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UNITED NATIONS INDUSTRIAL DEVELOPMENT ORGANIZATION
INTERNATIONAL CENTRE FOR SCIENCE AND HIGH TECHNOLOGY

H4.SMR/540-21

Second Training College on Physics and Technology of Lasers and Optical Fibres

21 January - 15 February 1991

Fibre Communication Systems

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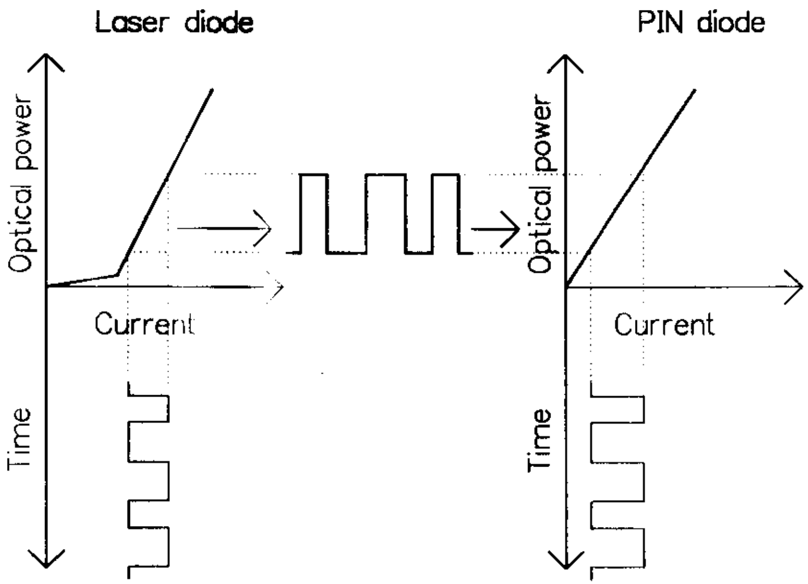
Course A2. Lesson 1.8

Optical systems I

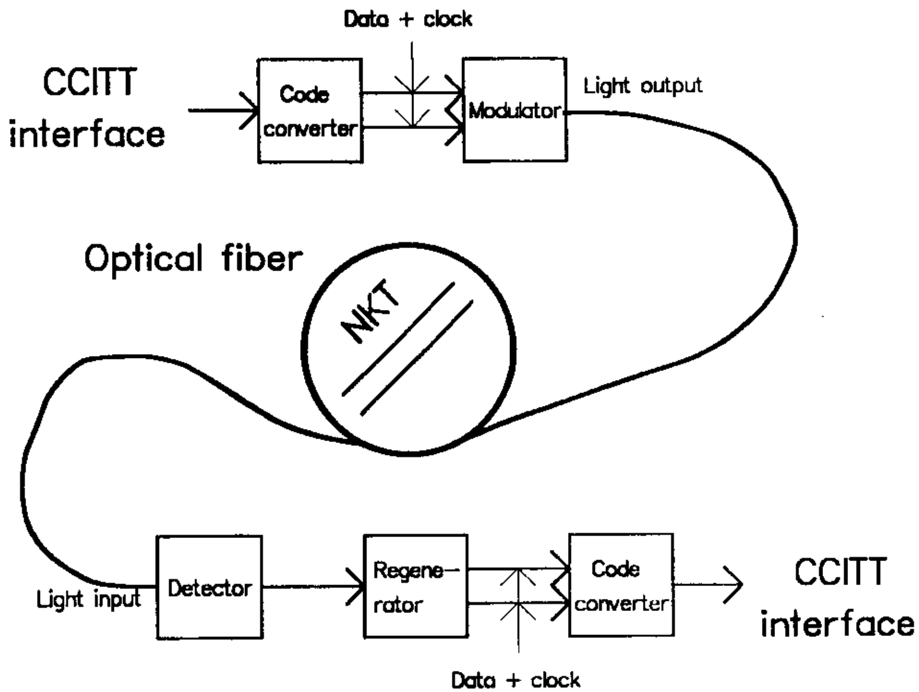
Lesson outline:

- Transmitter principles
- Receiver principles
- BER measurements
- Optical parameters
- Power budget

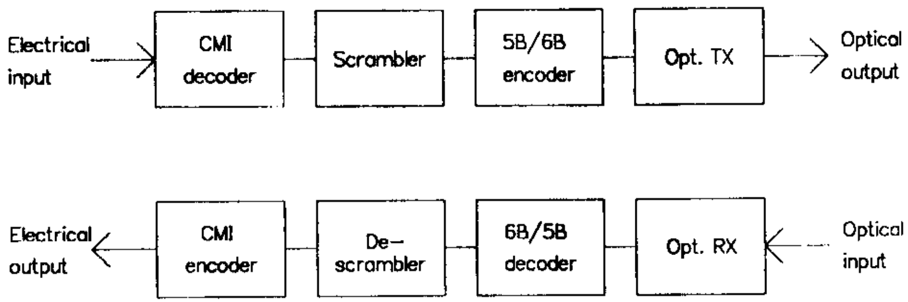
Intensity modulation and direct detection



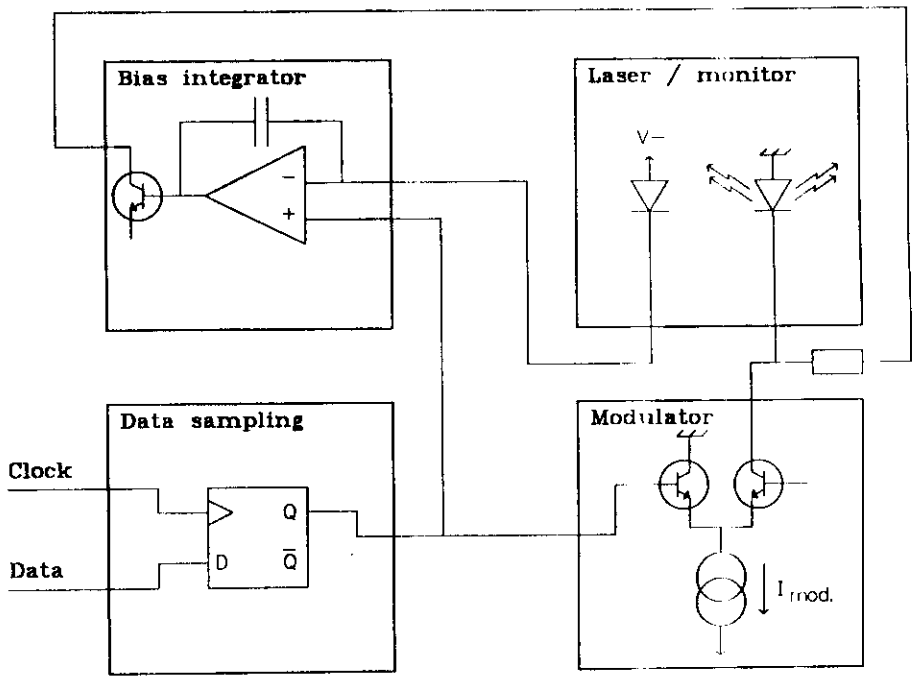
Basic optical system



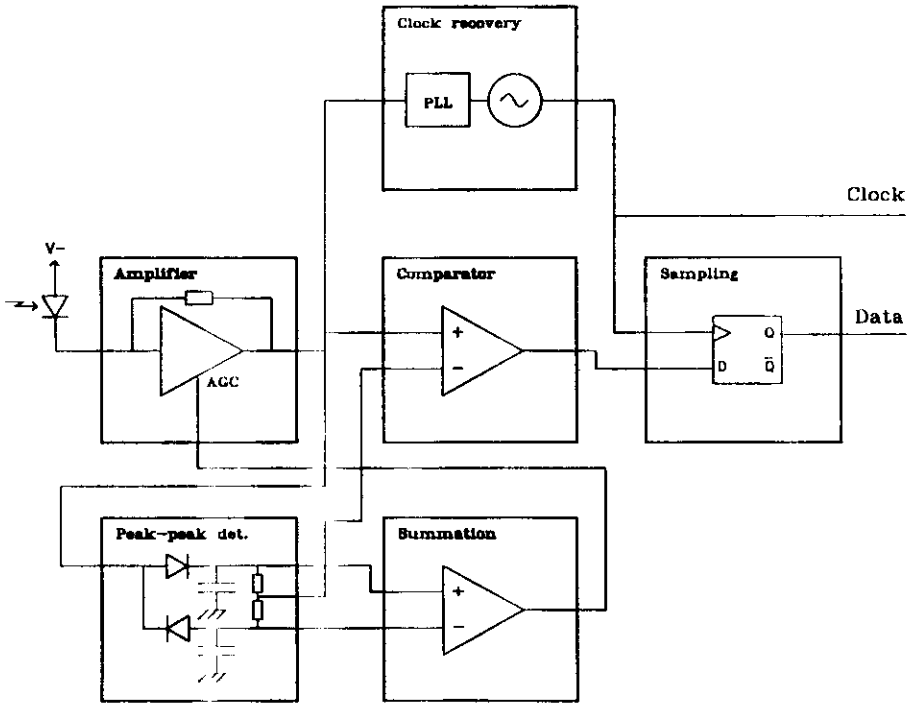
NKT 140 D – S



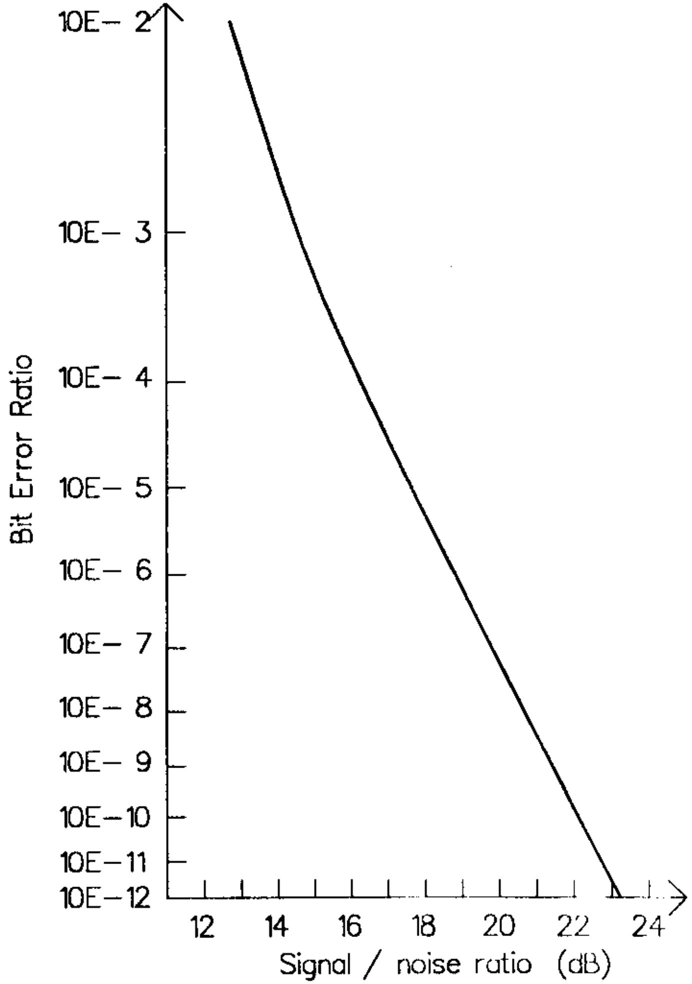
Optical transmitter with laser



Optical receiver with PIN



BER versus S/N ratio



Eyediagram transmitter

Bessing photo

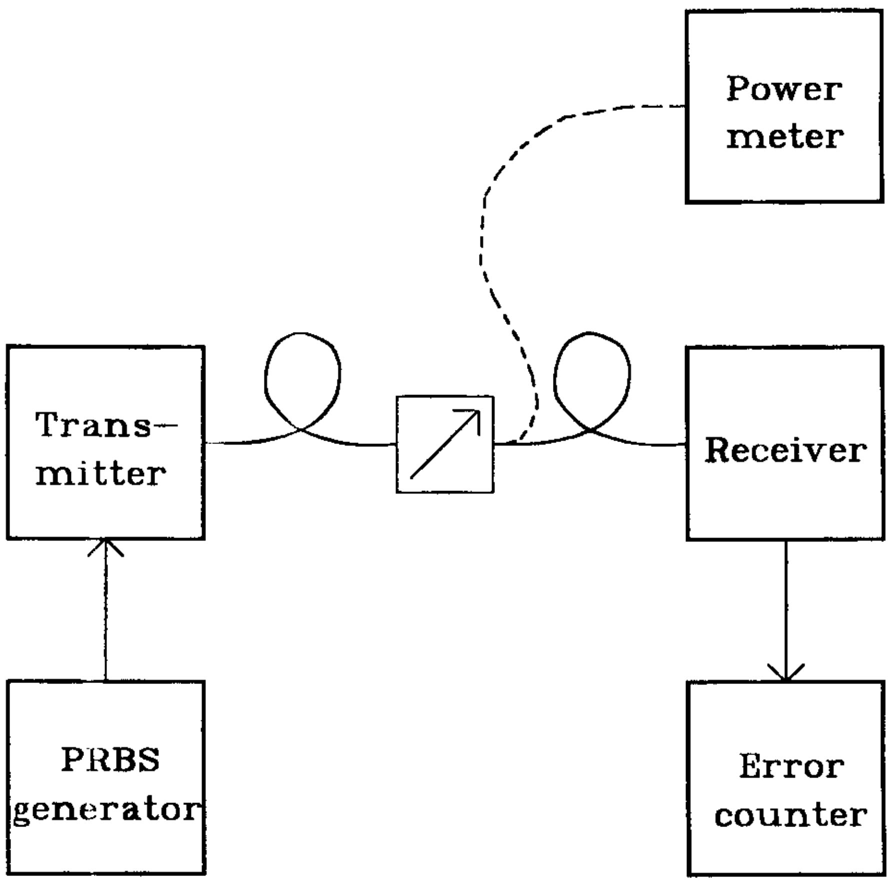
no. 041188-1

Eyediagram receiver

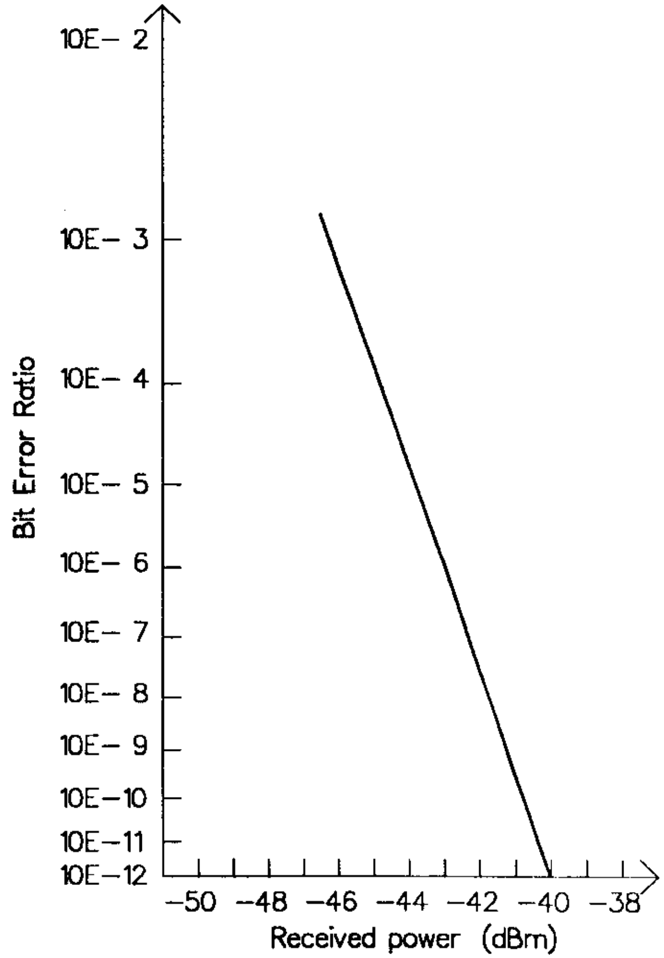
Bessing photo

no. 041188-2

BER measurement



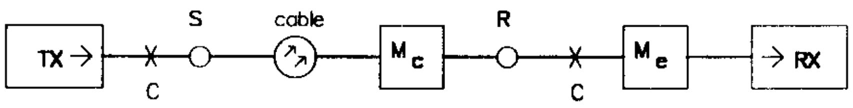
Typical BER curve



Subject Optical systems - I **Lesson** 1.8

Power budget 1550 nm 565E–S:

CCITT G.956



example 100 km:

Equipment

Output power	(typ.)	– 3 dBm
Receiver sensitivity	(typ.)	–36 dBm
Disp. penalty (max.2nsec/nm)		1 dB
Equipment margin		4 dB
SR–ratio (available for cable)		28 dB

Cable

Loss (100km x 0.23 dB/km)	23 .0 dB
Splice loss (25 x 0.10 dB)	2.5 dB
Cable margin	2.5 dB
Total cable loss	28.0 dB

Subject Optical systems - I **Lesson** 1.8

Optical power specifications for 565E–S 1550 nM

Transmitter:

Output power (adjusted)	–2,6 dBm	+/–0,20 dB
Connector loss	–0,7 dB	+0,3/–0,5dB
Output power (point S) at installation	–3,3 dBm	+0,5/–0,7dB
Change with temperature		+/–0,50 dB
Output power (point S) over temp.	–3,3 dBm	+1,0/–1,2 dB
Ageing (laser slope)		+0,3/–0,5dB
Output power (point S) end of life	**–3,3 dBm**	**+1,3/–1,7 dB**

Receiver:

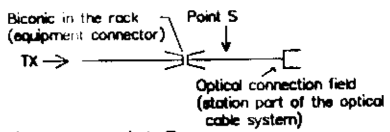
Sensitivity (point R) at installation	> –36,0 dBm	–0,5 dB
Change with temperature		+/–1,0 dB
Sensitivity (point R) over temp.	> –34,5 dBm	
Ageing		+/–0,5 dB
Sensitivity (point R) end of life	**> –34 dBm**	

Dispersion penalty for max. 2 ns/nm dispersion = 1 dB

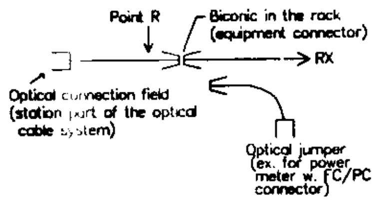
Subject Optical systems – I **Lesson** 1.8

Optical measurements

Correct point S power:



Correct point R power:



NKT TX adjustment	– 2.6 dBm
Connector loss	0.7 dB
Typically point S	– 3.3 dBm
Tolerance	+– 1.0 dB

– 4.3 dBm < S <– 2.3 dBm

NKT RX adjustment	< – 35.0 dBm
Tolerance	1.0 dB
Minimum point R	< – 34 dBm

If measured with Biconic – FC/PC jumper
Loss in Biconic connector Typ. 0.7 dB
max 1.2 dB

Point R + jumper < – 35 dBm

Subject Optical systems – I **Lesson** 1.8

Power Budget: XXXXXXXXXX – XXXX sea submarine cable system

System desciption: 220 km submarine unrepeatered cable system for 6 x 140 Mbit/s transmission.

System type: 140 Mbit/s, 1.5 um DFB Direct Detection system with INGaAs APD–Receiver. (NKT LTU–code: CU1586–2)

Fiber type: Loss–minimised fiber (CCITT rec. G.654)

Equipment:

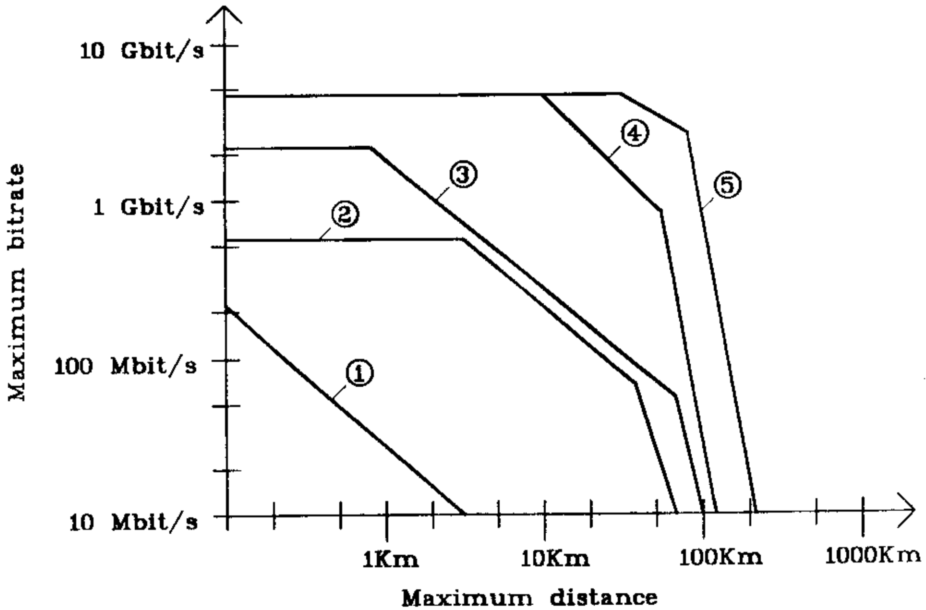
Transmitter output (typ) Receiver sensitivity at BER=10E–10 (typ)	+5 dBm –45 dBm	
System gain (typ) Dispersion penalty Equipment margin aging margin other margin (temperature etc.)	50 dB 1 dB 3 dB	 (1 dB) (2 dB)
Maximum permissible S–R attenuation at BER=10E–10 at end–of–life	46 dB	

Cable:

Cable loss at installation: (220 km x 0.19 dB/km) Terminal splices: (4/fiber x 0.05 dB) Cable termination units (FC/PC): (2/fiber x 0.5 dB)	 41.8 dB 0.2 dB 1.0 dB	
Total section loss at installation (measured between the S–R points) Cable margin Hydrogen aging: (0.0025 dB/km/25 years) Repair splices: (20 x 0.1 dB) Additional cable loss at repair: (10 repairs x 200 m x 0.19 dB/km)	 43.0 dB 3.0 dB	 (0.6 dB) (2.0 dB) (0.4 dB)
Total calculated cable loss at end–of–life:	46.0 dB	

Maximum receiver input: – 26 dBm

Transmission capacity of optical systems



1: 850nm LED / MM fiber
2: 1300nm LED / SM fiber
3: 1300nm LD /MM fiber
4: 1300nm LD / SM fiber
5: 1550nm DFB-LD / SM fiber

THO 1: "Optical Telecommunication Systems",
Peter Viereck,
NKT Elektronik,
January 1, 1987,
pp.1 to pp. 26.

NKT ELEKTRONIK

OPTICAL TELECOMMUNICATION SYSTEMS

by

Peter Viereck

NKT Elektronik
January 1, 1987

NKT ELEKTRONIK

1. Introduction

Optical fibre transmission for the time being is mainly used in the telecommunication network. Optical fibres are used in trunk-line interconnections for high speed digital communication over long distances.

During recent years optical fibres have completely taken over the rate of coaxial cables, which previously had been used in trunk networks. This is mainly due to the superior transmission qualities of the optical fibre, which are:

* Low attenuation (=> larger distance between regenerators)
* Large bandwidth (=> higher transmission capacity)

The larger distance between regenerators increases the reliability (MTBF) and therefore also the availability of the system.

Calculations show also that transmission in optical fibres is the most economical solution when we speak of transmission of digital signals with bit rates of 8 Mbit/s or more in the trunk network. The lowest bit rate at which optical transmission is economical is decreasing during these years as a result of explosive progress within this field.

Optical fibres have a number of advantages which are important in the establishing and running of large cable installations. The optical fibres are dielectrical which means that they are unable to conduct a current. This fact allows for the construction of completely metal-free cables, which can be used in locations where it is known that lightning in conventional cables is a problem.

In situations where special EMP-protection (Electromagnetic Pulse from nuclear explosions) is demanded, metal-free optical cables are ideal.

Furthermore, optical fibres have a very little cross-sectional area which makes it possible to manufacture much lighter cables compared to those previously used.

2. Signal sources in telecommunication systems

First it should be mentioned that this text deals with transmission of digital signals only.

In the telecommunication network, signals from several sources are transmitted. Telephone traffic still makes up by far the largest part, but new services such as data networks, alarm networks and transmission of TV and radio are expected to increase their part considerably during the next years.

A telephone channel has a bandwidth from 300 Hz to 3400 Hz. According to European standards this signal is sampled every 125 us and is digitized with 8 bit resolution. This results in a digital signal with a data rate of 64 Kbit/s.

When transmitting over longer distances, a number of telephone channels which are going in the same direction are multiplexed. In Tables 1 and 2 the multiplex hierarchies are shown according European and North American standards respectively. Both systems are recommended by CCITT (Comité Consulative Internationale Telegraphique et Telephonique).

In recent years the European and the North American systems have begun to approach each other, mainly because systems with bit rates of 139.264 Mbit/s and 564.992 Mbit/s have been installed in the U.S., corresponding to the 4th and 5th order in the European system. In the U.S. these signals are made by multiplexing three and twelve channels respectively, each at 44.7 Mbit/s. This corresponds to the T-3 level in the North American system.

PCM order	Data rate Mbit/s	No. Teleph. channels
1.	2.048	30
2.	8.448	120
3.	34.368	480
4.	139.264	1920
5.	4 x 139.264	7680

Table 1. Multiplex hierarchy, European standard.

System	Data rate Mbit/s	No. Teleph. channels
T - 1	1.554	24
T - 2	6.3	96
T - 3	44.7	672
T - 4	274.0	4032

Table 2. Multiplex hierarchy, North American standard.

3. Optical Telecommunication systems

The optical transmission systems to be used in the telecommunication network are in several areas different form other optical transmission systems. Here are some examples:

* Extremely high reliability required,
  MTBF (Mean Time Between Failure) 10-20 years per unit.

* Demand for maximum range, especially in
  undersea systems.

* Demand for constant supervision and possibility
  of prompt failure location.

The very strict demand for reliability was an important problem in the first laser based systems. The MTTF (Mean Time to Failure) of the lasers was only 1,000 hours which made these components unfit for telecommunication systems. However, the lifetime of the lasers has improved greatly and now most manufacturers state a MTTF of approximately 1,000,000 hours (approx. 100 years) at an ambient temperature of 50^{o}C. This means that the laser is no longer the dominant factor for the MTBF of the systems, although it is still the component with the highest failure rate.

The maximum range of a fibre optical transmission system which transmits over quartz glass fibres is reached by transmitting at a wavelength of about 1.55 um. At this wavelength the fibre has the lowest attenuation, about 0.2 to 0.4 dB/km. Nevertheless a wavelength of approx. 850 nm was used in the first optical telecommunication systems and here the loss in the fibre is very much larger, namely 2.5 to 3.5 dB/km. This is due to the fact that reliable semi-conductor lasers only were available at 850 nm at that time.

Semi-conductor lasers with a longer wavelength, namely 1300 nm, were

not commercially available until a few years later. At this wavelength the fibre has a fairly low attenuation of 0.5 to 1.0 dB/km and the bandwidth of the fibre has reached its maximum. Long distance transmission systems which are being installed in the next few years will mainly operate at 1300 nm on single mode fibres. Typical values for attenuation as a function of wavelength for high-quality fibres for use in the telecommunication network are shown in Figures 1 and 2.

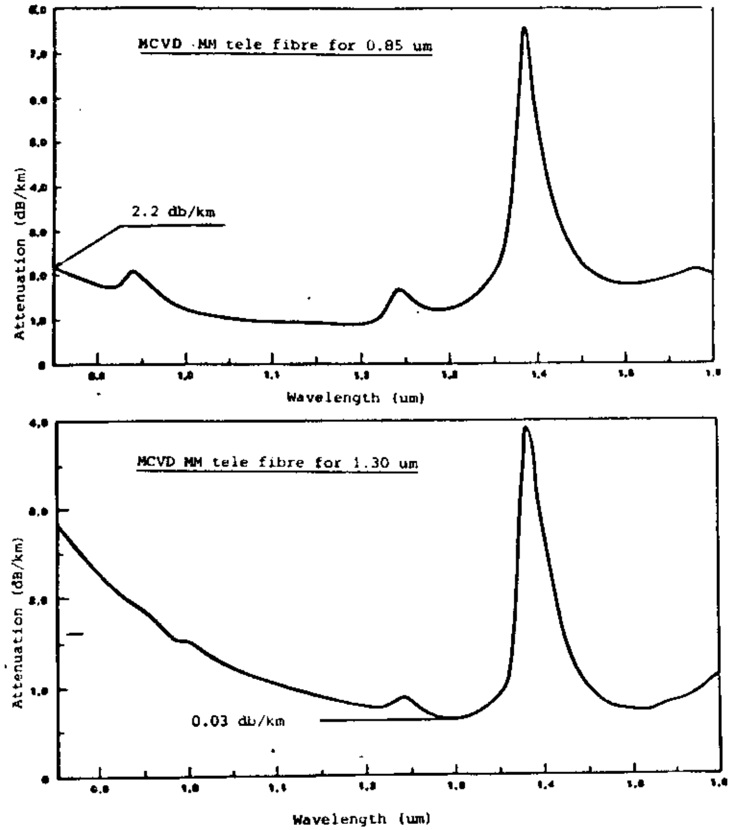


Fig. 1. Attenuation as a function of wavelength for NKT multimode fibres.

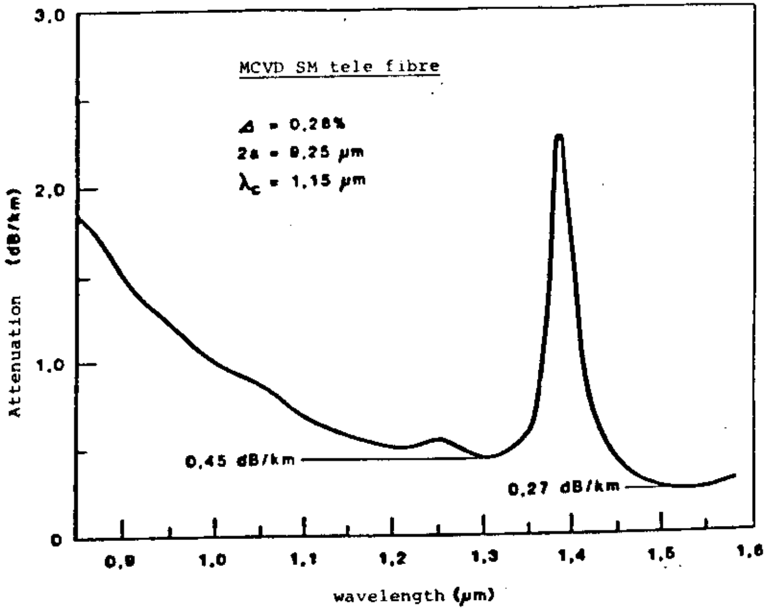


Fig. 2. Attenuation as a function of wavelength for NKT single mode fibres.

Optical communication systems operating at a wavelength of 1.55 um for use in normal telecommunication are now being developed. Special lasers are needed for these systems since even a single mode fibre has a limited bandwidth at 1.55 um due to the fibres' chromatic dispersion. This makes it necessary to reduce the spectral width for 1.55 um lasers, if they are to be used in high-speed systems with maximum distance between generators.

This principle is illustrated in Figures 3 and 4. If the laser in Figure 4 b) is used in a system with a distance between regenerators of 30 km, the total dispersion will be approx. 5 nm x 30 km x 15 ps/km/nm = 2250 ps. This means that with a bit rate of 565 Mbit/s, there will be a rather significant inter-symbol interference.

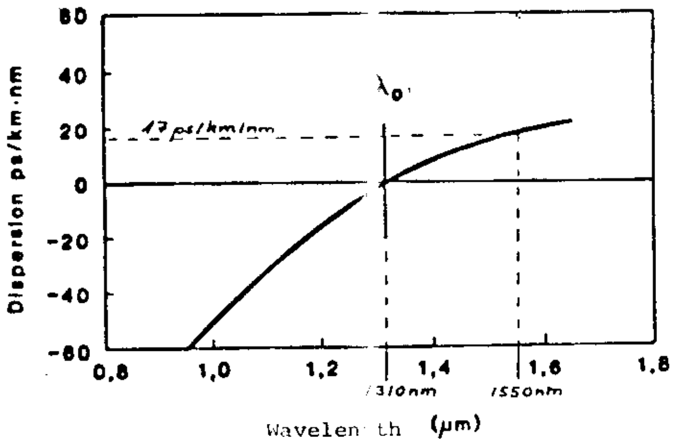
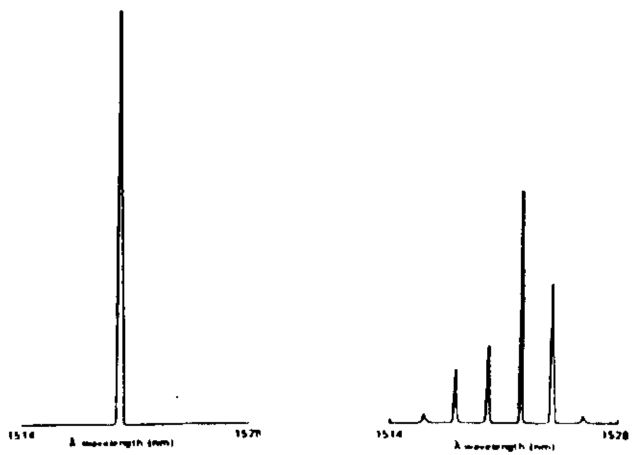


Fig. 3. Dispersion for single mode fibres as a function of wavelength. λ_o is the 0-dispersion wavelength.



a) Distributed Feedback (DFB) laser

b) Fabry-Perot (FP) laser

Fig. 4. Spectrum for modulated 1.55 um laser with and without reduction of spectral width. The Fabry- Perot (FP) laser oscillates in several longitudinal modes whereas the distributed feedback (DFB) laser has almost the entire power concentrated in a single mode.

The laser spectral width can be reduced by several techniques, some of which are as follows:

1) Stabilization with an external cavity.

2) Stabilization with using a grating on the laser crystal.

3) Stabilization with the help of a signal coupled from an unmodulated laser with a narrow spectrum.

4) External modulation of a laser having a narrow spectrum and operating continuously. The external modulator can be made of an electro-optic material, eg. $LiNbO_3$

The most promising method for the time being is 2), where a grating is placed on the laser crystal itself. If the grating is placed below or above the laser's active area, the laser is called a Distributed Feedback (DFB) laser, but if the grating is instead outside of the cavity, the laser is referred to as a Distributed Bragg Reflector (DBR).

4. Optical transmission systems

An optical telecommunication system is composed of two primary components: line terminals and regenerators as depicted in Figure 5.

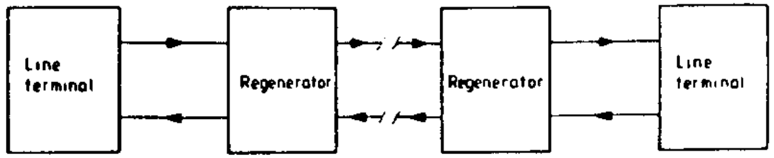


Fig. 5. Simple telecommunication system.

Some examples of typical maximum distance between regenerators are shown in Table 3.

MAXIMUM REGENERATOR SPACING					
PCM Order	Data Rate Mbit/s	850 nm multi mode Fabry-Perot laser	1300 nm multi mode Fabry-Perot laser	1300 km single mode Fabry-Perot laser	1550 nm single mode Distributed Feedback laser
3.	34	20 km	30 km	60 km	150 km
4.	140	12 km	20 km	50 km	120 km
5.	565			40 km	90 km

Table 3. Typical values for maximum regenerator distance for various fibre types as a function of the data rate. The values apply for normal terrestrial systems.

Block diagrams for a line terminal and a regenerator are shown in Figures 6 and 7.

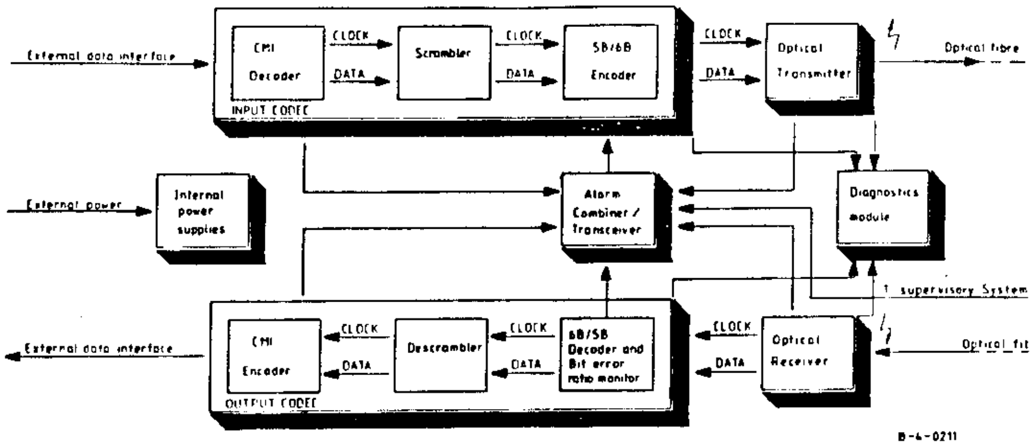


Fig. 6. Block diagram for line terminal, 140 Mbit/s system.

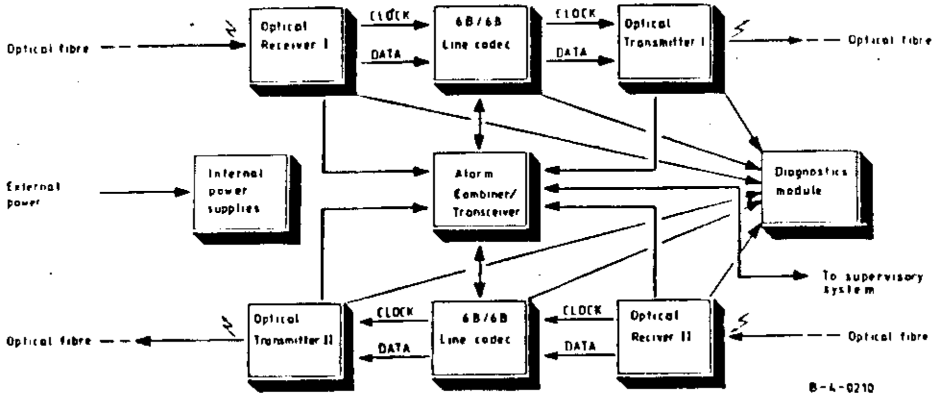


Fig. 7. Block diagram for regenerator, 140 Mbit/s system.

5. System calculations

System calculations aim to clarify how far certain transmitter/receiver equipment can send a certain signal, or to define what is required of the equipment and the optical fibre in order to be able to transmit a certain signal over a certain distance.

LOSS BUDGET

A system calculation can be presented as a simple linear equation when only the loss budget is concerned:

$P_S - P_R > d\,L_f + n\,L_s + M$ (all values in dB)

where

P_S	=	transmitter's output power measured in point S* immediately after the first connector
P_R	=	receiver's sensitivity at a bit error ratio of 10^{-10} measured in point R* immediately before the last connector
L_f	=	loss in the fibre per unit length dB/km
d	=	distance between transmitter and receiver, (fibre length)
L_s	=	average loss per splice
n	=	total number of splices
M	=	the desired system margin.

* For definitions of the points S and R please refer to Figure 8.

The equation shows that the total loss in the system plus the system's margin (the equation's right side) must not exceed the difference between the power that the transmitter can send, and the power that the receiver can detect.

As shown in the equation, the losses are proportional to the fibre length d. The total number of splices n = d/2 km + 1, where the cable length is normally approx. 2 km, and where there is one splice in every end in order to fit the station cables. (Station cables are single-fibre cables that connect the buried cables to line terminals and regenerators at the stations).

The loss budget is illustrated in the figure below.

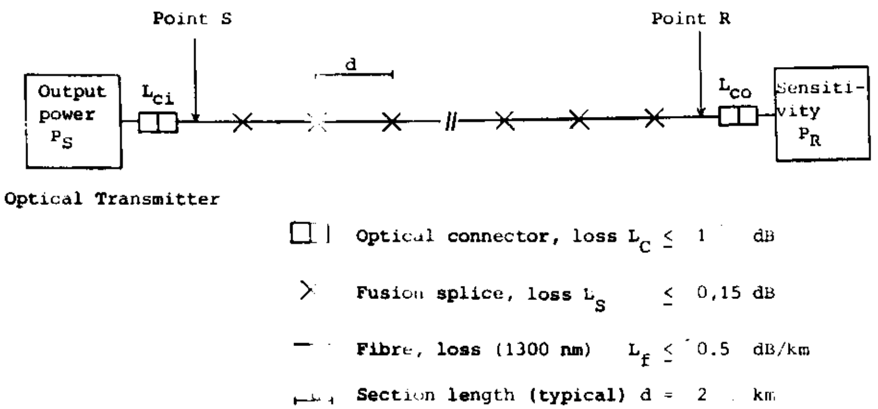


Fig. 8. Simple optical link illustrating the power budget.

In the following, the incoming dimensions in the loss calculation will be briefly discussed, and approximate values for these dimensions will be given.

P_S, optical output power:

The maximum allowable output power in the fiber from the semi-conductor lasers on the market today is ca. 0.5 mW (-3 dBm) using RZ-modulation (return to zero), or 1.0 mW (0 dBm) using NRZ-modulation (non return to zero).

P_R, sensitivity of the optical receiver:

The receiver's sensitivity is the smallest optical power measured on the optical connector at the receiver input that can be received with a given error ratio (usually BER = 10^{-10}, BER - Bit Error Ratio).

The sensitivity of an optical receiver depends on the data rate. Typical values for the sensitivity of high quality optical receivers are shown in Table 4.

Data Rate Mbit/s	850 nm (Si-APD)	1300 nm and 1550 nm
34	-56 dBm	-45 dBm (InGaAs-PIN)
140	-49 dBm	-40 dBm (InGaAs-PIN)
565		-35 dBm (Ge-APD)

Table 4. Typical values for sensitivity of optical receivers as a function of data rate and wavelength.

L_{ci}, loss in the input connector

The connector on the system's transmitter side can cause loss of about 1 dB. The reason for this loss is partly the simple Fresnel-reflection at the transition glass-air-glass in the connector, and partly the geometric imperfection of the two fibers that should be joined. According to the latest CCITT recommendations (Red book, Geneva 1984), the loss L_{ci} should be included in the specified output power, in the way that the output power from the laser pigtail is reduced by L_{ci} to give P_S.

L_{co}, loss in the output connector

The connector on the system's receiver side can cause a loss of 0 to 1.0 dB dependant of the coupling conditions (direct coupling to detector, coupling to multimode fibre, coupling to single mode fibre). According to CCITT the receiver sensitivity should be specified in point R. Therefore the loss L_{co} is included in P_R and does not appear in the loss budget.

L_s, loss per splice

The splice loss, that is, the loss from the joint between two fibers, can be very low (less than 0.1 dB) if the two fibers to be spliced have completely the same geometric and optical characteristics. The fibers are usually joined by melting the two ends together (fusion splice). Typical values for the splice loss are 0.2 dB for multimode fiber and 0.1 dB for single mode fiber.

In certain instances another splicing technique is used where the two fiber ends are glued together. The average splice loss with this technique is reported to be less than 0.05 dB.

M, the desired system margin

The system margin is measured as the difference between the output power that is present in the receiver at the time of installation, and the sensitivity that the receiver has at this time. The minimum size of this margin is decided by the expectations the system designer has about changes in the individual system parameters in the course of the system's lifetime, typically 15 years.

The output power from the laser can be reduced over a period of time if some form for feedback is not used to maintain a stable condition. Feedback such as this is normally used in laser-based systems, and the laser's output power can therefore be assumed to be constant in the laser's lifetime within ±1.0 dB. There is usually calculated a 3

dB margin of change in the output power for systems based on LED, because the output power is not stabilized in these systems.

Loss in buried cables shows some variation depending on temperature. These variations are dependent on the cable construction and the fiber's coating. A typical value would be ± 0.02 dB/km depending on the climate. The variation of the connector loss may be neglected in the temperature range where the connector is usually used (+10°C to +50°C).

The splice loss can rise significantly in the course of the cable's lifetime where repair of damaged cables is concerned. As a fundamental design rule it can be assumed that a cable is severed one time per kilometer in the course of its lifetime. In this case the splice loss will approximately double, for example from 3 dB to 6 dB. However, this so-called repair margin varies very much from one location to another.

The receiver sensitivity can vary 1 - 3 dB because of aging and temperature variations. The largest temperature variation is seen in receivers based on Ge-APD. The sensitivity typically decreases by 0.1 dB/°C for these receivers.

A total system margin between 6 and 10 dB must be seen as reasonable when the above-named factors are taken into consideration. In comparison, in satellite communication systems where there has been a great deal of experience and the tolerance of the components is less, the system margin is approximately 1 dB.

DISPERSIONS BUDGET

Dispersion is a measure of the broadening of an optical pulse propagating in the fiber (equivalent to the fiber bandwidth). Dispersion can be measured by sending a very short impulse (in principle an infinite, short pulse) in a fiber of a certain length. At the end of the fiber, the broadening of the impulse is measured, giving the dispersion.

Dispersion for a spliced link of multi mode fiber does not depend linearly on the dispersion of the individual lengths. Measurement results show that the dispersion for a link with a length $l = \sum_i l_i$ can be calculated in the following way:

$$D^2 = \left[\sum_i (D_i l_i)^{\frac{1}{0.75}} \right]^{1.5} + \left[\Delta\lambda \, D_k \sum_i l_i \right]^2$$

wave guide dispersion   chromatic dispersion

where D is the dispersion for the link and D_i is the dispersion for the individual length l_i measured with a light source with a very small spectral width.

D_i usually lies between 0.5 and 1.0 ns/km for 850 nm fiber, while it is less for 1300 nm fiber. The exponent 0.75 is empirically found and varies typically from 0.5 - 0.8.

$\Delta\lambda$ is the RMS - spectral width of the light source (laser or LED) which is used in the transmission system and D_c is the chromatic dispersion of the fibre.

The dispersion for a link of single mode fibres is calculated according to the more simple equation:

$$D = \Delta\lambda \, D_c \sum_i l_i$$

As a simple rule of thumb it can be stated that a dispersion below 30% of the bit length of the transmitted signal will result in a dispersion penalty of approximately 1 dB due to so-called mode partition noise (see Appendix). A more detailed analysis is necessary if you want to transmit in fibres with a higher dispersion.

6. Principles for optical transmitter and receiver

The basic elements of an optical transmission system are an optical transmitter, an optical fibre and an optical receiver. A simple optical transmission system is illustrated below.

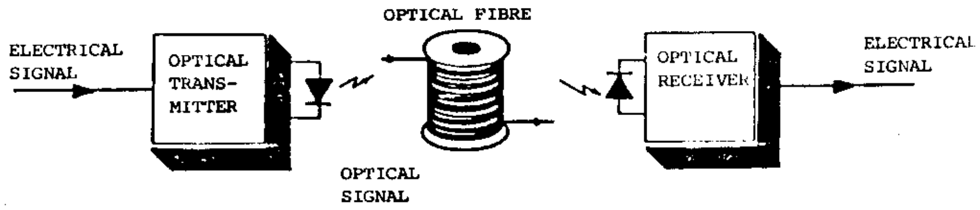


Fig. 9. Simple optical transmission system.

In the optical transmitter, the electrical input signal is used to modulate a light source. The light is coupled from the light source into the optical fibre where an the usual attenuation ranges from 0.25 to 3 dB/km dependent on wavelength. In the case of a digital system, the other end of the fibre is led to the optical receiver where the optical signals are converted to electrical signals, amplified and resampled.

Optical Transmitter

The optical transmitter consists of a light source which can be modulated. The most common modulation form is a simple on/off modulation where the light source is turned on or off, depending on which of the two binary symbols, 0 and 1, are transmitted.

The light source is either a semi-conductor laser or an LED (Light Emitting Diode) with a wavelength around 850 nm, 1300 nm or 1550 nm. These wavelengths are outside of the visible range.

A semi-conductor laser can be modulated with digital signals with a data rate up to approximately 3 Gbit/s (3 x 10^9 bit/sec). An LED is somewhat slower, having a maximum data rate of about 500 Mbit/s, but higher modulation speed may be realized using sophisticated LED structures and driving circuits.

It is easier to couple the light from a semi-conductor laser into an optical fibre than from an LED. When coupling from a laser, the typical loss is 2 - 5 dB, while when coupling from an LED the loss is around 15 dB, depending on the fibre type.

A third factor that makes the laser a suitable light source in telecommunication systems is its small spectral width. The spectral width for a laser is typically between 0.1 and 5 nm, while that of an LED is usually around 100 nm. A large spectral width leads to a widening of the pulse, caused by the chromatic dispersion, which means that light with different wavelengths propagates with differing velocities in the fiber. A typical value for chromatic dispersion is 80 psec/nm/km at 850 nm, 2 psec/nm/km at 1300 nm and 17 psec/nm/km at 1550 nm.

However, an LED is less expensive than a laser, and it also has a longer lifetime.

The characteristics of a laser diode at two different temperatures are shown below.

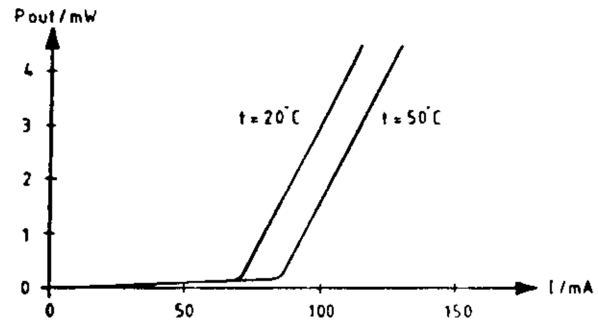


Fig. 10. Characteristics of a laser at two different temperatures.

The laser diode has a light-current characteristic that resembles the current voltage characteristic for a typical diode. The threshold current is dependent on temperature in such a way that a higher temperature results in a higher threshold current. The laser's threshold current also increases as the laser ages.

The laser's characteristics make it well-suited for use in digital systems, while it is less ideal for analog modulation. This is because the light-current characteristic is not completely linear.

Figure 11 shows a block diagram for an optical transmitter in a digital system. The data signal is converted first from the normal NRZ-format (non-return-to-zero) to the RZ-format (return-to-zero), where the duration of a high data impulse is cut in half. The signal that results is used to modulate the laser. The current through the laser is made up of a DC-contribution, the so-called bias, and an AC-contribution, controlled by the modulating signal. The current amplitude for the modulated signal is held constant for practical reasons, and changes in the optical output power are brought about by varying the bias current. The optical output power is monitored, and the feedback

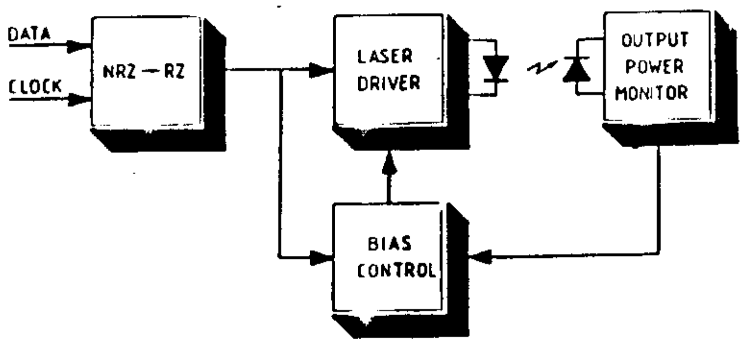


Fig. 11. Block diagram for an optical transmitter.

assures that a constant signal energy is held in each optical pulse independent of temperature, bit stream, and the laser's age.

Optical receiver

The optical receiver consists of a light-sensitive diode that is able to convert the received optical signal into an electric current. An Avalanche Photo Diode (APD) or a PIN-diode is usually used. Silicon diodes are almost always used at wavelengths below 1000 nm, while at longer wavelengths germanium or more exotic materials, for example indium-gallium-arsenide (InGaAs), are used.

A photo diode is equivalent to a current generator with a current proportional to the received light intensity. An avalanche diode can generate a higher current than a PIN-diode with the same light intensity, since the avalanche diode has an internal amplification of typ-

ically 10 - 100 times. However, an avalanche diode has a higher noise level than a PIN-diode, because the avalanche amplification is not constant from one light impulse to another.

After the conversion from light to current, the signal is amplified and the clock information is derived using a phase-locked loop or a surface accoustic wave (SAW) filter. The clock signal is used when re-sampling the amplified signal. If the signal/ noise ratio at the input to the optical receiver is large enough, there will be an undisturbed copy of the sent signal at the output of the receiver.

A block diagram for an optical receiver is shown below.

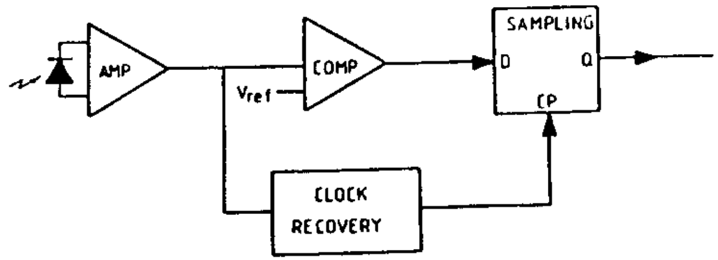


Fig. 12. Block diagram for an optical receiver.

7. Conclusion

Transmission via optical fiber is accepted as the most economical transmission method today in the digital trunk network.

A large number of systems are in operation around the world, and the growing pains are almost over. The systems today demonstrate a reliability that lives up to the traditional systems based on coaxial cables.

This means that telecommunication companies have a transmission medium available with such a large transmission capacity that they can easily cover any need for many years to come. Only the future will show which services the telecommunication companies will offer their customers via the coming digital trunk network, based on optical fibers, but one thing is completely sure: It will not be the network's transmission capacity that sets the limits.

January 1, 1987
PV/264e

Appendix

LASER NOISE

The purpose with this Appendix is to give a short, qualitative introduction to laser noise. The description is not in detail and it is without a special physical explanation of the noise mechanisms.

Laser noise can be characterized as being unintended variations in the transmitted light intensity and spectrum.

An ideal laser has a completely stable spectrum and a light intensity which is in directly proportional to the modulation current.

Intensity noise

However, in practice you may find intensity variations which ranges from 100 to 150 dB/Hz below the signal level. This noise is often characterized by the quantity RIN (Relative Intensity Noise), which can be measured by a modulation of the laser using a simple square-wave signal. This optical signal is detected and displayed on a spectrum analyzer. The spectrum will consists of a number of harmonic of the modulation frequences and of a "noise floor" between these. The ratio between the signal power and the noise intensity is called RIN.

The noise has a wide spectrum and is therefore most important in high speed systems. This noise source is only significant at bit rates of 565 Mbit/s and above.

RIN depends on the temperature, on the level of reflections which reach the laser again, for example from the connector, and on the biasing conditions.

RIN is independent of the chromatic dispersion of the fibre and is recognized as an amplitude noise present in the eye diagram of the optical receiver.

Spectral noise

The spectral noise is usually described as a noise which consists of three contributions:

a) **Mode jumps:** Sudden jumps in centre wavelength of up to 5 nm. These jumps can be induced by temperature and current variations or by variation in reflection.

b) **Mode partition noise:** Meaning that the spectrum from the laser diode not is completely stable. Both during modulation and continuous operation the optical power may be redistributed between the different longitudal modes.

c) **Chirp:** Meaning a rather small (0.1 to 0.2 nm) displacement of every longitudal mode. Chirp only occurs during modulation.

Spectral noise leads to phase noise in the eye diagram of the optical receiver. Common for all the spectral noise contributions is that they will only affect the transmission if the chromatic dispersion of the fibre exceeds a certain amount, corresponding to the fact that the phase noise in the received signal is comparable to the bit length of the transmitted signal.

Mode jumps are especially serious in 850 nm systems where the chromatic dispersion is about 80 ps/nm/km. There is no theory for the occurrence of these but examples of mode jumps induced by external reflections have been reported.

Mode partition noise is the limiting factor in many high speed systems operating at 565 Mbit/s and above when Fabry Perot lasers at 1300 nm are used. The theory of mode partition noise is described in K. Ogawa; Transact., IEEE-QE, vol. 8 (1982), p. 849-855.

Chirp is the limiting factor in long distance high speed systems based on DFB-lasers.

Subject: Optical Specifications **Lesson:** 3.2

Optical Specifications Lesson Outline

- **Optical Specifications**
- **Output Power**
- **Safety Power**
- **Extincion Ratio**
- **Receiver Sensitivity**
- **Dynamic Range**
- **Send/Receive Ratio**

Subject: Optical Specifications **Lesson:** 3.2

Optical Interface, 300 nm

Connector:

Single mode optic connector, DOR-RAN type SPA.

Optical fibre:

In acc. with CCITT c. G.652.

Bit rate:

167.117 Mbit/s ± 1 pm

Line code:

5B/6B

Data format:

NRZ

Laser type:

Fabry-Perot

Optical wavelength:

1310 ±10 nm

Spectral half width:

≤ 4 nm

Optical output power:

-5 to -2 dBm meas ed at point S acc. to CCITT Rec. G.9

Extinction ratio:

≥ 1:10

Safety power:

≤ -9 dBm (point S)

Receiver dynamic range:

-20 to -37 dBm

Receiver sensitivity:

Bit Error Ratio (BER) ≤ 10^{-10}, provided mean optical input ower ≥ -37 dBm, measured at point acc. to CCITT Rec. G.956 and provided extinction ratio for TX ≥ 1:10.

Send/Receive ratio:

18 ≤ S/R ≤ 31 dB cluding margin for dispersion penalty.
(Max. dispersion : 300 ps/nm).

Subject: Optical Specifications **Lesson:** 3.2

Output Power

Laser Specification:

Output power (CW):	min. 1.2 mW
Output power at threshold:	max. 0.05 mW
Drive current above threshold:	max. 35 mA at 1.0 mW
Output power variation due to Case temperature variation (-20 °C to +65 °C):	+/- 0.5 dB

Using a 40 mA Laser Driver Circuit:

Output power: (at 40 mA above threshold) (Note: a threshold power of max. 0.05 mW is not included)	min. 1.15 mW
Average output power: (50% Duty-cycle, P_{th} < 0.05 mW, and 40 mA drive current)	min. 0.58 mW ≈ min. - 2.4 dBm

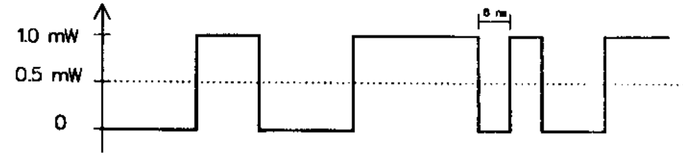
Point S calculation: (140 Mbit/s TX)

Laser Pigtail Output	-2.6 dBm	+/- 0.20 dB
Connector Loss	-0.7 dB	+0.3 / -0.5 dB
Output Power (Point S) at install.	-3.3 dBm	+0.5 / -0.7 dB
Change with Temperature		+/- 0.50 dB
Output Power (Point S) over temp.	-3.3 dBm	+1.0 / -1.2 dB
Ageing (laser slope)		+0.3 / -0.5 dB
Output Power (Point S) end-of-life	-3.3 dBm	+1.3 / -1.7 dB
=>	-2 to -5 dBm	

Subject Optical Specifications **Lesson** 3.2

Safety Power 140 DS

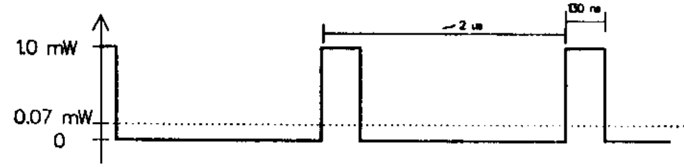
Transmitted data



$P_{peak-peak}$ = 1.0 mW $P_{avr.}$ = 0.5 mW
≈ - 3 dBm

Safety sequence

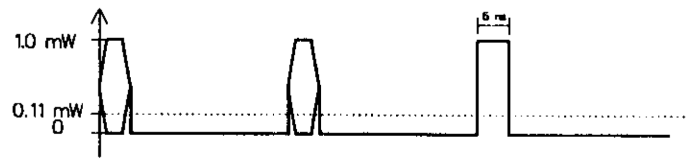
Note time scale !



$P_{peak-peak}$ = 1.0 mW $P_{avr.}$ = 0.07 mW (0.13/1.87)
≈ - 11.5 dBm

AIS data sequence

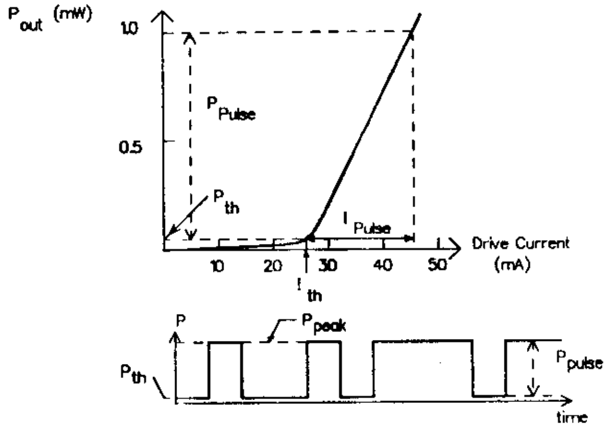
(Note: The Optical signal is inverted compared to the Electrical signal)



$P_{peak-peak}$ = 1.0 mW $P_{avr.}$ = 0.11 mW (2/18)
≈ - 9.5 dBm

Subject Optical Specifications **Lesson** 3.2

Extinction ratio



Extinction Ratio = P_{th} / P_{peak}

If $P_{avr.}$ = 0.6 mW and P_{th} << 0.05 mW

then

$P_{avr.}$ = 0.5 x (P_{peak} + P_{th}) (for a 50% duty-cycle)

⇓ P_{peak} = 2 x $P_{avr.}$ − P_{th}
= 2 x 0.6 mW − 0.05 mW
= 1.15 mW

⇓ Extinction Ratio: 0.05 mW/ 1.15 mW = 1 : 23

The Receiver detects only the pulse power P_{pulse} = P_{peak} − P_{th}
= 1.15 mW − 0.05 mW
= 1.10 mW, which corresponds to 0.4 dB Penalty (relative to 1.2 mW)

> For 140 DS: >
> If the Extinction Ratio is ≥ 1 : 10
> then the Receiver Sensitivity
> is reduced by ~~less~~ than 1 dB

Subject: Optical Specifications **Lesson:** 3.2

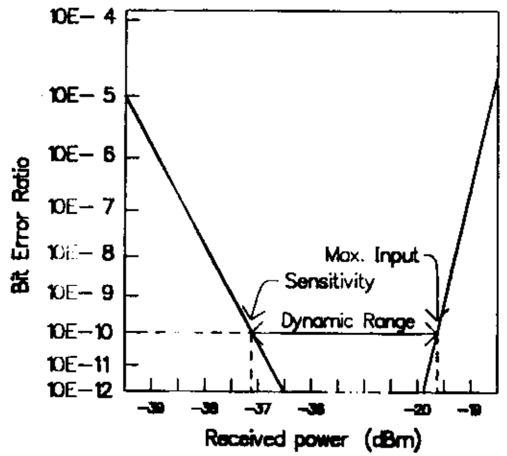
Receiver Sensitivity

Point R calculation: (140 Mbit/s 1300 nm RX)

Sensitivity (Point R) at install. Change with Temperature	< -38.5 dBm	+0.5 dB +/- 0.5 dB
Sensitivity (Point R) over temp. Ageing	< -38.5 dBm	+1.0 / -0.0 dB +/- 0.5 dB
Sensitivity (Point R) end-of-life =>	< -38.5 dBm < -37.0 dBm	+1.5 / -0.5 dB

Subject Optical Specifications **Lesson** 3.2

Dynamic Range



At an Input Power level above the Sensitivity, the Receiver detects and regenerates the signal with less than 10^{-10} Bit Errors

- The **Sensitivity** is maximum − 37 dBm at BER = 10^{-10}

At an Input Power level below the Maximum Input, the Receiver detects and regenerates the signal with less than 10^{-10} Bit Errors

- The maximum input level is minimum − 20 dBm at BER = 10^{-10}

The Dynamic Range is given as the Input Power levels where the Receiver detects and regenrates the signal with less than 10^{-10} Bit rrors

- The **Dynamic Range** is minimum 17 dB at BER = 10^{-10} (from − 20 dBm to − 37 dBm)

Subject: Optical Specifications **Lesson:** 3.2

Send/Receive (S/R) Ratio

Output Power (Worst Case min.) Point S:	**- 5 dBm**	**(min.)**
Receiver Sensitivity at BER = 10^{-10} (Worst Case) Point R:	**- 37 dBm**	**(max.)**
Dispersion Penalty: (when the total dispersion is less than 300 ps/nm)	**1 dB**	
MAXIMUM Allowable Attenuation:	**31 dB**	

Output Power (Worst Case Max.) Point S:	**- 2 dBm**	**(max.)**
Receiver Overload at BER = 10^{-10} (Worst Case) Point R:	**- 20 dBm**	**(min.)**
MINIMUM Allowable Attenuation:	**18 dB**	

Optical Systems II Lesson Outline

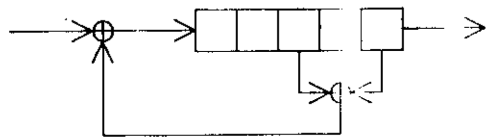
* Line Coding
* Alarm system
* Supervisory systems

Line Coding

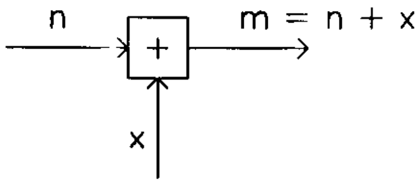
1. Re–organization of data

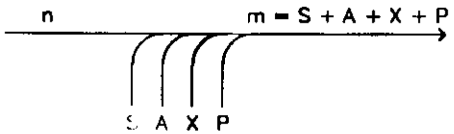
nB/mB (n bit into m bit code)

Scrambler



2. Additional Capacity in Line Code





S = Synchronization

A = Auxillary Channel
(Supervisory informtion,
Engineering Order Wire)

P = Parity of data bits
(for BER calculations)

X = Extra Data Channel

Line Codes

Typical Dataformates:

* NRZ Non–Return to Zero
* RZ Return to Zero
* CMI Codec Mark Inversion (140 M)
* HDB3 High Density Bipolar 3 (2,8,34 M)
* AMI Alternate Mark Inversion (565 M)
* 4B3T 4 Binary to 3 Ternary (140 M)

Typical Line Codes:

* 5B/6B	Balanced	(Germany, Philips)
* 7B/8B	Balanced	(UK: BT, STC)
* 12B/1P/1C	Balanced	(France)
* 24B/1P	Unbalanced	(AT&T, TAT–8)
* 10B/1P	Unbalanced	(Japan: NEC, Fujitzu)
* 5B/6B	Unbalanced	(NKT)

Line Code Parameters

* Synchronization time

  Average / 99 percentile for BER = 10^{-3}

* Error detection range

  Single errors / Saturation

* Bandwidth requirements

  CMI: 200 pct.

  5B/6B: 120 pct.

  16B/18B: 113 pct.

* Extra Capacity

  5B/6B Balanced: No extra capacity

  5B/6B Unbalanced: Aux. channels (Supervisory Information, Engineering Order Wire)

* Error Multiplication Factor

5B / 6B Coding Map

Input word	State 1; D = -1 Codeword	d	State 2; D = + 1 Codeword	d
0	101011	2	010100	-2
1	011100	0	011100	0
2	110001	0	110001	0
3	101001	0	101001	0
4	011001	0	011010	0
5	010011	0	010011	0
6	101100	0	101100	0
7	111001	2	000110	-2
8	100110	0	100110	0
9	010101	0	010101	0
10	010111	2	101000	-2
11	100111	2	011000	-2
12	110011	2	000111	0
13	011110	2	100001	-2
14	101110	2	010001	-2
15	110100	0	110100	0
16	001011	0	001011	0
17	011101	2	100010	-2
18	011011	2	100100	-2
19	111000	0	001100	-2
20	110110	2	001001	-2
21	111010	2	000101	-2
22	101010	0	101010	0
23	011001	0	011001	0
24	101101	2	010010	-2
25	001101	0	001101	0
26	110010	0	110010	0
27	010110	0	010110	0
28	100101	0	100101	0
29	100011	0	100011	0
30	001110	0	001110	0
31	110101	2	001010	-2

EXAMPLE: 5B/6B CODING

$2^5 = 32$ $6! / 3! \times 3! = 20$

Simple Balance Impossible !!!

Subject: Optical Systems - II **Lesson:** 2.4

6B / 8B Coding Map

Input word	Codeword	Input word	Codeword
0	10011001	32	01101100
1	10010011	33	01011100
2	01100011	34	00111100
3	10100011	35	01111000
4	01100110	36	11100010
5	11000011	37	01110010
6	00011101	38	01001110
7	10010101	39	11100100
8	10100110	40	11010010
9	00101101	41	10001110
10	01001101	42	00111010
11	01100101	43	00110011
12	01011001	44	01011010
13	10100101	45	11010100
14	11000101	46	10110100
15	01000111	47	00100111
16	10011100	48	10110010
17	01101001	49	10011010
18	10101001	50	01101010
19	11001001	51	01010011
20	01010110	52	00110110
21	00111001	53	00110101
22	01110001	54	10101100
23	00011011	55	10101010
24	10010110	56	11000110
25	11010001	57	10111000
26	00011110	58	01110100
27	00101011	59	11101000
28	00101110	60	11001100
29	01001011	61	11011000
30	10001011	62	11001010
31	00010111	63	01010101

EXAMPLE: 6B/8B CODING

$2^6 = 64$ $8! \,/\, 4! \times 4! = 70$

Simple Balance Possible !!!

Subject: Optical Systems - II **Lesson:** 2.4

COMPARISON OF 3 BALANCED CODES

SEARCH FOR NEW ALIGNMENT IS INITIATED WHEN TWICE MORE THAN C VIOLATIONS ARE FOUND IN A STRING OF CODE WORDS LESS OR EQUAL M

Comparison of some Parameters of considered Block-codes

	3B/4B	5B/6B	6B/8B
Bit-rate increase	1.33	1.2	1.33
Number of alphabets	2	2	1
Number of coder states	2	2	1
Number of terminal running disparity values*	2	2	1
Number of running disparity values	5	7	7
Max.number of consecutive identical digits	4	5	6
Mean mark density	0.5	0.5	0.5
Perc.of tot.power betw.fT' = 0 and fT' = 0.03	1.90 0/00	3.25 0/00	2.49 0/00
Error extension in decoding	1.5	2.37	1.8
Mean interval between consecutive false alarms with bit error rate 10^{-3}	$1.7\ 10^{20}$ T	$1.6\ 10^{21}$ T	$1.9\ 10^{22}$ T
Average alignment recovery time	887 T C = 15	1555 T C = 15	410 T C = 8
Max. alignment recov.time (99.9%)	2631 T M = 510	4295 T M = 315	1506 T M = 32

T is the digit time slot before the coding. For 140 MBit/s T ≈ 7.18 µsec and the max alignment recovery time (99.9 %) is 30.84 µsec (4295 T).

* disparity at end of codeword.

NKT Line Codes

34 DS and 140 DS frameformat

5B/6B (15B/18B)

5 data bits	S	5 data bits	A	5 data bits	P

S = Synchronization bit

A = Auxillary Channel (Supervisory ch., and EOW)

P = Parity of 15 data bits

565 ES frameformat

16B/18B (64B/72B)

16 data bits	1	0	16 data bits	U1	U2	16 data bits	0	1	16 data bits	A	P
	F0	F1					F2	F3			

F0–F3 = Synchronization Word

U1, U2 = Additional Data Channels (each 8.8 Mbit/s)

A = Auxillary Channel (Supervisory ch., and EOW)

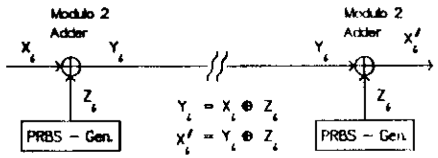
P = Parity of 64 data bits

Scrambling

* A Scrambler breaks up long periods of equal bits which may prevent correct syncronization

* A Scrambler secures equal probability for "mark" and "space" independant (almost) of input signal

Example: Set/Reset Scrambler

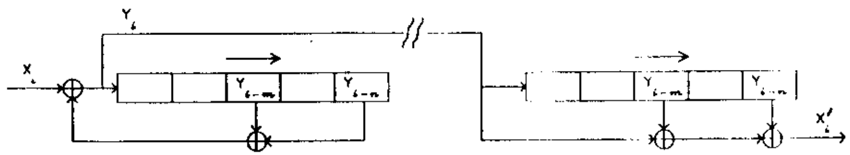


$Y_i = X_i \oplus Z_i$

$X'_i = Y_i \oplus Z_i = X_i \oplus Z_i \oplus Z_i = X_i$

Problem: SYNC !

Example: Self–Synchronizing Scrambler

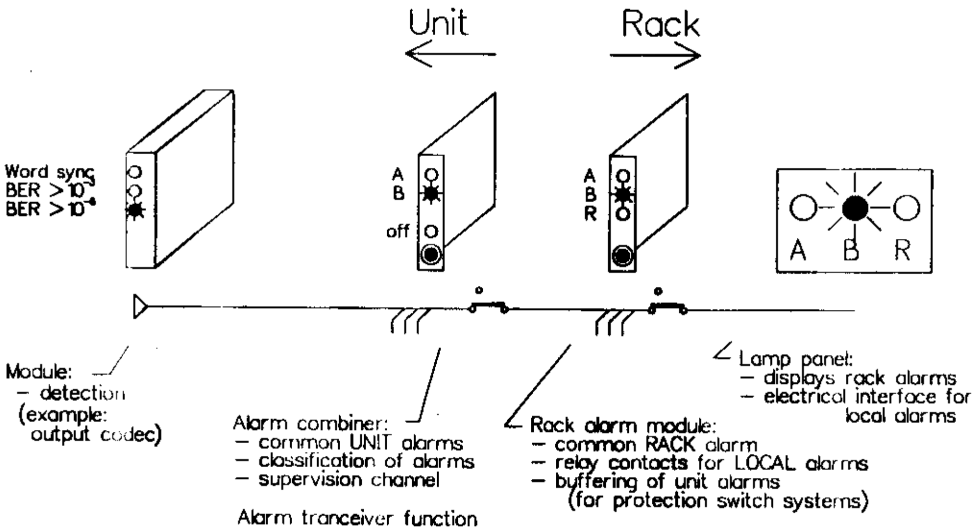


$Y_i = X_i \oplus Y_{i-m} \oplus Y_{i-n}$

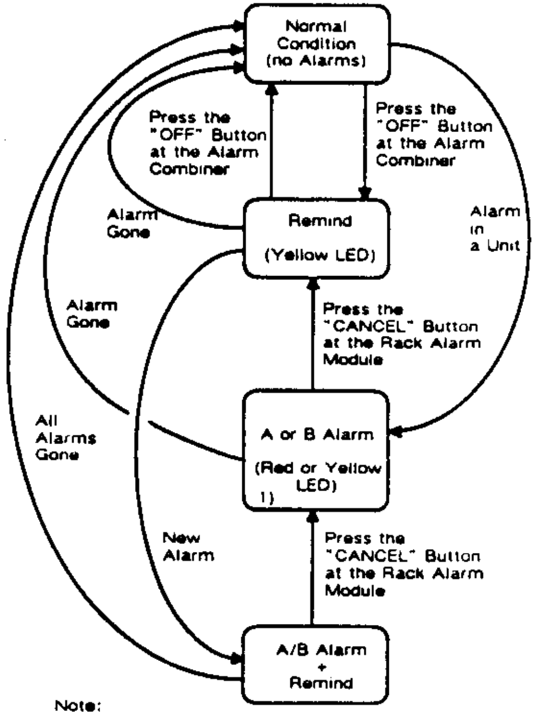
$X'_i = Y_i \oplus Y_{i-m} \oplus Y_{i-n} = X_i$

Error Multipl. !

Alarm System



Remind / Acknowledge Function



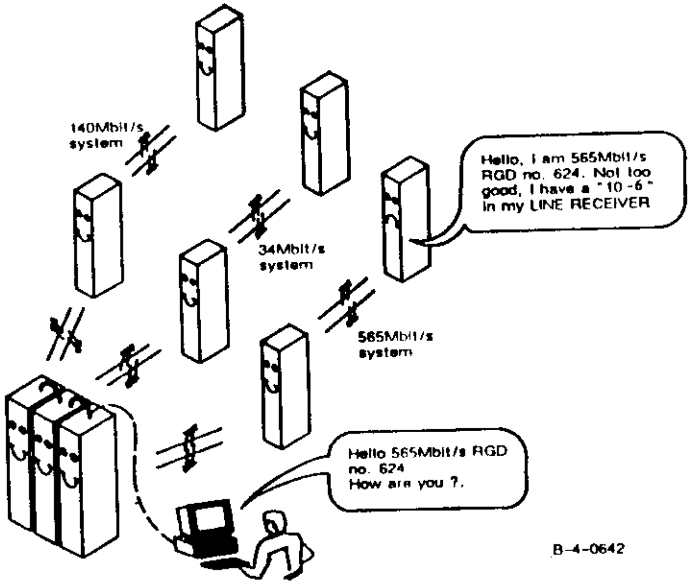
B-4-0377

Note:
The diagram shows the indication at the Rack Top

1) REMIND may also be present if activated in Unit (OFF-button at the Alarm Combiner)

Subject: Optical Systems - II **Lesson:** 2.4

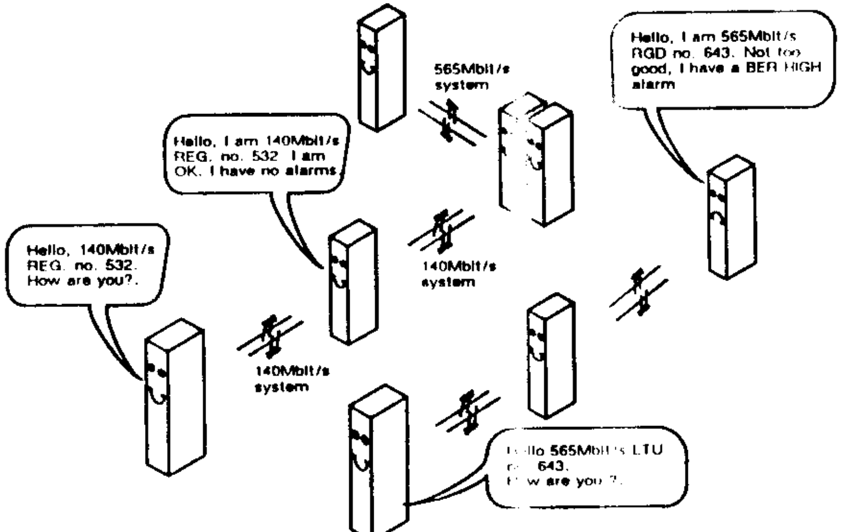
Centralized Supervisory System



B-4-0642

Subject: Optical Systems - II **Lesson:** 2.4

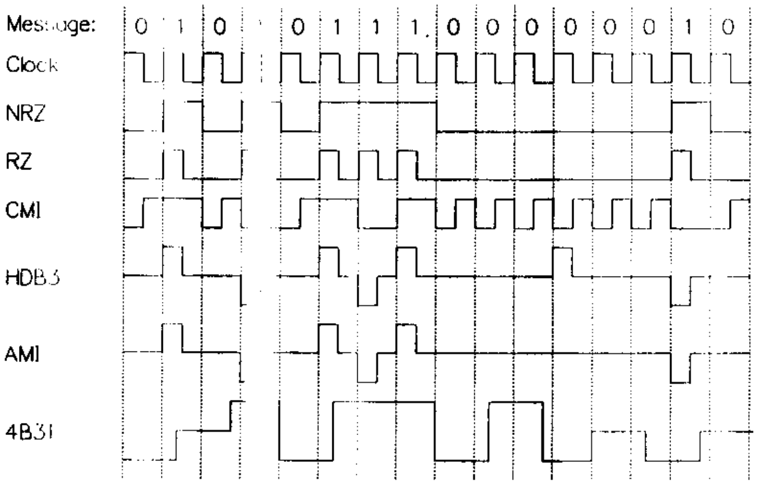
Decentralized Supervisory System with Flaut Location Unit



B-4-0641

Subject Optical Systems - II **Lesson** 2.4

Dataformates



Short list of code characteristics:

NRZ: The NRZ (Non Return to Zero) code is a 2 level code which is constant during the complete clock period. The output level is corressponding to the message.

RZ: In the RZ (Return to Zero) code the ones returns to the zero level after a half of the clock period.

CMI: In the CMI (Coded Mark Inversion) code the zeros are presented as a high pulse with a duration of a half clock period. The ones are presented in a whole clock period at a high or low level depending on the last "1". Compared to this last "1" the bit is inverted. It shall be noted that the required bandwidth for a CMI signal is twice the message bandwidth.

AMI: The AMI (Alternate Mark Inversion) is a 3 level code. each "1" is represented in a half clock period at a posetive or negative level. The sign of the "1" level will depend on the last "1" presented.

HDB3: The HDB3 (High Density Bipolar 3) code is allmost equal to the AMI code in terms of the 3 level coding. The difference occours when 4 or more zeros are transmitted just after each other, then an additional pulse (a violance pulse) is forced into the bit stream. The polarity of the violence pulse is equal to the last "1" pulse. More about the HDB3 code could be found in the appendixes to CCITT Rec. G.703.

4B3T: The 4 bit into 3 Tenary bit code is a 3 level code where each package of 4 bits is coded into 3 bits. The feature of this code is that the required bandwidth is reduced by 4/3 compared to the message bandwidth.

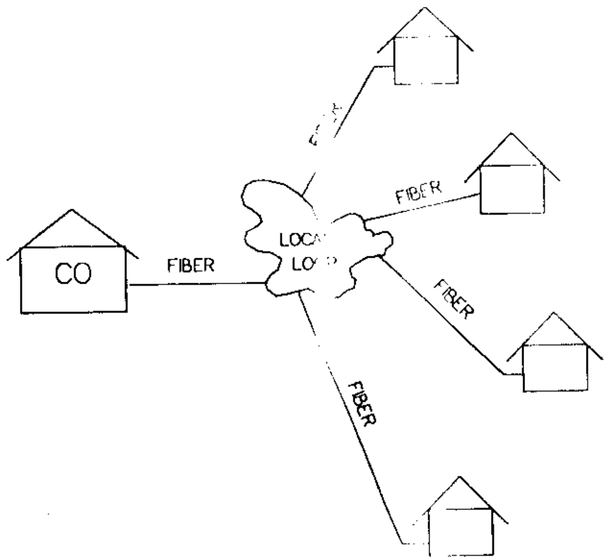
Subject Future Optical Communication – I **Lesson** 2.6

FIBER–TO–THE–HOME

* THE FTTH CONCEPT
* SERVICE ASPECTS
* NETWORK TOPOLOGY
* TRANSMISSION TECHNIQUES
* DIGITAL TV
* ANALOG TV
* FIELD TRIALS

Subject Future Optical Communication – I **Lesson** 2.6

THE FTTH CONCEPT



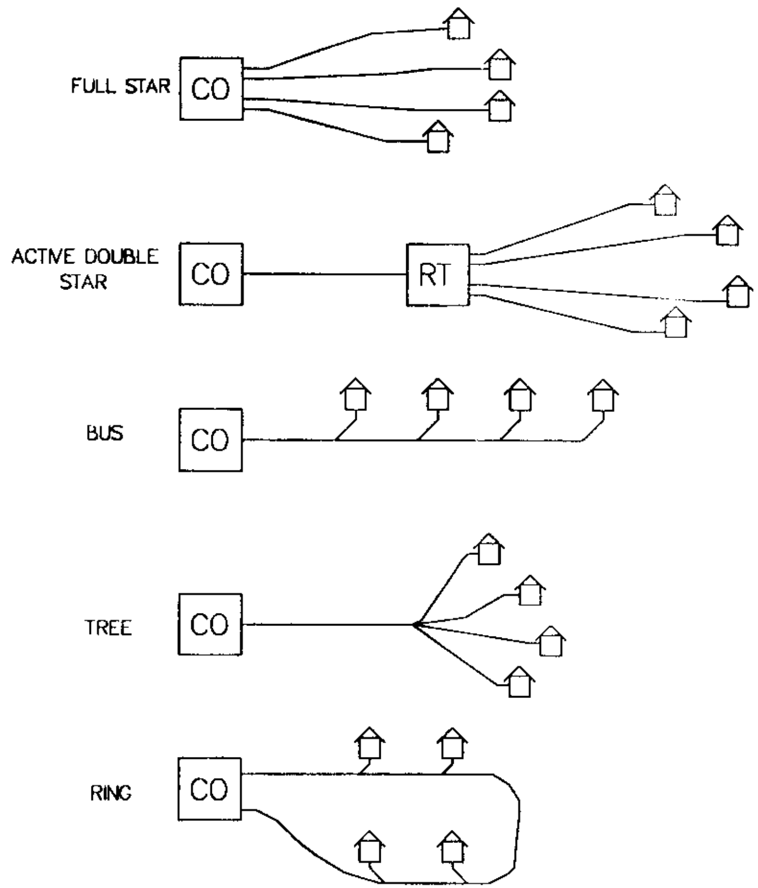
FTTH – ADVANTAGES

* MORE BANDWIDTH
* IMPROVED QUALITY
* NEW SERVICES
* POTENTIAL LOW COST
* FUTURE PROOF

SERVICE ASPECTS

* TELEPHONY
* ISDN
* TV (HDTV,PPV)
* RADIO
* COMPUTER LINK
* VIDEO TELEPHONE
* VIDEO CONFERENCE
* LIBRARY (TEXT,VIDEO,HI-FI)
* DATABASE
* HOME SHOPPING
* SECURITY (FIRE,BURGLARS)

NETWORK TOPOLOGY-I



NETWORK TOPOLOGY–II

NETWORK	ADVANTAGE	DISADVANTAGE
STAR	HIGH BANDWIDTH	HIGH FIBRE AND TX/RX CONSUMPTION
A.D.STAR	HIGH BANDWIDTH MODERATE FIBRE CONSUMPTION	TX/RX EQUIPMENT IN THE LOCAL LOOP
BUS TREE RING	MODERATE FIBER CONSUMPTION	LIMITED BANDWIDTH POOR PRIVACY JAMMING POSSIBLE

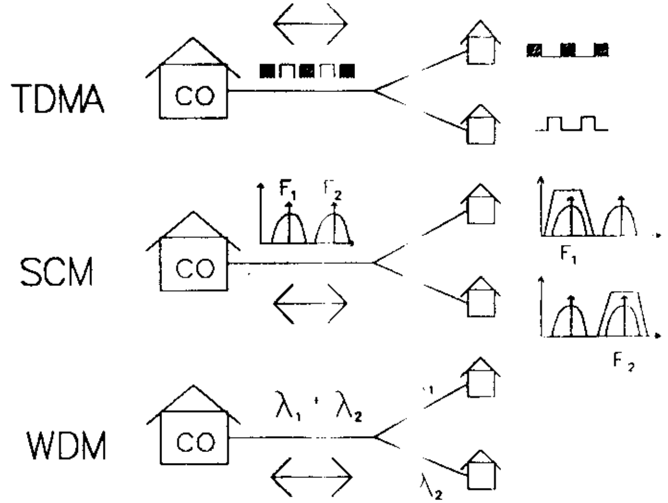
TRANSMISSION TECHNIQUES

MODULATION

* DIGITAL
* ANALOG

MULTIPLEXING

* Time Division Multiple Access
* SubCarrier Multiplexing
* (High–Density) Wavelength Division Multiplexing



DIGITAL TV

BITRATE PER CHANNEL	57 → 108 Mbit/s
NB. OF CHANNELS PER 565 Mbit/s Tx	9 → 5 CHANNELS
NB. OF CUSTOMERS PER Tx	1024 → 8192 CUSTOMERS

* WELL SUITED FOR LONG DISTANCE TRANSMISSION
* HIGHER BITRATE NEEDED FOR LOCAL LOOP DISTRIBUTION
* TYPICAL LOCAL LOOP IMPLEMENTATION IS SWITCHED TV
* D/A CONVERSION AT THE CUSTOMER END NECESSARY

ANALOG TV

	AM	FM
BANDWIDTH PER CHANNEL	7 → 8 MHz	≤40 MHz
TYPICAL NB. OF CHANNELS PER Tx	20 → 40	≥20
NB. OF CUSTOMERS PER Tx	4 → 8	16 → 64

* MANY CHANNELS ⇒ AM AND FM ARE LOCAL LOOP DISTRIBUTIO
* AM HAS A POOR POWER BUDGET (OPTICAL AMPLIFICATION)
* FM REQUIRES DEMODULATION AT THE CUSTOMER END

FIELD TRIALS

PLACE	USA	ENGLAND	GERMANY	USA
NAME	"SERIES 5"	"TPON/BPON"	"LOC II"	"HEATHROW"
SERVICE	TELEPHONY	TELEPHONY +16 FM-TV	TELEPHONY +23 AM-TV +HI-FI	TELEPHONY +4 DIGITAL TV
TYPE	FTTH(-C)	FTTH(-C)	FTTC	FTTH
NETWORK	DOUBLE STAR	TREE	BUS	2 DOUBLE STARS
MULTIPLEX	-	TDMA	2 FIBRES	WDM
CUSTOMERS PER Tx	1	32(→ 128) 16(→ 32)	24*8 24*4	1
BB UPGRADE		MORE FIBRE -HDWDM	MORE FIBRE	

WHAT IS SDH ?

THE NEW SYNCHRONOUS DIGITAL HIERACHY

Recommendations on SDH

Bit Rates
(Rec. G.707)
Network Node Interface
(Rec. G.708)
Multiplexing
(Rec. G.709)
Architechtures
(Rec. G.sna1)
Performance and Management Capabilities
(Rec. G.sna2)
Optical Interfaces
(Rec. G.957 (G.opt))
Line Systems
(Rec. G.958 (G.sls))
Structure on Recommendations on Multiplexing Equipment
(Rec. G.781 (G.smux-1))
Multiplexing Equipment
(Rec. G.782 (G.smux-2))
Multiplexing Functional Blocks
(Rec. G.783 (G.smux-3))
Management
(Rec. G.784 (G.smux-4))
Protocol Suites for Q Interfaces
(Rec. G.773)
Structure on Recommendations on Cross-Connect Equipment
(Rec. G.sdxc-1)
Cross-Connect Equipment
(Rec. G.sdxc-2)
Cross-Connect Functional
(Rec. G.sdxc-3)

SDH BITRATES:

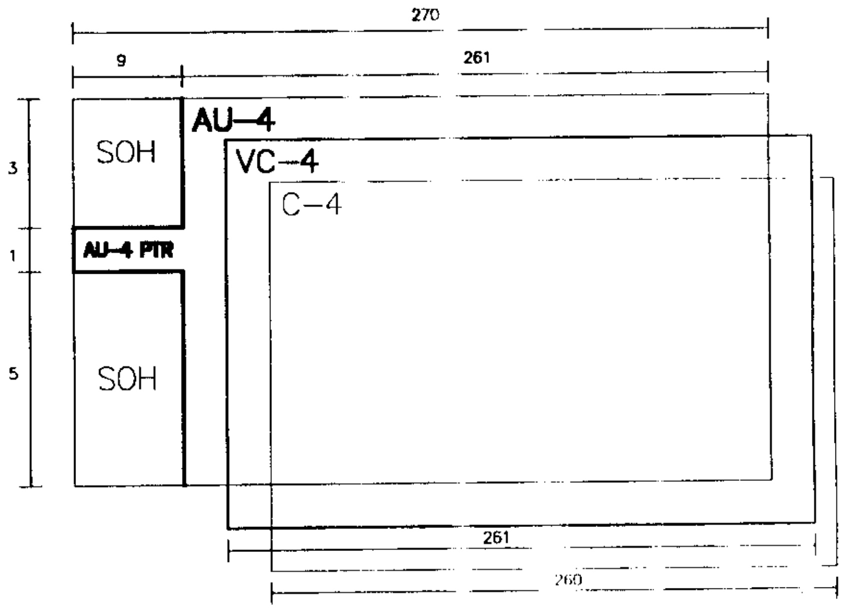
STM-1	155.520 Mb/s
STM-4	622.080 Mb/s
STM-16	2488.320 Mb/s
STM-N	N*155.520 Mb/s

NETWORK NODE INTERFACE

* PHYSICAL INTERFACE
  - optical
  - electrical

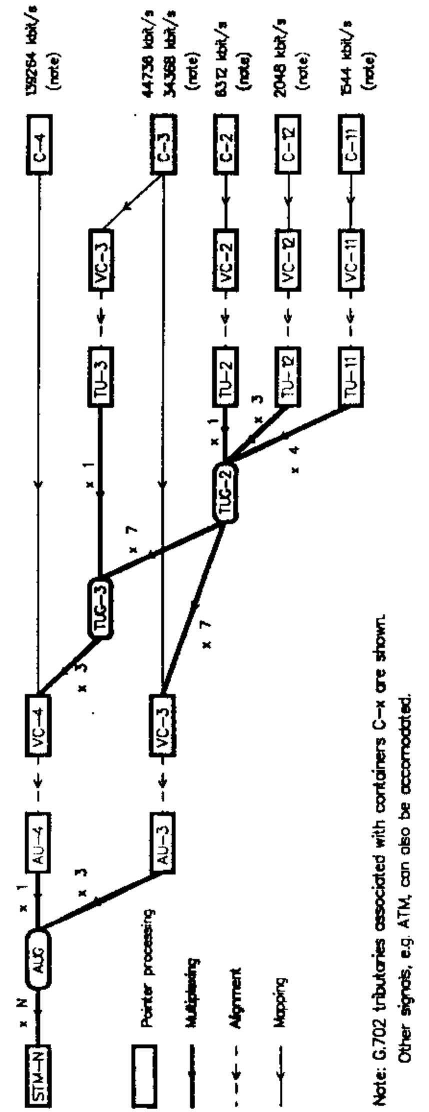
* "LINE CODE"
  - framing, A1, A2 & pointers
  - data comm. channel, D1–D12
  - eow, E1, E2
  - user channels, F1, F2
  - reg. sect. parity, B1 (BIP–8)
  - line sect. parity, 3*B2 (BIP–24)
  - aut. prot. switch signalling, K1, K2
  - identifiers C1, C2, J1

STM–1 FRAME



Subject Future Optical Communication – I **Lesson** 2.6

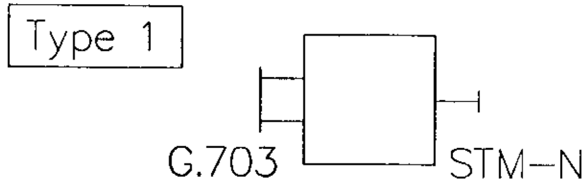
Multiplexing structure

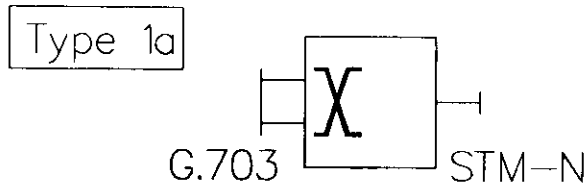


Note: G.702 tributaries associated with containers C–x are shown. Other signals, e.g. ATM, can also be accomodated.

Subject Future Optical Communication – I **Lesson** 2.6

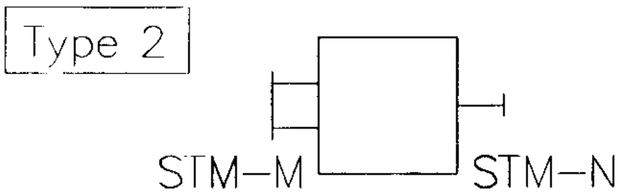
MULTIPLEXER TYPES

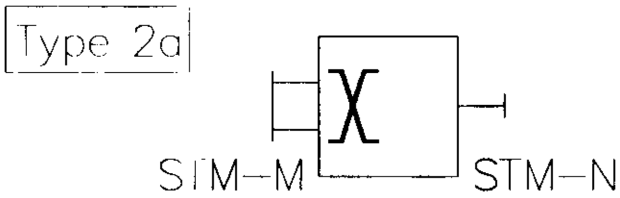




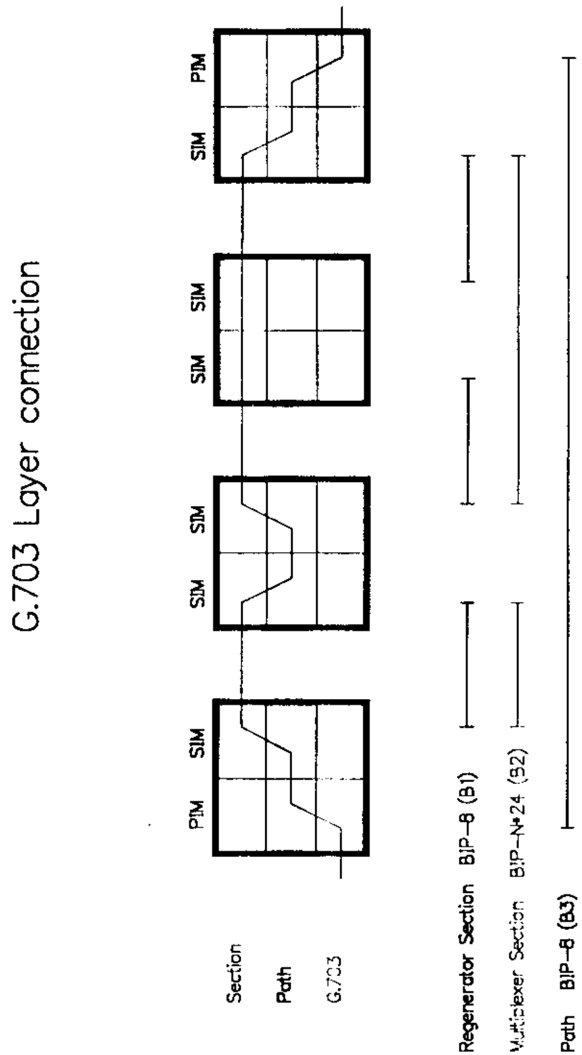
Terminal mux

MULTIPLEXER TYPES



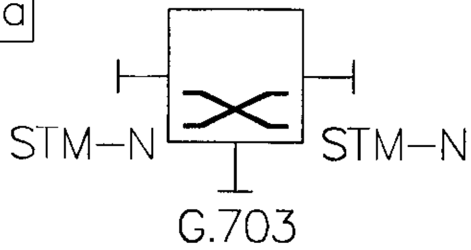


Terminal mux

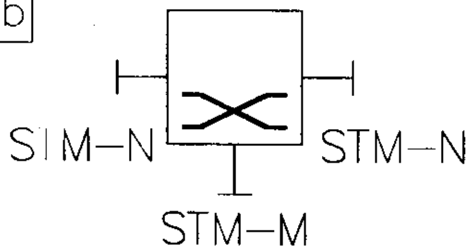


MULTIPLEXER TYPES

Type 3a



Type 3b



Add/Drop Mux

SDH ADVANTAGES

* Worldwide standard
* Large market
* Simple add/drop functions
* Simplified maintenance
* Fast provision of services
* Carries both hierachies
* SDH is economical !

SDH DISADVANTAGES

* Standardization not completed

* Risc of flaws in standards
  due to accellerated procedure

* Very high software content
  in products

* Full SDH—advantage only when
  large part of network is SDH

Subject Future Optical Communication – II **Lesson** 2.7

Coherent Communication

What is Coherent Communication ?

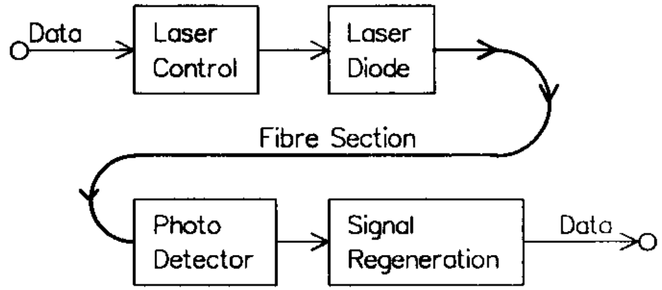
Why is Coherent Communication interesting ?

Which technical problems are there by Coherent Communication ?

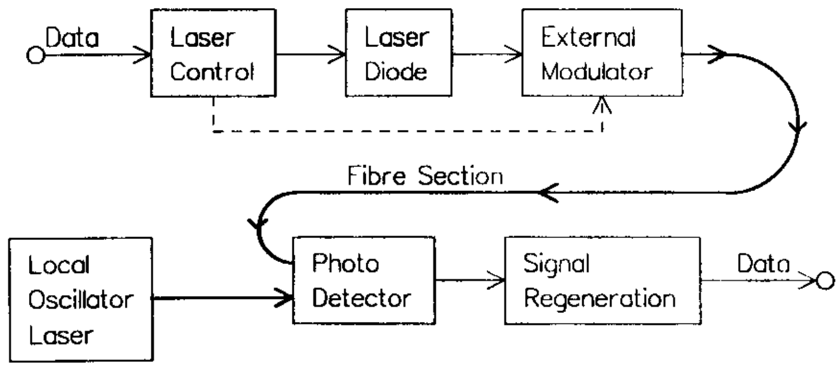
Subject Future Optical Communication – II **Lesson** 2.7

Fundamentals in Optical Communication

A. Direct Detection (DD) systems



B. Coherent Detection



The Photo Detector

Light – Current relation

$$i(t) = R \cdot P_{opt}(t) = k \cdot |E(t)|^2$$

$$\text{where } E(t) = z \cdot \sqrt{P_{opt}(t)} \cdot e^{j\omega t}$$

Photo current

A: Direct Detection

$$i(t) = R \cdot P_S(t)$$

Modulation: Amplitude–Modulation (ON/OFF)

B: Coherent Detection

due to interference between the optical fields

$$i(t) = k \cdot |E_S + E_{LO}|^2$$

$$\simeq R \cdot P_{LO} + \underbrace{2 \cdot R \cdot \sqrt{P_{LO} \cdot P_S(t)} \cdot \cos(\omega_{IF}(t) \cdot t + \Phi(t))}_{\text{Signal part}}$$

(when $P_{LO} >> P_S$)

Modulation: Amplitude/Intensity P_s (ASK)

Intermediat Frequence ω_{IF} (FSK)

Phase part Φ (PSK)

Coherent Detection technique gives:

Signal amplification by mixing with Local Oscillator,
the Signal is carried by the Intermediat Frequence ω_{IF}.
(Homodyne: $\omega_{IF} = 0$, Heterodyne: $\omega_{IF} \neq 0$)

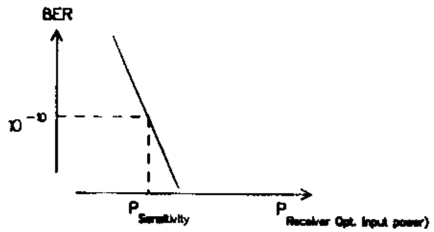
Subject Future Optical Communication - II **Lesson** 2.7

Advantages by Coherent compared to DD

A. Receiver Sensitivity Improvement

Definition of sensitivity

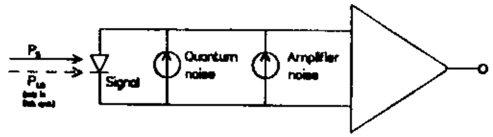
Lower optical input power level
corresponding to a given BER (Bit Error Rate)



The sensitivity is given by the Signal to Noise Ratio

Subject Future Optical Communication - II **Lesson** 2.7

Noise in Optical Receivers



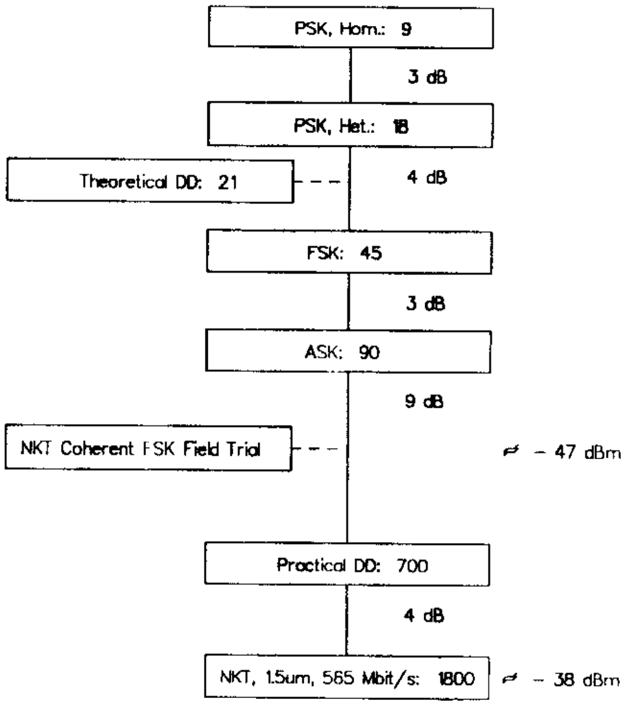
Signal and Noise for DD and Coherent Detection:

	Direct Detection	Coherent Detection
Signal	$\propto P_S^2$	$\propto P_S \cdot P_{Lo}$
Quantum noise	$\propto P_S$	$\propto P_{Lo}$
Amplifier noise	Const.	Const.
Signal/Noise	$\propto \frac{P_S^2}{P_S + Const.}$ $\propto \frac{P_S}{1 + \frac{Const.}{P_S}}$	$\propto \frac{P_S \cdot P_{Lo}}{P_{Lo} + Const.}$ $\propto \frac{P_S}{1 + \frac{Const.}{P_{Lo}}}$

Note: $P_{Lo} \gg P_S$

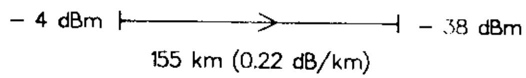
> The Signal to Noise Ratio is improved due to the Local Oscillator Mixixing

Sensitivity limits (photons per bit)



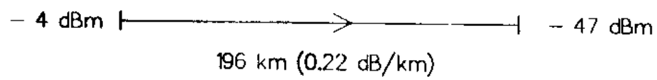
Note: The limits for the Coherent
Systems can only be obtained when
sufficient Local Oscillator power is available

Existing NKT 565 Mbit/s 1.5 um systems

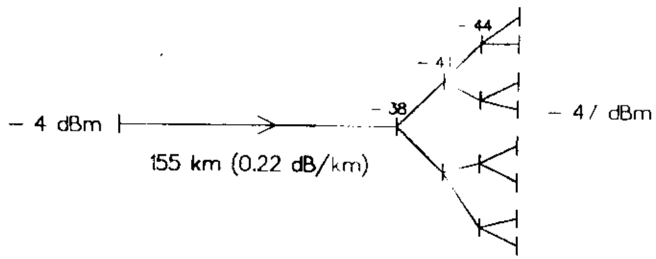


Use of ex. 9 dB sensitivity improvement:

Increase of the regenerator section length

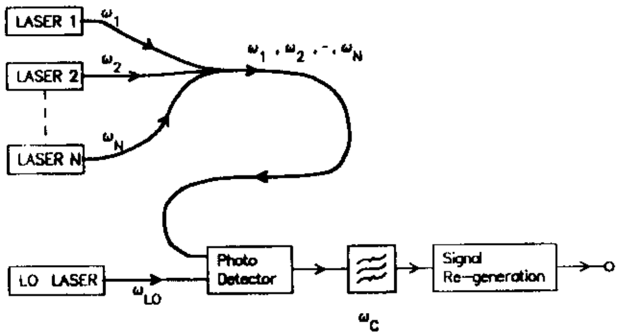


or passive distribution



B. Frequency Multiplexing

Many channels are transmitted at
different Optical frequencies
on only one fibre.



Frequency selection on IF level

$$\omega_N - \omega_{LO} = \omega_C$$

Channel width (when smallest channel seperation):

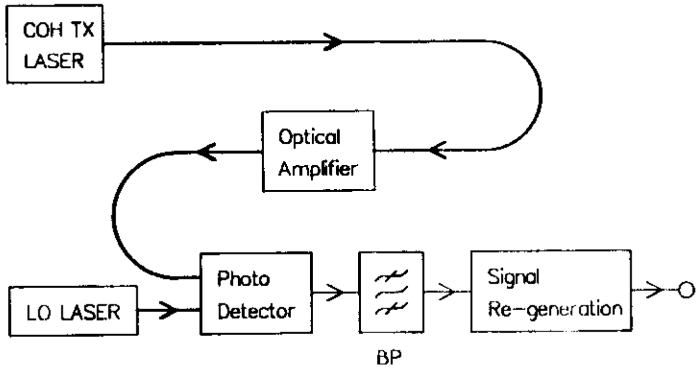
Homodyne: 1 times the bitrate

Heterodyne: 2 times the bitrate

Example: between 1540 nm and 1560 nm (Δf = 2500 GHz) about 2000 channels (each 630 Mbit/s) can be transmitted on one and only one fibre.

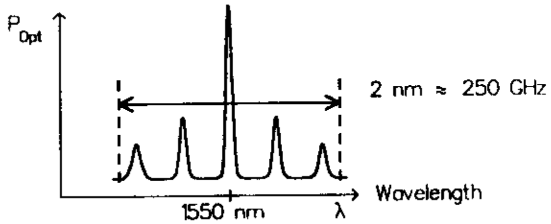
C. Including an Optical Amplifier

Optical Amplifiers (characterised by broadbanded optical noise) could be placed in the optical path with more than 20 dB gain per amplifier



Technical Problems

A. Laser Linewidth



Coherent Detection limits the upper relative linewidth

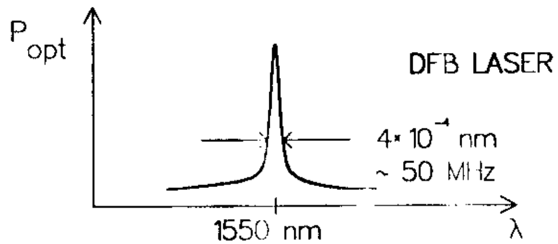
$$\Delta \nu = \frac{\nu_{IF}}{B}$$

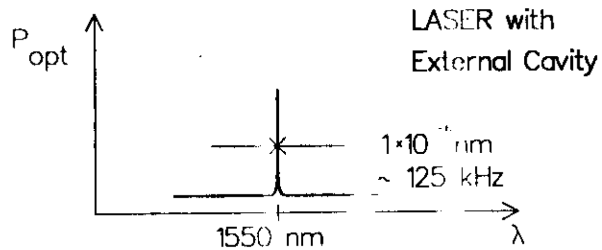
ν_{IF} = Linewidth on IF level
B = Bit rate

Note: The linewidth is the sum of the linewidth of the transmitter laser and the local oscillator laser.

Maximum relative linewidth

Modulation form		Δν	Δ f, B= 630 MHz
Phase Modulation	PSK	0.2 %	1.3 MHz
Differentiel PSK	DPSK	1 %	6 MHz
Frequency Modulation	FSK	15 %	100 MHZ
Amplitude Modulation	ASK	50 %	300 MHz

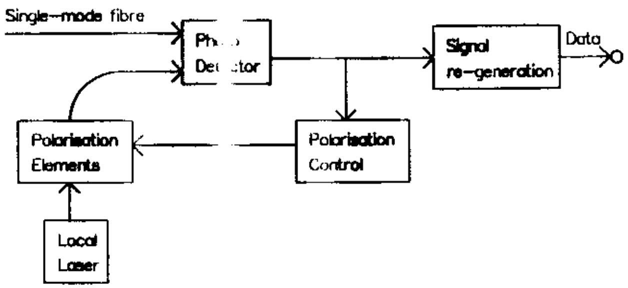




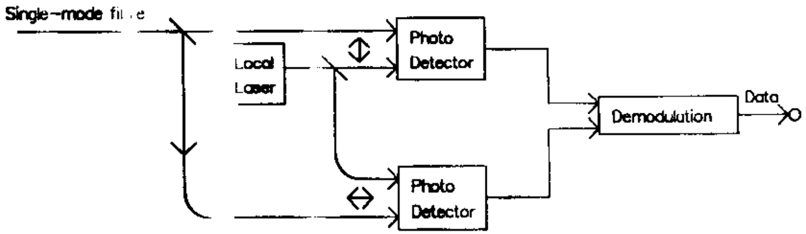
B. Polarisation

Ideel Mixing of the received optical signal requirers identical polarisation and field distribution.

1. Active Polarisation Control

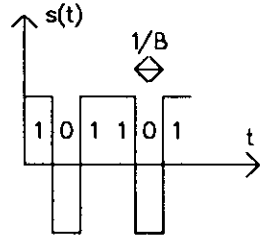


2. Polarisation independent receiver

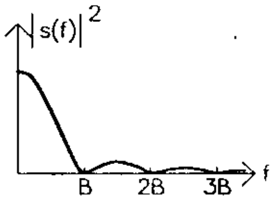


C. Receiver Bandwidth

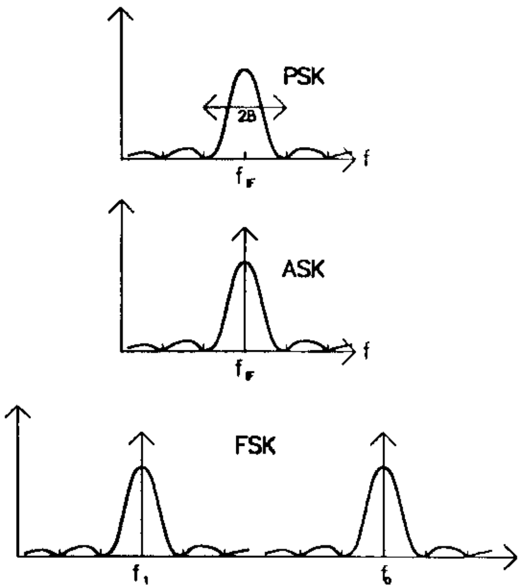
Digital signal



Frequency spectrum

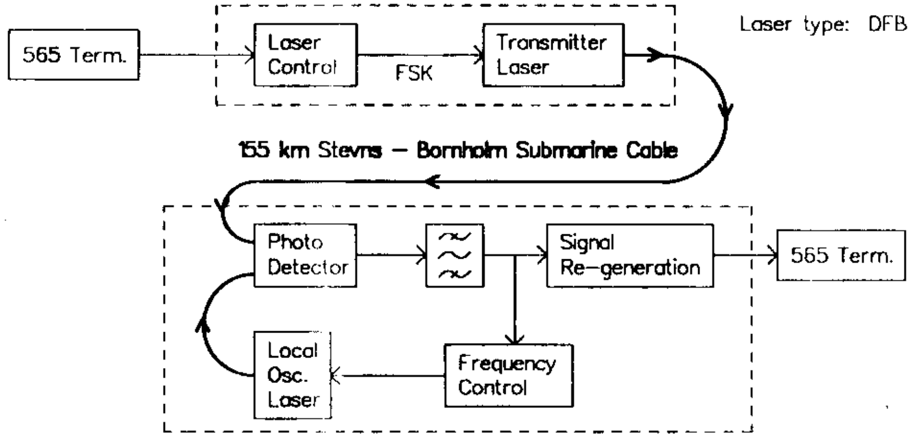


Spectra at IF level



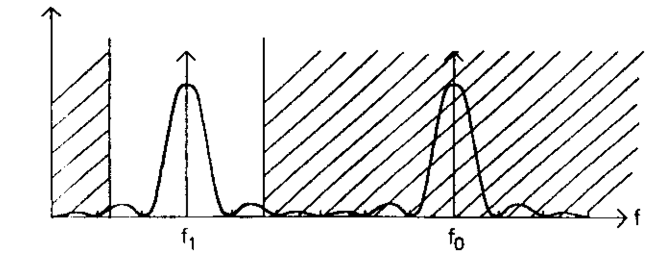
Coherent Field Trial

Laser type: DFB



Polarisation In-dependent receiver

Modulation Form: Single Filter FSK



IF Bandwidth: 2.7 GHz
IF center frequency: 2.7 GHz
Pass Band: 1.3 GHz – 4.0 GHz

COHERENT SYSTEMS

* IMPROVEMENT OF RECEIVER SENSITIVITY AT ALL BIT RATES

RESULTS OBTAINED AT NKT ELEKTRONIK

* 565 Mbit/s COHERENT TRANSMISSION WITHOUT ERRORS
* IMPROVEMENT OF RECEIVER SENSITIVITY BY 6 dB (SF–FSK)
* FIELD TRIAL SCHEDULED FOR JANUARY 1991

A. High Speed Communication (Giga bit communication).

Digital Telecommunication Bit Rates (1990).

* Commercially available : 0.6 Gb/s
* Presently developed/introduced : 2.5 Gb/s
* Reported experiments : 5–20 Gb/s

General problem.

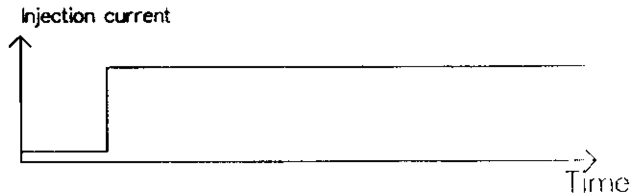
Designing electronics operating at GHz frequencies requires solid understanding of microwave technologies:

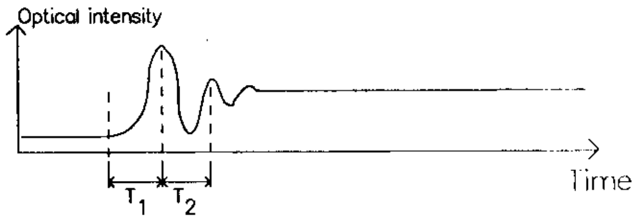
* Waveguide / Transmission line theory
* IC chip design (e.g GaAs)

Laser modulation concerns.

Relaxation oscillation, which is a laser resonance phenomena, leads to :

* Limited modulation
* Pulse distortion / pattern effect(shown below)
* Wavelength chirping / linewidth broadening





T_1 : Lasing delay

T_2 : Oscillation

Both T_1 anf T_2 must be small compared to a bit period.

Dealing with wavelength chirping

Wavelength chirping
+
Chromatic fibre dispersion ⟹ Pulse broadening

High bit rate (small bit period) makes pulse broadening fatal.

Wavelength chirping can be dealt with in several ways:

* Dispersion shifted fibres
* Low chirp lasers (e.g. MQW)
* External modulation
* FSK modulation / Optical bandpass filtering

Dispersion Shifted Fibre (DS fibre).

The DS fibre has zero dispersion at 1550 nm.

Drawbacks :

* Most already installed fibre is standard fibre.
* Higher loss than standard fibre.

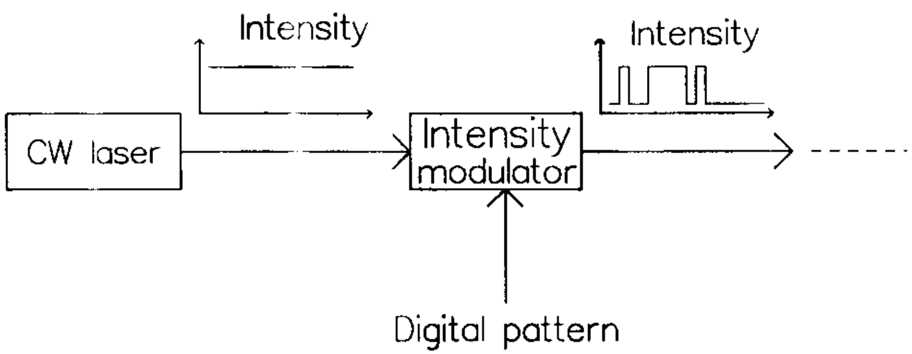
Low Chirp Lasers.

New laser structures like MQW (Multi Quantum Well) has higher resonance frequency.

Drawback :

* MQW lasers are not commercially available yet.

External Modulation.



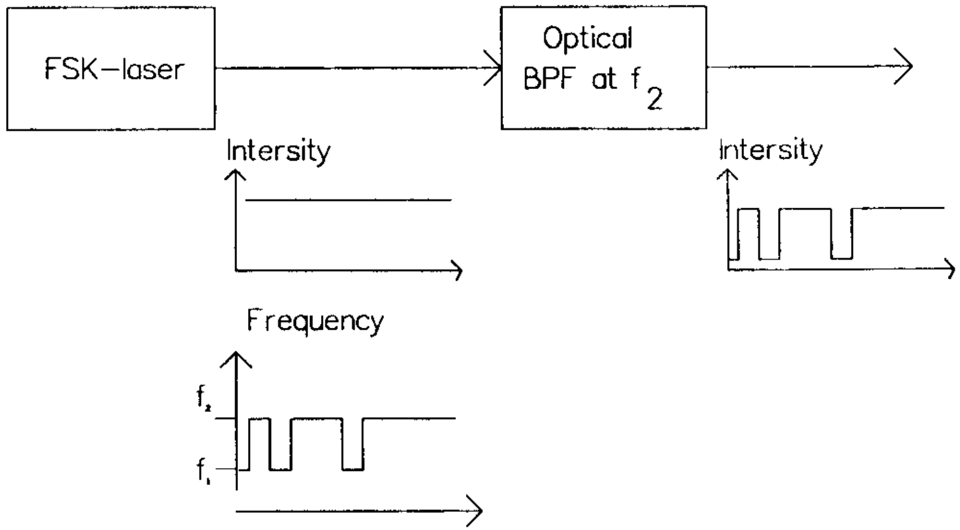
Intensity modulators can be made of $LiNbO_3$

Drawbracks :

* Insertion loss > 3 dB

* Typical drive voltage swing >5 dB
  (difficult at GHz frequencies)

FSK modulation/Optical bandpass filtering



The laser is frequency modulated (as with coherent communication). An interferometer filters one frequency away.

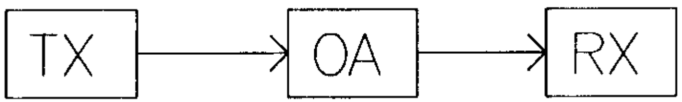
Drawback :

* Difficult to match laser and filter.

B. Optical Amplifiers (OA).

An OA amplifies optical signals without respect to:

* Modulation format (intensity, frequency or phase)
* Modulation speed

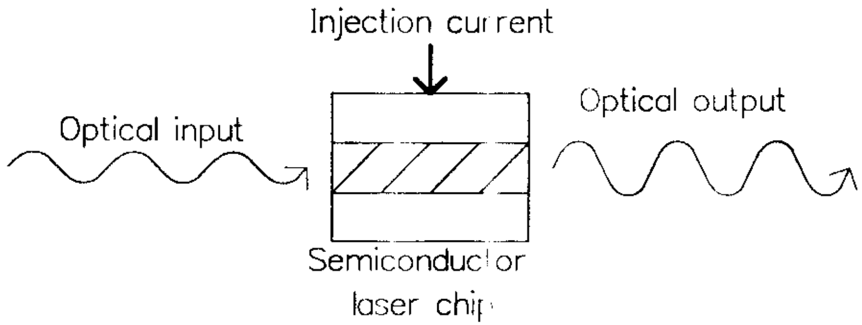


Goal: To compensate for transmission loss between TX and RX.

Amplifier types are:

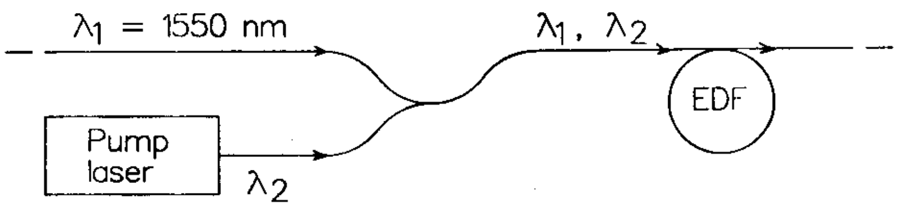
* Semiconductor amplifiers
* Fibre amplifiers

Semiconductor Amplifier.



A semiconductor laser chip with antireflection coated facets acts as optical amplifier.

Erbium Doped Fibre Amplifier.



λ_1 : Signal wavelength

λ_2 : Pump wavelength (e.g. 980 nm or 1480 nm)

EDF : Silica fibre with Erbium doped core

Amplification principle:

Strong pump power (e.g. 40 mW) is absorbed and converted into signal power by stimulated emission.

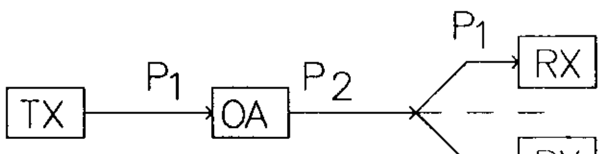
Amplifier characteristics:

Small signal gain: > 30 dB

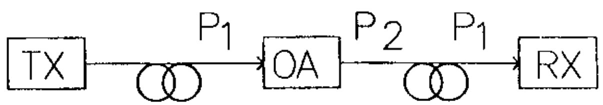
Maximum output power: > 10 dBm

Applications.

Transmission loss compensation:
(optical powers $P_1 < P_2$)



Branching loss comp.



Fibre attenuation loss comp.