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SECOND WORKSHOP ON
OPTICAL FIBRE COMMUNICATION
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OPTICAL FIBRE COMMUNICATIONS

AN INTRODUCTION

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OPTICAL FIBRE COMMUNICATIONS. AN INTRODUCTION

The transmission of signals through optical fibres is a relatively new development of the communications industry which began in the 1970ies and is spreading at a greatpace ever since. The optical fibre has proven to be a technically and economically advantageous and reliable device for transmitting large amounts of information between stations.Significant efforts are now being undertaken in order to bring the fibre from the local station to the individual subscriber. This continuous evolution has been possible thanks to the technological superiority that is evident when the new medium as compared to the classical transmission methods. In the following we will attemp an introduction to the key devices and to the system characteristics of the optical communication technology.

1. INTRODUCTORY REMARKS

The use of light to transmit simple information signals is as old as humanity itself. The old greeks have used light beams to send messages and some of their setups were remarkably sophisticated. The idea of using fibres of glass is perhaps quite old but it was only in the 1960ies that the implementation of lasers, fibres and solid state photodetectors in a novel system for information transfer was considered seriously. The reasons for the sudden inrease of interest in the optical method are of various origin but two of them seem to have been very important: a) the recognition that the capacity of the existing telecommunication network must be increased dramatically to meet the increasing demand and b) a number of technological breakthroughts that made possible the realization os fibre systems.

Indeed, fibreoptic systems possess a number of advantages in comparison with electrical wire systems and with radio and microwave links. Some of them are listed below:

Large information carrying capacity. The fibre most used today in trunk telecomminications is the monomode silica glass fibre. In digital systems, bit rates in the Gbit/s range are obtained without undue difficulty and bit rate times distance products of at least several hundred Mbit/s . km can be reached. In transmission lines with heavy traffic the large capacity offers a clear economic benefit by reducing the cost per channel. The physical reason for the high capacity is the:

a) very low optical loss, which is caused by absorption, a material property, and scattering, a property that is partly material and can be partly due to imperfections of the fibre geometry, and

b) very low dispersion, a physical phenomenon that limits the usuful bandwidth of the fibre causing light pulses to spread out in time as they propagate along the fibre.

Low cost. This refers mainly to the bulk material cost which is glass but also to the final product, the cable containing usually several fibres.

Small size and low weight. Compared with metallic cables, fibre cables are much less bulky for the same transmitting capacity and are much easier to transport and to install.

Electrical isolation. Glass fibres are nonconducting and noninductive and are thus not subject to electromagnetic interference effects. The lines show negligible crosstalk.

System flexibility. Since the transmission capacity of the fibre itself largely exceeds the bandwidth requirements of modern systems, upgrading at a later time is possible whilst the overall compatibility is retained.

High security. Glass fibres are difficult to tap and if they are, the tapping is likely to be detectable.

The situation today may be summarized as follows: The optical fibre has unequivocally won the race for linking central telephone offices, the so-called "trunk network", where the capacity of the transmitting system must be very high. The implementation of the fibre in the local network for connecting residential and business subscribers to a central office is making considerable progress but is still not yet widely accepted. The reasons are partly technical and partly economical and perhaps also political. All relevant facts seem to indicate, however, that it is a question of time before optical systems will take over the function of the classical metallic wire links in the local area network.

2. SYSTEM BASICS

To transmit signals with fibres one needs, at a minimum, an optical transmiter, a fibre and an optical receiver. In a practical system, electronic circuits are needed as an interface between the external network and the transmitter and between the receiver and the following electrical network, see Fig.1. The function of these circuits is to process the information in such a manner that the resulting electrical waveforms can be applied to the transmitter resp. to the electrical network following the receiver. This signal processing is not considered relevant to

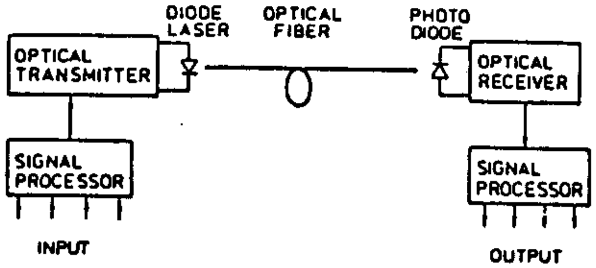


Fig.1 Diagram of a fibreoptic point-to-point transmission

the understanding of the fibre system per se and as a consequence it will not be treated here. We will thus concentrate on those parts that characterize the basic functions of the optical system and we will discuss their contribution to the information transmission.

The optical transmitter

The optical transmitter converts electrical signals into optical signals. The conversion is accomplished with a laser diode (LD) or a light emitting diode (LED) by changing the current through the device and detecting the variations of the light power. This approach is called direct modulation and is simple to implement. Usually the electrical signals have digital formats but a few analog applications can also be envisaged. In some cases it may be desirable to modulate the phase of the optical signal and to detect the phase of the received signal with coherent detection techniques. In very high bit-rate systems working at several Gbit/s external modulation of the light intensity or phase may bring advantages. This modulation is performed with help of integrated optic modulators which change the velocity of the light wave in a waveguide when an electrical signal is applied.

LD's and LED's are semiconductor devices that can be fabricated from various material systems. Two material systems are of particular interest: The GaAs/GaAlAs devices that emit in the 0.8 to 0.9 µm wavelength range and the InP/InGaAsP devices in the 1.0 to 1.6 µm range. Some of their characteristics are of special importance for communications. These are the optical signal power coupled into the fibre (a few milliwatts for a LD and up to 0.1 mW for a LED), the modulation frequency (up to 1 GHz for the fastest LED's and up to 20 GHz for the fastest LD's) and the spectral purity under modulation. This last parameter is important in high-frequency systems (at least 140 Mbit/s, depending on the combination laser/fibre).

The fibre

The fibre cable connecting transmitter and receiver in long-distance lines is made up of a number of sections, a few

kilometer length each, connected together. In we take into account the small cross-section of the fibre with core diameters ranging from several µm for single mode (monomode) fibres to 50 µm for multimode fibres it becomes clear that connecting fibres may represent a practical difficulty that does not exist with coaxial cables. Fibre joints and couplers to LD's and LED's of high reliability and quality are becoming available as technology advances.

Fibres for communications are usually made of silica glass in such a way as to cause the lowest possible signal attenuation and distortion. Attenuation and distortion of signal pulses limit the distances that can be spanned without repeaters and the maximum carrying capacity of the link.

The optical receiver

The conversion of the optical into the electrical signals takes place in the photodetector which is followed by electronic circuits for amplification and processing. The detector is a semiconductor device, in its simplest form a photodiode (PD) or a avalanche photodiode (APD) which allows an internal amplification of the photogenerated carriers.

The electrical noise of the detector is important in characterizing the sensitivity of the receiver which in turn determines the signal-to-noise ratio (SNR) for a given signal input. The SNR is an important quality criterion of the received signal. In a digital system the SNR is directly linked to the probability of error in deciding whether a pulse has been received or not. This is called the bit error rate (BER). Its maximum value is often set at 10^{-9}.

How does a typical fibreoptic system compare with a classical coaxial cable system ? The following table gives the repeaterless distances that can be overcome in the case of a 140 Mbit/s digital telephone transmission system (european time division multiplex hierarchy):

Transmission medium	Transmission capacity telephone channels	Repeater distance km
Optical fibre (LD, single mode)	1920	40 - 60
coaxial cable	1920	2 - 3

The benefit of using fibres is clearly demonstrated. The significantly longer transmission spans without cumbersome repeaters and the other advantages of the optical method are the reasons for the very rapid growth of the optical communications in the last years.

3. SOURCES AND TRANSMITTERS

LED's and LD's developed for optical communications meet successfully most of the requirements for efficient and reliable communication systems : emission wavelengths where fibre losses and pulse distortion are low, high speed, ease of modulation, adequate power, ruggedness and reliability. LD's are superior to LED's as regards speed, spectral purity and optical power coupled into the fibre. Systems based on LD's achieve much higher bit rate X distance products as compared with LED's. For this reason we will consider in the following sections mainly systems containing laser transmitters.

The laser diode

The realization of the laser diode dates back to 1962. The LD's of that time were homostructure pn junctions of GaAs. The LD's used today are of the double heterostructure (DH) diode type. In these diodes a thin semiconductor film that produces the laser beam - the active region - is placed between two cladding layers of higher band gap and lower refractive index. When the diode is biased in the forward direction, the electrons and holes are confined in the active region where they recombine giving rise to photons that have energies approximately equal to the band gap energy. The active layer acts also as an optical waveguide. The light is confined as an optical mode which propagates along the waveguide. In this manner, the optical losses are reduced since the light remains mostly in the waveguide and does not spread in the surrounding lossy regions.

The majority of the LD's are of the Fabry-Perot type. The optical cavity is formed by two parallel crystallographic planes which are perpendicular to the plane of the active layer, Fig.2.

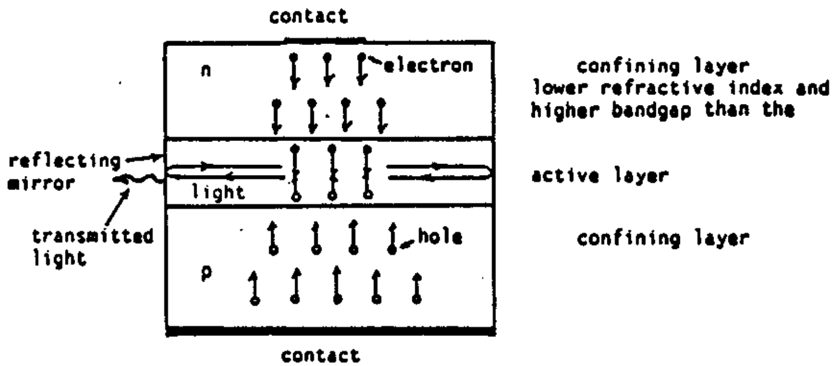


Fig.2 Principle of a LD having a double heterostructure.

The optical feedback is provided by reflections at the semiconductor-air interface. Inside the active layer standing waves are

built up between the mirrors which obey the simple relation:

$$q\lambda/2n = L$$

where q is an integer, λ the wavelength in vacuo, n the refractive index and L the distance between the mirrors (cavity length). Of all the possible wavelengths only a small number can be involved in the amplification process. What wavelengths will be present in the radiation is determined by the gain spectrum of the laser, Fig.3.

Fig.3 Standing waves in the optical cavity (laser resonator) (a) and gain spectrum with longitudinal modes (b)

The wavelengths that are present in the beam - the axial or longitudinal modes - have a spacing between them given by:

$$\Delta\lambda = -\lambda^2/2nL$$

The materials used for the fabrication of LD's are basically GaAs and InP. LD's containing the DH GaAlAs-GaAs-GaAlAs, GaAs being the acive layer, emit around .8 µm. LD's with the DH InP-InGaAsP-InP are fabricated so as to emit at 1.3 or at 1.55 µm. The wavelengths are chosen so as to correspond to the regions where the fibres have their lowest dispersion (1.3 µm) or their lowest loss (1.55 µm).

The output of a LD is an form of a narrow beam having an elliptic cross section. The optical field is usually denoted by E_{mpq} where q stands for the axial mode number and m and p for the transverse and lateral modes respectively specifying the field distribution perpendicular and parallel to the junction plane. In the transverse directiion the field is confined by the index discontinuities due to the DH. We call this mechanism index guiding. In the lateral direction, however, the field confinement depends on the method chosen for the fabrication of the diode. Generally spoken, there are two broad classes of LD's : the gain guided and the index guided, depending on whether the field is confined laterally by the distribution of the optical gain or by a variation of the refractive index. Two such structures are shown in Fig.4. In the gain guided case the current through the active region defines a gain accross that region which in turn determines the distribution of the field. Such lasers show drawbacks that may not be acceptable for high-speed modulation, especially in the region >1 µm. Index guided lasers contain lateral index discontinuities that confine the mode into a three-dimensional waveguide. They are the preferred LD's for 1.3 and 1.55 µm.

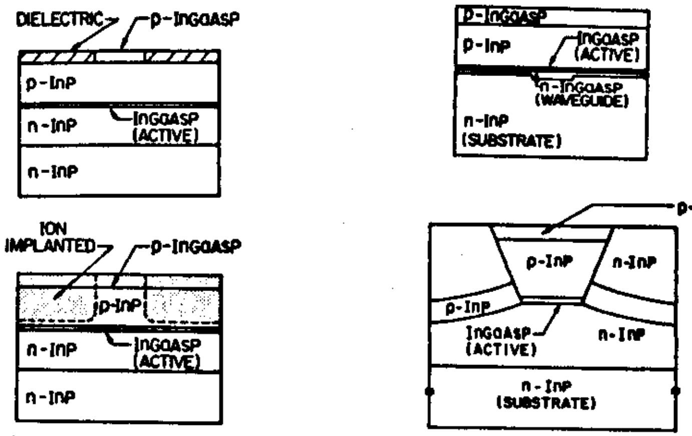


Fig.4 Gain-guided (left) and index guided (right) DH laser.

Perhaps the two most important characteristics of LD's are the optical power vs current and the spectrum. Fig.5 shows the light power per laser facet in mW vs current with the device temperature as a parameter for a 1.3 index guided LD. We note the strong dependence of the laser threshold on temperature, a fact that must be taken into account when designing electronic driving circuits.

LD's used in optical communications have in most cases only one mode in the transverse and lateral directions but may have several modes in the axial direction. Also, some lasers that are single mode (axial) under cw operation become multimode when they are pulsed. In high-capacity systems operating above 1 Gbit/s it is important to operate LD's that remain single mode under pulsed conditions. If this is not the case, the laser wavelength can jump unpredictably from one mode to another or the power can be emitted in a random fashion among several modes simultaneously. As a result, the quality of the transmission will be impaired. There are several methods that have been proposed to obtain a single mode laser (single frequency) under operation.

One approach towards the realization of a single frequency LD is the implementation of a feedback-selective mechanism in the device. In the distributed feedback laser (DFB) the feedback is not localized at the cavity mirrors as in a Fabry-Perot laser but is distributed throughout the cavity length. As Fig.5 shows, this is obtained by etching a periodic grating in one of the layers.

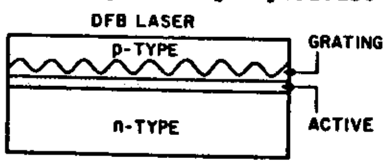


Fig.5 Schematic of a DFB laser.

Another method is to couple the laser cavity optically with another cavity. The lasers are labelled coupled cavity lasers and can be subdivided into categories depending on the art of the

second cavity. In any case, the important question to answer for all types of single mode lasers is whether side modes appear under high-speed modulation and how important is the frequency chirp, i.e. the shifting of the laser wavelength during each modulation cycle. Both phenomena become the limiting factors to high-speed modulation of lasers for optical communications.

Practically all LD's used in communications are modulated directly with the current. This direct modulation can be implemented without difficulty up to some GHz. Laboratory lasers have demonstrated even higher frequencies, about 20 GHz. For some reasons, however, external modulation at multi-GHz frequencies may be desirable. Integrated optic external modulators in GaAs and $LiNbO_3$ with excellent characteristics in the GHz region have been demonstrated and are now under intensive investigation for communication experiments.

The electronic drive circuits for LD's are significantly more complicated than the circuits for LED's. The circuits must provide some control of the bias current in order to compensate ageing and temperature effects. Moreover, an additional temperature stabilization using Peltier elements is required for most LD's in optical transmitters. A simple circuit is given in Fig.6.

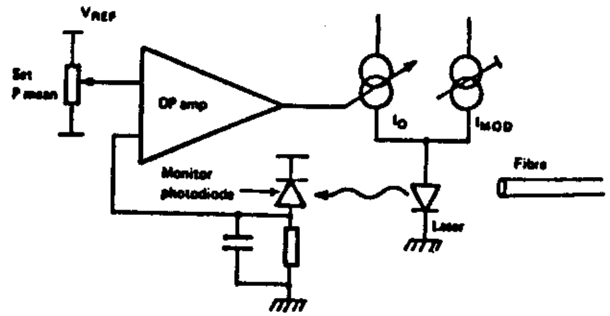


Fig.6 A LD drive circuit providing a dc and a modulation current to the LD and a feedback for stabilization of the mean optical power.

This circuit provides a feedback control of the mean power of the laser which can be adjusted to remain at a predetermined constant level. This is achieved ba detecting the light from the rear facet of the LD - the light from the front facet being coupled to the fibre - with a monitor photodiode and using the photovoltage in a feedback loop to set the bias. This feedback circuit is made to have a slow frequency response and so the mean power determined by the dc and the ac signal current is stabilized.

A major disadvantage of the above circuit is that when the modulating signal is removed, the feedback produces a current surge to compensate for the decreased mean power, which can be detrimental to the lifetime of the LD. This disadvantage is eliminated in the circuit of Fig.7.

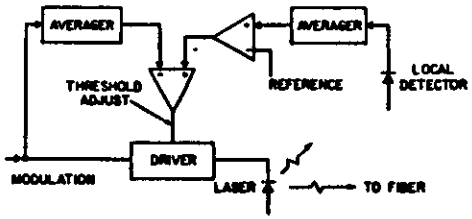


Fig.7 Laser drive circuit that monitors the modulating signal to provide a reference for the feedback loop.

In this circuit the modulation signal level is also monitored and is used in a second feedback loop. If the modulating signal is removed, the average value of it goes to zero and the dc current is automatically adjusted through the first feedback loop to reduce the output power. This circuit needs more complicated balancing and offset adjustments but provides an efficient drive method for digital transmitters.

An important tendency in the development of transmitters consists in the integration of the LD, the driver electronics and perhaps also optical waveguides on the same substrate. Great efforts are being undertaken in InP and GaAs integration but the technology is not yet ready for large scale applications. It is expected, however, that such optoelectronic IC's will find wide application in local area networks, subscriber and intraoffice systems.

4. DETECTORS AND RECEIVERS

Semiconductor photodiodes made of Silicon for the .8 µm range and of Indiumgalliumarsenidephosphide (InGaAsP) or Germanium for the 1.3 or 1.55 µm range are the preferred detectors for optical communications. The photodiodes are of the pin type (PD's) or the avalanche type (APD's), the difference being the internal amplification of the APD which allows the fabrication of more sensitive receivers.

The pin PD and the APD

The structure of a pin PD along with the electric field in the diode is shown in Fig.8. A low-conducting intrinsic zone (i) is placed between two conducting p- and n-zones. Most of the photons impinging onto the PD are absorbed in the i-zone where they create electron-hole pairs. The PD is biased in the reverse direction and so a strong electric field exists in the i-zone that separates the electrons from the holes. Consequently a photovoltage appears accross the terminals and a photocurrent will flow in an external circuit.

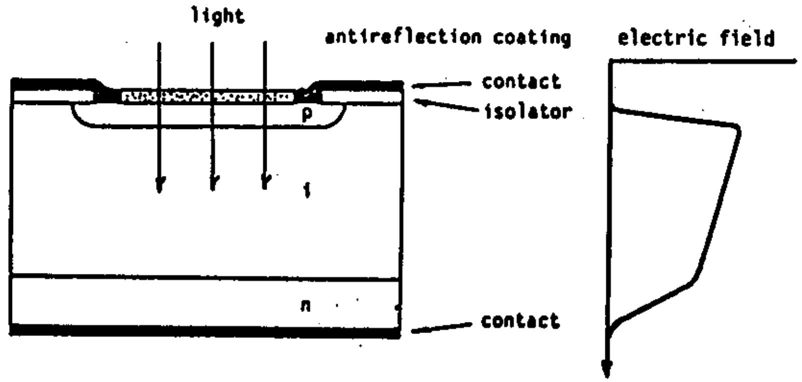


Fig.8 Pin photodiode structure and electric field

Three parameters are important for communication purposes: the efficiency of conversion optical power to electrical current, the speed of response and the noise. The photocurrent produced in a PD is proportional to the power absorbed. Pin detectors have an excellent linearity over many orders of magnitude but APD's are somewhat less linear because of the internal multiplication process The proportionality factor between power and current is a measure of the efficiency and is called Responsivity [A/W]. It is a function of wavelength as is shown in Fig.9

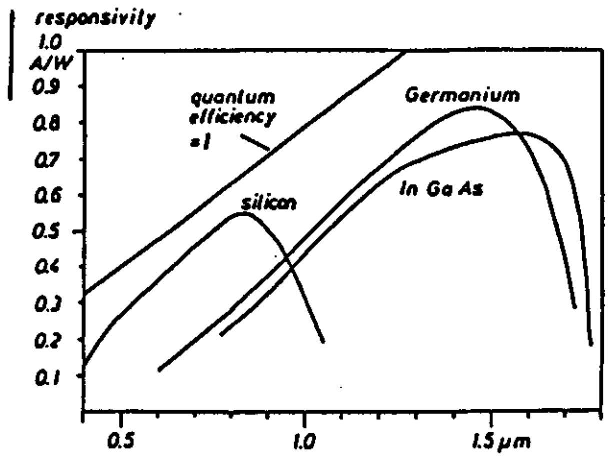


Fig.9 Responsivity of various PD's and its wavelength dependence.

The speed of response or equivalently the frequency of response is governed mainly by three different factors: a) diode capacitance, b) carrier diffusion time and c) carrier drift time through the depletion region which extends over the whole i-zone. Also parasitic elements, inductance and capacitance of the mount and the bonding wires, may contribute to the speed of response, particularly at high frequencies. The speed of response is measured by the rise and fall times of the current waveform produced in response to a very fast optical signal when the device is in series with a 50 Ohm load. Respose speeds below 100 ps can be obtained with properly designed InGaAsP, Ge and Si PD's. For a given PD the speed of response is maximized by biasing the device at the largest possible negative voltage.

The dominant source of noise in a PD is shot noise which results from the discreet nature of the carriers. The quantity used to describe the noise is the mean square noise current spectral density:

$$\overline{i_n^2} = 2eI \qquad \text{in } A^2/Hz.$$

The current I is the sum of the signal related photocurrent and of the dark current that flows in the device even in the absence of illumination. Thus the smallest detectable optical power in a frequency bandwidth B will be determined by the dark current as follows:

$$P_{min} = \sqrt{\overline{i_n^2}\, B}/R \qquad \text{at } I_{signal} = 0, \text{ and}$$

$$P_{min} = \sqrt{2eI_{dark}\, B}/R \qquad \text{in nW},$$

where R is the responsivity.

The noise equivalent power (NEP), a parameter that is given in PD datasheets, is defined as the fictitious optical power per square root of Hz causing the dark current:

$$NEP = \sqrt{2eI_{dark}}/R \qquad \text{in } W/\sqrt{Hz}$$

The equivalent circuit of the PD is shown in Fig.10. In operation

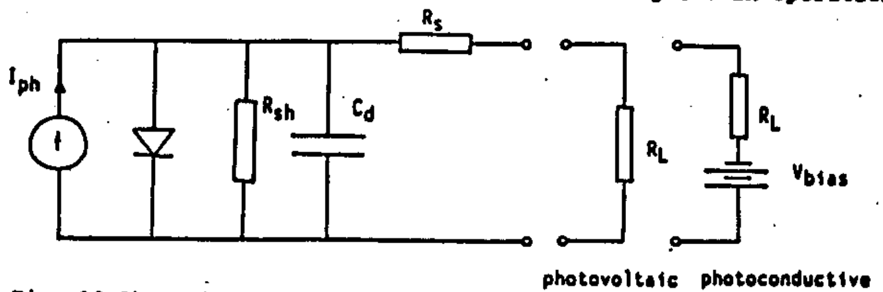
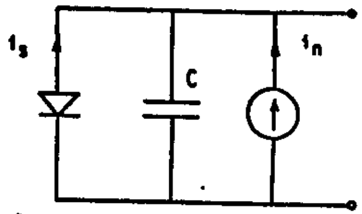


Fig. 10 Photodiode equivalent circuit.

we may represent the diode as a current generator with an ideal diode in parallel representing the effect of the pn-junction. R_s

is the series resistance, R_{sh} the shunt resistance and C_d the diode capacitance. Usually, $R_s << R_{sh}$ and $R_s << R_L$ and so we can simplify the circuit as given in Fig.11.



signal current $i_s = R.P_{optical}$

noise current $i_n = 2e(R.P_{opt} + I_{dark})$

Fig.11 Simplified noise equivalent circuit.

The circuit incorporates now a current noise source which produces a noise depending on signal power and on the dark current. In practical applications, however, the noise current may be significantly above the predicted level. The additional noise is generated by the impinging laser light. One of the reasons may be optical reflections from the fibre, connectors and splices. Another reason is the competition process between the laser modes to share the laser power.

In APD's the electric field in the semiconductor is so strong that the kinetic energy of the carriers becomes sufficient to produce ionization. An internal carrier multiplication process results which increases the sensitivity of the detector. Silicon is the preferred material at the .8 to .9 µm range but it becomes unfortunately transparent in the infrared. Ge APD's and InGaAs/InP APD's are used for wavelengths over 1 µm. Two such diodes are shown in Fig.12.

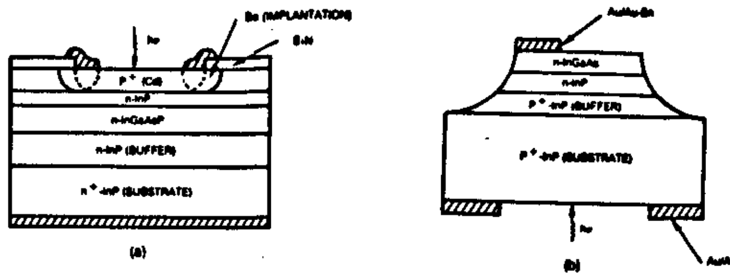


Fig.12 InGaAs/InP APD's. a) planar type and b) mesa type

These diodes are somehow different from the usual types in that they employ a separate region for absorption (InGaAs) and for amplification (InP). This structure has been shown to decrease the overall noise level of the device.

A diagram of a typical receiver circuit incorporating a PD or APD is given in Fig.13. The series resistance R_s is usually some Ohms. The amplifier input impedance is represented by the parallel combination of input resistance R_A and input capacitance C_A. The signal voltage accross R_L appears at the input of the amplifier and is multiplied by the gain to reach acceptable levels for further signal processing.

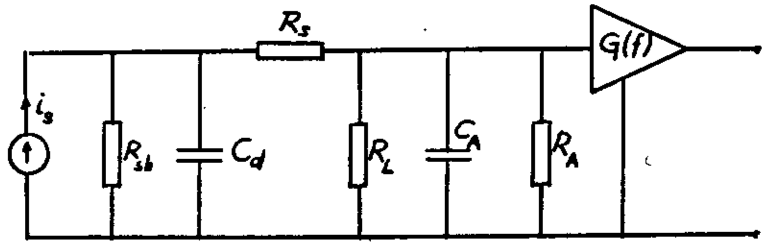


Fig.13 A simple receiver circuit and equivalent circuit.

An important factor that characterizes a receiver, is the signal-to-noise ratio SNR. It generally increases with increasing optical signal power. The higher the SNR, the better the transmission quality and the lower the probability of errors. The relationship between the Bit Error Rate (BER) and the SNR can be calculated under certain assumptions. In the practical situation a BER of 10^{-9} is acceptable but better BER values are required for special transmission cases.

5. SOME FIBRE BASICS

The fibres used widely today are the step-index and the graded-index type. Both are made of a cylindrical glass core of refractive index n_1 - approximately 1.5 - surrounded by a cladding also made of glass but with a slightly lower index n_2. A plastic coating (jacket) is used for mechanical protection. Fig.14 shows the step-index multimode fibre and the index

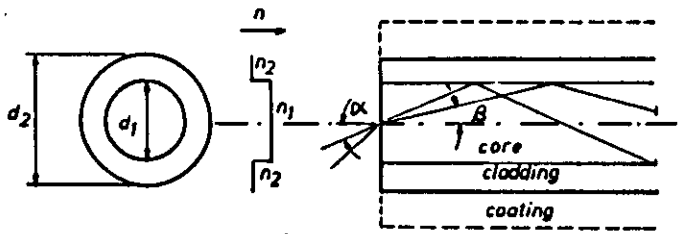


Fig.14 Step-index multimode fibre and index profile

profile. The light propagates through total internal reflection at the core/cladding boundary. Different angles give rise to different ray paths called modes. A characteristic parameter of the fibre is the numerical aperture (NA). The NA and the core diameter determine the coupling efficiency to a light source.

$$NA = n_1 (2\Delta)^{½} \quad \text{where } \Delta = (n_1 - n_2)/n_1$$

The larger the NA, the higher the optical power coupled in the fibre. Communication fibres with standardized core/cladding diameters 50/125µm have NA values around .2.

The main disadvantage of the step-index fibre is the limited bandwidth. The different modes travel different lengths and so a light pulse will broaden as it travels down the fibre. This phenomenon is called mode dispersion and it causes pulses that were separated in time at the fibre input to overlap at the output, which makes them difficult to distinguish. An answer to this problem is the graded-index fibre shown in Fig.15.

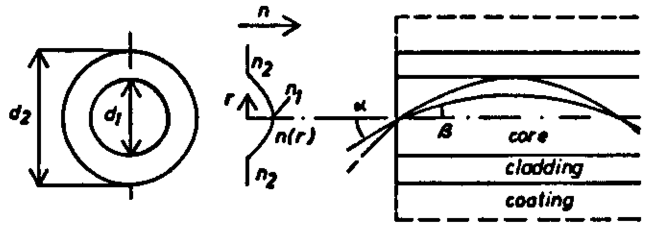


Fig.15 Graded-index multimode fibre and index profile

Due to the index profile, the longer path of the outer rays is compensated by their higher speed and so, ideally, no delay should occur between outer rays and axial rays. In the practical case, these fibres do show a significantly reduced pulse broadening but the remaining mode dispersion makes them unsuitable for bit rates in the Gbit/s region.

In a single-mode or monomode fibre only one mode (having two polarization directions) can propagate, see Fig.16.

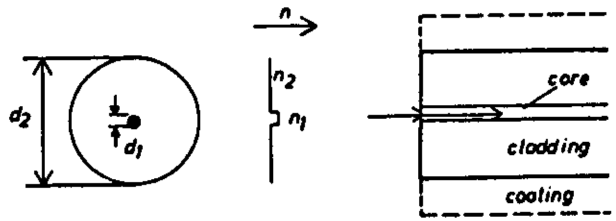


Fig.16 Single-mode (monomode) fibre and index profile.

The monomode fibre is in general fabricated as a step-index fibre with a very small core diameter of a few microns. This diameter depends on the indexes of core and cladding and on the wavelength. The cladding diameter is 125 μm as in the other cases.

The optical attenuation in a fibre

In every type of fibre, the optical power will be attenuated as the signals travel through the glass waveguide. The attenuaton is expressed in dB/km and is strongly wavelength dependent. Fig.17 gives this dependence for a range of commercial fibres.

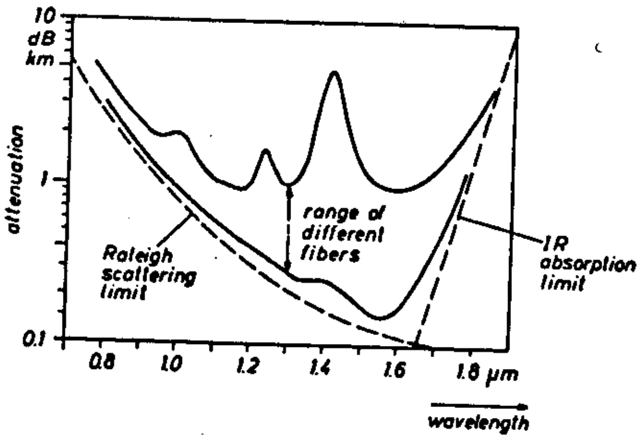


Fig.17. Optical attenuation vs. wavelength

The attenuation has a minimum of about .2 dB/km for good fibres at a wavelength of 1.55 μm where the newest generation of fibre systems operate. The physical causes of attenuation are

- Rayleigh scattering, proportional to $1/\lambda^4$,
- absorption, due to impurities in the glass, and
- bending losses in cables.

Even when one works at 1.55 μm, however, long cable lengths - over about 100 km - may still cause appreciable attenuation. For the transmission of high-speed pulses with monomode fibres, the limitation of the maximum repeaterless distance is more likely to come from dispersion that from attenuation. The reason is that although we have eliminated mode dispersion by choosing a monomode fibre, some other causes persist which broaden high-speed signal pulses.

Other causes of dispersion

The additional dispersive effects which are encountered in fibres are due to a) material dispersion and b) waveguide dispersion. These causes are effective when the source is not perfectly monochromatic as is of course the case with all real optical sources. This is why the two effects are called "chromatic dispersion", see Fig.18. Material dispersion is caused by the

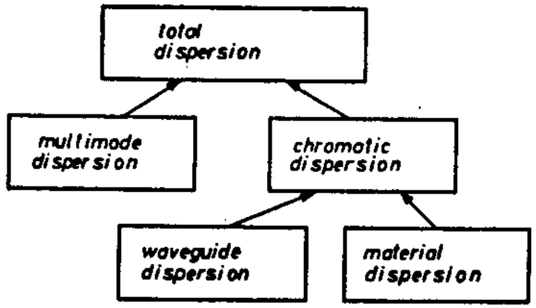


Fig.18. The various dispersion causes in a glass fibre.

wavelength dependence of the refractive index. This dispersion mechanism vanishes in silica glass at a wavelength around 1.3 μm. The consequence is that a narrow spectral source, like a dynamic single mode laser emitting at this wavelength will generate only negligible pulse spread resulting thus in larger bandwidth. The waveguide dispersion is for fibres used in communications less of a problem. In principle, it can be compensated by the material dispersion since the latter changes sign when the wavelength of zero dispersion is crossed. The real problem here is that the attenuation of the fibre is not minimum at the zero dispersion wavelength. One approach to solve it, is to shift the zero dispersion wavelength to 1.55 μm and/or to use lasers at 1.55 μm that have very small optical bandwidths even at high-speed modulation. Systems employing these techniques have demonstrated the possibility to transmit in the multi-Gbit/s region repeater-less over 100 km.

6. SYSTEM CONSIDERATIONS

The large majority of fibre communication systems use digital modulation methods for signal transmission. The most important advantage of a digital system versus an analog system is that of relative freedom from noise and distortion which enhances the quality of the link. In a digital system the laser is current modulated with bits of information and its power output jumps between two or more levels. It is usual to operate with two power levels (two level binary), "zero" and "one". By contrast in digital systems with metallic cables it is common to operate with positive and negative voltage levels in a multilevel system. This is, of course, impossible with light pulses since photons do not flow backwards!

The "one" level is represented by the presence of an optical power pulse and means that a predetermined signal amplitude has been reached. The "zero" level means the abscence of a pulse. The pulses occur between predetermined time slots. If the pulse occupies all the time slot available, then the signal is termed a "non-return to zero (NRZ) signal. If, on the contrary the pulse occupies only a fraction of the time slot the signal is called a "return to zero (RZ) signal. Fig.19 illustrates this terinology.

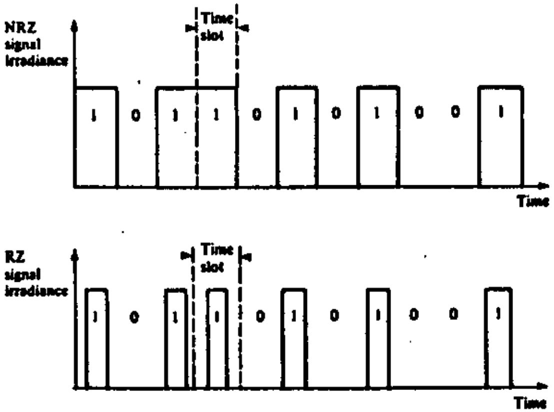


Fig.19 Illustration of a NRZ and a RZ data stream.

The pulses reaching the laser are obtained from the conversion of an analog signal into a digital one. The amplitude of the analog signal is sampled at a rate at least twice the rate of the highest frequency component in the signal. The quantization is usually performed with the help of eight bits and so the bit rate required will be 16 times the highest frequency component. For example, the highest frequency of a telephone channel is about 4 kHz. A digital system transmitting one telephone channel would thus require a rate of 16x4 kHz, i.e. 64 kbit per second.

The non-idealities of the fibre like attenuation and dispersion distort the pulses as they travel down the fibre. At the receiver we can, however, restore the original waveform provided, that we can during each time slot make the decision as to whether the time slot contains a "one" or a "zero". For this we have to define a decision level so that if the amplitude of the pulse exceeds this level at a predetermined time - the decision time - a "one" is recorded and if not a "zero" is recorded. Fig.20 illustrates such an example.
A commonly used criterion for characterizing qualitatively the proper function of a digital system is its "eye diagram".It is

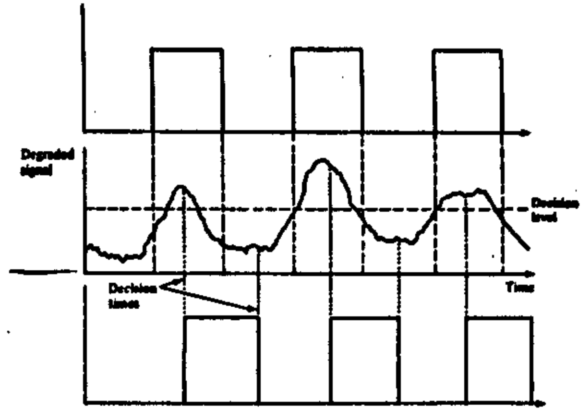


Fig. 20 Restoration of the original digital signal

obtained by applying the digital data stream to the vertical amplifier of an oscilloscope while triggering the scope with the system's clock. The quality of the eye diagram is an indication of the BER that can be achieved. If the eye has a large aperture, then a low BER can be expected and a high-quality transmission link is obtained. If the eye is "closed", a poor transmission quality is the result, Fig.21.

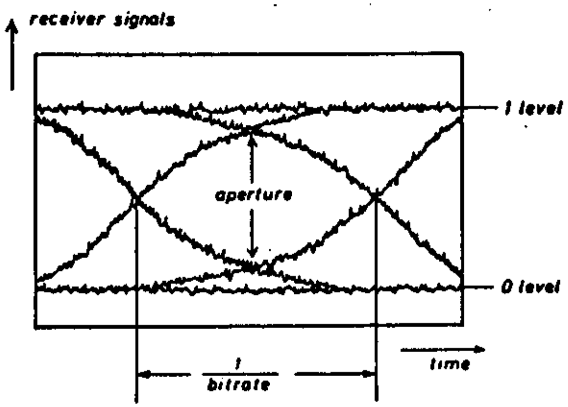


Fig.21 Eye diagram of a binary data stream.

The quality of the eye diagram is, of course, influenced by the noise of the system. There is, however, an additional phenomenon which can heavily alter the shape of the eye. It is called intersymbol interference. By this we understand the overlap of adjacent pulses which occurs due to pulse spreading after a long line of fibre. The result is that the lower level of the eye diagram shifts away from the zero level, the eye "closes" and the BER deteriorates. The intersymbol interference can be reduced by increasing the bandwidth and by using equalizers. However, these measures introduce more noise in the system and consequently a "bandwidth-noise" compromise has to be found.

In the practical situation the designer of a fibre communication system has, of course, as a first step to consider the requirements specified by the user that must be met. The following requirements are common to any system:

- # type of data and signals to be transmitted
- # bit rate or bandwidth
- # BER or SNR
- # link length

The designer is now faced with a number of choices for the components. For low bit rates (up to a few Mbit/s) and short (repeaterless) spans - up to a few km - one can choose a LED-pin PD combination with a multimode graded index fibre. Since the link length is short, components in the .0 -.9 µm region would be preferable because the represent a mature technology and they are reasonably priced. If the components cannot meet the data rate and/or distance requirements, then a laser-pin PD or APD combination may be chosen. The fibre should be chosen so as to have a total dispersion that allows the bandwidth to be accomodated. For systems that are likely to meet increasing demands in the future, it is advisable to install a good quality fibre so that the system can be upgraded at a later time by replacing only the terminal components.

At the other extreme of bit rate x distance products, a 1.3 or 1.55 µm laser, a single mode fibre and a high-speed pin or an APD should be combined. There is a broad region in the middle of these capacity requirements that can be covered by several possible component combinations. In general, however, a single mode fibre will be chosen because of the very large potential upgrading capabilities.

For every combination of components there will be a minimum average power which must reach the detector in order to achieve the required BER. Since the total link length is known, the total signal attenuation can be calculated by taking into account, besides the fibre attenuation, also the losses of fibre couplers and splices. By choosing the suitable source from the power point of view it should be kept in mind that what it is important is the power launched into the fibre. Also, it is possible that some power degradation might occur in the course of the lifespan of the device. For these reasons, a safety margin of 5 to 10 dB's might be required. We call these considerations and calculations the power budget.

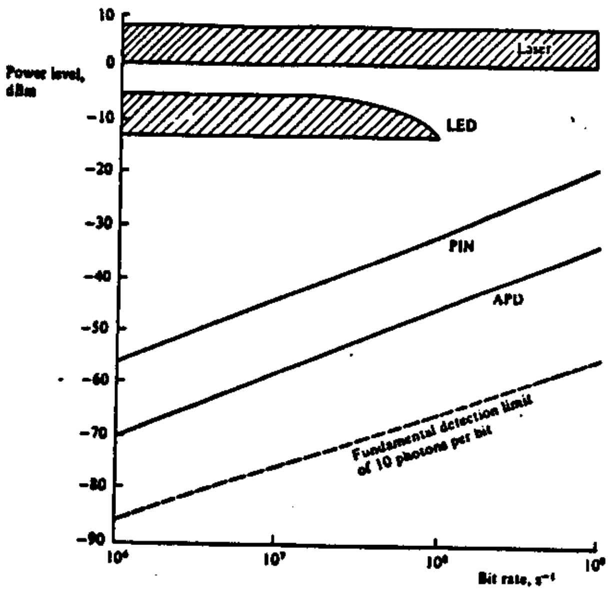


Fig.22 Illustration of the power budget for typical source-detector combinations versus data rate.

Fig.22 gives a rough estimate of the power budget with various combinations of optoelectronic components as a function of the bit rate. The upper shaded areas show typical powers that can be coupled from commercial LD's and LED's into fibres. As the technology of the devices progresses, higher power levels and higher direct modulation frequencies can be expected from commercially available devices. The lower curves show some typical receiver sensitivities. These also will undoubtably become better as the devices continue to improve.

For an engineer it is often practical to have a graphical representation of the dependence of the repeaterless span on bandwidth resp. bit rate. Taking as an example a simple low bit rate system for short distances with a .8 µm LED, a Si pin PD and a 50/125 µm multimode graded index fibre with NA=.2 we can calculate this relationsship for a given system margin as a parameter. In order to give a practical example, we assume some typical values for the components as follows:

- # average optical power coupled from the LED into the fibre -15 dBm
- # digital NRZ signals, 50% duty cycle
- # total fibre and splice losses 5 dB/km (conservative)
- # total connector losses for the whole link 6 dB

The average power required at the receiver in order to obtain a 10^{-9} BER can be calculated based on the noise analysis of the receiver circuit. A useful simplified relation is:

$$P_{av,req} = N_{ph,req} \cdot h\nu \, B/2$$

where $N_{ph,req}$ is the optical signal level, expressed as the required number of photons per pulse, in order to achieve the 10^{-9} BER. This photon number is divided by 2 because, due to the 50% duty cycle, the signal contains an equal number of "ones" and "zeros". B is the bandwidth and $h\nu$ the photon energy. The value of $N_{ph,req}$ will depend on receiver design and optimization. Let us assume a conservative value of 20000 photons per pulse for BER 10^{-9} and so the relation above becomes:

$$P_{av,req} \approx 2.5 \; 10^{-15} \; B$$

Knowing the power coupled into the fibre and also the value of $P_{av,req}$ for a given value of B, we can easily calculate the total fibre loss allowed which contains the fibre attenuation, splices and connector losses and the margin. Taking the assumptions above, we can find the repeaterless link length in km versus B. We further assume two margin values, an optimistic (3 dB) and a pessimistic one (10 dB). The curves we obtain are shown in Fig.23. We see that the repeaterless span is loss-limited up to high bandwidths and that the span decreases by 0.6 km each time the bandwidth is doubled. This is because when B is doubled, the value of $P_{av,req}$ increases by 3 dB and so the link length decreases by 0.6 km since the total loss of the fibre is 5 dB/km. The calculation assumes, of course, that the LED can indeed be modulated at high frequencies. LED's with modulation frequencies above about 100 MHz are, however, rare and so the curves are shown dotted at those high frequencies.

At those frequencies, the maximum transmission distance can be limited by pulse spreading causing intersymbol interference. The exact analysis of the influence of the intersymbol interference on receiver sensitivity is quite complicated. From this theory an approximate general rule emerges: If the full width to half-maximum of the pulse spreading t caused by the fibre remains below 50% of the spacing between pulses, then the sensitivity decrease of the receiver remains below 1 dB. Thus we can write:

$$\Delta t \; L \leq 1/2B, \qquad L \text{ being the fibre length.}$$

Suppose now that the fibre we want to implement causes a dispersion of 5 ns/km. We can draw on Fig.23 the curve which gives the limitation due to pulse spreading. We see that this curve has no consequence for low frequencies since the limitation is given by the loss. The dispersion limitation would be of consequence if the LED could have been modulated at very high frequencies and/or if a fibre cable with much less total loss could have been chosen

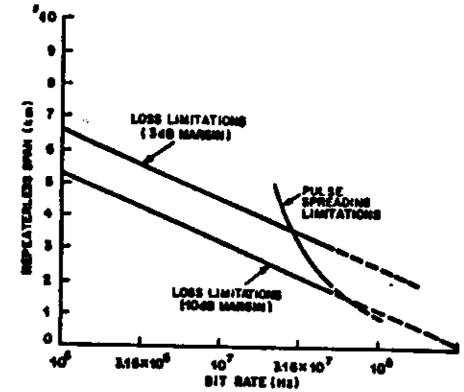


Fig.23 Repeaterless span versus bandwidth for a .8 μm LED/Si pin PD/multimode fibre system.

Let us now consider a long-wavelength system for high bandwidths. We will choose a monomode fibre to eliminate modal noise and a laser around 1.3 μm in order to minimize dispersion effects. Further we make the following assumptions:

- average optical power coupled into fibre -6 dBm
- total fibre and splice losses 0.5 dB/km
- total connector losses 6 dB
- margin 3 dB or 10 dB

As a receiver, we consider a high-speed pin photodiode and we assume that the receiver needs 20000 photons per pulse to achieve a BER of 10^{-9}. The required average power now becomes:

$$P_{av,req} \approx 1.5 \; 10^{-15} \; B$$

which is slightly less than in the previous example because of the reduced energy of the photons at longer wavelengths. proceeding similarly as before we can calculate the curves shown in Fig.24.

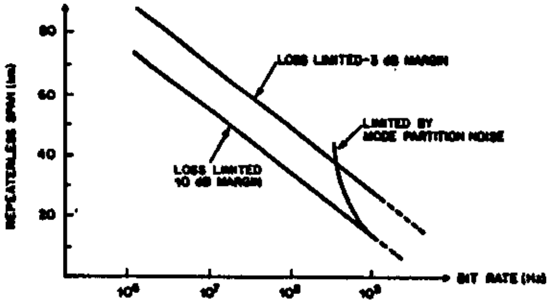


Fig.24 Repeaterless span versus frequency for a combination of 1.3 μm laser/monomode fibre/pin photodiode

Since we have a monomode fibre we expect pulse spreading to be caused by material dispersion because mode dispersion can be neglected. The laser we have in the transmitter will very probably be multimode under operation, even if the cw radiation shows single mode behaviour. Let us assume that the modes are spaced in a spectral band 4 nm wide around the wavelength where the fibre is specified by the manufacturer to have a total dispersion of 3.5 ps/km-nm, where nm implies here the spectral width of the source. The spread of the pulses per km will be 14 ps. We may accept a maximum spread of 1/5 the spacing between pulses. This is, of course, a more severe requirement than before but we have to be more careful because we want the system to operate at very high frequencies.

The physical origin of the pulse spread is the random distribution of laser power among several axial modes under modulation. The modes then travel at different velocities due to the fibre dispersion and as a consequence the received pulse at the end of the fibre will change its position and shape in an unpredictable manner. This combination of modal power distribution and material dispersion is called <u>mode partition noise</u> and causes the link length limitation at high frequencies. In our example the relation between L and B will be simply:

$$14 \; 10^{-12} \; L \leq 1/5B$$

The limitation by mode partition noise becomes effective at very high frequencies of the order of 500 MHz. At lower frequencies the losses of connectors and splices and the assumed value of margin are increasingly important as the fibre attenuation reaches low levels.

Mode partition noise is reduced when <u>dynamic single mode lasers</u> are used. The limitation encountered with these lasers is due to wavelength <u>chirp</u> under high-frequency modulation. Even under this limitation, however, such lasers allow the operation of systems in the multi Gbit/s range at repeaterless distances exceeding 100 km.

7. CONCLUSION

The advent of fibre transmission systems has opened a new era in communication technology. In the past few years, a tremendous expansion of the fibre telecommunications has taken place. Optical cables offer extremely low losses at large modulation bandwidths. As a consequence, systems with very large information carrying capacity (bit rates in the Gbit/s range) and with long repeater spans (over one hundred kilometers) have been developed. This is why optical fibres are the preferred choise for point-to-point long distance links with heavy traffic. Also, thanks to their immunity from electromagnetic radiation, fibres are installed in places where noise and sparks make communication links with metallic wires an unreliable solution.

Recent achievements on the research front seem to indicate that the short fibre link will find large scale applications in the local distribution network. These achievements pertain to the development of densely packaged integrated optoelectronic circuits for high-performance optical transmitters and receivers and to novel techniques for switching and routing optical signals. As the technology advances, an increasing penetration of fibre links into the local area network is expected soon, provided that some important questions pertaining to the cost of lightwave systems and to the right component combinations to be implemented can be satisfactorly answered.

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For further reading:

[1] J.Wilson and J.F.B. Hawkes, Optoelectronics: An Introduction, Prentice-Hall International Series in Optoelectronics, 1983.

[2] John Gowar, Optical Communication Systems, Prentice-Hall Intern. Series in Optoelectronics, 1984.

[3] Y. Suematsu and K.I. Iga, Introduction to Optical Fiber Communications, John Wiley, 1982.

[4] S.D. Personick, Fiber Optics, Plenum Press, 1985.

[5] G.P. Agrawal and N.K. Dutta, Long Wavelength Semiconductor Lasers, Van Nostrand, 1986.

[6] P.K. Cheo, Fiber Optics: Devices and Systems, Prentice-Hall, 1986.