FIBER OPTICS
HANDBOOK

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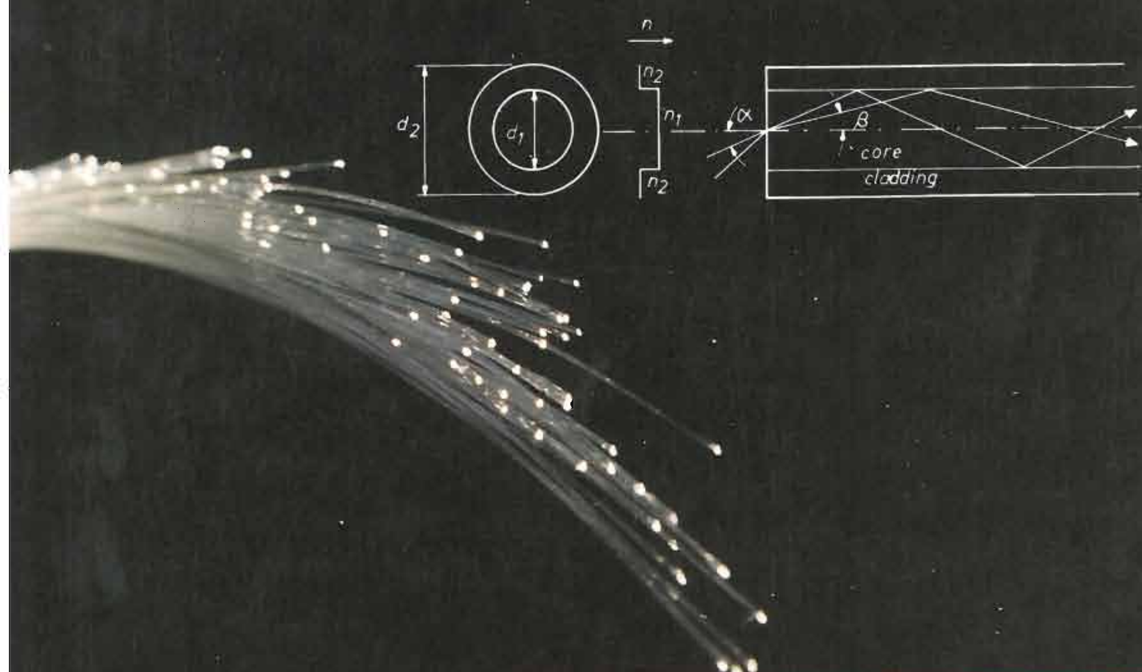

HEWLETT PACKARD

FIBER OPTICS HANDBOOK

An introduction and reference guide to
fiber optic technology and measurement techniques

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1. INTRODUCTION

The purpose of HP's FIBER OPTIC HANDBOOK is to provide basic information about fiber optic systems and components, and methods for evaluating their performance. Fibers offer clear advantages over conventional transmission media. These include lower attenuation, larger bandwidth and freedom from electromagnetic interference. Despite these advantages, the underlying basics and the techniques involved in fiber optics are more complicated than e.g. in coaxial cables. This book is intended to help answering many questions in a comprehensive and easy-to-read way.

The book is divided into two parts. The first part contains the overview articles, which summarize the present state of fiber optic technology:
"Pros and Cons of Fiber Optics",
"System Design",
"Fiber Optic Measurements"
"Laser Product Safety".

The second part and main part of the book comprises the "Fiber Optic Reference Guide". Emphasis is not so much on an explanation of technical terms, but on an overview of the entire field of fiber optics: the basics, tradeoffs, state of the art, typical device characteristics and measurements techniques. Many diagrams and a number of mathematical formulae are also given. For easy orientation the reference guide is subdivided into short chapters in alphabetical order.

The book should assist engineering work in the rapidly developing technology of fiber optics. The incentive for this technology occured in 1966, when the use of glass fibers as a transmission medium was first suggested. Since then the largest activities were in reducing the fiber attenuation from several hundreds of dB/km to an incredible 0.2 dB/km. In parallel to this, many other components for optical links were developed, the most difficult of which was a reliable solid-state laser.

Fiber optics are now on the verge of revolutionizing the communications world. It is expected that around the turn of the decade the majority of newly installed links or networks will be made from fibers. Currently (1983) the total investment in fiber optics is estimated to be in the order of $300 Million per year (corresponding to more than one hundred thousand kilometers of installed fiber) with annual growth rates of about 40%. Another market characteristic is the tremendous research and development activities around the world, which deliver new solutions and new devices almost on a daily basis. Examples are the investigations in integrated optics and fiber optic sensors.

The commercial fiber optical activities are in three different markets:

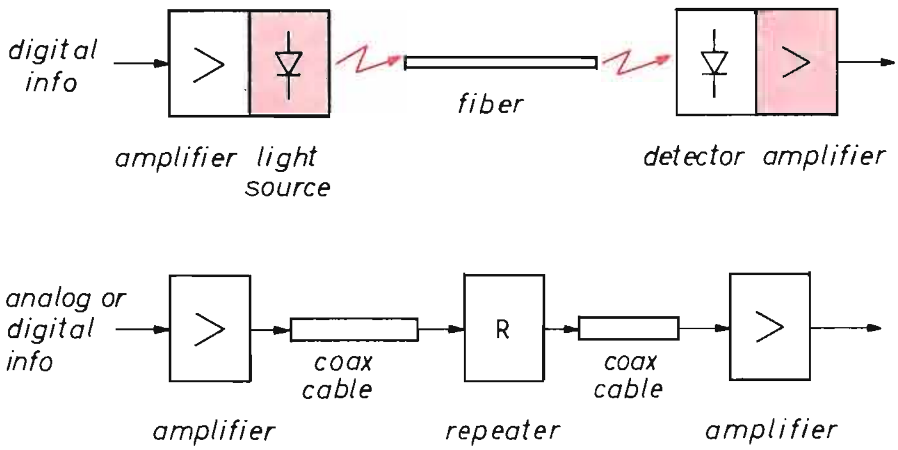
Telecommunication is the largest part with around 60% market share. Today most of the commercial interest is in the installation of high-performance trunk lines. Incidentally, the most advanced fiber techniques, including long wavelengths and monomode fibers, are already in use in this area. Here the prime motivation for installing fibers are the high bandwidth and the drastically reduced number of repeaters. Subscriber services are lagging somewhat behind, especially because of the high cost pressure and the missing standards in this area. Nevertheless, trial systems have been installed around the world and are preparing the grounds for further commercial systems. Because of the large bandwidth of fibers, new services like videophone, data exchange, audio and television will be offered to the subscriber.

The military/industrial market has around 30% market share. The number of different applications in this field is enormous, ranging from digital communication at various bit rates to analog video distribution. Transmission safety and freedom of electromagnetic interference are the driving forces, plus the low weight of fibers for airplane wiring and other military applications.

Still the smallest market is local area networks based on fibers, which are primarily installed in business environments. This segment is now around 10%, but it is growing faster than the telecommunication market. So far the major activities are in replacing electrical cables by point-to-point optical links, but more sophisticated networks utilizing optical star couplers have also been shown. Here the freedom of electromagnetic interference is the incentive again, because this translates into reduced bit errors and improved computer access.

2. PROS AND CONS OF FIBER OPTICS

Many different media are used to transmit information: e.g. wires, coaxial cables, waveguides and radio. Fiber optic cables compete against all of these, but most strongly against coaxial cables. Coaxial system examples are telephone trunk lines, cable television, intra-plant transmission of signals and digital information and ship/airplane wiring. Why should the industry switch from a well established concept to optical fibers? The purpose of this chapter is to clearly identify the advantages and disadvantages of fiber systems compared with coaxial cable systems.



FIBER SYSTEM VERSUS COAXIAL SYSTEM

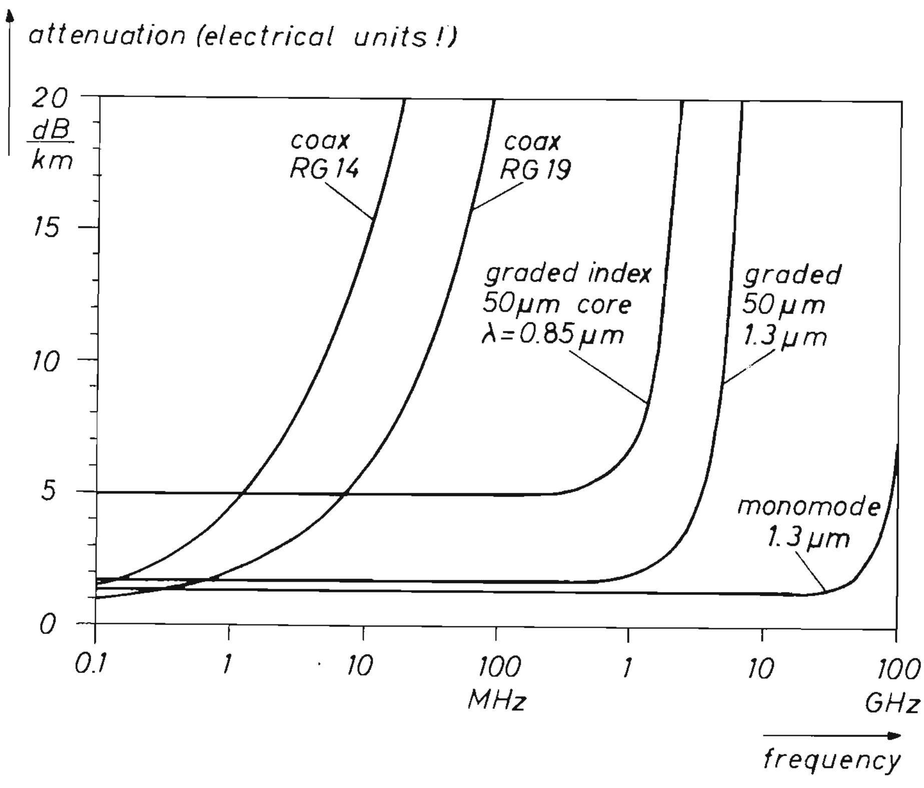
The system block diagrams in the figure reveal typical differences between optical and electrical systems. For example, fiber systems need electro-optical transducers. Despite the steadily declining cost of these components, they are still expensive: a short range/ low bandwidth transducer set sells for less than $100, whereas long range/ high bandwidth transducers may cost several thousands of dollars. The gain from this investment is a drastically reduced number of repeaters, or no repeaters at all. This saves cost and improves the reliability.

For the comparison of fiber cables with coaxial cables we will use the RG14 and RG19 coaxial communication cables as references. In keeping with their relatively high performance, these cables are quite bulky with their 14 and 29mm outside diameters compared to single-fiber cables having typical diameters of 3 to 5mm.

Weight is one of the disadvantages of coaxial cables: the RG 14 and RG19 cables weigh 350 and 1100 kg/km. Compare this to the typical weight of 12 kg/km for a single-fiber cable. This difference may become much more drastic in multichannel cables.

Noise immunity is poor in coaxial cables. They are sensitive to the electric and magnetic fields as generated by machinery, lightning or an electromagnetic pulse (EMP) from a nuclear exlosion. Ground loops and oscillations are also severe problems in coaxial cables. Fibers show none of these effects. Another important point is the fiber's freedom from crosstalk. Even if light is radiated by one fiber it cannot be recaptured by another fiber.

Another fiber advantage is security. It is complicated to tap a fiber: first, one has to isolate the bare fiber from the cable without breaking it. This will probably be the end of the spying attempt. Next, an optical tap must be made, the simplest of which is achieved by bending the fiber into a small radius. If a sufficient amount of power can be tapped, the tap can be detected either by monitoring the power at the system's receiver or with an optical time domain reflectometer. On the other hand, tapping a coaxial cable is easy to do and hard to detect.



FREQUENCY CHARACTERISTICS OF TYPICAL CABLES

The diagram compares the attenuation and bandwidth characteristics of the two RG cables with those of typical fibers, all of them for 1km length. Note that for the comparison only, attenuation is given in terms of electrical dB units, see →dB(optical) in the reference guide. The skin effect in a coaxial cable causes the attenuation to rise with the square root of the frequency, typically starting below 1 MHz. Serious pattern effects arise which must be corrected with filters. Thus the achievable repeater spacing is around 2km for a 100 Mbit/s coaxial link. In contrast, graded index fibers have low attenuation, extending to typically 1 GHz. This way repeater spacing can be as much as 20 km or more. Monomode fibers have been produced with 200 GHz x km bandwidth, promising a repeater spacing of more than 100 km at a 1 Gbit/s data rate.

There is one major difference between optical and electrical transmission: because of their inherent noise sources, fiber optics transmit digital information much better than analog information. The higher required bandwidth represents no problem for fibers. A problem for the broad introduction of fiber services is digital signal processing. Analog information such as voice, video and radio has to be digitally encoded and decoded which is not yet commercially available on a high volume basis. The digital revolution, also observed in conventional electronics, is thus important for the take-off of fiber optic systems. The inherent higher quality of digital systems will give further support. From this point of view, fiber optics can be introduced most easily in computer networks and in telephone trunk lines where the information is digital from the very beginning. It should be mentioned here that some analog systems also work quite acceptably on a fiber: one example is video transmission using frequency modulation. Those systems have been accepted as an intermediate step towards full digitization.

Low weight, reduced dimensions, and high flexibility makes the installation of fiber cables comparatively easy, be it pulling them through existing ducts or laying them into ground. Also, a drastically reduced number of repeaters, or no repeaters, are required. However, fiber splicing during installation and repair requires greater equipment sophistication and more highly skilled personnel.

Quality assurance is sometimes another point of concern. But go-nogo- and functional test equipment for two-port measurement is available for both fiber and coaxial cables, with fiber test equipment being more expensive and more difficult to operate. Time domain reflectometry allows one-port characterization of either type of cable. Again, optical time domain reflectometers (OTDR's) are more expensive than their electrical counterparts. They are now available for 20km unrepeatered fiber measurement, which is sufficient for most commercial links.

To summarize: we have found that fiber systems offer many technical advantages such as large information capacity, noise immunity, security and favourable physical properties. Some concerns may still exist about the ease of fiber splicing, a fiber optic soldering iron is not yet in sight. Fiber quality assurance may also be more tedious. The necessity to transmit digital information is another obstacle for some system requirements. To mention transmission line cost, high-performance fibers are already cheaper than high-performance coaxial cables, especially if repeaters are included in this comparison. A good graded index fiber cable costs around $1 per meter in 1983.

2. SYSTEM DESIGN

Various decisions have to be made when designing an optical transmissison system. Which wavelength should be used? Which transmitter: light emitting diode (LED), or laser? Which fiber: step index or graded index or monomode? Which receiver: pin diode or avalanche photodiode? In this article we want to present some of the tradeoffs leading to an application-tailored system.

Wavelength - Commercial components are available for two wavelength regions: the near-infrared region, ranging approximately from 780 to 900nm (typically 850nm), and the long-wavelength region, ranging approximately from 1200 to 1600nm (typically 1300 and 1550nm). Fiber optical engineering started in the 850nm - region, but the 1300nm wavelength offers a number of advantages. One advantage is fiber attenuation: at 1300nm the attenuation of a good graded index fiber is 0.6 dB/km and even lower at 1550nm. Compare this to 3.0 dB/km at 850nm. Another advantage is low material dispersion, resulting in high bandwidth. Material dispersion of the fiber arises from different group delays at different wavelengths, together with limited source linewidth. It goes through zero in the vicinity of 1300nm, whereas it is typically 100 ps/km x nm at 850nm.

Multimode dispersion - also called modal dispersion -, is pulse broadening arising from the different travelling speeds of different modes. It is also wavelength-dependent but there is no typical behaviour. Double window fibers are made for equal modal behaviour at 850 and 1300nm. Monomode fibers show negligible multimode dispersion above the so-called cut-off wavelength.

In summary, low attenuation and low chromatic dispersion are the reasons to choose 1300nm. Because of the low attenuation, simple LED's could replace lasers in some instances. Another reason to use the long wavelength is increased radiation safety, see the "Laser Product Safety" article.

Commercial LED's and lasers are currently only available for 850 and 1300nm, not yet for 1550nm. Detectors are available for any of these wavelengths, however long-wavelength detectors exhibit higher noise and thus are less sensitive. The most obvious reason to use 850nm is the price: both sources and detectors are around 3 times cheaper than their 1300nm counterparts. This difference may decrease when long wavelength devices reach high volume production status which some of the 850nm devices already have.

LED versus laser - Once again the price determines the performance. Light emitting diodes for fiber applications are economic: their prices range from below $10 and up to $100. Long wavelength LED's are more expensive. LED characteristics are:

high reliability and simple system integration, but low coupling efficiency, bandwidths up to 200MHz, spectral widths of typically 40nm and the associated larger chromatic dispersion. However the large spectral width also gives the benefit of low modal noise.

Lasers are expensive: their prices range from a couple of $100 up to a few $1000 in 1983. Their value is in high bandwidth (up to the Gigahertz range), high coupling efficiency, and low spectral width of typically 3nm. The latter results in low chromatic dispersion and high system bandwidth, but also in larger modal noise. Only in monomode fibers is modal noise not observed. The laser's disadvantages are sensitivity to overload currents, lower reliability and large drive currents beyond the so-called threshold current, necessitating cooling and power stabilization.

Multimode lasers, exhibiting a number of spectral lines, are most often used. Monomode lasers only exhibit one spectral line with a typical width of only 0.01nm. They are very sensitive to reflections which cause optical feedback noise. Also, they can only be used in conjunction with monomode fibers. Using them to drive multimode fibers leads to unacceptable modal noise. In contrast, driving monomode fibers with multimode lasers presents no problem.

At 1300nm, lasers could be replaced by LED's: simplicity, reasonable bandwidth (from larger spectral width, but lower chromatic dispersion), reasonable signal level (from lower coupling efficiency, but also lower fiber attenuation), and low modal noise would be obtained.

Fibers - The type of fiber has a large influence on multimode dispersion and the resulting bandwidth: typical numbers are 20 MHz x km for a step index fiber, 1 GHz x km for a graded index fiber, and 20 up to 200 GHz x km for a monomode fiber. Chromatic dispersion, which is mainly material dispersion, is not very dependent on the type of fiber. Little influence can also be observed on the low-frequency attenuation: surprisingly, the monomode fiber with its tiny core dimensions has the lowest attenuation and the lowest scattering losses. This can be attributed to the lower refractive index contrast and less doping material in a monomode fiber.

The three fiber types drastically differ in bandwidth, numerical aperture and core diameter, the latter leading to large differences in coupling efficiency to typical sources. Thus the major compromise to be made is price versus bandwidth and coupling efficiency. This situation is displayed in the table below, it shows typical coupling efficiencies to double-heterostructure lasers.

fiber type	price	core diameter	coupling efficiency	bandwidth
step index	$1/m	100-200µm	70%	20 MHz km
graded index	$1/m	50µm	40%	1 GHz km
monomode	$5/m	10µm	20%	100 GHz km

FIBER SELECTION TABLE

Finally let us compare the modal noise characteristics. Speckle patterns and the associated modal noise are strongest in graded index fibers. Due to the larger number of modes they tend to average out in a step index fiber. In a monomode fiber there is a uniformly illuminated core, because no different modes can interfere. Thus speckle patterns and modal noise do not exist in monomode fibers.

Detectors - Three types of detectors are competing against each other in the fiber optical world: pin diodes, avalanche photodiodes (APD), and the more recent pin - field effect transistors (pin-FET). The pin diode is the most basic structure. It offers good linearity, high bandwidth, and good temperature stability. Its disadvantage is low sensitivity as a system receiver: at 100 Mbit/s typically -42dBm optical power (time-average value) is required to achieve a bit error rate (BER) of 10^{-9}. In contrast, an APD is neither linear nor stable, but exhibits good sensitivity. Typically -50dBm optical power is required to meet the above described objective. High voltage (around 200 - 300V) has to be applied to the APD to achieve the necessary multiplication factor. Careful biasing involving feedback and sometimes temperature stabilization must be included in order to prevent breakdown or overload.

The latest device is the pin-FET, which is a hybrid or integrated two-device structure. It combines the advantages of good sensitivity and reasonable gain stability with no need for high voltages.

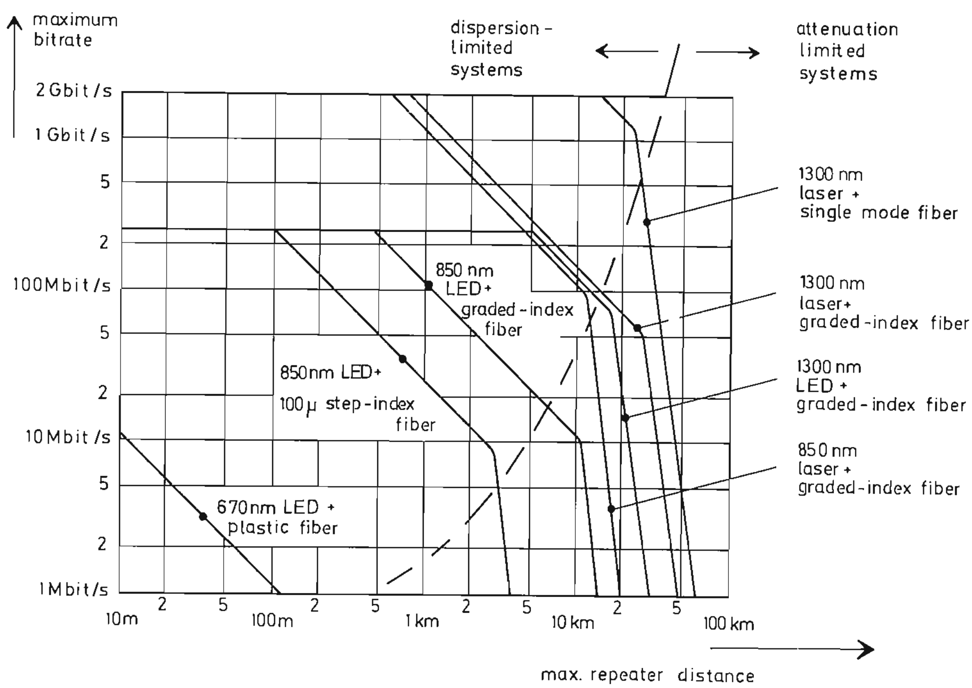
Pin-diodes are available in silicon covering the near-infrared region and in indium-gallium-arsenide-phosphide (InGaAsP) covering the long-wavelength region. Germanium pin-diodes cover the long-wavelength region and extend somewhat into the near-infrared region. Their disadvantage is lower sensitivity due to high dark current.

APD's are available in silicon for the near-infrared region and in Germanium for the long wavelength region. They have the same wavelength dependence as their pin counterparts. APD's made from InGaAsP are only slowly emerging from the laboratory. Their advantage over Germanium-APD's once again is lower dark current.

System choices - The transmission capacities of some particularly useful systems are presented in the figure. All curves refer to PIN-diode-receivers. The most economic solution consists of an LED and a 1mm plastic fiber. Because of its large multimode dispersion, such a system spans around 10m at 10 Mbit/s. A 100um fiber already spans 2km at the same bitrate. Those systems are mostly used in local area networks. Graded-index fibers further improve bandwidth and attenuation - 10km repeater spacing is the result. Switching to a laser is another improvement. However, the same performance can also be achieved by launching 1300nm with an LED. For the highest distances and data rates 1300nm or 1550nm lasers and single mode fibers are used exclusively.

Generally attenuation-limited and bandwidth-limited systems can be distinguished. The attenuation limit is reached whenever the received power equals the sensitivity of the receiver. Bandwidth limitation occurs whenever the transmitted pulses are too wide, resulting in unacceptable intersymbol interference.

Because of inherent noise sources, analog baseband transmission over fibers does not meet the normal voice or video requirements. There is some indication that linear single-mode lasers in conjunction with isolators (to prevent optical feedback noise) and monomode fibers with low birefringence may yield high performance analog systems. Until then, analog signals will most often be transmitted using frequency modulation.



TRANSMISSION CAPACITY OF DIFFERENT FIBER SYSTEMS

4. FIBER OPTIC MEASUREMENTS

A number of national and international organizations are involved in standardizing fiber measurements. In the United States the Electronic Industries Association (EIA) and the National Bureau of Standards (NBS) are most active. The EIA's proposals are published as Fiber Optic Test Procedures (FOTP) with the intention to generate Recommended Standards. The RS455 will finally gather all the test procedures. This article mostly summarizes the FOTP's because of their importance for the US industry. Other organizations include the British Standards Institution (BSI) and the German Deutsche Elektrotechnische Kommission (DKE). These have also established working groups in order to standardize measurement methods.

All the national groups are members of the International Electrotechnical Commission (IEC) which tries to set worldwide industry standards. However, national standards may differ from their proposals. The telephone companies' and post offices' requirements are independently standardized by the International Telegraph and Telephone Consultive Committee (CCITT).

Generally measurement standardization did not keep up with the fiber optical revolution. This is partly due to the complexity of the light transmission mechanics in a fiber: for an exact description and evaluation, hundreds of different waveguide modes would have to be considered in a multimode fiber. Unlike a coaxial cable, a multimode fiber is a 2 x n-port device, n being the number of possible modes. However, this kind of fiber characterization is impractical if not impossible. As a consequence the standardization groups have tried to concentrate on more global and practical measurement methods with the intention to achieve interlab reproducibility.

The EIA has first tried to establish a common fiber optic understanding by setting a terminology standard. This is published under RS440, based on an earlier work of the NBS. This effort tries to ease the problem that many engineers may use different words for the same phenomenon, and that the same word may have different meanings.

The term "equilibrium mode distribution" (EMD) was created in order to establish a basis for the above-mentioned global fiber characterization. It describes the modal power distribution in an undisturbed fiber at a long distance from the input port, typical distances are in the order of kilometers. However, this equilibrium can be approximated by the use of launch optics or mode filters, such as dummy fibers or mandrel wrap filters. A short 1-2m fiber is used to verify the far-field angle to be identical to the far-field angle of the long test fiber. According to EIA's FOTP 50, the short fiber must generate a far-field with a 5% intensity angle being identical to the long fiber angle within an angle tolerance of -3% ±3%.

In order to attain a linear dependence of the attenuation decibels on fiber length, the optical source must launch an equilibrium mode distribution into the fiber. Details of spectral attenuation measurements are given in FOTP 46. Additionally, attenuation measurements are often made utilizing the backscattering mechanism, see below.

Bandwidth and dispersion measurements are even more complicated: bandwidth does not linearly scale with fiber length. Below the so-called coupling length, bandwidth is the reciprocal of length, above this length bandwidth is the reciprocal of the square root of length. The source's spectral width also influences the bandwidth because of chromatic dispersion. To keep this influence small a narrow spectral width must be used. For example: in order to measure a bandwidth of 1 GHz x km for a graded index fiber of 1 km length at 850nm, the source's spectral width must be below 2nm in order to keep its influence below 10%. The exact procedures are give in FOTP 30 for bandwidth measurements in the frequency domain and in FOTP 51 for dispersion measurements in the time domain.

The fiber-optic community is still discussing whether bandwidth measurements should be made with an equilibrium mode distribution (so far yielding non-reproducible results), or with overfilling the fiber input via a mode scrambler. This last method is suggested in FOTP 54 and gives reproducible results, but does not necessarily allow a good prediction of the bandwidth of an actual link made from that fiber.

The far-field angle desribing the equilibrium is not to be confused with the far-field angle which defines the numerical aperture (NA). To measure the NA, a short 2m fiber must be excited with a large spot size and mode stripping must be done in order to remove the cladding modes. The FOTP 47 suggests the use of the 5% intensity angle for the NA. Originally the NA defined the maximum input angle of acceptance, but present NA data always refer to the measured output field.

Cable manufacturers also need to measure mechanical dimensions such as core and cladding diameters. These data are also important for connector manufacturers. While measurement of the cladding diameter can be done under a microscope, the core diameter is always based on the measurement of the refractive index profile. Different techniques are used to perform this measurement: most popular are the transmitted near-field method (FOTP 43) and the refracted near-field method (FOTP 44). The simpler transmitted near-field method is based on the idea that the near-field intensity of a 2m piece of fiber is proportional to the refractive index profile. To achieve this, the fiber input must be overfilled and a cladding mode stripper must be used. Since the transmitted near-field does not give a distinct core diameter value, the FOTP 58 suggests to intersect the measurement curve with a line defined by $n_2 + 0.025 (n_1 - n_2)$, n_1 being the maximum refractive index of the core and n_2 being the cladding index. The intersection points then define the core diameter.

Similar to attenuation in fibers, connector losses are also dependent on the light characteristics at the connector interfaces. This may be controlled by an adequate effective mode volume, which is suggested in FOTP 34.

Besides the classical two-port measurements, one-port attenuation measurements can be done utilizing the backscattering mechanism in fibers. Dispersion measurements and fiber length measurements are also possible this way. When measuring attenuation, an additional advantage arises from the possibility of detecting flaws and attenuation non-uniformities. However, these attenuation measurements may not exactly yield the same results as the two-port measurements. FOTP 59 proposes standards in backscattering light measurements.

It turns out that today many fibers on the production floor and in the field are characterized with two-port attenuation and backscattering measurements. While the two-port measurement gives accurate results for system designers and quality assurance personnel, the backscattering measurement reveals otherwise unobtainable characteristics along the fiber i.e. the fiber's signature, colloquially called the footprint.

Most of the other FOTP's deal with environmental effects on fibers, such as temperature, moisture, mechanical stress and radiation.

The biggest measurement standardization effort today is in multimode graded-index fibers which is due to their large market share. Thus we find a lack of standards in step-index multimode fibers and in monomode fibers. These problems will have to be solved with the growing importance of local area networks based on step-index fibers. Standardization groups have just started their work on monomode fibers which are the key components for long haul/ high speed communication.

Besides fiber measurements there is a whole measurement variety on optical sources and receivers. This group of components is called electro-optical transducers. Transducer standardization efforts have also been started. Repeater measurements consist of both types of measurements. Here are the main measurements tasks on optical sources, and why they are important for the overall system performance:

source measurement	affected system parameter
optical power	In attenuation limited systems the input power defines the repeater spacing. For a given fiber the input power affects the receiver's signal-to-noise ratio and the bit error rate in digital systems.
bandwidth, waveform	These characteristics influence the system's bandwidth. In a digital system the receiver's intersymbol interference, the eye pattern and the bit error rate are affected.
harmonic distortion	The linearity of an analog system is affected by the source's linearity.
signal-to-noise ratio	Optical sources carry appreciable amplitude noise, which affects the total system noise.
extinction ratio	For best noise performance digital receivers require high on-off power ratios.
wavelength	Fiber attenuation and bandwidth, thus repeater spacing, signal-to-noise ratio and bit error rate are dependent on wavelength.
spectral behaviour	The total spectral width determines the fiber's chromatic dispersion and the bandwidth. Modal noise and mode partitioning noise are also affected by the source's spectral width.
near/far field	These parameters define the coupling efficiency to a fiber. Additional nonlinearity may arise from non-perfect coupling

Other measurements are only relevant for the light generating component, be it LED or laser: threshold current, conversion factor, temperature dependence and lifetime. For most of these measurements an optical power meter is needed, capable of static and dynamic measurements. In order to check waveform and signal performance, a linear optical-to-electrical transducer should be included. The HP 8151A OPTICAL PULSE POWER METER is such an instrument, see the description below.

A similar set of measurement tasks can be set up for the receiving end:

receiver measurement	affected system parameter
sensitivity	The sensitivity defines the lowest optical input power for correct functioning of the system, and is thus important for repeater spacing, signal-to-noise ratio, bit error rate.
bandwidth, waveform	The total system bandwidth, the noise and the intersymbol interference are affected by the transfer function of the receiver.
signal-to-noise ratio	This parameter determines the quality of a transmission link, be it analog or digital.
Bit error rate, eye pattern, intersymbol interference	These parameters determine the quality of a digital transmission system.

Some measurements are specifically necessary for detectors like pin-detectors and avalanche-photodetectors (APD's): spectral responsivity, quantum efficiency, transition times, temperature dependence, dark current, noise equivalent power (NEP) and uniformity of the responsivity over the detector area. In any case a calibrated optical source with modulation capability and a wide range of power levels is necessary. These features can be found in the HP 8150A OPTICAL SIGNAL SOURCE.

THE HP 8150A OPTICAL SIGNAL SOURCE AND THE HP 8151A OPTICAL PULSE POWER METER PERFORMING A REPEATER MEASUREMENT

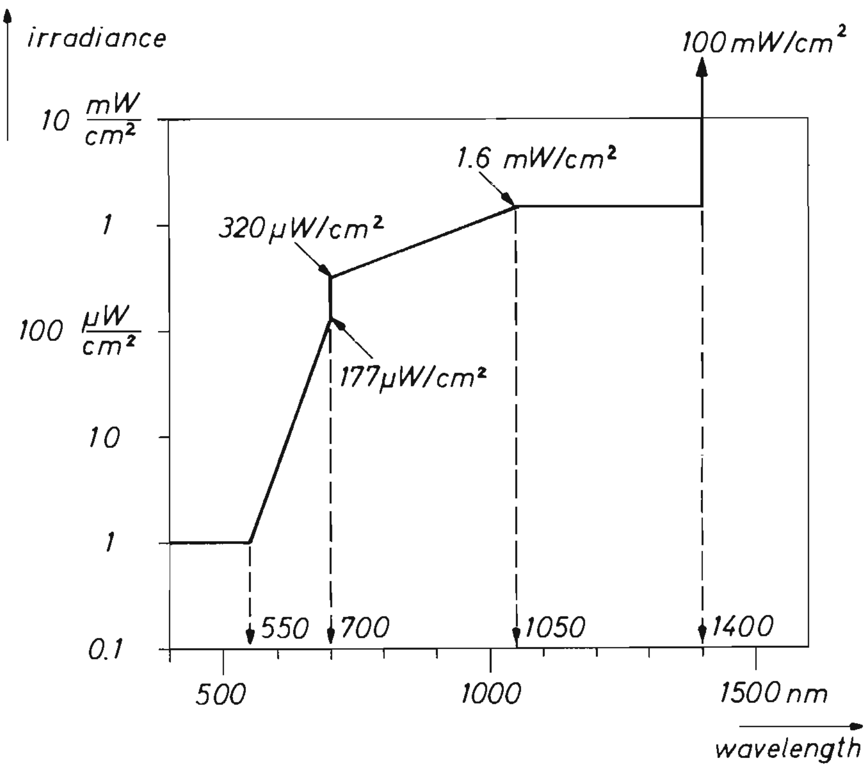
Both the optical signal source and the optical pulse power meter can be considered as basic fiber optic measurement tools. They were developed in order to provide reliable source and receiver measurements. Many fiber and optical component measurements can also be performed.

The HP 8150A OPTICAL SIGNAL SOURCE is a multiwaveform source based on an 850nm semiconductor laser. Its output is a 50µm core graded-index fiber. Laser modulation can either be done by an internal pulse-function generator from DC up to 50MHz or externally with any modulation signal up to 250MHz. Most important is the precise control of output power levels, with the wide range from 2mW down to 1nW. HP-IB programmability is standard.

The 8151A OPTICAL PULSE POWER METER actually hosts two in struments. First, an optical-to-electrical converter with a DC to 250MHz bandwidth, and secondly an optical power meter that is capable of measuring pulse power in addition to average power. The wavelength range is 550 - 950nm. As the concept is based on detachable optical heads, this range will be extended into the long-wavelength region. The 8151A is HP-IB programmable.

5. LASER PRODUCT SAFETY

Lasers and high radiance LED's may cause eye damage by absorption of light energy inside the retina. This potential hazard has been investigated by a number of scientists and national safety organizations. These organizations contribute to the recommendations of the International Electrotechnical Commission (IEC), in which all major industrial nations have representatives. Thus the IEC recommendations represent worldwide guidelines, although national standards may differ. Presently the IEC Committee 76 (laser equipment) is involved in radiation safety. Their work has resulted in the 76(CO)6 recommendation called "Radiation Safety of Laser Products, Equipment Classification, Requirements, and User's Guide", which is based on an earlier standard of the American National Standards Institute (ANSI). The IEC Committee 46E is also involved in laser safety. In this way the 46E working paper "Safety Aspects of Optical Fiber Systems - Hazard Evaluation" was created.



MAXIMUM PERMISSIBLE EXPOSURE FOR CONTINUOUS OPERATION

An important term throughout these papers is "Maximum Permissible Exposure" (MPE). It establishes the maximum safe radiation levels at the human eye's entrance surface, the cornea. For continuous operation these levels depend on wavelength, as shown in the diagram. For pulsed operation, they additionally depend on pulse duration and pulse repetition rate. Details are given below. The 76(CO)6 recommendation lists the MPE values from 200 nanometers up to 1 millimeter. Based on these limits it regulates the classification of laser products and gives detailed recommendations for both the manufacturer and the user. The 46E paper translates the MPE limits to practical fiber optic applications in the 400 to 1400nm wavelength range. Critical viewing distances are given for typical fiber optic sources. This article gives extracts of both of the papers.

MAXIMUM PERMISSIBLE EXPOSURE: Without health risk intrabeam viewing is restricted to the radiation levels at the cornea listed in the table. Single-pulse operation is assumed. However, the $3x10^4$s value is also valid for DC-operation. The 850nm wavelength in the table was chosen because of its popularity. Above 1400nm the MPE value are at least a factor of 50 higher than below 1400nm, see the maximum continuous exposure curve.

Notice that below 1ns the pulse power per unit area - also called irradiance - is limited. This was made to prevent explosion effects from high-power mode-locked lasers generating pulse durations in the order of picoseconds. At larger exposure times the pulse energy per unit area - also called radiant exposure - is the limiting factor. Above 1000 seconds up to $3x10^4$ seconds (approx. 8 hours) the power is assumed not to be accumulated any more, thus the power is limited again.

Exposure time	λ = 850nm	λ = 1050 to 1400nm
less than 1ns	10^{-3} Wcm^{-2}	$5x10^3$ Wcm^{-2}
1ns - 18µs	10^{-6} Wcm^{-2}	$5x10^{-6}$ Ws cm^{-2}
18µs - 50µs	$1.8x10^{-3}$ $t^{0.75}$ Ws cm^{-2}	$5x10^{-6}$ Ws cm^{-2}
50µs - 10^3s	$1.8x10^{-3}$ $t^{0.75}$ Ws cm^{-2}	$9x10^{-3}t^{0.75}$ Ws cm^{-2}
10^3s - $3x10^4$s	$0.64x10^{-3}$ W cm^{-2}	$1.6x10^{-3}$ W cm^{-2}

MAXIMUM PERMISSIBLE EXPOSURE FOR IMPORTANT F.O. WAVELENGTHS

For repetitive pulses, e.g. from an optical time-domain reflectometer, the pulse power must be lowered. This can be calculated using the table values in conjunction with a correction factor. For less than 10µs pulse duration the correction factor is

$c = (f/Hz)^{-1/2}$ between 1 and 278 Hz, and
$c = 0.06$ above 278 Hz.

For pulse trains not falling into this category consult the original IEC 76(CO)6 recommendation.

An aperture of 7mm diameter must be used to measure the radiation. This is considered the maximum pupil diameter of the human eye. Nevertheless the peak value has to be determined, not the integral over the aperture.

For the human eye most of the fiber optic sources can be considered as point sources. With this condition the 46E paper assists in calculating the critical viewing distance d_{min} from MPE values, assuming continous operation. These formulae can also be used for pulsed operation.

$$d_{min} = \left(\frac{P \text{ or } E}{\pi \, NA^2 \, MPE} \right)^{1/2} \qquad \text{for step index fibers,}$$

$$d_{min} = \left(\frac{2P \text{ or } 2E}{\pi \, NA^2 \, MPE} \right)^{1/2} \qquad \text{for graded index fibers,}$$

$$d_{min} = \left(\frac{P \text{ or } E}{\pi \sin A \sin B \, MPE} \right)^{1/2} \qquad \text{for LED's or lasers.}$$

P - total optical power (W)
E - total optical pulse energy
MPE - maximum permissible exposure
NA - the fiber's numerical aperture
A,B - half power, half width of LED or laser radiation

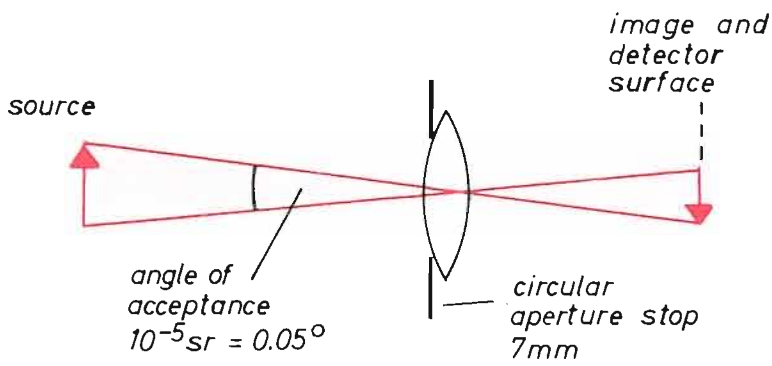
For 1mW continuous optical power the above equation leads to a critical viewing distance of 50mm from the end of a graded index fiber with NA = 0.2, assuming 850nm wavelength. At 1300nm this distance can be lowered to 32mm. Since the human eye cannot focus below 60mm, these sources are practically safe.

As an example for repetitive pulse let us consider the potential danger from an optical time-domain reflectometer (OTDR). The OTDR launches optical pulses of 1W optical power and 30ns pulse width at 850nm wavelength from a graded index output fiber. The fiber's numerical aperture is 0.2. The pulse repetition rate is 5kHz. Thus the radiant energy from each pulse is 0.03 µWs. If only a single pulse was launched the MPE would be 1µWs/cm^2. After applying the correction factor for repetitive pulses the MPE is only 0.06µWs/cm^2. The result from using this value for the "graded-index" formula is a minimum viewing distance of 2.8cm. Because of the mentioned focusing characteristics of the human eye, the OTDR can be considered to be safe.

CLASSIFICATION: The IEC demands all laser products to be classified in order to establish suitable means to protect anyone from larger than MPE levels. Unfortunately some classification procedures are even more complicated than the MPE limits would suggest. For example, class 3A products require

1. measurement of the total power (Watt) or pulse energy (Watt sec) within an aperture of 80mm diameter,
2. measurement of the irradiance (mW/cm^2) or radiant exposure (mWs/cm^2) averaged over a 7mm diameter aperture stop,
3. measurement of the radiance ($mW\ cm^{-2}sr^{-1}$) or integrated radiance ($mWs\ cm^{-2}sr^{-1}$).

The last measurement ensures local beam intensities not to be larger than prescribed by the MPE; sr stands for the solid angle in steradian. The setup for this measurement is shown in the figure.



RADIANCE MEASUREMENT USED FOR 3A CLASSIFICATION

Classification is then made according to the <u>accessible emission limits (AEL)</u>, which are different for each class. The AEL values are given in the IEC 76(CO)6 recommendation as a function of emission duration and wavelength. Here we only extracted classification limits for CW lasers (and LED's which are not explicitely mentioned). The exposure time used for the classification of CW lasers is 30000 seconds.

<u>Class 1</u> laser products are considered to be inherently safe. The table lists AEL values for typical fiber optical wavelengths and CW operation. Both the power and radiance criteria must be met.

AEL	λ = 850nm	λ = 1050 to 1400nm
power	0.24 mW	0.6 mW
radiance	1.28 $W\ cm^{-2}sr^{-1}$	3.2 $W\ cm^{-2}sr^{-1}$

ACCESSIBLE EMISSION LIMITS FOR CLASS 1 LASER PRODUCTS

Class 2 laser products are visible lasers ranging from 400 to 700nm. Within this range the human eye protects itself via the blink reflex, assumed to respond within 0.25 seconds. Thus the CW power from such sources may be 1mW maximum.

Class 3A products are not inherently safe. For the visible range from 400 to 700nm the accessible emission limits may be 5 times those of class 2. The table lists the AEL's for typical fiber optical wavelengths and CW operation.

AEL	λ = 850nm	λ = 1050 to 1400nm
power	1 mW	3 mW
irradiance	0.64 mW cm^{-2}	1.6 mW cm^{-2}
radiance	6.4 W $cm^{-2}sr^{-1}$	16 W $cm^{-2}sr^{-1}$

ACCESSSIBLE EMISSION LIMITS FOR CLASS 3A LASER PRODUCTS

Class 3B products may emit dangerous radiation levels. The only limitation in CW operated class 3B products is 0.5 Watt maximum power within the wavelength range from 315nm up to 1mm.

Class 4 is assigned to products exceeding the class 3B limits. These products are dangerous. Care must be taken to avoid exposure to even diffuse reflections.

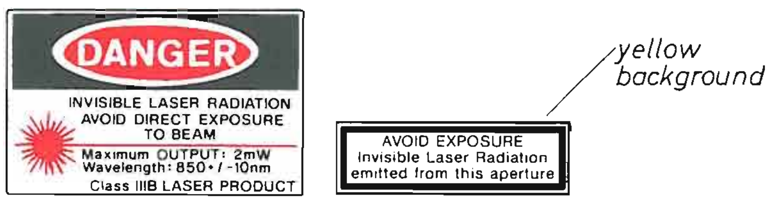
SAFETY EQUIREMENTS: For all laser products the following requirements have been established by the IEC. Safety information is normally required in local language.

* Protective housing to prevent higher than classified emission.
* Safety interlock in the protective housing to prevent access to non-classified emission levels.
* Classification labels on the product and in the promotional literature.
* Caution labels on service panels, interlocked or not
* User safety information in operator and service manuals

Class 2 products additionally must carry the laser warning label.

Classes 3A and 3B additionally must carry the warning label, a key control, an audible or visible "laser on" warning, a beam stop to automatically disable the laser if no access is required, and safe locations of instrument controls. Users should remove the key when the instument is not in use. Also they should wear protective glasses if other protection methods fail. User training is recommended. Additional 3B requirements are: a remote control switch to allow disabling the laser by a door circuit and an aperture label to indicate the location of the radiation output.

Class 4 reqirements are identical to those of class 3B. Avoid reflections!



LASER WARNING AND APERTURE LABEL EXAMPLES

HEWLETT
PACKARD

FIBER OPTICS REFERENCE GUIDE

Note that all terms refer to optical fiber systems and measurements. They may be used differently in other disciplines.
Whenever an arrow (→) appears in the text, it refers the reader to another key word of the reference guide.

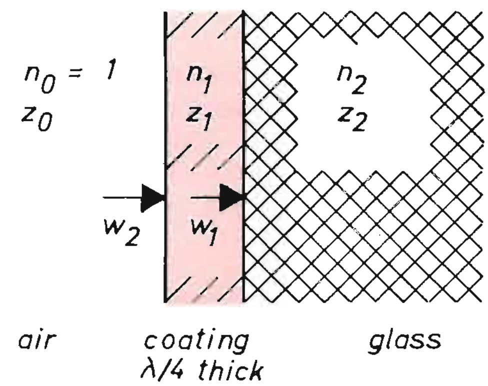
ACCEPTANCE ANGLE

See →numerical aperture.

ANTIREFLECTION (AR) COATING

An air-to-glass transition at normal (vertical) incidence causes 4% of the incident optical power to be reflected, be it internal or external →reflection. To avoid this, the glass can be coated with a quarter-wavelength optical layer, predominantly Magnesium Fluoride (MgF_2). This material has a refractive index of 1.38 at 550 nm and is quite durable. This way a total reflection of about 1.5% is achieved. For oblique incidence, the thickness of the layer can be specifically adjusted. The coating effect is wavelength-dependent, because the quarter-wavelength condition holds for one colour only. Multilayer coatings are used to reduce the wavelength depencence <u>and</u> the reflection.

To understand quarter-wavelength AR coating, the transmission-line concept can be applied (see →reflection).



THE EFFECT OF AR-COATING

The three materials in the figure are characterized by their →characteristic impedances Z_o, Z_1, Z_2 resulting from the refractive indices n_o=1, n_1, n_2. At the glass-to-coating boundary the actual impedance is

$$W_1 = Z_2 = Z_o/n_2$$

At the coating-to-air boundary, this impedance is converted by a λ/4-line with the characteristic impedance Z_1. The transmission-line theory yields:

$$W_2 = Z_1^2/W_1, \; Z_1 = Z_o/n_1$$

$$W_2 = Z_o n_2/n_1^2$$

Impedance matching at the coating-to-air boundary means $W_2 = Z_o$, which requires the coating index to be $n_1 = \sqrt{n_2}$. For glass with $n_2 = 1.5$, the ideal coating index should be $n_1 = 1.22$.

APD

See →avalanche photodiode.

ASTIGMATISM

This term is normally used to describe a lens error: an object point at some distance away from the optical axis cannot be imaged to another point if the lens shows astigmatism. Instead, the image shows two short perpendicular lines. The two lines are separated by some distance, called astigmatic distance. In between the two lines there is a blurred spot called the circle of least confusion.

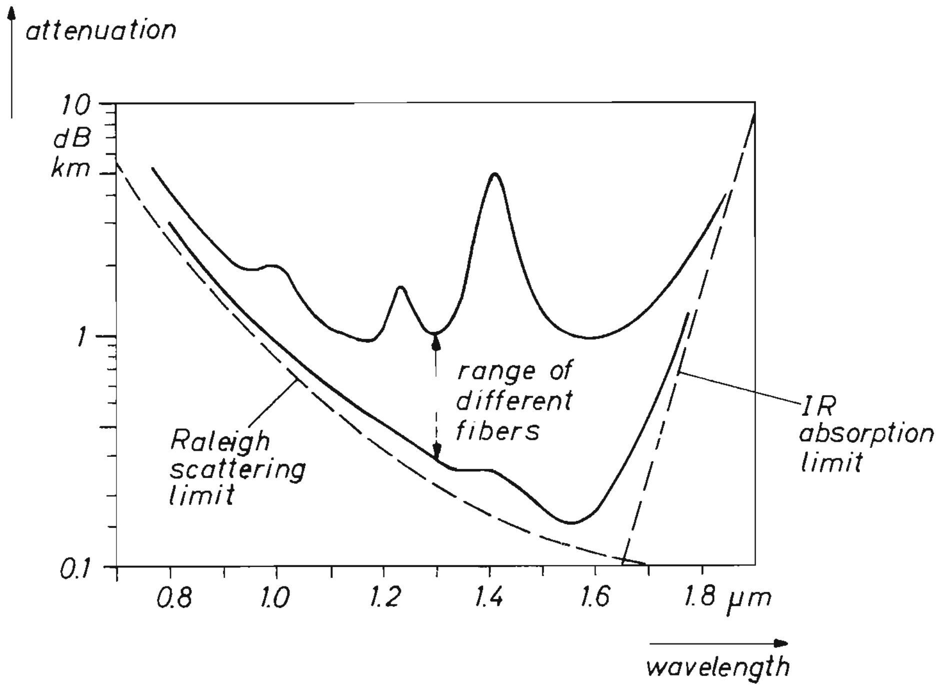
A similar phenomenon can be observed when imaging a laser facet through the optical axis of a perfect lens: when changing the distance between laser facet and lens, the image varies from an ellipse parallel to the junction to one perpendicular to it. The total object movement between the two ellipses has also been called astigmatism.

Typically double-heterostructure lasers have astigmatisms between 0 and 40 µm. The astigmatism constitutes a basic problem of imaging a laser facet to a fiber core: it causes two separate focus ellipses along the fiber axis, none of which will transfer all the light power. Cylindrical lenses can be used to solve this problem.

ATTENUATION OF A FIBER

The attenuation of silica fibers at low frequencies has three causes: Raleigh scattering, absorption, and bending loss. For high-frequency attenuation see →bandwidth of fibers.

Raleigh scattering is caused by microscopic non-uniformity of glass and its refractive index. A ray of light is partially scattered into many directions, thus some light energy is lost. Since the structure of glass is much finer than the wavelength, the attenuation due to scattering decreases with wavelength. It is proportional to $1/\lambda^4$.



WAVELENGTH DEPENDENCE OF FIBER ATTENUATION

Absorption depends on unwanted material in the fiber. Water (OH-ions) is the dominant absorber in most fibers, causing the peaks in optical loss at 1.25 and 1.39 μm. Above 1.7 μm, glass starts absorbing light energy due to the molecular resonance of SiO_2. The attenuation curve clearly shows why communication link designers prefer the 1.3 μm and the 1.55 μm wavelengths.

The optical power decays exponentially along the fiber:

$$P(x) = P_o \exp(-\alpha' x)$$

$P(x)$ - optical power at distance x from input
P_o - optical power at fiber input
α' - attenuation coefficient, [1/km]

As engineers are used to thinking in dB, the equation can be rewritten (using $\alpha = 4.35\ \alpha'$):

$$P(x) = P_o \cdot 10^{-\alpha x/10dB}$$

$$\log P(x) = \log P_o - \alpha x/10dB$$

α - attenuation coefficient, [dB/km]

Different modes are differently attenuated in a fiber. This effect is called <u>differential mode attenuation</u>. However, practical transmissive measurements (two-port measurements) cannot be made separately for each mode. Instead, always a large number of modes is present during a measurement. To achieve interlab reproducibility of attenuation measurements, →equilibrium mode distribution must be generated at the fiber input. Measurement variations of 1 dB/km on the same fiber have been found where no great effort was made to control this parameter.

Two methods are commonly used to perform attenuation measurements. The cutback method is the most accurate. After measuring the power at the far end, the fiber is cut near the input end without changing the launching conditions. The only problem of this method is its destructive nature. Thus the second method suggests to compare the attenuation measurement of a short reference fiber to that of the long test fiber.

The backcattering mechanism also delivers fiber attenuation numbers. These numbers are not identical to those obtained by two-port measurements. See →optical time domain reflectometer.

Pulse dispersion measurements, transmissive or reflective, are also useful in order to evaluate fiber attenuation. See →bandwidth of fibers.

ATTENUATOR

A number of optical measurements can only be made if variable optical power is available. Intensity control of LED's and laser diodes does not offer a wide dynamic range and also changes some of the light characteristics, like radiation pattern, modal structure, even wavelength. Many passive optical attenuators have been proposed, some of their principles are listed below. Quality criteria of variable attenuators are: attenuation range, lowest insertion loss, freedom of interference and reflections, independence of polarization and wavelength, low beam distortion, mechanical or electronic control.

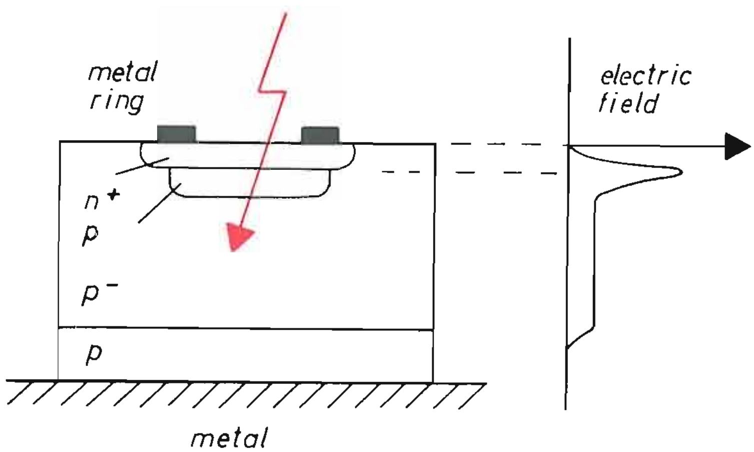
A simple continously variable attenuator can be made from a grey scale placed on a wheel, which can be rotated by a motor. The grey scale is realized by photographic film or by metallic coating of variable thickness. Also based on rotation, an attenuator can be made from two →polarizers. Attenuators based on the dependence of →reflection on the angle of beam incidence have also been proposed.

Much more attractive is a non-mechanical control of the attenuation. Liquid crystals for example rotate the polarization of light depending on the drive voltage applied. By placing the liquid crystal between two polarizers, electronically variable attenuation is possible. Rotation of polarization can also be done magnetically by the →Faraday effect.

Another solution is electrically induced birefringence, e.g. in lithium-niobate. The electric field converts linear polarization into elliptical and further into circular polarization, see →retarder. Thus a variable attenuator is feasable by placing lithium-niobate between two polarizers.

AVALANCHE PHOTODIODE (APD)

Due to their inherent gain, APD's have higher responsivity than →pin-diodes, which makes them very attractive for communication receivers. The APD construction is similar to the →pin-diode construction, except that a very high electric field is established in a special-doped backbiased pn-junction.



TYPICAL APD-STRUCTURE

Light enters into the nearly intrinsic p^- zone from the top or the bottom of the diode where it generates electron-hole pairs by absorption of the photons energy. Electrons then travel to the high electric field inside the pn-junction, where they generate new electrons via carrier multiplication (avalanche process). Each of the electrons statistically generates M new electrons. The total photocurrent then is

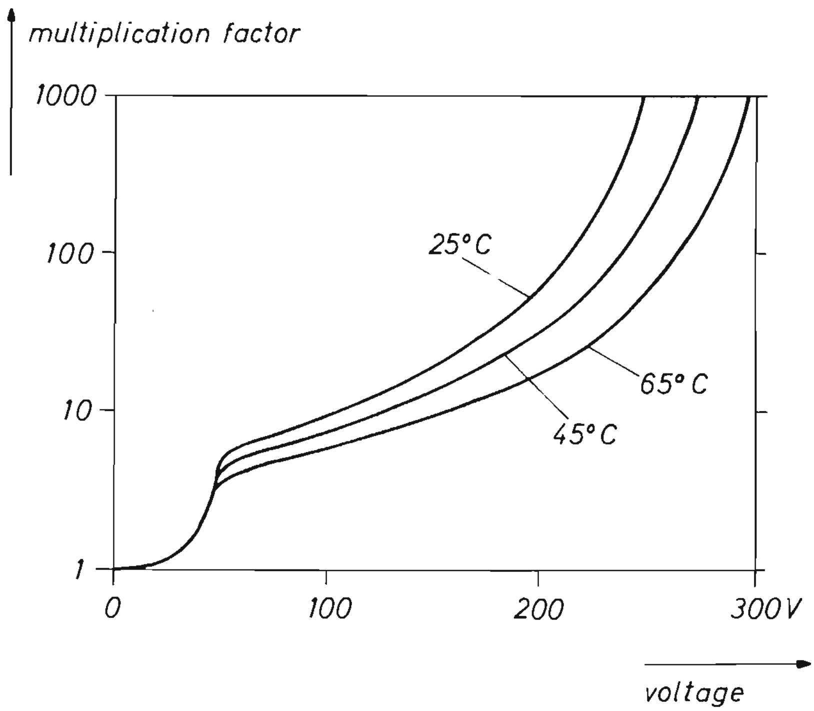
$$I = r\, M\, P_{opt}$$

r - responsivity, $r = 0.8\, \eta\, \lambda/\mu m$ [A/W], see →quantum efficiency

M - multiplication factor

P_{opt} - optical power

Data sheets either give r x M directly in [A/W], or r and M, or quantum efficiency η and M.



APD MULTIPLICATION FACTOR VERSUS VOLTAGE

Unfortunately, M strongly depends on the applied reverse voltage and on the temperature, which makes it difficult to reach a stable gain. A typical compromise between gain and stability is M = 50 - 150. Germanium APD's have lower gains, typically M = 20 to 40 at a reverse voltage of 20 - 30V. Even then, temperature and voltage stabilization is essential.

Another problem is non-linearity due to voltage drop across the load resistor, together with the very steep M = f(V) curves. A second non-linear effect is observed even with a zero load resistor: beyond a certain photocurrent the multiplication factor drops drastically as the current increases.

Current is also generated with no light present. Called dark current, it gives rise to additional noise and also limits the lowest detection level. Dark currents are dependent on the applied voltage and thus on the multiplication factor M. At 25°C the typical dark current of a silicon APD with 0.1 mm diameter active area is 1 - 10 nA for M = 100. A high 1 µA is observed in a germanium APDs with M = 20. See →noise of the APD.

APD dark currents are also very temperature-sensitive. In silicon diodes, dark current doubles every 8°C, in germanium diodes every 9 - 10°C. Here are some dynamic characteristics: silicon - APDs with 0.1 mm diameter active area have around 1pF parasitic capacitance at M = 100, risetime is 1 ns typical, and 3 dB (electrical) bandwidth is 100 - 500 MHz typical. The fastest diodes have 100 ps risetime. Germanium APDs with 0.1 mm diameter active area typically have 2pF parasitic capacitance at M = 20, but otherwise have very comparable characteristics.

The wavelength sensitivity of APDs (silicon and germanium) is similar to the sensitivity of pin-diodes, see →pin-diode. Long-wavelength APD-diodes made from indium-gallium-arsenide are still in the early research phase.

BACKSCATTERING

The →attenuation of fibers has two reasons: absorption and backscattering, also called Raleigh-scattering. Additional losses may occur from bending, splicing and connectorizing. The nature of the scattering process is light diffraction at the microscopic non-uniformities of the refractive index of glass. As the effect depends on the size of the discontinuities in relation to wavelength, the backscattering coefficient α_s is proportional to $1/\lambda^4$.

The scattered light partially travels back to the transmitter where it can be analysed via a directional coupler and signal processing, see →optical time domain reflectometer (OTDR). In conjunction with reflections at glass-air transitions, backscattering allows characterization of a fiber's attenuation, splice loss, breaks, length and even dispersion.

Let us assume a uniform fiber with an uniform attenuation coefficient $\alpha = \alpha_a$ (absorption) + α_s (scattering). An optical pulse with power P_o and pulse duration w is launched into the fiber. From →attenuation of a fiber we learn that at some distance z from the fiber input, the pulse power p has decreased to

$$p = P_o \, 10^{-\alpha z/10\mathrm{dB}}$$

At this point of the fiber, the scattered power $p \times \alpha_s \times dz$ is generated. Due to the limited →numerical aperture of the fiber, only the fraction S of the scattered power travels back, which is $p \times \alpha_s \times S \times dz$. After travelling back to the input, the backscattered power from point z has decreased to:

$$dp_{back} = P_o \, 10^{-2\alpha z/10\mathrm{dB}} \; \alpha_s \, S \, dz$$

We assume this to be the fraction generated by the pulse front. In order to reach the input at the same time, the pulse tail travels a length z - $\Delta z/2$, if Δz is the pulse length on the fiber. See the figure at the end of the chapter. Thus the total backscattered power at the input at a time t (starting from the pulse launching) can be approximated using $\Delta z/2$ as the power-contributing portion of the fiber:

$$P_{back}(z) = \alpha_s\, S\, P_o \frac{\Delta z}{2}\, 10^{-2\alpha z/10dB}$$

$$z = t\, v_{gr}/2$$

$$\Delta z = w\, v_{gr} = w\, c/n_{gr}$$

$$S = (NA/2n)^2$$

- α - total attenuation coefficient, [dB/km]
- α_s - scattering coefficient, [1/km]. α_s may also be given in [dB/km]. Multipy by 0.23 to get α_s in [1/km].
- S - backscattering factor, dimensionless
- P_o - launched power in the fiber, [Watt]
- t - round trip time from fiber input to location z
- Δz - pulse length on the fiber, [m]
- v_{gr} - group velocity, see →material dispersion
- c - speed of light, →constants
- n - refractive index of the fiber core center
- n_{gr} - group index, $n_{gr} = c/v_{gr}$
- w - pulse duration
- NA - the fiber's →numerical aperture

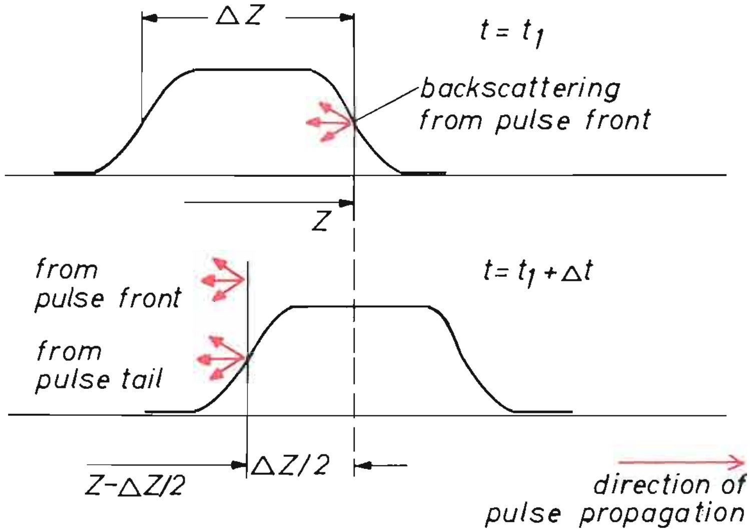
The resulting backscattered signal is the well-known exponential decay with length or time:

$$P_{back}(z) = \alpha_s \left(\frac{NA}{2n}\right)^2 P_o \frac{w\, c}{2n_{gr}}\, 10^{-2\alpha z/10dB}$$

Typical numbers for a graded-index fiber are α = 2.5dB/km, α_s = 0.5/km at 850nm, NA = 0.2, n= 1.5. Using z = 0 and w = 10ns, the peak of the backscattered signal is

$$P_{back}(0) = 2.2x10^{-6}\, P_o$$

Averaging techniques (see →boxcar averaging) are necessary to resolve such small signals. The backscattered signal decreases even more with increasing wavelength, because α_s is proportional to $1/\lambda^4$.

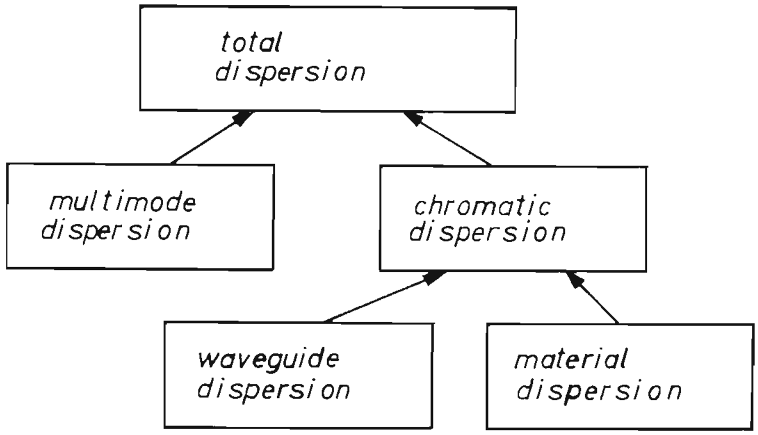


EXPLANATION OF THE Δz/2 UNCERTAINTY OF THE OTDR-SIGNAL

Improvement is possible by increasing the pulse width, but at the expense of length resolution: as the return signal at a time t stems from a fiber section $\Delta z/2 = cw/2n$, the uncertainty in locating a fiber problem is also $\Delta z/2$. Example: a pulse width w of 10 ns and a refractive index n= 1.5 results in an uncertainty $\Delta z/2$ = 1m, or $\pm$ 0.5m.

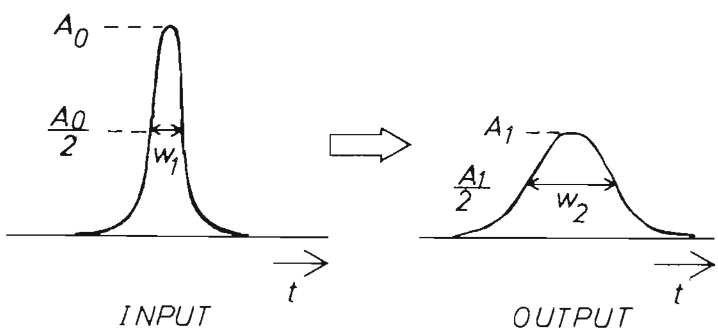
BANDWIDTH OF FIBERS

Fiber bandwidth and the related total dispersion (pulse broadening) are characterized by two effects: →multimode dispersion (also called intermode or modal dispersion) and →chromatic dispersion (also called intramode or spectral dispersion). The latter can again be subdivided into →material dispersion and →waveguide dispersion. Note that commercial bandwidth data are given for a zero-linewidth source, thus only indicating the multimode dispersion characteristics.



THE DISPERSION HIERARCHY

All dispersion effects can be characterized and measured in the time domain (ns/km), or in the frequency domain (MHz x km). Wile frequency domain data at different wavelengths are difficult to obtain, this task is somewhat easier in the time domain, see →Raman dispersion measurement. Not all but most modern fibers behave like Gaussian low pass filters, see →Gaussian pulse. For this ideal case the following relations can be set up: assuming a Gaussian pulse at the input of a 1 km fiber the output will also be Gaussian. Both responses are assumed to be measured with an infinite bandwidth detector.



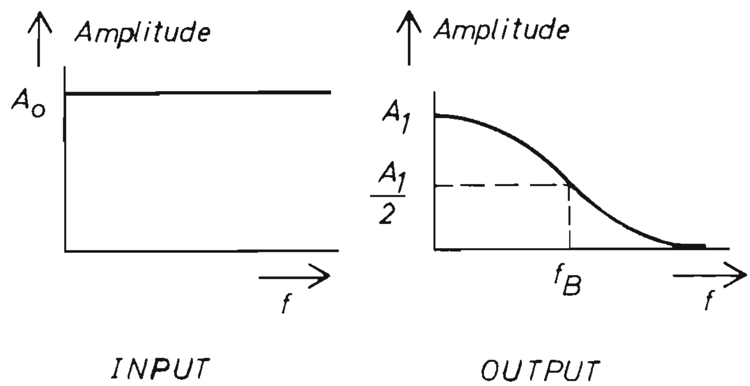
GAUSSIAN IMPULSES AT INPUT AND OUTPUT OF A FIBER

In the following all characteristics refer to a fiber of 1km length. Assuming w_1, w_2 to be the full width at half maximum electrical responses, the fiber dispersion Δt_f is

$$\Delta t_f = \sqrt{w_2^2 - w_1^2} \quad [\text{ns}]$$

Such a measurement can also yield the attenuation of the fiber: just divide the output pulse energy by the input pulse energy (use the pulse areas).

In the frequency domain, a network analyser can be used to measure bandwidth.



NETWORK ANALYSER PLOTS AT INPUT AND OUTPUT OF A FIBER

Here the fiber bandwidth is determined as the 6 dB(electrical), or 3 dB(optical) bandwidth, corresponding to 50% electrical signal, given in [MHz km]. See →dB(optical).

To convert bandwidth f_B to dispersion Δt_f, this equation can be used if the fiber has a →Gaussian behaviour:

$$\Delta t_f = \frac{0.44}{f_B} \quad [\text{ns/km}]$$

For other than Gaussian systems the Fourier transform should be used to convert from time domain to frequency domain.

To find the total dispersion Δt_f from →multimode dispersion Δt_{mod} and →chromatic dispersion Δt_{chr}, use

$$\Delta t_f = \sqrt{\Delta t^2_{mod} + \Delta t^2_{chr}}.$$

A practical example: a graded-index fiber of 1 km length has a multimode dispersion of 0.3 ns, corresponding to a 6 dB (electrical) bandwidth of 1.45 GHz. The fiber input is driven with a laser. The laser's center wavelength is 850 nm, at this wavelength the fiber's chromatic dispersion is 100ps/nm km. The laser has a 50% spectral width of 3nm, yielding an effective chromatic dispersion of 300ps/km.

The total dispersion of the 1km piece of fiber is

$$\Delta t_f = \sqrt{300^2 + 300^2}\ \text{ps} = 424\ \text{ps}$$

and the effective bandwidth is 1.02 GHz. To increase this bandwidth, use 1.3 µm to eliminate the chromatic dispersion, or use monomode fiber to eliminate the multimode dispersion, or both.

BEAMSPLITTER

Fiber optic measurements often need beamsplitting: for source monitoring and stabilization, for optical time-domain reflectometry and for interferometric measurements. Here are some desirable features of beamsplitters:

1. Constant beamsplitting ratio, independent of polarization and wavelength.
2. Low intrinsic loss.
3. Low reflection from the beam splitter surfaces.
4. Negligible beam perturbation.
5. Freedom of →interference effects and ghost images caused by reflections from more than one surface.

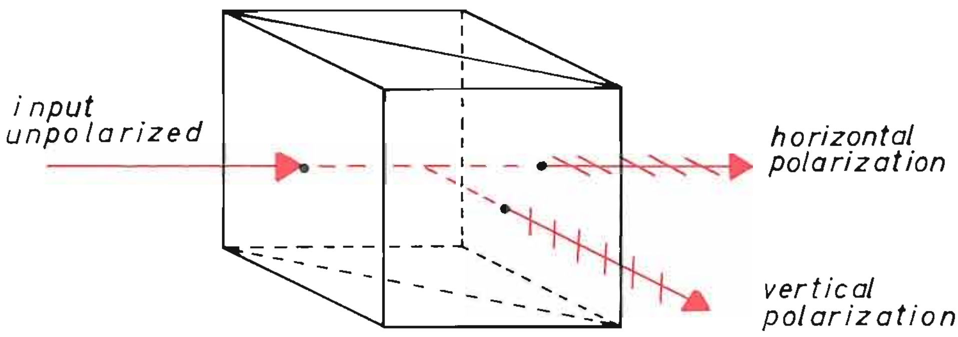
Principally, polarizing and non-polarizing beamsplitters have to be distinguished.

A simple beamsplitter based upon →reflection can be made from a glass plate oriented at a 45° angle. As this angle is close to Brewster's angle, each surface causes a reflection of 15% of mainly one polarization, while more than 99% of the other polarization passes. To avoid interference between the two surfaces, one of them should carry an →antireflection coating. This leaves a total reflection of 15%. A non-polarizing beamsplitter can be made using a much smaller angle e.g. 10°. This angle reduces the reflection to 4%, once again assuming one face to be coated.

Pellicle beamsplitters are made from a very thin (5 µm typically) membrane, in order to avoid ghost images. Their disadvantages are dependance on polarization and microphonic effects.

Beamsplitting cubes are made from two cemented prisms with a metal-dielectric film deposited in between the prisms. Their surfaces are antireflection-coated. The film is most often optimized for a 1:1 splitting ratio. It shows little dependence on polarization. Typically, 10% total power loss is achieved. The cubes have the same appearance as the polarizing beamsplitter in the figure.

Polarizing beamsplitters serve as polarizers and beamsplitters at the same time. Typical applications are in →optical time domain reflectometers and in disk optical recording and reading. The polarizing medium is either multilayer dielectric film (see →polarization) or calcite with its →birefringent nature.



POLARIZING BEAM SPLITTER BASED ON MULTILAYER DIELECTRIC FILM

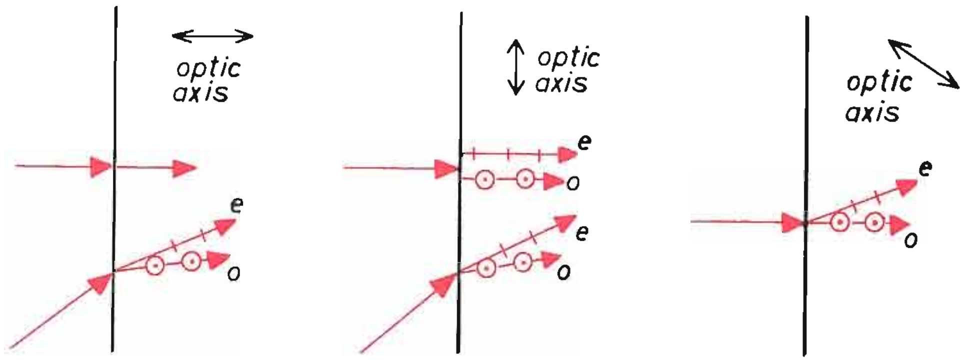
The most popular calcite based beamsplitter is the Glan-Thomson structure. Of all the beam splitters it has the lowest internal loss and the highest purity output polarization. It also consists of two prisms which are separated by an air gap this time. The →birefringence effect splits the input beam into two beams, which have orthogonal polarizations and are called ordinary and extraordinary. The ordinary ray is totally reflected which is caused by the material's higher index of refraction for this ray. The extraordinary ray essentially passes unaffected. The hypotenuse angle is not 45^o in a calcite beamsplitter, it has to be optimized for best splitting performance. Accordingly the reflected ray does not leave the cube at a 90^o angle either.

BER

See →bit error rate.

BIREFRINGENCE

A number of polarizing →beam splitters are based on birefringence. This effect, also called double refraction, is observed in many crystals such as quartz and calcite (calcium carbonate). It is also present in monomode fibers, see →modal noise and →multimode dispersion. Birefringence generally means that a single light beam is split into two beams inside a crystal. Only in one direction, called the optic axis, the beam is not maniplulated. Crystals with only one optic axis are called uniaxial. We will only discuss those.



BIREFRINGENCE IN CALCITE

If a light ray enters the crystal at an angle to the optic axis, then it is split into two rays. The polarization of one ray is perpendicular to the optic axis, it is called ordinary (o) ray. The polarization of the other ray is orthogonal to the polarization of the o-ray, it is called extraodinary (e). If the surface and the optic axis form an angle and the light is at normal incidence to the surface, then the e-ray violates Snell's law by being refracted at an "extraordinary" angle.

In calcite the o-ray experiences a refractive index of n = 1.66. For the e-ray the index depends on the angle to the optic axis, ranging from 1.49 (if vertical to the axis) to 1.66 (if parallel to the axis). Thus another result is different travel speeds, which is indicated by the different lengths of the vectors in the figure. →Retardation plates are based on this effect.

Caused by the electro-optic effect, the birefringence of some materials (e.g. lithium-niobate) depends on the strength of an applied electric field. The magneto-optic effect causes similar behaviour.

Optical activity refers to the phenomenon, that in some birefingent materials the plane of polarization is rotated, even if the light is parallel to the optic axis. In quartz, for example, the rotation depends on the length of the crystal. Optical activity can be caused by magnetic fields, too. It is then called →Faraday effect. For further details on double refraction, optical activity, electro-optics and magneto-optics consult the classical optical literature like [1] and [10].

BIREFRINGENCE NOISE

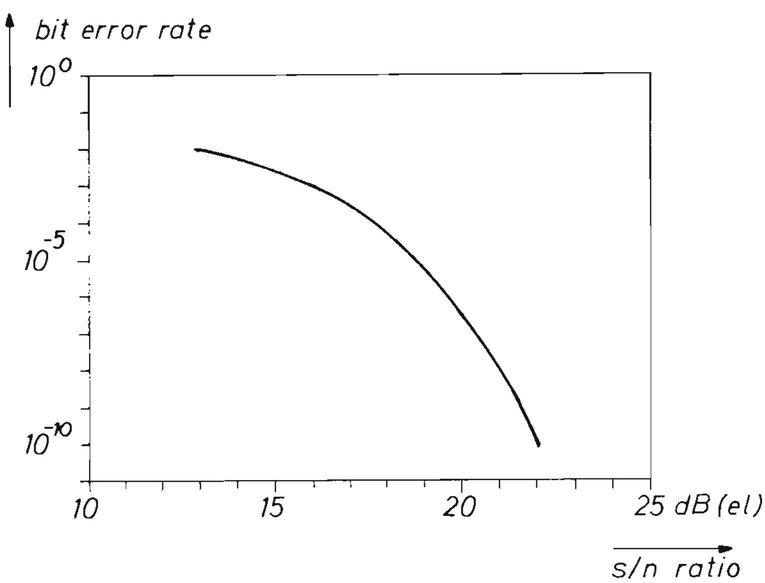
This effect is only observed in monomode fibers. See →modal noise, →multimode dispersion.

BIT ERROR RATE

The number of false bits relative to the total number of bits in a digital data stream is called bit error rate (BER). The BER is the main quality criterium for a transmission system. It can be measured by repetitively transmitting and receiving a suitable length of a pseudorandom bit sequence (PRBS). Many systems require a bit error rate of 10^{-9}, but local area network requirements can go up as high as 10^{-14}.

Many possible errors can influence the bit error rate: system noise - such as generator noise, transmission noise, receiver noise - is the dominating effect. But intersymbol interference caused by too low bandwidth can cause errors, too. See →eye pattern. Excessive jitter or sampling timing errors are other sources of problems.

Assuming a Gaussian distribution of noise amplitudes and identical noise power at the "1" and "0" levels the BER can be calculated from the signal-to-noise ratio, reference [11]. The result is shown in the diagram. It is based on zero intersymbol interference, zero jitter and no sampling errors.



BIT ERROR RATE DEPENDENCE ON SIGNAL-TO-NOISE RATIO

The signal-to-noise ratio SNR is defined in agreement to →noise in a receiver:

$$SNR = 10 \log (v_s^2 / \overline{v_n^2}) \quad [\text{dB(electrical)}]$$

v_s - peak signal amplitude
v_n - RMS noise amplitude

We find an SNR of 21.6 dB(electrical) to be sufficient for a BER of 10^{-9}. A slight deviation from this SNR drastically influences the BER, which makes a prediction difficult. Compare the 21.6 dB to a typical 50dB requirement for analog systems.

Practical receivers implying an avalanche-photodiode and a field-effect transistor amplifier reach the above requirement with an average optical power of -50dBm = 10nW and an extinction ratio >15, at 100 Mbit/s. A 10 Mbit/s system only requires an optical power of around -60dBm = 1nW.

BOLTZMANN'S CONSTANT (K)

See →constants.

BOXCAR AVERAGING

→Backscattering signals in an →optical time-domain reflectometer are normally buried in noise because of their tiny amplitudes. Boxcar averaging is the commonly used method to improve the signal-to-noise ratio. It is done by repetitively sampling the signal at each point in time, starting at the time t = 0. An arithmetic average of the samples is generated either with a low-pass filter or numerically. Then a variable delay is used to move to the next point in time. This way the boxcar averager scans the entire signal. The larger the number n of samples, the smaller the mean-square noise current:

$$\overline{i_{noise}^2} = const./n$$

The noise amplitude is around 6 times the square root of this value, assuming Gaussian distribution. Thus the noise amplitude is reduced with the square root of n.

BREWSTER'S ANGLE

See →reflection.

BRIGHTNESS

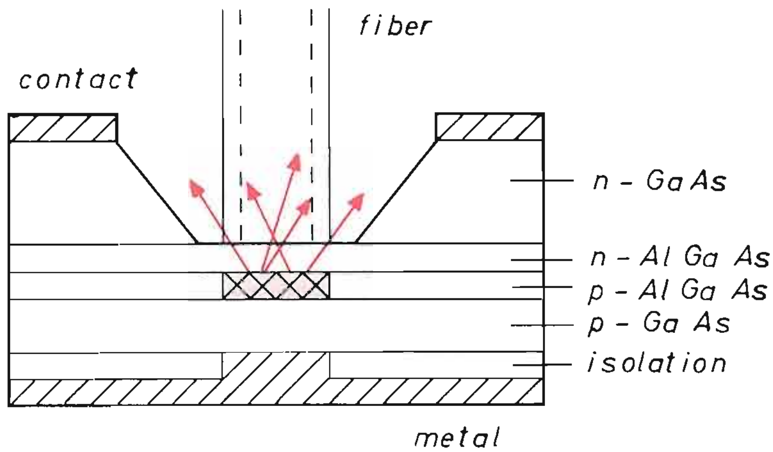
Obsolete photometric term, see →photometric units.

BUFFER

Material surrounding the fiber (core, cladding and coating) in order to protect it from physical damage. Sometimes the buffer is in close contact with the fiber, sometimes a buffer tube allows the fiber to move.

BURRUS-DIODE

A special construction of a →light emitting diode to achieve better efficiency in coupling a fiber to the diode.



BURRUS-DIODE STRUCTURE

Material absorption is reduced by etching a dip into the diode, also a special arrangement of contacts reduces the size of the light generating area to the fiber face area only. 200 MHz bandwidth can be achieved with this configuration.

BUS

See →network.

CHARACTERISTIC IMPEDANCE

The characteristic impedance Z of an →isotropic dielectric material is the ratio of the electric field amplitude to the magnetic field amplitude, referring to a transverse electromagnetic wave.

$$Z = \frac{1}{n} \sqrt{\mu_o/\epsilon_o}$$

μ_o - permeability of vacuum, see →constants
ϵ_o - dielectric constant of vacuum, see →constants
n - refractive index of the dielectric material, n = 1 for vacuum or air, n ≃ 1.5 for glass

CHARACTERISTIC TEMPERATURE

See →temperature dependence of the laser diode, →temperature dependence of the LED.

CHROMATIC DISPERSION

The speed of an optical pulse travelling in a fiber changes as its wavelength changes. Since any practical light source has a certain spectral width, this effect results in pulse broadening called chromatic dispersion or intramodal dispersion. Two physical phenomena contribute additively to chromatic dispersion: →material dispersion, which is caused by the wavelength-dependence of the fiber's refractive index and →waveguide dispersion, which is caused by the wavelength-dependence of the modal characteristics of a fiber. Waveguide dispersion can be neglected in multimode fibers.

Chromatic dispersion can be measured by the measurement of pulse travel time at different wavelengths, see →Raman dispersion measurement.

CLADDING

The layer of material surrounding the core of a fiber is called cladding. See →fiber.

CLADDING MODE

See →modes in a fiber.

CLADDING MODE STRIPPER

See →mode stripper.

COATING, ANTIREFLECTION

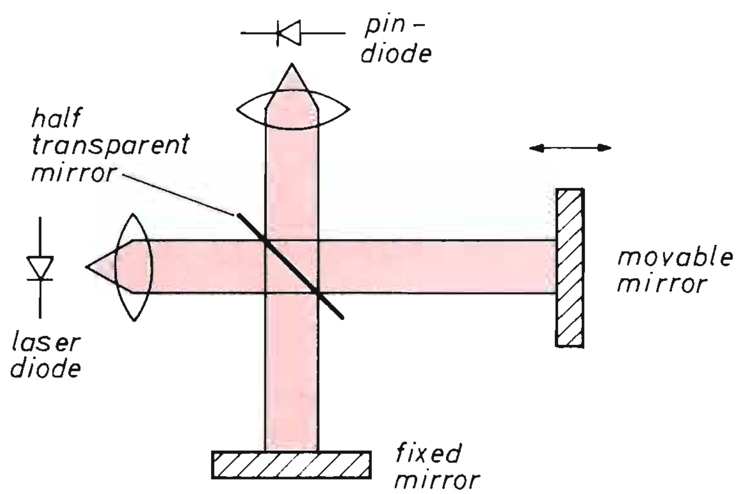
See →antireflection coating.

COATING OF THE FIBER

The material surrounding the cladding of a →fiber is called coating. Mostly made from plastic, it protects the fiber from damage. The coating's refractive index may be smaller than the cladding index, or larger, in which case the coating acts like a →mode stripper for cladding modes.

COHERENCE OF THE LASER EMISSION

Laser coherence is the dominating effect to cause modal noise in fiber systems. Coherence describes the fact that lasers generate waves with stable phases. It is called spatial coherence if it relates to the geometrics of a wavefront, or time coherence if the phases are stable within a time called coherence time. This paragraph is about time coherence only.



DETERMINATION OF THE COHERENCE LENGTH

A simple experiment explaining the coherence effect is described in [5]. Let us assume that a single longitudinal laser mode is split into two light beams of variable lengths (by using a movable mirror) and that the beams are then recombined again. If the two path lengths are equal or similar, then one observes interference. Alternating constructive and destructive interference results from changing one path length with respect to the other. If one makes the path length difference larger and larger, then the interference becomes less pronounced, until there is no interference at all.

The difference in distance, after which the interference maxima fall to the 1/e (e = 2.718) of the original value, is called coherence length. Coherence time is the time that light needs to travel the coherence length.

$$l_c = ct_c = \lambda^2/\Delta\lambda = c/\Delta f$$

l_c - coherence length
t_c - coherence time
λ - laser center wavelength
$\Delta\lambda$ - line width of a single longitudinal line
Δf - bandwidth of a single longitudinal line

It is important to notice that the coherence length is mainly determined by the width of just one longitudinal mode. For λ = 850 nm and $\Delta\lambda$ = 0.01 nm one gets l_c = 7 cm and t_c = 230ps. The coherence length only slightly decreases as the number of longitudinal modes increases.

As a practical consequence, speckle patterns (→modal noise) at the fiber end arise from interference if the fiber is not too long. After a certain length of the fiber (corresponding to our experiment) →multimode dispersion causes different path lengths of different modes. This destroys the interference, and a speckle pattern cannot be observed any more.
Example using a simplified model: a graded index fiber with multimode dispersion of 230ps/km at 850 nm shows a loss of speckles after 1 kilometer, corresponding to a laser coherence time of 230ps.

COLLIMATION

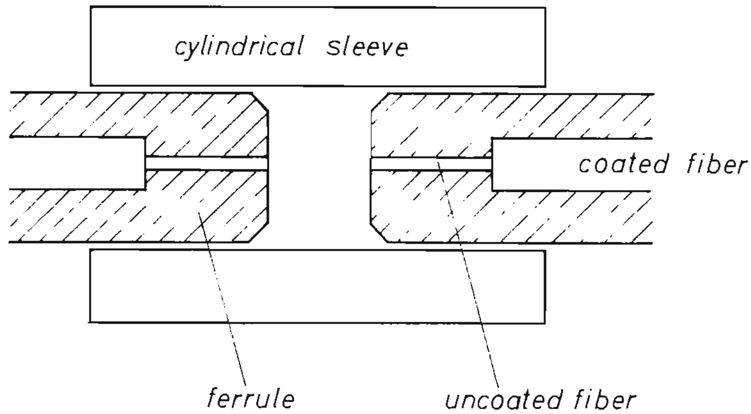
The conversion of a diverging radiation pattern to a parallel beam is called collimation. Conventional and →SELFOC lenses are used for this purpose. Because of lens errors and light sources not being point sources, this task can never be achieved perfectly. Sometimes additional cylindrical lenses are used to compensate for the →astigmatism of lasers.

CONCATENATION

The process of connecting pieces of fiber to a link, either by →splicing or by →connectors. For the effect of concatenation on fiber bandwidth, see →multimode dispersion.

CONNECTOR

A large variety of optical connectors has been invented. Most of them are based on butt-coupling two well-cleaved fibers to allow direct transition of optical power from one core to another.



PRINCIPLE OF A BUTT-COUPLED CONNECTOR

Such a connector is made by precisely centering the uncoated fibers into the ferrules and fixing them e.g. with epoxy. The ferrule- and fiber surfaces are ground and polished. Then the two ferrules are brought into contact inside a precisely guiding cylindrical sleeve. Lateral offset is the biggest loss contributor: in a 50µm graded-index fiber 0.5 dB(opt) additional loss results from a 5µm offset. 0.5dB loss also results from a gap of 35µm, or from a 2.5^{o} tilted fiber surface. Commercial connectors of this type typically reach 0.5 - 1dB optical loss. Sometimes →index matching liquids are used to further reduce the loss.

This type of connector is made in many different styles and dimensions. The only possible standardization seems to be in ferrule diameters: 2.5mm is a popular diameter. Such a standardization would at least allow a loose adaption of connectors of different manufacturers.

Lensed fiber connectors, employing a →collimation lens at each connector, have also achieved some popularity. These connectors cannot be easily degraded because scratching the lens surface is not as critical a scratching a fiber surface. Also they are not nearly as sensitive to dust as butt-coupled connectors. Good lensed connectors reach insertion losses below 1 dB(optical).

Some care is recommended when measuring connector insertion loss: it may be dependent on the modal distribution, and also will influence the modal distribution. One attempt to solve this problem is drive the connectored fiber with an →equilibrium mode distribution by carefully controlling the launching conditions. Another suggestion is to measure insertion loss as a function of the →effective mode volume.

CONSTANTS

These are the most important physical constants in conjunction with fiber optics:

h	=	6.62×10^{-34} Ws^2	Planck's constant
e	=	1.6×10^{-19} As	electron charge
c	=	2.998×10^{8} m/s	speed of light in vacuum
k	=	1.38×10-23 Ws/^{o}K	Boltzmann's constant
μ_o	=	1.257×10^{-6} As/m	permeability of vacuum
ϵ_o	=	8.85×10^{-12} s/(Ωm)	dielectric constant of vacuum
Z_o	=	376.7 Ω	characteristic impedance of vacuum

For the conversion of units, see →units.

CONVERSION OF UNITS

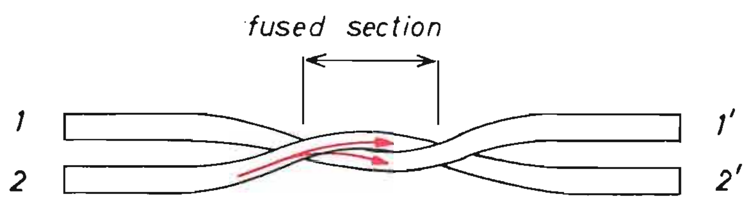
See →units.

CORE

The core is the central part of a →fiber. It is characterized by its refractive index being higher than index of the surrounding cladding. The core diameter is most often determined by measurement of the →near field.

COUPLER

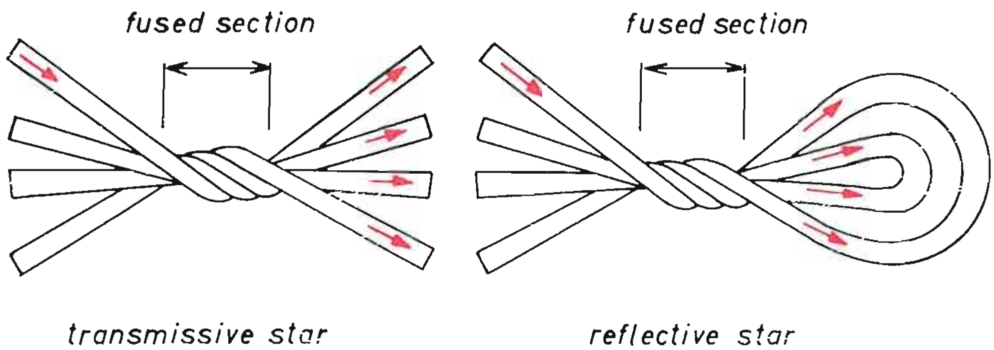
Couplers are key devices for local area networks based on fiber optics. They can also be used for monitoring purposes. Most common is a directional coupler made from two fused fibers, called twisted-pair coupler. This configuration can also be considered as a T-coupler if only three ports are used. It is made by twisting the fibers, then pulling them into biconical tapers under heat treatment.



TWISTED-PAIR COUPLER

In the fused section the fiber cores are still separated from each other. However, core modes are converted to cladding modes, thus partly coupling optical power from one fiber to the other. A 50 to 50% output power ratio is called 3 dB-coupler. Sometimes →mode stripping is done at the inputs and outputs to destroy unwanted cladding modes outside of the fused section. As this is a directional coupler (also called transmissive coupler), there is isolation between the two input ports.

A number of other T-coupler principles have also been realized. One is a joint of one input fiber with two side-by-side output fibers. Another alternative is imaging an input fiber onto two output fibers via concave mirrors. Also possible is a plain half-transparent mirror oriented at a 45° angle in conjunction with beam →collimation.



DIFFERENT STAR COUPLERS

The transmissive star coupler is the key device in a star-type →network. It connects each input with all outputs, whereas there is isolation between different inputs. Typically, the inputs are connected to the terminals' transmitters and the outputs are connected to the receivers.

Another type of network can be realized with a reflective star coupler. In contrast to the transmissive star, its ports are bidirectional, so they are used as inputs and outputs at the same time. Each port feeds each other port.

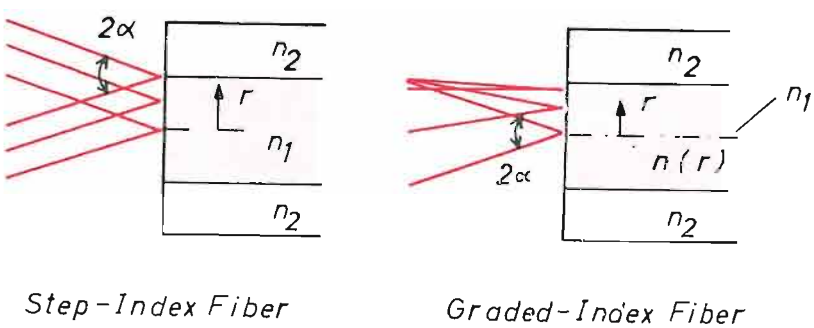
All couplers are predominantly characterized by two types of numbers. The coupling ratio is the optical power of a single output divided by the total output power. The excess loss is the ratio of the total output power divided by the total input power. The excess loss can be kept very low in modern couplers, losses of less than 2 dB have been realized for couplers made from 20 fibers. Other figures of merit are the uniformity of the coupling ratio and its independence on fiber modes.

COUPLING EFFICIENCY

Mainly two sorts of losses occur when coupling a source to a fiber. These are losses due to area mismatch and losses due to numerical aperture.

Area mismatch occurs when the area illuminated by the source is larger than the core of the fiber. This problem can be solved by using the smallest possible distance between source and fiber (butt coupling), provided the source is smaller than the core. If spacing is unavoidable, a lens should be used for imaging. Trying to reduce the size of the source with a lens will cause numerical aperture problems.

Even if the illuminated area is smaller than the fiber core, losses due to numerical aperture mismatch occur because the source usually emits into a larger cone than the fiber's acceptance cone. Step-index and graded-index fibers have different acceptance characteristics. The acceptance angle of a graded-index fiber depends on the distance from the core center, in contrast to step-index fibers.



FIBER ACCEPTANCE ANGLES

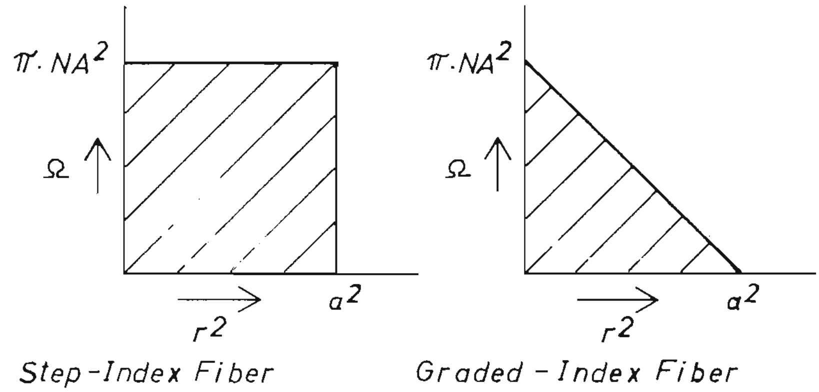
In step-index fibers, the linear acceptance angle α and the solid acceptance angle Ω are (assuming α to be small):

$$\sin\alpha = NA = \sqrt{n_1^2 - n_2^2}$$
$$\Omega = \pi\, NA^2$$

In graded-index fibers (n_1 - center index):

$$\sin\alpha = \sqrt{n^2(r) - n_2^2}$$
$$n(r) = \sqrt{n_1^2 - NA^2\,(r/a)^2}$$
$$NA = \sqrt{n_1^2 - n_2^2}$$
$$\Omega = \pi(n_1^2 - n_2^2 - NA^2\,(r/a)^2)$$

These characteristics are shown below; the shaded areas characterize the total volume of accepted rays. The lower acceptance of graded-index fibers is obvious.



FIBER ACCEPTANCE DIAGRAMS

In order to calculate the total coupled power from a source, its intensity on the fiber core must be integrated across the acceptance area. A formula for the power P_c coupled into a step-index fiber is given in [2]:

$$P_c = P_t \left[1 - (\cos\alpha)^{m+1} \right]$$

P_t - total power on the fiber core
α - half angle of fiber acceptance, see →fiber
m - parameter defining the source's beam angle.
For a Lambertian source use m = 1.
For other sources, see →Lambertian source anyway.

To reduce the mismatch of numerical apertures, a →tapered fiber can be used. The integrated lens increases the fiber's aperture, and thus increases α.

An LED typically can couple 10% of its power into a step-index fiber of 100 µm core diameter, and 1% into a 50 µm graded index fiber. LED-coupling into a monomode fiber yields unreasonable coupling efficiency. The low LED efficiencies result from large source sizes and wide-angle beams. A double-heterostructure laser typically reaches a 50% coupling efficiency to a 50 µm graded-index fiber and 10% to a monomode fiber. This is due to the laser's better beam quality.

COUPLING LENGTH

A fiber's multimode dispersion - which is inversely proportional to its bandwidth - normally rises linear with its length. Beyond the so-called coupling length it only rises with the square root of the length due to mode mixing. See →multimode dispersion.

CRITICAL ANGLE

The angle of total reflection, see →reflection.

CUTBACK METHOD

The measurement of fiber characteristics such as attenuation and dispersion depends on the input coupling characteristics. As these are hard to control, the cutback idea is to leave this parameter constant for both the item and the reference measurements: First the characteristic of the long fiber is measured, then the fiber is cut back to a length of 1 or 2 meters for the reference measurement. The disadvantage of this method is its destructive characteristic.

CUTOFF WAVELENGTH

A monomode fiber supports only one mode (the →fundamental mode), if the wavelength is longer than the cuttoff wavelength. Below this wavelength more modes may be guided. See →modes in a fiber.

DARK CURRENT

See →pin-diode, →noise of the pin-diode, →avalanche photodiode, →noise of the avalanche photodiode.

DB (ELECTRICAL)

See →dB(optical).

DB (OPTICAL)

Using decibels (dB) in conjunction with fiber optics sometimes causes confusion because the same ratio of optical signals may result in different dB numbers x. We assume the optical power P_{opt} is converted to electrical current I in a detector, P_{opt} being proportional to I:

$$x\ [dB(optical)] = 10 \log (P_{opt\ 1} / P_{opt\ 2}) = 10 \log (I_1/I_2)$$

We now assume P_{el} is electrical power generated by the same current I, P_{el} being proportional to I^2:

$$x[dB(electrical)] = 10 \log (P_{el\ 1}/P_{el\ 2}) = 20 \log (I_1/I_2)$$

Notice that the dB (electrical) number is twice as large as the dB (optical) number:

$$dB(electrical) = 2 \times dB(optical)$$

In conclusion, one should always verify whether optical or electrical power was used to calculate attenuation, signal/noise ratio etc. in decibels. We suggest making a clear distinction by writing dB(optical) or dB(electrical).

One area of confusion resulting from this is quite common: coaxial cable attenuation is always given in dB(electrical), whereas fiber attenuation is always in dB(optical). Thus a 20 dB/km electrical cable is equivalent to a 10 dB/km optical fiber because of the need to reconvert the optical signal to an electrical signal.

dBm

One milliwatt optical power is used as a reference when specifying an absolute optical power level P_{opt} in term of dBm:

$$dBm\ (optical) = 10 \log \left(P_{opt}/1mW \right)$$

System characteristics are often given as a function of the power level in dBm. Most often this parameter refers to the high level of the modulated signal.

DENSITY

See →optical density.

DICHROIC FILTER

See →polarizer.

DIFFERENTIAL MODE ATTENUATION

See →modes in a fiber, →attenuation.

DIFFERENTIAL MODE DELAY

See →multimode dispersion, →modes in a fiber.

DIFFRACTION

This term describes the bending of light rays exiting a narrow opening or passing an edge. The far field of a →laser diode is strongly influenced by diffraction.

DISPERSION

The technical term for pulse broadening is dispersion. See →bandwidth of fibers.

DOUBLE REFRACTION

See →birefringence.

DOUBLE-WINDOW FIBER

See →fiber, →multimode dispersion.

EFFECTIVE MODE VOLUME (EMV)

EMV is one way to describe the distribution of modes (mode filling) in multimode fibers.

$$EMV = (D_{eff} \; NA_{eff})^2$$

D_{eff} - full width half maximum →near field diameter (spot size)
NA_{eff} - sine of the half width at half maximum →far field angle. Don't confuse →NA, taken from the 5% angle.

Also →equilibrium mode distribution (EMD) can be described this way: a typical 50 µm graded-index fiber with a EMD spot size of 26 µm and a NA_{eff} = 0.11 (the correspondent NA is 0.2) yields EMV = 8.18 μm^2.

ELECTRO-OPTIC EFFECT

This term describes the change of a material's refractive index or the change of the →birefringence under the influence of an electric field. Lithium-Niobate ($LiNbO_3$) is such a material. The effect can be used to build optical →modulators.

EQUILIBRIUM MODE DISTRIBUTION (EMD)

A graded index fiber with a 50µm core typically allows around

500 different core modes, each of them having different propagation and attenuation characteristics. Mode mixing (also called mode coupling) at fiber imperfections such as microbending and ellipticity transfers power from one mode to another one. Beyond a certain mixing length of fiber a steady-state distribution of fiber modes can be observed to be independent of the launching conditions. This is called EMD and contains fewer modes than the number above. Modern low mode-mixing fibers may reach this equilibrium only after many kilometers.

Various methods are used to describe and to verify the EMD at the fiber output. Some methods recommend to measure the 5% (-13dB optical) angle of the →far field. Another method suggests analyzing the →near field and the far field in order to calculate the →effective mode volume EMV. In a graded-index fiber a numerical aperture of 70% (relative to the fiber's →numerical aperture, 5% points) together with a light spot diameter of 70% (relative to the core diameter, 5% points) can be assumed to be close to the equilibrium.

In order to reproducibly measure attenuation characteristics, it is important that the EMD is achieved after only a short length of the test fiber (2 meters). This can be realized by different methods. One method is to use a long dummy fiber of the same kind in front of the test fiber. More convenient are →mode filters, sometimes in conjunction with →mode strippers. Finally, launch optics may be used to create the 70%-distribution at the input of the test fiber. The quality of the launching method must be verified by cutting the test fiber near the input end, or by using an extra short piece of the fiber. Then the output of the short fiber must be analyzed as described above.

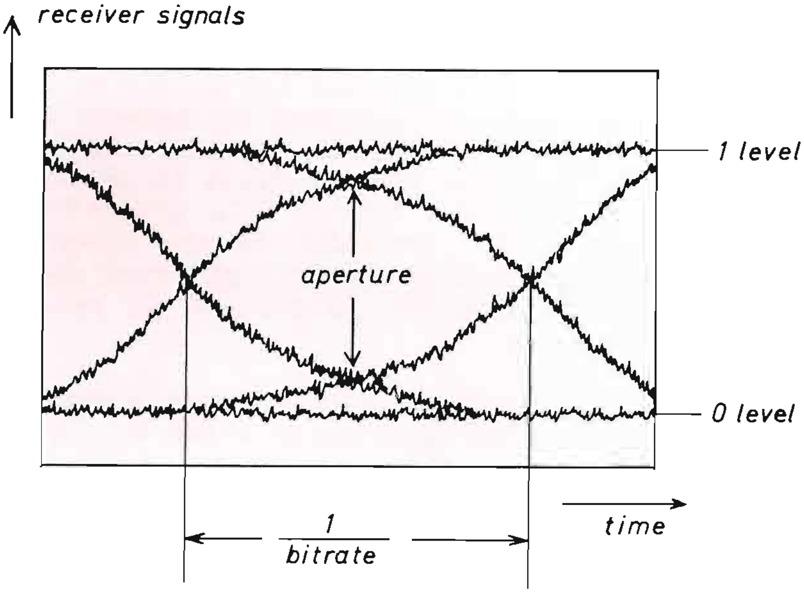
EXTINCTION RATIO

The ratio of the high level optical power to the low level optical power in a transmission system, be it analog or digital, is called extinction ratio. In contrast to electrical systems, the low level in high speed transmission systems cannot become zero, nor can the signal be made symmetrical to zero. This is due to the requirement of operating the laser at or above the threshold level, which is typically 1mW for a double-heterostructure laser, see →laser diode. Below threshold the laser diode considerably looses speed and linearity. In lower speed LED-systems the light can be switched on and off, making the extinction ratio infinite.

System designers require the extinction ratio to be larger than 10, because the noise attributed to the low level is small if the low level is close to zero. See →noise of a receiver.

EYE PATTERN

The proper function of a digital system can be quantitatively described by its →bit error rate (BER), or qualitatively by its eye pattern. The eye pattern is obtained by applying the digital data stream to the vertical amplifier of an oscilloscope and triggering the scope with the system's clock.



EYE PATTERN OF A BINARY DATA STREAM

The quality of the eye pattern, critical for achieving a low BER, is influenced by two phenomena. One is noise, which is proportional to the receiver's bandwidth, see →noise of a receiver. The other phenomenon is intersymbol interference, which arises from other bits interfering with the bit of interest. This way the lower level of the aperture in the diagram and the zero level are not identical. The intersymbol interference is inversely proportional to the bandwidth. Thus a bandwidth-compromise has to be made for the best possible eye aperture.

FARADAY EFFECT

Some materials including glass, are capable of rotating the orientation of linearly polarized light under the influence of a magnetic field. The magnetic field orientation must be parallel to the direction of propagation. The angle of rotation is proportional to the field strength and the thickness of the material. This effect can be used to build →modulators.

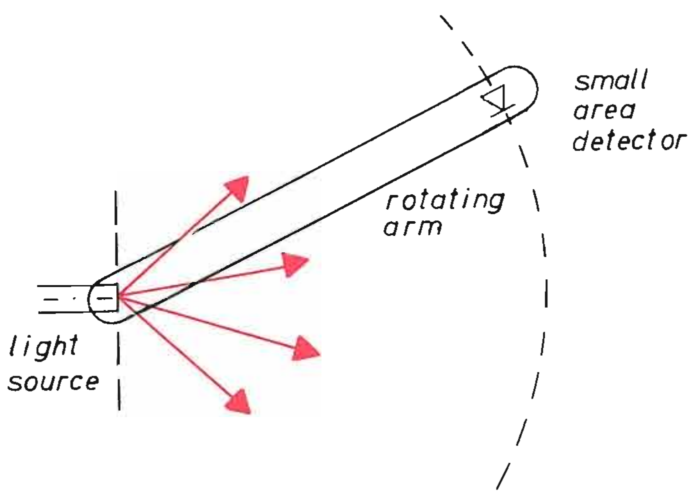
FAR FIELD RADIATION PATTERN

A light source is placed into the center of a sphere. The radiation intensity on the inner surface of the sphere is called far field intensity. Its analysis is important to determine →numerical aperture of sources or fibers and mode filling (see →equilibrium mode distribution) of fibers.

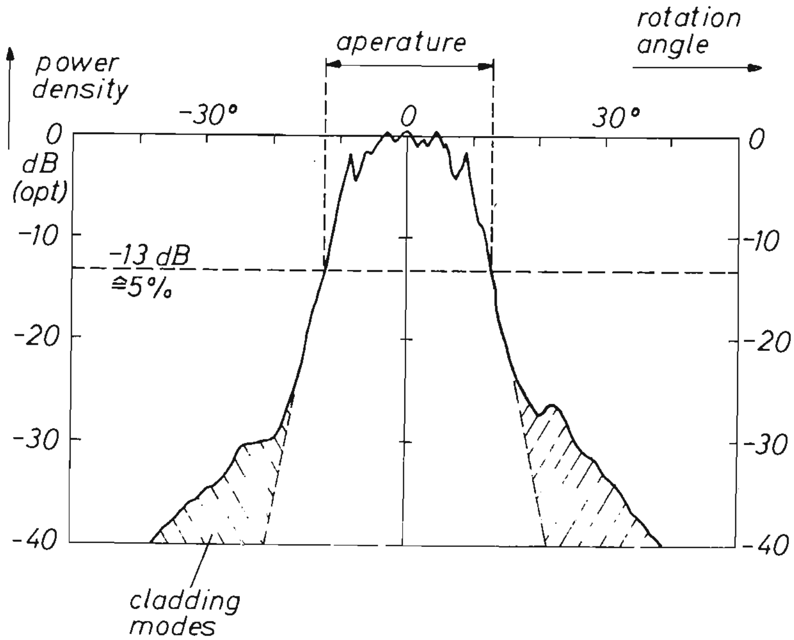
A good description of far-field measurements is given in [7]. Accordingly, the minimum measurement distance r depends on the source size d and the wavelength λ:

$$r > d^2/\lambda$$

More than 10r is normally used, which is approximately 10cm for a 100 µm step-index fiber at 850nm. This distance suffices for graded-index fibers, lasers, and most LED's, too. It is convenient for a far-field measurement apparatus based on a detector fixed to a rotating arm.



FAR FIELD SCANNING APPARATUS



OUTPUT FAR FIELD OF A 2 METER GRADED INDEX FIBER

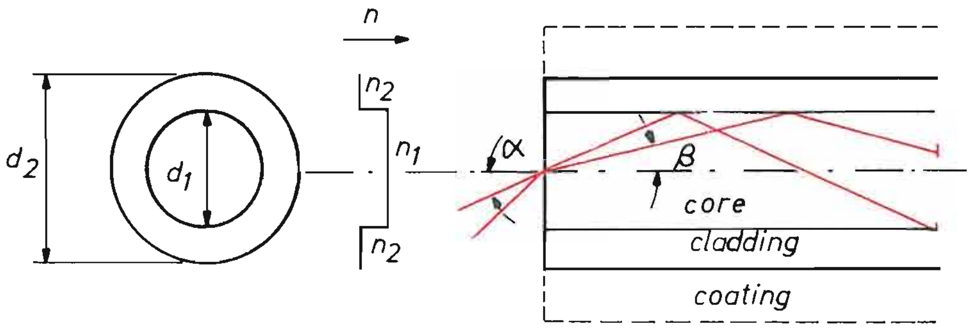
A number of interesting details can be learned from the far field measurement diagram. First, it indicates the determination of the fiber's numerical aperture, however the required →mode stripping was not carried out in this case. Since the refractive index of the fiber's coating was smaller than the cladding index, cladding modes were not absorbed. They cause the "wings" in the diagram. If the coating index was larger than the cladding index, these wings would not be observed. The ripple at the peak of the curve is actually an image of the speckle pattern. See →modal noise. The speckle pattern arises from driving the fiber with a laser. If driven with an LED, the speckle pattern would not be observed.

FDHM

Abbreviation for full duration at half maximum. Used to describe the width of a function, identical to full width at half maximum FWHM.

FIBER

Two main requirements determine the construction of optical fibers: low attenuation and high bandwidth. In order not to lose any light by radiation, the light transporting glass core (refractive index $n_1 \simeq 1.5$) is surrounded by a cladding made from glass with lower refractive index n_2. Plastic coating around the fiber supplies mechanical protection. In some instances the coating removes cladding →modes via a higher-than-glass refractive index.



STEP-INDEX MULTIMODE FIBER

A <u>step-index multimode fiber</u> guides light rays by total reflection at the core-cladding-boundary. Only rays with an angle $\cos \beta < n_2/n_1$ are guided. At the entrance of the fiber, this angle leads to a maximum coupling angle α_m.

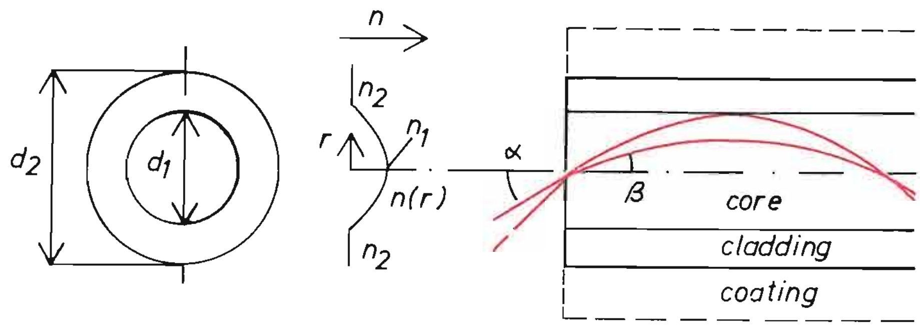
$$\sin \alpha_m = n_1 \sin \beta = \sqrt{n_1^2 - n_2^2}$$

The term $\sin \alpha_m$ is also called →<u>numerical aperture NA</u>. The NA and the core diameter d_1 determine the →coupling efficiency to a light source.

Step-index fibers have typical diameters of d_1/d_2 = 100/140µm minimum. Typical NA's are from 0.2 to 0.5. Low bandwidth is the most significant disadvantage of step-index fibers, the main cause being →multimode dispersion. As indicated in the figure, different modes travel different total path lengths. The larger the NA and the angle β, the larger the total number of guided →modes. The NA thus also defines the fiber's bandwidth.

Step-index fiber have also been made completely from plastic. So far, their application is in short links allowing higher attenuation.

<u>Graded-index fibers</u> represent a compromise in coupling efficiency in order to reach higher bandwidth. This is done by giving the core a non-uniform refractive index profile.



GRADED-INDEX FIBER

The profile causes the light to travel on wavelike tracks. The longer pathlength of the outer rays is compensated by the higher speed v of light in the outer core region: $v = c/n$. The angle of acceptance depends on the distance from the core center: it is maximum at the center and zero at the core-cladding boundary, in contrast to step-index fibers. Nevertheless, the numerical aperture NA of graded index fibers is defined identically to the step-index fiber:

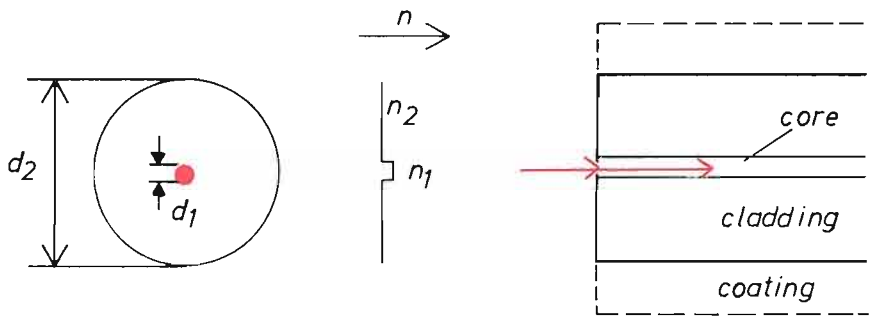
$$NA = \sqrt{n_1^2 - n_2^2}$$

The NA is typically 0.2 for graded-index fibers. One possible index profile, called power-law profile, is given by

$$n(r) = \sqrt{n_1^2 - NA^2 (r/a)^\alpha}, \quad r \leq a$$

The parameter α determines the effective speed differences of the →modes and thus the →bandwidth of the fiber. The profile is called parabolic if α = 2. The optimum α (very close to 2) is wavelength-dependent, which makes it difficult to manufacture high-bandwidth graded-index fibers for a wide wavelength range. A compromise between 850 nm and 1.3 µm is called double-window fiber. Graded-index fibers mostly have 50 µm core diameter and 125 µm cladding diameter.

For the highest performance in bandwidth, monomode fibers are used. The most simple construction of this fiber is the same as that of a step-index fiber, except the core diameter and the core-to-cladding index contrast is so small that only one mode can propagate. Typical monomode fiber dimensions are 5 -12µm core and 125µm cladding diameters.



MONOMODE FIBER

→Multimode dispersion in a monomode fiber is very small. It is only caused by different travel speeds of the two possible polarizations of the same mode. Unfortunately it is difficult to achieve a reasonable fiber →coupling efficiency to a source and to build connectors to match the cores with an accuracy of around 1 µm. For further information, see →modes in a fiber and →modal noise.

FLUX

See →radiometric units, →photometric units.

FRESNEL DIFFRACTION PATTERN

Synonym for →near field pattern.

FRESNEL REFLECTION

See →reflection.

FUNDAMENTAL MODE

This term is used for the lowest order fiber →mode. Descriptively it is the one which is transported without reflection at the core-to-cladding boundary.

FUSION SPLICE

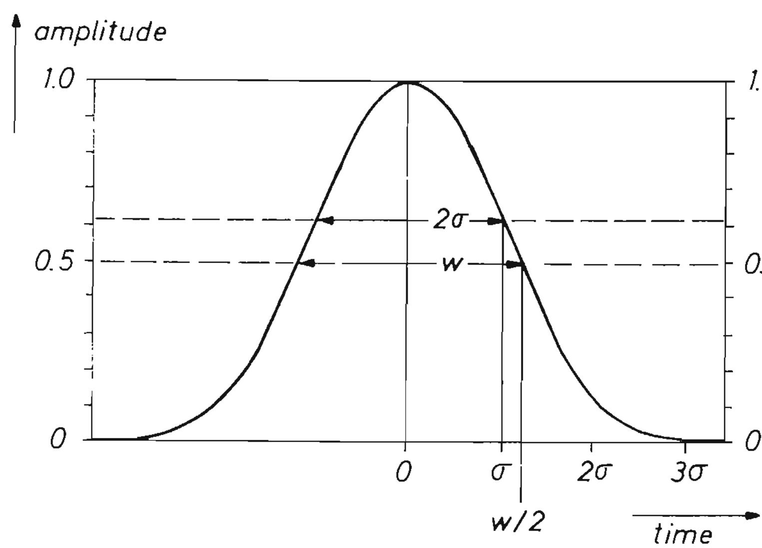
See →splice.

FWHM

Abbreviation for full width at half maximum. Used to describe the width of a function, identical to full duration at half maximum FDHM.

GAUSSIAN PULSE

The Gaussian pulse has the unique feature of its shape being invariant under Fourier transform, which means that the positive part of the time characteristic and the frequency characteristic have identical shapes. If an impulse (zero duration pulse) or a Gaussian pulse is applied to a low-pass filter with a Gaussian frequency characteristic, the resulting output pulse is again Gaussian. Many practical systems such as fibers with well-controlled index profile or laser diodes or detectors can be approximately described by the Gaussian shape, although it theoretically extends to + and - infinity.



GAUSSIAN PULSE

The mathematical description of the Gaussian pulse is given by

$$f(t) = \exp(-2.77\,(t/w)^2)$$

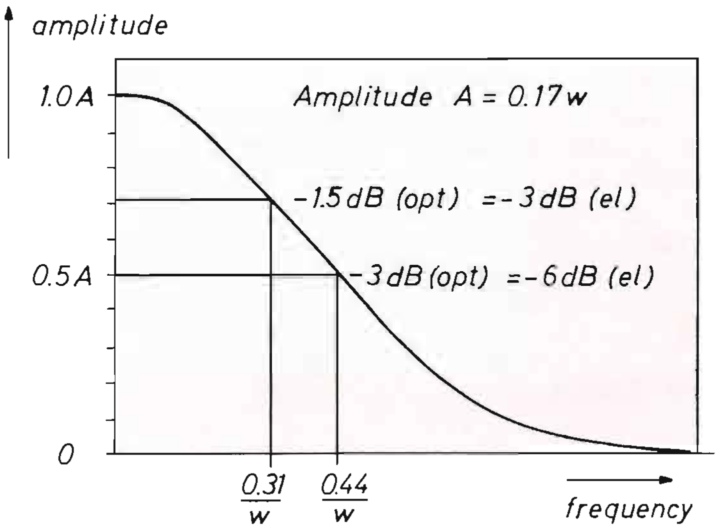
The factor 2.77 was chosen such that the full duration at half maximum (FDHM) is w. Sometimes the width of the Gaussian pulse is given by its RMS pulse width 2σ which is also shown in the diagram:

$$\sigma = 0.43\,w$$

σ stems from the Gaussian probability function and is called standard deviation in that case.

The Fourier transform (frequency domain) of the above pulse is

$$F(f) = 0.17\,w\,\exp(-3.56\,f^2 w^2)$$



FOURIER TRANSFORM OF THE GAUSSIAN PULSE

An impulse (zero-width pulse) shall be applied to a fiber with Gaussian characteristic. The 3 dB(optical) / 6 dB(electrical) bandwidth is called f_{3dB}. Then the bandwidth and the duration of the resulting Gaussian pulse are related by

$$f_{3dB} = 0.44 / w$$

In a practical measurement, w has to be determined from the quadratic sum of the individual pulse durations (e.g. laser 1, fiber 2, detector 3).

$$w^2 \text{ (system)} = w_1^2 + w_2^2 + w_3^2 + \ldots$$

GRADED-INDEX FIBER

See →fiber.

GRADED-INDEX LENS

See →Selfoc lens.

GROUP INDEX

See →material dispersion.

GROUP VELOCITY

Light is propagated in a fiber at a speed v, which is determined by the speed of light c in vacuum and the fiber's refractive index n: $v = c/n$. This speed is called phase velocity. If the light is modulated by a signal, then the signal travels at a slightly slower speed, which is termed group velocity. See →material dispersion.

IMPULSE RESPONSE

See →bandwidth of fibers.

INCIDANCE

See →radiometric units, →photometric units.

INDEX MATCHING

Reflections and associated losses from a fiber joint can be avoided by connecting the two fibers with a material whose refractive index is similar to the core index. Oil or optical cement are most often used for index matching.

Index matching can also be achieved between media of unequal indices. →Antireflection coating is one example.

INSERTION LOSS

See →coupling efficiency, →connector, →optical density.

INTENSITY

See →radiometric units, →photometric units.

INTERFERENCE

Two coherent light beams can add or subtract their electric fields, depending on their relative phases. This effect creates the speckle patterns of a fiber, see →modal noise, →coherence.

INTERSYMBOL INTERFERENCE

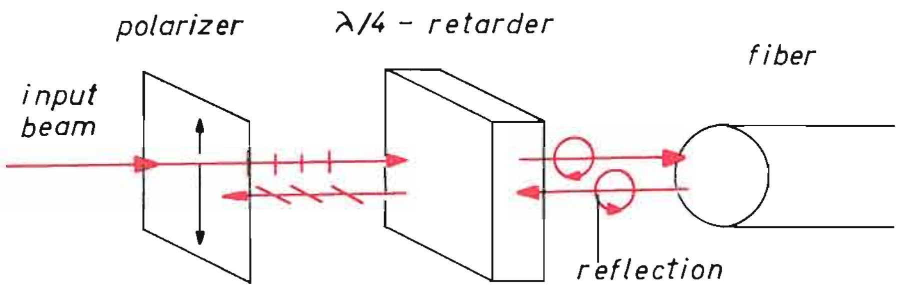
See →eye pattern.

IRRADIANCE

See →radiometric units.

ISOLATOR

An isolator is a non-reciprocal optical or electrical network, which means that the device's characteristics change if input and output are interchanged. Here it means, the device is only transporting optical power into one direction. Isolators are commonly used to avoid disturbing reflections back into the laser, which can cause extra →noise. Especially butt-coupling into a fiber with its 4% reflection may cause this problem. Isolators are based on the condition that input light is linearly polarized. The most common type uses a quarter-wave →retarder.



ISOLATOR BASED ON A QUARTER-WAVE RETARDER

The retarder converts linear polarization into circular polarization. When reflected, the polarization is still circularly polarized but with opposite sense of rotation. After another pass through the retarder, linear polarization is reestablished but at an orthogonal orientation, which is then blocked by the polarizer. The polarizer and the input surface of the retarder must be antireflection-coated for this task.

ISOTROPIC

A material, e.g. an optical glass, is called isotropic if its physical characteristics, optical and electrical, are not dependent on the direction in which they are measured. See →birefringence as an example for non-isotropic material characteristics.

LAMBERTIAN SOURCE

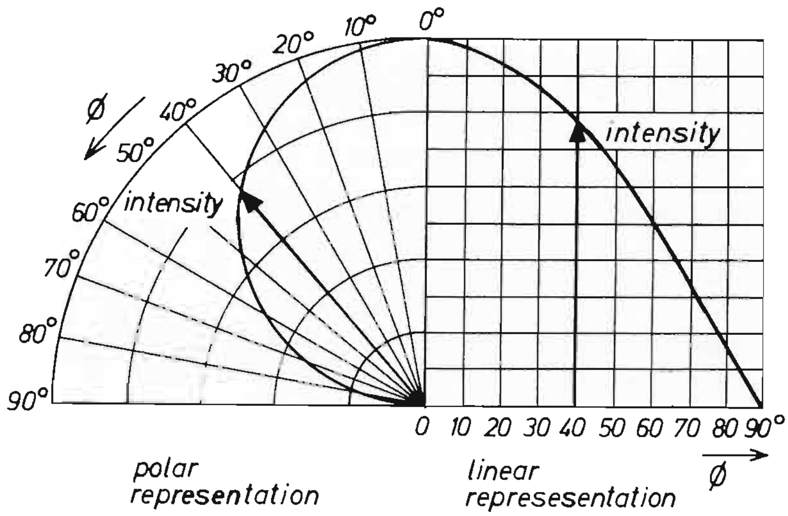
This type of source is defined by a uniformly diffusing light emitting flat surface. LED's sometimes come close to this model.

LAMBERTIAN SOURCE

The diagram shows the →far-field radiation intensity I from such a source, measured on a sphere:

$$I = I_o \cos \phi \quad [\text{watt/ster}] \text{ or } [\text{lumen/ster}] = [\text{cd}]$$

ϕ - linear viewing angle
I_o - maximum intensity



INTENSITY PROFILE OF A LAMBERTIAN SOURCE

Note that the intensity in the polar representation is characterized by half a circle. The total →flux (power) within the half sphere (2π steradian) is:

$$P = \pi I_o \quad [\text{lumen}] \text{ or } [\text{Watt}]$$

This relation can be used to estimate the total LED-power P when only the maximum intensity I_o is given.

Example: $I_o = 1$ mcd at 555 nm

$= 1 \times 10^{-3}$ lumen/ster

$= \dfrac{10^{-3}}{683}$ Watt/ster (from →photometric units)

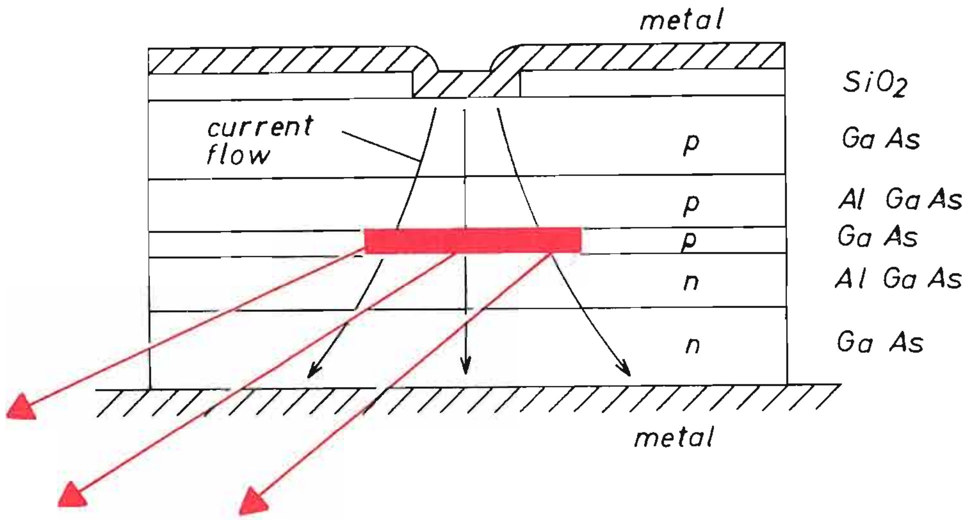
$P = \dfrac{\pi 10^{-3}}{683}$ Watt $= 4$ µW

Most fiber optical sources have beam profiles which are narrower than the Lambertian source. According to [2], these sources can be approximated by the following formula and by selecting an adequate value of m:

$$I = I_o (\cos \phi)^m$$

LASER DIODE (CW TYPE)

The light generating process of a LD is similar to the one in a →LED, also the materials used are the same. The LD differences are small light generating volume and the high concentration of injected carriers. This results in a high optical gain, a narrow →spectrum, and →coherence. The figure shows a 850nm gallium-aluminium-arsenide (GaAlAs) laser diode with double heterostructure and gain guiding.



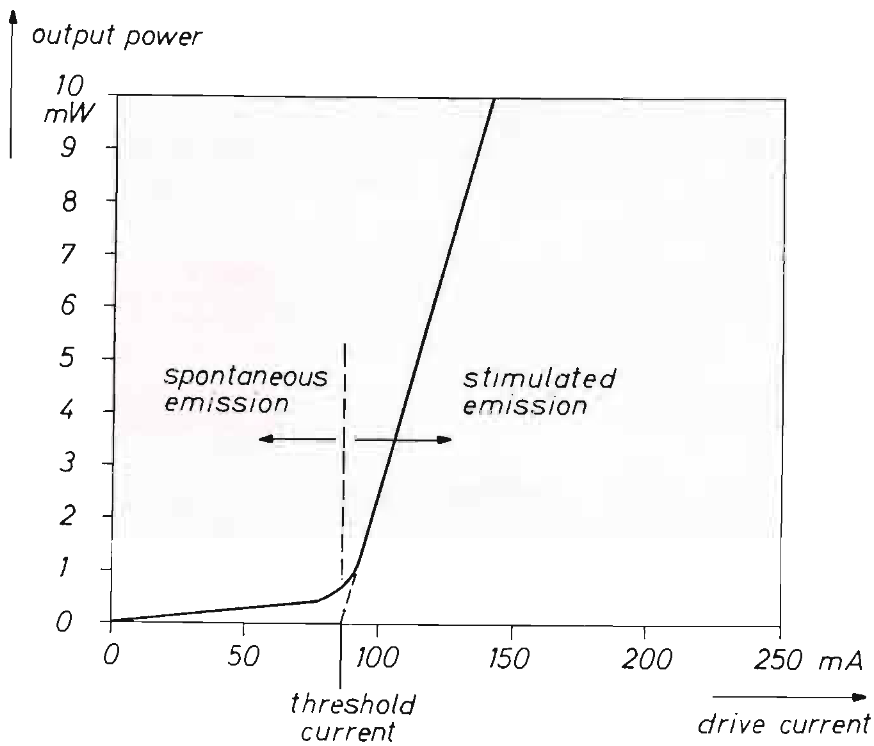
DOUBLE-HETERO STRUCTURE LASER DIODE

The active region of the LD is enclosed by two aluminum enriched layers of lower refractive index to provide optical guidance and enclosure of injected carriers. The lateral confinement of the active zone is either achieved by the current flow (gain guided laser), or by lateral zones of lower refractive index (index guided laser). The typical zone dimensions are 5-10 µm width and 0.1 to 0.2 µm thickness.

Because of the confinement, light can only exit from the front and back faces of the laser. These faces are semi-transparent mirrors which form a resonator cavity. The two faces have very similar radiation characteristics. In the spontaneous (LED-) region of the laser curve the →spectrum is quite similar to an →LED. The typical gain in this region is 5 µW/mA per face, which is less than typical LED gains.

LASER DIODE (CW TYPE)

At a certain current density inside the active region, the optical gain exceeds the channel losses and the emission changes from spontaneous to stimulated (also called induced, or lasing). The critical current density determines the threshold current. This current is exceptionally low in double-heterostructure lasers, typically 50 to 150mA.

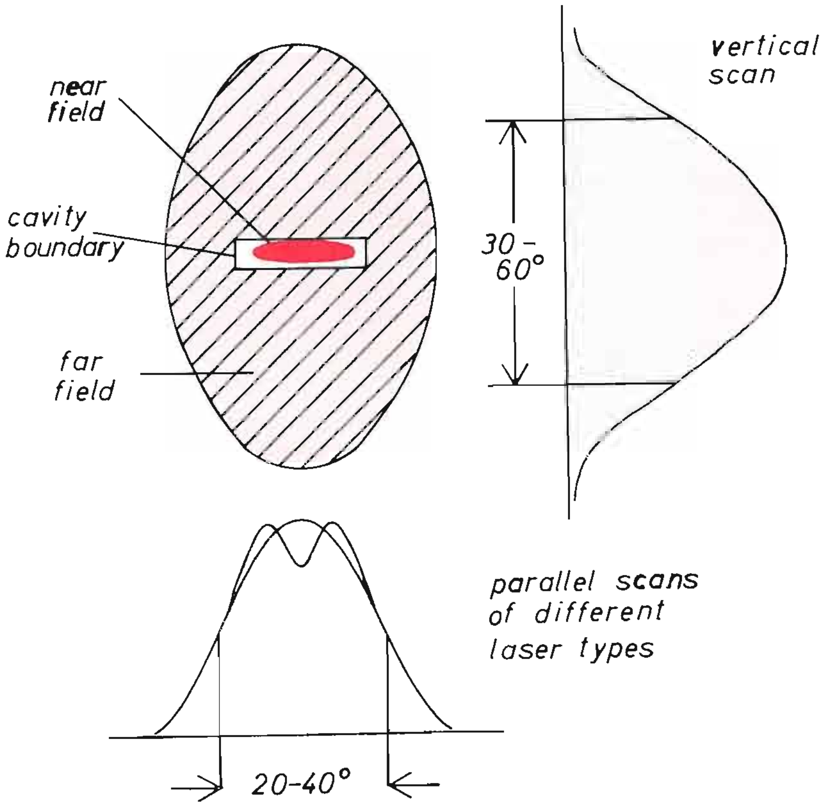


POWER-CURRENT CHARACTERISTIC OF A LASER DIODE

The differential gain in the stimulated (laser) region is typically 200 µW/mA. The gain decreases with rising temperature, see →temperature dependance of the laser diode. The laser has a diode-like voltage-to-current characteristic with 1.8V threshold. The series resistance is <5 Ω typical. The linearity in the laser region is quite good for modern lasers, typically -40 dB (electrical) total harmonic distortion for 50% modulation depth can be reached for a gain-guided laser. Index-guided lasers have a sharper transition between the two regions and an even better linearity. Some care is recommended when dealing with linearity because different portions of the laser radiation show different linearity characteristics. Sometimes integral measurements are made, sometimes only the portion coupled into a fiber is considered.

In older lasers severe distortions of the laser curve can often be observed; they are called kinks. They are caused by transverse mode jumps inside the laser cavity. This effect can also be provoked by reflections back into the laser and is then called optical feedback noise (see →noise of the laser diode).

Gain guided lasers typically show multilongitudinal modes with many discrete lines in their →spectrum. Index guided lasers have fewer or only one main mode (monomode laser).



LASER DIODE RADIATION PATTERN

The radiation pattern (→far field) of an LD has an elliptical shape. The ellipticity stems from diffraction effects at the junction-parallel and the junction-perpendicular cavity boundaries. Some newer lasers exhibit well pronounced peaks in the parallel scan, as indicated in the figure. The →near-field of a laser diode is elliptical too, but with perpendicular orientation as indicated in the figure. Also see →astigmatism.

In contrast to LED's, lasers generate partially polarized light. The polarization orientation is parallel to the junction. The purity of the polarization is better than 90%, if the laser is operated in the lasing region. The light is non-polarized if the laser is operated in the LED-region.

Typical maximum bandwidth for modulation is between 500MHz up to 3GHz, well suited for today's high speed electronics.

Maximum obtainable optical power depends on the duty cycle: for unmodulated DC-operation the maximum power is between 5 and 20mW. For narrow pulse modulation (e.g. 5 ns pulse width), maximum power can go as high as 500 mW.

Because of the →temperature dependance of the laser power, the high quescient point power and lifetime considerations, lasers are often cooled and temperature-stabilized, using Peltier coolers. For the temperature effect on wavelength, see →temperature dependance of the laser diode. Also see →spectrum of a laser diode, →noise of the laser diode, →coherence, →coupling efficiency, →astigmatism.

LASER DIODE (PULSE TYPE)

Pulse lasers are normally used in high power pulse applications such as in an →optical time-domain reflectometer. The most common pulse laser is of the single-heterostructure type, which is somewhat simpler than the double-heterostructure laser: only one Gallium-aluminum-arsenide layer is used for optical guiding. See →laser diode (cw-type) for the construction of the double-heterostructure laser.

The peak power from such a laser is typically 3 Watts for 100µm stripe width, and more for larger widths. The height of the active zone is typically 2µm. Both these values are in the order of 10 times larger than those of double-heterostructure lasers, resulting in a 100 times larger emitting area. Thus the →coupling efficiency to fibers is drastically reduced. The generation of the maximum power is normally limited to around 200ns pulse width at a maximum duty cycle between 0.01 nd 0.1%. This is due to the high threshold current which is typically 2-5 Amperes for the above mentioned 100µm stripe width. The current necessary to reach the peak power is 10 to 20 Amperes. Accordingly, the peak voltage may reach 10 Volts.

Such a laser allows many transversal and longitudinal modes in its large resonant cavity. This leads to a somewhat wider spectral width when compared to double-heterostructure laser: typically 3 to 10nm. The fastest transition time of single-heterostructure devices is around 0.5ns.

Lasers of this type are also available as series-connected stacks: such lasers are capable of delivering up to a few hundred Watts pulse power. However, an even larger emitting area has to be taken into account.

Pulse operation also seems available with double-heterostructure lasers: although non-specified up to now, pulse powers of more than 1 Watt at 20ns pulse duration have been measured in the laboratory. For fiber optic test and measurement the usage of such devices may be more attractive because these are the same devices as used in real communication systems. Thus the good coupling efficiency and other favourable characteristics can be maintained.

LAUNCH NUMERICAL APERTURE

See →numerical aperture, →coupling efficiency, →effective mode volume, and →equilibrium mode distribution.

LAUNCH OPTICS

One of the methods to generate an →equilibrium mode distribution (EMD) in a fiber is by launch optics. A light spot size of 70% ±5% of the core diameter (measured at the 5% intensity points) in conjunction with a launch angle of 70% ±5% of the fiber's →numerical aperture have been found to give good results. This kind of beam geometry can be achieved with a combination of lenses and apertures, together with a beam splitter and viewing optics to inspect the light reflected back from the input surface of the fiber. This way the exact position of the fiber with respect to the light spot can be verified.

LEAKY MODE

See →modes in a fiber.

LED

See →light emitting diode.

LENSED FIBER

See →tapered fiber.

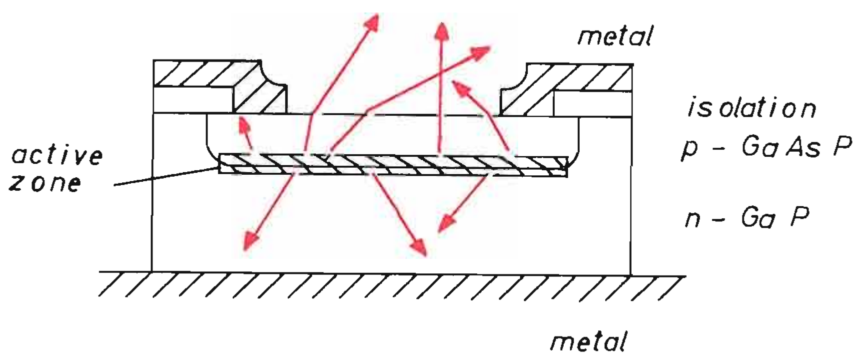
LIGHT EMITTING DIODE (LED)

The light generating process of a LED or laser is determined by recombination of electrons and holes inside a pn-junction, thereby generating photons. This effect is called electroluminescence. The bandgap energy E of the material combination defines the wavelength:

$$\lambda = \frac{h\,c}{E}$$

h - Planck's constant, see →constants
c - speed of light, →constants

For pure gallium-arsenide λ is 900 nm. By adding aluminium, the wavelength can be lowered to 780nm. For even lower wavelengths into the visible region, gallium-arsenide-phosphide or gallium-phosphide is used. For longer wavelengths, indium-gallium-arsenide-phosphide is the common material. In a LED, the light has a theoretical 360° spherical radiation characteristic, which in practice is limited by the diode's mechanical construction, such as light reflection at the base metallization and by absorption within the semiconductor material.

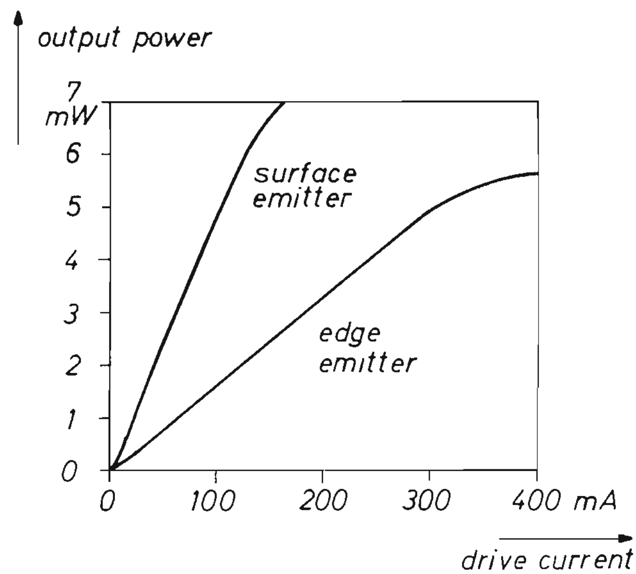


VISIBLE LED CONSTRUCTION

The →numerical aperture can vary from 0.9 for a wide angle LED to 0.2 for a narrow angle lensed LED. Even though the NA of 0.2 is quite small, the emitting area is large as compared to a laser. The resulting low power density drastically reduces the power which can be coupled to a graded index fiber, and makes coupling to a monomode fiber almost impossible (→coupling efficiency).

Another disadvantage of the LED is its comparatively low bandwidth. Typically, 200 MHz is the limit for good diodes. Advantages of the LED are very linear dependance of the optical power on the applied current, and low power consumption as compared to lasers. High reliability is a benefit from low current density. As LED's are not very sensitive to overloads, simple drive circuits can be used.

Typical efficiency is 50 µW/mA, with no threshold current required.



TYPCIAL LED CHARACTERISTICS

Various LED constructions have been made in order to improve the coupling efficiency to a fiber, such as the →Burrus diode or the edge emitting LED. The latter uses two embedding layers of lower refractive index for beam confinement, similar to the construction of a →laser diode.

Also see →spectrum of a LED, and →temperature dependence of an LED.

LOSS

See →attenuation, →coupling efficiency, and →optical density.

LP-MODE

Abbreviation for linear polarized mode. See →modes in a fiber.

LUMINANCE

See →photometric units.

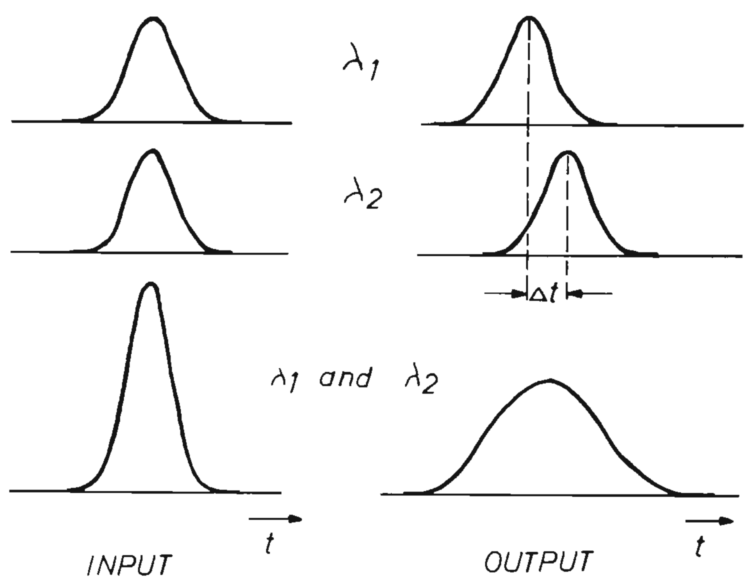
MAGNETO-OPTIC EFFECT

This term includes different mechanisms in which a magnetic field changes the optical characteristics of a material. Two of these effects are induced →birefringence and the →Faraday effect. Both can be used to build →modulators.

MATERIAL DISPERSION

Material dispersion and →waveguide dispersion are both parts of the →chromatic dispersion, contributing to the total →bandwidth of fibers. For multimode fibers, waveguide dispersion can be neglected. It is only important in monomode fibers.

Material dispersion, dimension [ps/(nm km)], refers to the wavelength dependance of the fiber's refractive index n and the associated differences in speed of light. Many practical light sources have a spectral width of at least one nanometer. Different components within this spectrum travel at different speeds.



PULSE BROADENING DUE TO MATERIAL DISPERSION

As waveguide dispersion is described separately, it is sufficient to replace all the modes by just one planar wave (still unmodulated):

$$E = A \exp(j(\omega t - \beta z))$$
$$\omega = 2\pi c/\lambda$$
$$\beta = 2\pi n/\lambda$$

E - electric field vector
A - amplitude vector
ω - 2π x optical frequency
β - propagation constant along z
z - length dimension along of the fiber
c - speed of light in vacuum, see →constants
λ - wavelength in vacuum
n - refractive index of the fiber core

The phase velocity of the above wave is identical to the speed of light in glass:

$$v_{ph} = \omega/\beta = c/n$$

If the wave carries an information via amplitude modulation, then the information travels at a somewhat lower speed called group velocity:

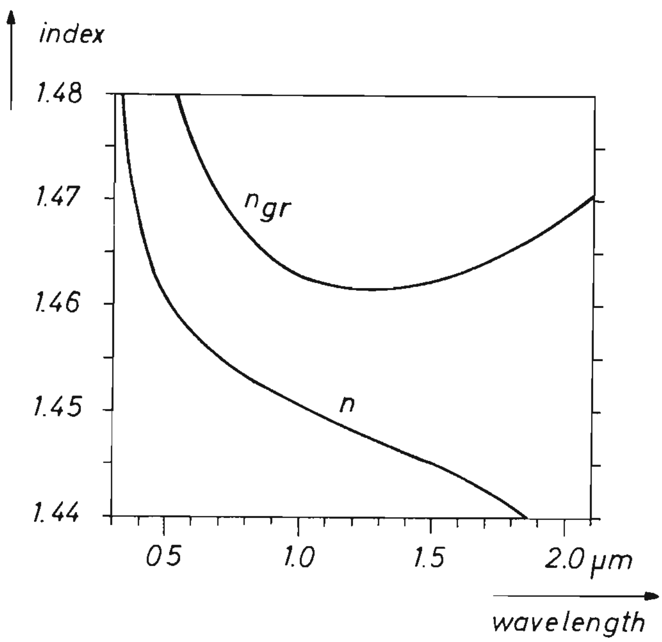
$$v_{gr} = d\omega/d\beta$$

From the group velocity, the total group travel time on the fiber length L can be found after some manipulation:

$$t_{gr} = \frac{L}{v_{gr}} = \frac{L}{c}\left(n - \frac{\lambda dn}{d\lambda}\right)$$

From this term the group refractive index n_{gr} can be derived:

$$n_{gr} = \frac{c}{v_{gr}}$$
$$= n - \lambda \frac{dn}{d\lambda}$$



REFRACTIVE INDEX AND GROUP REFRACTIVE INDEX OF QUARTZ

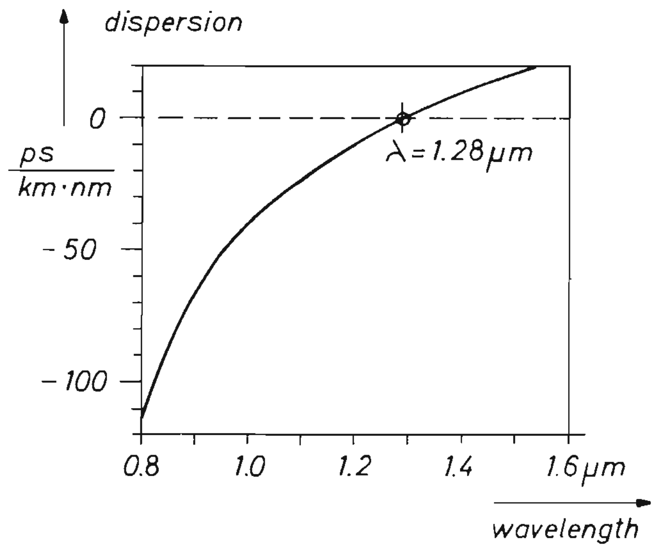
The diagram shows n and n_{gr} of quartz. At 1.28 µm, the group index has a horizontal tangent. This means no material dispersion at 1.3 µm, due to no change in group index.

In order to calculate material dispersion, we assume a source spectral width of $\Delta\lambda$ causing a difference Δt_{mat} in group travel time:

$$\Delta t_{mat} = \frac{dt_{gr}}{d\lambda} \Delta\lambda$$

$$= \frac{L\lambda\Delta\lambda}{c} \frac{d^2n}{d\lambda^2}$$

The result of this derivation is shown in the diagram. Zero dispersion corresponds to the turning point of the n-curve and to the minimum of the n_{gr}-curve.



MATERIAL DISPERSION OF QUARTZ

At 1.28 μm, zero material dispersion is reached in quartz. By adding GeO_2 the zero-dispersion point can be shifted to longer wavelengths. At the classical 0.85 μm wavelength, material dispersion is around 100 ps/(km x nm). A source line width of 3 nm causes 300ps/km material dispersion at 850 nm.

The material dispersion of a multimode fiber cannot be measured directly since →multimode dispersion disturbs the measurement. Quadratic subtraction (see →bandwidth of fibers) is possible, or using a refractive index measurement and the above equations.

MERIDIONAL RAY

This ray intersects the symmetry axis of a lens or fiber. Rays parallel to the axis are a special case of this class of rays. Only meridional rays are considered when determining the →numerical aperture of a fiber or lens.

MESIAL POWER

This term describes the mathematical average between high level and low level powers of a modulated light signal, using:

mesial power = (high level + low level)/2

The mesial power level is independent of the duty cycle and should not be confused with the average power level.

MICROBENDING

Mechanical stress in a fiber may introduce local discontinuities called microbending. This results in unwanted light radiation, extra loss and →mode coupling.

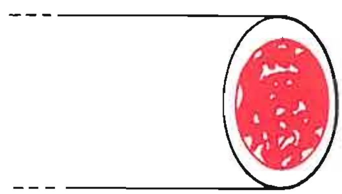
MODAL DISPERSION

Obsolete term for →multimode dispersion.

MODAL NOISE

Modal noise refers to noise generated in fibers or at fiber interfaces.

When coupled into a multimode fiber, each spectral laser line (longitudinal mode) splits up into many fiber waveguide modes. At the end of the fiber the modes interfere and cause a speckle pattern, both in the near and far fields. Adjacent longitudinal laser modes only weakly interfere because of their >50 GHz frequency difference. Graded-index fibers show more pronounced speckle patterns than step-index fibers, due to fewer waveguide modes and lower multimode dispersion in graded-index fibers.



SPECKLE PATTERN AT THE END OF A GRADED-INDEX FIBER

As the speckle pattern is based on phase relations, it is phase-sensitive. Thus the speckle pattern is always moving because the necessary phase changes are already caused by small movements and temperature changes of the fiber.

If two well cleaved fibers are brought into contact, then no noise enhancement can be observed, if all the power is transmitted. If there is an radial offset, then the output speckle pattern of the first fiber core moves statistically across the core boundary of the second fiber, causing modal noise. The same problem arises at the transition of a fiber to a small-area detector.

To avoid modal noise, several methods can be applied:

1. Use good connectors or splices.
2. Don't use connectors close to the transmitter. The speckle pattern is more pronounced due to stronger coherence within a certain distance from the source. See →coherence.
3. Use lasers with many longitudinal modes or LED's. Since each of the laser modes creates its own speckle pattern, the patterns overlap and average. Caution: the total laser line width increases the →chromatic dispersion.
4. Use monomode fibers in conjunction with multimode or monomode lasers. Monomode fibers don't show speckle patterns, because there is only one waveguide mode and no chance of interference.
5. Use large area detectors or good imaging.

Another type of modal noise is polarization noise (also called birefringence noise) in monomode fibers. The two possible polarizations of the same mode may have different propagation constants, and thus may be split up in time. In this case modal noise arises whenever power is statistically transported from one mode to another. See →multimode dispersion.

A detailed article about modal noise is reference [9].

MODE COMPETITION NOISE

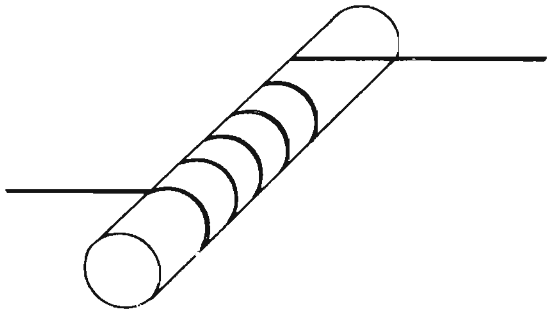
See →noise of the laser diode.

MODE COUPLING

See →multimode dispersion.

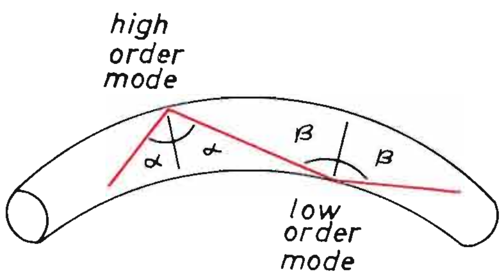
MODE FILTER

Also called mode mixer or mode scrambler. The purpose of this device is to establish an →equilibrium mode distribution in a graded-index or step-index fiber independent of the light-launching conditions. Two principles are commonly used: mandrel-wrap filters and specific launching fibers.



MANDREL WRAP FILTER

A mandrel wrap filter for a 50 µm graded-index fiber typically consists of a 12.7 mm (0.5 inch) diameter rod with 5 turns of coated fiber. The exact number of turns and the rod diameter have to be determined empirically by measuring the resulting modal distribution. The fiber tension should be such that the fiber does not move by itself. This filter causes low order modes to be converted to high order modes and vice-versa, until equilibrium mode distribution is reached. Highest order modes are forced to leave the core and are converted to cladding modes, or they completely leave the fiber by radiation. Due to this effect, a mandrel-wrap filter always introduces a loss of a few dB.

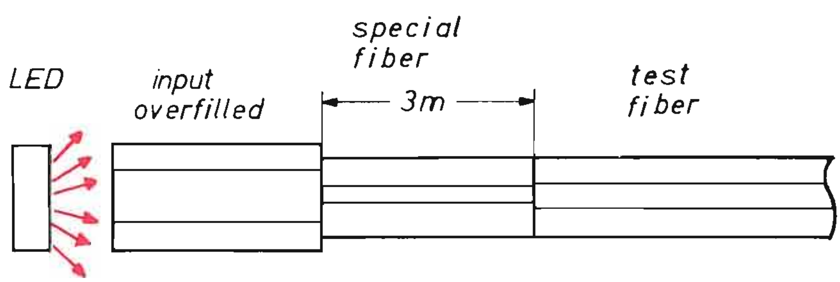


EFFECT OF CURVATURE ON FIBER MODES

The figure demonstrates the conversion of a high-order mode into a low-order mode. Reversing the beam direction generates the opposite effect. A mandrel-wrap filter should always be followed by a cladding →mode stripper in order to remove the unwanted cladding modes.

A similar mode filter realization is bending the fiber to a serpentine by pressing it into an adequately shaped surface.

The first approach to a launching fiber is the usage of a sufficiently long fiber of the same type as the fiber to be measured. Its length depends on the degree of mode mixing (see →multimode dispersion), 1 to 2 km are widely used for graded-index fiber measurement. To get rid of this bulky arrangement a combination of special fibers has been found to do the same task.



Step-index	graded-index	graded-index
100 µm core	40 µm core	50 µm core
NA 0.23	NA 0.16	NA 0.2

MODE FILTER USING A SPECIAL FIBER COMBINATION

The basic idea of this mode filter is to create a launching condition close to the 70% condition, as described under →equilibrium mode distribution. The 40 µm fiber in the figure has to be specially made, its detailed technical description tends to belong to the fiber manufacturer's know-how secrets.

In any case, the butt-coupling of the mode filter to the test fiber must be done very precisely in order not to destroy the modal distribution. →Index matching is recommended for best performance.

MODE LOCKING

Mode locking is typically performed in a gas laser in order to generate ultrashort optical pulses, e.g. for multimode dispersion measurements. Typical pulse durations are from 100 down to 0.1 picoseconds. With L being the laser cavity length and c being the speed of light, the pulse repetition rate f is

$$f = c/2L$$

Passive mode locking is achieved by placing a saturable absorber into the laser cavity. This type of absorber has the property that its light transmission increases as the light intensity increases. Consequently, a recirculating pulse in the laser cavity experiences a higher net gain than a lower level signal. This way the pulse amplitude is increased and the pulse duration is reduced on subsequent passes through the cavity.

Active mode locking is achieved by modulating the loss in the laser cavity at the above determined frequency. The effect of this is similar to passive mode locking: a pulse recirculating inside the laser cavity experiences the highest net gain if it passes through the modulator during the lowest loss portion of the cycle. Light recirculating before or after this time experiences a higher loss. Thus in steady state a continous pulse train results.

MODE MIXER

See →mode filter.

MODE PARTITIONING NOISE

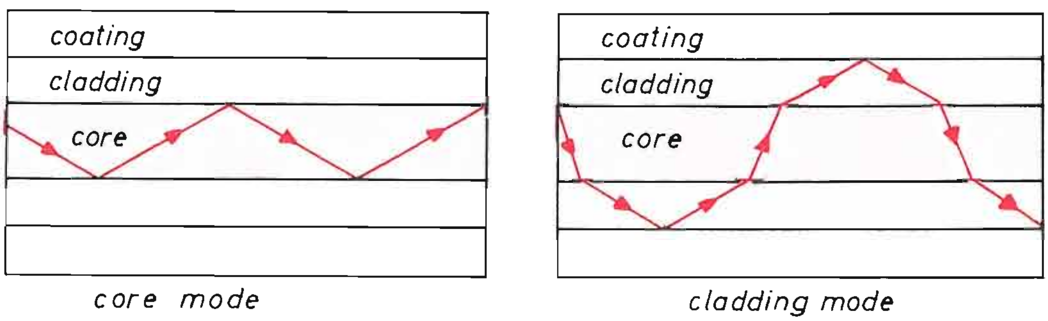
See →noise of the laser diode.

MODE SCRAMBLER

See →mode filter.

MODES IN A FIBER

Electromagnetic light waves propagating in a fiber can be subdivided into low-loss core modes and lossy cladding modes. Leaky modes have characteristics of both of them. The term mode refers to a single electromagnetic wave satisfying Maxwell's equations and the boundary conditions given by the fiber.



MODES IN A STEP-INDEX FIBER

The guiding of core modes can superficially be explained by ray optics and total reflection at the core-cladding boundary. More correctly, the propagation must be determined by wave optics. This concept reveals that all possible beams in a wavefront of one mode must have the same phase in order to propagate along the fiber. This phase condition only allows a limited number N of modes to propagate. N can be calculated using the V-number (also called normalized frequency). For a step-index fiber this relation is set up below. The number N of possible guided modes includes both possible polarizations of one mode.

$$N = V^2/2$$

$$V = \frac{2\pi a}{\lambda} \sqrt{n_1^2 - n_2^2}$$

a - core radius
λ - wavelength in vacuum
n_1 - refractive index of the fiber core
n_2 - cladding index

For a graded-index fiber with parabolic profile, N must be divided by 2.

To find the exact solutions for electric and magnetic fields, Maxwell's equations have to be solved, which leads to complicated HE and EH modes. A practical approximation has been made by introducing the so-called LP modes, LP stands for linear polarized. These modes are transverse electromagnetic waves, in which both the electric and the magnetic fields are perpendicular to the direction of propagation. LP modes exist in fibers with low refractive index contrast $\Delta \ll 1$:

$$\Delta = (n_1^2 - n_2^2)/2n_1^2 \simeq (n_1 - n_2)/n_1$$

All practical fibers fulfil the above condition, which is important to reach high →bandwidth. This can be explained with the →numerical aperture: a low difference in refractive indices results in a small numerical aperture, which only allows small angle deviations from the direction of propagation. Thus the total flight time (see →phase velocity) of different modes (correspondent to different angles) is almost identical, which yields low →multimode dispersion and high bandwidth. Typical Δ numbers are 2×10^{-2} for multimode fibers and 2×10^{-3} for monomode fibers. Those fibers are called weakly guiding.

Another consequence from the low index difference is that each core mode also carries some power in the cladding, which directly follows from the electromagnetic boundary conditions. Thus the cladding must be of good optical quality, too. The power density shows an exponential decay in the cladding. In a monomode fiber the power portion in the cladding is particularly strong.

Except for the so-called fundamental LP_{01} mode (also called HE_{11}-mode), each mode has a certain cut-off wavelength. High order modes have short cut-off wavelengths. Starting from the fundamental mode the next-order mode in a step-index fiber, called LP_{11} mode, can only be guided if the wavelength is shorter than the cut-off wavelenght, or if V is larger than 2.405.

$$\lambda_{cutoff} = 3.7 \ a \ n_1 \sqrt{\Delta}$$

This shows the concept of the monomode fiber: the fundamental mode can always be guided, but guiding of the next order mode is prevented by making $V < 2.405$. From the previous equations we find that with $\lambda = 850$ nm, $n_1 = 1.46$, $\Delta = 2x10^{-3}$ the core diameter must be $2a \leq 7$ µm. At 1.3 µm the same numbers require $2a \leq 10.7$ µm. These small dimensions make it very difficult to couple monomode fibers to light sources (→see coupling efficiency) and to make monomode fiber joints. As mentioned before, the optical power is also transported in the cladding of a monomode fiber, especially due to its very low index contrast.

Light energy can be transported by leaky modes over some distance. They can be characterized by being excited close to but outside of the numerical aperture cone. Some power is transported in the core, some in the cladding. Another characteristic is that these modes don't show the typical exponential power decay in the cladding. Instead the power density is quite evenly distributed in the cladding.

As indicated in the figure, cladding modes are reflected at the cladding-to-coating boundary, then refracted into the core and again refracted into the cladding Because of the larger angles against the fiber axis, cladding modes can easily be located in the →far field taken from the end of a fiber. Some fiber coatings have a higher index than the cladding index. In this case only a small fraction of the light is reflected from the coating. The rest is absorbed in the low-purity coating, which makes these fibers good cladding →mode strippers.

Each of the modes has different propagation constants. The terms "differential mode attenuation" and "differential mode delay" were created to describe this phenomenon. Differential mode delay is the reason for pulse broadening, which is termed →multimode dispersion. The propagation constants of individual modes cannot be measured selectively. Thus the fiber under test should be driven with an →equlilibrium mode distribution, in order to simulate a steady-state modal distribution.

MODES OF A LASER

See →spectrum of a multimode laser.

MODE STRIPPER

For some of the fiber measurements, it is important to remove optical power from the fiber cladding (see →modes in a fiber), in order to analyze the core only.

A 100m-piece of fiber will perform this task, since the attenuation of the cladding modes is much higher than the attenuation of the core modes. In some instances, it is desirable to remove the cladding modes on a short piece of fiber. To do so, all insulation, buffering and coating must be removed from the fiber, and the remaining core and cladding must be immersed in a liquid with higher refractive index than the cladding index, i.e. immersion oil, glycerin, and some epoxy materials. A length of a few centimeters is sufficient.

Some fiber coatings have a larger-than-glass refractive index. In this case the coating itself acts like a cladding-mode stripper.

MODE VOLUME

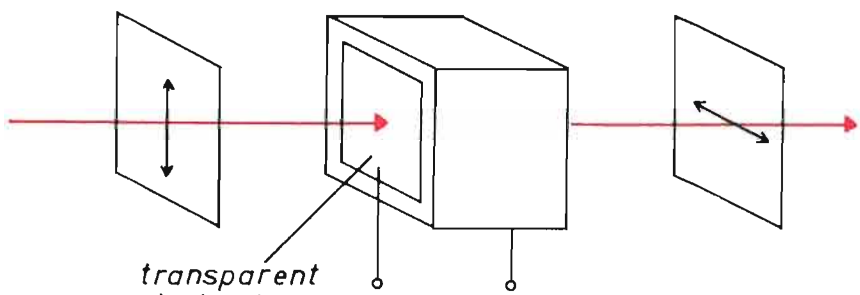
See →effective mode volume, →equilibrium mode distribution.

MODULATOR

Direct light modulation via the laser's drive current causes dynamic effects on the emitted spectrum, such as changes in peak wavelength and in laser modes. The latter effect is particularly strong in monomode lasers. Other light sources, e.g. gas lasers, may not be capable of being modulated at all. This makes external modulators attractive.

Optical modulators are mostly based an either the electro-optic effect (change of the →refractive index or of the →birefringence) or on the magneto-optic effect, e.g. the Faraday effect (change of the plane of polarization). Acousto-optical modulators are also quite popular.
The Pockels cell is the most common optical modulator. It is based on electrically induced →birefringence in certain crystals, which in this case converts plane-polarized light into light of elliptical or circular →polarization, depending on the voltage applied. After adding one polarizer on either side of

the crystal, light can be electrically modulated by changing the shape of the polarization ellipse, see →retarder. When no voltage is applied, no birefringence occurs and the light is extinguished via the two cross-coupled polarizers.



POCKELS CELL MODULATOR

Pockels cells are made in either a longitudinal or transverse fashion. In the longitudinal case the electric field is applied in parallel to the light propagation, thus transparent or ring electrodes are needed. In the transverse case the electric field is perpendicular to the direction of propagation. Pockels cells have been made with bandwidths from DC to beyond 1 GHz in a travelling electric wave fashion. Extinction ratios of 100:1 up to more than 1000:1 have been reached. The disadvantage of the Pockels cell is the high drive voltage required, typically 2000 Volts or more.

Thus the efforts have concentrated on reducing this voltage. One way of achieving this is by using single-mode optical waveguides implanted into materials like lithium-niobate ($LiNbO_3$). This material also exhibits electrically induced birefringence. A practical realization is the Mach-Zehnder interferometric modulator: a single-mode optical waveguide is divided into two branches which are then electrically modulated 180° out of phase. After recombining the two branches, total transmission occurs for equal optical phases (zero Volts drive), and extinction occurs for 180° optical phase difference. These modulators only need below 5 Volts drive voltage. Their disadvantage is the low coupling efficiency to the single mode waveguides and the resulting high insertion loss.

A more thorough description of optical modulators is given in [1] and [3].

MONOCHROMATOR

A monochromator is a wavelength-tunable narrowband optical filter, mostly based on a diffraction grating. Tuning is possible by varying the grating's angle with respect to the light source. Thus spectrum analysis of a light source can be made, or a certain wavelength from a white light source can be selected for test purposes.

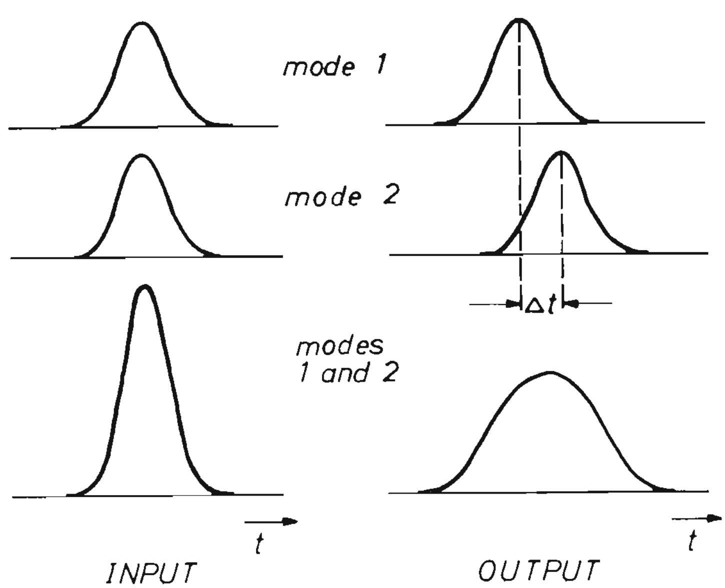
MONOMODE

This term refers to either a monomode →fiber or a monomode →laser diode.

MULTIMODE DISPERSION

Fiber bandwidth specifications refer to multimode dispersion (also called intermode dispersion), which is pulse broadening due to optical power running via different waveguide →modes. In order to calculate the total fiber bandwidth, →chromatic dispersion has to be added quadratically. In case the frequency response behaves like a Gaussian low pass filter, multimode dispersion Δt_{mod} and the 3 dB(optical) multimode bandwidth are related by

$$f_{3dB} = 0.44 / \Delta t_{mod}$$



PULSE BROADENING DUE TO MULTIMODE DISPERSION

In contrast to the figure, step index fibers may contain around 1000 modes, graded index fibers with identical core diameter one half of this, and monomode fibers only one mode.

A typical number for multimode dispersion of step-index fibers is 20 ns/km, corresponding to a 3 dB(optical) bandwidth of 20 MHz km. This can directly be attributed to the difference in path lengths between the fundamental zero-angle mode and the highest order modes. Multimode dispersion in a step index fiber is given by:

$$\Delta t_{mod} = \frac{NA^2}{2nc} \quad L$$

NA - →numerical aperture
n - refractive index of the fiber core
c - speed of light, see →constants

In graded index →fibers the refractive index profile is often optimized in such a way that all the waveguide modes travel at the same effective speed. Accordingly, the multimode dispersion of graded-index fibers can be as low as 50 ps/km, corresponding to a 3 dB (optical) bandwidth of 9 GHz. Practical fibers don't reach this bandwidth due to the problem in exactly controlling the index profile. Also, the optimum profile is wavelength dependent, double-window fibers represent a profile compromise between the best performances at 850 nm and 1.3 µm.

In monomode fibers multimode dispersion and polarization noise (also called birefringence noise) arise from the different speeds of the two possible polarizations of the same mode. This problem can be solved by either preserving the polarization by a special fiber construction, or by spinning the fiber in order to reach uniform propagation constants. 200 GHz x km bandwidth have been reached this way.

Multimode dispersion is measured by launching a narrow pulse into the fiber, typically around 100 ps. The shortest pulses can be generated by →mode locking. The spectral width must be so small, that →chromatic dispersion does not influence the measurement. Generally, multimode →lasers suffice for step-index measurements. Monomode lasers must be used for high-performance graded-index fibers. The launching conditions influence the dispersion measurement, too. Overfilling the core and the numerical aperture is standard. Using the more desirable →equilibrium mode distribution so far shows lower measurement reproducibility.

Mode mixing means transfer of optical power from one waveguide mode into another, to be observed at connectors, splices and in the fiber itself. One practical consequence is the problem in predicting the multimode dispersion of a long fiber. For short lengths, dispersion rises linear with length. Beyond the so-called coupling length L_c, mode mixing causes the dispersion to rise with the square of the length (Ref [6], k is a constant):

$$\Delta t = k\, L^{-1} \qquad \text{for } L < L_c,$$

$$\Delta t = k\, (L_c + \sqrt{L-L_c}\,)^{-1} \qquad \text{for } L > L_c.$$

Step-index fibers have strong mode-mixing, so the square-law holds after only a short length. Modern graded-index fibers have very weak mode coupling, so the square-law is only observed after 2 km, in some cases after 20 km. Another popular approximation to length dependence of the dispersion is

$$\Delta t = k'\, L^{-m}$$

with a typical m = 0.8, varying between 0.7 and 0.9 (k' is a constant). Also a consequence from mode mixing is the problem in predicting the multimode dispersion of a concatenated link made of spliced fibers. Ideal mode mixing at each splice would result in a square law dependence, just like cascading a series of de-coupled low pass filters. Practical concatenated links show dispersion to be somewhere in between linear with length and linear with the square root of length, in which case the above approximation can be used again. Mode mixing at splices leads to the astounding higher bandwidth of a spliced fiber as compared to a one-piece fiber.

MULTIMODE FIBER

All step-index and graded-index fibers except monomode fibers are multimodal. See →fiber.

MULTIMODE LASER

See →laser.

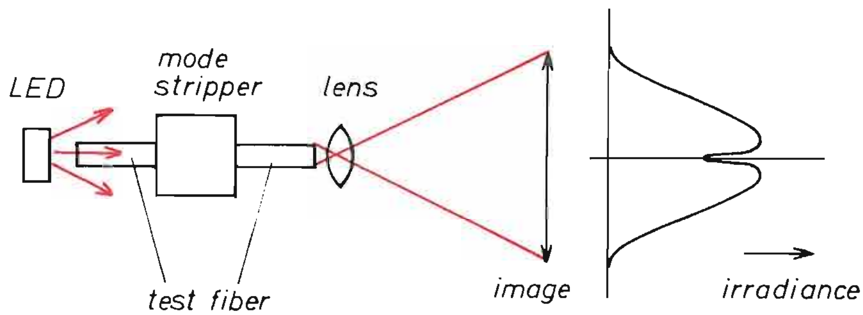
NA

See →numerical aperture.

NEAR-FIELD

This term describes the intensity on the surface of a radiating source such as an LED, laser or the end of a fiber. With near field measurements the refractive index profile of a fiber can be measured. Another application is the determination of the fiber's mode filling (see →effective mode volume).

It can be shown that the transmitted near field intensity of a uniformly filled short fiber (2m) is linearly dependent on the refractive index profile. At the fiber input an LED can be used to overfill the fiber, and a →mode stripper shold be used to remove unwanted cladding modes. Because of the typically very small emitting areas, the near field cannot be measured directly, instead imaging techniques must be applied. A microscope objective with a magnification of 40 to 100 is used to generate a much larger image via projection, in this case of a fiber core. The 50 µm core of a graded-index fiber can thus be converted to a 5 mm diameter image, still being quite small but large enough to be inspected or digitized.



TRANSMITTED NEAR-FIELD MEASUREMENT OF THE INDEX PROFILE

The small index dip at the fiber center is typical for graded index fibers and is related to the specifics of the manufacturing process. Under the influence of non-avoidable leaky →modes the measured intensity profile slightly differs from the refractive index profile. Also, this method does not give a clear indication of the core diameter. Thus the EIA suggests to intersect the measurement curve with a line defined by n_3 and to determine the core diameter from the intersection points.

$$n_3 = n_2 + 0.025\,(n_1 - n_2).$$

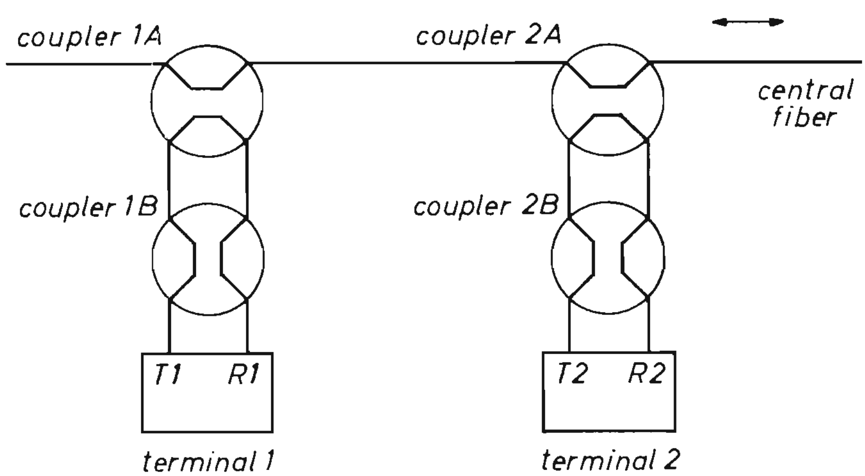
n_1 - maximum refractive index of the core
n_2 - refractive index of the cladding

A more accurate index measurement can be made with the refracted near-field method, in which case a focused laser beam is used to scan the input surface of the fiber. Different from before, the output power distribution of non-captured modes is analyzed.

NETWORK (LOCAL AREA)

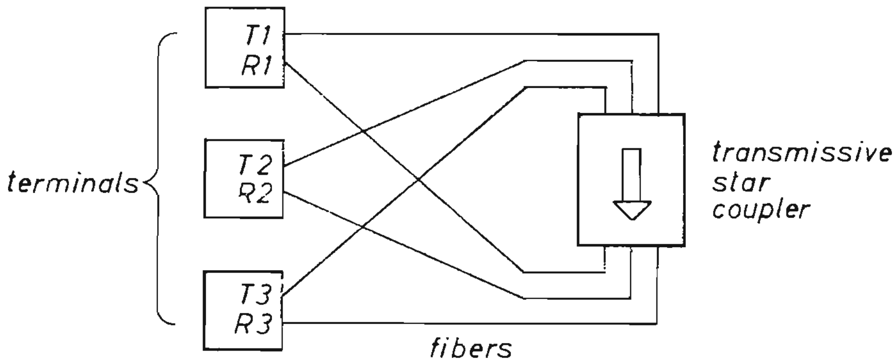
The family of computer networks, industrial control networks, airplane and ship buses, and other short distance - multiuser links is called local area networks. Most of these are still electrical networks. Examples are the IEEE 802 "Ethernet" bus type network and the MIL 1553B twisted pair bus. The reason for the rising interest in optical networks can be found in the advantages of fibers in comparison to electrical cables: noise immunity, freedom from ground loops, high bandwidth and low weight. The information flow design criteria in optical networks do not differ from those in electrical networks. The classical network topologies like bus (also called linear network), loop, star and hybrids of all of them are also possible with fibers, but their implementation is different from electrical networks. This is a consequence from the lack of direct fiber access. Instead, directional →couplers must be used for tapping. These couplers can only receive from or transmit into one direction of the bus.

Here we present two popular network topologies as examples for fiber optical implementations: the bus and the star. Both networks are capable of exchanging information between each of the terminals.



BIDIRECTIONAL BUS-TYPE NETWORK

Since couplers are unidirectional devices, bidirectional transmission can only be achieved by the usage of two couplers at each terminal. Practically the bidirectional scheme causes nontrivial crosstalk problems. Therefore systems employing 2 buses have been proposed, where the information flow on each fiber is always into one direction only. Basically fiber optical bus networks can only be used for a small number of users because of the subsequent coupler losses, when the signal travels along the fiber. The different dynamic range reqirements of the receivers are also a problem.



STAR-TYPE NETWORK TOPOLOGY

The star network requires a higher amount of wiring, but offers a number of advantages. All receiver signal levels would be identical if the fibers would have the same length. Most important, it can accomodate more terminals because of its lower losses. In a star network the power decibels only decay as the logarithm of the number of terminals, whereas in bus network the dependence is linear.

Fiber networks are generally made with large core, large numerical aperture step-index fibers and LED's for simplicity reasons. The lower bandwidth of these fibers is well suited to the required data rates, which usually is a few Megahertz maximum.

NOISE, BIREFRINGENCE

Birefringence noise is only observed in monomode fibers. See →modal noise, →multimode dispersion.

NOISE EQUIVALENT BANDWIDTH

In case of white noise the noise power is proportional to the system's bandwidth. However, the noise equivalent bandwidth B_n is not equal to the signal bandwidth B_s, here defined as the 3dB(electrical)-frequency. Instead, B_n is determined this way: the square of the transfer function is approximated by a rectangle of equal area, with the rectangle height being the maximimun of the transfer curve and the width being the noise equivalent bandwidth. A practical result for systems with 1 pole is

$$B_n = \pi B_s / 2$$

This formula can also be used for Gaussian low pass filters and first order resonant filters.

NOISE EQUIVALENT POWER

See →noise of the pin-diode, →noise of the avalanche photodiode.

NOISE, MODAL

See →modal noise.

NOISE, MODE COMPETITION

For mode competition noise, see →noise of the laser diode.

NOISE, MODE PARTITIONING

For mode partitioning noise, see →noise of the laser diode.

NOISE OF A RECEIVER

See →receiver.

NOISE OF THE AVALANCHE PHOTODIODE

Like in a pin-diode (→noise of the pin-diode) shot noise also exists in APD's. In an →APD, the mean square of the noise current is multiplied with the square of the multiplication factor M. An additional factor F(M) is called excess noise factor and stems from the statistical nature of the multiplication process:

$$\overline{i_n^2} = 2e\, B_n\, I'\, M^2\, F(M)$$

e - electron charge, →constants
I' - original current (before multiplication)
B_n - →noise equivalent bandwidth

With the actual current being I = M I' we get:

$$\overline{i_n^2} = 2e\ B_n\ I\ M\ F(M)$$
$$= 2e\ B_n\ (I_{signal} + I_{dark})\ M\ F(M)$$

I_{signal} - actual current due to signal (after multiplication)
I_{dark} - actual dark current (after multiplication)

For M>50 a coarse approximation for F(M) is

$$F(M) = M^x$$

x = 0.2 - 0.5 for silicon diodes
x = 0.9 - 1 for germanium diodes

I_{dark} defines the smallest detectable power, called noise equivalent power NEP

$$NEP = \frac{1}{r\ M} \sqrt{2e\ B_n\ I_{dark}\ M\ F(M)}$$

$$= \frac{1}{r} \sqrt{2e\ B_n\ I_{dark}\ F(M)\ /\ M}$$

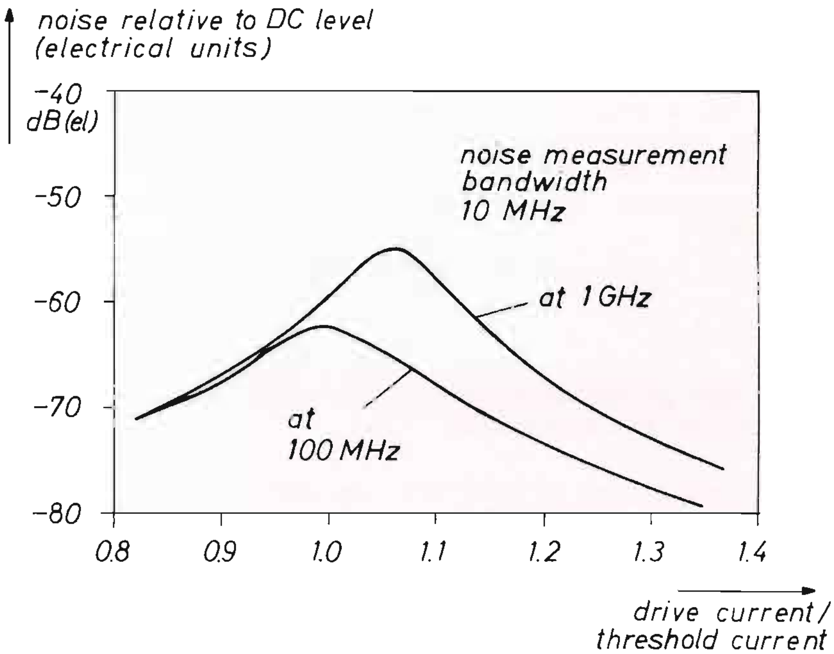
r - primary photodetector responsivity r = 0.8 ηλ/μm, see →quantum efficiency

As I_{dark}/M is identical to the original pin-diode's dark current, the NEP of an APD is higher than the NEP of a pin-diode by F(M). Only in a complete detector-amplifier system the APD shows lower NEP, see →receiver.

Typical NEP's are 5×10^{-14} W/√Hz at 900nm for silicon APD's, and 5×10^{-13} W/√Hz at 1300nm for germanium APD's.

NOISE OF THE LASER DIODE

For laser phase noise see →coherence. The subject of this paragraph is the noise associated with the laser's optical power. It has several reasons. Whenever light is converted to an electrical signal, shot noise is generated (see →noise of the pin-diode). In lasers additional noise is caused by the laser emission process. Typically the noise power increases with rising optical power, reaches a maximum at the threshold level, and decays at higher power levels.



LASER NOISE DEPENDENCE ON DRIVE CURRENT

A third noise generating effect is mode competition noise, also called mode partition noise when determined at the end of a fiber. In a multimode laser all of the longitudinal modes are in competition, so the spectral distribution is time dependent. The normal spectral distribution (→spectrum of the laser diode) is only a time average. Looking at one single mode only, its signal-to-noise ratio SNR can be 30-40 dB (electrical) worse than the SNR of all the modes together. In single mode lasers this effect does not exist. Since each of the modes corresponds to a different colour, →chromatic dispersion of the fiber separates these modes. This not only lowers the system bandwidth, but also increases the noise level, 10 dB (electrical) higher noise level is a typical value for a multimode laser and a graded index fiber of 1 km length.

A fourth effect is optical feedback noise. Light reflected back into the laser (from the fiber input, output or other fiber interfaces) causes the laser oscillation to be disturbed. Monomode lasers (index-guided) are disturbed by only 10^{-4} to 10^{-6} of the generated power, multimode (gain-guided) lasers are sensitive to 10^{-3} to 10^{-4}.

One way to avoid reflections is to use optical isolators. A tapered fiber as an integrated lens is a less effective solution, but has the advantage of good coupling efficiency. Also see →modal noise.

NOISE OF THE PIN-DIODE

The dominant noise source in a pin-diode is shot noise, which is generated by the statistical process of single electrons passing a pn-junction. In a photodetector, this noise is closely related to the statistical arrival of photons at the detector. The mean square noise current i_n is directly related to the diode's average current I:

$$\overline{i_n^2} = 2e\,I\,B_n$$

e - electron charge →constants
B_n - →noise equivalent bandwidth

The current I consists of current related to signal (I_{signal}), and dark current (I_{dark}) (→pin-diode):

$$\overline{i_n^2} = 2e\,B_n\,(I_{signal} + I_{dark})$$

The dark current thus defines the smallest detectable optical power P_{min}:

$$P_{min} = \frac{1}{r}\,(\overline{i_n^2})^{1/2}\quad (I_{signal} = 0) \quad = \quad \frac{1}{r}\,\sqrt{2\,e\,B_n\,I_{dark}}\quad [W]$$

r - responsivity [A/W] (see →pin-diode, →quantum efficiency)

This term, slightly manipulated, is called <u>noise equivalent power NEP</u>. It means a fictitious optical power per square root of Hertz causing the dark current. It is given in many photodiode datasheets.

$$NEP = \frac{1}{r}\,\sqrt{2e\,I_{dark}}\quad [W/\sqrt{Hz}]$$

There is no sense in trying to measure smaller amounts of power than the NEP.

Some typical device characteristics:

For a silicon diode, $1mm^2$ active area, dark current 5 nA, 25°C, 800nm, the NEP is $8x10^{-14}$ W/√Hz.
For a germanium diode, 0.2 mm diameter area, dark current 0.5 µA, 25°C, 1300 nm, the NEP is $1x10^{-12}$ W/√Hz.
For a InGaAs diode, 0.1 mm diameter area, dark current 60 nA, 25°C, 1300nm, the NEP is $2.7x10^{-13}$ W/√Hz.

In a real receiver, noise sources like resistors and transistors increase the NEP (see →receiver).

NOISE, OPTICAL FEEDBACK

For optical feedback noise, see →noise of the laser diode.

NOISE, POLARIZATION

Polarization noise is only observed in monomode fibers. See →modal noise, →multimode dispersion.

NOISE, QUANTUM

See →quantum noise.

NOISE, SHOT

For shot noise, see →noise of the pin-diode, →noise of the avalanche photodiode.

NUMERICAL APERTURE (NA)

For a lens or a fiber, the NA historically is defined as the sine of half the maximum angle of acceptance:

$$NA = \sin \alpha, \quad 2\alpha = \text{full acceptance angle.}$$

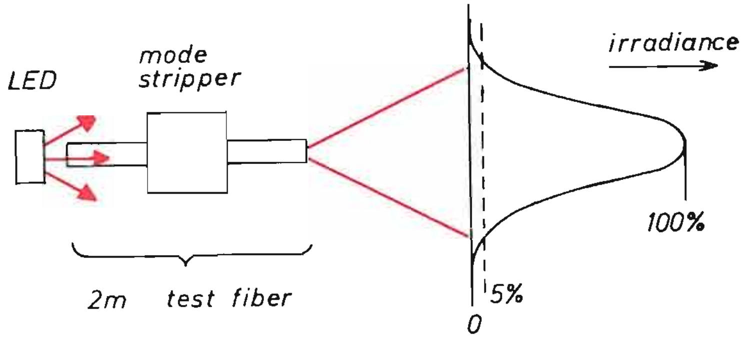
For a fiber, only →meridional rays leading to guided core modes are considered, see →fiber, and →coupling efficiency.

$$NA = \sin \alpha = \sqrt{n_1^2 - n_2^2}$$

n_1 - core refractive index
n_2 - cladding refractive index

For step-index fibers this equation is rather simple. In graded index fibers n_1 depends on the core profile: the largest acceptance angle is measured at the core center. Accordingly, the core center's index must be used to calculate the NA. Typical NA numbers are 0.3 - 0.4 for step index fibers, 0.2 for graded index fibers, and 0.1 for monomode fibers.

As the direction of the light rays is reversible, the NA can also be determined using the maximum →far field angle of the fiber output. Practical measurements are always based on the evaluation of the far field.



NUMERICAL APERTURE MEASUREMENT

Since these measurements do not show a clear cut-off angle, one proposed standard for measuring the NA of graded-index fibers suggests the evaluation of the →far field of a 2m piece of fiber. The sine of the 5% optical power angle, correspondent to -13dB (optical), has been found to be in best agreement with the NA. At the input, the fiber must be overfilled with a large spot size, and a →mode stripper must be used to remove the cladding modes. This resuls in →skew rays being excited, too, but graded-index fibers show smaller than maximum acceptance angles for skew rays. Thus skew rays do not affect the NA-measurement of graded-index fibers.

Step-index fibers have larger acceptance for skew rays than for meridional rays, so this measurement method cannot be applied. In order to only launch meridional rays, a small spot excitation at the center of the fiber has been proposed.

OPTICAL DENSITY

The optical density D characterizes the power budget or power density budget of light when transmitted through a sheet of material at normal incidence.

$$D = \log P_o/P_1$$

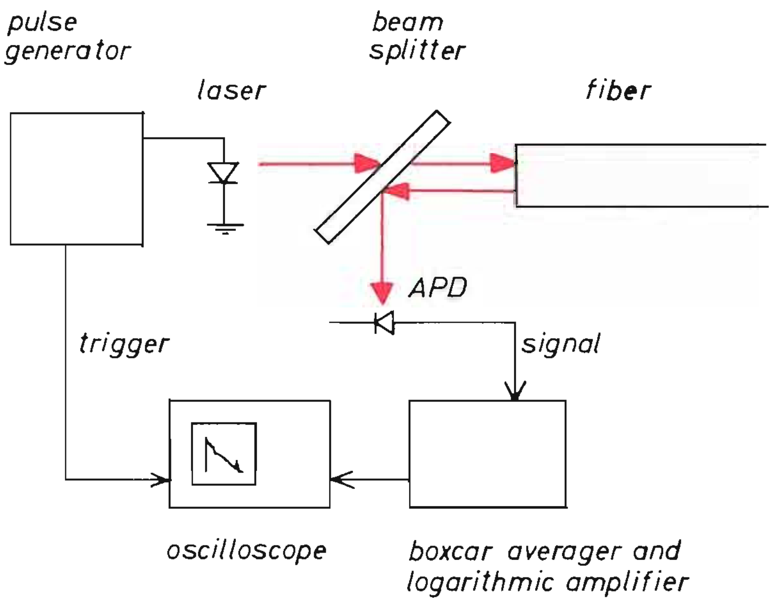
P_o is the input power, P_1 the output power. The associated loss may consist of reflection and absorption. Optical density must be multiplied by -10 to calculate the loss in dB(optical).

OPTICAL FEEDBACK NOISE

See →noise of the laser diode.

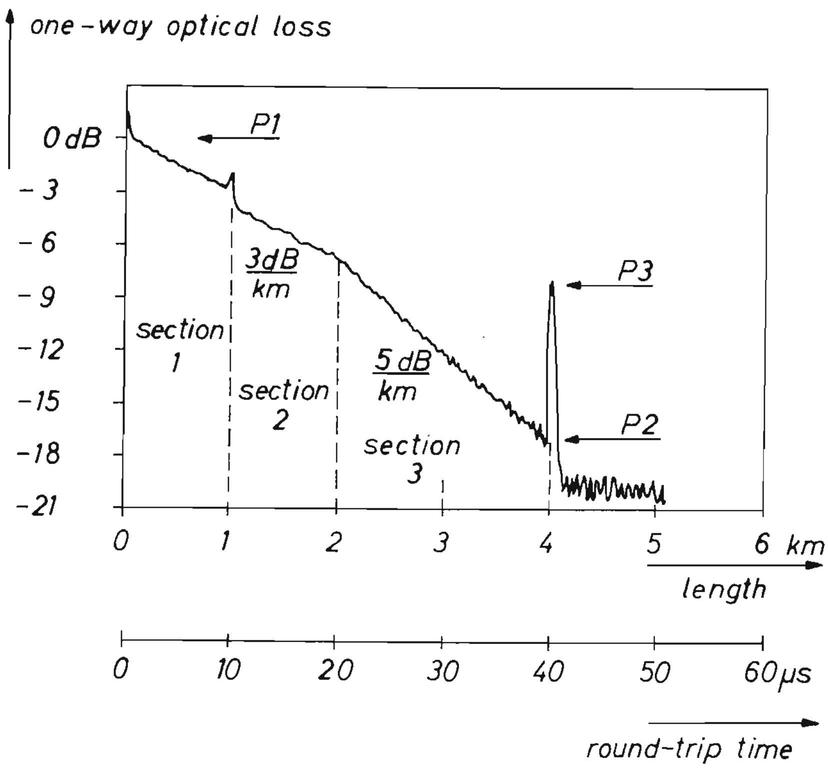
OPTICAL TIME DOMAIN REFLECTOMETER (OTDR)

The OTDR is an important tool to characterize a fiber's attenuation, uniformity, splice loss, breaks and length. Even dispersion can be measured with a suitable, short pulse width OTDR. Its main advantage is one-port operation at the fiber input with no need to access the fiber output.



OTDR INSTRUMENT PRINCIPLE

A typical OTDR arrangement is shown in the figure. A pulse generator drives a laser diode which then launches high power optical pulses (100mW up to several watts) with pulse widths of 5ns up to 100ns and repetition rates of a few kilohertz into the fiber. The signal returning from the fiber is separated from the launched signal by a directional coupler, such as a →polarizing beam splitter or a twisted →pair coupler. An →avalanche photodiode is used as a detector, its signal is fed to a →boxcar averager and then to a logarithmic amplifier. This then drives the vertical amplifier of an oscilloscope. The diagram shows a typical OTDR signal. Vertical scaling is in one-way optical dB. The horizontal scaling was adjusted for a →group index of 1.5.



OTDR SIGNAL FROM A 4km-FIBER

The reflection from the fiber front is the largest signal in an OTDR. If the laser emits polarized light, then the front reflex can be suppressed by using a polarizing →beam splitter. The splitter separates the polarized front reflex and the unpolarized backscattered light. Then the return signal is caused by reflections at imperfections in the fiber (such as bubbles, splices, breaks) and by the →backscattering process.

From the backscattering process we learn that the logarithm of the return signal is linear with respect to length or time for a uniform fiber. The slope is proportional to the attenuation coefficient, assuming otherwise constant fiber parameters.

The shown OTDR signal stems from three spliced fiber pieces being 1 km, 1 km and 2 km long: sections 1 and 2 are of the same type fiber with a total attenuation of 3 dB/km, section 3 is made from a 5 dB/km fiber. At the splice between fibers 1 and 2 a small reflection plus a splice loss of 0.6 dB can be observed. The other splice shows no loss.

According to the →backscattering theory, the starting backscattered power P_1 can be calculated by setting the length parameter $z = 0$:

$$P_1 = \alpha_s \left(\frac{NA}{2n}\right)^2 P_o \frac{w\,c}{2n_{gr}}$$

For symbol interpretation, see →backscattering. For a pulse width w of 10ns, a typical result is $P_1 = 2\times10^{-6}$ of the input power P_o, indicating the need for averaging. The backscattering amplitude P_2 from the end of the fiber, assuming uniform attenuation, results from P_1 and the round-trip loss $2\alpha L$:

$$P_2 = P_1\ 10^{-2\alpha L/10dB}$$

The amplitude P_3 of the fiber end reflection can be calculated from the input power P_o, the round-trip loss $2\alpha L$ and the →reflection coefficient r= 4% for a clean break at the fiber end. Incidentally, 4% is identical to 14dB (optical) signal loss. Also, we assume no amplitude reduction due to fiber dispersion:

$$P_3 = r\,P_o\ 10^{-2\alpha L/10dB}$$

The uncertainty in localizing a fiber problem also comes from the →backscattering theory: the uncertainty is proportional to the width of the launched pulse. For 100ns pulse width, the uncertainty is 10m, or ± 5m.

Results from attenuation measurement by time-domain reflectometry are not identical with those obtained by classical two-port measurements. For example: the OTDR signal may exhibit a step into the positive direction at a location where the fiber's numerical aperture changes. This certainly does not mean a gain in the fiber. Another problem is that the modal distribution of the backscatter signal is different from the →equilibrium mode distribution, which is normally required for attenuation measurements. The big advantage of the backscattering method is the "inside view" of the fiber. Thus many fiber manufacturers measure fiber attenuation by backscattering and by two-port measurement.

Optical time domain reflectometry is also suitable for fiber →bandwidth/dispersion measurements. To do so, a narrow subnanosecond pulse is launched and the pulse width of the end reflection is measured.

Noise and the related difficulty to analyze a long length of fiber are the biggest problems in today's OTDRs. State-of-the-art 850nm OTDRs allow 43 dB (optical) one-way loss, corresponding to 20km of modern, low-loss graded-index fibers, to still detect a clean fiber end. To make fiber end detection possible, the P_3 signal in the diagram must still be clearly distinguishable from noise.

The backscattering signal range (i.e. the range between the P_1 and P_2 signals) is much smaller. For the largest possible backscattering signal one would be tempted to use a large pulse width. On the other hand, this would reduce the length resolution. Thus a pulse-width compromise has to be chosen. The backscattering signal range in commercial OTDR's is not larger than 23 dB one-way loss, corresponding to 10 km, before the signal disappears inside ± 0.1 dB (optical) peak to peak noise. These numbers refer to 100ns pulse width, or a length resolution of ±5 meters. The situation is indicated at the P_2 level in the diagram.

Instead of launching single pulses with high amplitude, a more recent technique uses pseudo-random sequences at the fiber input, in order to increase the total amount of power in the fiber and to get a larger backscattering signal. In this case correlation techniques must be used for signal analysis.

PARAXIAL RAY

A light ray close to and nearly parallel with the optical axis of a lens or fiber is called paraxial. These rays are a special class of the →meridional rays.

PCS

Abbreviation for →plastic clad silica fiber, a fiber with a silica core and a plastic cladding. This construction improves the fiber's flexibility, but increases its attenuation.

PHASE VELOCITY

The speed of light in a medium is called phase velocity v_{ph}, which for a uniform medium is

$$v_{ph} = c/n = \omega/\beta$$

c - speed of light, see →constants
n - refractive index
ω - 2π x optical frequency
β - propagation constant

For glass with n = 1.5 the phase velocity is around 20cm/ns. Phase velocity is different from group velocity, see →material dispersion.

PHOTOCURRENT

Current caused by conversion of photons into electrons in a →pin-diode or in an →avalanche photodiode (APD). Additional current due to multiplication in an APD is not part of the photocurrent, neither is dark current.

PHOTODIODE

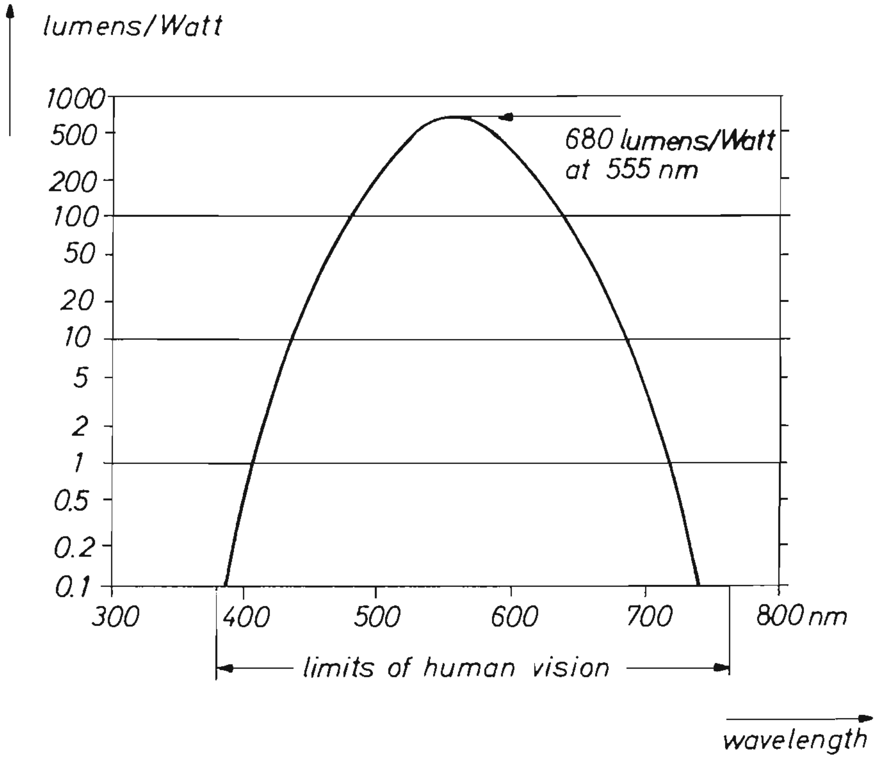
See →pin-diode, →avalanche photodiode.

PHOTOMETRIC UNITS

These units use the human eye as wavelength dependant measurement standard, to convert them to absolute units see below:

Flux	P[lumen]
Flux density	$E = P/A$, [lumen/m²] = [lux]
Intensity	$I = P/\Omega$ [lumen/sr] = [candela] = [cd]
Sterance/luminance	$L = I/A$ [cd/cm²]
Solid angle	Ω = [steradian] = [sr], see →steradian
Area	A[cm²], [m²]

Instead of flux density, luminous incidance can be used in conjunction with a detector, or luminous excitance in conjunction with a light source. Note that instead of these terms most of the optical literature uses the term intensity. The obsolete term brightness was formerly used instead of sterance or luminance.



SENSITIVITY OF THE HUMAN EYE FOR DAY VISION

To convert photometric into radiometric units, use the spectral sensitivity curve. This curve is the standard observer curve for day vision. It is also known as the "photopic curve", which was suggested by the Commision Internationale de l'Eclairage (CIE).

PHOTON

A quantum of light is called photon. Its energy E_{ph} depends on wavelength:

$$E_{ph} = h\ f = h\ c/\lambda$$

h - Planck's constant, see →constants
f - frequency of the light
c - speed of light, see →constants
λ - wavelength of the light

At 850nm, a photon's energy is 23.4×10^{-20} Ws. At 1300nm, the energy is 15.2×10^{-20} Ws.

PHOTOVOLTAIC EFFECT

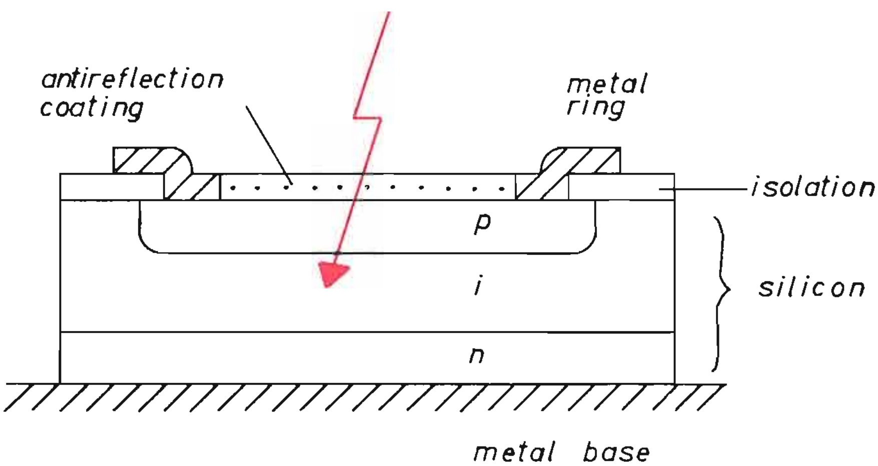
See →pin-diode.

PIGTAIL

For the ease of connection to a fiber, some manufacturers supply sources and photodiodes with a short length of fiber, called pigtail.

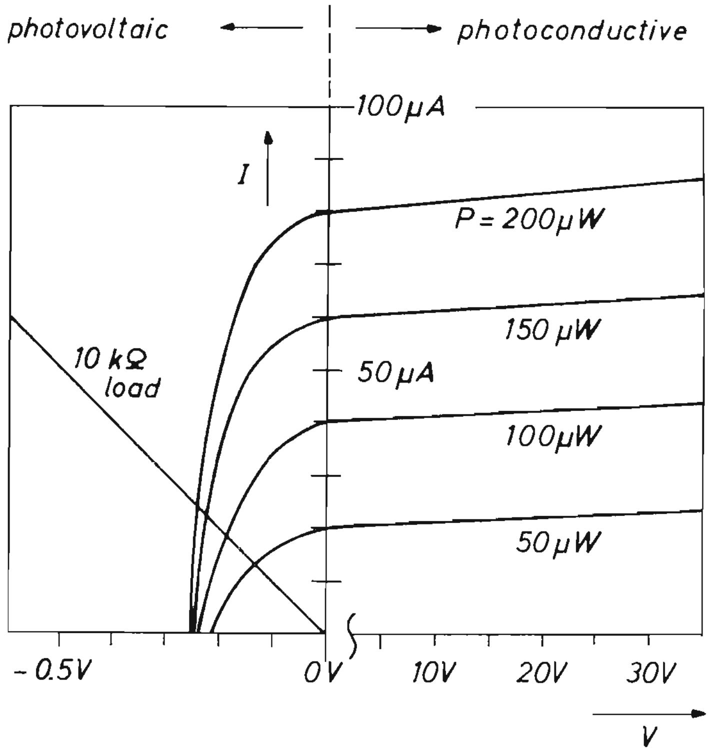
PIN-DIODE

The pin-diode is the most important detector type due to its simplicity, stability and bandwidth. Highly conductive p and n-zones on either side of a low conducting intrinsic zone characterize the pin-diode. Silicon is the common material for the near-infrared (850 nm) - region, whereas Germanium or Indium-gallium-arsenide-phosphide must be used for the region above 1 µm.



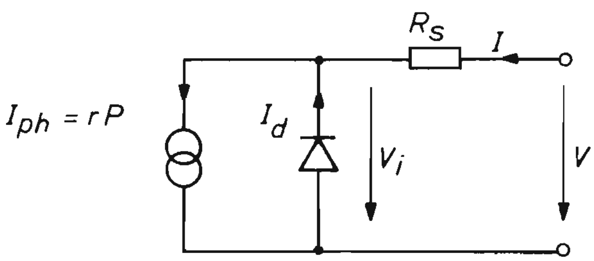
SILICON PIN-DIODE STRUCTURE

Photons enter the i-zone via a connecting metal ring and a shallow p-region to generate electron-hole pairs. The pin-diode is normally back-biased, so the generated charges drift to the p and n zones, being pulled by the electric field in between. A typical pin diode output characteristic shows the two possible operating modes: photoconductive and photovoltaic. Also shown are correspondent load resistors.



PIN-DIODE ELECTRICAL CHARACTERISTIC

The photovoltaic mode refers to operation in the left quadrant with no voltage source required. This mode of operation is indicated by the load resistor in the diagram. There is no current in the "dark" condition, which makes this mode attractive for low light level detection. The figure shows an electrical model of the photovoltaic mode of the pin-diode.



PIN-DIODE MODEL FOR THE PHOTOVOLTAIC MODE

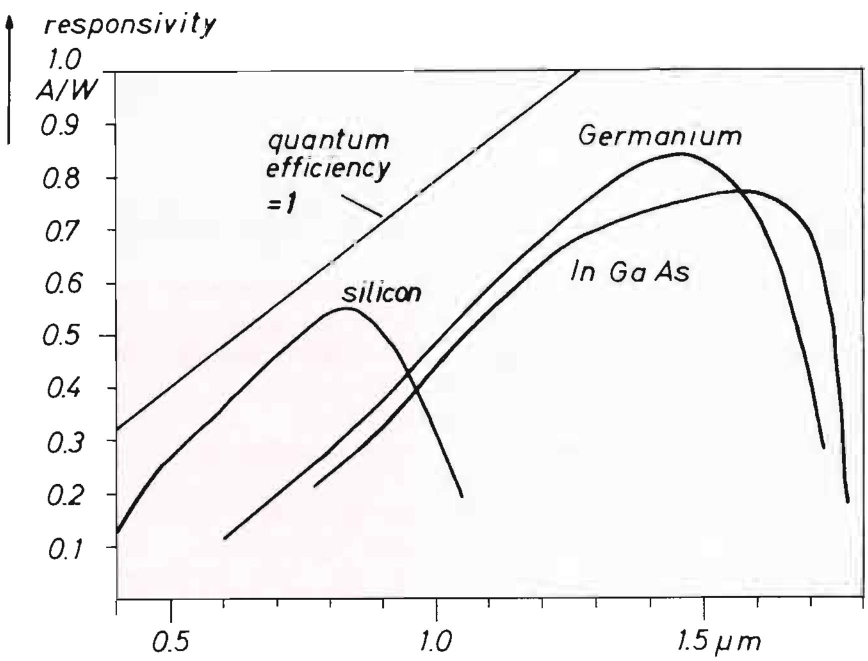
Referring to the model the following equations can be established:

$$I_{ph} = r\,P$$
$$r = 0.8\ \eta\lambda/\mu m$$
$$V_i = -\,V_T \ln(1 + I_d/I_s)$$

r = responsivity, see →quantum efficiency
P = optical power
I_d = diode current
I_s = diode saturation current
V_T = kT/e = 26mV at 300K, see →constants

The model shows the photocurrent I_{ph} being shunted by a normal pn-diode, and an intrinsic series resistor R_s limiting the maximum current from the diode. Typical series resistance is 50 Ω from a 1 mm diameter silicon photodiode. In agreement with this model, the pin-diode generates a voltage which is the logarithm of the incident optical power, if no load resistor is connected. When the diode operates into a short circuit, R_S creates a voltage drop. This starts limiting the photocurrent typically at a power level of 1 mW, depending on the diode's active area. The real drawback of the photovoltaic mode is its lower bandwidth due to much larger capacitance.

In the photoconductive (backbiased) mode a voltage source is applied, which decreases the junction capacitance into the 1pF-range. This mode offers good light-current linearity up to 1 mW optical power for 1 mm diameter silicon diodes. Its responsivity r is identical to the one in the photovoltaic mode. r is either given by a →quantum efficiency number, or directly in [A/W]. Typical values are r = 0.1 - 0.5 A/W, depending on wavelength and detector material, being slightly temperature-dependent.



RESPONSIVITY OF TYPICAL DETECTORS

Unfortunately, a temperature-dependent dark current is also generated, resulting in problems with measuring low light levels, and in extra noise (→noise of the pin-diode). Typical dark current of 1 mm diameter diodes at 25°C are 5 nA for a silicon diode, 12 µA for a germanium diode and 6 µA for a InGaAsP-diode. This is the reason why germanium and InGaAsP-diodes have very small active areas, typically 0.1-0.2 mm in diameter. Temperature-sensitivity of the dark current is very high, it typically doubles every 7°C in silicon, every 8°C in germanium and every 10°C in InGaAsP.

PLANCK'S CONSTANT

See →constants.

PLASTIC CLAD SILICA FIBER (PCS)

A step index fiber made from a silica core and a plastic cladding, such as silicone. The idea of such a fiber is a large core while maintaining a good flexibility. The result is good coupling efficiency and large →numerical aperture, but higher loss. Such a fiber may have advantages up to a link length of a few hundred meters.

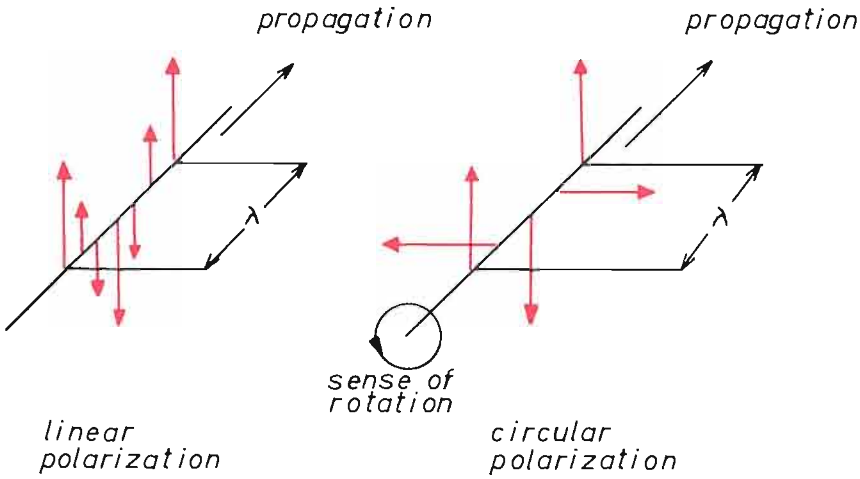
POCKELS CELL

See →modulator.

POLARIZATION

The electromagnetic theory requires the electric and magnetic field vectors of an unbounded wave to be in a plane perpendicular to the direction of propagation. If, additionally, the electric (or magnetic) vector is in only one direction of that plane, the light is called linearly or plane-polarized. A polarizer can be used to distinguish polarized light from unpolarized light.

If the electric field vector rotates by 360° within one wavelength, the light is called circularly polarized. This type of polarization can also be thought of as two orthogonal linear polarizations being 90° out of phase. The figure shows the field vectors of both types at a fixed time. Both of the packages of vectors are travelling at the speed of light c. In order to distinguish light of circular polarization from unpolarized light, a →retarder can be used to reconstruct linear polarization. A more general type of polarization is called elliptical. It is similar to the circular polarization, except the length of the field vector is defined by an ellipse and not a circle. This characteristic can be analyzed with a polarizer.



FIELD VECTORS OF POLARIZED LIGHT

A large number of passive optical components are based on the polarization effect, e.g. →polarizers, →isolators, →modulators, and →beam splitters. By the use of →retardation plates the plane of polarization can be rotated, or linear polarization can be changed to circular and vice-versa.

A polarizer creates linear polarization by transmitting one plane of vibration, whereas the perpendicular plane is more or less suppressed. Polarization can be easily realized by using the reflection from light incidence onto glass oriented at Brewster's angle (see →reflection). A more effective polarizer is a pile of glass plates oriented at Brewster's angle, reference [10]. The amount of polarized light is increased by adding the reflections from each surface. A practical realization is a multilayer dielectric film cemented into glass prisms. This way, high-purity reflection of one plane of polarization is achieved, whereas the other plane of polarization is almost completely transmitted. A variable attenuator can be realized using two polarizers and rotating one polarizer with respect to the other.

A third polarizer type is the calcite (calcium-carbonate) →beam-splitter cube, which is based on the calcite's double refraction effect: the crystal shows different refractive indices for different polarizations of light. This effect is used to construct total reflection for one polarization and total transmission for the other.

A fourth type is realized with plastic dichroic polarizing film by stretching the film into one direction. Thus the molecules are oriented in a special way, which allows only one polarization to pass.

The main quality criterium for polarizers is the extinction ratio. In order to measure it, two polarizers are arranged in series and exposed to light. First the polarizers are oriented perpendicularly, then identically. The ratio of the two transmitted powers is called extinction ratio e. Typical values are $e = 10^{-2}$ for multilayer dielectric films, 10^{-4} for dichroic films and 10^{-5} for calcite cubes.

POLARIZATION NOISE

This effect is only observed in monomode fibers, see →multimode dispersion, →modal noise.

POWER

See →radiometric units.

PREFORM

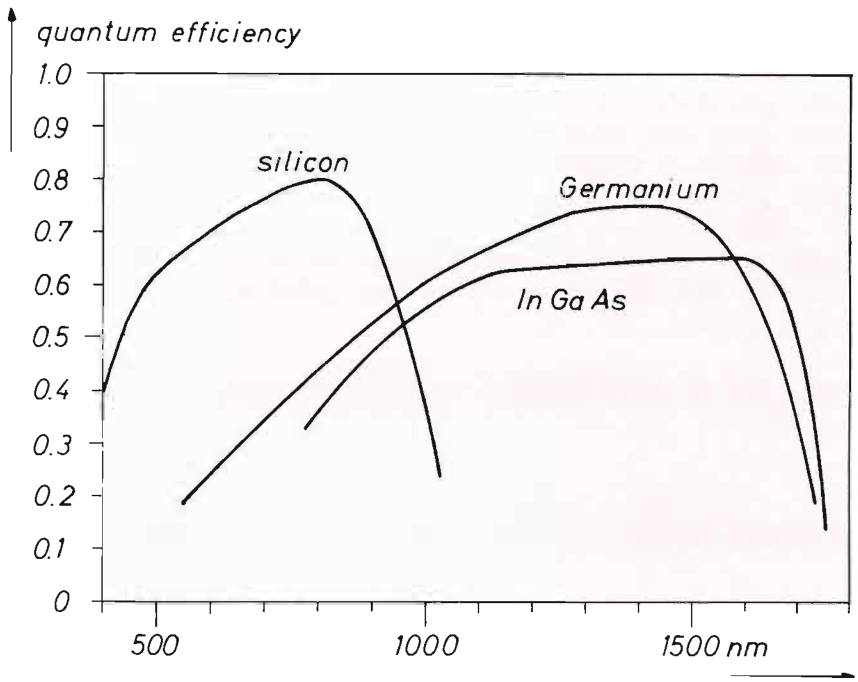
A glass rod from which the final fiber is drawn, made by various techniques, e.g. chemical vapor deposition.

PROFILE

For a fiber's refractive index profile, see →fiber.

QUANTUM EFFICIENCY

In a photodetector the quantum effiency η is the ratio of the number of generated electron-hole pairs to the number of incident photons. As the generation process is of statistical nature, η only describes a time-average. η depends on wavelength, detector material and angle of incidence. It is always <1.



QUANTUM EFFICIENCY OF TYPICAL DETECTORS

The number n_{ph} of photons contained in the optical power P_{opt} during the time t can be calculated with the knowledge of the energy contained in each photon E_{ph}, see →photon.

$$n_{ph} = t\, P_{opt}/E_{ph} = t\, P_{opt}/(h\, f)$$

Each photon statistically generates η electron-hole-pairs in a photodetector. So, the number n_{el} of generated electrons during the time t is:

$$n_{el} = \eta\, n_{ph} = I\, t/e$$

e - electron charge →constants
I - photo current

Now the photodetector's <u>responsivity r</u> (the ratio of generated current to absorbed optical power) can be calculated using the above equations:

$$r = I/P_{opt}$$

$$= \frac{\eta\, e}{h\, f} = \frac{\eta\, e\, \lambda}{h\, c}$$

$$= 0.8\, \eta\, \lambda/\mu m \quad [A/W]$$

The responsivity turns out to be a function of the quantum efficiency and the wavelength only.

QUANTUM NOISE

Quantum noise arises from the discrete nature of light: single photons are generated in a light source at random times. One of the results from the photon statistics is the number of necessary photons to detect a single light pulse in an ideal receiver. For a detection probability of 10^{-9}, 21 photons are needed, assuming a quantum efficiency $\eta = 1$. This is called quantum limit and establishes the ultimate sensitivity of a receiver. Practical systems always operate well above the quantum limit, e.g. at 400 →photons per pulse.

Also see →noise of a receiver, →bit error rate.

RADIANCE

See →radiometric units.

RADIOMETRIC UNITS

These non-wavelength dependent units are mostly used in conjunction with fiber optics, however some LEDs are still specified in photometric units.

power, flux	P[watt]
power density, flux density, irradiance or incidance at a detector, emittance or exitance at a source	$H = P/A$, [watt/cm^2]
intensity	$I = P/\Omega$, [watt/steradian]
sterance, radiance	$L = I/A$ [watt/(ster cm^2)]
solid angle	Ω[steradian], see →steradian
area	A[cm^2]

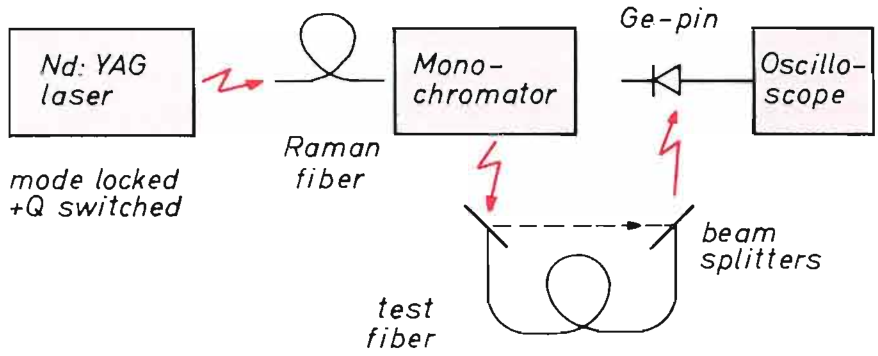
Note that most of the optical literature mistakenly uses the term intensity instead of the correct term power density. Power density H relates to the electric field amplitude E, the material's refractive index n and the characteristic impedance Z_o of vacuum by:

$$H = \frac{n\ E^2}{2\ Z_o}$$

The term brightness is an obsolete →photometric term.

RAMAN DISPERSION MEASUREMENT

The Raman scattering effect was proposed in 1980, reference [4], for the measurement of the →chromatic dispersion of multimode and monomode fibers. Since then this arrangement is used in many laboratories.



DISPERSION MEASUREMENT USING THE RAMAN LASER

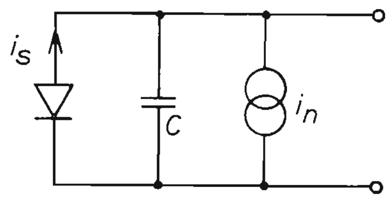
The Nd:YAG laser is mode locked at 100 MHz and Q-switched at 1kHz. It launches optical pulses of 1.06 µm, 1kW power, and 200ps pulse duration into short monomode fiber. In the fiber the 1.06 µm line is converted to a non-uniform spectrum ranging from 1.06 µm up to 1.8µm due to non-linear effects called Raman scattering. This spectrum is then filtered by a monochromator and launched into the long test fiber. Analysis of the pulse delay in comparison to the reference pulse determines the chromatic dispersion, which is the combined effect of waveguide and material dispersion.

Analysis of the output pulse duration also yields the fiber's multimode dispersion, if the launching conditions are carefully controlled and the spectral width is sufficiently small.

RECEIVER

This paragraph describes the realization of practical receivers with special attention to their noise performance.

The photodiode, the conversion resistor and the amplifier contribute to the total noise in an optical receiver. Additionally the received optical power may also carry amplitude noise, such as laser noise, →mode partitioning noise or →modal noise. In agreement with →noise of the pin-diode and →noise of the avalanche photodiode, a common model for both detector diodes can be established.



signal: $i_s = r M P_{opt}$

noise: $\overline{i_n^2} = 2eB_n(rP_{opt} + I_{dark})M^2F_{(M)}$

ELECTRICAL MODEL FOR BOTH PIN AND APD DIODES

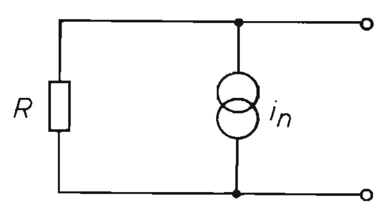
- r - primary responsivity of the photodetector [A/W]
- M - multiplication factor, M = 1 for pin-diodes
- P_{opt} - optical power (signal and bias)
- e - electron charge, see →constants
- B_n - →noise equivalent bandwidth
- I_{dark} - primary dark current (without multiplication)
- $F(M)$ - excess noise factor in APD's, F(M) = 1 for pin-diodes.

The mean square noise term in the figure indicates the statistical nature of the noise current's amplitude. As the noise term is proportional to the →noise equivalent bandwidth B_n, it is called "white" noise. The noise amplitude statistic can be assumed to be Gaussian, with the standard deviation σ being the square root of the noise term. Accordingly the peak-to-peak amplitude is around 6 times σ.

One consequence from the noise term is its dependence on the absolute optical power. This explains why a "one" in a binary sequence is always more noisy than a "zero". It further explains the system designer's desire for a high →extinction ratio, and also why the discriminator level in a system receiver is often set to a more negative level than the →mesial power level.

The resistor model also shows a white noise behaviour. The terms in the figure are:

- k - Boltzmann's constant, see →constants
- T - absolute temperature in Kelvin
- B_n - →noise equivalent bandwidth.

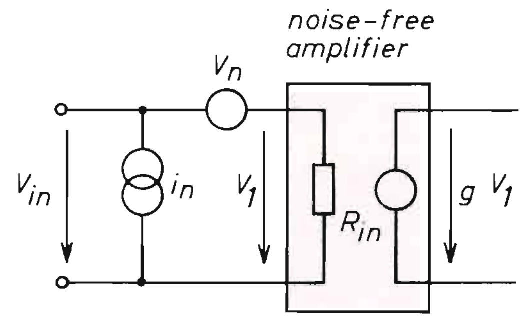


R = noise-free resistor

$\overline{i_n^2} = 4KTB_n/R$

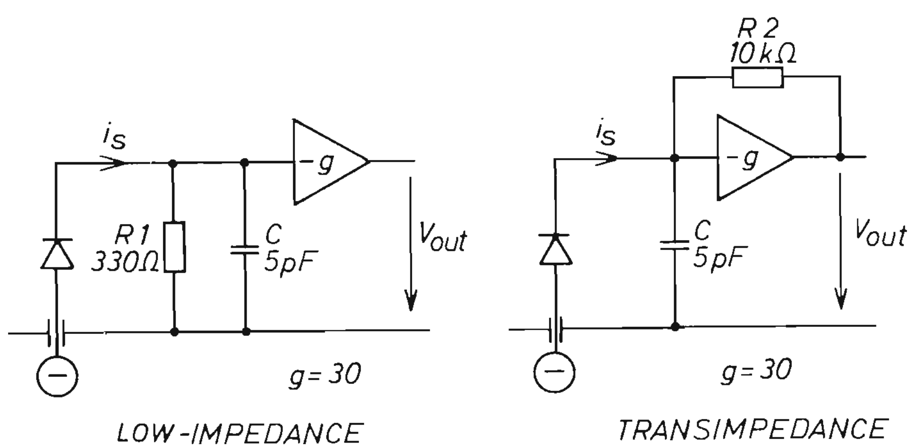
NOISE MODEL OF A RESISTOR

The noise sources of practical amplifiers can be almost completely attibuted to the input stage. These noise sources generally are not white, because all transistors exhibit higher noise intensity at low frequencies, which is called 1/f noise.



NOISE MODEL OF AN AMPLIFIER

As an example we will demonstrate the noise performance of two practical receivers: the low-impedance type, whose bandwidth is determined by the RC input network, and the transimpedance type. The bandwidth of both receivers shall be 100 MHz, suitable for a bit rate of 100 Mbit/s with a non-return-to-zero (NRZ) format.



PRACTICAL EXAMPLES OF CLASSICAL OPTICAL RECEIVERS

For equal bandwidth the conversion resistor has to be made smaller in the low-impedance amplifier than in the transimpedance amplifier: 330Ω versus 10kΩ. This is because the bandwidth of the transimpedance amplifier is determined by the capacitor and the feedback resistor divided by the amplifier's open loop gain. The voltage gain of the common amplifier cell is assumed to be g=30, with the input resistance being infinite. Both cells are assumed to be noiseless. Pin - photodiodes shall be used: r = 0.4mA/mW, M = 1, F(M) = 1. We assume an even distribution of "ones" and "zeros". For the analysis we further set:

P_{opt}("1"-level)	$= P_1$	$= 1\ \mu W = -30$ dBm
P_{opt}("0"-level)		$= 0$
$P_{average}$	$= P_a$	$\simeq 0.5\ \mu W = -33$ dBm
I_{dark}		$= 5$ nA
T		$= 300$ K

Here are the approximate results for the low-impedance receiver:

signal bandwidth	B_s	$= 1/2\pi R_1 C = 96$ MHz
"1" output level	v_1	$= -R_1 g i_s = -R_1 g r P_1 = -4$ mV
noise equ. bandwidth	B_n	$= 1/4R_1C = 150$ MHz
average output noise	$\overline{v_n^2}$	$= g^2 R_1^2 B_n\ [2erP_a + 2eI_{dark} + 4kT/R_1]$
		$= 1.5\times10^{16}[6.4\times10^{-26} + 1.6\times10^{-27} + 5\times10^{-23}]$
		$= 7.4 \times 10^{-7}\ V^2$
input related noise	NEP	$= v_n(RMS)/(grR_1)$
		$= 217$ nW(average) $= -37.7$ dBm
signal/noise ratio	SNR	$= 10 \log (v_1^2/\overline{v_n^2})$
		$= 13.3$ dB(electrical)

In this case the resistor noise dominates the other terms. Instead of 0.5 µW an average power of 1.3 uW (-28.8 dBm) would be needed to achieve an SNR of 21.6 dB(electrical), which is required in a digital binary transmission for a bit error rate of 10^{-9}. See →bit error rate.

The analysis of the transimpedance amplifier yields the following approximate results:

signal bandwidth	B_s	$= g/2\pi R_2 C = 96$ MHz
"1" output level	v_1	$= -R_2 i_s = -R_2 r P_1 = -4$ mV
noise equ. bandwidth	B_n	$= g/4RC = 150$ MHz
average output noise	$\overline{v_n^2}$	$= R_2^2 B_n\ [2erP_a + 2eI_{dark} + 4kT/R_2]$
		$= 1.5\times10^{16}[6.4\times10^{-26} + 2\times10^{-27} + 1.7\times10^{-24}]$
		$= 2.78 \times 10^{-8}\ V^2$

input related noise NEP $= v_n(RMS)/(rR_2)$
$= 41.7$ nW(average) = -43.8dBm

signal/noise ratio SNR $= 10 \log (v_1^2/\overline{v_n^2})$
$= 27.6$ dB(electrical)

Having an SNR which is 14.3 dB(electrical) better than before, the transimpedance amplifier only needs 0.25 µW (-36 dBm) average optical power for the required 21.6 dB(electrical) signal-to-noise ratio. This is due to the lower noise generated by the larger resistor in the transimpedance scheme. In addition to the lower noise, the transimpedance receiver is also more stable and linear, because its parameters are not directly dependent upon the gain of the active components.

Practical receivers use even larger load resistors in order to further reduce the resistive noise. This converts the low-impedance amplifier to the high-impedance amplifier, which has a much reduced bandwidth. Equalization networks must be used to emphasize the high-frequency components of the signal. A disadvantage of the high-impedance amplifier is its integrating behaviour, which requires a larger dynamic range. A high-impedance amplifier reaches a →sensitivity of -40 dBm average optical power for a bit error rate of 10^{-9} at 100 Mbit/s, even when taking the amplifier noise into account.

FET- and bipolar amplifiers in conjunction with pin-detectors perform equally well at 100 Mbit/s: as stated before, the sensitivity is around -40 dBm. Beyond 100 Mbit/s bipolar amplifiers offer the better sensitivity. Below 100 Mbit/s FET amplifiers are preferred: at 10 Mbit/s the FET amplifier's sensitivity can be improved to -55 dBm.

Highest performance systems use APD's instead of pin-diodes. The sensitivity can be improved by another 6 to 8 dB(optical) this way.

Also see →bit error rate (BER).

A much more thorough article about the design of optical receivers can be found in [8].

REFLECTANCE

The ratio of reflected power to incident power, also see →reflection.

REFLECTION

At the boundary of two dielectric media, or of air and a dielectric medium, reflection occurs upon the transition of light. This effect plays a key role in fiber optics.

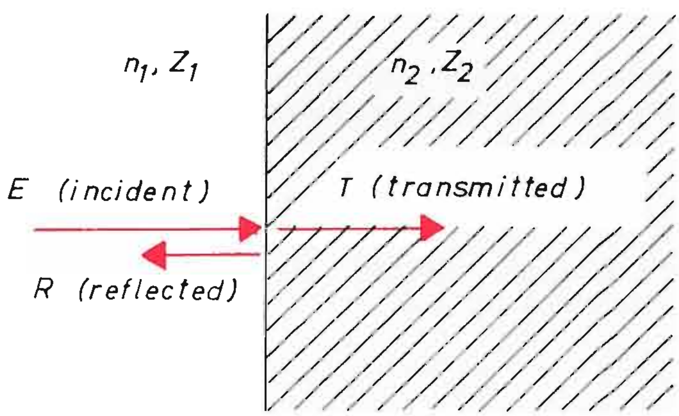
Optical guiding in a →fiber is only possible by total internal reflection at the core-cladding boundary. It thus defines the →numerical aperture of a fiber too. Reflection also causes loss of optical power in various combinations of fibers, and it causes additional →noise when transmitted back to a laser. Dielectric reflection can be utilized to construct partially transparent mirrors for power splitting and monitoring purposes. Also polarizing →beam splitters are based on reflection.

Reflection is mostly treated using Fresnel's laws, see below. Here we present a different approach. The concept of →characteristic impedance, well-known by electronic engineers, can be applied to understand reflection. The characteristic impedance Z_n of an isotropic dielectric is

$$Z_n = Z_o/n, \quad Z_o = 377\Omega$$

Z_o - characteristic impedance of vacuum
n - refractive index of the dielectric material, n = 1 for air, $n \simeq 1.5$ for glass

For normal incidence (beam vertical to the boundary) the classical transmission line theory then provides the amplitude-reflection factor r_A, which is the ratio of the reflected electric field amplitude R to the incident amplitude E.



A RAY OF LIGHT PROPAGATING FROM RARE TO DENSE

$$r_A = \frac{Z_2 - Z_1}{Z_2 + Z_1}, \quad \text{with} \quad Z_1 = \frac{Z_o}{n_1}, \quad Z_2 = \frac{Z_o}{n_2}$$

$$r_A = \frac{n_1 - n_2}{n_1 + n_2}$$

For an air-to-glass transition the amplitude reflection factor is $r_A = -0.2$, indicating a phase change. For a glass-to-air transition we find $r_A = 0.2$ with no phase change. As the reflected power density is proportional to the square of the reflected amplitude, the resulting power-reflection factor r_p (normally called reflection factor r only) is:

$$r_p = \left(\frac{n_1 - n_2}{n_1 + n_2}\right)^2 = r$$

This equation gives the same result for a rare-to-dense or vice-versa transition: for a glass-to-air-transition the reflection factor is 0.04 = 4%, be it external or internal reflection.

At normal incidence, the power densities on either side must be equal:

$$n_2 T^2 = n_1 (E^2 - R^2)$$

Notice that the terms on either side contain their refractive indices. This stems from power density H being defined by:

$$H = \frac{1}{2} \frac{E^2}{Z_n} = \frac{n \, E^2}{2 \, Z_o}$$

E - electric field amplitude
Z_n - characteristic impedance of a dielectric with index n
Z_o - characteristic impedance of vacuum

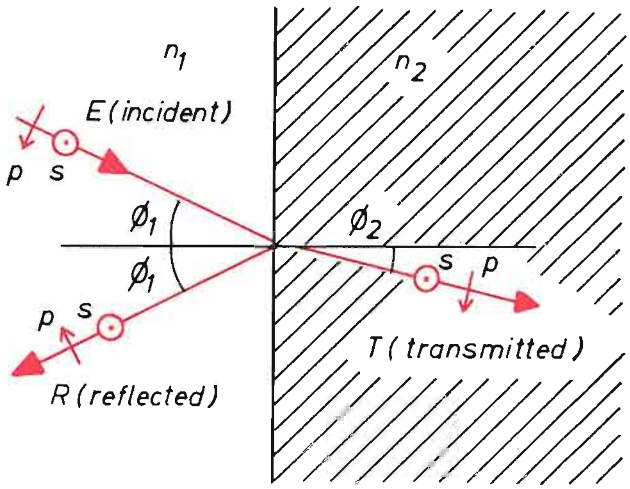
To summarize, the following electric field amplitudes can be found:

$$R = \left|\frac{n_1 - n_2}{n_1 + n_2}\right| E$$

$$T = \frac{2n_1}{n_1 + n_2} E$$

So far, only normal incidence has been considered. For oblique incidence, the transmitted ray path is bent according to Snell's law:

$$n_1 \sin \phi_1 = n_2 \sin \phi_2$$



REFLECTION AND REFRACTION AT OBLIQUE INCIDENCE
(Rare to dense transition)

Total reflection only occurs at parallel incidence ($\phi_1 = 90^o$) for a rare-to-dense transition. For a dense-to-rare transition ($n_1 > n_2$) total reflection occurs when the refracted ray reaches $\phi_2 = 90^o$. For this case the critical angle of total reflection ϕ_c in the dense material can be calculated using Snell's law:

$$\sin \phi_c = n_2/n_1$$

Using $n_1 = 1.5$ for glass and $n_2 = 1$ for air, the critical angle is $\phi_1 = \phi_C = 41.8^o$.

To calculate the intensities for oblique incidence, the light must first be split up into its two planes of polarization: p for parallel to the plane of the paper, s for perpendicular (German: senkrecht). Each of these polarizations reacts different upon the transition. This is described by Fresnel's laws of reflection:

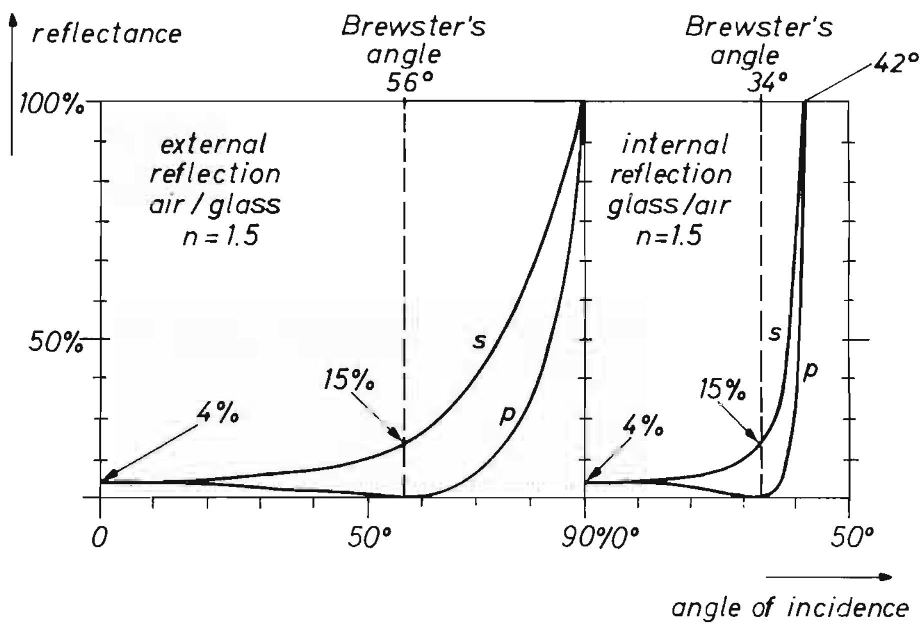
$$\frac{R_s}{E_s} = r_s = -\frac{\sin(\phi_1 - \phi_2)}{\sin(\phi_1 + \phi_2)}$$

$$\frac{R_p}{E_p} = r_p = \frac{\tan(\phi_1 - \phi_2)}{\tan(\phi_1 + \phi_2)}$$

$$\frac{T_s}{E_s} = t_s = \frac{2 \sin \phi_2 \cos \phi_1}{\sin (\phi_1 + \phi_2)}$$

$$\frac{T_p}{E_p} = t_p = \frac{2 \sin \phi_2 \cos \phi_2}{\sin (\phi_1 + \phi_2) \cos (\phi_1 - \phi_2)}$$

Note that E, R and T are electric field amplitudes, not power densities. The evaluation of these formulas shows that the s-polarized part of the reflection is always 180^{o} phase changed. The p-polarized part is not phase changed for small angles of incidence according to the usual convention of positive field vector directions shown in the figure. As before, the actual power densities are proportional to the squares of the amplitudes. The reflection diagram displays power density results. It should be noted that the transmission-line theory can also be applied for oblique incidence.



REFLECTION FROM GLASS/AIR INTERFACES VERSUS INCIDENCE ANGLE

Analyzing the above graphs we find the reflected power being 4% for both internal and external reflection at normal incidence. The two polarizations separate with growing angle, until at Brewster's angle ϕ_B, there is total transmission of the parallel polarization and the reflection is totally s-polarized:

$$\phi_1 = \phi_B = \arctan (n_2/n_1),$$

which follows from the condition $r_p = 0$, yielding $\phi_1 + \phi_2 = 90^o$. A ray of light entering a glass plate at the external Brewster's angle intersects the second surface at the corresponding internal Brewster's angle. Thus a glass plate oriented at Brewster's angle supplies total transmission of one polarization (assuming no absorption). Making the angle even larger increases the reflection, until total reflection is reached. Also see →antireflection coating.

REFRACTED NEAR-FIELD METHOD

A special method for the determination of the refractive index profile and the core diameter of a fiber. See →near field.

REFRACTIVE INDEX (N)

A material's refractive index n is the ratio of the speed of light c in vacuum to the speed of light v_{ph} in the material. v_{ph} is called →phase velocity, also see →material dispersion.

See →fiber and →near field for the refractive index profile of a fiber.

REFRACTIVE INDEX CONTRAST (Δ)

Δ expresses the differences in refractive index of the fiber core center n_1 and the cladding n_2:

$$\Delta = (n_1^2 - n_2^2)/2n_1^2 \simeq (n_1 - n_2)/n_1$$

This number has a strong influence on the fiber →modes, and thus also influences →multimode dispersion.

REFRACTION

The paragraph →reflection also treats refraction.

REPEATER SPACING

A large repeater spacing is the prime motivation for the installation of fiber optic communication systems. We will use an example to show the calculation of repeater spacing in an attenuation limited digital system. In such a system the receiver performance is not influenced by the dispersion of the fiber. This situation is typical for many of today's commercial fiber systems. Our system utilizes a laser diode source, a graded index fiber, and a receiver with an avalanche photodiode (APD).

power into the fiber (2mW)	+ 3 dBm
receiver sensitivity (100 Mbit/s)	- 50 dBm
attenuation of 2 connectors	4 dB
system margin	5 dB
attenuation between repeaters	41 dB
fiber attenuation (850 nm)	3 dB/km
splice attenuation (1 splice / km)	0.3 dB/km
reserve for repair splices	0.3 dB/km
cable attenuation	3.6 dB/km
repeater spacing 41/3.6 =	11.4 km

This is a typical repeater spacing for systems using the 850nm wavelength. An improvement of a factor of 4 is possible by switching to 1300nm.

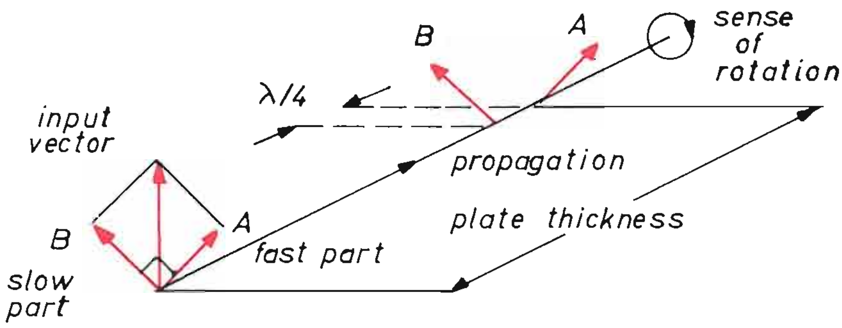
RESPONSIVITY

The responsivity of a detector is the ratio of its output current to the input optical power. The term sensitivity is a formerly used obsolete term for responsivity. See →quantum efficiency.

RETARDER

Retarder plates are made from materials showing →birefringence such as calcite. This effect causes different polarization orientations to travel at different speeds inside the crystal, whenever the direction of propagation is perpendicular to the optic axis.

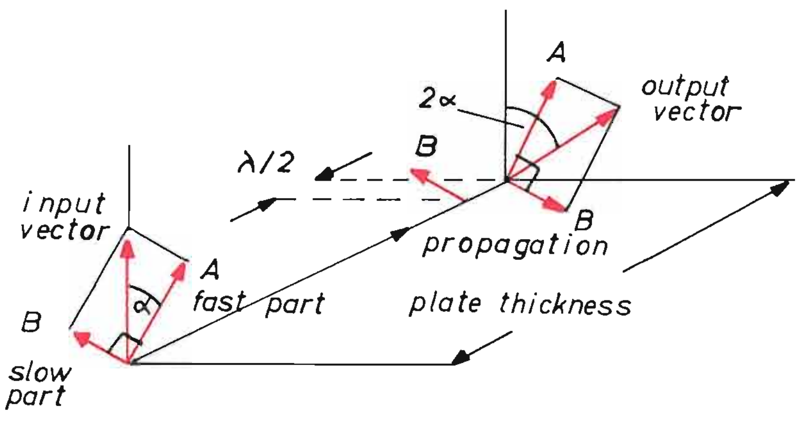
A quarter-wave retarder can convert linear →polarization to circular polarization (or vice-versa). To do so, the polarization of the input beam must be oriented in such a way that it can be mathematically split up into two beams of equal amplitde but orthogonal polarizations, one being in the slow direction (ordinary ray in calcite), one being in the fast direction (extraordinary ray in calcite).



FUNCTION OF A QUARTER-WAVE RETARDER

The figure shows how the two input polarizations are separated in time, until at the end of the plate they have a quarter wave difference. This is the characteristic of circular polarization. Elliptical polarization results from other-than-45° orientation or other-than-quarter wavelength thickness. The quarter-wave retarder can be used to build →isolators.

A half-wave retarder rotates the plane of polarization by 2α, if α is the angle between the plane of the input polarization and the "fast" plane of the crystal.



FUNCTION OF A HALF-WAVE RETARDER

The illustration shows the B-part being rotated by 180°, whereas the A-part has kept its orientation. This corresponds to the mentioned 2α-rotation of polarization. Rotating the crystal results in a twice as large rotation of the polarization.

RMS PULSE DURATION

See →root-mean-square pulse duration.

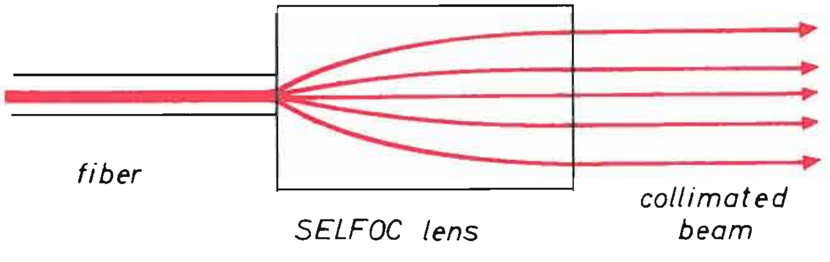
ROOT-MEAN-SQUARE PULSE DURATION

This term describes the 1/e - pulse duration of a →Gaussian pulse, which is slightly smaller than the full width at half maximum pulse duration.

SELFOC LENS

SELFOC is a tradename of the Nippon Sheet Glass Co. Their lenses are actually rod lenses with a graded refractive index profile. They are increasingly used instead of conventional spherical lenses for various fiber optical imaging tasks. The reasons for this popularity are small size relative to numerical aperture, flat surfaces and the possibility to permanently attach a fiber to one of the surfaces (due to the focal point being on the surface). It should be noted that the imaging quality of Selfoc lenses is inferior to the one of good spherical lenses, since the index profile cannot be as perfectly controlled as the radius of a spherical lens.

While in a conventional lens the ray refraction is at the lense's surface only, a SELFOC lens is based on internal ray bending. This is caused by a refractive index which decreases quadratically with the distance from the lens axis. The lense's numerical aperture also decreases with the distance from the lens axis. Thus the lens resembles a graded index fiber. A certain wavelength dependence arises from the lense's material dispersion.



BEAM COLLIMATION UTILIZING A QUARTER-PITCH SELFOC LENS

The sketched beam collimation is achieved by careful control of the lense's length, which is quarter of a total ray cycle in this case. When the beam direction is reversed, a collimated beam can be focused onto a fiber or a small-area detector. Two of these lenses may form a connector which is insensitive to radial and axial misalignments.

SELFOC lenses are normally available in multiples of quarter pitches. For example, a point source can be converted to a point image with a half-pitch lens. For the imaging of a semiconductor laser a certain spacing to the lens is mandatory. Shorter than quarter pitch lenses are used for this task. In conjunction with a semitransparent mirror SELFOC lenses can be used to build fiber power splitters. They can also be used together with colour-selective filters to build wavelength-division multiplexers.

Typical SELFOC data are: diameters 1 - 2mm, quarter pitch lengths 3.3 - 6.5mm, numerical apertures 0.37 - 0.46. Low reflectance surface coating can also be supplied.

SENSITIVITY

The sensitivity is the minimum optical power (time-average) at the →receiver input, which is required for the proper function of the system. Don't confuse this term with →responsivity.

SHOT NOISE

See →noise of the pin-diode, →noise of the avalanche photodiode.

SIGNAL-TO-NOISE RATIO

See →receiver and →bit error rate.

SINGLE MODE

Synonym for monomode. See →fiber, or →laser diode.

SKEW RAY

Generally rays are not parallel and not intersecting the symmetry axis of a lens or fiber. These rays are called skew rays in contrast to the →meridional rays. Rays of this nature may lead to incorrect results when measuring →numerical aperture.

SNELL'S LAW

See →reflection.

SOLID ANGLE

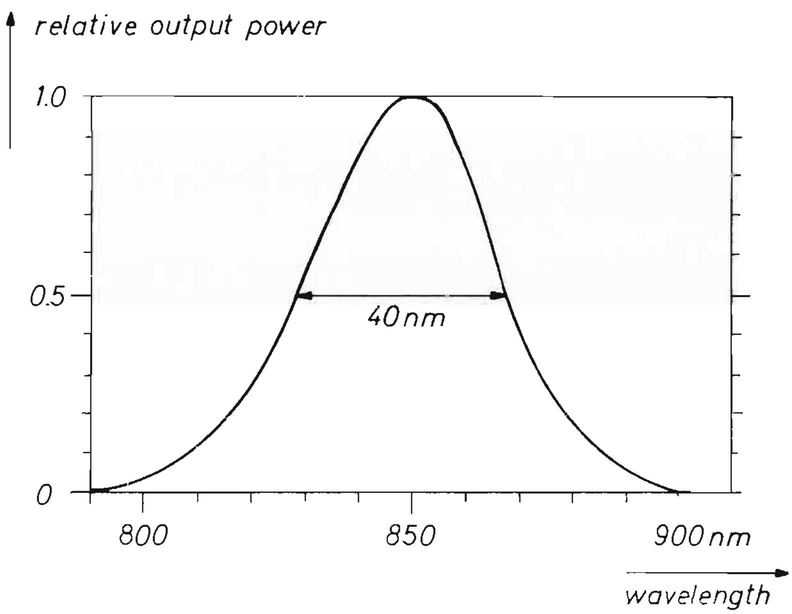
See →steradian.

SPECKLE PATTERN

See →modal noise, →coherence.

SPECTRUM OF AN LED

In contrast to the laser diode, an 850nm LED has a continuous spectrum with a full width, half maximum of 30-50 nm. 1300nm LED's have a spectral width of 80 to 100nm.

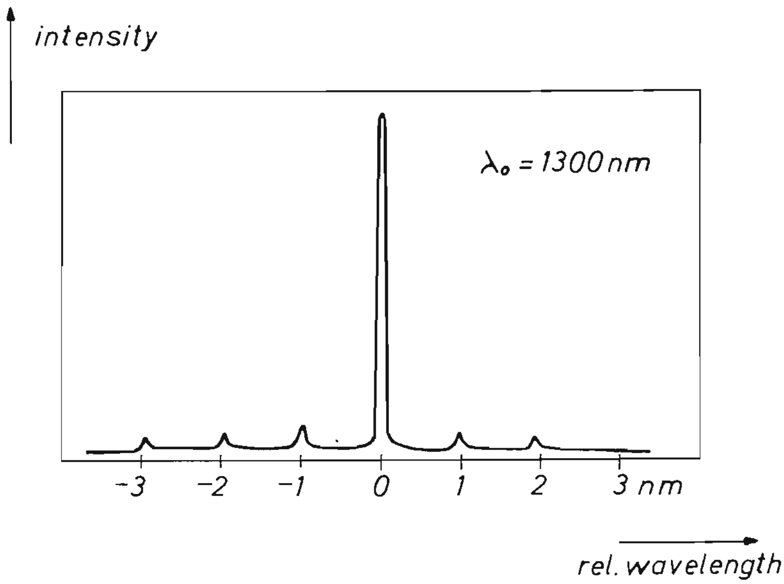


SPECTRUM OF AN 850NM LED

This limits fiber system bandwidth due to →chromatic dispersion, in addition to the LEDs inherent low bandwidth. On the other hand, →modal noise and →mode partitioning noise do not exist in LED systems.

SPECTRUM OF A MONOMODE LASER

Monomode lasers, usually of the index guided type (see →laser), show essentially one monochromatic line with a linewidth $\Delta\lambda$ of less than 0.01 nm, corresponding to a line bandwidth of around 1 GHz. Even less than 100 MHz was observed.



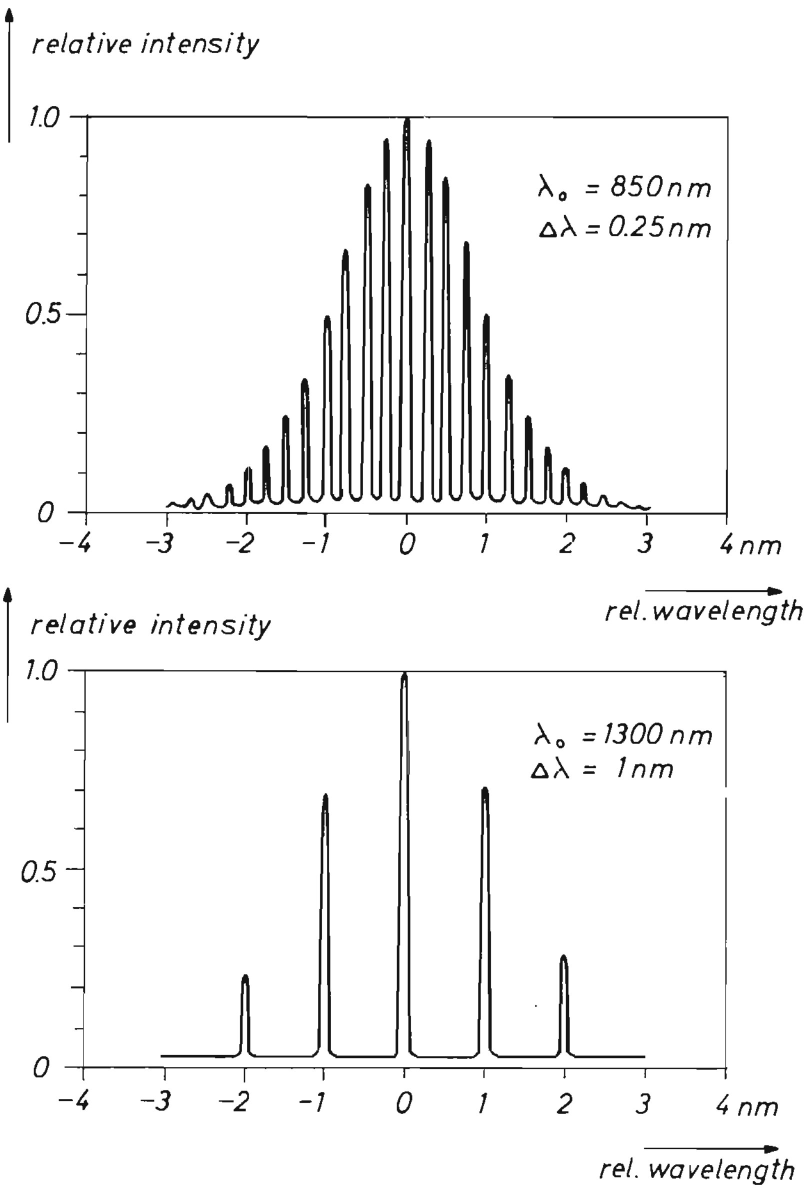
MONOMODE LASER SPECTRUM

Adjacent modes have very low amplitude as compared to the main mode. However, the laser needs some time to establish its mode equilibrium. In a pulsed application the monomode laser looks like a multimode laser (→spectrum of a multimode laser) during the first 1-2 nsec. This decreases the monomode lasers performance in high speed digital systems, because it then has some of the disadvantages of multimode lasers (see →noise of a laser, →chromatic dispersion).

SPECTRUM OF A MULTIMODE LASER

The peak wavelength of a laser is determined by its material (see →LED), whereas the fine structure is formed by its geometry. Typical GaAlAs lasers of the double-heterostrucure type with gain guiding (see →laser) show 10-20 longitudinal modes with a typical overall spectral width between 2 and 5 nm and a line spacing of about 0.2 nm.

Indium-gallium-arsenide-phosphide lasers typically exhibit a line spacing of 0.8 nm.



MULTIMODE LASER SPECTRA

The spacing is determined by the difference in wavelength of two adjacent modes leading to an integer number m of wave cycles inside the round-trip cavity length L:

$m\ \lambda_{c1} = 2L$ (mode no. m)
$(m + 1)\ \lambda_{c2} = 2L$ (mode no. m + 1)

λ_c - wavelength inside the laser cavity, $\lambda_c = \lambda/n$
n - refractive index inside the cavity

From these equations, the mode spacing $\Delta\lambda$ between two adjacent modes and the corresponding frequency difference are:

$$\Delta\lambda \simeq \lambda^2/(2L\ n^2)$$

$$\Delta f = c\Delta\lambda/\lambda^2 = c/(2L\ n^2)$$

The overall spectral width is determined by the quality of the guiding of the electromagnetic field inside the cavity, the two classical guiding types are index-guiding (narrow width) and gain-guiding (wide width) (see →laser).

The center frequency of a 850nm laser is f_c = 350 THz. The line spacing differential frequency using $\Delta\lambda$ = 0.2 nm is typically Δf = 80 GHz, and the typical overall spectral bandwidth B, using a total line width of 3 nm, is B = 1.2 THz. The typical width of a single longitudinal line is less than 0.01 nm, corresponding to around 1 GHz, sometimes even as low as 100 MHz.

Spectral analysis of the line spacing can be made with good monochromators, while the width of a single line can only be measured with an interferometer.

SPLICE

Two fibers can be permanently joined together by splicing. This is mostly done by arc welding or optical cementing. Typical splice loss is 0.2 dB (optical) for graded-index fibers.

STAR COUPLER

See →coupler.

STEADY-STATE-DISTRIBUTION

See →equilibrium mode distribution.

STEP-INDEX FIBER

See →fiber.

STERADIAN (UNIT SR)

The radiation characteristics of optical components are expressed in terms of the solid spherical angle Ω. Its unit is steradian, which is defined by an area of A of $1cm^2$ on the surface of a sphere with the radius r of 1cm. The largest possible angle is defined by a whole sphere: 4π sr

$$\Omega = A/r^2, \quad \text{unit steradian [sr]}$$

For small angles, the conversion from linear angle ϕ to spherical angle Ω is:

$$\Omega = \pi \sin^2 \phi$$

See →radiometric units, →photometric units, and →coupling efficiency.

STERANCE

See →radiometric units, →photometric units.

SUNLIGHT

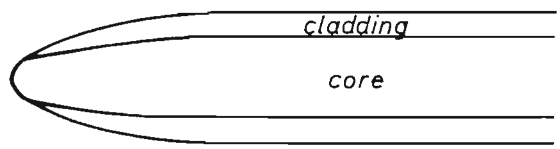
For a comparison with other light sources we give some characteristics of sunlight. On a clear day at vertical incidence, the sunlight intensity is around 90 mW/cm^2, and its spectrum ranges from 300 nm up to 2000 nm with a peak at 480 nm.

TAP

A tap is a device to couple a fraction of the optical power from a fiber to a receiver or monitor. See →coupler.

TAPERED FIBER

Fiber tapering is sometimes done in order to increase the →coupling efficiency to a laser. It has the additional advantage of low reflection, thus providing lower →noise of the laser diode. The higher coupling efficiency can be explained by the increase in →numerical aperture.



INTEGRATED LENS UTILIZING A TAPERED FIBER

A fiber taper can be made by pulling a fiber under heat exposure, e.g. using a splicing apparatus. The tapered section is then broken and once again heat treated to form the lens.

TEE COUPLER

See →coupler.

TE MODE

Abbreviation for transverse electric →mode. The electric field of this mode is perpendicular to the direction of propagation. In a fiber →meridional rays correspond to either TE or →TM modes.

TEM MODE

Abbreviation for transverse electromagnetic →mode. Both the electric and the magnetic field vectors are perpendicular to the direction of propagation.

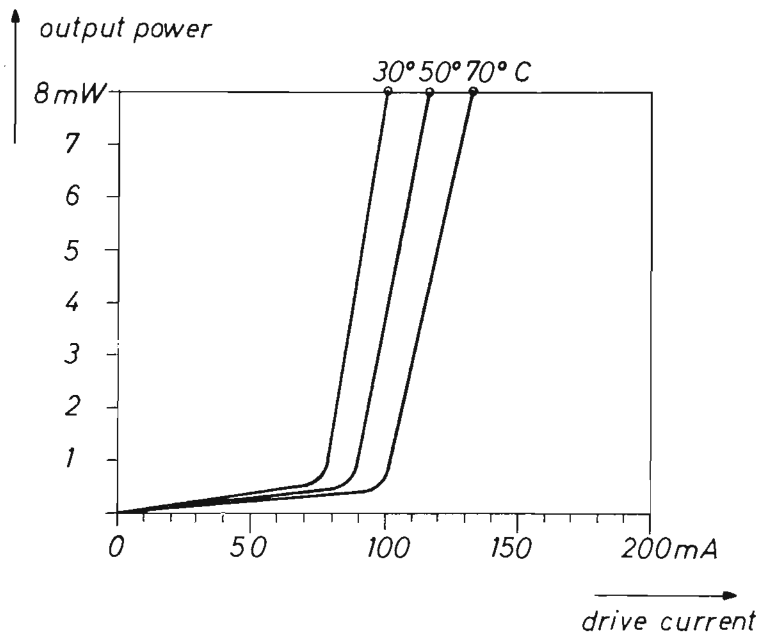
TEMPERATURE DEPENDENCE OF THE LASER DIODE

Temperature has a large effect on the laser diode. In 850nm lasers the differential gain is lowered by typically 0.8% per ^{o}C. The threshold current typically rises by 1% per ^{o}C heatsink temperature. In 1300nm lasers the threshold current rises around 2% per ^{o}C. The temperature dependence of the threshold current is sometimes expressed in terms of the characteristic temperature T_o:

$$I/I_o = \exp(T/T_o) \quad \text{, leading to:}$$
$$\Delta I/I = \Delta T/T_o \; .$$

I_o - original bias current
I - bias current at elevated temperature
ΔI - change in bias current to maintain the optical power
T - temperature
ΔT - change in temperature

For 850nm GaAlAs-lasers T_o is typically 150° Kelvin. For 1300nm GaInAsP-lasers T_o is around 60° Kelvin.



EFFECT OF TEMPERATURE ON THE LASER DIODE

The wavelength is temperature-dependent, too. It typically increases by 1nm per 3°C for a 850nm laser. In order to reduce these effects, the laser heatsink is often temperature-stabilized using Peltier-type thermoelectric coolers. Temperature rise also occurs due to the laser's internal power dissipation, causing a droop when driven with a step-function pulse.

TEMPERATURE DEPENDENCE OF THE LED

In →temperature dependence of the laser diode, the characteristic temperature model was established. This model and the characteristic temperature values can be used for LED's, too. Accordingly, the additional current needed to maintain the optical power is 0.8% per °C in 850nm-diodes, and around 2% per °C in 1300nm LED's.

THRESHOLD CURRENT

See →laser diode.

TM MODE

Abbreviation for transverse magnetic →mode. The magnetic field of this mode is perpendicular to the direction of propagation. In a fiber, →meridional rays correspond to either TM or →TE modes.

TRANSIMPEDANCE AMPLIFIER

See →receiver.

UNITS

1 Farad	=	1 s/Ω	(second/Ohm)
1 Ω (Ohm)	=	1 V/A	(Volt/ampere)
1 coulomb	=	1 As	(Ampere second)
1 Henry	=	1 Ωs	(Ohm second)
1 joule	=	1 Ws	(watt second)
1 W (watt)	=	1 V A	(volt ampere)
1 Angstroem	=	10^{-10} m	(meter)
1 µm	=	10^{-6} m	
1 mm	=	0.001 m	
1 cm	=	0.01 m	
1 inch	=	2.54 cm	(centimeter)
1 foot	=	30.5 cm	
1 mile	=	1.6093 km	(kilometer)
1 newton	=	0.102 kp	(kilopond)
1 dyn	=	1.02×10^{-6} kp	
1 erg	=	10^{-7} joule	
	=	10.2×10^{-9} kp m	
1 pound	=	0.4536 kg	(kilogram)
°Celsius (centigrade)	=	(°F - 32) x 5/9	
Kelvin	=	°C + 273.16	

To convert lumen into Watt see →photometric units.

WAVEGUIDE DISPERSION

Being part of the →chromatic dispersion, waveguide dispersion is pulse broadening in a fiber due to finite spectral width of the light source, even when the fiber's refractive index is assumed to be constant. The reason is that the geometry of the fiber causes the propagation constant of each mode to change if the wavelength changes.

In graded-index and step-index fibers waveguide dispersion can be neglected. It can only be observed in monomode fibers. A typical waveguide dispersion value of a monomode fiber is -2ps/km nm at 1300nm. A practical consequence from this is a shift of the zero dispersion point of a monomode fiber: if the fiber shows zero material dispersion at a wavelength of 1.30 µm, the net chromatic dispersion may be zero at a wavelength of 1.33 µm.

Don't confuse this term with →multimode dispersion.

WAVELENGTH DIVISION MULTIPLEXING (WDM)

The information capacity of a fiber system can be increased by transmitting more than one colour. Suitable →couplers must be utilized at the input and filtering is required at the output. Filtering is mostly achieved with either interference filters or diffraction gratings. Quite often, one colour is used for the transmission into one direction and a second colour for transmission into the opposite direction. Typical wavelength sets are 850 nm plus 1.3 µm, but systems using 4 colours with a spacing of only 30 nm have also been published.

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Please take a few minutes to complete and return the questionnaire below.

Your instant response is highly appreciated because it will help us to identify and design the products that you need for your applications.

Thank you!

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FIBER OPTICS TEST QUESTIONNAIRE

1) APPLICATION FIELD

- ○ Components, Fibers, modules
- ○ Local Area Network
- ○ Communication (<100 km)
- ○ Aerospace
- ○ Computer interface
- ○ Machine control / Industrial automation
- ○ Communication (0.1 to 10 km)

others: ______________________

2) a) MAIN MEASUREMENTS (Most frequent in my specific application)

____

____

b) TEST EQUIPMENT USED: ______________________

____

3) MAIN MEASUREMENT PROBLEMS (Most difficult to do)

____

____

4) TECHNICAL INFORMATION

Wavelength used: ________ Signal transmitted: ○ digital ○ analog

Modulation Frequency: _____ Typ. System Length: ______________

Power Level in: ________ out: ________ Connector used: ________

Transmitter

Laser ○ Monomode ○ Multimode

LED ○ Surface ○ Edge Emitter

○ Super Radiant

Receiver

○ PIN ○ PIN-FET ○ APD

Sensitivity: ______________

Dynamic: ______________

Fiber Characteristics: ______________________

5) FUTURE NEEDS FOR FIBER OPTICS TESTING AND EQUIPMENT

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