CHAPTER CONTENTS

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8.0 Fiber Optics

Objectives

This section will:

- Review some basic optics theory
- Examine optical fiber cable characteristics
- Examine optical source cable characteristics
- Introduce solitons

8.1 General Principles

Great minds such as Newton and Einstein devoted much time and effort trying to understand the nature of light. It is a very complex subject, full of things that on occasion seem to defy even the most rational mind.

The subject of physics in general and optics in particular, contains numerous laws and principles. These are merely observations and help to explain what light does, but not why it does it. Throughout the ages, various experiments have been performed to try to reduce the complex behavior of light to a few simple patterns. The net result is a sort of hybrid understanding, which doesn't quite satisfy anyone.

Interesting tutorials on light can be found at the Fermi Lab and other websites:

http://www.fnal.gov/pub/light/light_page0.html

http://acept.la.asu.edu/PiN/rdg/color/color.shtml

http://www2.ncsu.edu/unity/lockers/users/f/felder/public/kenny/papers/quantum.html

http://www.sciencenook.com/gdt/nt_iipw.htm

http://theory.uwinnipeg.ca/mod_tech/tech.html

http://www.yankee.us.com/TEW/TEW96paper.html

http://www.mikeholt.com/studies/fiber.htm

http://www.imagineeringezine.com/ttaoc/theory-lt.html

http://www.sff.net/people/Jeff.Hecht/history.html

http://www.networkcomputing.com/netdesign/1012cable10.html

http://www.commspecial.com/fiberguide.htm

http://www.lascomm.com/tutorial.htm

There are several on line journals dealing with light, fiber optics, and related topics:

http://www.photonics.com/

http://www.photonicsonline.com/content/homepage/default.asp

http://www.photonicsspectra.com/

http://www.optics.org/
http://www.fiberopticsonline.com/content/homepage/default.asp
http://www.bway.net/~jscruggs/color.html
http://www.imagineeringezine.com/index.htm
http://www.networkcomputing.com/
http://www.cableu.net/
http://fiberoptic.com/
http://www.lucent.com/minds/techjournal/

Handbook of Optical Through the Air Communications by David A. Johnson, P.E.

Preface
Introduction
Light Detectors
Light Theory
Light Emitters
Light System Configurations
Light Processing Theory
Optical Receiver Circuits
Optical Transmitter Circuits

Also check out:

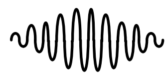
Light Measurement Handbook by Alex Ryer
Fiber Optic Sensor Technology Handbook by Davis et. al.
Philips Online Data Handbook
http://www.relcominc.com/carrier-band/handbook/repeatermanual.htm

8.1.1 Wave-Particle Duality

In 1678 Huygens showed that reflection and refraction could be explained by wave theory. While not rejecting the wave theory entirely, Einstein in 1905 suggested that light could be thought of as a small energy packet called a photon. This idea although not actually original, seemed to explain the Compton effect later discovered in 1921.

Today light is generally thought of as an electromagnetic wave when it is propagating. However, when it interacts with matter by means of emission or absorption, it is preferable to think in terms of photons. Photons have energy, but no rest mass. If a photon stops, it ceases to exist as a particle, and is transformed into some other form of energy, such as heat.

A rather hybrid way of thinking of light, is as a wave packet. Perhaps someday, a better model will be developed.



Wave Packet

Light in the everyday world is incoherent. That is to say that the wave packets arrive in a chaotic, random fashion. On the other hand, coherent light as generated from a laser has the wave packets synchronized or in phase.

The perceived color of light is a function of its wavelength. The characteristic wavelength in the packet is related to its velocity and frequency:

$$v = \lambda f$$

$$\begin{aligned} \text{where} \quad v &= \text{velocity} \\ \lambda &= \text{wavelength} \\ f &= \text{frequency} \end{aligned}$$

It has been experimentally determined that the velocity of light in a vacuum, is about 299,793,000 meters per second. Fiber optic systems operate at a frequency of approximately 3 x 10^8 GHz, with the most common transmission bands at wavelengths of 0.8 - 0.9 μm and 1.2 - 1.4 μm.

The amount of energy in light can be determined by quantum theory and is proportional to frequency and given by:

$$E = hf = \frac{hc}{\lambda}$$

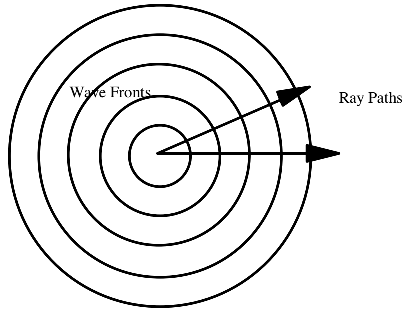
$$\begin{aligned} \text{where} \quad E &= \text{energy in Joules} \\ h &= 6.625 \times 10^{-34} \frac{J}{\sec} = \text{Planck's constant} \\ f &= \text{frequency} \\ c &= 3 \times 10^{8} \frac{m}{\sec} = \text{velocity of light} \\ \lambda &= \text{wavelength} \end{aligned}$$

The radiated spectral energy in watts per unit area is given by:

$$I_\lambda = \frac{2\pi}{\lambda^5}\left[\frac{hc^2}{e^{hc/\lambda kT} - 1}\right] d_\lambda$$

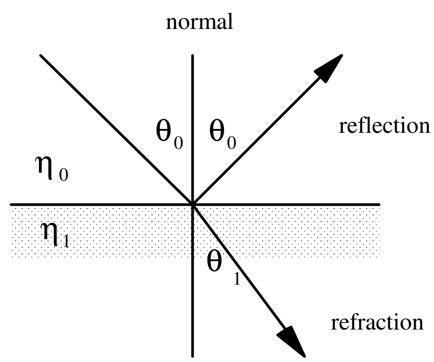
$$\begin{aligned} \text{where} \quad k &= \text{Boltzmann's Constant } 1.38 \times 10^{-23} \frac{J}{^{o}K} \\ T &= \text{temperature in } ^{o}\text{K} \\ d_\lambda &= \text{wavelength interval} \end{aligned}$$

If we examine light at the macroscopic level, we observe that waves radiate spherically from their source. This is readily observable with incoherent sources and less pronounced with coherent sources. At a large distance, the wavefront flattens out into a plane wave. A ray path shows the direction that the wave or photon is traveling. In the case of a point source, this might resemble:



When light strikes an object, it can be reflected, refracted, or absorbed. A ray of light striking the boundary between two dissimilar transparent materials is usually split into reflected and refracted rays with generally very little absorption.

Different wavelengths of light travel at the same velocity in a vacuum, but this is not true in other mediums. This change in velocity leads to refraction and color separation. If the speed is slowed in a medium, the ray is redirected towards the normal. As light leaves a slower medium and enters a faster one, it accelerates instantaneously and is redirected away from the normal. This is generally explained by the particle having a zero rest mass, a mechanism that remains a complete mystery.



By convention, the angles involved in reflection and refraction are measured with respect to the normal at the point of contact. All three components are in the same plane [there are some exceptions]. In the above illustration, the plane of incidence is the paper.

8.1.2 Displacement and Polarization

Energy displacement in waves can be either longitudinal or transverse with respect to the direction of travel. Longitudinal waves such as sound and seismic waves, are displaced in the direction of travel. Transverse waves such as radio and water waves are displaced at right angles to the direction of propagation.

In most cases, light travels as a TEM† wave, having electric and magnetic fields perpendicular to the direction of travel. There is no particular reason for the electrical displacement component in light to favor any particular orientation. Therefor, it can be rotated or polarized at any angle and still be perpendicular to the direction of propagation. This is the case with sunlight.

The combined effect of many simultaneous waves is the vector sum of all of their components. This is known as the superposition principle. This principle holds true with all forms of waves, including light. This raises an interesting question: Since the polarization of natural light is totally random, why don't the electric field components of all the waves simply average out to zero and the light cancel itself out?

A cancellation effect does occur, but to observe it, the light must be coherent. Traditionally coherent light was created by passing light from some distant source through a small hole. This effectively selects light coming from only a very small part of the originating source thus causing it to be more uniform. Today, it is easier to use a laser, which is not only very coherent, but also essentially monochromatic.

Interference patterns of light and dark areas can be observed when coherent waves intersect. However, the waves do not annihilate one another. This generates yet another observational law, the conservation of energy: energy can not be destroyed. It can only be transformed. Why this is true remains a very profound mystery.

A second argument often presented to explain why light does not self extinguish is its particle nature. Since photons travel at incredible speeds, they are obviously not in any one place for very long. Therefor it is highly unlikely that two photons would be in exactly the same place at the same time. But even if they did, the conservation law prevents them from simply vanishing into nonexistence.

Unpolarized light can be polarized by absorption, scattering and reflection.

8.1.3 Reflection

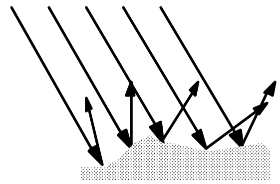
There are two types of reflection: diffuse and specular.

8.1.3.1 Diffuse Reflection

This is the most common form of reflection. If the illuminated object has surface irregularities substantially larger than the light wavelength, the light is scattered in all directions. Because of this phenomenon, we can see other objects.

† Transverse Electro-Magnetic

Light



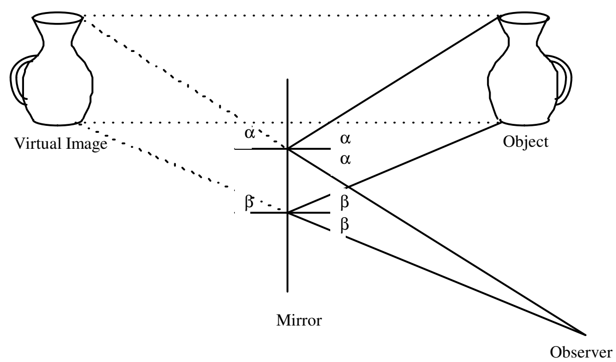
Diffuse Reflection

Sunlight contains all of the perceived colors in such a way that their combined values look colorless. When it strikes an object, some wavelengths are absorbed, while others are reflected. The perceived color is the vector sum of all the reflected waves.

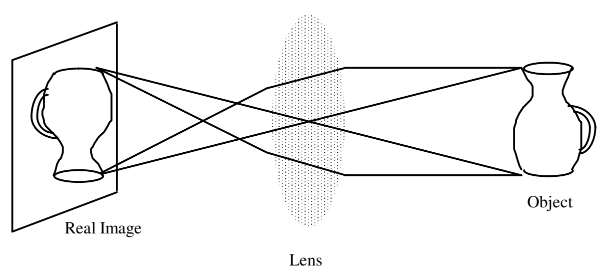
8.1.3.2 Specular Reflection

Light striking a smooth surface is reflected at the same angle with which it strikes, but suffers some loss. Instead of seeing the reflecting surface, one sees an image of where the light originates.

The reflected light can have the appearance of coming from either in front of or behind the reflecting surface. If the image appears to be behind the surface, as in the case of a mirror, it is referred to as a virtual image.



If the image is seen on a screen placed in front of the reflecting surface, it is called a real image. This principle is used in reflecting telescopes. Real images are most often generated by refraction and are used in cameras and projectors.



8.1.3.3 Variable Reflective Coatings

About 4% of light striking a smooth air-glass boundary is reflected. This can be reduced by applying non-reflecting coatings. Photographers and fiber optics designers are interested in non-glare coatings, since reflection reduces the amount of light entering and exiting the glass.

By depositing a thin high refractive index film over a thin low refractive index film, the amount of reflection can be increased to about 50%. This principle is used to make a beam splitter, a device of great value in optical measuring equipment and color TV cameras.

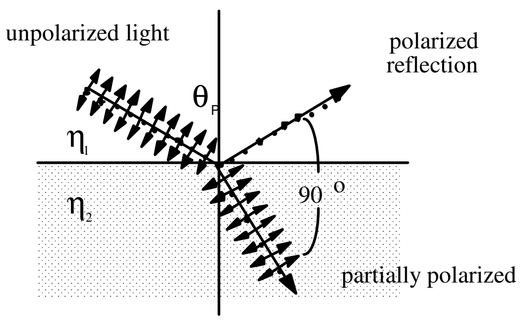
8.1.3.4 External Reflection

A phase reversal occurs when light is reflected by a more optically dense medium. This also happens when radio waves strike a metallic surface. The electric field component is short-circuited. Since the incident and reflected fields cancel at the point of incidence, the reflected waves are equal in amplitude but opposite in phase to the incident wave.

The relationship between angle of incidence and amount of reflection is very complex. At normal incidence, a reflecting surface reflects all components equally well. However, at other angles, objects prefer to reflect light having the electric field component perpendicular to the plane of incidence. At the extreme case, Brewster's angle, only perpendicular components are reflected, and complete polarization occurs. Brewster's angle is defined by:

$$\tan(\theta_P) = \frac{\eta_2}{\eta_1}$$

At Brewster's angle, the reflected and refracted rays are at right angles to each other.



Polarization by Reflection at Brewster's Angle

When noncoherent light strikes glass, about 15% of the perpendicular components are reflected, and none of the others. The refracted ray consists of the remaining 85% of the perpendicular component as well as all other orientations. The polarized reflection can be enhanced by stacking many thin glass plates together.

8.1.3.5 Internal Reflection

If light strikes an optically less dense medium, the reflected wave is not phase reversed. When the angle of incidence is greater than the critical angle, total internal reflection occurs.

However, a refracted beam of sorts does exist. It is sometimes designated as frustrated total reflection or more commonly evanescent wave. This wave does not dissipate power, and extends only a few wavelengths into the faster medium. It decays exponentially according to the relationship:

$$e^{-\alpha x}$$

$$\text{where} \quad \alpha = k_o \sqrt{n_1^{\,2} \sin^2 \Theta_i - n_2^{\,2}}$$

$$k_o = \text{free space propagation factor}$$

$$\Theta_i = \text{angle of incidence}$$

$$x = \text{distance into the faster medium}$$

8.1.4 Refraction

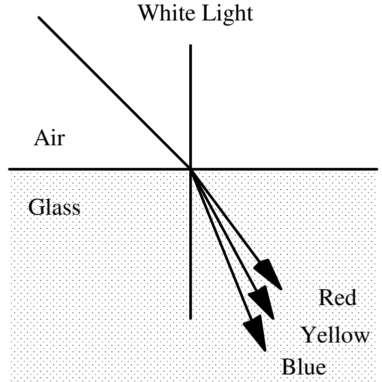
Refracted rays create diverse effects ranging from the rainbow to the apparent bending of sticks protruding into water. From experimentation, it was observed that the ratio of the sines of the incident and refracted rays is constant:

$$\frac{\sin(\theta_0)}{\sin(\theta_1)} = \text{constant}$$

This constant is actually a function of the optical wavelength. Therefor, white light is separated into its various color components when refracted.

If the originating medium is a vacuum, this ratio is known as the refractive index. In practice, the refractive index for air is 1.000293 for yellow light. Therefor, for terrestrial measurements, air is regarded as a vacuum, with a refractive index of 1.

Refraction of White Light

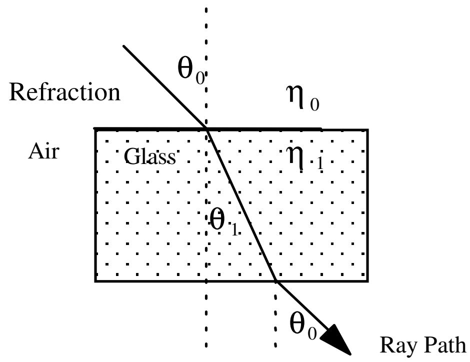


The relationship between the incident and refracted angles is given by Snell's Law:

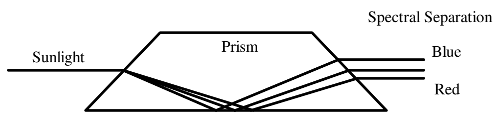
$$\eta_0 \sin(\theta_0) = \eta_1 \sin(\theta_1)$$

When a light ray passes through a glass block, it is refracted twice. If the block has parallel faces, the ray will resume it original angle of attack but is slightly displaced.

The refractive index of a material is the ratio of the speed of light in a vacuum to the speed of light in the specific material.

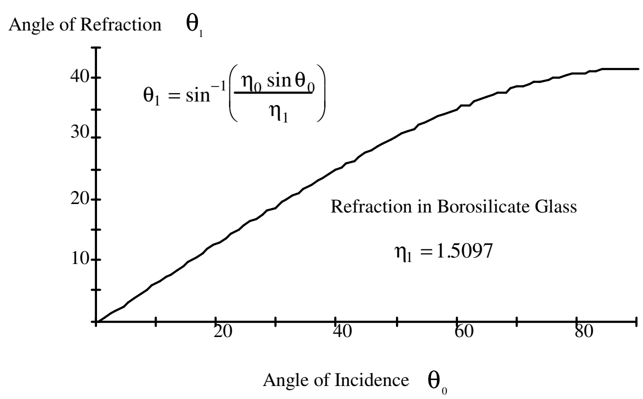


If the faces are not parallel, such as in a prism, the white light is separated into its various spectral components.



In some cases these simple rules of reflection and refraction are not valid. Reflection for example, assumes a smooth boundary, and Snell's law of refraction assumes an isotopic material. The velocity of light varies with direction in anisotopic materials.

Snell's Law predicts the following refraction response in glass:



Snell's law has its limitations. At a high angle of incidence, normally transparent objects become excellent reflectors. It also does not take into account the polarization or wavelength of light. The relationship between angle of incidence, amount of reflection, and degree of polarization, is quite complex.

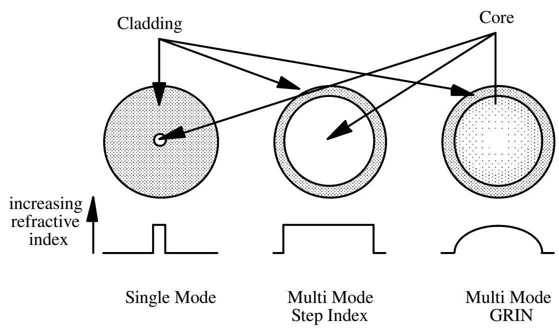
8.2 Fiber Characteristics

The international standard for the cladding diameter of optical fibers is 125 microns (µm). This allows standard tools to be used to fit connectors and splices. However, the internal diameter and composition of a fiber strand can vary considerably.

There are three primary classifications of fiber strands:

Fiber Type	Comments
Single Mode	Maximum core diameter: 10 µm Highest transmission capacity Requires laser light source
Multimode	Core diameter: 50 - 85 µm Uses LEDs More reliable Requires more repeaters due to dispersion [6 - 7 km at 45 Mbps, 4 km at 45 Mbps]
GRIN	Self-focusing, reduced the number of modes Index of refraction increases parabolically towards the center

Fiber Cross Section and Refractive Index

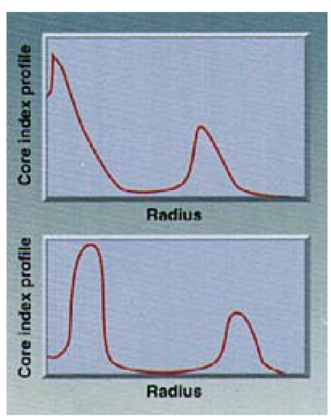


Single mode fibers have a core diameter of 8-10 µm.

Multimode core sizes are 50 µm to 62.5 µm. Larger core sizes generally have greater bandwidth and are easier to couple and interconnect.

Large Effective Area Fiber

Some of the new exotic fibers used on long haul networks have more complex profiles. http://www.corningfiber.com/library/r1083.htm



Large-effective-area fiber designs under development include profiles with a triangular central region and outer ring (top) and dual-ring design (bottom).

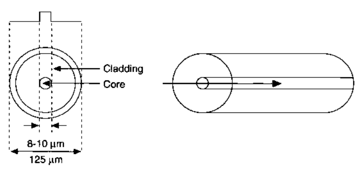
The outer ring is designed to distribute light out from the central region to produce a larger field distribution and to guide light strongly at large radii. This reduces peak power in the core, increases the effective area, and improves bending performance by preventing light from leading out to the cladding. Although both profiles result in a large-effective-area fiber, they have slightly different characteristics: the triangular core design provides slightly lower attenuation, while the dual-ring design broadens the peak field distribution, increasing the effective area.

EDFA repeaters and DWDM have caused a fundamental shift in fiber design. The high light output of EDFA repeaters causes some undesirable non-linear effects, which can degrade system performance. Increasing effective area reduces the light intensity. This improves the power handling capability, increases the signal-to-noise ratio, lowers bit error ratio, increases repeater spacing and increases capacity.

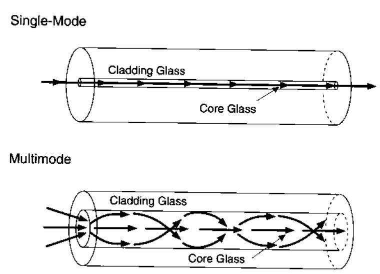
Single Mode

Single mode fiber has a step index profile, which refers to the shape of its refractive index profile over a cross section of fiber.

In a single mode fiber, light is concentrated in the core; however, some light travels in the inner part of the cladding at normal operating wavelengths. The diameter of the spot of light as it travels through the fiber is called the mode field diameter (MFD). MFD is an important parameter for determining splice loss and the fiber's resistance to bend induced loss.



Multimode Fiber

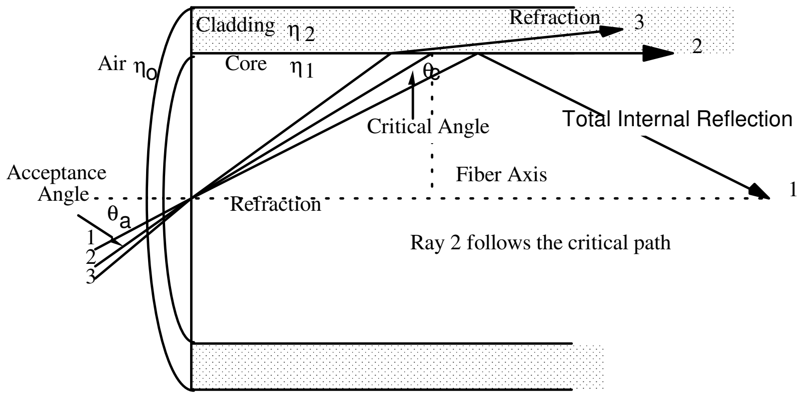


It might appear that multimode fibers have higher information carrying capacity, because they have a larger core and can therefore pass more light. However, the opposite is true. Single mode fibers support higher data rates.

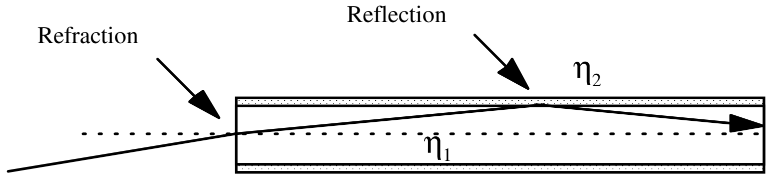
The high bandwidth capacity makes single mode fiber ideal for many long distance applications. Multimode fiber is used primarily in premise applications, where transmission distances are less than two kilometers.

Optical Principles

Applying some of the basic concepts of optics to a single glass fiber encased in a glass jacket having a lower refractive index, we observe:



8.2.1 Internal Reflection



Total internal reflection occurs if two conditions are met:

- The fiber core has a higher index of refraction than the cladding
- The angle of incidence is greater than the critical angle

$$\sin(\theta_c) = \frac{\eta_2}{\eta_1}$$

$$\text{where } \eta = \text{refractive index} = \frac{c}{v}$$

8.2.2 Acceptance Angle

Light entering a fiber is refracted at entry. If the entry angle is less than the critical angle, it gets reflected internally when it strikes the cladding and propagates down the fiber core. If the light enters at an angle greater than the acceptance angle, it gets refracted into the cladding and lost. This acceptance angle, is defined by:

$$\theta_a = \theta_{0(\max)} = \sin^{-1}\left(\frac{\sqrt{\eta_1^{\;2} - \eta_2^{\;2}}}{\eta_0}\right)$$

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$$\text{where } \eta_0 = \text{originating medium}$$
$$\eta_1 = \text{core}$$
$$\eta_2 = \text{cladding}$$

Show Me The Math!

The acceptance angle is not a function of core diameter. However, the combination of a small angle and small core, does have a dramatic effect on coupling efficiency.

8.2.3 Numerical Aperture

Numerical aperture is a figure of merit used to characterize the light gathering ability of a fiber.

$$NA = \frac{\sqrt{\eta_1^{\ 2} - \eta_2^{\ 2}}}{\eta_0} \approx \frac{\eta_1 \sqrt{2\Delta}}{\eta_0}$$

$$\text{since } \eta_1 \approx \eta_2$$

$$\Delta = \frac{\eta_1 - \eta_2}{\eta_1} \text{ or } \frac{\eta_1 - \eta_2}{\eta_2}$$

Aperture phenomena is normally a function of physical size, but in this case it is a function of refractive indices or critical angle.

8.2.4 Modes

The TE and TM propagation modes are similar to those found in µ waves, but there are also hybrid (EH & HE) modes. In the hybrid modes, both E and H fields have a component in the direction of travel. Meridian or skew rays, pass through the longitudinal axis of the fiber, spiral down the fiber in a hybrid TE or TM mode. The larger the fiber, the more modes.

The parameter V is referred to as the normalized frequency and is related to the number of modes that can propagate down the fiber.

$$V = \pi \frac{d}{\lambda} \sqrt{\eta_1^{\ 2} - \eta_2^{\ 2}} \approx \pi \frac{d}{\lambda} NA$$

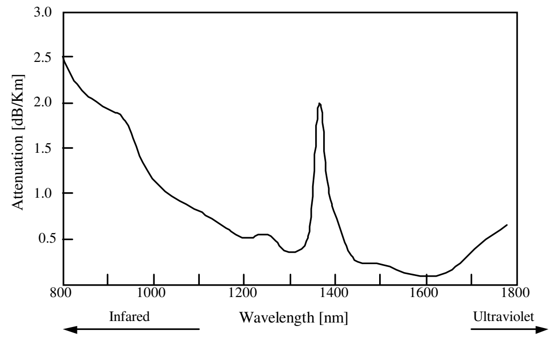
$$\text{Number of possible modes} \approx \frac{1}{2} V^2 \approx \frac{1}{2} \left(\pi \frac{d}{\lambda} NA \right)^2$$

If $V <$ 2.405, only a single mode axial ray can propagate. As a side point, this number is the first root of the zero order Bessel Function. To propagate a single mode, the fiber core diameter must be approximately 10 µm or less.

8.2.5 Loss

Perhaps the single most important source of signal loss is coupling loss. For a laser diode, it may be near 3 dB, but for LEDs, it is about 20 dB. This difference is largely due to limited acceptance angle of the fiber, and the spherical spreading of an incoherent light source such as an LED.

Fiber Transmission Windows[1]



Generally, fibers are grouped into three loss categories:

- Low-loss: < 10 dB/km
- Medium loss: ≈ 10 - 100 dB/km
- High loss: > 100 dB/km

Only low-loss fibers are of any interest in large-scale communications systems. Attenuation of 0.35 dB/km at a wavelength of 1.3 µm and 0.2 dB/km at 1.55 µm are being achieved. This is very near the theoretical limit for silica-based glass. Loss is a complex function of wavelength and material properties.

8.2.5.1 Intrinsic Absorption

Glass tends to absorb light in the ultraviolet region. Hence it is not possible to get a suntan while indoors. Glass also absorbs light in the infrared region between 700 - 1200 nm, because of the resonant nature of the silicon-oxygen bond in the glass.

8.2.5.2 Impurities

Impurities in the fiber absorb photons and generate heat. Some of these impurities are dopants added to obtain certain optical properties. Most loss of this type is caused by transition metal ions of copper, iron, cobalt and chromium or hydroxyl (OH^-) ions associated with water molecules. The OH^- radicals have strong absorption bands at 730, 950, 1380 & 2240 nm. A 1 ppm impurity causes a 1 dB/km loss at 950 nm, and a 50 dB/km loss at 1380 nm.

Fibers have low loss windows at 725, 820, 875, 1300 & 1550 nm. The 1300 nm window also offers low dispersion.

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1 Based on *Telecommunication Transmission Handbook* 3rd ed, Roger L freeman, Figure 11.3

8.2.5.3 Scattering

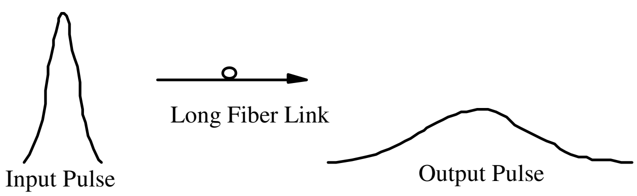
Small incongruities, such as variations in fiber density due to uneven distribution of oxide concentrations and variations in fiber geometry will scatter the photons, some of which may be lost in the cladding.

8.2.5.4 Rayleigh Scattering

As glass fiber cools in the manufacturing process, minute variations in glass density, hence refractive index, occur. These regions are less than a wavelength across, and introduce a scattering loss inversely proportional to the 4th power of the wavelength. Since it is a basic physical limitation, it represents the theoretical minimum limit for attenuation. It amounts to approximately a 2.5 dB/km loss at 820 nm and drops to less than 1 dB/km loss at 1000 nm. Most other losses are due to coupling and splicing.

8.2.6 Dispersion

Dispersion is a time spreading of a waveform. The three basic types of dispersion are: intermodal, material or chromatic, and waveguide dispersion. Dispersion has the effect of limiting the data bandwidth, since adjacent pulses would tend to smear into one another.



8.2.6.1 Modal Dispersion

Modal dispersion causes pulse spreading since different modes take slightly different paths as they zig zag along the fiber:

$$\text{shortest path} = L \qquad \text{(fiber length)}$$

$$\text{longest path} = L\frac{\eta_1}{\eta_2}$$

$$\text{maximum path difference} = \Delta l = L\left(\frac{\eta_1}{\eta_2} - 1\right)$$

$$\text{let } \Delta = \frac{\eta_1 - \eta_2}{\eta_1} \qquad \therefore \Delta l = L\frac{\Delta}{1-\Delta}$$

The lowest order mode will travel the direct route down the center of the fiber. Higher order modes will ricochet down the fiber, thus taking a longer path. The modal dispersion or time delay between highest and lowest order modes is given by:

$$\Delta t_m = L\frac{\eta_1}{c}\frac{\Delta}{1-\Delta} \quad (\text{usually specified in } \eta Sec/Km)$$

Graded index fibers are much more difficult to analyze, but they have a minimum theoretical modal dispersion of:

$$\Delta t_m = L\frac{\eta_1}{8c}\Delta^2$$

where η_1 = refractive index at core centre

8.2.6.2 Chromatic [Material] Dispersion

Velocity of propagation is a function of refractive index, which in turn is a function of wavelength. As a result, the velocity of light in a medium is dependent on its wavelength. Since no light source is truly monochromatic but is composed of a narrow range of wavelengths, this creates another form of interference namely chromatic dispersion.

Chromatic dispersion is proportional to the second derivative of the refractive index with respect to wavelength:

$$\Delta t_c = L\frac{\lambda_0}{c}\frac{d^2\eta}{d\lambda^2}\lambda_{3dB}$$

$$\text{where } \lambda_0 = \text{center wavelength}$$

$$\lambda_{3dB} = \text{spectral width}$$

The chromatic dispersion coefficient is given by:

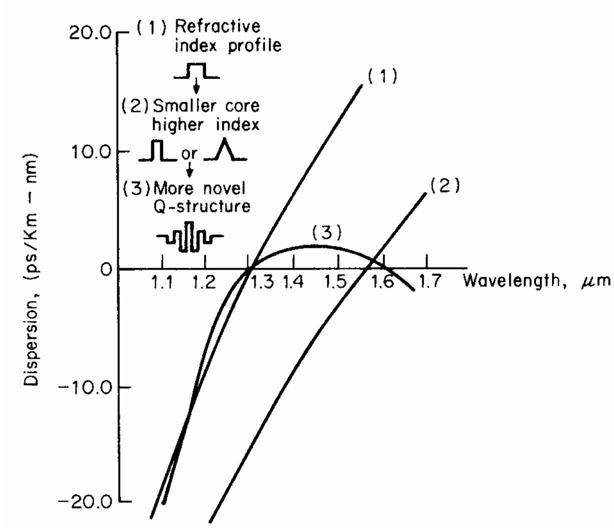
$$D_c = \frac{\Delta t_c}{\lambda_{3dB}} \quad \frac{\text{picoSec}}{\text{nm}-\text{Km}}$$

An alternate expression for the chromatic dispersion of an arbitrary length of fiber [in Km] is:

$$\Delta t_c = D_c \lambda_{3dB} L$$

For wavelengths shorter than 1.3 µm the dispersion coefficient is positive, thus in the visible spectrum, red light travels faster than blue light. For wavelengths longer than 1.3 µm the coefficient becomes negative and the velocity of light increases as the wavelength decreases. This change in the polarity of the chromatic dispersion coefficient is one of the phenomena used to support soliton transmission.

Chromatic dispersion in single mode fiber[2]

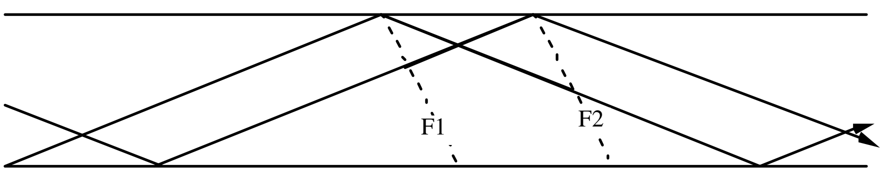


8.2.6.3 Four Wave Mixing

This phenomenon, which is similar to inter-modulation distortion, occurs when wave division multiplexing is used over dispersion-shifted fiber. This characteristic has been somewhat addressed by the development of *Truewave* fiber, which uses controlled chromatic dispersion.[3]

8.2.6.4 Waveguide Dispersion

Dispersion also occurs simply because the electromagnetic signals are guided down a conduit. Guided waves of the same frequency have a constant wave front separation as they are reflected.



Wavefront Separation

If the waves are in phase at front F1, then they will be out of phase at front F2, since the two rays traveled a different length. The phase relationship on successive reflections remains fixed if the two rays are of the same wavelength.

2 *Electronic Communications Handbook*, Andrew F Inglis, McGraw Hill, 1988, Figure 8.4

3 *Truewave fiber overcomes chromatic dispersion and four-wave mixing*, Lightwave, December 1994

However, since no light source is truly monochromatic, slightly different wavelengths are present. Consequently, a phase separation occurs on reflecting wave fronts, thus broadening a pulse.

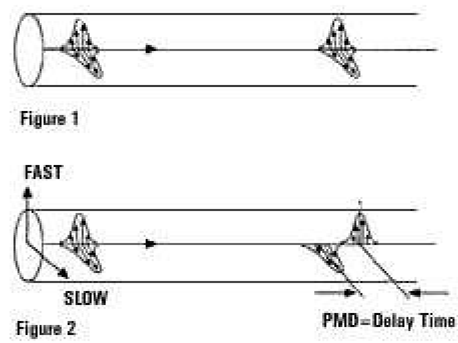
The theoretical peak value of this dispersion is given by:

$$D_w = 6.6 \frac{ps}{nm-Km}$$

$$\Delta t_w = D_w \times \lambda_{3dB} \times L$$

8.2.6.5 Polarization Mode Dispersion

PMD is a complex optical effect that can occur in single-mode optical fibers. It is a type of dispersion that can result in either the impairment of analog video picture quality in a system with high channel count or reduced span length for high-speed digital (>2.4 Gbps) systems.



Single-mode fibers support two quadrature polarizations. Perfect fibers would propagate both components at exactly the same velocity. However, in practice, the two components may travel at different velocity and arrive at the end of the fiber at different times.

Core non-circularity is a significant contributor to PMD in fiber. This can be caused in the manufacturing process or in external stress placed on the fiber.

8.2.6.6 Total Dispersion

The most significant dispersion mechanism in multimode fibers is modal dispersion. In single mode fibers operating at 1.3 µm, waveguide dispersion dominates. The total dispersion is the rms value of the three basic types of dispersion:

$$\Delta t_{total} = \sqrt{\Delta t_m{}^2 + \Delta t_c{}^2 + \Delta t_w{}^2}$$

8.2.6.7 Bandwidth

Given a transmitted pulse width of τ, the width of the received pulse is:

$$\tau_r = \tau + \Delta t_{total}$$

and a maximum bit rate of:

$$B = \frac{1}{\tau_r} = \frac{1}{\tau + \Delta t_{total}}$$

This limit is not always achieved, and a safety margin of a factor of 5 is sometimes included:

$$\therefore B = \frac{1}{\tau + 5\Delta t_{total}}$$

If the data pulse is sufficiently small, only dispersion will limit the data bandwidth:

$$\therefore B_{\max} \approx \frac{1}{5\Delta t_{total}}$$

Reducing modal dispersion can increase the bit rate. This can be accomplished by:

- Reducing fiber diameter
- Decrease the difference between core and cladding indices
- Increase wavelength

8.2.6.8 Non-Zero Dispersion Shifted Fiber

TrueWave RS Fiber

8.3 Fiber Cables

Advances in Optical Fiber by Able

Corning - CPC6 Fiber

Corning - CPC6 Fiber 2

Under Water Fiber Deployment by Harrison et. al.

BB - Fiber Optic Transmission

Because glass stands are quite fragile, they must be placed inside a protective sheath with internal strengthening cables. Furthermore, it is often necessary to provide copper power conductors in the same cable to power optical repeaters along the way. This is particularly true for outside plant.

Most fiber cables contain bundles of fibers wrapped around strengthening members, but some of the newer high-density fibers use a ribbon cable type of construction. These fiber bundles can be placed in slots cut into a core, and the surrounded by a protective sheath.

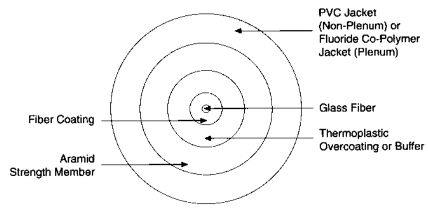
8.3.1 Basic Cable Design

There are two basic cable designs:

- Tight-buffered cable - primarily used inside buildings
- Loose-tube cable- used in outside-plant

8.3.1.1 Tight Buffered Cable

Single-fiber tight-buffered cables are used as pigtails, patch cords and jumpers to terminate loose-tube cables directly into opto-electronic transmitters, receivers and other active and passive components.

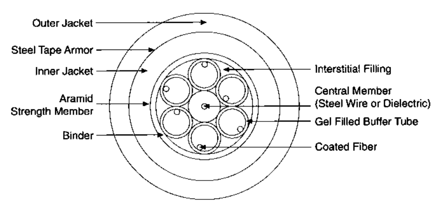


Tight-Buffered Cable

In this design, the buffering material is in direct contact with the fiber. This is suited for jumper cables connecting outside plant cables to terminal equipment, and linking various devices in a premises network.

8.3.1.2 Loose Tube Cable

Loose-tube cables typically hold up to 12 fibers per buffer and may contain more than 200 fibers. The modular design permits easy drop-off of fiber groups. It also helps in identification and administration of fibers.



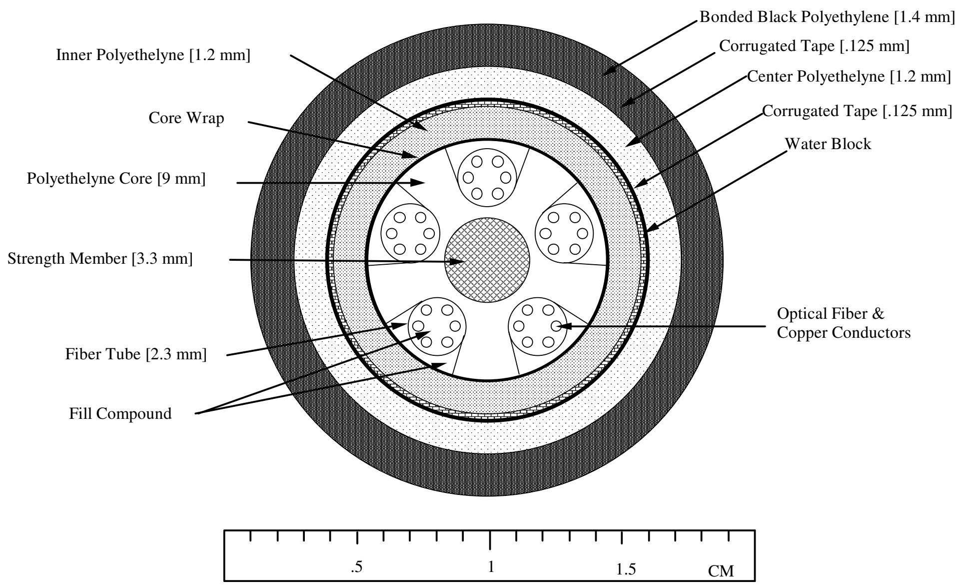
Loose-Tube Cable

The color-coded plastic buffer tubes house and protect optical fibers. A gel-filling compound impedes water penetration. Excess fiber length (relative to buffer tube length) insulates fibers from stresses of installation and environmental loading. Buffer tubes are stranded around a dielectric or steel central member, which serves as an anti-buckling element.

An outer polyethylene jacket is extruded over the core. If armoring is required, a corrugated steel tape is formed around a single jacketed cable with an additional jacket extruded over the armor.

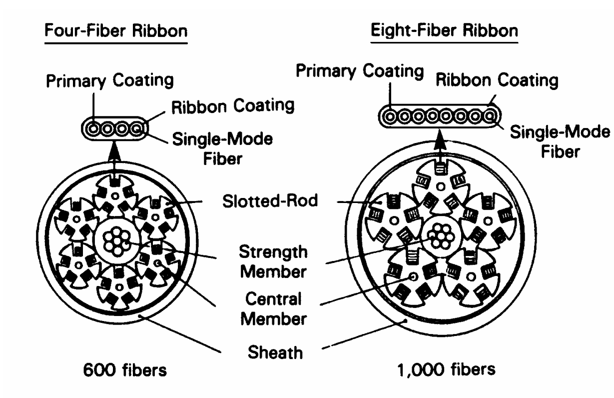
Notes

Typical Fiber Optic Cable Cross Section



Multi-fiber cables are used for intra-building, risers, general building and plenum applications. In such cases the environment is much more friendly and higher fiber densities are possible.

High Density Fiber[4]



Configuration of high-density SM optical fiber cables

8.3.1.3 Plenum Cable

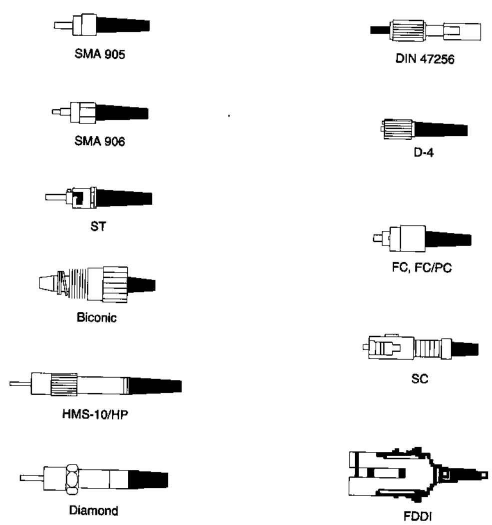
The NEC† states that all cable installed in plenum spaces must be installed in metal conduit unless classified by an approved agency as having fire resistant, low smoke producing characteristics.

4 *Japanese Subscriber Loop Network and Fiber Optic Loop Development*, IEEE Communications, March 1991, Figure 9

Cables that are not classified by an approved agency, such as Underwriters Laboratories (UL), as having fire resistant, low smoke characteristics must be installed in conduit. Conduit installation can increase the initial installed cost of a cable system by an average of 100 percent, and rerouting cables in conduit to accommodate moves, adds and changes is costly and disruptive.

Cables made with several different materials have the UL low smoke, low flame spread classification. However, plenum cables insulated with TEFLON fluoropolymer resin provide superior electrical performance at a reasonable cost for all computer, voice, data, video, control and life safety systems.

Connector Styles



8.4 Optical Sources

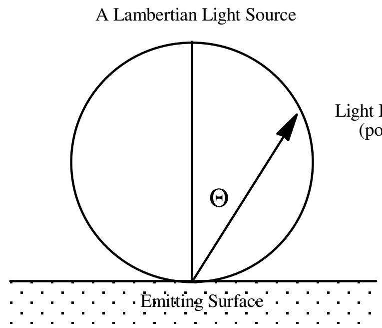
There are a number of optical sources suitable for fiber transmission. Two of the most common are LEDs and laser diodes.

Two fundamental light source characteristics are: radiation pattern, and wavelength. The radiation pattern or emission profile may be described by:

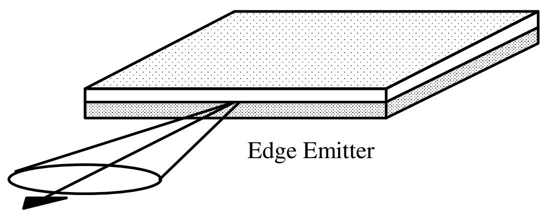
$$P = (P_o \cos\Theta)^m$$

where the angle of radiation is from the surface normal. The exponent for a Lambertian source is $m = 1$. At an angle of 60^0 the output power drops in half.

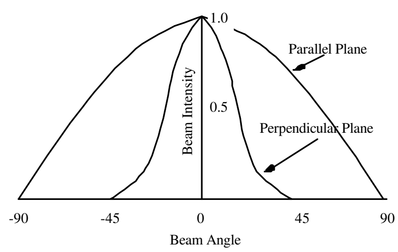
† National Electrical Code



The beam intensity on a surface radiator is symmetric about the radiation axis. However, this is not the case with an edge radiator.



A plot of the output power vs. angle in the two planes may resemble:



LEDs can be fabricated as surface or edge emitting devices. LDs on the other hand, are currently fabricated only as edge emitters. Edge emitters tend to concentrate the energy and have higher coupling efficiencies than surface radiators.

The power coupled to a fiber with an acceptance angle θ_a is

$$P_C = P_T\left[1-(\cos\theta_a)^{m+1}\right]$$

where P_T is the total source power.

Light-Emitting Semiconductors

Material	Bandgap Energy [eV] at 300^{o} K	Wavelength [µm]
Ge	0.7	1.77
Si	1.1	1.13
GaAs	1.4	0.89
AlGaAs	1.4 – 1.55	0.89 – 0.80
InGaAs	0.95 – 1.24	1.3 – 1.0
InGaAsP	0.73 – 1.35	1.70 – .92
GaAsP	1.8 - 2	0.67 -0.62
GaP	2.2	0.57
CdS	2.4	0.52

To convert the semiconductor energy gap to an emitted wavelength:

$$\lambda = \frac{hc}{eV \times 1.6 \times 10^{-19}}$$

Light Source Characteristics[5]

Characteristic	LED	Laser Diode	Laser Diode [Single mode]
Spectral Width [nm]	200 – 100	1 – 5	< .2
Rise Time [ns]	2 – 250	.1 – 1	.1 – 1
Modulation Bandwidth [MHz]	< 300	< 2000	~ 2000
Coupling Efficiency	Low	Moderate	Moderate
Fiber	Multimode	Single mode	Single mode
Temperature Sensitivity	Low	High	High
Complexity	Low	High	High
Cost	Low	Medium	High
Path Length	Moderate	Long	Very long

8.4.1 LEDs

The optical output power of an LED is directly proportional to the forward current flowing through it. A typical LED used in fiber applications operates at around 50 to 100 ma and has a forward drop of about 1.2 to 1.8 volts. This wide range of operation supports digital and analog intensity modulation.

There is a practical limit to the highest frequency that can be used to analog modulate an LED. This limit is set by the carrier lifetime in the junction.

The output power is given by:

5 *Fiber Optic Communications*, Joseph C. Palais, 1984

_____ Notes _____

$$\lambda = \frac{h}{e \times 1.6 \times 1^{-1}}$$

If the period of the modulation signal is equal to the carrier lifetime, the output power drops in half. Therefor the 3 dB bandwidth is $1/(2\pi\tau)$ Hz. Typical modulation bandwidths range from 1 to 100 MHz, but some are as high as 300 MHz.

Another way to determine the upper frequency cutoff is to inject a step current and measure the risetime of the radiated output power. The 3 dB bandwidth is then $0.35/t_r$. The rise time of LEDs range from 1 to 250 nSec.

The optical output does not consist of a single wavelength of light, but rather a narrow band of wavelengths. LEDs operating in the 0.8 to 0.9 µm region, generally have spectral widths of 20 to 50 nm, and diodes radiating at longer wavelengths, have widths of about 50 to 100 nm.

LEDs are quite reliable if operated within their design limitations. Life expectancies are about 10^5 hours or 11 years.

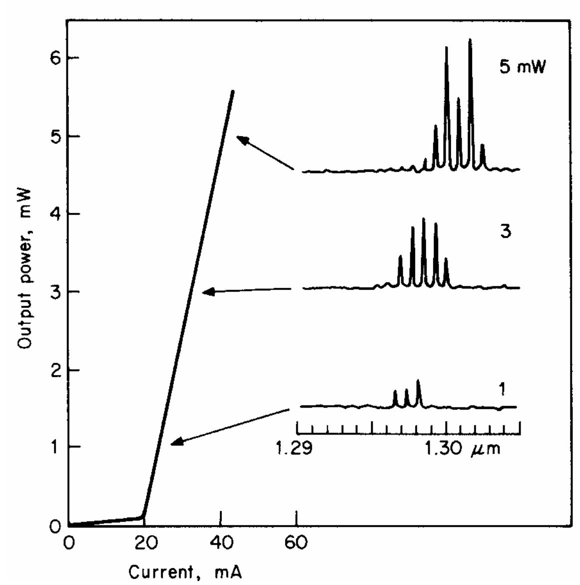
8.4.2 Laser Diodes

LDs have much lower spectral widths than LEDs, in the region of 1 nm. This has a tremendous advantage on certain fiber systems where dispersion limits the effective bit rate.

A laser diode functions as an LED until a lasing threshold is reached. This threshold is a function of aging and temperature. The emitted wavelength is also temperature dependent, and varies about 0.2nm per °C, which corresponds to about 896 Hz at a wavelength of 0.82 µm.

Notes

Laser Output Power[6]



A laser diode analog modulator circuit is similar to the LED circuit. One difference is the need for a higher operating current. Since the laser diode can be modulated at a much higher rate than an LED, a choke should be placed in the dc source path.

When using digital modulation, the current is reduced to just below the threshold current, to turn it off.

Short-wave lasers operating in the region of 0.78 to 0.9 μm are constructed of GaAs and AlGaAs. Infrared or long wave lasers are fabricated from layers of InGaAsP and InP.

There are various laser types:[7]

6 *Electronic Communications Handbook*, Andrew F Inglis, McGraw Hill, 1988, Figure 8.7

7 *Intensity Modulation and Noise Characterization of High-Speed Semiconductor Lasers*, IEEE LTS, May 1991

LASER DIODES FROM THE INTERNET

The following information was taken from An Overview of Laser Diode Characteristics By Tyll Herstens, which can be obtained at:

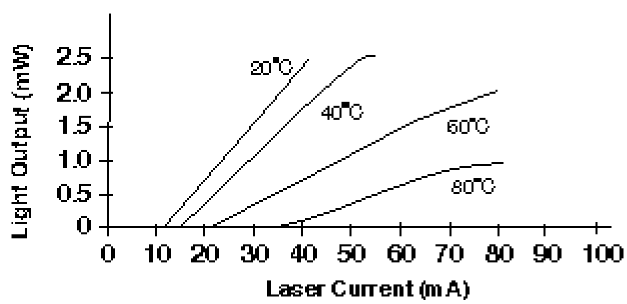
http://www.ilxlightwave.com/appnotes/05/no5i.htm

Laser diode characterization can be broken down into five categories:

- Electrical - Measurement of light output, voltage drop, and photodiode monitor current. Derivative analysis of this data may also be performed
- Spatial - Output light intensity profile in the far and near field and pointing angle of the radiation pattern.
- Spectral - Spectral data acquired to calculate spectral width, center wavelength, and to observe mode structure.
- Optical - Measurement of astigmatism and other wavefront errors.
- Dynamic - Measurement of noise, intermodulation distortion,rise time, fall time, chirping, and so on.

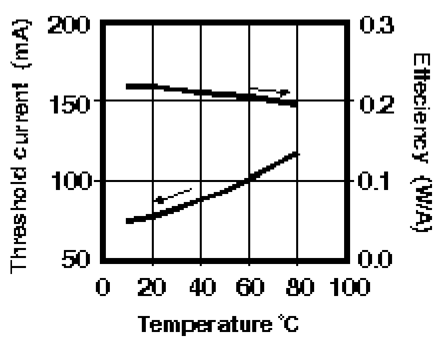
The L/I Curve

The most common of the diode laser characteristics is the L/I curve.



It plots the drive current vs. the output light intensity. It is used to determine the laser's operating point and threshold current. The laser threshold typically increases and the efficiency decreases with temperature.

The diode laser efficiency in mW/mA is derived from The L/I curve.



Laser efficiencies are typically about 0.3 mW/mA at 25° C, and drop about 0.01 mW/mA for 10°C increase in temperature.

Tracking Ratio

Many diode laser packages include a photodiode that detects the light intensity at the back of the laser cavity. This is used as a feedback source for the laser drive circuits, to stabilize the laser output.

The output current of this diode is directly proportional to the light output of the laser. This relationship is known as the tracking ratio and is measured in mA/mW. It indicates changes in coupling efficiency and can be used to detect mechanical instabilities in the fiber mounting or other changes.

The V/I Curve

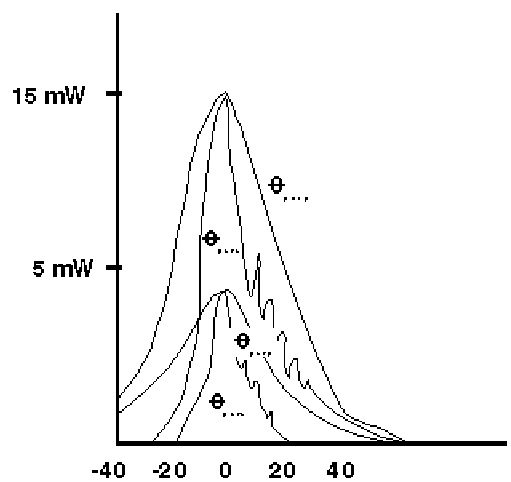
This characteristic is similar to any other type of semiconductor.

The typical voltage drop across a diode laser at operating power is 1.5 volts. Applying large reverse voltage damages laser diodes.

The Far-Field Pattern.

The average laser emits a cone of light, with an elliptical cross section. The divergence angles are measured by the full-angular-width-at-half-maximum light power. Typical values are 30° and 12°, respectively.

Far-field characteristics of a diode laser.



The conventional method for acquiring far-field data is to sweep a small-area

Spectral Characteristics

Generally, 1300-nm and 1550-nm devices are mutlimode devices, with a spectral halfwidth of about 3nm. The exception to this is the distributed feedback laser (DFB), where a spectral halfwidth is typically less than 0.1 nm.

At present, visible-wavelength lasers are multimode devices.

Tunability

The two parameters that cause the laser's center wavelength to shift are junction temperature and drive current. Changes in temperature affect the bandgap of the semiconductor junction and therefore the peak wavelength of the cavity gain profile. Typical values for temperature tuning coefficients are 0.25 nm/°C in 780-nm devices and 0.4nm/°C in 1300-nm and 1550-nm devices.

8.4.3 Optical Modulation

There are several different ways to modulate an optical carrier:

- Direct modulation of the carrier power by an analog or digital baseband signal
- Intensity modulation of the optical carrier by an amplitude modulated subcarrier.
- Intensity modulation of the optical carrier by a frequency modulated subcarrier.
- Direct frequency modulation of the optical carrier

Baseband modulation is typically used in the telecommunications industry where binary signals are used to directly vary the light intensity.

The CATV industry tends to place individual broadcast channels of RF carriers, which are then used to modulate the beam. In this case the signals are all analog.

8.4.3.1 LEDs

In order to analog modulate an LED, the forward bias current is set to half its maximum value. If the average forward current is varied sinusoidaly, the optical output power varies as follows:

$$P = P_{DC}(1+m)\cos \omega t$$

where $m = \frac{P_S}{P_{DC}} = \frac{m'}{\sqrt{1+\omega^2\tau^2}}$

$$m' = \frac{I_S}{I_{DC}}$$

$$\tau = \text{carrier life time } [\tfrac{1}{\tau} = \text{modulation bandwidth}]$$

$$\omega = \text{signal radian frequency}$$

Ideally, the output power should be a linear function of the bias current, but in practice, nonlinearities arise. One of the major sources of LED nonlinearity is junction heating. This causes the actual output power to be of the form:

$$P = P_{DC} + ai_s + bi_s{}^2$$

and gives rise to intermodulation distortion.

When using digitally modulating an LED, the diode is simply driven between saturation and cutoff. No consideration is given to nonlinearities. The switching speed is generally limited to about 100 MHz.

8.5 Solitons

In the 19th century John Scott Russell, a Scottish shipbuilder and engineer, was the first to describe a soliton. He observed a wave travelling for miles through a canal without losing its shape. No dispersion!

Solitons are a nonlinear dispersive wave described by the Korteweg – de Vries equation:

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} = -\beta\frac{\partial^3 u}{\partial x^2}$$

Solutions of this equation are of the form: $u(x,t) = u(\xi)$ where $\xi = x\text{-}ct$ and c is some constant velocity, and are used to describe soliton propagation.

Solitons can propagate without distortion if two different dispersion mechanisms compensate for each other:

- The refractive index of glass fiber changes slightly with light intensity. This is known as the Kerr effect.
- The refractive index of glass fiber changes slightly with wavelength.

It is possible to create a pulse with just the right combination of intensity and wavelengths that these two dispersive forces cancel each other out. This creates a pulse that can propagate for extremely long distances.

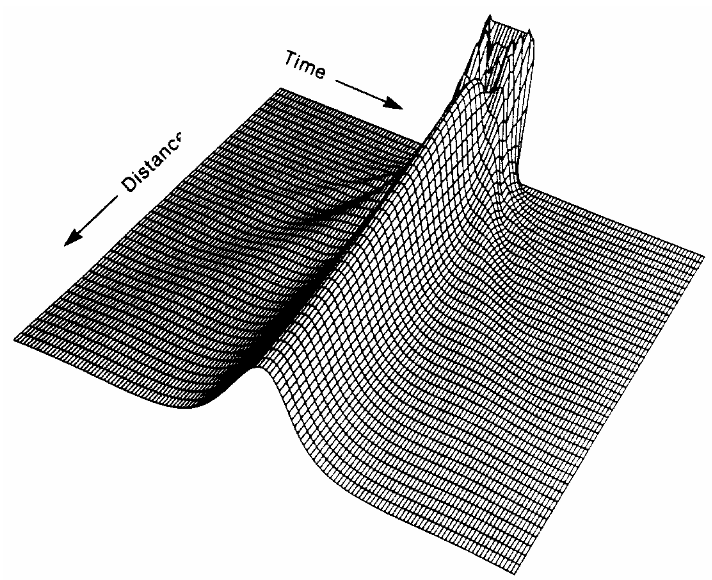
A one-picosecond pulse injected into a single mode fiber, contains about 1000 optical cycles. This burst consists of a very narrow range of frequencies. These frequencies would normally start to disperse. At wavelengths shorter than 1.3 µm, the shorter wavelengths will be in front and the longer wavelengths will fall behind. At wavelengths longer than 1.3 µm, the longer wavelengths will be in front.

If the light burst is intense enough, the Kerr effect will increase the refractive index of the glass relative to the pulse intensity. This is exactly the same phenomenon that supports fiber transmission. The cladding has a higher refractive index than the core. As a result, the intense light burst gets trapped between the two dimmer wings of the pulse where the refractive index is lower. Since velocity decreases as refractive index increases, the instantaneous phase of the burst gets altered. This is called self-modulation and the pulse becomes chirped.

Chirping is a condition where the signal disperses such that the longer wavelength components travel in front of the shorter wavelengths or vise versa. In the case of the soliton, the Kerr effect pushes the short wavelengths to the front and long wavelengths to the back of the pulse. However, the chromatic dispersion coefficient is negative, pushing the long wavelengths to the front and the short wavelengths to the back. The net result is a pulse that does not change its shape or its spectrum as it propagates.

Fortunately, solitons do not have to start out with their characteristic shape. If a pulse of the right intensity and width is injected into a negative chromatic dispersion single mode fiber, it will form itself into a soliton.

Soliton Simulation[8]



In 1992 scientists at AT&T Bell Laboratories have demonstrated error-free transmission of solitons at 5 Gbps over 15,000 Km and at 10 Gbps over 11,000 Km.

It has been suggested that with optical amplifiers and appropriate filters to remove timing uncertainties, it should be possible to create 20 Gbps links across the Atlantic.

News

After introducing the investor-owned undersea cable model with Atlantic Crossing 1 (AC-1) in May 1998, Global Crossing Ltd. (Hamilton, Bermuda) launched a global network of both undersea and terrestrial fiber projects. Now the carrier is returning to where it began to build Atlantic Crossing 2 (AC-2), a $500 million, 2.5 Tb/s undersea fiber optic cable slated for service in the first quarter of 2001.

AC-2 will add a third cable across the Atlantic for the Global Crossing network and integrate with the two cables of AC-1, which are in service. To enhance the reliability of the transatlantic network, Global Crossing seeks diverse landing sites for AC-2. Global Crossing is considering sites in the UK and Ireland for the eastern landing, and sites in the US along the New England or New York State shoreline.

AC-2 represents an undersea capacity increase of more than 25 times what is now available on the trans-Atlantic route—twice the capacity of any undersea

8 *Molding light into solitons*, fig. 3, IEEE Spectrum, March 1993

cable previously announced, according to Global Crossing. It also cites forecasts that call for bandwidth demand to increase 80% per year on the route.

Global Crossing upgraded the capacity of AC-1 from 40 Gb/s to 80 Gb/s in the fourth quarter of 1998 (see *Tyco to Upgrade Atlantic Crossing* and *Global Crossing To Expand Transatlantic Capacity*).

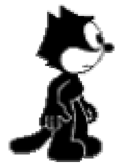
Global Crossing says that it is in the final stages of selecting vendors to supply and install the new system. It currently relies heavily on Tyco Submarine Systems.

New York, NY-based Viatel Inc. will expand its Circe Pan-European Network by 2,300 route km. Proceeds of a $365 million offering of debt securities the company completed last week will cover the construction and provision costs of the new network infrastructure. The new build, configured as two interlocking rings, Circe Four and Five, will link major cities in France and Switzerland to those portions of the network already completed or under construction. The expansion brings the total size of the Circe Pan-European Network to more than 7,500 route km.

Circe Rings Four and Five will be part of a larger five-ring broadband infrastructure that will link more than 42 major European cities in the UK, Belgium, France, Germany, Switzerland, and The Netherlands. This bi-directional self-healing network supports advanced data services (i.e., ATM, IP, and frame relay), multimedia and e-commerce applications, and voice telephony.

Circe Ring One is an 1,800 route km infrastructure linking London, Amsterdam, Rotterdam, The Netherlands, Antwerp, Brussels, Paris, and Amiens. Construction was completed in mid-February and began carrying commercial traffic on March 15. Circe Rings Two and Three, 3,400 route km in length, extend the network into Eastern France and throughout Germany. Construction on Rings Two and Three is anticipated to be completed early in third quarter 1999 and first quarter 2000, respectively. Construction on Circe Rings Four and Five should be completed by the second quarter of 2000.

_____ Notes _____



Review Questions

Quick Quiz

1. The most common wavelengths for telecom optical transmission are ______________ µm and ______________ µm
2. In free space, light travels as a [TE, TM, TEM] wave.
3. What is diffuse reflection?

   ____

   ____

   ____

4. In ordinary glass, blue has a higher refractive index than red. [True, False]
5. The refractive index of GRIN fiber [increases, decreases] towards the center.
6. There is no relationship between acceptance angle and numerical aperture. [True, False]
7. For telecommunications systems, fiber must have a loss of __________ dB per km or less.
8. Raleigh scattering is inversely proportional to ____________________.
9. List four types of dispersion :

   1. ____
   2. ____
   3. ____
   4. ____

10. Wavelengths [shorter, longer] than 1.3 µm tend to have negative chromatic dispersion coefficients in multimode fiber.
11. Total dispersion is the sum of all of the dispersions. [True, False]
12. Suggest three ways to increase the intensity modulation bit rate though a fiber:

    1. ____
    2. ____
    3. ____

13. Solitons [are, are not] frequency chirped.
14. Light intensity has no effect on the optical properties of glass fiber. [True, False]
15. Phase reversal does not occur with [internal, external] reflections.
16. Optical spectral separation can occur when passes through objects with [parallel, non-parallel] faces.
17. Snell's law is valid at all angles of incidence. [True, False]
18. Acceptance angle is a function of optical fiber core diameter. [True, False]
19. To propagate a single mode, the fiber core diameter must be approximately __________ μm or less.
20. The single most important source of signal loss in LED fiber based systems is:

    ____

21. Life expectancy of a properly used LED is about ____________________.
22. List 4 ways to optically modulate an optical carrier:

    a) ____
    b) ____
    c) ____
    d) ____

23. The Kerr effect occurs when the refractive index of glass changes with light [intensity, wavelength].
24. List 3 conditions required to form solitons:

    a) ____
    b) ____
    c) ____

Analytical Problems

1. Given a 10 Km fiber cable with the following characteristics:

$$\eta_1 = 1.475$$
$$\eta_2 = 1.465$$
$$d = 50\,\mu m$$
$$\lambda = 1.35\,\mu m$$

Find:

a) The critical angle
b) Numerical aperture
c) Acceptance angle

d) Normalized cutoff frequency

e) Number of modes supported

f) Estimate the modal dispersion limited bandwidth

2. Stating any and all assumptions, show that:

$$NA = \frac{\sqrt{\eta_1^2 - \eta_2^2}}{\eta_0} \approx \frac{\eta_1\sqrt{2\Delta}}{\eta_0}$$

3. Stating any and all assumptions, show that the modal dispersion for multimode step index fiber is given by:

$$\Delta t_m = L\frac{\eta_1}{c}\frac{\Delta}{1-\Delta}$$

Composition Questions

1. What is the critical angle in a fiber optic link?
2. How can modal dispersion be reduced in optical fiber?

For Further Research

Palais, Fiber Optic Communications
Sandbank, Optical Fibre Communications Systems

Fiber
http://www.corningfiber.com/
http://www.opticalres.com/gentle95.html#Optics
http://www.lascomm.com/
http://www.occfiber.com/
http://www.fibrecomms.co.uk/
http://www.piap.ch/fib/index.html
http://www.alcatel.com/

Solitons
http://www.ma.hw.ac.uk/solitons/
http://bugs.wpi.edu:8080/EE535/hwk96/hwk5cd96/li/li.html

SONET
http://www.techguide.com/comm/sec_html/sonet.shtml

FDDI
http://www.cisco.com/univercd/cc/td/doc/cisintwk/ito_doc/55773.html