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INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS
I.C.T.P., P.O. BOX 586, 34100 TRIESTE, ITALY, CABLE CENTRATOM TRIESTE

H4.SMR/453-7

**TRAINING COLLEGE ON
PHYSICS AND CHARACTERIZATION
OF LASERS AND OPTICAL FIBRES**

**(5 February - 2 March 1990)**

# FIBREOPTIC EXPERIMENTAL DIGITAL TRANSMISSION SYSTEM

**G. Guekos and M. Blaser**

**ETH Honggerberg
Zurich
Switzerland**

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ICTP, TRIESTE, 5.FEBRUARY - 2. MARCH 1990

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by G. Guekos and M. Blaser, ETH Zurich, Switzerland



## FIBEROPTIC EXPERIMENTAL DIGITAL TRANSMISSION SYSTEM

The purpose of this experiment is an introduction to the art of the communication technology through optical fibers.The aim is to assemble a transmission system from commercially available devices and circuits,to characterize the performance of the system with measurements and to compare the results with theoretical predictions.

In the first part of this manuscript some basic information on fiberoptic communication technology is given. In the second part experimental details of the system to be built are described and the required measurements are explained.

## PART ONE

## INTRODUCTION TO THE FIBEROPTIC COMMUNICATION TECHNOLOGY

In this part a general introduction to the state of the art of the transmission technology through optical fibers will be presented.This introduction will concentrate on methods,devices and circuits that are widely used in this technique today and will be also used in the present experiment.The aim of this introduction is to bring the reader who has no deep knowledge of optical communications in acquaintance with some basic facts so that he can proceed easily with the experiments that follow this section.

### INTRODUCTION AND MOTIVATION

The advent of the fiberoptic transmission in the seventies has opened a new era in telecommunication technology.The reasons for the rapid advance of the fiber communications lie in the significant technical and economic advantages of the new technology as compared with the classical transmission methods using metallic wires.We are now witnessing a tremendous changeover from wires and coaxial cables to fibers in that broad application area usually called information services.It can reasonably be anticipated that in the future most telephones, television sets,personal computers and large computers,machines, instruments and the like will be linked by fibers.

In order to provide a first technical background,it seems useful to give the main advantages and special features offered by optical fibers.

#### Large information transmitting capacity

Today's widely used monomode fibers, associated with high-speed lasers and receivers are capable of transmitting digital information in the multi-Gbit/s range and have bit-rate times distance products of several hundred Gbit/s.km.Even simple multimode graded index fibers have bit-rate times distance products of at least several hundred Mbit/s.km.In transmission lines with heavy traffic the large carrying capacity of the fiber offers a clear economic benefit by reducing the cost per channel.This large capacity is possible because of the following two major fiber characteristics:

**Very low loss.**
Fibers drawn routinely have reached loss figures of about 0.2 dB/km at 1.55 μm wavelength, 0.5 dB/km at 1.3 μm and 2.5 dB/km at .85 μm. These low loss figures are currently permitting long distance applications with wide repeater spacing - over 50 km - and short haul applications with no repeaters.In comparison,coaxial cable systems would need,depending on the bandwidth to be transmitted,repeater spacings of several hundred meters to a few kilometers.



**Very low dispersion**
Dispersion is the term associated with the physical effect that limits the useful bandwidth of a fiber.The lower the dispersion,the larger the bandwidth.Since more will be said on dispersion in one of the following paragraphs we need only retain here that modern fibers have lowest dispersion values at 1.3 μm which correspond to large bandwidth x distance products ,i.e. at least 1 GHz.km for multimode fibers and significantly higher for monomode fibers.

#### Low cost

Since the basic material for fibers is glass - $SiO_2$ - with various dopants to control the refractive index, and because glass is very abundant in the earth's crust and only small quantities for the fabrication are needed,the fiber has the inherent advantage over the metallic copper cable of very low potential cost.Thanks to improved manufacturing techniques fiber cable costs per meter are in the same range as coaxial cables for comparable applications.An economic comparison,however,should consider the whole transmission system and not only the cable.In this respect,fiber optics feature much better than metallic cables at least in the long haul transmission application area because of the high information density they can carry which is more adapted to the increasing demands of the communication age.

#### Small size and weight

Compared to metallic cables,fiber cables have much less weight and are extremely compact so that savings in weight and volume can be realized in many applications like in PTT underground cable ducts,in in-house cabling for equipment and computer links,in aircraft wiring etc.

#### Electrical isolation

Due to the electrical insulator properties of glass,fiber cables are ideally suitable for use in applications where potential differences may appear between the ends of the cable.In addition fibers present no earth loop or EMP problems and they cannot produce sparkings from short circuit or abrasion effects.

#### Immunity to electromagnetic (EM) radiation and absence of radiation

Light travelling in a glass fiber is immune to EM interference and therefore the optical signal cannot be disturbed by environmental fields and by noise signals emanating from other sources.As a consequence, cross-talk which can be an annoyance in many metallic cable transmissions, is nonexisting in optical fibers. Also, a glass fiber in itself does not radiate radio or noise signals and so does not induce cross-talk to neighbour transmission lines.

#### High security

Compared to a metallic cable, it is very difficult - albeit not impossible - to tap an optical fiber and therefore the optical transmission bears in itself a high degree of security.

The above characteristics clearly demonstrate the attractivity of the glass fiber for the transmission of information in a broad bandwidth and up to very long repeaterless distances. We now turn our attention to the basic elements of a fiber transmission system and discuss their respective functions.

BASIC SYSTEM CONSIDERATIONS

The block diagram of a fiber communication system is given in Fig.1.

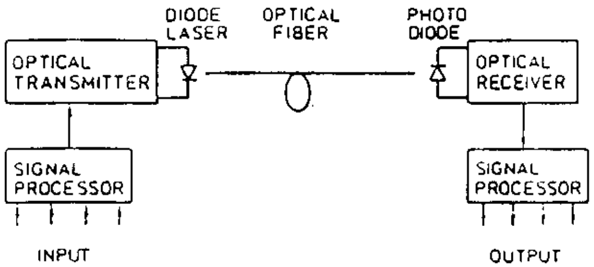



Fig.1 Block diagram of a fiberoptic point-to-point communication link.

The main parts of the system are:

The optical transmitter

The most important components of the transmitter are the optical source, which is a laser diode or a light emitting diode LED, and the signal processor/modulator which modulates the current through the source and consequently the optical beam intensity with the signals to be transmitted.

Laser diodes (LD's) and LED's are widely used devices in optical communications.They have the merit to allow direct modulation on their output intensity by simply varying the diode current. This can be done at low electric powers - typical voltages are 2 - 3 V and currents 50 - 100 mA - and up to very high frequencies. A LD can be modulated from dc up to some GHz whilst the upper frequency is somewhat lower for a LED, perhaps a few hundred MHz. The advantage of the LD over the LED is not only the larger frequency range. LD's can inject significantly more optical power into the fiber as compared to the average LED. The amount of power coupled to the fiber depends on a number of factors but if we take a typical 1.3 μm monomode fiber system, the signal power coupled from a LD amounts to a few mW whereas less than 100 μW can be coupled from the LED. As a consequence, systems with LD's allow the implementation of long unrepeatered transmission lines but LED's are restricted to short communication lines.



The function of the processor/modulator is to electronically process the incoming signals for the type of modulation - digital or analog - and for the modulation format - AM, FM, PPM, PCM etc - to be used and to impress a modulation current to the diode. The circuit that modulates the diode is usually called a driver and it acts as a current source for the diode.

The optical fiber

The optical fiber cable is made up of a number of fiber sections - for long-distance lines sections of a few kilometer each are used - which are connected together to form the desired transmission length. If we take into consideration the small cross sections of the fibers with core diameters ranging from several μm for monomode to 50 μm for multimode fibers it becomes clear that connecting and disconnecting fibers may present a practical difficulty which does not exist in coaxial cables. The same applies to the coupling of the fiber to the optical source and to the detector. As the technology advances, however, high quality fiber joints and couplers are gradually becoming available which cause very little additional loss or other disturbances in the system.

As the signal travels down the fiber line it becomes attenuated because of losses and scattering in the glass and also distorted due to the dispersive effects of glass. As a result, a weak signal of about some μWatts or even less will appear at the fiber end and will impinge onto the optical detector.

The optical receiver

The receiver contains the photodetector device for the conversion of the optical signals into electrical signals and electronic circuits for amplification and signal processing. The detector is usually a semiconductor photodiode (PD) which may have internal amplification of the photogenerated electrical carriers and is then called a avalanche photodiode (APD).

A crucial parameter in receiver design is the noise of the detector circuit. The signal-to-noise ratio (SNR) is determined by the noise characteristics of the PD or APD, the noise of the following amplifier and by the power reaching the detector. One feature that distinguishes an optical receiver from an electrical receiver of a conventional coaxial cable communication system is that the optical receiver noise contains a component which is proportional to the received optical power. As a result, the noise power will be signal dependent.

The SNR determines the quality of the received signal. In a digital system the SNR is directly linked to the probability of error in deciding whether or not a pulse has been transmitted.This probability is called bit error rate (BER) and the maximum value tolerated for a digital system is usually equal to $10^{-9}$ which means that the maximum detection error allowed is one bit out of a stream of one billion bits. How does an optical fiber communication system compare with a classical coaxial cable system with regard to the maximum repeaterless distance? The answer will of course depend on various parameters such as modulation type and format, bandwidth and bit rate etc. In order to set a frame for the comparison, let us suppose that we consider the transmission of a pulse code modulated (PCM) signal at a rate of 140 Mbit/s ( european time division multiplex hierarchy ). The results are summarized in the following table:

| Transmission medium | Transmission Capacity Telephone channels | Repeater Distance km |
|---|---|---|
| Optical fiber (LD, monomode) | 1920 | 40 - 60 |
| coaxial cable | 1920 | 2 - 3 |

For a point-to-point long distance transmission the benefit of using optical fibers is clearly demonstrated from the table. This together with other advantages offered by the fiber technology is the reason of the rapid growth of the optical communication links.

Let us now have a look into the different blocks of a typical fiberoptic system. The various devices and circuits will be shown and their respective functions explained.

## OPTICAL SOURCES AND TRANSMITTERS

The most important optical source for a fiber system is by far the laser diode (LD). However, for relatively low bit rates - i.e. less than 140 Mbit/s - and for short repeaterless links - up to a few km - the light emitting diode (LED) may bring some advantages in terms of circuit simplicity and reliability. Only the LD is introduced here, the basic physical principles underlying its operation are explained and the main characteristics discussed.

### The laser diode for optical communications

A laser diode is a semiconductor pn-junction device that emits laser light when a bias voltage in the forward direction is applied across its terminals.There are several types of LD's, the most important of which for fiberoptics applications are the following:

GalliumAluminumArsenide/GalliumArsenide (GaAlAs/GaAs) emitting at a wavelength of about 0.8 μm, and, IndiumPhosphide/IndiumGalliumArsenidePhosphide (InP/InGaAsP) emitting at 1.3 and 1.55 μm depending on material composition.

The choice of the right type of LD depends on the application envisaged. For very long repeaterless distances and high bit



rates a InP/InGaAsP LD should be chosen because at 1.3 and 1.55 μm the best results regarding bandwidth x distance product can be obtained from monomode fibers. The GaAlAs/GaAs LD can be used in short distance links - 5 to 10 km - and at moderate bit rates.

The light generation mechanism of a LD and a LED is basically the same. Because of the external voltage applied, electrons and holes are flowing in the semiconductor in opposite directions. A large number of these carriers recombine with each other and release the recombination energy in form of photons that propagate isotropically in the semiconductor.One important difference between a LD and a LED is the fact that two opposite end surfaces perpendicular to the pn-junction of the LD are formed as mirrorlike planes, strictly parallel to each other. This configuration is called an optical resonator or a Fabry-Perot resonator.We can conceive the optical resonator as the cavity formed by the two mirrors and filled with the semiconductor layer where most of the photons are produced. We call this layer the "active layer" of the LD. Fig.2 shows the principle of a LD.

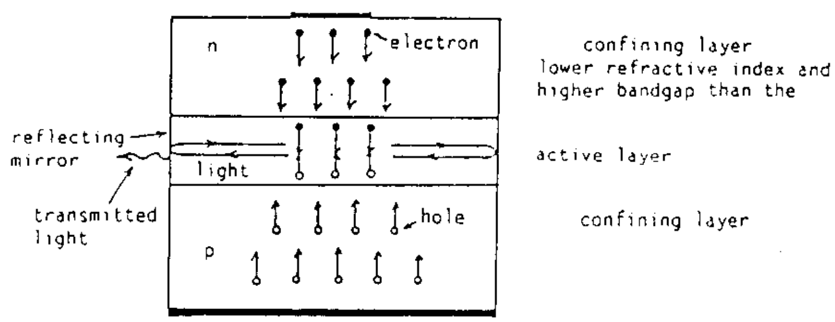



Fig.2 Principle of a semiconductor diode laser with a double heterostructure. LASER = Light Amplifier by Stimulated Emission of Radiation

This is now how the laser light is generated in the LD. Of all the photons created in the active layer a large part will propagate away and will escape from the semiconductor-air interfaces after suffering a certain attenuation in the material. This is the "spontaneous radiation" and is physically the same as in a LED. A small part of the generated photons, however, will strike the mirrors perpendicularly and will be reflected back into the active layer with a reflection coefficient of about 35 %. These photons will be amplified in number as they travel back and forth through the active layer provided that the semiconductor is energetically inverted which means that there are much more free electrons in the conduction band of the semiconductor than in the valence band.We call this state of affairs a "population inversion". The amplification of the number of photons is accomplished by a process called "stimulated emission" in which a photon can create an exact replica of itself and travel with it further in the material.

There are, however, also some loss mechanisms that cause an attenuation of the light that is being reflected between the mirrors. The most important are absorption and scattering in the layer and reflection losses at the mirrors. When the amplification of the light intensity exceeds the losses, a laser oscillation starts. We can increase the amplification, i.e. the optical gain by simply increasing the current through the diode. The current needed for the laser oscillation to set-in is called the threshold current. In actual LD's this current lies between 20 and 100 mA at room temperature.

The light that escapes from the partially reflecting mirrors is the laser beam that can be coupled into the optical fiber or can be used for monitor purposes. Inside the diode standing waves are built-up between the mirrors which obey the simple relation:

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

where L is the distance between the mirrors (cavity length), n the refractive index, $\lambda$ the wavelength and q an integer. 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.

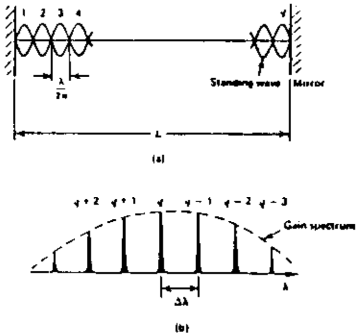



Fig.3 Standing waves in a laser resonator (a) and gain spectrum with longitudinal modes (b)

The wavelengths that are present in the laser beam are called axial or longitudinal modes of the laser. The mode spacing between two consecutive modes is:

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

For example, in a .8 μm LD having n=3.5 and L=300 μm, $\Delta\lambda$ becomes 3 A. The number q itself is large, q=2625



Depending on the application one or more axial modes are desired. The corresponding LD's are then called monomode or single-mode and multimode LD's. Although the number of modes can be influenced by the diode current, i.e. by the shape of the gain curve, it is the geometry of the laser and the physical parameters of the semiconductor layers that determine the monomode or multimode character of the laser. Fig.4 shows optical spectra of a commercially available monomode and a multimode LD.

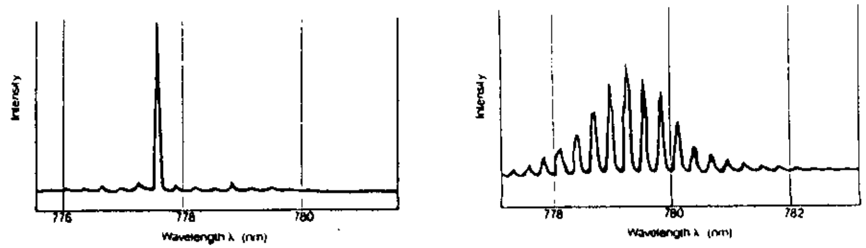



Fig.4 Intensity spectra of a monomode (left) and a multimode (right) LD

Let us now have a closer look into the actual geometry of a .8 μm GaAlAs/GaAs LD. Fig.5 shows a schematic representation of such a LD and a fiber positioned in front of it.

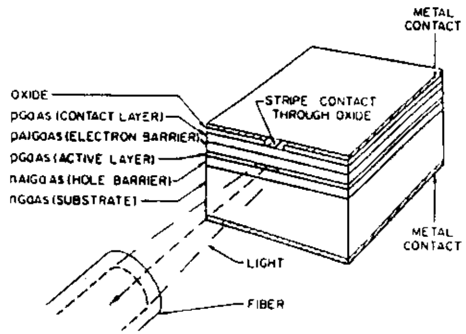



Fig.5 Schematic diagram of a stripe contact gain-guided LD

The diode consists of thin semiconductor layers grown onto a GaAs substrate. We notice that the active layer is enbedded between two layers made of GaAlAs. This structure is called a "double-heterostructure" and it has two very important consequences for the operation of the diode:

a. The active layer - GaAs - has a higher index of refraction than the two adjacent layers. Oblique rays that originate in the active layer and are incident to the GaAs/GaAlAs interfaces undergo total internal reflection due to the well known law of optics. The rays are thus guided along the layer by multiple reflections until they reach the end mirrors where they are again reflected back into the layer.In this way the photons are confined in the GaAs layer where they are amplified by stimulated emission. This effect is called "optical confinement"

b. The active layer has also a smaller energy band-gap than the GaAlAs layers. The electrons flowing from the n- into the p-semiconductor find a potential barrier at the GaAs/p-GaAlAs interface.The same reasoning applies for holes which find a potential barrier at the GaAs/n-GaAlAs interface. The consequence is that the electrons and the holes are made to recombine in a geometrically well defined region between the two potential barriers, the active layer. This effect - the "electrical confinement" - makes it easier to obtain a high photon density in the thin active layer ( ~0.1 µm ), to invert the population and to achieve laser action by stimulated emission of radiation.

Not the whole GaAs layer is however inverted in the practical situation but only a 5 to S µm wide zone is made to act as the laser cavity, as shown in Fig.5. In the figure, the lateral confinement of the zone and thus its width is determined by the current flow. A stripe contact on the p side is formed by using an intermediate oxide isolating layer and the current flow is consequently confined in the middle of the active layer. This type of laser is called a "gain-guided" LD. It is also possible to confine the zone by using lateral material of lower index of refraction ("index-guided" LD).

The light-current characteristic of a typical .8 µm LD is given in Fig.6 where the cw ( cw=continuous wave ) optical power emitted from one of the two laser facets is plotted against the dc diode current.

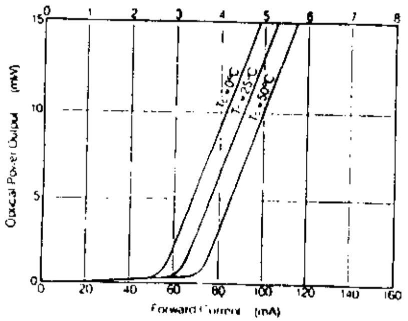



Fig.6 Optical power versus dc laser diode current at different temperatures



Below the threshold current the optical power is very low and changes little with current. However, after the laser threshold is reached, the power increases steeply and approximately in a linear fashion with current.At room temperature power levels of at least 10 mW are easily obtained with low-priced commercial LD's whereas LD's offering powers in the .1 to 1 Watt range are also available. It is also clear from Fig.5 that the power output of LD's is very temperature sensitive. Since in most applications temperature variations can be expected, it is necessary to control the temperature of the package mounting and to provide an electronic feedback loop for the LD current in order to obtain a constant optical power. Unlike with most other laser sources, the beam emitted from a LD shows a poor collimation as is demonstrated in Fig.7. The space distribution of the light intensity away from the laser, the so-called "far-field", has typically an elliptical shape which is due to optical diffraction effects at the boundaries of the optical resonator cavity. In plane parallel to the junction the full angle at half peak intensity is about 20 to 40° but it becomes larger when measured vertical to the junction to about 30 to 60°.

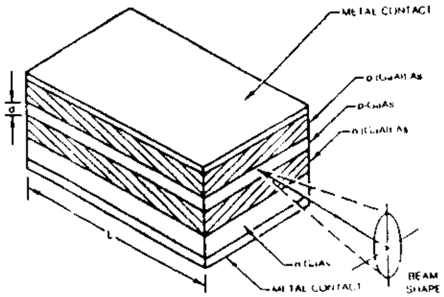



Fig.7 Schematic diagram of a double-heterostructure LD showing the far-field pattern of the radiation emitted from an end mirror

It is clear from Fig.7 that the use of appropriate lenses is mandatory if a parallel laser beam is required.

The light from the LD is partially polarized. The direction of polarization is parallel to the junction and the degree of polarization can be better than 90 % when the LD is operated well into the lasing region.

What is important in a fiberoptic telecommunication system is not the power emitted by the laser but the power that can be coupled into the fiber. The reason that not all the power from the LD can be coupled into the fiber is that the intensity field pattern of the LD is not matched to the field pattern that is accepted by the fiber. Some popular methods of coupling a LD beam into a 50 µm core multimode fiber are shown in Fig.8.

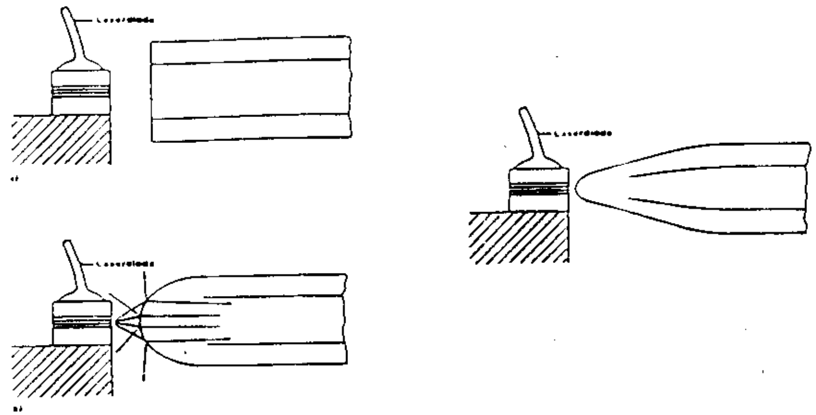


Fig.8 Some coupling methods between a LD and a multimode fiber

Direct coupling (" butt joint") results to about 35% efficiency (a). If the fiber end is molten as a spherical lens, about 50% efficiency is obtained (b). Still higher efficiency is achieved, about 60% if a tapered fiber is used (c). It is of course more difficult to couple LD's with monomode fibers because of the small dimensions of the fiber core (diameter ~8 μm). The use of taper lensed fibers has been quite successful with efficiencies ranging from 20 to 45%.

The straightforward method to modulate the light intensity of a LD is to modulate the diode current. The usual way to do so for the transmission of digital signals is to apply a dc current near the threshold current and to add an incremental current in order to modulate the laser from low (off) to high (on) optical output see Fig.9.

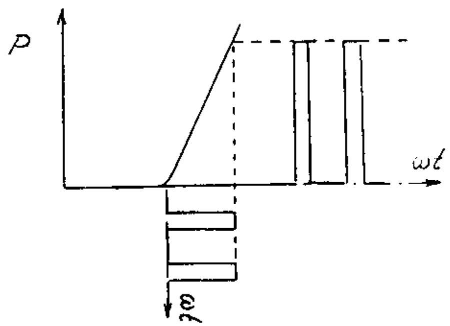



Fig.9 Current modulation of the LD intensity with a digital signal



The application of a dc current is necessary for the elimination of the turn-on delay that would otherwise be present if the diode is pulsed from zero current. The response speed of the LD is usually a fraction of a nanosecond thus allowing modulation bandwidths of several GHz if the device is mounted on a high-speed package. Even low-priced LD's in "compact disc" mounts can achieve several hundred MHz modulation bandwidths without undue difficulty. Special LD's have been demonstrated that reach bandwidths in excess of 20 GHz.

The modulation of the laser output is accomplished by use of electronic drive circuits that generate the needed dc and ac components of the LD current. The impedance of the LD is usually low - typically 3 to 5 ohms - and the electronic driver circuit is thus acting as a current source.

Modulating a LD is more demanding than modulating the output of a LED. The reason is the threshold characteristic of the laser output and the significant temperature dependence of the light-current curve. It is thus necessary to provide an adjustable bias current to the LD in order to compensate temperature and ageing variations. Moreover, an additional temperature stabilization using Peltier elements is required for most LD's in optical transmitter circuits. A simple LD drive circuit is given in Fig.10.

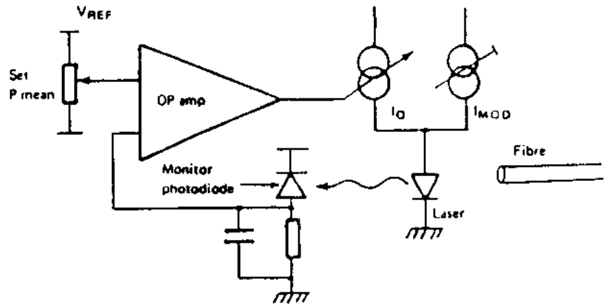



Fig.10 A laser drive circuit providing a dc and a modulation current to the LD and a feedback for stabilizing the mean optical power

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 by detecting the light from the rear facet of the LD - the light from the front facet being coupled to the fiber - with a monitor photodiode and using the photovoltage in a feedback loop to set the bias. The feedback circuit is made to have a slow frequency response and so the mean power determined by the dc and the modulating 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 laser. This disadvantage is eliminated in the circuit of Fig.11.

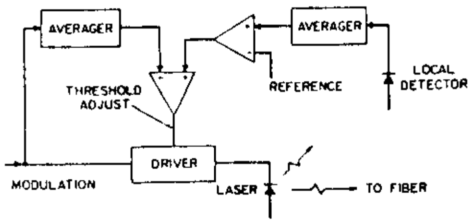



Fig.11 Laser drive circuit that monitors the modulating signal to provide a reference for the feedback loop

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 with 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.

## FIBRES FOR OPTICAL COMMUNICATIONS

The main types of optical fibers that are extensively used in signal transmission are presented and their relevant optical characteristics discussed. Light propagates in a fiber according to the laws of reflection and refraction. Although these laws are known for centuries, serious attemps to send communication signals through fibers began only in the 1960's. Today, fibers dominate the long-distance point-to-point cable links and are on the verge of large scale implementation in the local area networks. The reasons for their tremendous expansion are their advantages as compared to metallic wires and particulary the combination of low attenuation and high bandwidth.

### Fiber geometry and light propagation

The fibers used widely today are the step-index and the graded-index fiber. 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 $n_2$. Plastic coating is used for mechanical protection.



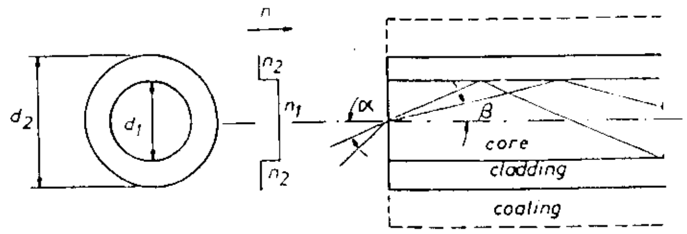



Fig.12 Step-index multimode fiber with index profile

Fig.12 shows schematically a step-index multimode fiber of the type used in communications.The light rays propagate through the fiber by total internal reflection at the core/cladding boundary.The figure shows two meridional ray paths. Of course,non-meridional rays can also propagate. They are called skew rays. A ray incident on the front end of the fiber at an angle α is refracted at an angle β and falls on the core/cladding interface with an angle 90-β. For total reflection to occur the relation

$$\cos\beta < n_2/n_1$$

must be satisfied. This relation leads to the maximum angle $\alpha_m$ that that can support total reflection:

$$\sin\alpha_m = n_1 \sin\beta = (n_1^2 - n_2^2)^{1/2} = NA$$

NA is the numerical aperture of the fiber. The NA and the core diameter determine the coupling efficiency to a light source. Sometimes the quantity Δ is introduced:

$$\Delta = (n_2 - n_1)/n_1$$

The NA then becomes:

$$NA \approx n_1 (2\Delta)^{1/2}$$

To illustrate the above relations we consider a step-index fiber in air with $n_1$=1.52 and $n_2$=1.50. We calculate:

$$\Delta \approx 0.013, \quad NA \approx 0.25, \text{ and}$$

$$\alpha_m \approx 14.3°$$

Step-index fibers for communications have often standardized core/cladding diameters. A typical example is 50/125 μm with NA values around 0.2.

The main disadvantage of the step-index fiber is its limited bandwidth which is caused by the mode dispersion. As indicated in the figure, different angles α give rise to different ray paths, called modes, that travel different total lengths to the fiber end. The power of an optical pulse coupled into the fiber will be spread among the various modes having each its own travel time in the fiber. As a result the pulse will broaden as it propagates through the fiber. The larger the angle α the larger the number of guided modes. The NA thus also defines the fiber's bandwidth.

The graded-index fiber is fabricated so as to drastically reduce the mode dispersion. It is schematically represented in Fig.13.

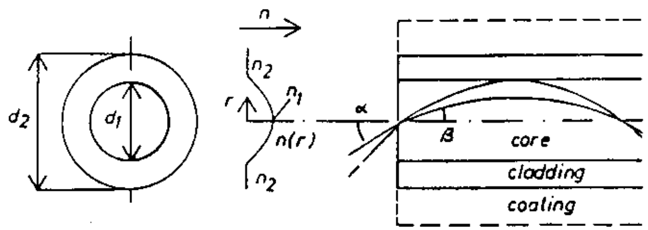



Fig.13 Graded-index multimode fiber with index profile

The refractive index of the core is now not uniform but has maximum value in the center and a minimum value at the boundary to the cladding. A typical index profile is shown in the figure. The profile causes the rays to follow smooth curves rather than the zig-zag of the step-index fiber. An outer ray traverses a longer path than a central ray but does so in a region where the velocity of light v=c/n is much higher than in the center region of the fiber. So,the longer path length is compensated by the higher speed and, ideally, no time delays between the different modes occur.

The NA is defined identically as for step-index fibers

$$NA = (n_1^2 - n_2^2)^{1/2}$$

and is typically about 0.2 for 50/125 μm fibers.A widely used index profile is given by:

$$n(r) = \left[n_1^2 - NA^2 \, (r/a)^f\right]^{1/2}$$

where a is the core radius. The optimum value of the parameter $f$ for minimum mode dispersion is close to two ( parabolic profile ) but this value is wavelength dependent. It is thus difficult to fabricate graded-index fibers that have a very large bandwidth in a broad wavelength range.

## Modes in a fiber

The concept of light rays and their total reflection at the core/cladding boundary may be simple but does not describe accurately the light propagation in a fiber. Electromagnetic wave theory must be applied for the characterization of the exact propagation conditions in a fiber. One important result of this



theory is that only a limited number of modes are allowed to propagate that can satisfy a precise phase condition as they travel throught the glass waveguide. For step-index fibers this number N is given by:

$$N = V^2/2, \quad \text{where}$$

$$V = (2\pi a/\lambda) \cdot (n_1^2 - n_2^2)^{1/2}$$

being the wavelength in vacuo. For graded-index fibers with parabolic profile N must be divided by two.

Example: Let us calculate N for a step-index fiber with $n_1=1.52$, $n_2=1.50$, $2a=50\mu m$ and $\lambda=0.8\mu m$. The V value becomes

$$V = 48.26, \text{ and}$$

$$N \approx 1164 \text{ modes.}$$

It can be shown that if $V \leq 2.405$ only one mode may be propagated. In terms of the radius of the fiber this condition becomes

$$a \leq 2.405 \; /2\pi(n_1^2 - n_2^2)^{1/2}$$

If we use the same values as above the diameter 2a of a single mode - monomode - fiber should be less than 2.5μm at 0.8μm wavelength.

The highest performance in terms of bandwidth is indeed offered by the monomode fiber which is represented schematically in Fig.14.

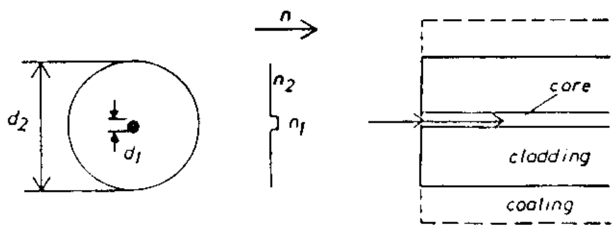



Fig.14 Single-mode (monomode) fiber with index profile

The monomode fiber is usually constructed as a step-index fiber having a small refractive index difference between core and cladding and a small core diameter - about 5 to 10 μm - that only one mode, having two polarization directions, can propagate. The diameter of the cladding is also 125μm as with the other types.

Although the optical coupling to sources and the mechanical requirements for connectors are more severe than with multimode fibers, monomode fibers are used widely in optical communications because of the higher performance they offer, not only for large distance but also for applications in local networks.

The optical attenuation in a fiber

In every type of fiber, the optical power will be attenuated as the signals travels through the glass waveguide. The attenuation can be described by the exponential law:

$$P(l) = P_o \exp(-\alpha_f l)$$

where $P(l)$ = optical power at distance l in mW
$P_o$ = optical power at fiber input in mW
$\alpha_f$ = attenuation coefficient of fiber in 1/km

Since it is more convenient to give the attenuation figures in dB/km, the equation can be rewritten as:

$$P(l) = P_o . 10^{-\alpha . l/10}$$

the attenuation coefficient α is here in dB/km.

The attenuation is wavelength dependent. Fig.15 gives this dependence for typical commercial fibers.

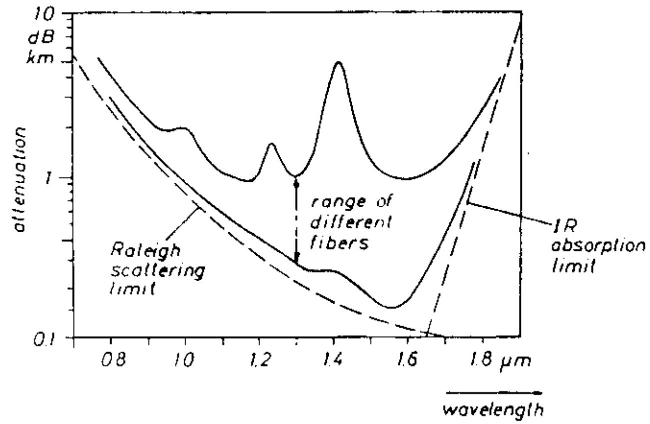



Fig.15 Wavelength dependence of attenuation for typical commercial fibers and theoretical limits of attenuation

The lowest attenuation occurs at 1.55µm where only 0.16 dB/km has been achieved at the laboratory whilst commercial fibers show slightly higher values. The attenuation at 1.3µm is less than 0.5 dB/km but increases to about 3 dB/km at 0.8µm wavelength. These values hold for low frequencies where the possible attenuation due to dispersion effects is negligible.



The physical causes of the attenuation are

# Rayleigh scattering,
# absorption, and
# bending losses.

The origin of the Rayleigh scattering is the structural and compositional non-uniformity of the glass material that causes light to be partially scattered in many directions. Since the structure of glass is finer than the wavelengths used, this scattering decreases with wavelength. It can be shown that it is proportional to $1/\lambda^4$.

Absorption in the visible and near-infrared arises mainly because of impurities present in the glass, like metal ions (e.g. $Fe^{3+}$, $Cu^{2+}$) or hydroxyl ions (-OH). Thanks to modern fabrication technology, the influence of the impurities has been minimized.

Other causes of dispersion and fiber bandwidth

As we have seen, the obvious way to eliminate multimode dispersion is the use of monomode fibers. Even then, however, there remain other causes of dispersion that prevent the fiber bandwidth becoming infinite. These causes are effective when the source used is not perfectly monochromatic as is of course the case with all real optical sourses. Two additional dispersive effects are due to

# material dispersion, and
# waveguide dispersion.

Fig.15 shows schematically the dispersion causes and how they add up to the total dispersion.

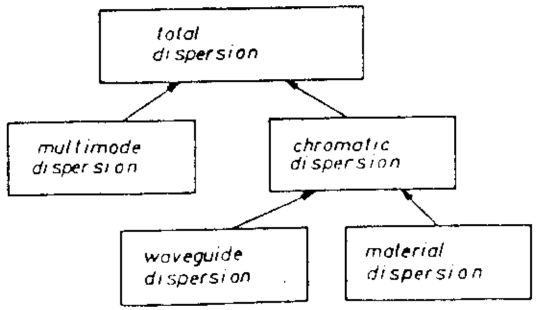



Fig.16 The various dispersion causes in a glass fiber

Material dispersion is due to the wavelength dependence of the refractive index. Since an input pulse can never be monochromatic, the various wavelengths composing the pulse will travel at different velocities and the pulse will broaden at the fiber output.

<u>Waveguide dispersion</u> arises because - as can be shown theoretically - the velocity of a mode depends on wavelegth via the parameter V. This applies even if the refractive index were independent of wavelength. The waveguide dispersion is for monomode fibers used in telecommunications much smaller than the material dispersion. Both dispersion types cause the so-called <u>"chromatic dispersion"</u>.

Let us now consider the material dispersion. Theory demonstrates that the spread in time of an initially very narrow pulse after travelling a distance l is given by:

$$\Delta t_{mat} = (-l.\lambda/c)(d^2n/d\lambda^2)\Delta\lambda$$

where $\Delta\lambda$ is the optical spectral width of the source. This relation shows the advantage gained by using lasers with narrow spectra against LED's which have much broader spectral widths.

An interesting fact about the material dispersion is that it becomes zero in pure silica glass ($SiO_2$) at a wavelength around 1.3µm, Fig.17.

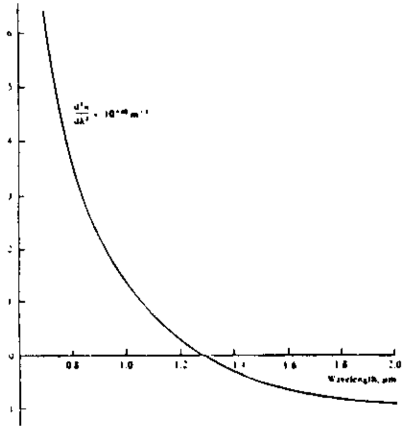


Fig.17 Variation of the quantity $d^2n/d\lambda^2$, which is proportional to the material dispersion, with wavelength

The consequence is that a <u>narrow spectral source</u> emitting at this wavelength will generate only <u>negligible pulse spread</u> thus resulting in <u>higher bandwidth</u>. It is also interesting to note that the sign of the dispersion becomes negative after crossing the point of zero dispersion and has thus the opposite sign as the waveguide dispersion. It should then be in principle possible to compensate material and waveguide dispersion by carefully choosing the wavelength of a very narrow source in a monomode



fiber link. Although this is very difficult to achieve in practice, monomode fibers with only a few ps $km^{-1}nm^{-1}$ dispersion are commercially available. The nm data defines here the spectral width of the source.

The dispersion effects are usually characterized and measured in the <u>time domain</u> (ns/km) or <u>frequency domain</u> (MHzxkm). A precise theory is fairly complicate but a simplifying approximation can be made by assuming the fiber to behave as a <u>Gaussian low-pass</u> filter. If the input optical pulse to the fiber is Gaussian at $w_1$ full width at half maximum (FWHM), the output will also be Gaussian at $w_2$ FWHM, see Fig.18.

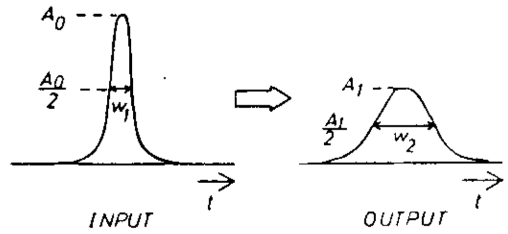



Fig.18 Optical Gaussian impulses at input and output of fiber

Let us consider for the following a <u>standard length of 1 km</u>. The fiber dispersion characterized by the spread $t_f$ will be:

$$\Delta t_f = (w_2^2 - w_1^2)^{½} \text{ in ns or ps}$$

Here $\Delta t_f$ means the total dispersion which is composed by <u>mode, material and waveguide dispersion</u>

$$\Delta t_f = (\Delta t_{mod}^2 + \Delta t_{mat}^2 + \Delta t_{wav}^2)^{½}$$

<u>Example:</u> Let us consider a 50/125µm graded-index fiber of 1 km length and let us assume that its mode dispersion is 300ps. The fiber link has a laser source at 0.8µm of 40 A spectral width (FWHM) and the material dispersion of the fiber at this wavelength is 100 ps $km^{-1}nm^{-1}$. We neglect the waveguide dispersion. The pulse spread due to the material dispersion is consequently 400 ps $km^{-1}$. The total dispersion will be:

$$\Delta t_f = [(300^2 + 400^2)]^{½} = 500 \text{ ps for 1 km of}$$

fiber.

In the frequency domain, <u>network analysers</u> are used to experimentally determine the bandwidth. A typical set of input - output waveforms is given in Fig.19. The bandwidth of the fiber is determined as the 3 $dB_{opt}$ point or the 6 $dB_{el}$ point on the measured curve.

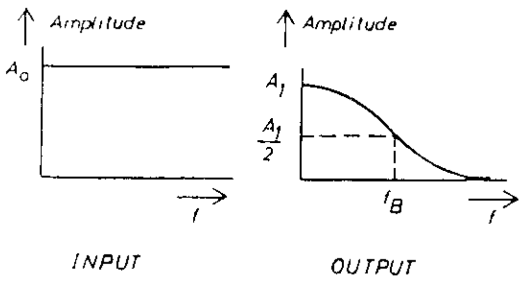



Fig.19 Frequency domain analysis at input and output of fiber for the determination of the transmission bandwidth

<u>Note</u> The validity of the relation $dB_{el} = 2 \times dB_{opt}$ is explained in the appendix

The relation between dispersion and bandwidth is simple if the assumption of a Gaussian behavior is made.

$$\Delta t_f = 0.44/B$$ B=Bandwidth in GHz and $t_f$ the dispersion in ns.

Using the practical example of above, the bandwidth of our 1 km long fiber is calculated as

$$B = 0.88 \text{ GHz}$$

We can increase this bandwidth by taking a monomode fiber (to eliminate mode dispersion) and a 1.3µm LD to drastically reduce material dispersion



## OPTICAL DETECTORS AND RECEIVERS

<u>Semiconductor photodiodes</u> made of Silicon for the 0.8µm wavelength range and of Indiumgalliumarsenide (InGaAs) or Germanium for the 1.3 to 1.55µm range are the prefered detectors for fiber communications. The photodiodes are of the <u>pin-type</u> or the <u>avalanche-type</u> (APD) the difference being that the APD allows the fabrication of more <u>sensitive receivers</u> due to the internal amplification process of the photodiode. This is particularly important at high frequencies and at long transmission distances.

In the following the Silicon pin diode will be discussed since it will be the detector of the experimental set-up. The characteristics of the diode will be presented and a noise analysis of some typical receiver circuits will be carried out in order to relate the receiver noise to the bit error rate of a communication system.

### <u>The pin photodiode</u>

The structure of a pin photodiode (PD) is shown in Fig.20. A low-conducting <u>intrinsic semiconductor zone</u> is sandwiched between two thin heavily doped, i.e. highly conducting p and n zones. Photons reach the i zone through the antireflection coating and the p zone and they are absorbed by the semiconductor creating <u>electron-hole pairs.</u> In a PD biased in the reverse direction, as is normally the case in a receiver circuit, an <u>electric field</u> exists in the i zone that separates the electrons from the holes pulling them in opposite directions. Consequently a <u>photovoltage</u> appears accross the diode terminals and a <u>photocurrent</u> will flow in an external circuit.

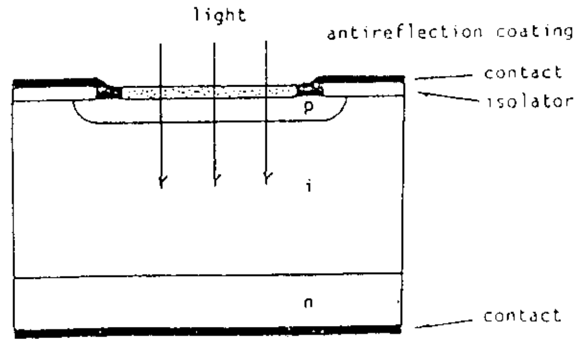



Fig.20 Pin photodiode structure

In operation we may represent the diode as a <u>current generator</u> with an ideal diode in parallel, the latter being there to simulate the effect of the pn junction. Fig.21 gives the simplified <u>equivalent circuit</u> of the PD.

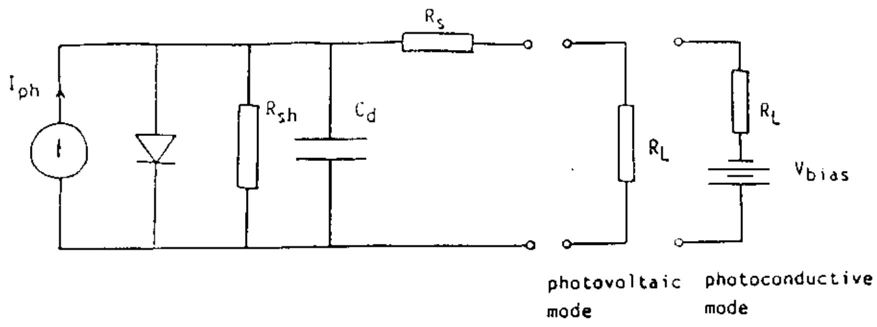



Fig.21 Photodiode equivalent circuit

$R_s$ is the series resistance, $R_{sh}$ the shunt resistance which is normally much larger than $R_s$ and $C_d$ is the diode capacitance. The photocurrent $I_{ph}$ is given by:

$$I_{ph} = \eta e \lambda P/hc = R\ P$$

e is the electronic charge, $\eta$ the quantum efficiency, i.e. the ratio of the number of generated electron-hole pairs to the number of incident photons, $\lambda$ the wavelength, h the Planck's constant, c the velocity of light and P the optical power incident onto the detector. R is the responsivity of the PD in A/W. It is seen from the above relation that the photocurrent depends linearly on the optical power. Without external bias an internal diffusion field exists and the device is said to operate in the photovoltaic mode. With external bias the PD operates in the photoconductive mode. The current-voltage characteristics for both operation modes are given in Fig.22. The current-voltage equation is given by:

$$I = I_s\,[\exp(eV/kT)-1] - I_{ph}$$

$I_s$ is the saturation current of the PD.

In a receiver circuit a relatively large negative voltage is applied (10 to 20 V) and the diode current will be:

$$I = I_s - I_{ph}$$

Without incident light a current will flow equal to the saturation current. We call the current in this case the dark current.

In practical values, for a 1 mm² silicon PD the linearity current-light is very good up to about 1 mW optical power. The capacitance decreases with external bias to about 1 pF at large voltages (20 to 40 V). The dark current is approximately 5 to 10 nA at 25 °C but is very temperature sensitive. It doubles every 7°C in silicon PD's.



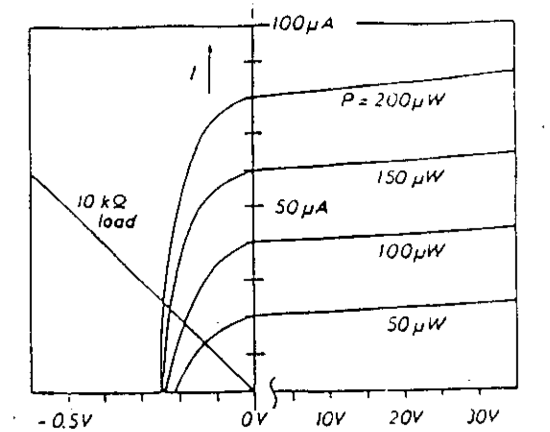



Fig.22 Pin photodiode electrical charecteristics

The responsivity of a silicon PD as a function of wavelength is shown in Fig.23. For the benefit of comparison the responsivities of the two other PD types used in fiberoptic communication for 1.3 and 1.55μm systems are also shown in Fig.23.

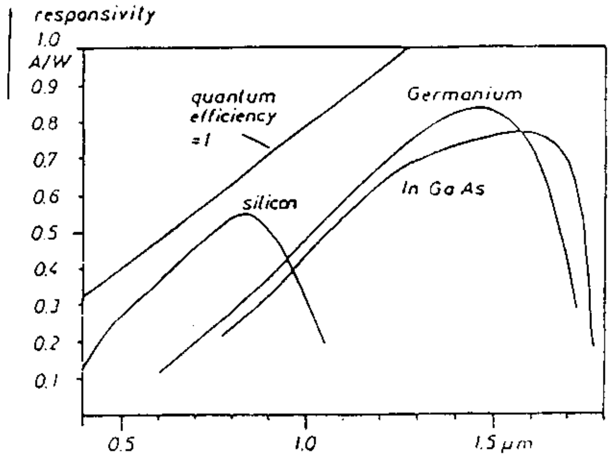



Fig.23 Wavelength dependence of responsivity

The frequency response of a PD is governed mainly by three factors: a) diode capacitance, b) carrier diffusion time and c) carrier drift time through the depletion region. For reverse bias the diode capacitance is practically the junction capacitance due to the charge stored in the depletion layer.

If we assume that $R_{sh} >> R_s + R_L$ and $R_L >> R_s$ as is generally the case in a practical system we can define a **cut-off frequency** $f_c$ as follows:

$$f_c = 1/2\pi R_L C_d$$

Since $C_d$ decreases with increasing negative bias, PD's should be operated at large bias for high-frequency response.

The diffusion time of carriers that are generated outside the depletion region towards this region can result in a "slow tail" in the response to a high-speed optical pulse.

**Noise of the pin photodiode**

The knowledge of PD noise is of great importance because it directly influences the **quality of the signal** at the output of the receiver circuit.

In a pin PD a dominant source of noise is **shot noise** which results from the discrete nature of the carriers. The quantity used to describe it is the **mean square noise current spectral density** $i_n$.

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

The current I is the sum of the signal related photocurrent and of the dark current. Thus, the **smallest detectable optical power** in a frequency bandwidth B will be determined by the dark current as follows:

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

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

The **noise equivalent power** NEP, a parameter given in many PD datasheets, is defined as the fictitious optical power per square root of Hertz causing the dark current

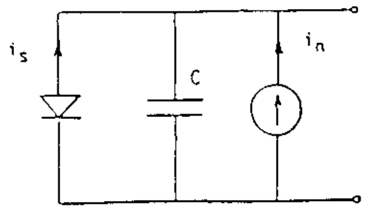
$$NEP = \sqrt{2eI_{dark}}\ /R \quad \text{in } W/\sqrt{Hz}$$

As an example, let us consider a silicon PD with 1 mm diameter. A typical dark current would be 5 nA and the associated NEP 8 $10^{-14}$ $W/\sqrt{Hz}$.

We can now complete the equivalent circuit of the PD by inserting a **noise current source** as shown in Fig.24. In this figure some simplifications are made. The shunt resistance $R_{sh}$ and the series resistance $R_s$ have been omitted under the assumption that $R_{sh}$ is much larger than the sum of $R_s$ and $R_L$ and that $R_L$ is much larger than $R_s$.

A word of caution is, however, necessary. If laser light is detected by the PD, the noise current can be significantly above the level predicted by the theory and given by the equation in the figure. The additional noise originates in the laser






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

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

Fig.24 Simplified noise euqivalent circuit of a PD

radiation and may be due to different causes, such as the laser process itself or the power competition between the modes. Also, fluctuations of the laser power due to optical reflections from the fiber, connectors or splices back into the laser are possible and are measured in practical situations. For the sake of simplicity we will assume in the following calculations that this additional noise can be neglected and that the PD produces only shot noise as given above.

Before we proceed with the calculations of typical receivers we should have a look at the noise produced by a resistor R at a temperature T. This is called **"thermal noise"** and is described by the noise voltage $u_n$ appearing at the resistor terminals. The spectral density of the mean square noise voltage is:

$$\overline{u_n^2} = 4kT\,R \quad \text{in } V^2/Hz$$

An alternative way to describe this noise is to assume a current source in parallel with the resistor which generates the mean square noise current spectral density

$$\overline{i_n^2} = 4kT/R \quad \text{in } A^2/Hz$$

**Practical receiver design**

Two widely used practical receiver circuits are the

**# low-impedance receiver, and the**
**# transimpedance receiver.**

Fig. 25 shows the circuit diagram of the low-impedance receiver. The PD is in series with the impedance $R_i || C_i$ and the photocurrent produces a voltage drop across the impedance which is subsequently amplified in the following amplifier. The resistance $R_i$ may be thougth in the real situation as the parallel combination of the load resistor $R_L$, the diode shunt resistor $R_{sh}$ and the amplifier input resistor $R_A$, neglecting the diode series resistor.

$$1/R_i = 1/R_{sh} + 1/R_L + 1/R_A$$

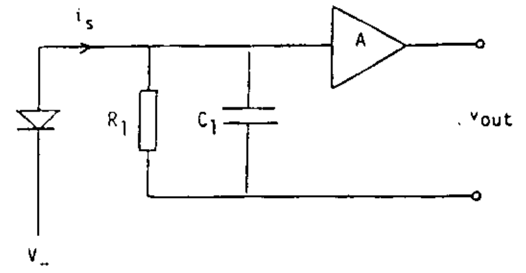



Fig.25 Schematic representation of the low-impedance receiver

The capacitor $C_1$ is the parallel combination of the diode $C_d$, the amplifier $C_A$ and the stray capacitance $C_s$:

$$C_1 = C_d + C_A + C_s$$

A sinusoidally varying optical power produces a signal photodiode current $i_s$ which in turn gives rise to a sinusoidally varying voltage $v_{in}$ at the amplifier input:

$$v_{in}(f) = R_1 . i_s(f)/(1+j2\Pi f C_1 R_1)$$

Let us assume that we use an amplifier with constant gain A in the frequency band of interest. We further assume a digital signal with optical detected power $P_1$ at the "1" level and 0 at the "0" level and an even distribution of "ones" and "zeros". The signal bandwidth B will be

$$B = 1/2\Pi R_1 C_1$$

The output voltage $v_{out}$ for the "1" level is:

$$v_{out} = R_1 . A . i_s = R_1 . A . P_1 . R, \quad R = \text{responsivity}.$$

The noise voltage at the output is the sum of the amplified noise voltages appearing across the resistor $R_1$ and generated by the signal current, the dark current and the thermal noise current. To these currents we have to add the noise generated by the amplifier itself. It can be shown that this noise gives rise to two terms:

- $4\overline{v_A^2}/3R_1$ where $v_A$ is the equivalent voltage noise of the amplifier, and
- $\overline{i_A^2}$ where $i_A$ is the equivalent current noise of the amplifier

The average mean square value of the output noise voltage is, assuming an even distribution of "1"s and "0"s:

$$\overline{v_n^2} = A^2 \cdot R_1^2 \; B \left(2eR\frac{P_1}{2} + 2eI_{dark} + \frac{4kT}{R_1} + \frac{4}{3}\frac{\overline{v_A^2}}{R_1^2} + \overline{i_A^2}\right)$$



We can now write for the signal-to-noise ratio SNR at the output:

$$SNR = 10 \log (v_{out}^2/\overline{v_n^2}) = 10 \log \left(\frac{P_1^2 R^2}{B(eP_1 R + 2eI_{dark} + \frac{4kT}{R_1} + \frac{4}{3}\frac{\overline{v_A^2}}{R_1^2} + \overline{i_A^2})}\right)$$

Numerical example:
We assume a 140 Mbit/s digital transmission system and a receiver characterized by the following values:

$P_1 = 1\mu W = -30dBm$; $I_{dark} = 10nA$; $R = 0.4A/W$; $A = 40$; $C_1 = 5pF$;

$B = 70MHz$ suitable for 140Mbit/s digital transmission

$v_A = 2nV/\sqrt{Hz}$; $i_A = 2pA/\sqrt{Hz}$; $k = 1.38\ 10^{-23}$ J/K

The resistor $R_1$ becomes $R_1 = 1/2\Pi BC_1 = 455$ Ohm.

We assume the shunt resistance of the PD and the input resistance of the amplifier to be much larger than the load and so we can choose a 470 ohm resistor as load resistor. This will cause a slightly lower bandwidth than required ≈ 68 MHz. For the "1" level the output voltage is

$$v_{out} = 7.5 \text{ mV}$$

The noise output is

$$\overline{v_n^2} = 2.5\ 10^{16}(6.4\ 10^{-26} + 3.2\ 10^{-27} + 3.5\ 10^{-23} + 2.4\ 10^{-23} + 4\ \ 10^{-24})$$

$$= 1.6\ 10^{-6}\ V^2$$

It is evident that in our case the resistor is the most important noise source but the noise contribution of the amplifier we have arbitrarily chosen comes close to it. Unfortunately we cannot minimize the resistor noise because if we increase the resistor, thus reducing its noise contribution, the signal bandwidth will decrease. The only way to improve the SNR is to choose a very low noise amplifier. With the values above the SNR becomes:

$$SNR = 15.5 \text{ dB (electrical)}$$

The SNR is related to the bit error rate BER i.e. to the number of false bits relative to the total number of bits in the data stream. Many systems require a BER of $10^{-9}$. Under some simplifying assumptions we can calculate the BER as a function of the SNR. The result is plotted in Fig.26. It turns out that for a BER of $10^{-9}$ a SNR of 21.6 dB is required. This value is clearly above the value calculated for our system. In order to obtain a SNR of 21.6 dB we would have to increase the power on the PD, e.g. by increasing the power emitted by the source. A rough estimate of the power increase required can be made. Since the SNR should improve by 6 dB (electrical, from 15.5 to 21.6), the optical power would have to be larger by 3 dB (optical). Instead of 0.5 μW average power (-33 dBm), we should have 1 μW at the PD (-30 dBm) or 2 μW for the "1" level.

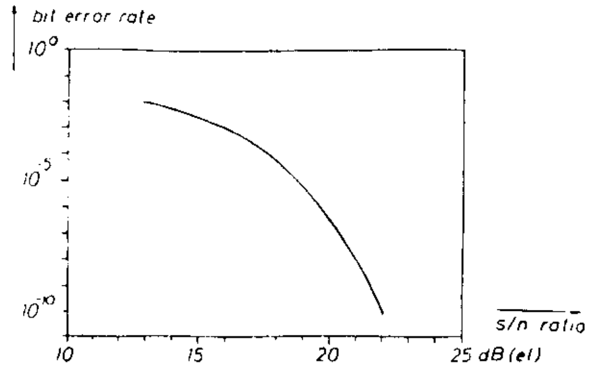



Fig.26 BER versus SNR

The transimpedance receiver is given in Fig.27. If the amplifier has a large input impedance, the resistance $R_3$ which is the parallel combination of diode shunt and amplifier input resistance can be made large and the PD current will flow through the resistor $R_2$. The calculations yield:

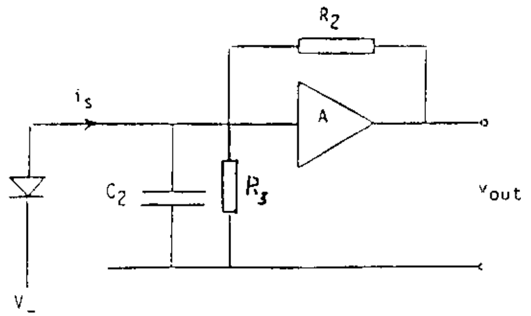



Fig.27 Transimpedance receiver circuit.

Signal bandwidth $B = A/2\Pi R_2 C_2$

"1" level output $v_{out} = R_2 i_s = R_2 P_1 R$

output noise voltage $\overline{v_n^2} = R_2^2 B \left(2e \frac{P_1}{2} R + 2eI_{dark} + \frac{4kT}{R_2} + \frac{4}{3} \frac{\overline{v_A^2}}{R_2^2} + \overline{i_A^2}\right)$

SNR $SNR = 10 \log (v_{out}^2 / \overline{v_n^2})$

We should now compare the SNR's of the two receivers. We see that the formulas are the same except that the resistance $R_1$ has been replaced by $R_2$. It is clear that for the same bandwidth the resistance $R_1$ will be much smaller than $R_2$, provided that the amplification A is large. As a consequence, the SNR of the transimpedance will be significantly higher if we are careful to choose a low-noise amplifier, i.e. an amplifier with a low value of $i_A$.



## Numerical example

For the benefice of comparison we assume the same values as in the example for the low-impedance receiver. We obtain:

Resistor $R_2 = A/2\Pi BC_2 = 18.7$ kohm

By taking $R_2 = 18$ kohm, B will be 70.7 MHz.

Output voltage $v_{out} = 7.2$ mV

output noise voltage

$\overline{v_o^2} = 2.3\ 10^{16} (6.4\ 10^{-26} + 3.2\ 10^{-27} + 9.2\ 10^{-25} + 1.6\ 10^{-26} + 4\ 10^{-24}) =$

$= 1.15\ 10^{-7}\ V^2$

We see that the reasistor noise and the noise due to the voltage noise source of the amplifier are now much lower than in the previous example. The dominant noise term is the amplifier current noise but the average noise voltage is significantly lower than in the previous case.

The SNR becomes SNR = 26,5 dB (electrical)

This value is much higher than the value required for BER $10^{-9}$.

The examples above demonstrate the potential of the transimpedance receiver. The only problem with this popular circuit is one of amplifier stability. The feedback loop may result to unwanted oscillations . The design of a stable transimpedance receiver requires careful layout and effective screening of the sensitive components.

## SYSTEM PERFORMANCE

The large majority of fiberoptic 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" state means the absence of a pulse. The pulses occur within 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.28 illustrates this terminology.

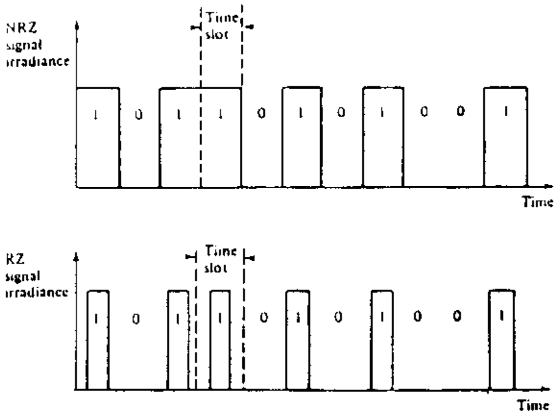



Fig.28 Illustration of a NRZ and a RZ data stream.

The pulses reaching the laser are obtained from the conversion of the 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 quantisation 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 16 x 4 kHz, i.e. 64 kbit per second.

The pulses reaching the detector are distorted due to the non-idealities of the system like attenuation and dispersion. 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 introduce 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.29 illustrates such an example.

A commonly used criterion for characterizing qualitatively the proper function of a digital system is its eye diagram. It is 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



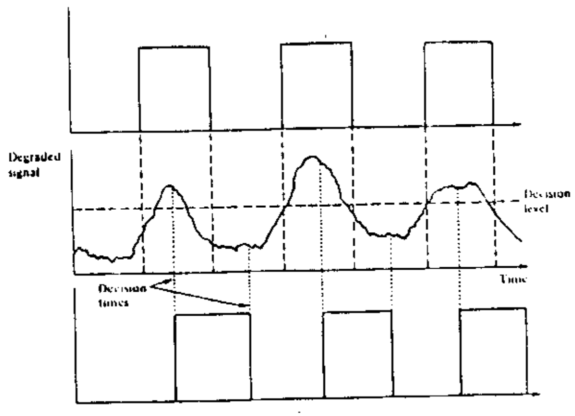



Fig.29 Restoration of the original digital signal

of the BER that can be achieved. In 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 should be expected, Fig.30.

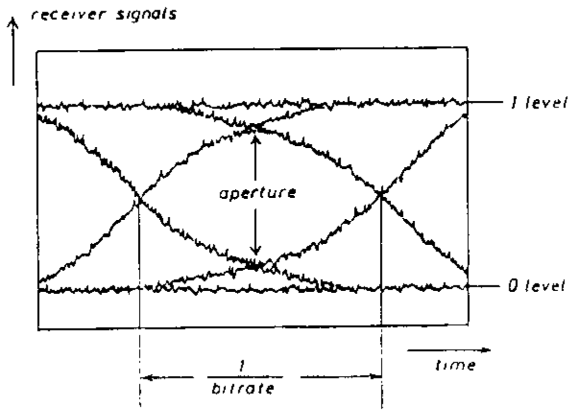



Fig.30 Eye diagram of a binary data stream.

The quality of the eye diagram is, of course, influenced by the noise of the system. There is, however, also an additional phenomenon influencing the eye diagram. 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 fiber. The result is that the lower level of the eye diagram shift away from the zero level, the eye "closes" and the BER deteriorates. The intersysmbol 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 for the best possible eye aperture.

Let us now consider some typical component combinations, incl. LD's, LED's, PD's and APD's, that may occur in a typical system. The design of a fibersystem may in practice be a complicated matter but usually four main inputs are necessary for the designer:

# bit rate or bandwidth
# BER or SNR
# link length and number of terminals, and
# type of data and signal waveforms.

The usual way to start is to calculate the total dispersion caused by the fiber-source combination for the length considered. The choice of the fiber-source combination will be dictated basically by the bit rate of the system. Obviously, both transmitter and receiver circuit should be capable of handling the bit rate. If a pin PD can be used, there is no reason to use the more complicated APD. For every system there will be a minimum average power that must reach the detector in order to achieve the required BER. If the fiber length is known, the total signal attenuation can be calculated by taking into account also the losses of the couplers and splices. Then the choice of the LD or LED source can be undertaken. It is important to know the power that can be launched from the source into the fiber. This power should be high enough to overcome the attenuation and to bring the power level required at the receiver input. A safety margin of 5 to 10 dB's is often required. We call these considerations and calculations the "<u>power budget</u>".

Fig.31 gives a rough estimate of the power budget that can be obtained with various combinations as a function of bit rate. The upper shaded areas show typical powers that can be coupled from commercial LD's and LED's into fibers. As technology progresses, higher power levels and higher frequencies can be expected from commercially available devices for BER $10^{-9}$. The lower curves show some typical receiver sensitivities that can be expected from commercial components. One can reasonably expect an improvement of these sensitivities towards the theoretical detection limit.

<u>Example</u> We wish to operate a 140 Mbit/s system by using a 1.3 μm LD-monomode fiber combination. From Fig.31 we take as the "worst case" launched power 0 dBm. The total loss that we can tolerate if we take a pin PD receiver is about 28 dB. Allowing a safety margin of 5 dB and assuming mean line losses ( fiber + couplers + splices ) of 1 dB/km we obtain a maximum range of 23 km. This range increases to about 37 km if a APD is used.

In the example given here the bit rate is relatively low so that a multimode fiber could have been used instead of a monomode one because dispersion effects have a small influence at bit rates



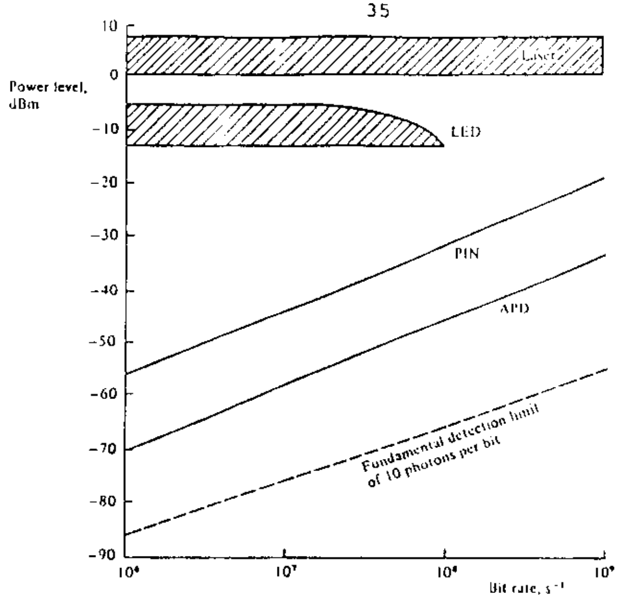



Fig.31 Illustration of the power budget for typical source-detector combinations versus data rate

below approximately 400 to 500 Mbit/s and the fiber length is determined primarily by attenuation. It is, however, advisable to install monomode fibers even at low bit rates because of the possibility to upgrade the system to higher bit rates at a later stage as demand requires.

Most of the fibers implemented today are for telephone trunk lines carrying a large number of simultaneous telephone conversations between telephone centrals but applications of fibers for distributing telephone channels from the telephone central to substations or even to individual customers are rapidly advancing along with applications in video transmission and distribution, computer links etc. The following table shows the digital rates commonly used in Europe and the United States for telephone transmission and the approximate number of telephone channels that can be simultaneously transmitted.

| Digital rates ( Mbit/s ) | Approx. number of channels ( 1 channel = 64 kbit/s ) |
|---|---|
| Europe | |
| 2.048 | 32 |
| 8.448 | 120 (=4 x 30) |
| 34.368 | 480 (=4 x 120) |
| 139.364 | 1920 (=4 x 480) |

| | |
|---|---|
| 565 | 7680 (=4 x 1920) |
| USA | |
| 1.544 (T1) | 24 |
| 6.312 (T2) | 96 (=4 x 24) |
| 46.304 (T3) | 672 (=4 x 96) |
| 281 (T4) | 4032 (=4 x 672) |

## PROBLEMS

**It is important to try to solve the following problems before the experimental investigations. The problems give you an idea of the optical powers to be expected at the input of the receivers which are used in the experiments and help you save valuable time with the experimental adjustments.**

1. Low-impedance receiver

For a BER of $10^{-9}$ calculate the mean optical power necessary at the receiver input under the following assumptions:

NRZ digital link ( for the BER vs SNR relationship see Fig.26 ) multimode graded index fiber, bandwidth 2 MHz, pin silicon detector responsivity at 0.8 μm equal to 0.33 A/W, Resistance $R_L$ ( see Fig.25 ) equal to 50 ohm. Neglect the dark current. Suppose that you use a noise free amplifier.

How to proceed:Use the equation given above for the SNR, simplify, and solve for the optical power level "1".

Give the result in dBm and nW.

$k = 1.38\ 10^{-23}$ J/K
$e = 1.6\ 10^{-9}$ As

In the real situation more power will be needed at the PD to produce the BER required because of the noise of the amplifier and of the laser. Add some 8 to 10 dBm's to obtain a more realistic level of the power needed.

2. Transimpedance receiver

Same as above but with $R_2$ = 47 kohm, for diagram of the receiver see Fig.27.

The contribution of the amplifier noise is here less severe than in the case of the low-impedance. For a low-priced amplifier perhaps 5 dBm would additionally be required.



## PART TWO

## E X P E R I M E N T A L   I N V E S T I G A T I O N S

The purpose of the following experimental work is the assembly of a fiberoptic communication link and the performance of measurements for the determination of the basic operational characteristics of the link. The link is composed of the following subsystems:

* Laser Transmitter
* Fiber cable
* Optical Receiver

### Laser Transmitter

The laser transmitter comprises the laser diode emitting at .78 μm ( "compact disk" type laser), two bi-convex lenses , an optical shutter and a x-y-translation stage holding the front-end of the fiber cable. All the components are mounted on a small optical bench. The laser is rigidly mounted and has two electrical connecting coaxial cables: one labeled "laser" which connects the laser diode to the BNC connector on the board of the optical bench and the other labeled "monitor photodiode" which connects the silicon photodiode inside the laser diode package to a second BNC connector on the bench. The monitor photodiode is used for monitoring the power output of the laser beam. Its photocurrent is used to maintain a practically constant laser intensity with the help of an optoelectronic feedback circuit in the "Laser Driver" plug-in unit (see also explanation of the function of the plug-in units).

The bi-convex lens in front of the laser is rigidly positioned so as to collimate the laser beam. Do not attemp to move the lens because the collimation is very sensitive even to small displacements. The second bi-convex lens is used to focus the laser beam onto the front-end ot the fiber. This lens can be gently moved in the bench so as to obtain the best coupling results of the laser light into the fiber.

The x-y-translation stage is used to position the front-end of the fiber onto the focus of the laser beam. By smoothly mooving both the second lens and the translation stage the coupling of light in the fiber can be optimized.

### Fiber cable

The fiber cable is composed of three parts: The main cable of a length of 2.2 km placed in a plexiglass box having two connectors on the front face and two separate 1.5 m long cables which are used for connecting the main cable with the laser transmitter and the optical receiver. The fiber has the following characteristics:

* Attenuation at 800 nm : 2.6 dB/km
* Bandwidth at 800 nm : min 300 MHz.km, max 400 MHz.km
* Fiber-Fiber connector losses : min 2 dB, max 3 dB
* Fiber-Photodetector connector losses: min 2 dB, max 3 dB

Optical Receiver

Two types of receiver circuits are used in the corresponding plug-in units:

a) Low impedance receiver, and
b) Transimpedance receiver.

Both receivers have Silicon pin photodiodes as detecting devices. The idea is to apply both receivers and to compare the results of the Bit Error Rate measurements in order to be able to corroborate the conclusions of the theoretical analysis regarding the differences in sensitivity of the two circuits.

MEASUREMENTS

Perform the following measurements and plot immediately the results on the blank pages supplied with this manuscript in order to obtain a first comparison between theory and experiment.

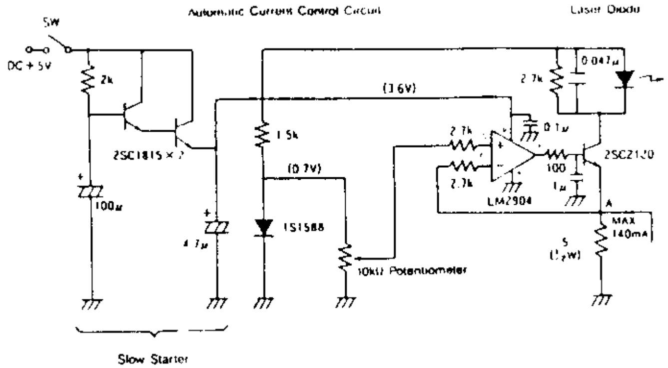
A.Laser power versus dc current

The purpose is to obtain the light-current relation of the laser diode by measuring the optical power output of the laser with a large area Silicon photodiode as the dc diode current is increased from below threshold to some value above it. You need the following items to carry out this measurement:

* Laser Transmitter
* one digital voltmeter/amperemeter Fluke
* one digital voltmeter/amperemeter Hewlett-Packard
* plug-in labeled "Laser power vs dc current measurement"
* large area silicon photodiode

The plug-in contains the circuit given in the following figure. The dc current through the laser diode is set with the 10 kohm potentiometer. This appears at the front of the plug-in as a 10-turn potentiometer and is labeled "Laser current adjustment". The laser current also flows through the 5 ohm resistor so that the voltage at point A is directly proportional to the LD current. This voltage appears between the two terminals at the front of the plug-in unit which are labeled "$V_{out}$ $-I_{LD}$".






IMPORTANT

Before making any connections to the plug-in unit make sure to turn the potentiometer of the plug-in to zero and to switch the plug-in unit off. The laser may be damaged if you attemp to connect or disconnect it from the plug-in while power is on.

Now perform the measurement by going through the following steps:

a) Connect with a coaxial cable the laser diode to the BNC output jack of the plug-in unit labeled "to laser diode" while power is off and the potentiometer is turned to zero.

b) Place the supplied large area ( approx. 1 cm² ) Silicon photodiode in front of the laser on the optical bench and connect the photodiode to the Hewlett-Packard digital amperemeter. By doing so, the short-circuit current of the photodiode will be measured.This current is identical to the photocurrent if we neglect the dark current which is much smaller than the photocurrent for the amount of optical power measured in our experiment.The photocurrent is proportional to the optical power detected by the photodiode.

c) Connect the Fluke digital voltmeter ( mV resolution ) to the terminals labeled "$V_{out}$ $-I_{LD}$" of the plug-in unit.

d) Turn on the power of the plug-in unit

e) Turn slowly the potentiometer.Now,a dc current through the laser diode should begin to flow. A voltage is displayed on the voltmeter measuring "Vout $-I_{LD}$". Divide this voltage by 5 Ohm to obtain the current through the laser. In order to obtain the optical power impinging onto the photodiode,multiply the number of microamperes displayed on the Hewlett-Packard amperemeter by the factor 3.3 μWatt/μA.This factor is determined by the sensitivity of the silicon photodiode at the wavelength of the laser.

Note: Due to background illumination, photocurrent will be flowing in the photodiode even while the laser is turned off. Subtract this value from the value measured when the laser is operating to obtain the actual photocurrent.

**CAUTION :** **The maximum laser power allowed is 5 mW for dc diode current. Be certain never to exceed this power limit**

At the lasing threshold and just above it the laser power increases very steeply with current. In that region the measurements should be carried out very carefully.

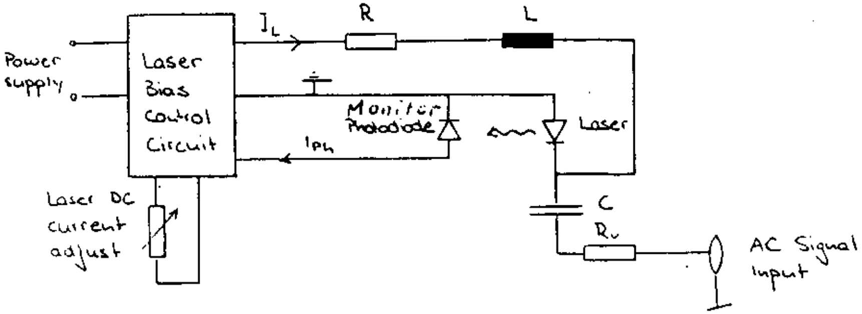
After you have performed the above measurement, turn the potentiometer back to zero and switch the power of the plug-in unit off. Disconnect the laser and the photodiode.

B.Optical losses from laser to receiver

The purpose is to measure the optical losses that occur in the system between the laser and the pin photodiode at the receiver front-end. The following items are needed for the measurement:

* Laser Transmitter
* Fiber cable
* Laser driver (plug-in unit)
* Large area Silicon photodiode
* Transimpedance receiver (plug-in unit)

The plug-in unit "Laser driver" contains the following circuit:




The purpose of this circuit is to provide a laser power output which remains unaffected by changes of the environmental temperature. The photocurrent of the monitor photodiode inside the laser package is used in a feedback circuit to change the laser diode current as the temperature varies so as to maintain a constant power output. The potentiometer at the front of the plug-in unit "Laser Driver" labeled "Laser current adjustment" is used to set a dc operating point on the Light-Current characteristic of the laser diode.



## IMPORTANT

**Turn the potentiometer of the plug-in unit "Laser driver" to zero and switch the power of the plug-in unit off before making the following connections otherwise the laser may be permanently damaged.**

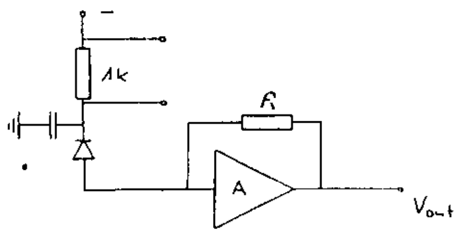
Now connect through coaxial cables the laser diode to the BNC output jack of the plug-in unit labeled "to Laserdiode" and the monitor photodiode to the BNC output jack labeled "to monitor photodiode". Do not confuse the monitor photodiode , which is inside the laser package, with the large area photodiode, which is used to measure laser power. The dc laser current can again be monitored by measuring the voltage appearing between the terminals labeled "$V_{out}$-$I_{LD}$". Divide the voltage by 5 Ohms to find the laser current.

Turn now the power of the plug-in unit on and set a dc current of the laser corresponding to about 2.5 mW optical power by turning slowly the potentiometer. The current corresponding to 2.5 mW can be obtained from the "Light-current" characteristic of the laser measured under "**A.Laser power versus dc current**"

Note You can measure again the laser power by placing the large area photodiode in front of the laser and measuring the photocurrent. To this effect connect the photodiode to the Hewlett-Packard digital amperemeter and measure the photocurrent.

After you have set the operating point of the laser at 2.5 mW attach the optical cable to the laser transmitter and try to inject the maximum possible power into the fiber. To this effect connect the main cable in the plexiglass box with the transmitter by using one of the two short (approx. 1.5 m) pieces of cable. Place one cable connector in the xy translation stage and secure it with the two small side scews. Place the other connector of the short cable into the female jack of the plexiglass box. With the other short piece of optical cable connect the main cable to the transimpedance receiver. Take care not to damage the optical connectors. Now, you have a 2.2 km fiber connection from the laser transmitter to the optical receiver.

The plug-in labeled "Transimpedance receiver" contains a circuit, the block diagram of which is given below:



A characteristic of this receiver is that the flow of the photocurrent produced in the detector is exclusively through the feedback resistor R because the input impedance of the operational amplifier is usually very much larger than R. It follows:

output voltage $V_{out} = R \; I_{det}$,

where $I_{det}$ is the photocurrent containing an ac signal. More details on the operational characteristics of the transimpedance receiver are given in the first part of this document. What is needed for the moment is the measurement of the dc photocurrent generated by the detection of the light power from the fiber cable impinging on the pin photodiode. This current can be measured from the voltage drop across the resistor $R_b$=1 kohm. The resistor terminals appear on the front of the plug-in unit and are labeled "$V_{out}$-$I_{det}$" Connect the Hewlett-Packard digital voltmeter with µV resolution to perform the measurement. Multiply the photocurrent by 3,3 µW/µA to obtain the optical power impinging onto the photodiode.

The power coupled into the fiber can now be <u>maximized</u> by using the second biconvex lens after the laser and the xy-translation stage containing the fiber front connector. This procedure must be carried out very carefully. It can be time consuming. A usual way to do it is the following:

a) Focus with the second lens the laser radiation onto the plane of the translation stage containing the fiber front face. Use a small white piece of paper to find the focus. The radiation is partly visible and you will see a small spot appearing on the paper. Move gently the lens to obtain a good focus.

b) Adjust the position of the fiber with the xy-translation stage into the focus. Do not touch now the lens. By moving very smoothly the translation stage you should obtain a photocurrent in the pin photodiode of the transimpedance receiver.

c) Maximize the photocurrent by adjusting both the translation stage and the lens. You should obtain at least a few microamps photocurrent.

After you have maximized the laser-fiber coupling make the following measurements:

a) Measure with the large area photodiode the optical power emitted by the laser. To do so place the photodiode in front of the laser, connect the Hewlett-Packard digital Amperemeter(µA-resolution) to the photodiode and measure the photocurrent. Convert as usual to optical power units.

b) Measure the power focussed onto the front end of the fiber by placing the large area photodiode in front of the translation stage. Make certain to minimize the background light falling on the photodiode



c) From the previous measurement, note the power detected by the photodiode of the tranimpedance amplifier.

You can now answer the following questions:

1. What is the loss in decibel of the optical focussing system of the transmitter (two biconvex lenses) ?

2 What is the power coupled into the fiber? In order to answer this question you will have to make some assumptions on the connector losses. Assume the following values:

* fiber-to-fiber connector 2-3 dB each
* fiber-to-photodiode connector 2-3 dB

From the loss characteristics of fiber and connectors calculate the power coupled into the fiber based on the measured value of the power impinging onto the photodiode of the receiver. You will note that this power is different from the power measured at the focus point at the front end of the fiber. Explain the reason for the discrepancy.What is the coupling efficiency from the laser into the fiber?

3. What is the loss of the whole fiber transmitting section?

4. What is the total optical loss of the system between laser and receiver?

<u>C.Bit-Error-Rate (BER) vs optical power</u>

The purpose of this experiment is the determination of the BER as a function of the received mean optical power for two types of receiver circuits

a)Low impedance receiver, and
b)Transimpedance receiver.

The received power can be varied

- by placing the supplied <u>gray filters</u> in front of the optical fiber in the optical transmitter, and
- by adjusting the <u>shutter</u> opening in the transmitter.

For this measurement you need the following items:

* Laser transmitter
* Laser Driver plug-in unit
* Transimpedance Receiver plug-in unit
* Low-impedance Receiver plug-in unit
* 40 dB Signal Amplifier plug-in unit
* BER measuring set
* Philips oscilloscope
* Hewlett Packard digital voltmeter
* Fluke digital voltmeter

In order to efficiently perform this measurement it is important to calculate first the sensitivity of the receivers by solving the problems stated in the first part of this manuscript. The sensitivity gives you an idea of the optical powers involved in the BER measurement.

Now proceed as follows :

Low impedance receiver

Follow the steps outlined below. Start by having all equipment switched off.

1. Turn potentiometer of Laser Driver counterclockwise to zero. Connect the transmitter to the Laser Driver by connecting the laser and the monitor photodiode through coax cables with the plug-in unit "Laser Driver". Connect the Fluke voltmeter to the Laser Driver for the measurement of the laser current.

Switch the Laser Driver on.

Note the laser current. Its value should be slightly above the threshold determined earlier corresponding to an operating point given schematically in the figure below.


If the laser current is not at such a value, do not continue the experiment and ask for assistance.

2. Connect the optical fiber cable to the transmitter and to the Low-Impedance Receiver. Connect the Hewlett-Packard microvoltmeter across the terminals labeled $V_{out}-I_{det}$ of the Low-Impedance Receiver. The voltage $V_{out}$ is measured across a 1 kohm resistor in series with the PD inside the Low-Impedance Receiver.

Switch on the Low-Impedance Receiver. You will notice that a voltage of some mV is displayed on the Hewlett-Packard corresponding to some μA photodiode current.

If the voltmeter does not display any voltage or if the voltage is much lower than a few mV and the laser is properly set, then some optical misalignement has probably occured. Realign the optical transmitter so as to couple as much as possible power into the fiber and continue.

3. Switch now the laser off by switching the plug-in unit "Laser Driver" off. Be always sure the potentiometer is in the zero position before switching off. The Hewlett-Packard voltmeter will



now indicate a very small value, perhaps 10 to 20 μV corresponding to 10 to 20 nA photodiode current. This is the dark current of the photodiode. This value is important because it must be subtracted from the value measured when an optical signal is detected in order to obtain the real mean signal current.

4. Switch the laser on.

5. Set the front panel controls of the BER set as follows:

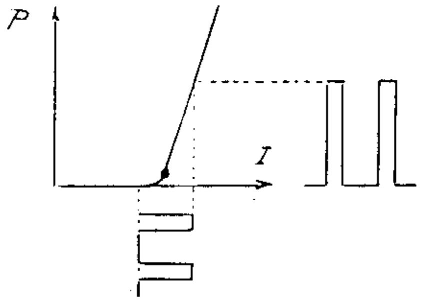
| Control | Function | set as follows: |
| --- | --- | --- |
| 1 | Signal | Connect to terminal "ac signal out" of the Low-Impedance plug-in. Use two BNC cables connected together through a T-coaxial connector and plug the "male" of the T into the oscilloscope, channel A or B. |
| 2 | Clock | Connect to control 5 |
| 3 | Slope | Set to positive clock edge |
| 4 | Generator | Connect to "ac signal in" of the "Laser Driver" plug-in unit. |
| 5 | Clock | this is now connected to control 2 |
| 6 | Clock | Set at CAL |
| 7 | Bitrate | Set at 2048 kbit/s |
| 8 | Code | Set at NRZ/TTL |
| 9 | | nonexisting |
| 10 | Pattern | Set at pseudorandom $2^{15}-1$ |
| 11 | Digital word | do not set |
| 12 | | nonexisting |
| 13 | | nonexisting |
| 14 | Error test | do not set |
| 15 | | nonexisting |
| 16 | | nonexisting |
| 17 | Evaluation | Set at $10^6$ bit |
| 18 | | press the button 1X/Rep for 1X |
| 19 | Interval | do not set |
| 20 | Error | Set at BIT |
| 21 | PRINT | Set to OFF |
| 22 | | do not set |

Set the oscilloscope controls as follows:

| | |
| --- | --- |
| Ampl/Div | 0.1 V |
| time/Div | 1 μs, magn. x5 |
| AC/DC | DC |
| A&B/ADD | A&B |
| A/B | A |
| TRIG | + , INT, AC |

Switch on the BER set.

The laser diode current is now modulated by a 2 Mbit/s pulse train to which a large number of random pulses is superimposed.The pulse amplitude is approx.26 mA peak-peak,corresponding to a 2 V signal from the BER set divided by 75 Ohm impedance of the Laser Driver input.Since the operating point of the laser had been set slightly above the threshold before the modulation, the "zeros" are now well below threshold but the "ones" well above it.This state of affairs can be visualized by drawing the following figure:




After having switched the BER set on, notice that

1. a small signal appears on the oscilloscope, amplitude <0.1 $V_{pp}$

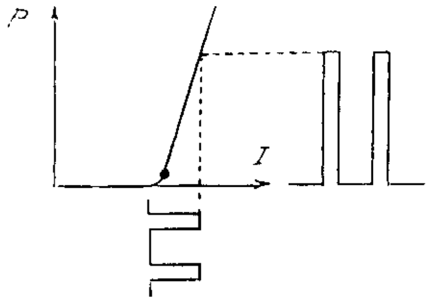
2. the voltage displayed on the Fluke voltmeter decreases.This voltage corresponds to the laser current which has a dc component equal to the laser current at the operating point set before and an ac component due to the modulation signal.The value measured with the Fluke voltmeter is therefore a mean value of the current.This current now jumps between two values according to the state of the modulating signal.Since the mean current is lower that the operating point value,the signal reaching the laser contains more "zeros" than "ones" and the resulting mean current decreases.

3. The mean current through the photodiode has decreased for the same reason as the laser current.

Now proceed with the following adjustments:

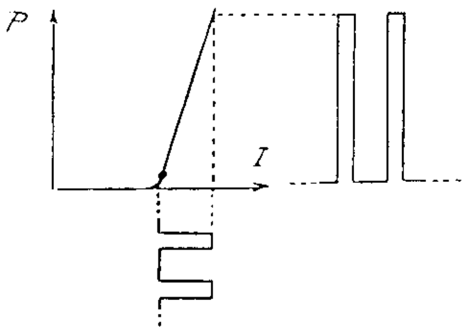
- increase slowly the laser current by turning clockwise the potentiometer labeled "Laser current adjustment" of the "Laser Driver" plug-in. Increase the current until you reach approximately 0.2 Volt signal amplitude on the oscilloscope.As you increase the laser current you shift the baseline of the modulating signal to higher currents and you obtain more photocurrent as illustrated in the figure below.The "zeros" are still below threshold but the optical signal amplitude is now larger than before.
Note also that as you increase the laser current the baseline of the oscilloscope trace remains at the same position because the optical "zeros" still correspond to zero optical power.






- Increase further the laser current until the baseline of the electrical signal through the laser reaches the threshold current.<u>NOW STOP TURNING THE POTENTIOMETER</u>.You can check whether the beseline is located at the threshold current by observing the oscilloscope trace while turning the potentiometer.The baseline of the oscilloscope trace remains pinned at the same level as long as the baseline of the modulating signal is below threshold.As soon as the threshold is reached,the baseline of the oscilloscope trace shifts to higher voltages (the oscilloscope must be in the "DC" mode).The signal amplitude on the oscilloscope should be now at least 0.4 V.

The following figure illustrates the new state of affairs.




Now try the first Bit Error Rate measurement:

- Set control 17 "Evaluation" at $10^6$ bit error ratio.
- Push control 18 START/CLEAR button.

The BER set displays 0 -6 meaning that there is no false bit in a stream of $10^6$ bits.
Repeat the measurement for $10^7$ and $10^8$ bits.The display should read 0 -7 and 0 -8.

The reason that no false bit is measured is that the received power is very high. In this case the noise of the photodetector circuit is of no consequence for the detection process and since we have now built a good operating transmission system no false bit is detected. In order to be able to perform the measurement of the Bit Error Rate the optical power detected must be reduced drastically.

The reduction of the optical power will be carried out by inserting the supplied optical neutral density filters in front of the fiber front face and by closing the mechanical shutter of the transmitter.

It is important of course to have an idea of the order of magnitude of the power on the photodiode that causes a BER of say $10^{-9}$. Otherwise the search for false bits may take too long! The range of the expected power can be obtained by solving the theoretical problem given in part one. For the experiment proceed as follows:

Insert Filters 1 or/and 2 or/and 3 in front of the fiber in the optical transmitter setup. Tilt them carefully so as to obtain a photodetector current between 1 and 2 µA. The signal received by the BER set is now much too small for a measurement as you also notice on the oscilloscope. Note that at least about 50 mV are required for a measurement, the maximum signal level allowed being about 4 V. The signal at the output of the Low-Impedance Receiver must be further amplified. This is done with help of the plug-in unit labeled "40 dB Signal Amplifier" meaning that the signal voltage at the amplifier input is amplified 40dB or 100 times. The 3dB bandwidth is 2MHz.

Connect the output of the Low-Impedance plug-in unit to the input of the 40dB amplifier. Connect the output of the amplifier to the BER set via the oscilloscope as previously. Switch the amplifier on. You will notice that a signal trace of several hundred millivolts amplitude appears on the oscilloscope.

IMPORTANT NOTICE:

If the baseline of the oscilloscope trace is not at the same level as before switching the Signal Amplifier on, turn very carefully the "offset adjust" potentiometer on the front of the plug-in unit "40 dB Signal Amplifier" and shift the baseline to its original position.

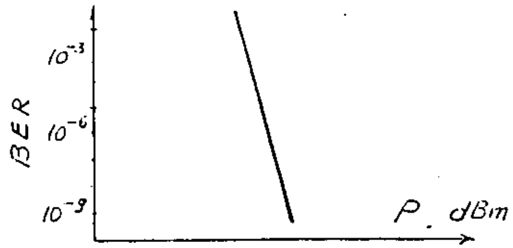
Set the error ratio at $10^6$ and try to make a BER measurement. If the result displayed is still 0 -6 then reduce the optical power detected by slitghtly tilting the filters and/or by gently closing the shutter. Now a very small current flows through the photodiode. Try a BER measurement again and repeat the procedure until you obtain a value for the Bit Error Rate. When you are at this stage, note the indication on the Hewlett-Packard which you will need for the calculation of the received mean optical signal power.



Do not forget to subtract the dark current from the measured value of the mean photodiode current in order to obtain the mean optical signal current. From this value calculate the mean optical signal power impinging onto the photodiode.

Decrease or increase the optical power very slightly, say of the order of a few tenths of a microwatt and measure again the BER. Make a couple of measurements for the same optical signal. You will notice that the results will deviate from each other. This is not surprising since the signal level is very low and the receiver noise becomes gradually an important factor as the optical power is decreased. Take a mean value of the results and plot it on the supplied logarithmic paper.

Try to perform these measurements by changing the optical power within a range of say + 3dBm from the power level corresponding to $10^{-9}$ or $10^{-8}$ BER. You should now obtain a curve the shape of which is given below:




Ideally the relationship between BER and optical signal power should be linear for the log drawing chosen. Due to noise, jitter and other possible electrical and mechanical instabilities your points are probably not lying on a perfect straight line. Don't be disappointed, some deviation from the linear curve is always present in a real system!

**Terminate the experiment by going through the following steps:**

1. Turn potentiometer of the "Laser Driver" plug-in fully counterclockwise to zero
2. Switch off the BER measuring set
3. Switch off the "Laser Driver" plug-in
4. Switch off the transimpedance receiver
5. Switch off the 40 dB signal amplifier

Transimpedance Receiver

Follow the steps outlined below. Start by having all equipment switched off.

1. Turn potentiometer of Laser Driver counterclockwise to zero. Connect the transmitter to the Laser Driver by connecting the laser and the monitor photodiode through coax cables with the

plug-in unit "Laser Driver". Connect the Fluke voltmeter to the Laser Driver for the measurement of the laser current.

**Switch the Laser Driver on.**

Note the laser current.Its value should be slightly above the threshold determined earlier corresponding to an operating point given schematically in the figure below.


**If the laser current is not at such a value,** do not continue the **experiment and ask for assistance.**

2.Connect the optical fiber cable to the transmitter and to the Transimpedance Receiver.Connect the Hewlett-Packard microvoltmeter across the terminals labeled $V_{out}$-$I_{det}$ of the transimpedance receiver.The voltage $V_{out}$ is measured across a 1 kohm resistor in series with the PD inside the transimpedance circuit.

Switch on the Transimpedance Receiver.You will notice that a voltage of some mV is displayed on the Hewlett-Packard corresponding to some µA photodiode current.

If the Voltmeter does not display any voltage or if the voltage is much lower than a few mV and the laser is properly set, then some optical misalignement has probably occured.Realign the optical transmitter so as to couple as much as possible power into the fiber and continue.

3.Switch now the laser off by switching the plug-in unit "Laser Driver" off.Be always sure the potentiometer is in the zero position before switching off.The Hewlett-Packard voltmeter will now indicate a very small value,perhaps 10 to 20 µV corresponding to 10 to 20 nA photodiode current.This is the dark current of the photodiode. This value is important because it must be subtracted from the value measured when an optical signal is detected in order to obtain the real mean signal current.

4. Switch the laser on.

5. Set the front panel controls of the BER set as follows:



| Control | Function | set as follows: |
|---|---|---|
| 1 | Signal | Connect to terminal "ac signal out" of the Transimpedance plug-in.Use two BNC cables connected together through a T-coaxial connector and plug the "male" of the T into the oscilloscope,channel A or B. |
| 2 | Clock | Connect to control 5 |
| 3 | Slope | Set to positive clock edge |
| 4 | Generator | Connect to "ac signal in" of the "Laser Driver" plug-in unit. |
| 5 | Clock | this is now connected to control 2 |
| 6 | Clock | Set at CAL |
| 7 | Bitrate | Set at 2048 kbit/s |
| 8 | Code | Set at NRZ/TTL |
| 9 | | nonexisting |
| 10 | Pattern | Set at pseudorandom $2^{15}-1$ |
| 11 | Digital word | do not set |
| 12 | | nonexisting |
| 13 | | nonexisting |
| 14 | Error test | do not set |
| 15 | | nonexisting |
| 16 | | nonexisting |
| 17 | Evaluation | Set at $10^6$ bit |
| 18 | | press the button 1X/Rep for 1X |
| 19 | Interval | do not set |
| 20 | Error | Set at BIT |
| 21 | PRINT | Set to OFF |
| 22 | | do not set |

Set the oscilloscope controls as follows:

| | |
|---|---|
| Ampl/Div | 1 V |
| time/Div | 1 µs, magn. x5 |
| AC/DC | DC |
| A&B/ADD | A&B |
| A/B | A |
| TRIG | + , INT, DC |

Switch on the BER set.

The laser diode current is now modulated by a 2 Mbit/s pulse train to which a large number of random pulses is superimposed.The pulse amplitude is approx.26 mA peak-peak,corresponding to a 2 V signal from the BER set divided by 75 Ohm impedance of the Laser Driver input.Since the operating point of the laser had been set slightly above the threshold before the modulation, the "zeros" are now well below threshold but the "ones" well above it.This is the same state of affairs as discussed above for the case of the Low-impedance Receiver.

After having switched the BER set on, notice that

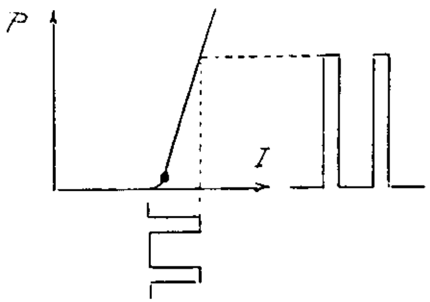
1. a small signal appears on the oscilloscope, amplitude <0.5 $V_{pp}$

2. the voltage displayed on the Fluke voltmeter decreases. This voltage corresponds to the laser current which has a dc component equal to the laser current at the operating point set before and an ac component due to the modulation signal. The value measured with the Fluke voltmeter is therefore a mean value of the current. This current now jumps between two values according to the state of the modulating signal. Since the mean current is lower that the operating point value, the signal reaching the laser contains more "zeros" than "ones" and the resulting mean current decreases.

3. The mean current through the photodiode has decreased for the same reason as the laser current.

Now proceed with the following adjustments:

- increase slowly the laser current by turning clockwise the potentiometer labeled "Laser current adjustment" of the "Laser Driver" plug-in. Increase the current until you reach approximately 1 Volt signal amplitude on the oscilloscope. As you increase the laser current you shift the baseline of the modulating signal to higher currents and you obtain more photocurrent as illustrated in the Figure below:




The "zeros" are still below threshold but the optical signal amplitude is now larger than before.

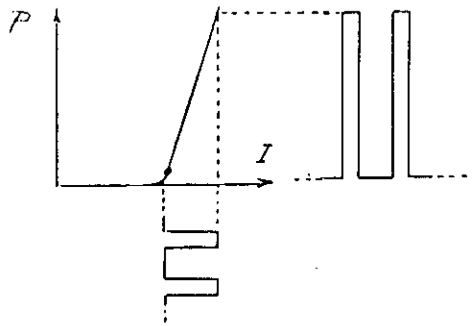
Note also that as you increase the laser current the baseline of the oscilloscope trace remains at the same position because the optical "zeros" still correspond to zero optical power.

- Increase further the laser current until the baseline of the electrical signal through the laser reaches the threshold current. NOW STOP TURNING THE POTENTIOMETER. You can check whether the beseline is located at the threshold current by observing the oscilloscope trace while turning the potentiometer. The baseline of the oscilloscope trace remais pinned at the same level as long as the baseline of the modulating signal is below threshold. As soon as the threshold is reached, the baseline of the oscilloscope



trace shifts to higher voltages (the oscilloscope must be in the "DC" mode). The signal amplitude on the oscilloscope should be now at least 2 V.

The following figure illustrates the new state of affairs.




Now try the first Bit Error Rate measurement:

- Set control 17 "Evaluation" at $10^6$ bit error ratio.
- Push control 18 START/CLEAR button.

The BER set displays 0 -6 meaning that there is no false bit in a stream of $10^6$ bits.
Repeat the measurement for $10^7$ and $10^8$ bits. The display should read 0 -7 and 0 -8.

The reason that no false bit is measured is that the received power is very high. In this case the noise of the photodetector circuit is of no consequence for the detection process and since we have now built a good operating transmission system no false bit is detected. In order to be able to perform the measurement of the Bit Error Rate the optical power detected must be reduced drastically.

The reduction of the optical power will be carried out by inserting the supplied optical neutral density filters in front of the fiber front face and by closing the mechanical shutter of the transmitter.

It is important of course to have an idea of the order of magnitude of the power on the photodiode that causes a BER of say $10^{-9}$. Otherwise the search for false bits may take too long! The range of the expected power can be obtained by solving the theoretical problem given in Section 1. For the experiment proceed as follows:

Insert Filters 1 or/and 2 or/and 3 in front of the fiber in the optical transmitter setup. Tilt them carefully so as to obtain a photodetector current of less than 1 μA. The signal received by the BER set is now much too small for a measurement as you also notice on the oscilloscope. Note that at least about 50 mV are required for a measurement, the maximum signal level allowed being about 4 V. The signal at the output of the Transimpedance Receiver must be further amplified.This is done with help of the plug-in unit labeled "40 dB Signal Amplifier" meaning that the signal voltage at the amplifier input is amplified 40dB or 100 times.The 3dB bandwidth is 2MHz.

Connect the output of the Transimpedance plug in unit to the input of the 40dB amplifier.Connect the output of the amplifier to the BER set via the oscilloscope as previously.Switch the amplifier on.You will notice that a clear signal trace of a few volts amplitude appears on the oscilloscope.

IMPORTANT NOTICE:

If the baseline of the oscilloscope trace is not at the same level as before switching the Signal Amplifier on, turn very carefully the "offset adjust" potentiometer on the front of the plug-in unit "40 dB Signal Amplifier" and shift the baseline to its original position

Set the error ratio at $10^6$ and try to make a BER measurement.If the result displayed is still 0 -6 then reduce the optical power detected by slitghtly tilting the filters and/or by gently closing the shutter.Now a very small current flows through the photodiode. Try a BER measurement again and repeat the procedure until you obtain a value for the Bit Error Rate.When you are at this stage,note the indication on the Hewlett-Packard which you will need for the calculation of the received mean optical signal power.

Do not forget to subtract the dark current from the measured value of the mean photodiode current in order to obtain the mean optical signal current. From this value calculate the mean optical signal power impinging onto the photodiode.

Decrease or increase the optical power very slightly , say of the order of a few nanowatts, and measure again the BER.Make a couple of measurements for the same optical signal.You will notice that the results will deviate from each other.This is not surprising since the signal level is very low and the receiver noise becomes gradually an important factor as the optical power is decreased. Take a mean value of the results and plot it on the supplied logarithmic paper.

Try to perform these measurements by changing the optical power within a range of say + 3dBm from the power level corresponding to $10^{-9}$ or $10^{-8}$ BER. You should now obtain a curve of the same shape as given in the figure above in the case of the Low-Impedance Receiver but shifted to lower optical powers.

Ideally the relationship between BER and optical signal power should be linear for the log drawing chosen. Due to noise,jitter and other possible electrical and mechanical instabilities your



points are probably not lying on a perfect straight line.

**Terminate the experiment by going through the following steps:**

1. Turn potentiometer of the "Laser Driver" plug-in fully counterclockwise to zero
2. Switch off the BER measuring set
3. Switch off the "Laser Driver" plug-in
4. Switch off the transimpedance receiver
5. Switch off the 40 dB signal amplifier.

******************************************************************

## APPENDIX

The validity of the relation $dB_{electrical} = 2 \times dB_{optical}$ relies on the following consideration:

An optical power $P_{opt}$ detected by a photodetector produces a photocurrent I which is proportional to the optical power:

$$P_{opt} \sim I$$

A value of x <u>optical dB's</u> is per definition

$$x\ [dB_{opt}] = 10 \log(P_{opt1}/P_{opt2}) = 10 \log(I_1/I_2)$$

The photocurrent I produces an electrical power $P_{el}$:

$$P_{el} \sim I^2$$

A value of y <u>electrical dB's</u> is per definition:

$$y\ [dB_{el}] = 10 \log(P_{el1}/P_{el2}) = 20 \log(I_1/I_2)$$
$$= 20 \log(I_1/I_2)$$

Consequently, if decibels are used to describe the same phenomenon, e.g. attenuation of a signal in a fiber, then the electrical dB number is twice as large as the optical dB number



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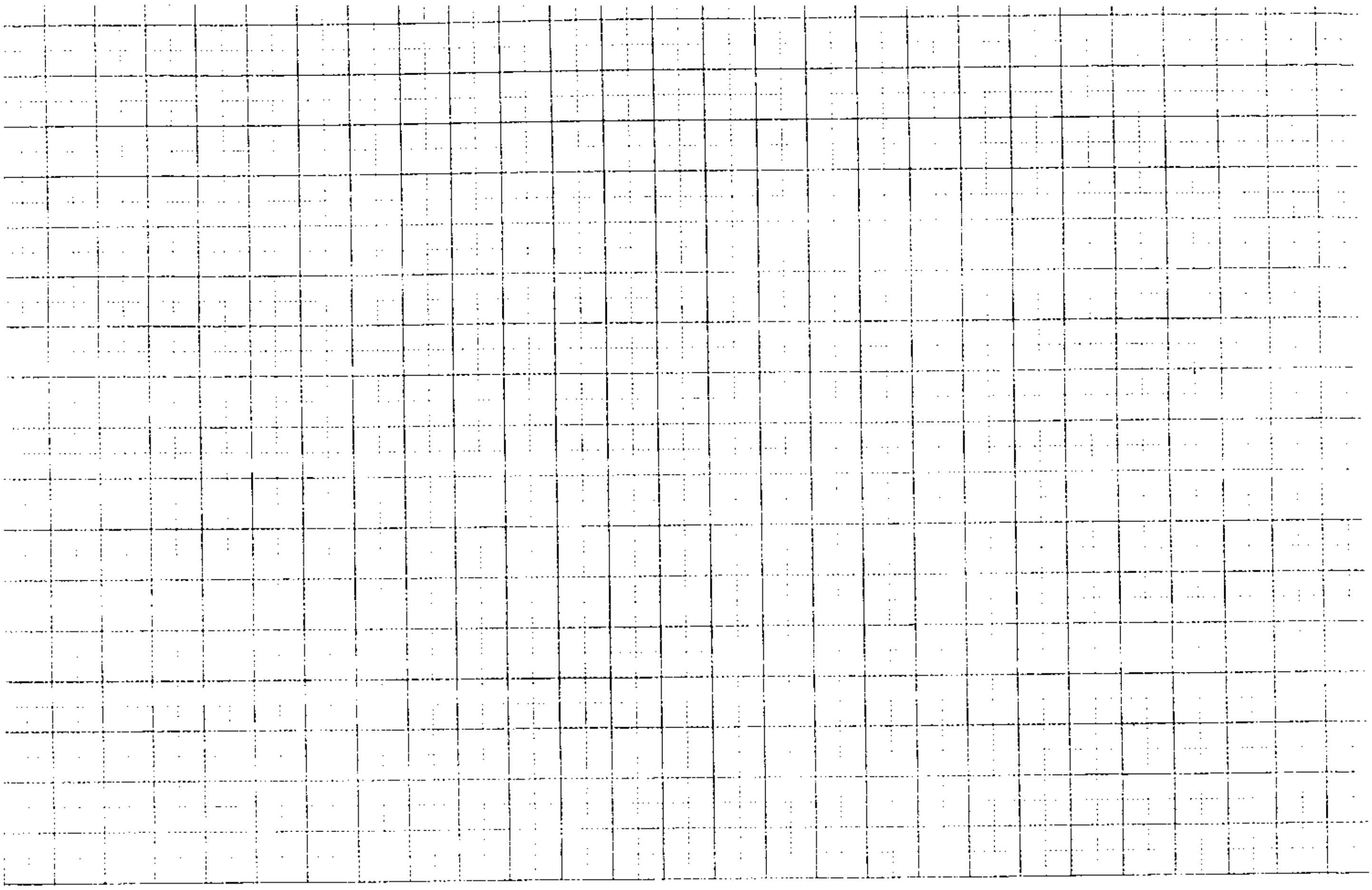
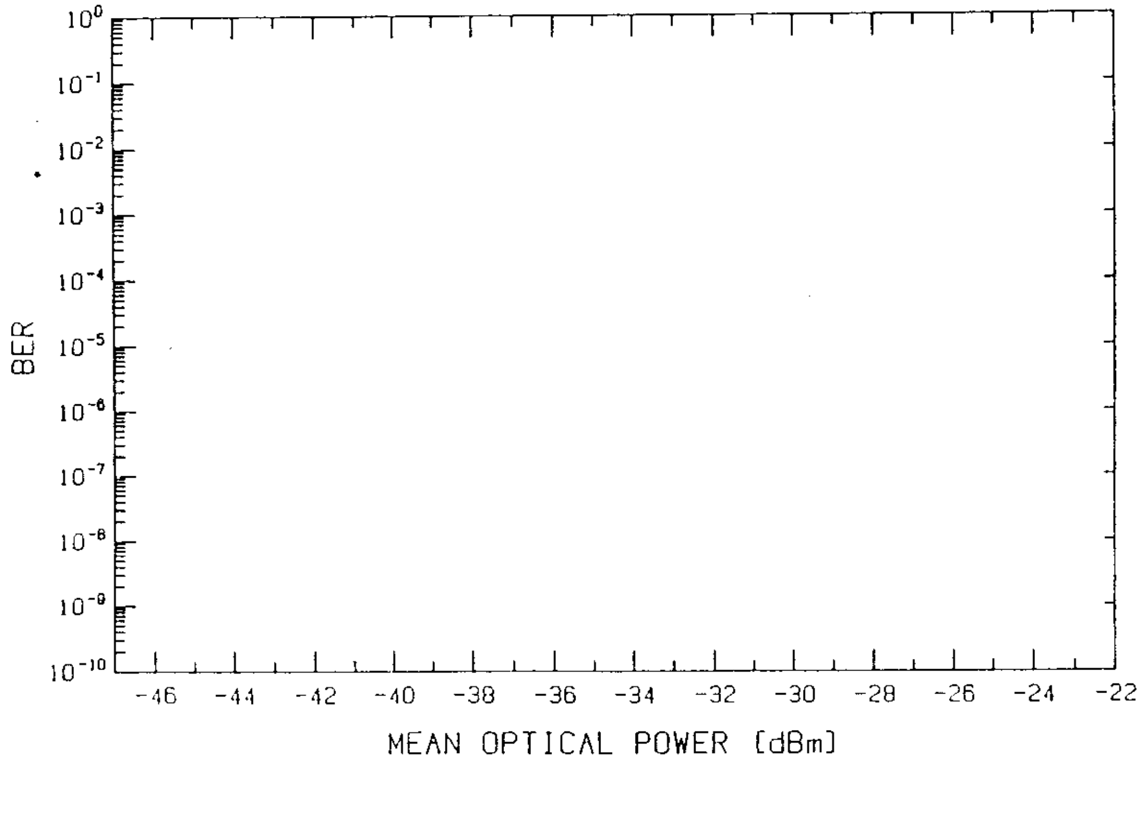
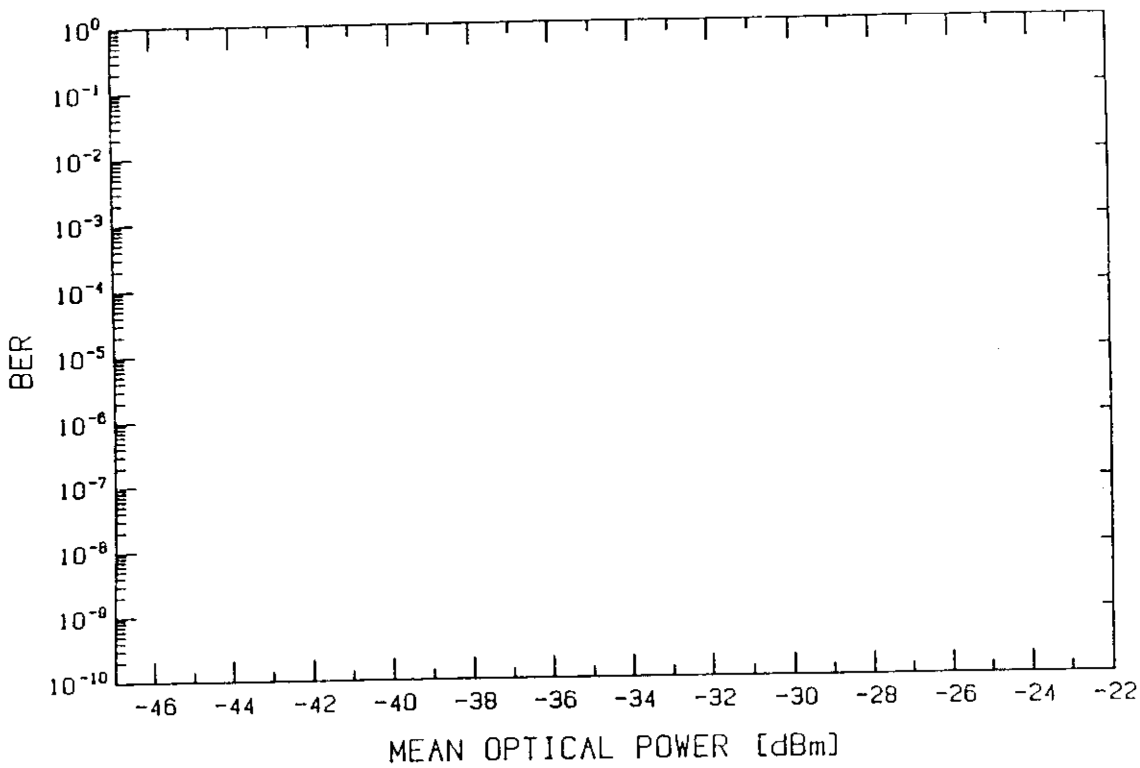




BER
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7
10^-8
10^-9
10^-10
-46
-44
-42
-40
-38
-36
-34
-32
-30
-28
-26
-24
-22
MEAN OPTICAL POWER [dBm]



BER
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7
10^-8
10^-9
10^-10
-46
-44
-42
-40
-38
-36
-34
-32
-30
-28
-26
-24
-22
MEAN OPTICAL POWER [dBm]