a specific fiber in the cable, but this is awkward and costly –

Jürgen Gier and Baldur Stummer

565-Mbit/s Line Equipment for Optical Communication over Single-Mode Fibers

Optical transmission systems operating at high bit rates are expected to provide the solution to the future demand for links with high transmission capacity. The system described here transmits four plesiochronous signals each with a rate of 140 Mbit/s at a transmission rate of 565 Mbit/s over single-mode fibers. In the line terminating equipment the same muldex is used as in the 565 Mbit/s coaxial cable system. By using a 5B/6B line code at the optical interface and an in-service monitoring system the alarm states and bit error rate of each regenerative repeater can be continuously supervised. Taking into account repair splices and a system margin of 6 dB, repeater spacings of about 30 km and more are obtained.

With the increasing use of digital switching and digital transmission in public communications networks, the demand for long-haul transmission systems with high bit rates is also growing. Many telecommunications administrations who already have a comprehensive coaxial cable network will use this network to provide low-cost digital transmission as soon as possible. For such applications, digital transmission systems for up to 565 Mbit/s have been developed, which will be installed in the coming years. However, the repeater spacing, e.g. of the 565-Mbit/s coaxial cable system, is limited to about 1.5 km.

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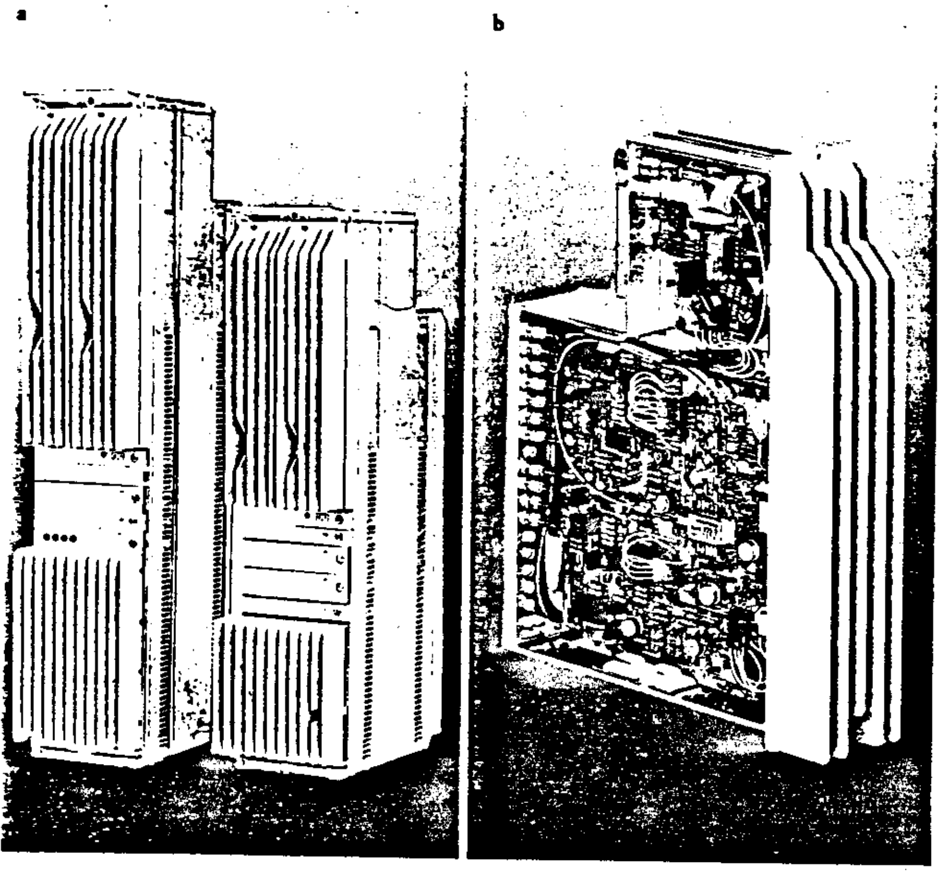
Operational optical waveguide systems using single-mode fibers and an optical wavelength of 1300 nm already permit repeater spacings of about 30 km, however. On newly installed digital routes using optical waveguide transmission systems, considerable improvements are anticipated regarding costs, operation and maintenance. An optical waveguide transmission system of this kind for a transmission rate of 565 Mbit/s (7680 speech channels) is described here; Fig. 1 shows the line terminating and line repeater insets. The system is designed to be an operational system including facilities for supervision and maintenance. These are in particular an in-service performance monitoring (ISM) system which includes the possibility of locating faulty regenerative repeaters, where a separate service-channel wire pair is not required. The in-service performance monitoring system is employed in the same way in 140-Mbit/s and 565-Mbit/s coaxial cable systems as well as in 140-Mbit/s optical waveguide systems. This concept of uniform system supervision is advantageous for supervision and maintenance of transmission networks in which coaxial cables and optical waveguide cables are combined.

System overview

Fig. 2 shows the functional circuit diagram of the 565-Mbit/s optical waveguide transmission system. The principle of combining the functions of a 140/565-Mbit/s multiplexer with the line terminating equipment was chosen for the following reasons:

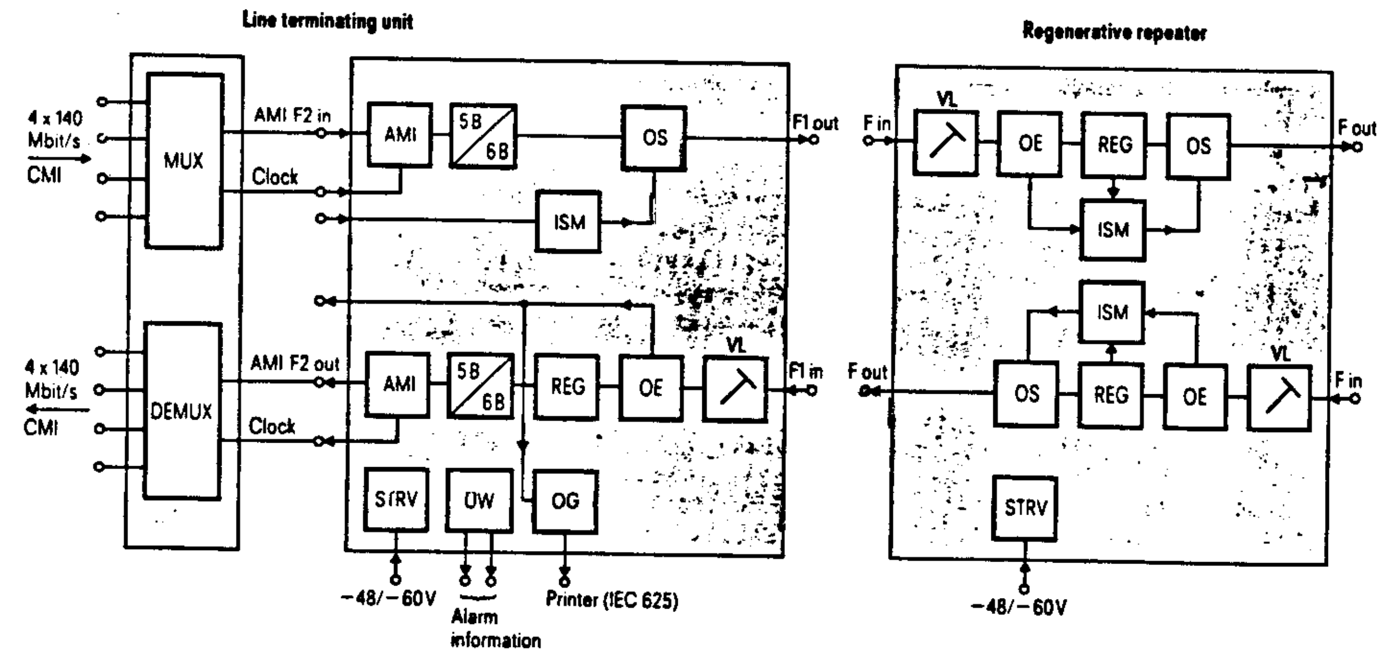
- A 140-Mbit/s interface is defined in CCITT Recommendation G.703 [1].
- There are currently no digital sources of bit rates higher than 140 Mbit/s.
- Monitoring of the end-to-end performance may be based partially on the existing frame structure of the multiplex signal.
- The necessary independence of bit sequence may be achieved by using a line code together with a scrambler, which can be reset by the frame alignment signal of the multiplexer. There is no multiplication of errors, as occurs with free-running scramblers, and the scrambler can be operated on the input side of the multiplexer with a relatively low rate of only 140 Mbit/s.
- Thanks to the functional integration of these units, a complex interface between muldex and line terminating equipment is not required [2].

The muldex section of the system, in compliance with CCITT Recommendation G.922, is the same as that used



ig. 1 Line terminating unit and regenerative repeater of style 7R construction (a), ptical transmitter of the regenerative repeater (b)

for the 565-Mbit/s coaxial cable system. Due to the identical frame and scrambler structure, it is possible to connect together coaxial cable and optical waveguide line sections directly via the 565-Mbit/s interface. In an initial version, the system operates at an optical wavelength of 1300 nm and a guaranteed permissible cable loss of 21 dB with a system margin of 6 dB at a bit error rate of 10^{-10}. Assuming single-mode fibers with an attenuation of 0.7 dB/km (including splices) the repeater spacing is 30 km. At the latest after 100 repeater sections (about 3000 km) a line terminating unit must be installed. In the receive-side demultiplexer the accumulated jitter is reduced to a value well within the CCITT specifications for 140-Mbit/s interfaces. For this reason this concept even permits interconnection of several such line sections to form a digital line path. The in-service performance monitoring (ISM) system performs continuous checks in each regenerative repeater for code law violations during operation and transmits its results to the supervisory line terminating unit. This information is transmitted together with the main



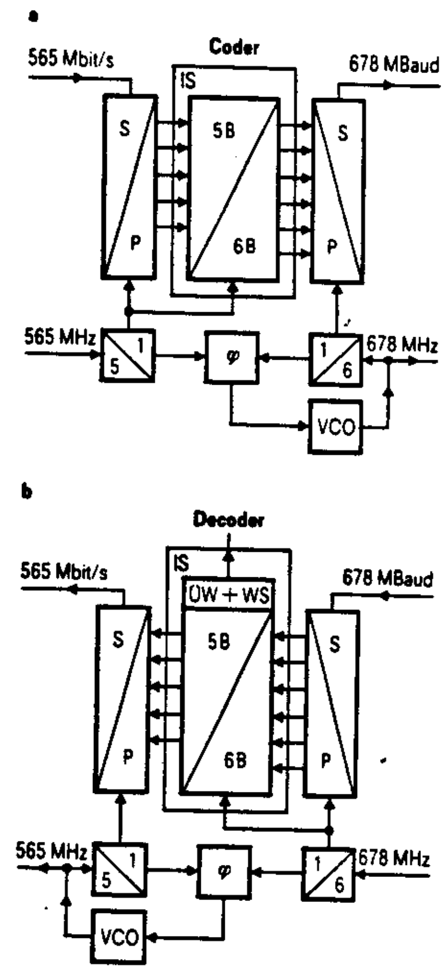
'6B	Line coding	DEMUX	Demultiplexer	OS	Optical transmitter
MI	Pseudo-ternary disconnection point code (alternate mark inversion)	ISM	In-service monitoring	REG	Signal regenerator
MI	CCITT interface code (coded mark inversion)	MUX	Multiplexer	STRV	Power supply
		OE	Optical receiver	UW	Monitoring unit
		OG	Fault-locating unit	VL	Optical attenuator (line building-out network)

ig. 2 Functional circuit diagram of the 565-Mbit/s line equipment

Transmission capacity	4 × 140 Mbit/s, plesiochronous
Line symbol rate	678 Mbauds
Transmission code	5B/6B, NRZ
Optical waveguide	Single-mode fiber
Optical wavelength	1300 nm
Optical transmitter	InGaAsP-LD
Guaranteed output level including connector and extinction losses	≥ −6 dBm (mean value)
Optical receiver	Ge-APD
Optical receive power (BER ≤ 10^{-10}) including connector loss (guaranteed value)	≤ −33 dBm (mean value)
Recommended system margin	6 dB
Allowable attenuation of cable section	21 dB
Dynamic range	≥ 20 dB
Line monitoring	In-service performance monitoring
Clock recovery	SAW filter

APD Avalanche photo-diode
BER Bit error rate
LD Laser diode
NRZ Non-return-to-zero
SAM Separate absorption and multiplication
SAW Surface acoustic wave

Table Main system characteristics



φ Phase discriminator
IS Integrated circuit
P/S Parallel-series converter
S/P Series-parallel converter
ÜW Monitoring for code law violation
VCO Voltage-controlled oscillator
WS Word alignment unit

Fig. 3 Coding (a) and decoding (b) of the 5B/6B line signal

digital signal over the same optical waveguide, and hence no additional transmission medium is required for the supervision signal.

The table lists the main system characteristics.

Line code

Line codes are used for converting the signals into a format that is best suited for transmission over a given channel. The line code must satisfy numerous requirements:

- It must match the signal spectrum to the channel characteristics (noise, bandwidth, etc).
- It must assure bit sequence independent transmission quality and simplify clock extraction and signal regeneration.
- Sufficient redundancy must be made available for supervision on the route and for locating faulty equipment.
- Redundancy must on the other hand be kept to a minimum, in order to minimize the requirements regarding circuit speed and bandwidth of transmission medium.

When these factors are taken into account, a 5B/6B line code is well suited for a 565-Mbit/s optical waveguide transmission system (Fig. 3) [3].

The following considerations favor the choice of this code:

- A binary signal is most suitable for transmission over optical waveguides.
- The low-frequency content of the signal spectrum is negligibly small because of the limited running digital sum (RDS ≤ ±3).
- The signal transition density is high and very evenly distributed; the number of consecutive symbols of the same polarity is limited to five. A reference clock can thus be derived economically and reliably from the signal with low jitter.
- The code permits continuous supervision of the bit error rate (BER) of regenerative repeaters by detection of any violation of the RDS limits as a result of faults. Throughout the range from very low to very high bit error rates the relationship between actual faults and detected code violations is very close and to a great extent independent of the signal and fault statistics.

5B/6B coders and decoders are designed partly as ECL (emitter coupled logic) gate arrays.

Performance monitoring system

The provided in-service performance monitoring system (ISM) detects code law violations in regenerative repeaters and transmits the results from each regenerative repeater to the monitoring station by using telemetry methods (Fig. 4).

The telemetry signal modulates the optical transmit power (peak-to-peak) of the main signal with a very small modulation factor. The ISM system therefore requires no additional transmission medium. Status signals of the regenerative repeaters (e.g. bit error rate) are encoded in information blocks (messages) that are passed on from one repeater to the next.

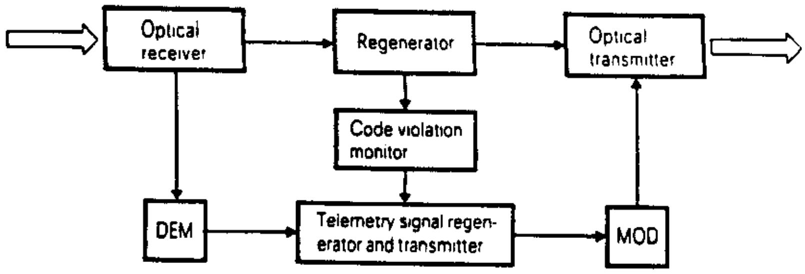
Each regenerative repeater regenerates the incoming message chain and adds its own message to the end of the chain.

This is a cyclic process in both transmission directions. In normal operation, a new cycle is initiated by the message transmitted from the line terminating unit. In the event of route interruption, the first regenerative repeater detecting loss of input signal automatically starts the message chain.

Incoming messages are evaluated and analyzed by a microprocessor-controlled supervision and fault-locating unit in the terminal station. By counting, the individual messages can be assigned to their respective regenerative repeaters and thus fault locations can be determined. The information is either indicated on a display unit or made available at a printer interface. The fault-locating can be programmed either to indicate information from selected individual regenerative repeaters or to continuously supervise only those repeaters in which a settable BER threshold is exceeded or those giving a status alarm.

In this way, any deterioration in transmission quality can be detected early enough to start adequate maintenance activities.

The circuitry of the ISM in the regenerative repeaters comprises the code violation monitor as part of an IC for signal regeneration in bipolar high-speed technology and two integrated CMOS circuits, containing the functions of the telemetry regenerator and transmitter.



DEM Demodulator
MOD Modulator

Fig. 4 In-service monitoring

Signal regeneration

Fig. 5 shows the basic principle of the receiver, decision and clock recovery circuits.

The AGC keeps the output signal of the receive amplifier constant; a pulse-shaping filter provides an optimum signal shape for the decision circuit. This is a bipolar IC with gate delays of less than 300 ps. This circuit performs both amplitude and time regeneration of the transmit signal and extracts and amplifies the clock signal. For actual clock filtering a surface acoustic wave filter is used.

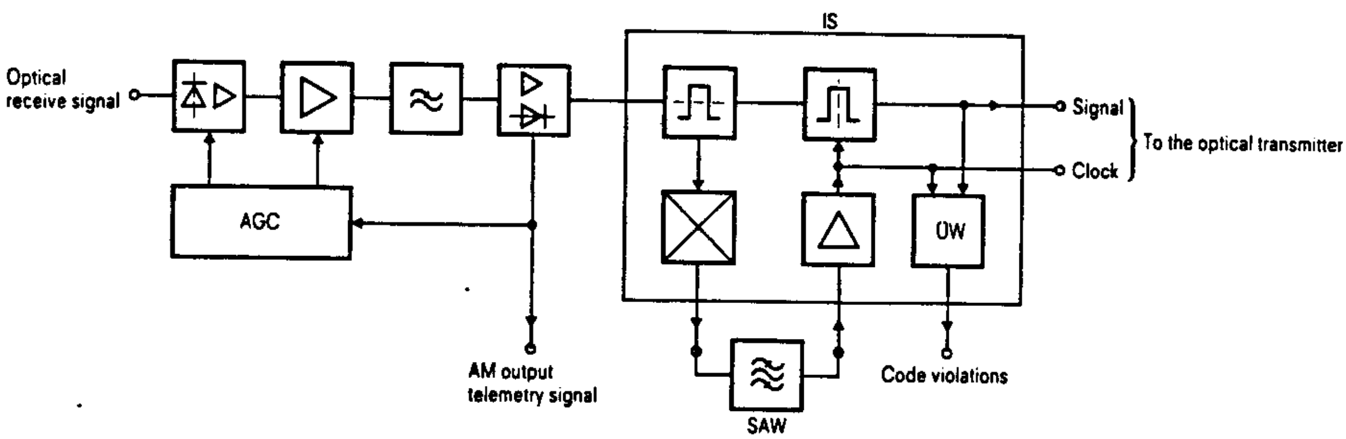
Furthermore, this IC supplies fault pulses to the ISM system whenever code violations have occurred in the receive signal.

Optical transmitter

The system is designed for operation with single-mode fibers having a dispersion minimum at 1300 nm. Use is made of InGaAsP-BH (buried heterostructure) laser diodes with a spectral width of ≤ 4 nm (half-power width).

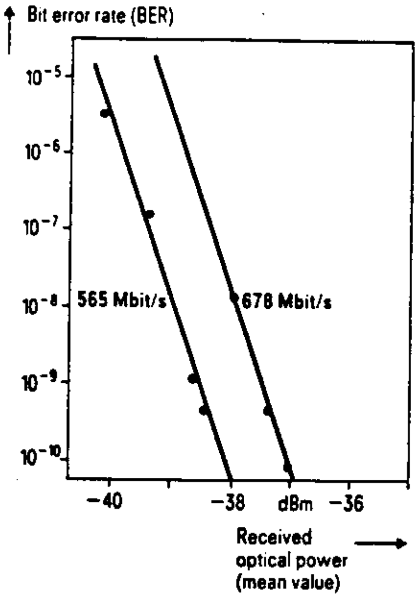
In order to achieve a long operating life of the laser transmitter

- the laser diode is actively cooled to 25 °C with a Peltier cooling element, independently of high ambient temperatures, and
- the laser drive current is controlled with regard to dc bias and modulation-current amplitude so that optimum operation is guaranteed even if the laser characteristics change.



AGC Automatic gain control
IS Integrated circuit
UW Monitoring for code law violation
SAW Surface acoustic wave

Fig. 5 Receiver and regenerator



• Ge-APD (Avalanche-Photodiode)

Fig. 6 Receiver sensitivity at various bit rates (route length $S = 37.8$ km; temperature $T = 25$ °C)

The amplitude modulation of the 678-Mbaud digital signal is about 4% of the digital signal amplitude. The laser threshold current is monitored; if it exceeds 150% of its initial value an alarm is transmitted.

Optical receiver

In the optical receiver a Ge-APD (avalanche photo-diode) and a preamplifier stage with a transimpedance of 1 kΩ are used. The achieved values of the receiver sensitivity are plotted in Fig. 6. The loss of sensitivity due to an increase in dark current in the Ge-APD for a temperature rise from 25 to 60°C is typically about 2.5 dB with an APD of 100 µm in diameter. A 30 µm APD will reduce that temperature penalty to approximately 0.5 dB.

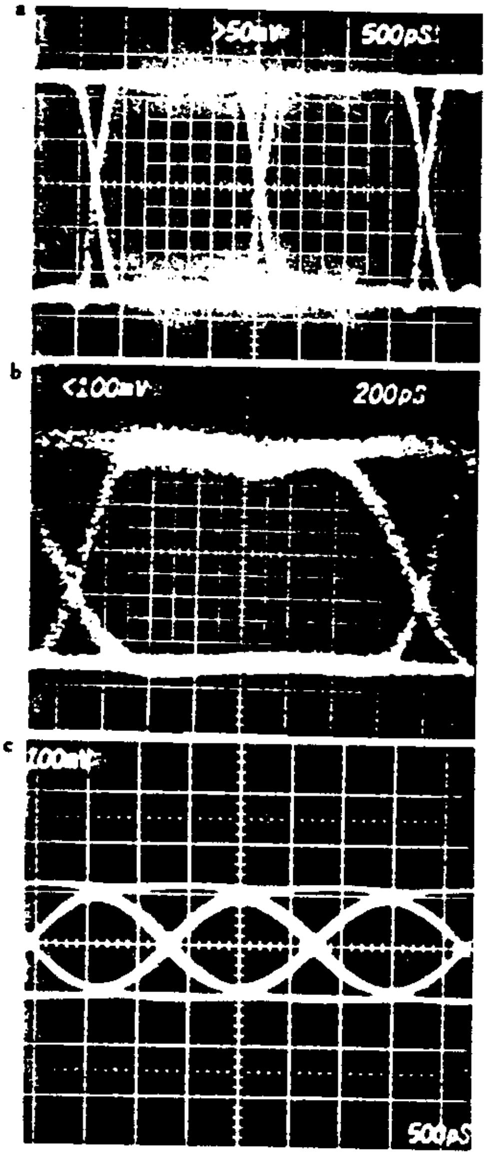


Fig. 7 Eye diagrams for
a Laser diode drive current ($I_{p-p} = 20$ mA)
b Optical output signal (mean value of optical transmit power $\bar{P} = -3$ dBm)
c Signal at decision circuit output (mean value of optical receive power $\bar{P} = -33$ dBm)

Test results

Transmission tests were carried out with different fiber route lengths up to 37.8 km and at bit rates of 565 and 678 Mbit/s. As expected, no appreciable influence of dispersion was found with laser diodes having a spectral half-power width of up to 4 nm in a wavelength range with a dispersion of less than 5 ps/nm · km over 37.8 km. The extent of the signal distortion depends on the used laser diode. BH laser diodes of recent manufacture have very low sensitivity to optical reflection. The loss of sensitivity due to reflection at state-of-the-art optical connectors is less than 0.5 dB.

Fig. 7 shows eye diagrams of the laser diode drive current, of the optical output power and of the transmission signal at the input of the decision circuit. Due to the 5B/6B code the diagrams are practically unaffected by the statistics of the 565-Mbit/s signal.

Conclusion

The design, realization and test results of an optical waveguide transmission system for 565 Mbit/s with single-mode fibers using a wavelength of 1300 nm have been described. BH-Fabry-Perot laser diodes available today are well suited for use in operational transmission systems with regenerative repeater spacings of about 30 km and more.

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Field Performance of 565 Mbit/s Optical Fibre Line System

Venkataraman Nagarajan and Glenn Nordqvist

Ericssor's optical fibre high-speed system ZAM 565-1 has been installed between St. Paul and Dallas and made operational during the first quarter of 1986. The system has a capacity of 8 064 telephone channels and uses single mode fibre as the transmission medium at a wavelength of 1 300 nm. It has henceforth become one of the very first of this kind to carry normal traffic, providing the long-haul telecommunication services for US SPRINT. Elaborate tests conducted on the fibre and the equipment during the installation and operational phases of the 2 400 km long fibre optic route confirmed the practical viability of this high speed digital optical system.
The authors present the system and cable performance results from the installation.

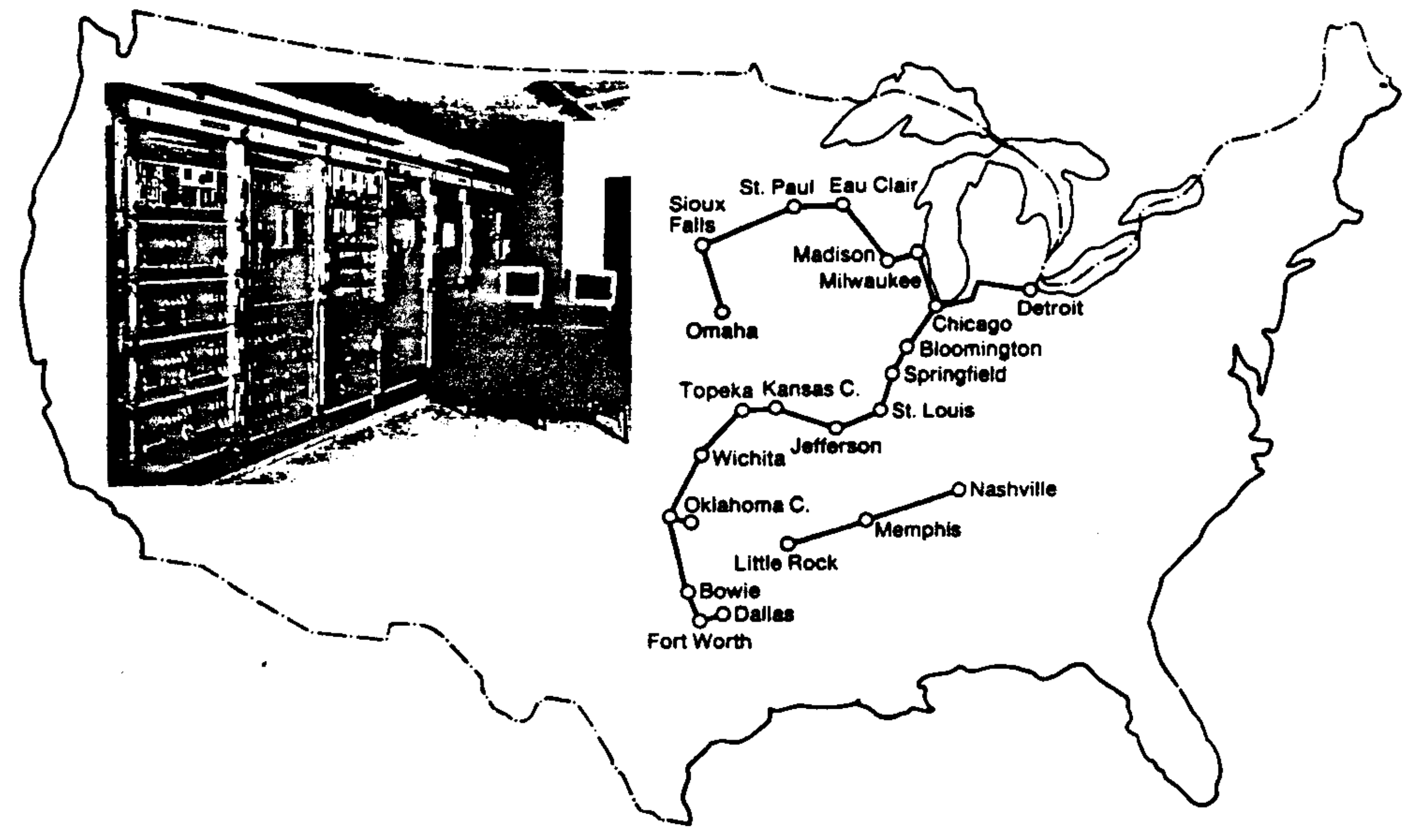
optical fibres
optical links
installation
telephone lines
electronic equipment testing

The trend towards an all digital/all fibre network is fast emerging all over the world, thanks to the technical/economical advantages of optical fibre transmission systems. Some of the interexchange telecommunication carriers in the United States caught up with this pace at a very early stage, by installing single mode fibre optic cables along the railroads and highways at low costs. In order to exploit the enormous information bandwith potential of the single mode fibres already installed, they required a high capacity system to meet their service demands at a reasonable cost.

In the above context, the economic advantage of installing a high speed 565 Mbit/s optical fibre system compared with a number of low-order 140 Mbit/s systems or a 405 Mbit/s system decided the final selection. Hence, currently in the majority of the US long-haul network applications, 565 Mbit/s systems are widely preferred as the optimum choice for providing high bit-rate service to the customers. Improved reliability and maintenance aspects further justify the use of 565 Mbit/s system. The ever-increasing traffic demands call for consideration of system upgrading possibilities in the near future, using the existing single mode fibre. In this perspective also, the 565 Mbit/s system has emerged out as a suitable building block amenable for such future upgrading plans.

Realizing the above urgent and huge demand in the US market, Ericsson developed this high-technology equipment and delivered to US SPRINT, one of its first customers. The system had been designed with stringent performance requirements and in connection with the first longest installation of

Fig. 1
The 565 Mbit/s optical fibre route between St. Paul and Dallas, USA
The total route length is approximately 2400 km



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2400 km system length (St. Paul – Dallas), fig 1, field performance of the system and the cable was verified. Also any possible degradations for long-term operation over long chains of cascaded repeaters were studied and the results were found quite satisfactory.

The most important parameters for an optical fibre line system, which determine the maximum transmission span, are:
- the attenuation and dispersion of the fibre
- the optical output power and spectral width of the transmitter
- the sensitivity of the receiver
- the bit error rate
- the jitter.

System overview

The basic version of the 565 Mbit/s line system[1] consists of terminal equipment and line repeaters, fig. 2. The terminal equipment has a DSX 3 electrical interface (45 Mbit/s) and a 600 Mbaud optical interface. A 600 Mbaud electrical interface is also available. It will be suitable for upgrading to future systems with higher transmission capacity. The muldex version, with an interface for the 140 Mbit/s in the CEPT hierarchy, has been designed with due consideration paid to cable-TV applications. The muldex versions accordingly multiplexes and demultiplexes twelve 45 Mbit/s or four 140 Mbit/s signals.

In addition to the muldex unit the terminal equipment contains a terminal repeater. Its main purpose is to convert the electric 600 Mbaud signal to an optical signal in the send direction and vice versa in the receive direction. The repeater also includes an interface for the connection of a fault location signal and service telephone.

The line repeater contains an optical transmitter and receiver for each direction of transmission, a fault detector unit and an interface for a service telephone. Information regarding faults is transmitted via the fibre carrying the traffic and is processed in the fault location magazine. Fault location can thus be carried out during operation.

Operational reliability and supervision

A system must not only have good performance but also good operational reliability. Components and printed board assembly designs are selected with this in mind. The system reliability can be improved further through the use of a standby line system designated Protection Switch Line. Between one and eighteen systems can be connected via the standby system. It also offers the possibility of setting priority levels for the systems that have access to the standby. The switchover is initiated by an alarm and can be carried out manually or automatically. It can also be controlled from an operator terminal. An alarm is given in the case of a fault in the multiplexed 600 Mbaud stream or the 45 Mbit/s streams. The safety level can be set in accordance with the customer's requirements. Switchover takes place for complex faults of 50 ms. The standby system is designed with reliable components. It can never reduce the operational reliability of the ordinary systems since the latter are restored if a fault should occur in the standby system.

Fig. 2
The equipment in the 565 Mbit/s project

PS1:N Switchover equipment
PROT Standby line

Muldex and terminal repeaters

Line repeaters

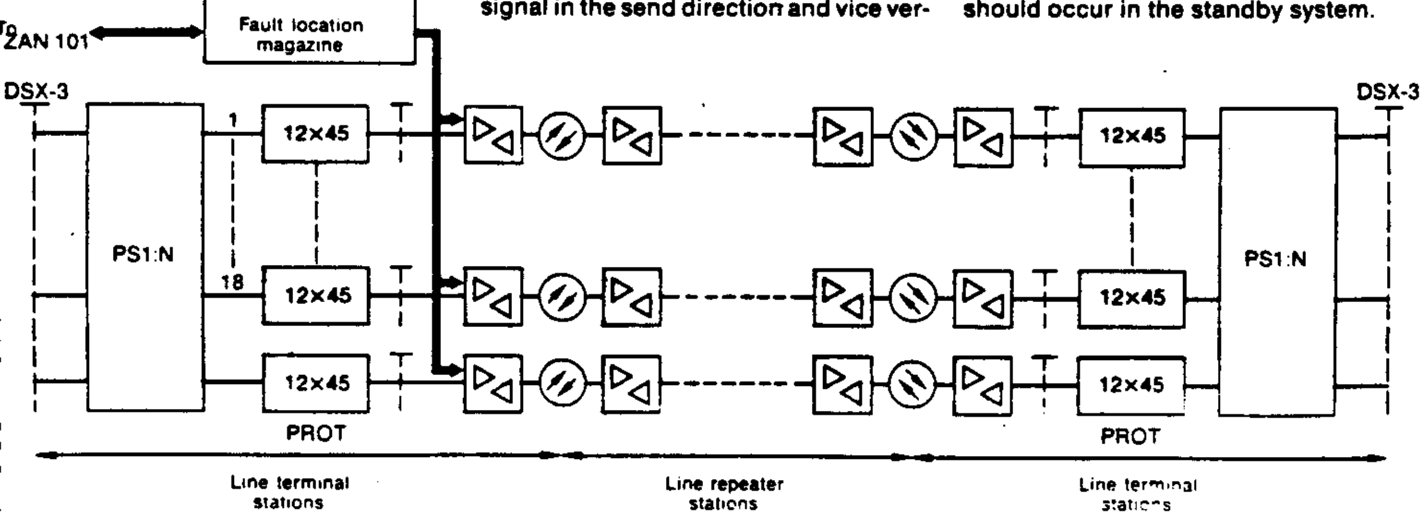


Fig. 3
Bit error rate, BER, as a function of the optical input power with temperature as the parameter

T = −20 C

T = +25 C

T = +70°C

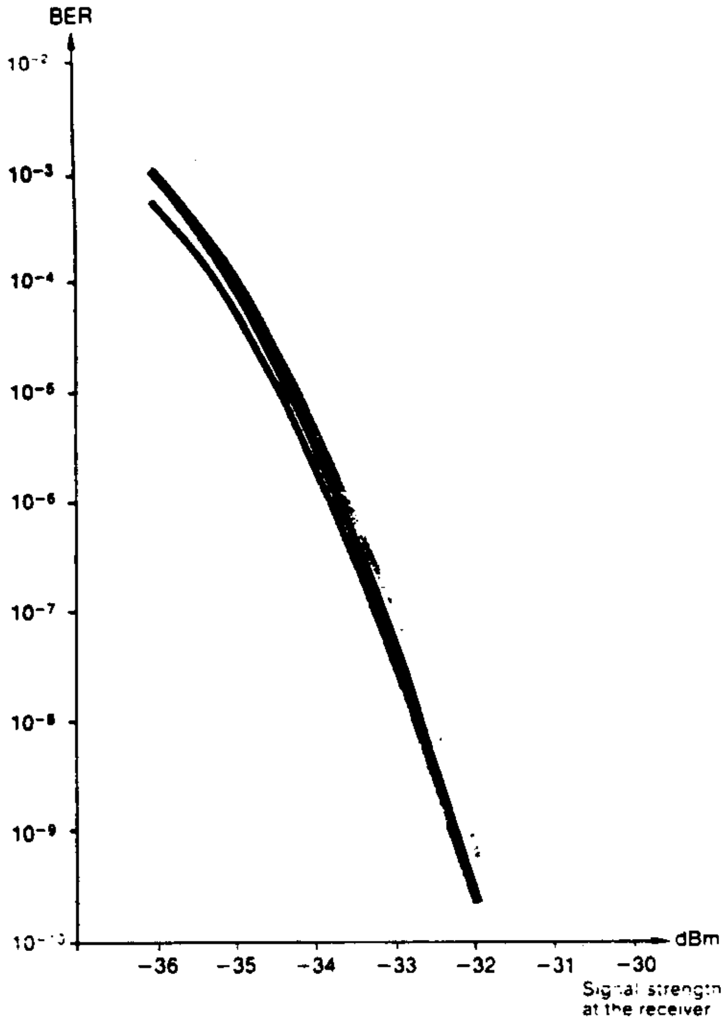
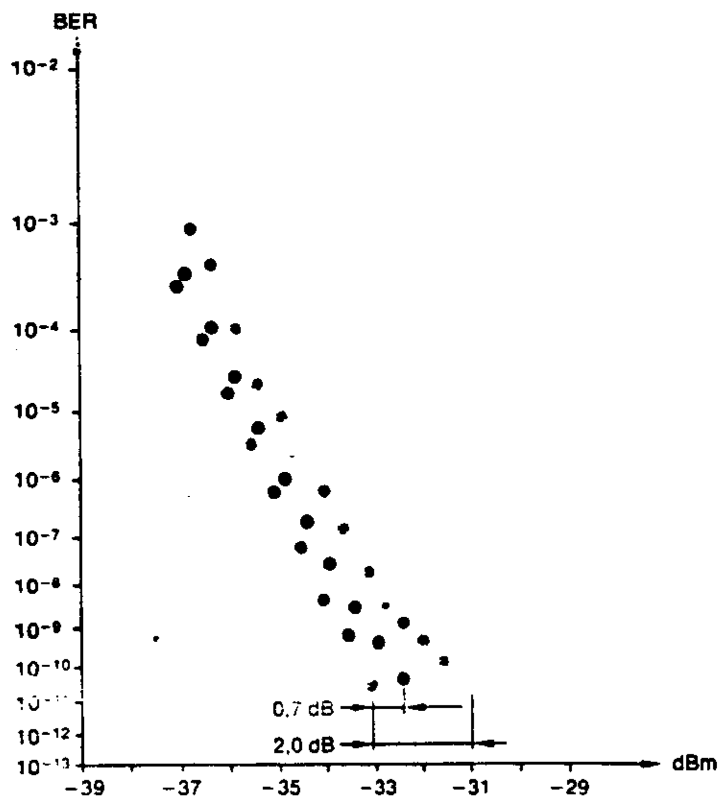


Fig. 4
Bit error rate, BER, as a function of the optical input power with dispersion as the parameter

Dispersion = 0 ps/nm

Dispersion = 119 ps/nm

Dispersion = 157 ps/nm



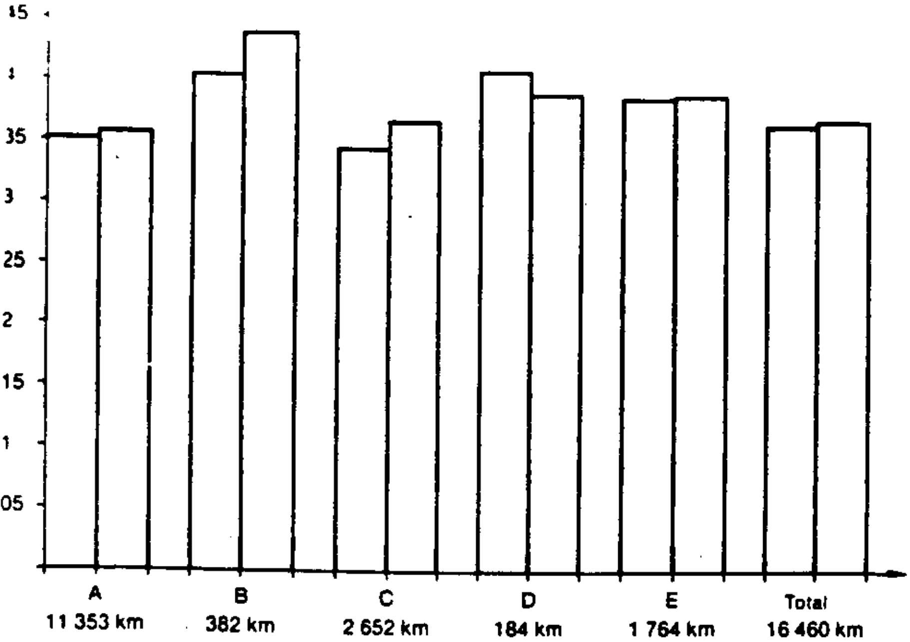
Fault location system ZAN 201 can be used to supervise transmission systems which include ZAM 565-1. Transmission supervision system ZAN 101 offers centralized supervision and alarm assembly.[2,3]

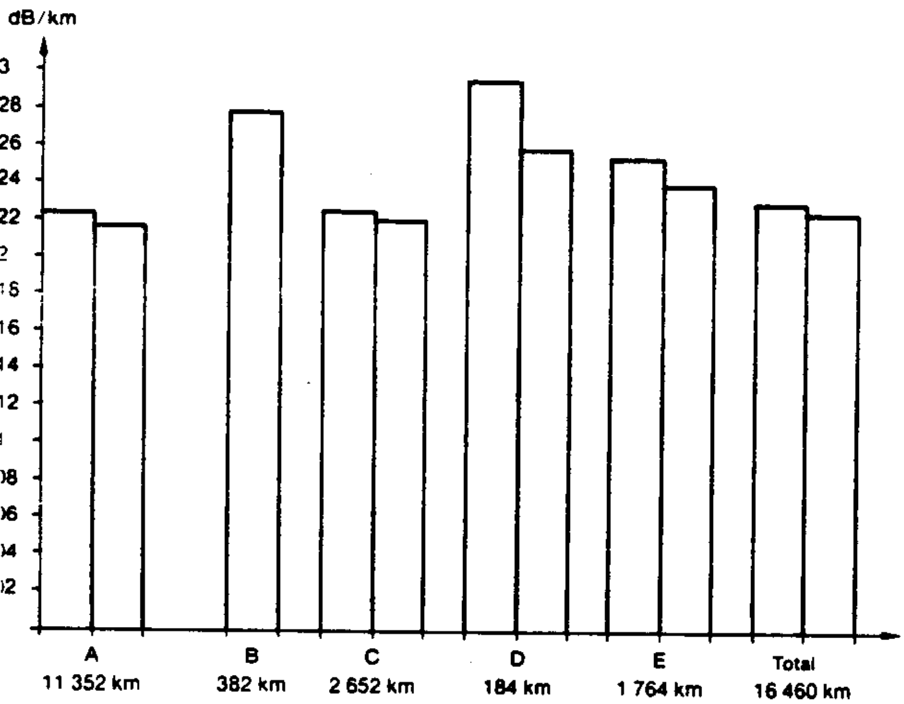
Maximum permissible cable section attenuation

The system specification states that the attenuation of a cable section may amount to 24 dB without the bit error rate, BER, exceeding 1×10^{-11}. The attenuation value includes contributions from the cable and splices. Due consideration has been given to the deterioration caused by the dispersion of a 40 km long line, since cable sections are of that length in most long-distance networks. The margins allowed for ageing, temperature dependence and dispersion are shown in the adjoining figures.

Measurements have shown that the deterioration caused by temperature variations is considerably less than the allowance, see fig. 3.

A fibre causes dispersion of the pulses the size of which is dependent on the wavelength and spectral content of the transmitted light. The dispersion results in higher BER, fig. 4, and may, if not kept





5a, top
e attenuation with different cable lengths, sured at 1310 nm

Buried

On a drum

5b. bottom
attenuation with different cable lengths, sured at 1550 nm

under control, lead to the system being unable to operate without errors regardless of the input power. The system has been designed to tolerate a dispersion of 100 ps/nm, at the wavelengths 1290 and 1320 nm. This interval is suitable for present-day single-mode fibres, which have zero dispersion at approximately 1310 nm.

Network structure

The first installation of Ericsson's 565 Mbit/s system in the US SPRINT network consists of systems in normal operation and standby systems (protection switch lines). The network now in operation is intended both as the backbone of a future more extensive long-distance network and as local networks in cities. Some lines are also leased to private networks.

During 1985 US SPRINT laid almost 6400 km (4000 miles) of buried cable and put 5960 km (over 3700 miles) of it into operation. Ultimately the network will comprise 37 000 km (23 000 miles) of buried optical fibre cable.

Measurements

Extensive measurements have been carried out in order to determine the attenuation and dispersion of fibres and the accumulated effect of jitter and bit errors over a number of cascade-coupled amplifiers.

A large amount of data has been obtained through measurements on cable on drums. Measurements were made on 3630 cable drums with an average of 4.22 km of cable each. The fibre cables contain between 10 and 70 fibres. Altogether the drums held over 15 million metres of fibre of different manufactures. Hitherto over 31 000 fibre splices have been made, with a mean attenuation of 0.13 dB. Data for 10 068 cable sections has been recorded. On average the cable sections contain 24 fibres and have a length of 33.8 km.

The optical fibres now being installed are intended for use with both the present and the next generation of transmission systems. At present light having a wavelength of 1310 nm is used, but when suitable lasers and detectors are available the 1 550 nm wavelength will be used. US SPRINT has specified fibre data for both 1310 and 1550 nm. Attenuation measurements have been made at both wavelengths.

Figs. 5a and 5b show the attenuation per km of fibres from different manufacturers. Measurements were made on the cables both on drums and after burial, using an optical time domain reflectometer (OTDR) connected to a Hewlett Packard personal computer. Measurement data from the newly laid cable constitutes an important reference for future maintenance. Fig. 6 shows the attenuation of all fibres in the route between Fort Worth, Texas, and El Reno, Oklahoma, a distance of 394 km. The results show that the route meets the set requirement, 0.5 db/km, satisfactorily.

Fig. 6
Overall attenuation of different fibres on the route between Fort Worth and El Reno, measured at 1310 nm

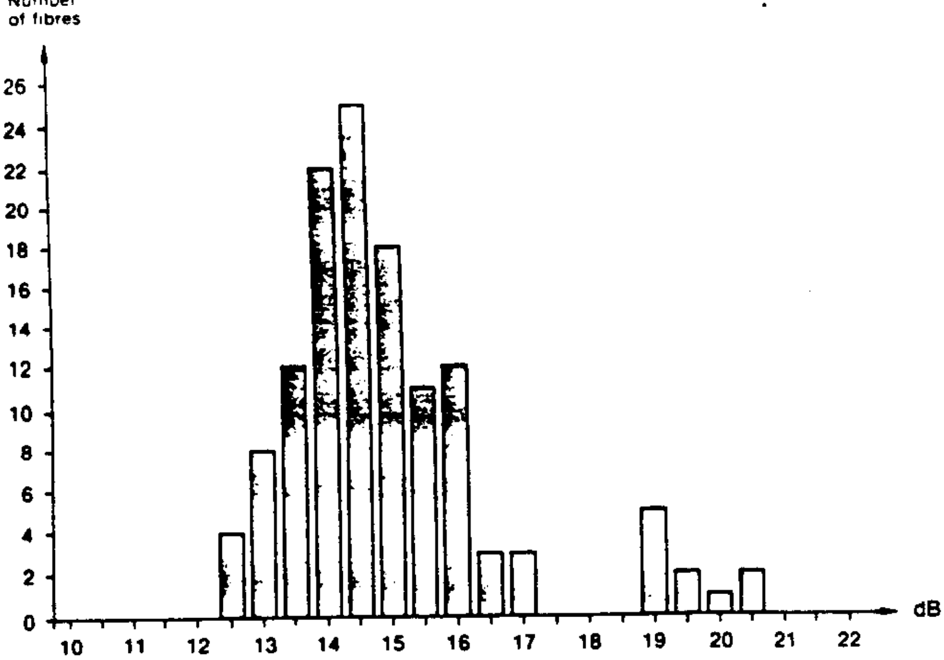


Fig. 7
OTDR curve showing the change in signal strength along a 35 km long route. The measurement was made at 1550 nm

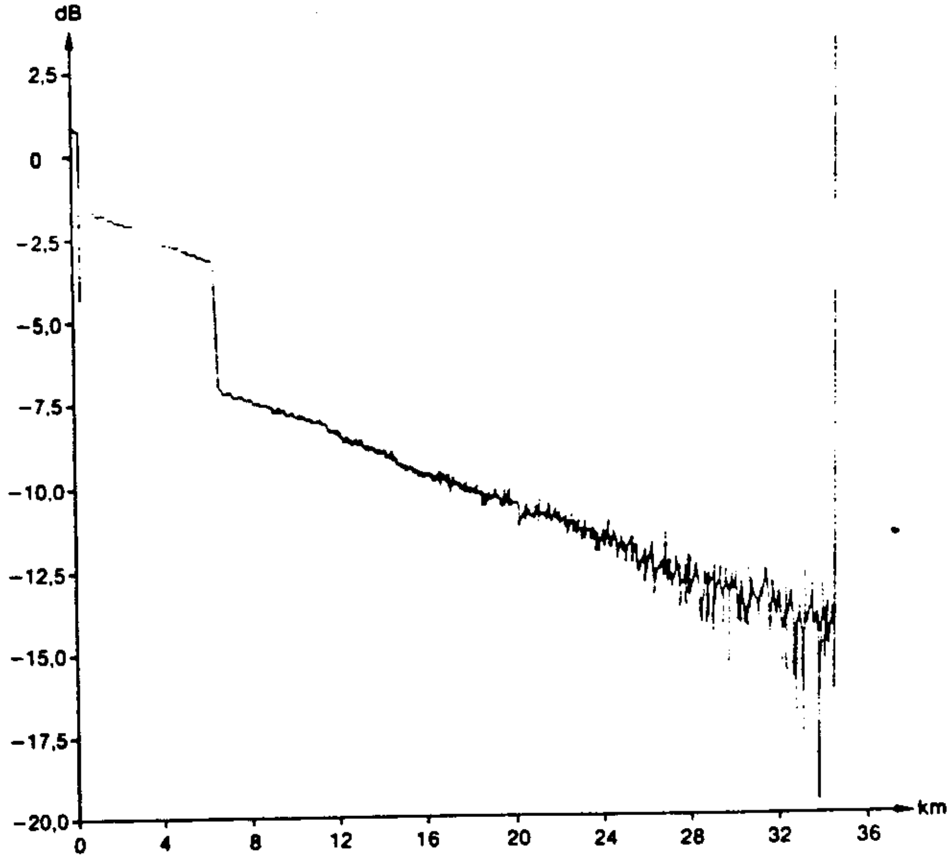


Fig. 8
Dispersion as a function of the light wavelength, measured over a 35 km long fibre. The dispersion is zero at a wavelength of 1310 nm. At 1550 nm the dispersion is 17 ps/nm km

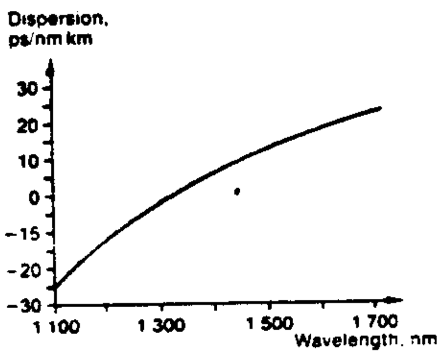


Fig. 7 shows the change in the signal level over a distance of 35 km, measured with OTDR. Abnormal conditions are easily spotted since the measurement was made at 1550 nm, where the fibre attenuation is low. For example, the increase in attenuation at approximately 6 km shows a fault that occurred during the cable laying.

Fig. 8 gives the results of dispersion measurements made at a wavelength of 1550 nm.

From the point of view of maintenance, cables with a loose buffer jacket are preferrable to cables with a tight jacket since they seem to be less prone to microbending problems.

Bit error rate

The bit error rate, BER, of the system is the most important measure of performance. Ageing factors, reduced output power, spectral changes in the laser and reduced receiver sensitivity, may have a negative effect on BER. In one measure-and 50 cascade-coupled line repeaters respectively

Data after 25 line repeaters

Data after 50 line repeaters

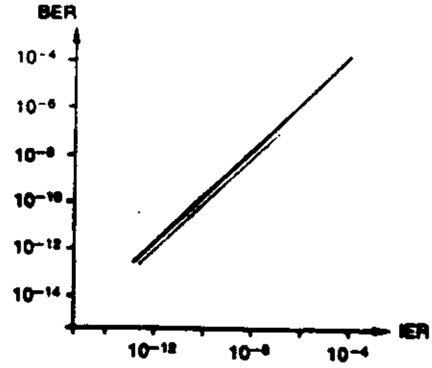
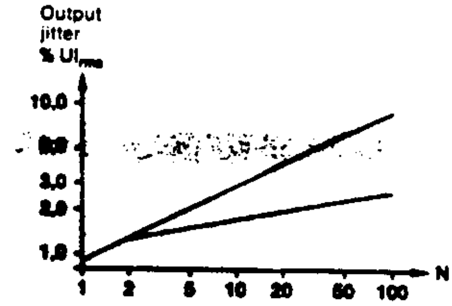


Fig. 10, far right
Jitter accumulation over 66 line repeaters, measured on the 600 Mbaud signal
N = number of line repeaters

$N^{0.5}$ addition law

Measured values



Jitter

In a perfect system all pulse edges arrive exactly at predetermined moments, but in real systems the edges are displaced slightly. This time displacement is called jitter. The jitter is caused partly by systematic and partly by statistically varying factors. A complete description of the jitter therefore requires a distribution diagram. The data provided for the size of the jitter can either be the maximum displacement peak-to-peak or the r.m.s. value of the distribution function. The jitter could be given as a time but in order to convey a better idea of the effect of the jitter on the system it is given as a fraction of the time it takes to send a bit in the system. This time is designated as unit interval, UI. The UI for the 600 Mbaud signal is 1.67 ns and for the 45 Mbit/s signal 22.35 ns. Jitter in line systems causes bit errors because of faulty sampling and is particularly serious in long, cascade-coupled repeater chains.

ment the system was monitored for 48 hours, during which time no bit errors occurred. This corresponds to a BER of less than 1×10^{-14}. Measurements were also made in order to investigate whether bit errors generate new errors when the signal is sent via a long chain of intermediate repeaters. Errors were injected at the start point at a rate IER (injected error rate). BER was measured when the signal had passed 25 and 50 intermediate repeaters. The results show that there was no error accumulation for the 50 repeaters, fig. 9.

Jitter accumulation and tolerance

The jitter measurements were made on the installed system with 66 cascade-coupled line repeaters. The output jitter was measured on the 600 MHz clock in the terminal. The jitter accumulated in the chain of line repeaters was calculated on the assumption that each repeater made the same contribution to the jitter. The systematic jitter addition was assumed to follow the $N^{0.5}$ law, where N is the number of line repeaters. The measurements at the 600 Mbaud interface indicated that the addition was systematic, but in a more favourable way than the $N^{0.5}$ law, fig. 10. After 66 line repeaters the accumulated line jitter was 3% UI_{rms} (approximately 0.30 UI_{p-p}) at the 600 Mbaud interface and well below 0.1 UI_{p-p} at the 45 Mbit/s interface, fig. 11. The measurements showed that the set requirements were met with a good margin, which was very satisfying as jitter was one of the greatest problems in the development of ZAM 565.

The output signal from the muldex is free from jitter because the bit streams coming in to the muldex unit are stored in a buffer store and then sent out under the control of a free-running high-stability oscillator. Hence jitter is not transmitted from one line section to another.

The requirements regarding the system tolerance to incoming jitter on the 45 Mbit/s streams are given in the DSX 3 specification. Fig. 12 shows the results of the measurements. The system tolerates incoming jitter to an extent well above the requirements.

System recovery

After a signal failure of one minute or more the system with 66 line repeaters is restored within 16 s. This is well below the specified limit of 5 s for 10 line repeaters.

Optical output power and receiver sensitivity

The optical output power of the transmitters and the sensitivity of the receivers have been measured in order to verify important repeater data after manufacture, fig. 13. Typical values are −4.5 dBm for the output power and −33.5 dBm for the sensitivity (BER = 1×10^{-9}). The line repeaters in the system had margins of 10−15 dB to the sensitivity limits, which means that large deterioration can be allowed during their service life.

Fig. 11, right
Output jitter on the 45 Mbit/s signal from the muldex after looping of twelve 45 Mbit/s tributaries

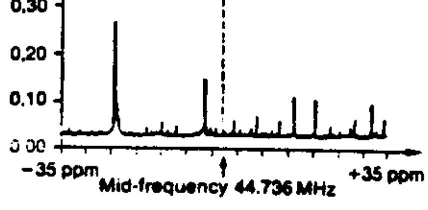


Fig. 12, far right
The ability of the system to tolerate jitter on the 45 Mbit/s input signal to the muldex

Requirement

Measured

Limit of the instrument measuring range

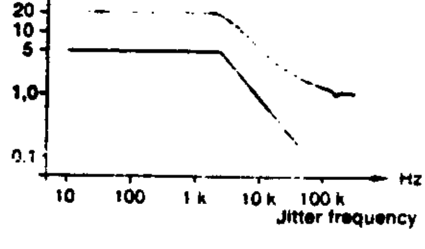
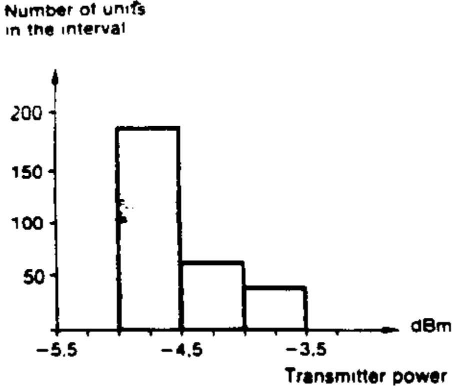
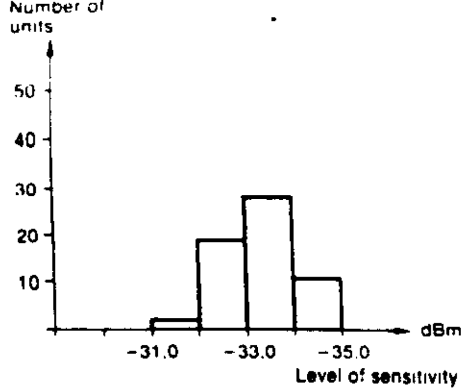


Fig. 13a. right
Measurement of the optical output power of approximately 300 laser transmitters. −5.5 dBm is a guaranteed value

Fig 13b, far right
The sensitivity of approximately 60 working receivers at a BER = 1 x 10⁻⁹ and with fibre lengths varying between 30 and 35 km





Summary

An optical fibre line system for 565 Mbit/s in operation in a long-haul network has been described. It works with good margins with repeater section lengths of over 40 km. This has been achieved thanks to the optimised design of the terminal and line repeaters. Very little jitter accumulation was obtained even with cascade-coupling of many repeaters, making the system ideally suitable for really long-haul sections between two terminals. The performance spreads of a large number of repeaters lie well within the typical specifications, illustrating further the quality standards of the system.

The results of the cable measurements illustrated in the article were presented by Terry Yake, US SPRINT, in a paper at the Stockholm Maintenance Conference, 1986.

Power budget

Transmitter	
Output power	>−4.5 dBm
Temperature dependence, ageing	1.0 dB
Guaranteed value	−5.5 dBm
Receiver	
Sensitivity at BER = 1×10^{-11}	<−31.5 dBm
Margin for dispersion (Dispersion < 100 ps/nm at 1290 and 1320 nm)	1.0 dB
Temperature dependence, ageing	1.0 dB
Guaranteed value	−29.5 dBm

The guaranteed values given above permit a maximum attenuation of 24 dB for a cable section. The system in the present version has been improved through the introduction of low-loss connectors. The section attenuation now amounts to 25 dB.

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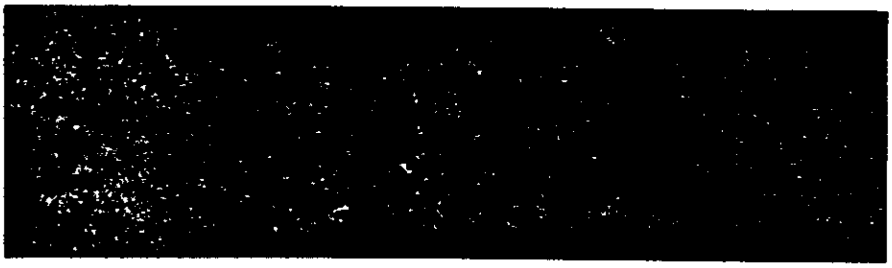
Diode Lasers vs. LEDs in the Singlemode Fiber System

A Vote for Diode Lasers

by Eugene I. Gordon

The high-speed potential of singlemode optical fibers makes them an attractive choice for many low-end telecommunications and data communications applications at a wavelength of 1.3 micrometers. For many of these applications, singlemode fiber is not initially essential. However, the potential for later use at higher speeds makes the investment in singlemode fiber safer than making a first investment in multimode fiber, which has limited bandwidth, and then making a second investment in singlemode fiber. On the other hand, connectors, sources, and detectors suitable for singlemode fiber applications are more expensive than their multimode counterparts. So the differential expense becomes an important element in the tradeoff equation.

The detector choice is typically a p-i-n field-effect transistor (pinFET) for either multimode or singlemode fiber applications. The diameter of the sensitive region of the detector is usually compatible with standard multimode dimensions. In particular, a singlemode fiber can be used as the input to a multimode fiber pigtail or a multimode active device mount with little loss. Thus, the same receiver with a multimode fiber pigtail or multimode connector can usually be used for either multimode or singlemode fiber applications. A singlemode fiber pigtail is required only in very-high-speed



applications where the sensitive area of the detector is deliberately kept quite small to reduce device capacitance.

The choice of source is much more complex. The dominant determining factor is system loss budget. Depending on the system margin, as defined by the designers, the transmitter and receiver requirements are stated in terms of device margin, the ratio in decibels of the peak transmitter power and the peak receiver sensitivity. Device margin requirements for singlemode applications are typically in the range of 20 to 25 decibels. Although some special situations lead to requirements outside this range, this discussion will stick with the 20-25 dB window. There are three sources of potential interest: surface-emitting light-emitting diodes (SELEDs), edge-emitting LEDs (E^2LEDs), and diode lasers.

SELEDs

The SELED (Figure 1a), basically a cheap and simple device, would be the source of choice if the loss budget allowed. The peak power coupled into a singlemode fiber by an SELED is in the range of −33 to −27 dBm.

The higher values of power are experimental extremes. The highest practical value for low-speed applications is about −30 dBm and is slightly lower for high-speed applications (i.e., for data rates in excess of 100 megabits per second). The best receiver sensitivities one can expect in practice are about −45 dBm. Thus, simple arithmetic shows that SELEDs don't fall into our defined margin window for most applications.

E^2LEDs

The E^2LED (Figure 1b) is a misnomer, as described below. It closely resembles a diode laser, except that the active region is truncated before reaching the rear facet, so that the feedback path is eliminated. The waveguide structure is usually one of the geometries used for singlemode diode laser applications. The coupling to the singlemode fiber is the same, typically using a lensed, tapered singlemode fiber or a cleaved singlemode fiber coupled in close proximity to the output facet. When the E^2LED is operated at a current that corresponds to the beginning of

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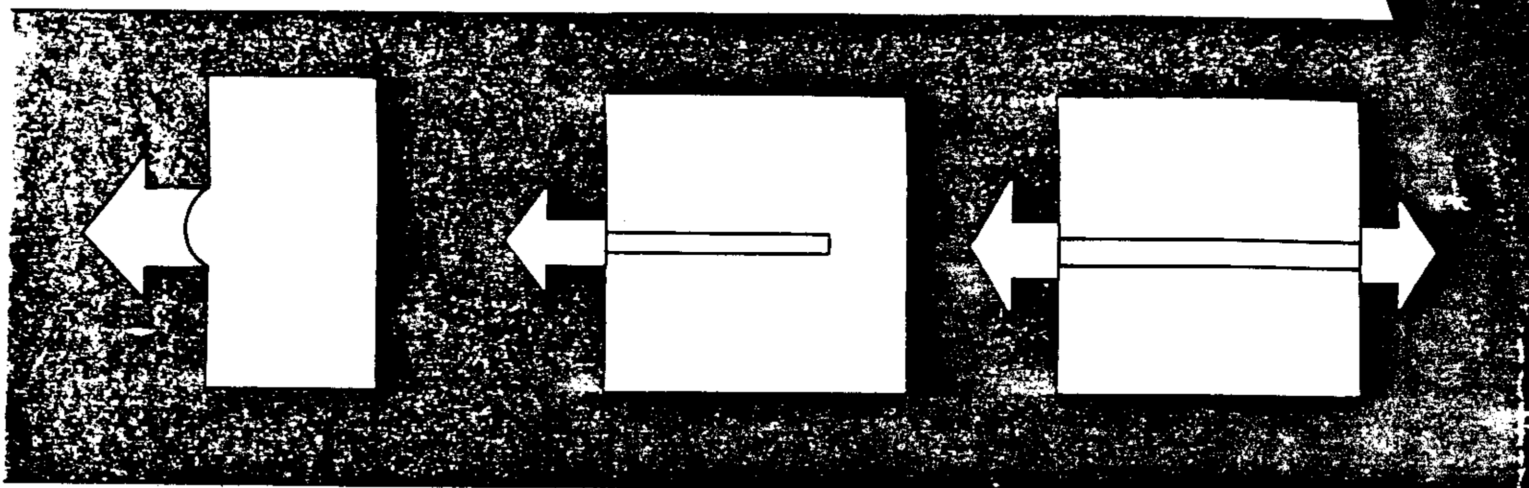

Figure 1. Simplified versions of the a) surface-emitting LED, b) edge-emitting LED, and c) diode laser.

optical transparency in the waveguide, the optical power coupled into a singlemode fiber is about −25 dBm, or right at the margin of utility as described here.

Only under these circumstances does the device operate as a true LED. To achieve higher source power (say, in the range of −20 to −13 dBm coupled into the fiber), the driving current must be raised to a value such that the waveguide amplifies the light. If the waveguide were not truncated (allowing feedback from the rear facet so that it would be a Fabry-Perot-type diode laser), the device would exhibit the conventional "hockey stick" light versus current characteristic curve. At drive currents that high, the device would be a diode laser operating well above threshold. In other words, the E^2LED, when driven hard enough, is really operated as a nonregenerative or superradiant laser. Hence, the name is misleading.

For the indicated coupling power levels of −20 to −13 dBm and device margins of 20-25 dB, the required receiver sensitivity would be −45 to −33 dBm. Thus, E^2LEDs are possible solutions and are attracting great interest.

Diode Lasers

For diode lasers and E^2LEDs, the dominant costs are in the packaging, testing, and burn-in. The differences in chip costs, assuming nominal yields, are trivial. In properly designed, manufactured, and tested diode lasers and E^2LEDs, the cost differential for the final packaged, tested devices is typically minimal.

The laser, to achieve the required reliability factors, puts about −10 dBm into the pigtail. Thus, the required receiver sensitivity is −35 to −30 dBm. Such pinFET receivers cost substantially less than receivers designed for the range of −45 to −33 dBm. As a result, a system based on a low-power laser and a low-sensitivity receiver should cost noticeably less than a system based on an E^2LED and a more-sensitive receiver providing identical device margins. The price differential for the pair is likely to be 20-40 percent. The arguments on volume pricing will soon shift from the blackboard to the marketplace; with estimates for the pair at $600 in 1987 and $150 in 1990.

What About Temperature Sensitivity?

Modern, high-performance lasers are temperature controlled, typically at 25°C, to control the wavelength. Earlier models were cooled for reliability reasons as well. However, operation up to 60°C with long life is possible with present-generation devices. The laser has a backface monitor so that power output, even with large temperature variations, can be easily controlled. The E^2LED has no back face monitor, so the power output at constant drive current can vary widely. In effect, the output power temperature dependence of an E^2LED transmitter is much worse than that of a diode laser transmitter, although the E^2LED drive current can be varied as a function of temperature to provide correction.

The saving feature is that receivers for this application have substantial dynamic range available to the high side and can correct for power increases in the E^2LED transmitter when the temperature goes down. In this case, the E^2LED should be rated at the maximum operating temperature for performance comparisons to a diode laser.

And What of Reliability?

Because the E^2LED depends on gain in the active waveguide to achieve the required output power, it is hardly as impervious to active layer defects as the SELED and falls far short in reliability. However, reductions in gain resulting from crystal defects or other deficiencies are much more important in diode lasers. Thus, everything else being equal, the E^2LED should be more reliable than the diode laser.

However, everything else is not quite equal. The E^2LED operates at three to five times the drive current of a diode laser (100 to 200 milliamps versus 30 to 40 mA for the diode laser). Although current is a significant degradation factor in long-wavelength diode lasers and E^2LEDs, it is not generally appreciated. The relative difference in drive current described above involves a degradation factor of the order of 10^4 for similar waveguide structures. The acceleration factor for lasers between 25°C and 60°C, based on an activation energy of 0.8 electronvolts (as measured for Lytel lasers) is 37. This is essentially compensated by the reduced operating current of a low-power laser. Thus, a low-power laser should have reliability at least as good as the conventional high-performance laser at 25°C—greater than one million hours for a 20% increase in operating current. Even though the E^2LED might have better reliability, the reliability of the diode laser is sufficient.

The diode laser draws significantly lower power, is faster, and has a much narrower spectral output than the E^2LED. But none of these are dominant factors for this application. The diode laser wins because it allows the use of a substantially lower-cost receiver. □

Table 3 — Predicted Loop-Plant Performance Using Low-Current E²LEDs

Launch power (dBm at +70°C)		−30.0		
Connector loss (dB)		2.0		
Power Margin (dB)		6.0		
Data rate (Mb/s)	1.5	6.3	45.0	140.0
Receiver sensitivity (dBm)	−54.0	−51.0	−45.0	−42.0
Link length (km at 0.75 dB/km)	21.3	17.3	9.3	5.3

Inexpensive automated packaging technology is the key to reducing the cost of light sources for the subscriber loop. Surface-emitters are more tolerant of fiber misalignment during packaging than are edge-emitters, but edge-emitters produce more than twice as much fiber-coupled power and operate at less than half the drive current of surface-emitters. It seems reasonable to assume that development of automated packaging technology will equalize the cost of packaging SELEDs, E²LEDs, and diode lasers over time. Under such a scenario, LED transmitters would still be cheaper and more reliable than diode laser transmitters, because there would be no need for rear-facet optical monitors and output power stabilization circuitry.

System Power Budgets for LEDs

The best application for LEDs in the loop plant will be at data rates of less than 200 Mb/s, where link lengths in excess of 5 km can be realized with simple and potentially inexpensive transmitters and receivers. Table 3 summarizes some near-term system possibilities with low-current E²LEDs, realistic production receiver sensitivities, and conservative allowances for fiber cabling losses. The projected link lengths were derived assuming average fiber losses of 0.75 dB/km, an excess margin of 8 dB (including 2 dB for connector losses), and an average fiber-coupled power of −30 dBm, corresponding to the output of a low-current E²LED at a junction temperature of +85°C.

Practical transmission distances of more than 9 km at 45 Mb/s and more than 5 km at 140 Mb/s can be achieved using low-current E²LEDs with peak drives of less than 25 mA. In a recent laboratory system test[4], E²LEDs driven at 20 mA and operated from −20°C to +75°C demonstrated 45 Mb/s transmission over 12.9 km of singlemode fiber.

Since SELEDs yield 2 to 3 dB less coupler power than low-current E²LEDs, their best application will be at shorter link lengths or lower data rates. Using the conservative system power budget considerations given in Table 3, mesa-structure SELEDs can be expected to yield link lengths of 6 to 8 km at 45 Mb/s and 3 to 4 km at 140 Mb/s.

Conclusions

The diode lasers available at present have not demonstrated the high temperature reliability believed necessary for loop-plant applications. LEDs have been shown to have more than an order-of-magnitude higher reliability than diode lasers and can be operated over a wide temperature range without stabilization circuitry.

System power budget analyses predict link lengths of 5 to 10 km at data rates as high as 140 Mb/s for low-current E²LEDs in combination with production receivers. In an evolutionary approach to the single-mode fiber loop plant, inexpensive LED-based systems could be used to economically justify fiber installations for near-future service requirements. Once singlemode fiber is established in the loop plant, high-speed diode laser transmission equipment can be phased in as demand develops for broadband video services.

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Diode Lasers vs. LEDs in the Singlemode Fiber System

A Vote for Light-Emitting Diodes

by Donald M. Fye

Because of its high information-carrying capacity, singlemode fiber has become the dominant transmission medium for new fiberoptic system installations. Extension of fiberoptics to the subscriber loop plant will require the development of inexpensive receivers and transmitters designed for high reliability in outside-plant environments. System requirements for subscriber-loop applications call for device operation over a temperature range of −40°C to +85°C with lifetimes of more than 10^6 hours (roughly one hundred years) at 60°C. Average lifetimes of more than one hundred years are necessary to keep device failures at a level of less than one percent per year when millions of devices are fielded.

While loop-plant applications impose demanding environmental and reliability requirements, the short link lengths allow use of low-power optical sources. Practical subscriber-loop systems can be realized with optical transmitters delivering as little as 1 microwatt (−30 dBm) average power into singlemode fiber. In combination with potentially inexpensive production receivers, such transmitters could satisfy the vast majority of loop-plant applications by allowing link lengths of 5 to 10 kilometers at data rates as high as 140 megabits per second.

Recent experiments have demonstrated that surface- and edge-emitting LEDs coupled to singlemode fiber can be used instead of diode lasers to satisfy transmission requirements in the subscriber loop. Table 1 contains a general comparison of diode laser and LED characteristics. When compared to diode lasers, LEDs can offer advantages in higher reliability, reduced temperature sensitivity, less complicated drive circuit requirements, immunity to optical feedback, higher yields, and simpler packaging technology.

As illustrated in Figures 1a and 1b, LED transmitters are much simpler and more economical than diode laser transmitters. A properly designed LED will operate over the entire −40°C to +85°C temperature range without the need for feedback-controlled temperature or output power stabilization. Simplicity and reliability are critical to the introduction of singlemode fiber into subscriber loops. LEDs can be used to satisfy present requirements economically, and diode lasers can be used for future service upgrades requiring higher speed and output powers.

Selecting an LED for Loop Applications

Both surface-emitting LEDs (SELEDs) and edge-emitting LEDs (E^2LEDs) have been considered for

Table 1 — Comparison of LED and Diode Laser Characteristics

Characteristic	LED	Diode Laser
Coupled Power	<100 μW	>1 mW
Spectral Width	>30 nm	<5 nm
Rise Time	≥1 ns	≤1 ns
Feedback Sensitivity	None	High
Temperature Sensitivity	Low	High
Cooling and Optical Monitor	Not Needed	Required
Drive Circuitry	Simple	Complex
Reliability (at 25°C)	[illegible] hours	[illegible] hours

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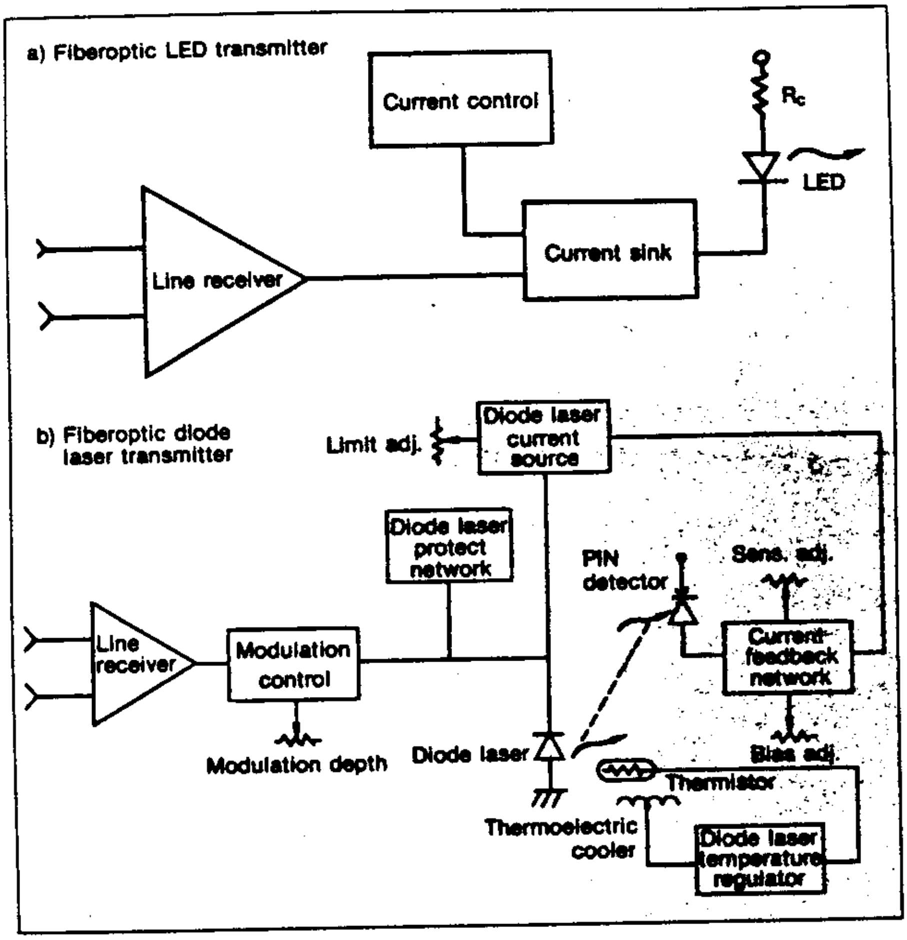

Figure 1. Comparison of LED (a) and diode laser (b) transmitters. The LED does not require a thermoelectric cooler or rear-facet optical power monitor.

subscriber-loop applications. E^2LEDs are similar in structure to diode lasers, but they have truncated contact stripes and/or front-facet antireflection coatings to elevate the lasing threshold current. Table 2 summarizes and compares the operating characteristics of surface-emitters, superluminescent edge-emitters, and low-current edge-emitters. It is important to distinguish between E^2LEDs optimized for low-current operation and superluminescent E^2LEDs, which operate at high drive currents and have substantial internal gain. While superluminescent E^2LEDs can couple as much as 60 to 250 μW (−12 to −6 dBm) into singlemode fiber, such devices operate at drive currents in excess of 100 milliamps and require the use of thermoelectric elements or rear-facet optical monitors to stabilize the optical output over a wide range of ambient temperatures. The temperature sensitivity, high drive currents, and unproven reliability of superluminescent E^2LEDs make them a poor choice for use in the loop plant.

In contrast to superluminescent E^2LEDs, both mesa-structure SELEDs and low-current E^2LEDs are promising candidates for use in the loop plant. Mesa-structure SELEDs offer excellent thermal stability, but the best reported devices[1,2] require drive currents of 50 to 100 mA to couple 1.5 to 2 μW into singlemode fiber at 25°C. Index-guided short-cavity E^2LEDs designed for low-current operation[3] can couple 7 μW (−22 dBm) into singlemode fiber at drive currents of only 20 mA. At a temperature of +85°C, low-current E^2LEDs yield fiber-coupled powers of 2 to 3 μW (−27 to −25 dBm), while mesa-structure SELEDs yield coupled powers of 1 to 1.5 μW (−30 to −28 dBm). Both surface-emitters and low-current edge-emitters can be operated over the full −40°C to +85°C loop-plant temperature range without thermoelectric coolers or output power stabilization circuitry.

The issue of device reliability is the most important factor favoring the use of LEDs in the loop plant. The most reliable diode lasers, selected through sophisticated screening procedures, have extrapolated lifetimes of 2 × 10^5 hours (25 years) at 60°C. This reliability does not satisfy the 10^6-hour device lifetimes required for loop-plant applications. On the other hand, several different edge-emitting and surface-emitting LED structures have demonstrated reliabilities of 10^6 to 10^7 hours at +70°C.

Also, device lifetimes decrease roughly as the square of the operating current density. Even when operated at fiber-coupled powers of only −10 dBm, diode lasers without thermoelectric coolers require drive currents of 60 mA or more when the ambient temperature is +85°C. Since low-current E^2LEDs operate at peak drive currents of only 20 to 30 mA, they will be substantially more reliable than diode lasers. The order-of-magnitude reliability advantage of LEDs will result in lower costs because of higher yields and simpler reliability screening.

Table 2 — Advantages and Disadvantages of Types of LEDs for Singlemode Fiber Subscriber-Loop Applications

- Surface-Emitters
  - \+ Lowest temperature sensitivity (<1%/°C)
  - \+ High reliability (>10^9 hours at 50°C)
  - − Broadest emission spectra (>120 nm)
  - − High drive current (50-100 mA)
  - − Lowest coupled power (≤2 μW)
- Superluminescent Edge-Emitters
  - \+ Highest coupled power (60-250 μW)
  - \+ Narrowest emission spectra (30-50 nm)
  - − Highest temperature sensitivity (≥3%/°C)
  - − High drive current (≈100 mA)
  - − Unproved reliability
- Low-Current Edge-Emitters
  - \+ Good temperature stability (≈1-2%/°C)
  - \+ Low operating current (≈20 mA)
  - \+ Moderate coupled power ([illegible])

DeBdolls

LONG-WAVELENGTH DFB LASERS EXTEND REPEATERLESS DISTANCES IN BRITISH TELECOM DEMONSTRATION

British Telecom Research Labs converted existing 565-Mbit/s transmission equipment from operation at 1.3 to 1.55 μm. The longer wavelength components included commercially available linewidth-narrowed diode lasers. Experiments with the converted equipment achieved repeaterless transmission over distances in excess of 100 km.

By S. Whitt, T.S. Brown, and S.L. Arambepola

By mid-1988 the British Telecom (BT) long lines or trunk network will be capable of providing a wholly digital service on a network dominated by 140-Mbit/s transmission over single-mode fiber. This network will consist mainly of point-to-point trunk lines between major centers of population, which in the U.K. are generally separated by less than 100 km.

Demand for transmission capacity is expected to increase significantly in the near future, and the rapid introduction of higher-capacity equipment, such as 565-Mbit/s systems, will probably be the practical response. Among the key objectives behind the development of this digital network is achieving high reliability and performance through longer repeater spans and greater integration than traditionally associated with coaxial cable systems.

With advances in fiberoptic technology, further improvements in system reliability and performance are now possible at no increase in system cost. By exploiting this new technology, it is feasible to develop repeaterless optical systems for use in the U.K. trunk network.

This article reports the development of a long-haul 565-Mbit/s optical fiber system offering repeater spacings in excess of 100 km when operating at a wavelength of 1.55 μm.

Repeaters and reliability

Optical fiber transmission equipment that is currently being installed to digitize the BT trunk network was designed to allow up to 30 km between repeater station sites, corresponding to the spacing of existing BT surface buildings. This strategy obviates the need for buried repeater equipment and cable-born power feeding. It thus contributes to overall system reliability. Never-

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theless, a substantial quantity of equipment is still required at each repeater site where suitable power and floor or rack space must be provided.

In addition to the basic hardware requirements for each repeater, it is common practice to provide a supervisory monitoring facility in systems that employ more than one repeater. This is included as a diagnostic tool to aid speedy repair of faulty systems. But this facility can itself be viewed as reliability overhead because extra hardware and software must be provided at every repeater site and at both terminals.

Thus, major cost reductions and reliability improvements can be made if the intermediate repeater equipment can be designed out (see table).

From looking at the transmission curve of silica fiber, it is apparent that systems designed to exploit the low-loss "window" at 1.55 μm would be capable of very long distance transmission. Under laboratory conditions, data at 140 Mbit/s have been transmitted over 223 km,[1] and at 565 Mbit/s, transmission distances of 204 km have been reported.[2]

For production systems under operational conditions, however, far more conservative figures are usually quoted. Allowances are made for factors such as production tolerances and aging margins. Nevertheless, the use of a production 565-Mbit/s, 1.3-μm optical system operating with satisfactory margins over 45 km of standard installed cable has been reported.[3]

Attenuation and dispersion as limiting factors

There are two factors that restrict the reach of an optical fiber system. These are the loss and dispersion limits.

Systems operating at 1.3 μm generally have been limited by the path loss associated with the fiberoptic cable. At this wavelength, dispersion tends not to be a significant penalty for bit rates below about 1 Gbit/s.

At the 1.55-μm window of conventional silica fiber, attenuation is at a minimum. To exploit this performance, however, the problem with dispersion must be taken into account.

One way to avoid this problem is to install dispersion-shifted fiber, since it has a dispersion minimum in the 1.55-μm region. Alternatively, optical sources with narrow linewidth can be used. For a 565-Mbit/s system operating over 100 km of fiber with 18-ps/km/nm dispersion, it is desirable to keep the optical linewidth below 0.25 nm.

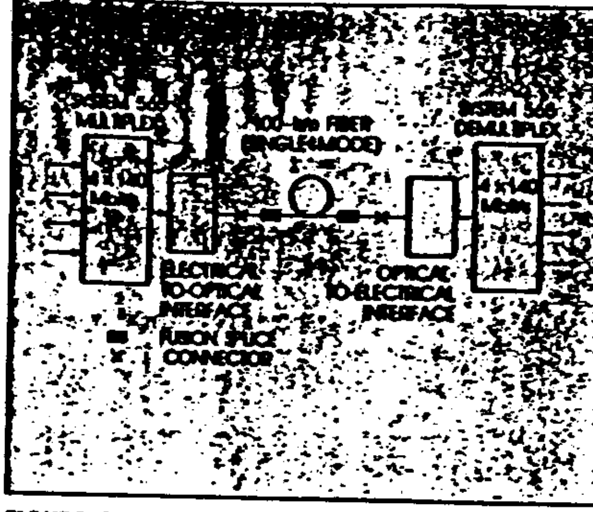

FIGURE 1. British Telecom Research Labs conducted system trials in which existing 1.3-μm transmission equipment was converted to 1.55-μm using commercially available linewidth-narrowed lasers and PINFET receivers. The system included 20 splices and two connectors.

Bearing in mind that the fiberoptic cable being installed in the BT network contains conventional single-mode fiber, *not* the dispersion-shifted variety, the only option available is the use of a narrow-linewidth source such as the distributed-feedback (DFB) laser.

In addition to this requirement for the optical transmitter, a sensitive receiver is also needed for a complete system at 1.55 μm to be viable. There are several choices of receiver for this longer wavelength, each with individual technical merits.[4]

Assuming that a narrow-linewidth laser is available, the feasibility of a 100-km system

100-km ROUTE COMPARISON

	REPEATERED	UNREPEATERED
Terminals	2	2
Repeater stations	1–6 (typical)	0
Remote supervisory	1–6	0
Terminal supervisory	2	0
Physical space needs	3–8 sites	2 sites
Power consumption	high	low
Reliability	poor	high
Cost	high	low

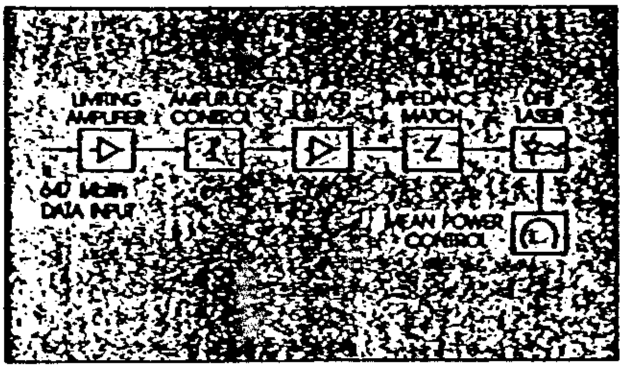

FIGURE 2. The distributed-feedback laser used in the transmitter included thermoelectric cooler, thermistor, and feedback photodiode.

depends on the system power budget. Consider a typical case:

Fiber loss at 1.55 μm (production fiber)	<0.2 dB/km
Splice loss	<0.25 dB/splice
Typical route loss (20 splices)	<25 dB
Transmitted optical power	−3 dBm
Receiver sensitivity	< −34 dBm
Operating margin	>6 dB

In this scenario, the receiver sensitivity is based on bit error rates of 10^{-10} at 647 Mbaud. The −34 dBm value includes design penalties due to the data regeneration process and the loss due to an optical connector at the receiver. Figure 1 shows the location of splices and connectors for this case. Note that the multiplexer combines four 140-Mbit/s data streams into a 565-Mbit/s channel, but the 7B8B line coding increases the actual line rate to 647 Mbaud.

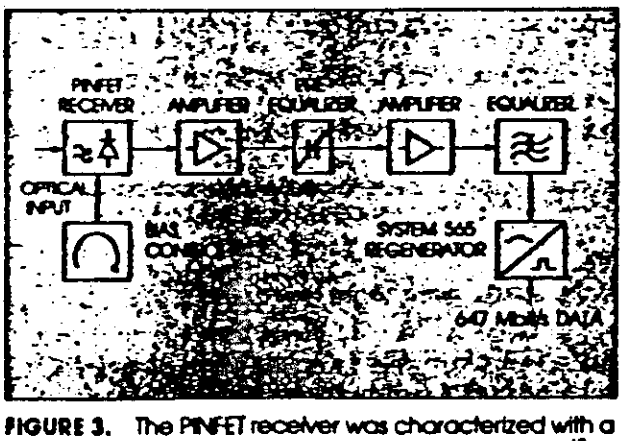

FIGURE 3. The PINFET receiver was characterized with a sensitivity less than -34 dBm with a bit error rate of 10^{-10} at 647 Mbaud. This figure includes the design penalties due to the data regeneration and the loss of one optical connector.

Long-wavelength experiments

Although the theoretical basis for long-haul optical fiber transmission at 1.55 μm has existed, it is only within the past year or so that suitable components have become commercially available.

An experimental system similar to that described above and shown in Fig. 1 was set up using adapted BT "System 565" equipment.[3] In this setup, the original 1.3-μm optoelectronic components were replaced by compatible 1.55-μm devices.

The laser used in the transmitter was an available DFB device with a wavelength of 1553 nm, output power of −2.0 dBm, and spectral linewidth <0.2 nm. The chosen laser incorporated a thermoelectric cooler, thermistor, and backfacet monitor photodiode in a hermetic high-speed "butterfly" package. Figure 2 shows the laser and drive circuit.

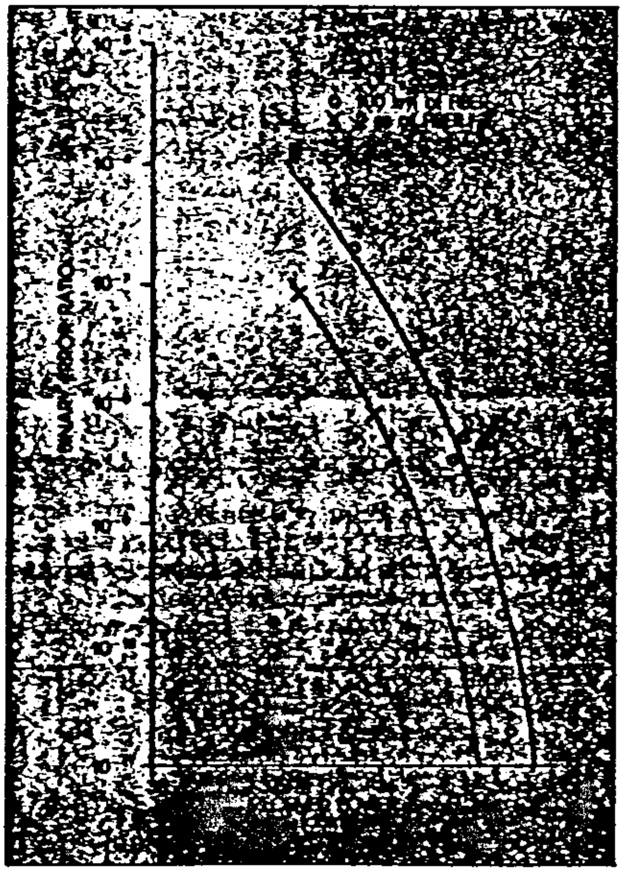

FIGURE 4. The receiver performance over 100 km shows a dispersion penalty in comparison to a short reference length of fiber. Nonetheless, the 100-km experiment achieved a system margin of 9.76 dB.

For the receiver, a high-impedance PINFET device was used (see Fig. 3). It provided sensitivity of −34.5 dBm for a 10^{-10} BER at 647 Mbaud. The receiver incorporated the planar PIN diode and custom GaAs integrated circuit in a high-speed package similar to that of the laser source.

All results were obtained using complete "System 565" multiplex equipment operated over various lengths of single-mode fiber. These trials included spans up to 100 km.

Operating over 50 km, a system margin of 19.4 dB was recorded. The 100-km link achieved 9.76 dB. The performance over the 100-km link is shown in Fig. 4, along with transmission over a short fiber segment to show the dispersion penalty.

These trials show that the existing optical fiber systems, which have been restricted to trunk transmission distances of about 30 km, can be upgraded with the new 1.55-μm component technology. At this wavelength, it is practical to install long-haul routes with spans in excess of 100 km. Repeaterless spans of this length would lead to a significant reduction in installed equipment. The consequence of this would be reduced transmission costs and improved system reliability. □

Acknowledgments
The authors would like to thank BT&D Technologies Ltd. for supplying the optical receiver, which was characterized by R.C. Hooper and A. McDonna. Acknowledgment is made to Fulcrum Communications Ltd. for supplying the "System 565" equipment and to the director of technology applications, British Telecom Research Laboratories, for permission to publish this paper.

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Coherent Optical Fiber Transmission

TATSUYA KIMURA, SENIOR MEMBER, IEEE

(Invited Paper)

Abstract—Essential technologies for developing coherent optical fiber transmission systems are reviewed from the viewpoint of regenerative repeater spacing and transmission data rate improvements. After describing the system features behind these advantages, recent progress in individual device and system technologies is delineated. Such progress includes frequency stabilization and linewidth reduction of semiconductor lasers, optical phase or frequency modulation, AM and FM noise suppression in coherent receivers, optical polarization stabilization and control in signal transmission, and optical direct amplification. Also described is progress in coherent optical transmission experiments carried out in many laboratories. Finally, future problems are discussed on the basis of the current state of the art.

I. Introduction

FROM THE time of the invention of lasers in 1960, research efforts started to utilize coherent properties of laser light for optical communications. Signal transmission using the optical frequency or phase modulation scheme, instead of intensity modulation, was one of the initial focuses of research interest. Optical heterodyne or homodyne detection was shown in 1962 to improve the signal-to-noise ratio (S/N) above that of direct detection [1]. The information capacity of various communications systems including heterodyne and homodyne receiver systems was discussed [2]. A heterodyne-detection transmission experiment using 3.39-μm He–Ne lasers demonstrated a significant S/N improvement in 1967 [3]. The concept of frequency-division multiplexing using coherent detection schemes was proposed in 1970 [4]. Such obstacles as short lifetime and insufficient stability in lasers as well as severe turbulence and instability of transmission media, however, prevented further study into important devices and systems.

Improvement in the 1970's in the lifetime of semiconductor lasers as well as in the loss characteristics of optical fibers led to a large optical communications success. Simple and reliable modulation–demodulation technologies, such as direct intensity modulation of semiconductor lasers and direct power detection using avalanche photodiodes (APD's) or p-i-n photodiodes, are used in the present fiber systems. These systems already surpass conventional coaxial cable and radio relay systems in terms of transmission performance. In these systems, however, the coherent laser light properties are not fully utilized, but rather, the optical energy of the noisy carrier wave is used instead to convey information. The transmitted signal spectrum is not transform-limited, but typically spreads to 1 THz. These features signify that the high level of success gained by present fiber-optic systems results mainly from the low-loss and broad-band characteristics of optical fibers. Furthermore, the features indicate that present optical fiber transmission systems still have room for further development from the viewpoint of modulation–demodulation technology.

The latter half of the 1970's witnessed the development of semiconductor optical device technology for providing semiconductor lasers having good reproducibility, which could operate in a single longitudinal mode. An interference experiment of AlGaAs laser light transmitted through a 4.15-km single-mode fiber cable was reported in 1978 by NTT's Musashino Laboratories [5]. This experiment revealed two important features. First, the semiconductor laser is capable of producing a sufficiently narrow linewidth output under the proper conditions to exhibit clear interference fringes. Second, the single-mode fiber is capable of maintaining a stable polarization direction over several kilometers. These features strongly suggested the possibility of coherent optical signal transmission through fibers using compact and convenient semiconductor lasers, as well as the possiblity of polarization-division multiplexing in optical fibers.

Encouraged by the experiment, the receiving levels in various optical demodulation schemes were evaluated to confirm the usefulness of frequency or phase modulation and heterodyne or homodyne demodulation [6]. In the course of this study, a proposal was put forth to utilize the optical heterodyne detection scheme for broad-band signal transmission by modulating the lightwave with a radio frequency (RF) subcarrier consisting of frequency-multiplexed intermediate frequency (IF) signals [7]. This modulation–demodulation scheme, however, was evaluated as having poor receiver sensitivity [6], because the two sidebands created by the RF subcarrier deteriorate the S/N performance of the demodulation.

This type of system was named a "coherent optical fiber transmission system," following the suggestion of Hara, with the comprehensive features of the system being reported in 1981 [8]. At present, coherent optical transmission is being studied on a worldwide scale, particularly in the fields of fiber communications [8]–[15] and intersatellite communications [16].

This paper reviews the essential technologies underlying the development of coherent optical fiber systems, as well as recent progress in transmission experiments. After the basic configuration of coherent optical fiber transmis-

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sion systems is briefly described in Section II, system advantages of improving both the regenerative repeater spacing and transmission data rate are discussed in Section III. Explained in detail here are the system features of improved transmitting and receiving signal levels, modulation bandwidth and fiber transmission capacity, all of which lead to the advantages noted. The essential technologies for realizing coherent optical fiber transmission are summarized in Section IV. Section V presents current coherent laser sources from the viewpoints of oscillation frequency stabilization and spectral linewidth reduction in semiconductor lasers. Section VI discusses angle modulation schemes using semiconductor lasers as well as coherent detection schemes for suppressing local oscillator AM/FM noise. The recent states of polarization-maintaining fibers as well as polarization controllers are detailed in Section VII. Section VIII briefly mentions optical amplifier technology. Summarizing significant system experiments in the progress of coherent optical transmission research, Section IX portrays the latest state in transmission experiments. Finally, Section X outlines the present state of technology and sums up future areas of concern essential to the continuing development of coherent optical fiber transmission systems.

II. System Configuration

The basic configuration of the coherent optical fiber transmission system is illustrated in Fig. 1. Laser light possessing a sufficiently stable frequency or phase is used as the carrier wave in this system. The transmitter launches an optical amplitude-shift-keying (ASK), frequncy-shift-keying (FSK), or phase-shift-keying (PSK) signal. Either optical heterodyne or homodyne detection is performed in the receiver for highly sensitive detection using a local oscillator.

The transmitter basically consists of a laser oscillator and a modulator. Internal modulation of the laser oscillator may be used in place of an external modulator. A post amplifier may be installed to compensate for power loss in the modulator and to boost the optical signal level to that of the maximum input power for the optical fiber employed. A beat-note signal between the transmitted signal and the local oscillator wave, that is, an intermediate frequency (IF) signal, is obtained by optical heterodyne detection using a square-law detector. The IF signal is demodulated into the baseband signal through envelope, differential, or synchronous detection. In a homodyne detection system, the demodulated baseband signal is directly extracted via its optical mixing process since the local oscillator light has the same frequency as the carrier wave.

An optical fiber which maintains the polarization state of the propagating signal is utilized as the transmission medium since coherent detection schemes are sensitive to the polarization states of both the transmitted signal and the local oscillator waves. A conventional single-mode fiber, in conjunction with a polarization controller, may be employed instead of the polarization-maintaining fiber.

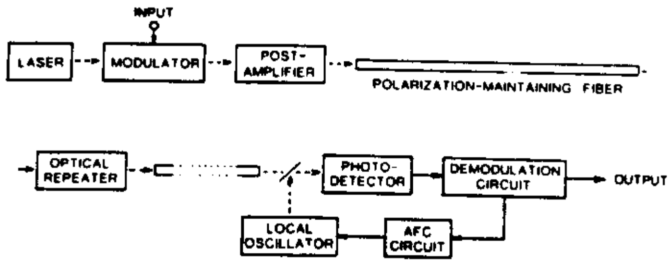


Fig. 1. Basic configuration for coherent optical fiber transmission systems.

Finally, optical amplifiers may be installed as intermediate repeaters to compensate for fiber transmission loss.

III. System Advantages

Coherent optical fiber transmission systems are advantageous in that they improve the regenerative repeater spacing as well as the transmission data rate over conventional intensity-modulation direct-detection systems. These advantages, which motivated the beginning of the research and development of coherent optical fiber transmission systems, are derived from five principal improvments.

A. Receiver Sensitivity Improvement Using Optical Heterodyne or Homodyne Detection [6]

The main noise source determining the S/N of optical heterodyne or homodyne detection is the quantum noise of the transmitted signal light. This is significantly different from the fact that APD multiplication noise and load-resistance thermal noise dominate the receiver sensitivity in conventional direct detection. At present, the most sensitive APD receiver in the long wavelength region requires about 700 photon/bit for binary on-off signals to achieve an error rate of 10^{-9} [17]. Coherent detection can be accomplished with a smaller photon number than direct detection. The required receiving signal level, for example, is 18 photon/bit for binary PSK homodyne detection and about 1.4 photon/bit for coded 32-level FSK coherent detection [16]. The theoretical channel capacity of optical communications systems derived by quantum mechanical treatment corresponds to a receiving level of 0.02 photon/bit [2].

B. Improvement of Power Handling Level in Single-Mode Fibers Using Angle Modulation Schemes

The maximum input power for single-mode fibers is limited by such nonlinear interaction occurring in their small-core area as stimulated Brillouin scattering (SBS) or stimulated Raman scattering (SRS) [18]. The critical power determined by SBS is 2–3 mW for single-frequency 1.55-μm input light. SBS dominates the power handling level of conventional intensity modulation systems. This effect is not actually evident at present because direct intensity modulation of semiconductor lasers causes enormous frequency chirping. Improvement of single-frequency operation under direct modulation [19], however, must face this limitation. On the other hand, constant-amplitude angle modulation signals having randomly modulated phases not only alleviate the SBS difficulty [20], but also suppress the self-phase modulation effect [18], which limits fiber input power to less than several hundred milliwatts. Consequently, angle modulation schemes will have a critical fiber input power of a few watts as determined by SRS.

C. Improvement of Launched Power Using High-Power Post-Amplifiers

Semiconductor-laser linear amplifiers [21], such as Fabry–Perot-type (i.e., resonant-type) and traveling-wave-type amplifiers, amplify optical angle modulation signals as well as amplitude or intensity modulation signals. Although these amplifiers have a maximum unsaturation ouput power of 0–10 dBm at a wavelength of 1.55 μm, it would seem very difficult to increase the output power to a few watts of the fiber input power determined by SRS. On the other hand, injection-locked oscillators [22], which amplify only a constant-envelope angle modulation signal, are potentially good post-amplifiers, since they emit an output power larger than that of linear amplifiers. Essentially, an output power of 10–20 dBm is available using the injection-locked amplifier composed of a conventional semiconductor laser. Phase-locked array lasers [23], which achieve a high output power above a few watts under the continuous wave (CW) operation condition, can be used as injection-locked oscillators. Since fiber Raman amplifiers [24] are expected to have relatively high saturation power, they may also be used as post-amplifiers provided that reliable high-power pump lasers are available for 1.55-μm signal amplification.

D. Improvement of Modulation Bandwidth

Modulation speed in the direct intensity modulation of semiconductor lasers is limited to the resonance frequency, above which modulation efficiency is inversely proportional to the square of the modulation frequency. The direct frequency modulation of semiconductor lasers [25], however, relaxes the limitation caused by the resonance property. This is because the frequency shift normalized by the unit modulation current, namely the FM efficiency, is inversely proportional to the modulation frequency which is higher than the resonance. Electrooptic waveguide modulators [26] also achieve a phase modulation whose bandwidth is broader than the direct intensity modulation limit.

E. Dissolution of Bandwidth Limitation in Optical Fibers

Wavelength dispersion of single-mode fibers imposes a bandwidth limitation on conventional systems, since an optical signal generated by the direct intensity modulation of semiconductor lasers is accompanied by an unintended spectral spread due to the carrier modulation effect. In coherent systems, however, the limitation is alleviated because the transform-limited spectrum is obtained by modulating the single-frequency carrier wave.

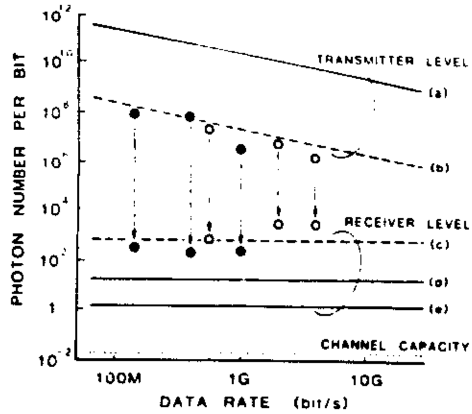


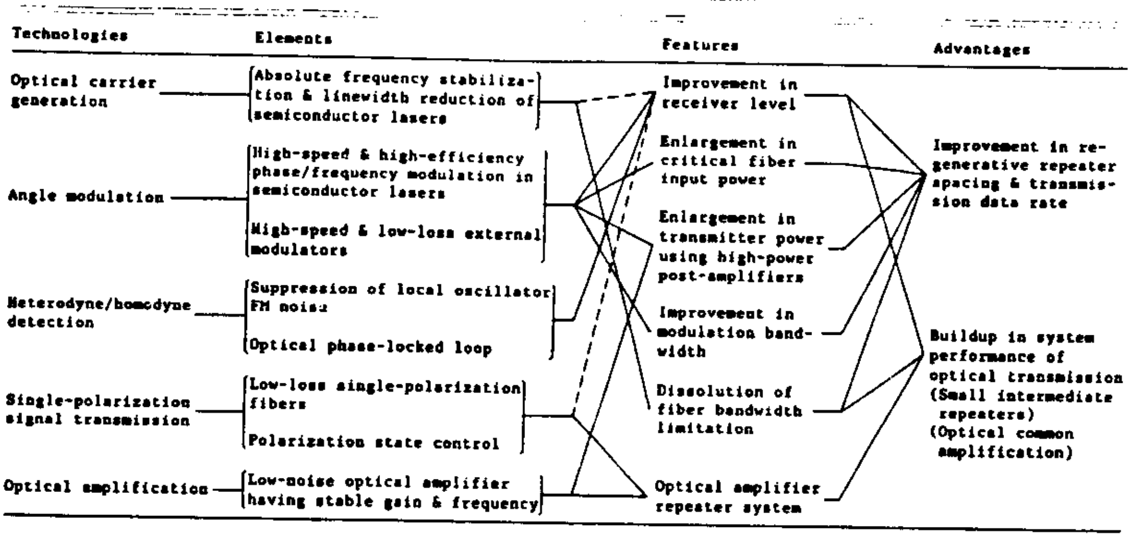
Fig. 2. Transmitter and receiver levels in coherent optical systems and intensity-modulation direct-detection systems. (*a*) and (*b*) are transmitter levels for angle modulation schemes and intensity/amplitude modulation schemes, and are determined by stimulated Raman scattering and stimulated Brillouin scattering, respectively. (*c*), (*d*), and (*e*) are receiver levels for APD direct detection, PSK homodyne detection, and coded 32-level FSK heterodyne detection, respectively. Closed and open circles are those levels in coherent optical transmission experiments and conventional system experiments, respectively.

Fig. 2 illustrates the relationship between the transmitting and receiving signal levels and the transmission data rate. Coherent modulation-demodulation schemes demonstrate the possibility of achieving an approximate 20-dB improvement in receiver sensitivity and one of about 30 dB in the transmitting signal level over conventional intensity-modulation direct-detection schemes. At a data rate of 1 GHz, coherent transmission systems theoretically admit a transmission loss totaling up to about 90 dB, which corresponds to a fiber length of more than 400 km.

Long-haul terrestrial or undersea systems are promising applications of coherent optical fiber transmission. Coherent modulation–demodulation schemes can be applied to subscriber systems, especially distribution networks where many terminals simultaneously receive signals. This is because the large signal gain obtained by coherent techniques can compensate for the bridging loss which constitutes the dominant loss factor in passive distribution systems.

Optical heterodyne and homodyne detection, in conjunction with an electric filter which follows, have a frequency filtering function for removing unwanted noise existing outside the signal band. This is advantageous for building up system performance by installing optical amplifier repeaters since spontaneous emission, which represents the dominant noise source in optical amplifiers, can be filtered out. A coherent optical fiber transmission system loaded with only semiconductor laser amplifier repeaters, as opposed to electronic regenerative repeaters, has been theoretically predicted to have a good potential for transoceanic undersea system use over a circuit length of 10 000 km [8]. Optical amplifier repeaters, which are fabricated in small sizes, are effective in the common amplification of frequency-division-multiplexing signals, and

TABLE I
ESSENTIAL TECHNOLOGIES, KEY ELEMENTS, AND SYSTEM FEATURES OF COHERENT OPTICAL FIBER TRANSMISSION



are adaptive to a change of modulation schemes as well as transmission data rates.

The first improvement becomes more evident in the 2–10 μm wavelength region [6], where the possibilities of ultralow-loss fibers have been predicted [27]. Since photodetectors are fabricated from narrow-bandgap semiconductors in this wavelength region, dark current due to the diffusion current becomes the dominant noise source. Direct detection deteriorates its performance, but coherent optical detection can still achieve a quantum-noise-limited operation.

IV. Relevant Technologies for Developing Current Systems

Essential technologies for realizing the system features described in Section III are single-frequency carrier generation, angle modulation, heterodyne or homodyne detection, single-polarization signal transmission, and optical amplification. Table I relates these essential technologies and their key elements, which affect the features in Section III as well as the two principal resulting advantages.

With respect to coherent optical carrier generation, frequency stabilization and spectral linewidth reduction of semiconductor lasers are important subjects. A completely frequency-stabilized master oscillator is required to synchronize the entire system especially for a large-scale coherent network system consisting of coherent subsystems. To achieve highly efficient angle modulation of the optical carrier wave, phase or frequency modulation schemes using semiconductor lasers should be extensively studied. It is important to maintain a narrow carrier wave linewidth even under the modulation condition. High-speed and low-loss external modulators are also assential devices in line for development.

In coherent detection schemes, suppression of S/N degradation due to the AM and FM noise of local oscillators is one of the main subjects of concern. Since homodyne receivers must track the carrier signal phase, the optical phase-locked loop (PLL) technique is indispensable. To accomplish the polarization-plane matching between the transmitted signal and the local oscillator waves in coherent receivers, low-loss single-polarization fibers should be developed which maintain the polarization state of the transmitted signal light. Development of polarization control devices attached to the fiber output end also becomes important if polarization fluctuation in conventional single-mode fibers is very small and slow. With respect to optical amplification technology, low-noise optical amplifiers having stable gain and frequency are important devices for post-amplifier application as well as for optical repeater application developments.

V. Coherent Laser Sources

The master oscillator, to which the entire coherent network system is synchronized, or the transmitter oscillator, which provides an optical carrier wave, must have such properties as long life, stable frequency, and narrow spectral linewidth. The candidates for the coherent light sources in the low-loss wavelength region of optical fibers are 1.52-μm He–Ne lasers, 1.33-μm Nd:YAG lasers, 1.32-μm lithium neodymium tetraphosphate (LNP) lasers, and 1.3–1.6 μm InGaAsP semiconductor lasers.

Semiconductor lasers are the most promising oscillators and the most interesting objects of research because of their long life and great efficiency. When semiconductor lasers are used as coherent laser sources, they have three principal drawbacks. First, the oscillation longitudinal mode jumps due to the temperature changes and device aging degradation occurring over a long period of time. Second, the oscillation frequency is sensitive to both temperature and injection current changes, even if laser operation is continued in the single longitudinal mode. The frequency changes by 10–20 GHz/degree relative to temperature and by 1–5 GHz/mA relative to injection current. Third, the FM noise, which determines the spectral linewidth, is large since semiconductor lasers have small active-layer volumes and hence small cavity-Q values. Both Fabry-Perot and distributed feedback (DFB) InGaAsP lasers oscillating at 1.5 μm exhibit spectral linewidths of 10–100 MHz [28], [29]. For reference, Fig. 3 shows the linewidth for several kinds of coherent modulation-demodulation schemes necessary to achieve a 10^{-9} error rate [8], [30]. It is clear that the spectral linewidth of the optical carrier wave, as well as that of the local oscillator, must generally be 10^{-3}–10^{-4} times smaller than the transmission data rate.

DFB lasers, phase-shift DFB lasers, and distributed Bragg reflector (DBR) lasers show promise in overcoming the first problem. Their own frequency-selective structures control oscillation behavior and achieve single longitudinal mode operation.

Concerning the second problem, the oscillation frequency of a semiconductor laser can be locked to such a frequency reference as a Fabry-Perot interferometer or an absorption spectral line of gaseous atoms or molecules [31]–[33]. Frequency stabilization is carried out by extracing an error signal and feeding it back to countermodulate the laser temperature or injection current. A frequency stability of 10^{-12}–10^{-11} at an average time of 100 s has thus far been achieved [31], where this characteristic actually means the frequency traceability of a semiconductor laser to the frequency reference. An absorption line exhibits a highly stable frequency over a long term, permitting the development of a semiconductor laser having an absolute standard frequency. An absorption line of NH_3, which is found in the 1.5-μm wavelength region, for example, exhibits a center frequency shift toward a temperataure change $(\Delta f/f)/\Delta T$ of 10^{-14} degrees^{-1} through the second-order Doppler effect [34], while a Fabry–Perot cavity whose housing is made of a low-expansion material, such as super-invar or quartz glass, shows a frequency shift of $10^{-7}-10^{-6}$ degrees^{-1}. An InGaAsP DFB laser stabilized to an NH_3 absorption line at 1.52 μm has recently been reported [33]. Besides NH_3, such gaseous molecules as CO_2, H_2O, and CH_3Cl possess absorption spectra in 1.3–1.7 μm wavelength region. Important for future systems, then, are the detailed assignment of absorption lines and the search for new absorption media.

Enlarging the laser cavity-Q value by employing a long cavity structure [35] is one effective example for solving the third problem. An external cavity structure having a mirror or a diffraction grating also increases the effective cavity-Q value, and thus serves to reduce the spectral linewidth [36]. An external-cavity 1.5-μm InGaAsP laser, in which the laser facet facing an external grating was antireflection-coated, achieved a spectral linewidth below 1 kHz [37]. Furthermore, the linewidth reduction factor [38] and operation stability [39] of external cavity lasers have been extensively discussed as promising solutions.

Negative frequency feedback control of semiconductor lasers reduces FM noise and spectral linewidth [40]–[41]. Under such a scheme, the FM noise of a semiconductor laser is extracted first through an optical frequency discriminator, for example, a Michelson interferometer. The laser oscillation frequency is then modulated by superposing the error signal on the bias current to cancel out the original FM noise. Except for a broader feedback bandwidth, this scheme basically involves the same operation principle as the above-mentioned frequency stabilization scheme. Theoretically, negative frequency feedback control offers the possibility of spectral linewidth decreasing below the modified Schawlow–Townes limit [41]. Reported experiments confirm, however, that a time delay around a feedback loop dominates the FM noise reduction factor [40]. Reduction of the loop time delay, which can be achieved by utilizing optoelectronic integration circuit (OEIC) technology [43], is indispensable for ensuring the success of this method.

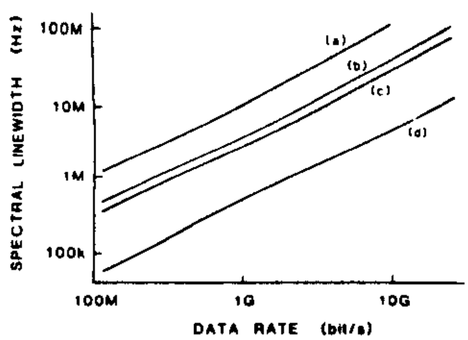


Fig. 3. Spectral linewidth required for coherent detection systems. (*a*) FSK heterodyne detection with frequency shift equal to data rate. (*b*) PSK heterodyne differential detection. (*c*) FSK heterodyne detection with frequency shift of 0.5 times data rate. (*d*) PSK heterodyne synchronous detection and PSK homodyne detection. (PLL bandwidth is 0.01 times data rate.)

It is important when developing semiconductor lasers to simultaneously achieve stable frequency and narrow linewidth. Combining the above frequency stabilization and linewidth reduction schemes is one direct way toward such simultaneous achievement. The frequency stabilization of a narrow-linewidth external-cavity laser may be automatically achieved by inserting a dispersive medium into the cavity.

Additionally important is the study of the individual noise characteristics of semiconductor lasers. Laser FM noise basically stems from the spontaneous emission coupled to a lasing mode. In semiconductor lasers, AM noise, that is, photon number fluctuation, generated through the same mechanism as FM noise, competes with carrier number fluctuation and then enhances FM noise through the dispersion characteristics of the laser medium [35]. This FM noise enhancement factor is the so-called α-parameter [44], [45]. Although FM noise possessing the f^{-1} power spectrum has been observed in a low-frequency region [46], its cause is still being discussed. The theory of noise in semiconductor lasers has been well-established by using the quantum mechanical Langevin equation [47]. This method has additionally been studied to expand it to treatment of the density-matrix master equation and the quantum mechanical Fokker–Planck equation [35]. Moreover, it is essential to take a close look at the elec-

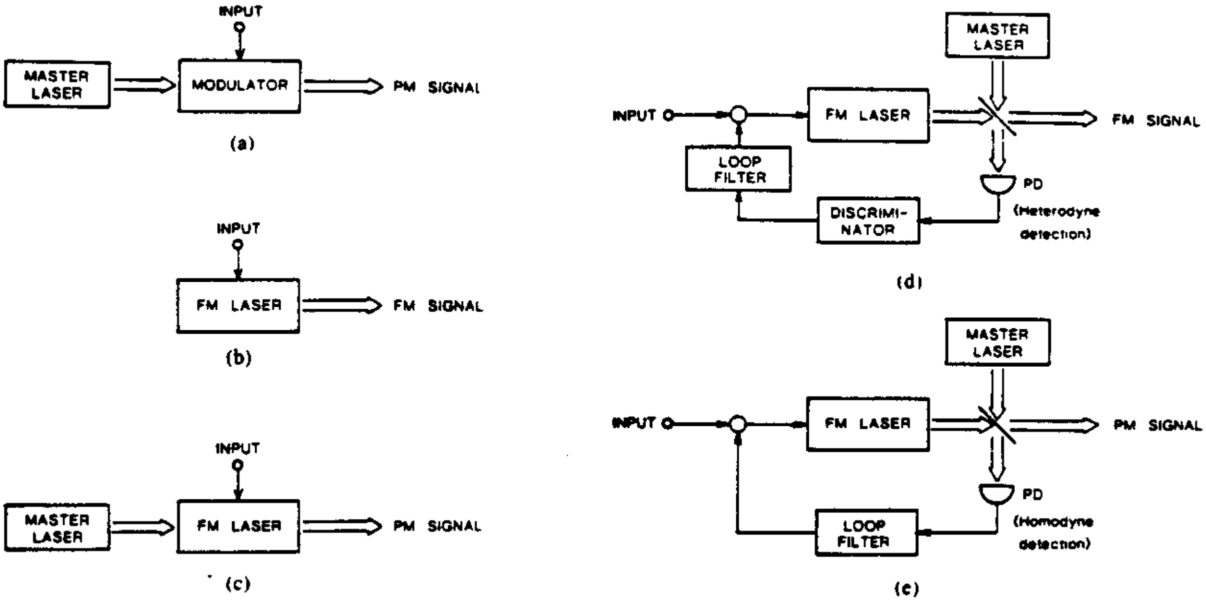


Fig. 4. Transmitter configurations for angle modulation schemes. (a) Phase modulation using external electrooptic modulator. (b) Frequency modulation by direct modulation of FM semiconductor laser injection current. (c) Phase modulation using injection locking technique. (d) Frequency modulation in optical FMFB configuration. (e) Phase modulation in optical PLL configuration.

tron system present in semiconductor lasers by means of quantum statistical treatment.

VI. Modulation–Demodulation Technology

Angle modulation is a promising modulation scheme in coherent optical transmission because of the various advantages described previously in Section III. PSK and MSK (minimum-shift-keying) achieve the most sensitive detection among binary modulation schemes. Of great interest along this line is MFSK (multiple-frequency-shift-keying), which improves receiver sensitivity through multilevel signaling. For PSK signal generation, a conventional guided-wave electrooptic phase modulator can be used, which is installed just behind a frequency-stabilized CW laser as shown in Fig. 4(a). Besides external phase modulators, direct modulation of semicondutor lasers can be applied to FSK and PSK signal generation. The basic transmitter configurations for these modulation schemes using semicondutor lasers are shown in Fig. 4(b)–(e).

An optical FM signal is obtained by directly modulating the injection current of conventional single-longitudinal mode semiconductor lasers [25]. Direct frequency modulation characteristics are determined by the carrier modulation effect in the high-modulation frequency region, and by the temperature modulation effect in the low-frequency region. Amplitude and phase characteristics of direct frequency modulation have previously been measured in detail [25], [48]. Although the FM response of semiconductor lasers is not uniform, a frequency shift of 100 MHz to 1 GHz is easily obtained without serious intensity modulation. Direct frequency modulation of semicondutor lasers has the advantage of a simple transmitter configuration as shown in Fig. 4(b). The inherent spectral linewidth of a semiconductor laser, which may result in on drawback for this method, can be suppressed, for example, by an external cavity configuration at the expense of FM efficiency degradation [36]. Nonuniform FM characteristics can also be compensated for by electrically equalizing the modulation input current [49].

Optical phase modulation is achieved by direct current modulation of a semiconductor laser into which external coherent laser light is injected [50], as shown in Fig. 4(c). The output signal phase relative to the input light phase is zero when the injected laser frequency is exactly tuned to the input signal frequency. It changes by $\pi/2$ rad when the injected laser frequency is detuned away from the input light frequency to the locking bandwidth limit. The cutoff modulation frequency in this method is determined by the injection locking bandwidth. Even if the inherent spectral linewidth of the injection locked laser is rather broad, it is reduced to the level of the injected signal linewidth [51].

In conjunction with electrical negative feedback techniques, direct frequency modulation of semiconductor lasers generates optical FM/PM signals having uniform modulation frequency characteristics and narrow spectral linewidths [52], [53]. As shown in Fig. 4(d), a fraction of the output signal from a frequency-modulated semiconductor laser is demodulated by heterodyne frequency-discrimination detection with master laser light having a stable frequency and narrow linewidth. After being phase-reversed, the demodulated signal is fed back to counter-modulate the injection current of the modulated laser. This negative feedback loop structure, which is normally called frequency modulation feedback (FMFB), suppresses both the FM noise and nonuniform FM response to the semiconductor laser [52].

A feedback loop structure using the homodyne detection scheme shown in Fig. 4(e), that is, the phase-locked loop (PLL), is effective for PM signal generation [53]. For this phase modulation method, the loop bandwidth of the PLL determines the cutoff modulation frequency. Since the loop delay time of these schemes practically limits the effective modulation bandwidth, its reduction, for example, by integrating the feedback loop components, is indispensable.

Essential to the above modulation methods using semiconductor lasers are a flat FM response, a high FM efficiency, and a suppressed spurious intensity modulation. Composite semiconductor lasers having a DFB laser region and a modulator region have been developed to satisfy such requirements [14], [54]. Supplying a modulation input signal to the modulator region effectively demonstrated flat frequency modulation caused mainly by the carrier modulation effect. A modulation efficiency of 1–2 GHz/mA and a cutoff frequency of several hundred megahertz were achieved. A two-section laser having different α-parameters was also proposed through a critical look at the direct frequency modulation mechanism in semiconductor lasers [55]. The push–pull operation was indicated as a possible means for achieving the above requirements. Furthermore, a DFB laser having electrically separated multielectrodes has recently been developed [56]. By controlling the modulation current to each electrode, frequency modulation exhibiting a frequency shift of up to 12 GHz was demonstrated at a 1-GHz modulation frequency under constant output power operation.

Optical signals are demodulated by heterodyne or homodyne detection using a local oscillator. FM noise of the local oscillator, as well as that of the transmitter laser, causes S/N degradation in receivers through FM-AM or PM-AM conversion, and determines a lower limit of error-rate performance [49]. Excess AM noise of the local oscillator, which is due to the resonance characteristics of a semiconductor laser, also deteriorates the S/N, and then, in this case, degrades the receiving signal level [49]. In order to remove the effect of local oscillator FM noise, a semiconductor laser must be used whose spectral linewidth is suppressed, for example, by an external cavity configuration. As was shown in Fig. 3, laser linewidth requirements have been estimated for individual modulation–demodulation schemes [8], [30], [49], [57], [58].

Excess AM noise of a semiconductor laser decreases with an increase in the bias level, so that high-bias operation is effective in suppressing the AM noise [35]. The local oscillator's excess AM noise can also be suppressed by the so-called balanced-mixer receiver, which basically consists of a 50–50 percent beamsplitter, two balanced photodetectors, and a hybrid junction having a π phase shift [59]. The AM noise is completely removed by differentially composing the signals detected by two detectors. The transmitted signal, on the other hand, is coherently doubled because of the initial π phase difference.

In homodyne detection, optical PLL techniques are essential for achieving homodyne receiver sensitivity which is 3 dB better than heterodyne performance. An optical PLL basically consists of a phase detector, a loop filter, and a voltage-controlled oscillator (VCO), where a photodetector and a local oscillator actually act as the phase detector and the VCO, respectively. The optical phase difference between the incoming signal and the local oscillator wave, that is, the phase error signal, is detected by the phase detector, and is then fed back to the VCO to effectively track the carrier phase. An optical PLL has been demonstrated in a recent homodyne detection experiment of a 140-Mbit/s PSK signal transmitted over a 30-km cabled fiber [60]. An optical PLL like the Costas-type has also been demonstrated using 10.6-μm CO_2 lasers [61]. The stationary phase error, which is an important parameter of optical PLL's, should be minimized since it results in a lower bit error rate limit.

Phase error noise of the PLL caused by the FM noise of both the signal and local oscillator waves can be suppressed by increasing the loop bandwidth. On the other hand, phase error noise due to shot noise and the local oscillator's excess AM noise is enhanced by the broad loop bandwidth. In this connection, the optimum system parameters and the required spectral linewidth have been evaluated for a balanced PLL and a decision-driven PLL [58].

Since an optical PLL is presently rather difficult to construct, efforts to demonstrate coherent optical fiber transmission have mainly concentrated on heterodyne detection systems. Such systems are inferior to homodyne systems in their attainable transmission data rate, however, for two reasons. First, heterodyne detection requires a receiver bandwidth wider than that of homodyne detection, and second, the response speed of photodetectors practically limits the maximum data rate. In order to overcome these problems, phase-diversity receivers, such as the three-phase detection receiver [62] and the in-phase and quadrature (IQ) detection receiver [63], have been demonstrated. Phase diversity techniques achieve heterodyne detection performance and allow the homodyne receiver bandwidth to be used without the need for installing optical PLL's.

The broad-band frequency modulation feedback (FMFB) and PLL configurations mentioned in this section are applicable to heterodyne and homodyne receivers, respectively, where FM semiconductor lasers operate as local oscillators [64]. Provided that the feedback bandwidth is so large that the incoming signal spectrum can be covered, the local oscillator follows the incoming signal and suppresses its own FM noise through the negative feedback control process. The local oscillator provides an incoming signal replica having a large power level. For angle modulation signals, the optical FMFB and PLL act as optical amplifiers whose ultimate noise figures in FM or PM signal amplification are 3 and 0 dB, respectively. Amplified optical signals are demodulated by direct detection following optical FM-AM or PA-AM conversion.

An optical PLL receiver, in conjunction with an FMFB transmitter, presents a promising system configuration for continuous-phase MFSK (CPMFSK) signal transmission.

VII. Optical Fibers

Optical heterodyne or homodyne efficiency strongly depends on polarization-state matching between the transmitted signal and local oscillator waves. Since the local oscillator generally emits linearly polarized light, the polarization state of the optical receiving signal must be made linear. In order to achieve this, two approaches have thus been attempted. One is to develop optical fibers which maintain the polarization plane of the incident linearly polarized light during propagation [65]. The other is to install polarization control devices at the output end of conventional single-mode fibers [66].

With respect to the first approach, an optical fiber having axial asymmetry in its cross section is used. When the cross section of a conventional single-mode fiber is intentionally deformed away from axial symmetry, degeneracy of two possible polarization modes is removed. Two eigenpolarization modes [67], orthogonal to each other, can then propagate through such deformed fibers. In order to transmit one of the two eigenpolarization modes, only the polarization mode should be launched into the fiber, while mode conversion to another eigenmode must be suppressed during propagation.

An important parameter describing the performance of a polarization-maintaining fiber is the extinction ratio at the fiber output end, which is defined by the power ratio of the unwanted mode to the launched mode [65]. The extinction ratio is given as a function of the mode coupling coefficient, which is determined by the modal birefringence $\delta\beta$ and by the power spectrum of the fiber perturbations. Here, the modal birefringence is defined as the propagation constant difference between the two eigenpolarization modes. In order to achieve a small extinction ratio, the modal birefringence $\delta\beta$ should be made large or, on the other hand, the beat length $\Lambda = 2\pi/\delta\beta$ should be made small [65].

Several types of polarization-maintaining optical fibers have been proposed to increase modal birefringence. Early proposals included fibers having geometrically asymmetric refractive-index profiles, such as elliptical-core fibers [68]. The thermal-stress-induced anisotropy due to the asymmetric thermal expansion coefficient was subsequently pointed out as being more effective for enhancing modal birefringence [68], [69]. The thermally induced modal birefringence has been theoretically treated for specific profiles [70], [71]. Thermally-stressed polarization-maintaining fibers, such as elliptical jacket [72], PANDA [73], and bow-tie [74] fibers, have been fabricated. Among these, the shortest beat length thus far achieved has been $\Lambda = 0.8$ mm [72]. These polarization-maintaining fibers can actually convey either of the two eigenpolarization modes. In order to permit only one polarization mode to propagate through such fibers, an attempt to impose a cutoff condition on the other mode has been made by introducing a loss difference between the two eigenpolarization modes [75], [76].

Since polarization-maintaining fibers are still undergoing development, coherent optical transmission experiments have thus far mainly used only conventional single-mode fibers. It is essential that polarization-maintaining fibers have a small loss comparable to that of conventional single-mode fibers. Suppression of the extinction ratio, as well as reduction of fiber loss, is also indispensable. Significantly, a 2.4-km polarization-maintaining fiber whose loss approached that of the single-mode fiber has recently been fabricated [77]. The loss characteristic of this fiber is shown in Fig. 5, with a minimal fiber loss of 0.25 dB/km being achieved at 1.57 μm. Moreover, an extinction ratio of -29 dB was achieved for a 2.4-km fiber length, which corresponds to a mode coupling coefficient of 5.2×10^{-7} m^{-1}. These results indicate the possibility that polarization-maintaining fibers can be practically used in coherent optical fiber transmission systems.

The extinction ratio is shown in Fig. 6 as a function of the mode coupling coefficient for cases with and without a loss difference occurring between the two polarization modes [78]. The mode coupling coefficient must be suppressed by increasing the modal birefringence and by decreasing the fiber perturbations. Introduction of the loss difference, which leads to saturation in the extinction ratio for a long fiber, is effective for achieving a small extinction ratio although it may cause an increase in propagation mode loss. It is thus important to develop thermally stressed polarization-maintaining fibers possessing both low loss and a small extinction ratio.

Both internal and external perturbations existing randomly along optical fibers cause mode coupling to occur between the two orthogonal polarization modes. Internal perturbations, such as scattering center inhomogeneity and core–cladding interface irregularity, depend on the fiber fabrication technology employed. Improvement of uniformity along the fiber axis is effective for suppressing mode conversion, and simultaneously, for decreasing fiber loss. To effectively obtain information about internal perturbations, it is important to directly measure the coupling coefficient under suppressed external fluctuation conditions [79]. The power spectra of external perturbations should also be evaluated.

By introducing polarization-maintaining fibers instead of conventional single-mode fibers, polarization-state matching between signal and local oscillator waves can be easily carried out without the necessity for any additional polarization control scheme. Polarization-maintaining fibers are of great advantage in developing sophisticated coherent systems using optical amplifiers and optical integrated circuits, which are often sensitive to the polarization state of input signals. Moreover, polarization-maintaining fibers offer the possibility of polarization-division multiplexing.

With the second approach for achieving high heterodyne or homodyne efficiency through controlling the polarization state of the transmitted signal at the fiber output

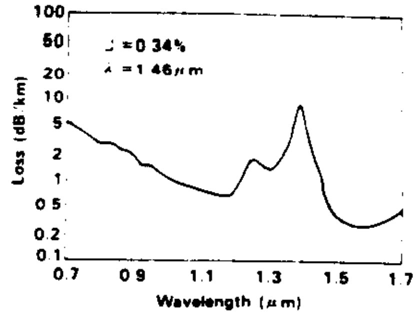


Fig. 5. Loss spectrum of a polarization-maintaining fiber (after Hosaka *et al.* [77]). Refractive index difference Δ is 0.34 percent. Core diameter $2a$ is 8.9 μm. Cladding diameter $2b$ is 200 μm. Cutoff wavelength λ_c is 1.46 μm.

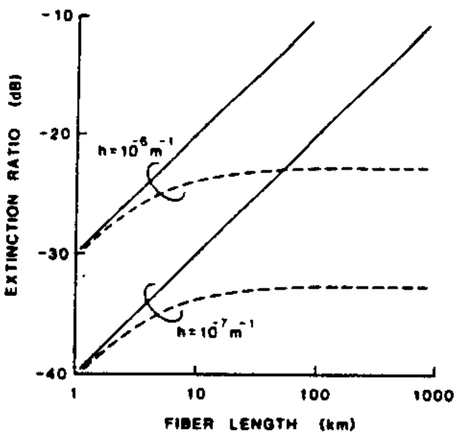


Fig. 6. Extinction ratio as a function of mode coupling coefficient h. Solid lines indicate no loss difference between two polarization modes. Broken lines indicate loss difference (0.2 dB/km: 1 dB/km).

end, conventional single-mode fibers can be used. In fact, it has been reported that polarization-state fluctuation following 30-km single-mode fiber transmission was small and slow enough to be easily suppressed by automatic polarization control devices [80]. This method presents the obvious advantage of using well-developed low-loss single-mode fibers without the need for any structural modification. Additionally, polarization control techniques allow twisted fibers [81] to be used, provided that circularly polarized light is launched into the fiber. Such techniques utilize the fact that clockwise and counterclockwise circular polarizations become eigenmodes when shearing stress is induced by twisting a nearly round core fiber [82]. Polarization dispersion of the twisted fiber approaches zero as the twist rate increases. Twisted fibers are advantageous in their easy connection or splicing free of precise polarization-plane matching. Moreover, if local oscillator light can be circularly polarized, a polarization controller may be completely unnecessary.

Polarization control schemes at the fiber output end are divided into two categories: phase compensation [66] and polarization diversity [83]. Phase compensation, basically simulating the operation of half- and quarter-wave plates, adjusts the polarization state of the transmitted signal to that of the local oscillator light. After extracting a fraction of the transmitted light and detecting its polarization state, phase compensation is accomplished by the feedback control of newly introduced birefringence. The additional birefringence is induced, for example, by applying stress on an optical fiber or by controlling birefringence in a dedicated electrooptic crystal.

With the polarization diversity scheme [83], the two orthogonal polarization modes of the signal light are heterodyne or homodyne detected individually and then combined electrically to obtain a polarization-independent signal. The feedback control of the polarization state of the incoming signal may be employed to suppress the S/N degradation. Important parameters in all polarization control schemes are response speed, insertion loss, output stability and device size. Continuous follow up of the input signal polarization state is also an important requirement [84].

VIII. Optical Amplifiers

Optical amplifiers may be used as post-amplifiers and intermediate line repeaters. Semiconductor laser amplifiers [21] are classified into two categories: linear amplification and injection-locked oscillators. Fabry–Perot cavity-type [85], [86] and traveling-wave-type [87], [88] semiconductor laser amplifiers belong to the first category. The Fabry–Perot cavity-type amplifier, which is biased just below the threshold, achieves linear amplification utilizing stimulated emission. The traveling-wave-type amplifier, made by antireflection coating the facets of a Fabry–Perot-type amplifier, uses a single-pass gain through its active layer. The injection-locked oscillator, on the other hand, is a semiconductor laser whose phase or frequency is controlled by weak optical injected signals [22], [51]. Fiber-Raman amplifiers [24], [89], [90] and fiber-Brillouin amplifiers [91], which utilize stimulated Raman scattering and stimulated Brillouin scattering in an optical fiber, respectively, may be applied to coherent optical fiber transmission systems. The above-mentioned optical FMFB and PLL using FM semiconductor lasers can also be regarded as optical amplifiers.

Important device characteristics of optical amplifiers as applied to coherent optical fiber transmission are small-signal gain, saturation output power, frequency bandwidth and noise figure [21]. These characteristics, as well as the features and problems, are summarized in Table II for each of the above optical amplifiers. Since a Fabry–Perot cavity-type amplifier inherently has an optical frequency filtering function, its noise figure and excess noise bandwidth can be decreased by employing a low-reflectivity input facet and a high-reflectivity output facet [85]. Here, the excess noise bandwidth is defined by the spontaneous emission power of the amplifier normalized by the small-signal gain.

The traveling-wave-type amplifier is superior to Fabry–Perot cavity-type amplifiers provided that narrow-band optical filters, which remove spontaneous emission, are provided. Traveling-wave-type amplifiers and fiber Raman amplifiers have a broad bandwidth over 1 THz, making them advantageous for the common amplification of

TABLE II
CHARACTERISTICS, PRINCIPAL FEATURES, AND PROBLEMS OF OPTICAL AMPLIFIERS

	Fabry-Perot-type semiconductor laser amplifier	Traveling-wave-type semiconductor laser amplifier	Injection-locked semiconductor laser amplifier	Fiber Raman amplifier	Semiconductor laser PLL circuit
Small-signal gain	25-35 dB	~20 dB	20-30 dB	20-30 dB	50-60 dB
Saturation output level	-10 to 0 dBm	0-10 dBm	10-20 dBm	~20 dBm	~10 dBm
Bandwidth	1-3 GHz	~1 THz	0.5-1 GHz	~1 THz	~100 MHz
Noise figure (Experiment)	3 dB (6-9 dB)	3 dB (6-9 dB)	3 dB (6-9 dB)	3 dB	0 dB
Excess noise bandwidth	Medium	Large	Small	Medium	Small
Input/output coupling loss	Medium	Medium	Medium	Low	Medium
Gain stability against frequency deviation	Medium	High	Low	Medium	Low
Features	Spontaneous emission filtering function	Broad bandwidth Common amplification	Suppression of spontaneous emission by gain saturation & filtering function	Broad bandwidth Small coupling loss	High gain Small noise figure
Problems	Small output power	Need for narrow-band optical filter	Need for frequency stabilization	Need for reliable pump laser in 1.5 μm region	Excessive loop delay time
References	(85)(86)	(87)(88)	(22)(51)	(89)(90)	(64)

frequency-division multiplexing signals. Fiber-Brillouin amplifiers have narrow bandwidths, which are inherently about 15 MHz for silica fibers at a 1.5-μm wavelength, prompting attempts to broaden the Brillouin bandwidth through frequency modulation of the pump light [91]. Injection-locked oscillators, which have a small excess noise bandwidth and a high power output, can be applied to the power amplication of angle modification signals. The principal feature of the PLL using a semiconductor laser is its theoretical noise figure limit of 0 dB in terms of PM signal amplification [64], while other amplifiers have a limit of 3 dB.

IX. System Experiments

A large number of system experiments in laboratories using coherent techniques have been reported so far. These experiments, however, do not exhibit the ultimate in coherent system performance yet since they are based mainly on conventional optical device technologies. The principal keys in the development stage continue to be verifying the system operation, confirming feasibility, and elucidating the technological problems to be solved. This section reviews the significant experiments which fostered steady improvements in coherent optical transmission technology. The latest transmission experiments are also introduced.

Table III summarizes four of the most significant reports on coherent optical system experiments. The first coherent optical transmission experiment was made in 1967 using two 3.39-μm He–Ne lasers [3]. A 50-kHz FM signal transmitted across 150 m of space was received by heterodyne frequency-discrimination detection. Also demonstrated was receiver sensitivity improvement over a conventional photodetector receiver. Laser FM noise and atmospheric turbulence, both of which determined the system performance, were quantitatively evaluated. The causes of laser FM noise were closely discussed and stable He–Ne lasers were specially designed accordingly.

Two independent semiconductor lasers were used in the heterodyne detection system experiment reported in 1980 [92]. An AlGaAs laser operating in a single longitudinal mode was directly frequency-modulated through injection current modulation. A 100-Mbit/s FSK signal was heterodyne-detected using another AlGaAs laser as a local oscillator. Direct frequency modulation of a semiconductor laser, whose characteristics were measured in the modulation frequency region of 150–900 MHz, demonstrated its usefulness for coherent optical transmission.

Long-fiber transmission over 100 km was demonstrated in 1983, using a 1.52-μm He–Ne laser and an external cavity InGaAsP laser as a transmitter laser and a local oscillator, respectively [93]. A 140-Mbit/s PSK heterodyne coherent detection was carried out, with a receiver sensitivity improvement of 14 dB above direct detection being achieved. This experiment using conventional single-mode fibers indicated that the polarization state fluctuation following propagation over 100 km was so small and slow as to be compensated for by manual adjustment using a fiber polarization controller.

In 1984 two 1.57-μm InGaAsP–DFB lasers were used in a coherent transmission system whose line length was 105 km [94]. Direct frequency modulation generated a

TABLE III
DISTINCTIVE COHERENT OPTICAL SYSTEM EXPERIMENTS

	(a)	(b)	(c)	(d)
Light sources	He-Ne lasers	AlGaAs lasers	He-Ne laser (TR) External-cavity InGaAsP laser (LO)	InGaAsP-DFB lasers
Wavelength	3.39 μm	0.83 μm	1.52 μm	1.57 μm
Modulation	FM (50 kHz) Direct modulation (Cavity length)	FSK (100 Mbit/s) Direct modulation (Injection current)	PSK (140 Mbit/s) Phase modulator	FSK (100 Mbit/s) Direct modulation (Injection current)
Demodulation	Heterodyne frequency-discrimination detection	Heterodyne frequency-discrimination detection	Heterodyne synchronous detection	Heterodyne single-filter detection
Transmission medium	Space (150 m)	Space (Face-to-face)	Single-mode fiber (109 km)	Single-mode fiber (105 km)
Features	Quantitative evaluation of laser FM noise & atmospheric turbulence	Usefulness of direct frequency modulation in semiconductor laser Broadband FM signal	Small polarization-state fluctuation 1.5-μm narrow-linewidth lasers	Suppression of nonflat FM response using Manchester coding Single-filter detection suppressing S/N degradation due to FM noise
Year	1967	1980	1983	1984
References	(3)	(92)	(93)	(94)

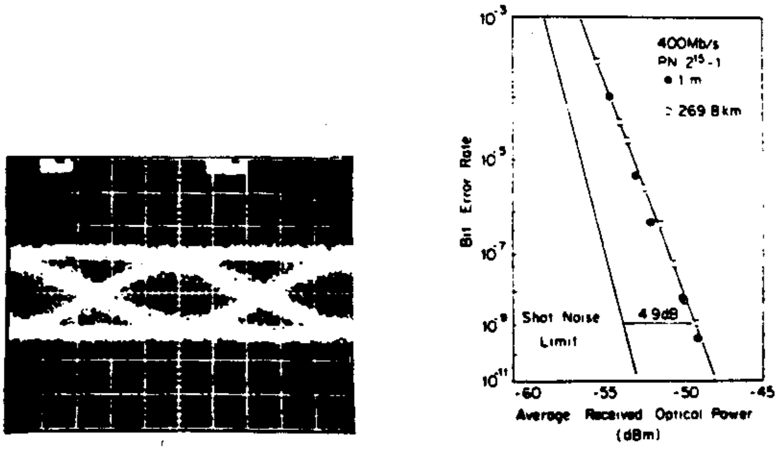
100-Mbit/s FSK signal in which nonuniform FM response was suppressed by utilizing Manchester coding. S/N degradation due to laser FM noise was relaxed by using a single-filter detection scheme in the electronic demodulation stage after optical heterodyne detection. Thereafter, a 140-Mbit/s · 243-km FSK heterodyne single-filter detection transmission experiment was demonstrated using a phase-tunable DFB laser in the transmitter [14].

More recently 400-Mbit/s · 270-km [95] and 1-Gbit/s · 150-km [15] heterodyne detection experiments have been reported. The former experiment used two external-cavity DFB lasers oscillating at 1.546 μm for its transmitter and local oscillator. The beat spectrum linewidth between the two lasers was less than 200 kHz. Direct modulation of the transmitter laser, in which an LC circuit was used to achieve a flat FM response, created a 400-Mbit/s continuous-phase FSK signal having a frequency shift of nearly 250 MHz, where the residual amplitude modulation was less than 0.5 dB. The transmitter laser output power and fiber input power were 10.6 and 5.5 dBm, respectively. A conventional single-mode fiber was used, and transmitted signal polarization was manually adjusted with a fiber-optic polarization controller. The total fiber loss, including splicing, was 53 dB at 1.546 μm. After heterodyne detection with an InGaAs-p-i-n photodiode, the continuous-phase FSK signal was demodulated by differential demodulation. The received eye pattern and the error-rate performance for a 2^{15}-1 pseudorandom binary sequence are shown in Fig. 7(a) and (b), respectively. A receiver sensitivity of −49 dBm was achieved for an error rate of 10^{-9}. In the course of this experiment, a 400-Mbit/s continuous-phase FSK signal having a 0.5 modulation index, that is, a 400-Mbit/s minimum-shift-keying (MSK) signal, has been transmitted over a 289-km pure-silica-core single-mode fiber [96].

The latter experimental system was a DPSK system using separate 1.5-μm buried heterostructure (BH) lasers having external grating cavities of 5-kHz spectral linewidths [15]. PSK modulation was performed with a titanium-diffused lithium niobate waveguide phase modulator having 1-cm-long traveling-wave electrodes. A signal greater than −3 dBm was coupled into a single-mode fiber. The total fiber loss, including connector and splice losses, was 39.6 dB. The polarization state of local oscillator light was adjusted to that of the transmitted signal. A balanced-mixer receiver composed of InGaAs-p-i-n photodetectors was employed. A receiver sensitivity of −44.5 dBm achieved at 1 Gbit/s corresponded to an improvement of 7.5 dB over the best direct detection result.

The transmitting and receiving signal levels of these two experiments, as well as those of the above 140-Mbit/s · 243-km experiment [14], are indicated in Fig. 2. Also indicated are those of the 565-Mbit/s · 240-km [17], 2-Gbit/s · 141-km [17], and 4-Gbit/s · 117-km [97] intensity-modulation direct-detection system experiments. The latter conventional system experiment, followed by a recent 8-Gbit/s · 68-km transmission experiment [98], used an external waveguide modulator, while the first two utilized direct intensity modulation of the semiconductor lasers.

The above system experiments are all heterodyne detection systems. Although polarization-maintaining fibers were not used in the fiber transmission experiments, conventional single-mode fibers were used in conjunction with polarization control devices. In the 1.3–1.6-μm wavelength range, homodyne detection using two separate He-Ne lasers and a balanced optical PLL receiver was demonstrated in a 140-Mbit/s PSK signal transmission experiment over a 30-km single-mode fiber [60]. Moreover, a 10.5-km polarization-maintaining fiber has recently been employed in a 400-Mbit/s FSK heterodyne



(a) (b)

Fig. 7. (a) Received eye pattern and (b) error-rate performace in 400-Mbit/s · 270-km FSK transmission experiment (after Iwashita *et al.* [95]).

detection experiment [99]. Two Fabry-Perot-type 1.5-μm amplifiers were used as in-line repeaters in a 100-Mbit/s ASK heterodyne detection experiment [100], following 0.8-μm tandem amplifier experiments [85].

X. Conclusions

Research on coherent optical transmission has produced a large number of fruitful results since it was received in the late 1970's. A demonstration of direct frequency modulation capability in semiconductor lasers was one of the most encouraging works leading to steady improvements in coherent transmission technologies. The absolute frequency stabilization of 1.5-μm semiconductor lasers also made available an essential technology for providing stable carrier waves to systems in the low-loss wavelength region of fibers. A double-balanced optical heterodyne or homodyne receiver additionally proved to be a unique proposal for removing the excess AM noise of a local oscillator and for achieving quantum-limited performance. Furthermore, a negative-frequency-feedback-controlled semiconductor laser, applicable to both transmitter and receiver configurations for angle modulation signals, presented itself as a new idea for suppressing laser FM noise as well as nonuniform FM response. In addition, an injection-locked semiconductor laser demonstrated its own potential as a post-amplifier and as a PM signal transmitter. Also, an evaluation of fiber birefringence pointing out usefulness of thermal-stress-induced anisotropy opened the way for single-polarization fiber development. Importantly as well, transmission experiments have come to successfully demonstrate the principal system features leading to longer transmission lengths and larger data rates.

The ultimate goal of coherent optical fiber transmission consists of fully utilizing the coherent properties of laser light as well as low-loss and broad-bandwidth characteristics of the optical fibers themselves. Single-frequency semiconductor laser technology, optoelectronic integrated circuit (OEIC) technology, and new technologies based upon these fundamental device technologies will solidify the foundation necessary for developing coherent optical fiber transmission systems.

Several of the definite research targets for the future include the following.

a) A narrow-linewidth semiconductor laser whose oscillation frequency is stabilized to an absolute frequency reference during a long period of time, for example, over 10 000 h.

b) A high-speed FM semiconductor laser having a suppressed temperature modulation effect as well as suppressed intensity modulation.

c) An OEIC negative-feedback-controlled semiconductor laser configuration potentially applicable to wide-band optical FMFB's and PLL's.

d) A single-polarization fiber capable of simultaneously decreasing fiber loss and mode coupling.

e) A low-noise optical amplifier having stable frequency and gain.

f) Optical passive devices such as low-loss narrow-band optical filters and low-loss optical isolators.

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