

THE PHYSICS OF OPTICAL COMPONENTS

1.1 INTRODUCTION

The study of optical components requires knowledge of two disciplines, the physics of light and the physics of matter (mostly solid-state). Not to underestimate them, other disciplines such as metallurgy, chemistry, and crystallography are equally critical, but for the purpose of this book they are of secondary importance. Here we focus on that part of the physics of light and matter that helps one to understand how optical components work and what their issues are so that we can better appreciate how optical communications systems and networks are built, and how they can be built better, more efficiently, and at lower cost.

The study of light is not new. In antiquity, light intrigued many cultures and religions, and at least one ancient religion worshiped light. However, some ancient scientists realized that although light had wonderful and unexplained properties, particularly as it passed through colorful crystals, these properties were not caused by divine intervention, but they were real and therefore they could be scientifically explained. This curiosity finally demystified the properties of light. Perhaps the mythological story of Prometheus is an attempt to convey in lay language the message that light is for people to use and understand.

Once light was demystified, people used it in a number of applications, including the earliest optical communications network, which was constructed with light towers and used torches to signal a message from one tower to another (as Aeschylus wrote in his play *Agamemnon*). This optical network proved effective but vulnerable to interception, and Aeneas Takitos (a 4th c. B.C. military scientist from the town of Stymphalos) developed encoding techniques to transmit coded optical messages securely. The applications with light continued, and although today ancient applications sound trivial and

This chapter contains device specifications for illustrative and educational purposes. Because specifications are continuously changing, no responsibility is assumed for correctness. The reader is encouraged to consult the most current manufacturers' data sheets.

elementary, at the time they were considered marvelous and state-of-the-art, exactly as our state-of-the-art achievements will be considered by future generations. In that regard, *today is yesterday's future, and today is tomorrow's past*.

In the pursuit of explaining the properties of light, scientists discovered that both visible and invisible light truly consist of a continuum of components and many scientists tried to decompose it. Of course, nature did it in a natural way when light passed through a prismatic crystal. From this research effort, it was discovered that even the chlorine yellow line can be split into two lines by using a strong magnetic field. Soon it was proven that light was electromagnetic energy, but it also was discovered that light consists of quantized particles called photons. This discovery raised many eyebrows and created some animosity. Similarly, the propagation properties of light in transparent materials and in optical waveguides were studied. And this is history.

Today many interesting materials have been developed, and glass-fiber is the chosen transmission medium for high-speed, high-reliability, and long-distance terrestrial and submarine communications. Currently, bit rates at 40 Gbps are used in a single fiber. With *dense wavelength division multiplexing* (DWDM), the aggregate bandwidth has exceeded one terabit per second. DWDM systems with 160 wavelengths have been announced, and 1000 wavelengths have been on the experimenter's workbench for some time. What does this mean? A 40-wavelength DWDM system at 40 Gbps per wavelength has an aggregate bandwidth of 1.6 Tbps, a bandwidth that can transport in a single fiber the contents of about 45,000 volumes of an encyclopedia in 1 second.

Table 1.1 Units and site in decimal

Number	10^N	Name	Time Unit	Bit Rate	Length Unit
1,000,000,000,000,000	10^{15}	1 quadrillion	(see note 1)	Peta-bps (Pbps)	Kilometer (km)
1,000,000,000,000	10^{12}	1 trillion		Tera-bps (Tbps)	
1,000,000,000	10^9	1 billion		Giga-bps (Gbps)	
1,000,000	10^6	1 million		Mega-bps (Mbps)	
1,000	10^3	1 thousand		Kilo-bps (Kbps)	
				(see note 3)	
100	10^2	1 hundred	Second (s) (see note 2)	Bit-per-second (bps)	Meter (m)
10	10^1	Ten			
1	10^0	One			
0.1	10^{-1}	One-tenth	Millisecond (ms)		Decameter (dm)
0.01	10^{-2}	One-hundredth			Centimeter (cm)
0.001	10^{-3}	One-thousandth			Millimeter (mm)
0.000 001	10^{-6}	One-millionth	Microsecond (μ s)		Micrometer (μ m)
0.000 000 001	10^{-9}	One-billionth	Nanosecond (ns)		Nanometer (nm)
0.000 000 000 001	10^{-12}	One-trillionth	Picosecond (ps)		Picometer (pm)
0.000 000 000 000 001	10^{-15}	One-quadrillionth	Femtosecond (fs)		

¹Blank entries signify an uncommon unit.

²One day has 86,400 seconds; light travels at about 10^{10} cm/sec or 30 cm/ns.

³The bit rate of uncompressed PCM voice is 64 Kbps.

⁴3.4 nm is the length of one helical turn of a DNA strand.

If a file of 1 terabit was transmitted using a 56-Kbps modem, it would take about 7 months (i.e., without interruption); at 40 Gbps it would take just 25 seconds!

Denser DWDM systems are currently a trend that increases not only both the number of wavelength density per fiber and the aggregate bit rate, but also the length of fiber without signal amplification (Fig. 1.1).

Certain numbers mentioned in this book may seem very small or very large. Table 1.1 puts into perspective what these number mean, such as a picosecond (ps) or a terabit per second (Tbps):

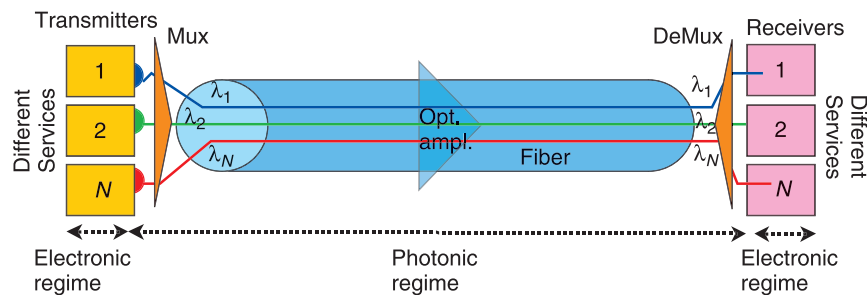


Figure 1.1 A conceptual DWDM path with many wavelength-channels in the same fiber.

1.2 THE NATURE OF LIGHT

The surprising dual nature property of light a couple or so centuries ago, which sounded like a contradiction, is accepted and well understood (well, we think so): one nature is (electromagnetic) wave and the other nature is particle.

1.2.1 The Wave Nature of Light

The wave nature of light is the same as that of radio waves and X-ray waves. As such, it is subject to reflection, refraction, diffraction, interference, polarization, fading, loss, and so on. Thus, being an electromagnetic wave, light interacts with any charges that may be present in the neighboring space. Therefore, to measure the force (magnitude and direction) of the electric field of light at any point in space, a theoretical positive charge is introduced at that point. Similarly, to measure the force (magnitude and direction) of the magnetic field, a theoretical elemental magnetic dipole is introduced at that point.

An electromagnetic wave, and thus light, is characterized by frequency and wavelength, as well as by phase and propagation speed with respect to a reference point.

- Frequency is the number of peak waves in a second, and wavelength is the traveled distance of a complete wave (e.g., peak-to-peak) in free space or in a medium. The unit for frequency is cycles per second or hertz, and the unit for wavelength is nanometer (nm) or micrometer (mm). An older unit that is also encountered is the angstrom; one angstrom is equal to 10^{-10} meters.
- Phase with respect to a reference point is the phase angle difference between the peaks of the wave with that point.

- Propagation speed is the distance traveled by a peak of a wave within the unit of time.

Monochromatic light, or single color light, is light that consists of waves that are all of exactly the same “single” frequency. Waves that propagate in space have a spherical front. However, to simplify the mathematical analysis, electromagnetic waves are considered planar. Thus, light is described by the Maxwell’s electromagnetic plane wave equations:

$$\nabla^2 E = (1/v^2)(\eta^2 E/\eta t^2)$$

$$\nabla^2 H = (1/v^2)(\eta^2 H/\eta t^2)$$

$$\nabla D = \rho$$

and

$$\nabla B = 0$$

where ∇ is the Laplacian operator; u is the speed of the wave in a medium; E and H are the electric and magnetic fields, respectively; D is the electric displacement vector (its gradient is the charge density ρ); and B is the magnetic induction vector. These four vectors are interrelated as

$$D = \varepsilon_0 E + P$$

$$B = \mu_0 H + M$$

where ε_0 and μ_0 are the dielectric permittivity and permeability, respectively, both constants of free space, and P and M are the electric polarization and the magnetic polarization of the wave, respectively.

When an electromagnetic wave propagates in a linear (e.g., noncrystalline) medium, the electric polarization is expressed as

$$P = \varepsilon_0 \chi E$$

where χ is the electric susceptibility of the medium (in a nonlinear medium, this is expressed as a tensor); note that in a nonlinear medium, the latter relationship includes higher-order terms.

Moreover, the dielectric constant of the material, ε , is connected with the susceptibility as

$$\varepsilon = \varepsilon_0(1 + \chi)$$

The propagation of a plane wave (Fig. 1.2) is described by the two relationships:

$$E(r, t) = E_0 e^{-j(\omega t - k \cdot r)}$$

and

$$H(r, t) = H_0 e^{-j(\omega t - k \cdot r)}$$

where ω is the angular frequency, r is the directional vector, and k is the wave vector, which is connected with the dielectric constant by the relationship

$$k = |k| = \omega \theta (\mu_0 \varepsilon)$$

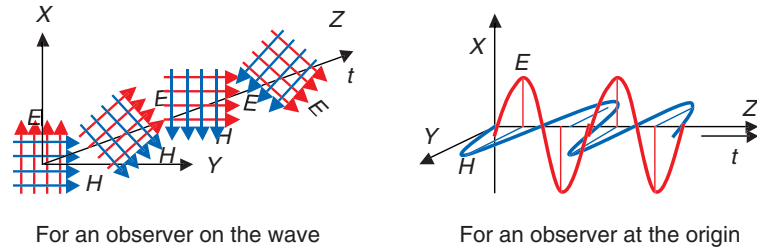


Figure 1.2 Graphical representation of an E - H plane wave evolution.

The aforementioned two wave relationships are complex numbers, and they consist of a real term, $\cos(x)$, and an imaginary term, $\sin(x)$. However, since the measurable quantity is the only real part, they are simplified as

$$E(r, t) = E_0 \cos(\omega t - k \cdot r)$$

and

$$H(r, t) = H_0 \cos(\omega t - k \cdot r)$$

Finally, when the (monochromatic) plane wave travels in free space, it travels at a maximum and constant speed (since μ_0 and ϵ_0 are constant quantities):

$$c = \omega/k = 1/[\sqrt{(\mu_0 \epsilon_0)}]$$

where $c = 2.99792458 \times 10^{10}$ cm/sec, or ~ 30 cm/nsec

When light travels in a medium (other than free space), its velocity u is expressed by

$$u = \omega/k = 1/[\sqrt{(\mu \epsilon)}]$$

The speed of light, u , in a medium is always smaller than c because $\mu > \mu_0$ and $\epsilon > \epsilon_0$.

1.2.1.1 Photometric Terms

Comparing two light sources or two illuminated objects, one can tell which one is brighter. Such comparisons are useful, but they do not provide precisely the absolute value of light brightness. As a consequence, certain measurable units must be introduced.

- (Total) *luminous flux*, Φ , is the rate of optical energy flow (or number of photons per second) emitted by a point light source in all directions; it is measured in lumens (lm). In radiometric terms, this is known as optical power and is measured in watts.
- *Luminous* (or *candle*) *intensity*, I , is the rate emitted in a solid angle of a spherical surface area equal to its radius (e.g., radius = 1 m, surface area = 1 m²). Luminous intensity is measured in *candelas* or *candles* (cd). The luminous intensity of a sphere is $\Phi/4\pi$.
- *Illuminance*, E , is the flux density at an area A (m²), or the luminous flux per unit area; it is measured in *lux* (lx). The illuminance at a point of a spherical

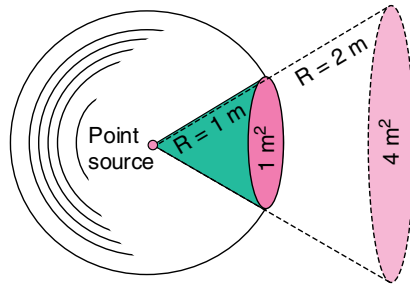


Figure 1.3 Definition of luminous (or candle) intensity and the law of inverse square.

surface is $E = \Phi/4\pi R^2$. Illuminance refers to light received by a surface. Since the luminous intensity I of the sphere is $\Phi/4\pi$, then $E = I/R^2$. This is known as *the law of inverse squares* (Fig. 1.3).

- **Luminance**, B , is the amount of optical energy emitted by a lighted surface per unit of time and per unit of solid angle and per unit of projected area. Luminance is measured in cd/m^2 and is also known as nit (nt).

Some examples of luminance are (in cd/m^2):

Clear blue sky:	10^4
Sun:	1.6×10^9
Candle:	2×10^6
Fluorescent lamp:	10^4

Table 1.2 summarizes the photometric units that are used in optics and optical communications, their measuring units, and their dimensions (M = mass, T = time, L = length):

Table 1.2 Photometric units (M = mass, T = time, L = length)

Definition	Photometric Unit	Dimensions
Energy	Luminous energy (talbot)	ML^2T^{-2}
Energy per unit area	Luminous density (talbot/ m^2)	MT^{-2}
Energy per unit time	Luminous flux (lumen)	ML^2T^{-3}
Flux per unit area	Luminous emittance (lumen/ m^2 or lambert)	MT^{-3}
Flux per unit solid angle	Luminous intensity (lumen/steradian)	ML^2T^{-3}
Flux per unit solid angle per unit projected area	Luminance (candela/ m^2)	MT^{-3}
Flux input per unit area	Illuminance (meter-candela)	MT^{-3}
Ratio of reflected to incident flux	Luminous reflectance	
Ratio of transmitted to incident flux	Luminous transmittance	
Ratio of absorbed to incident flux	Luminous absorptance	

1.2.1.2 Radiometric Terms

Similar to photometric terms, radiometric terms are defined as follows:

- *Radiant power* (ϕ) or optical power is the rate of flow of radiant energy, and it is measured in watts (w).
- *Radiant energy* (Q) is the energy transferred by electromagnetic waves. It is the time integral of radiant power and is measured in joules (J).
- *Radiant intensity* (I) is the radiant power per unit solid angle, and it is measured in watts/steradian (w/sr).
- *Radiance* (L) in a given direction is the radiant intensity per unit of projected area of the source as viewed from that direction, and it is measured in w/sr·m².
- *Spectral radiance* (L_λ) is the radiance per unit wavelength interval at a given wavelength, and it is measured in watts/steradian-unit area-wavelength interval (w/sr·m²·nm).
- *Irradiance* (E) or power density is the radiant power per unit area incident upon a surface, and it is measured in watts/square meter (w/m²).
- *Spectral irradiance* (E_λ) is the irradiance per unit wavelength interval at a given wavelength, and it is measured in watts/unit area-unit wavelength interval (w/m²·nm).

1.2.2 The Particle Nature of Light

Like all particles, light exerts pressure and causes a wheel to spin (Compton's experiment). Thus, light is described in terms of number of particles or *photons*, the smallest quantity of monochromatic light, described by the energy (E) equation

$$E = h\nu$$

where h is Planck's constant, $6.6260755 \times 10^{-34}$ (joule-second), and ν is the frequency of light.

Visible light (light that the human eye can see, such as light from an incandescent lightbulb) consists of a continuum of wavelengths that span the (visible) spectrum from deep red (700 nm) to deep violet-blue (400 nm) (Fig. 1.4).

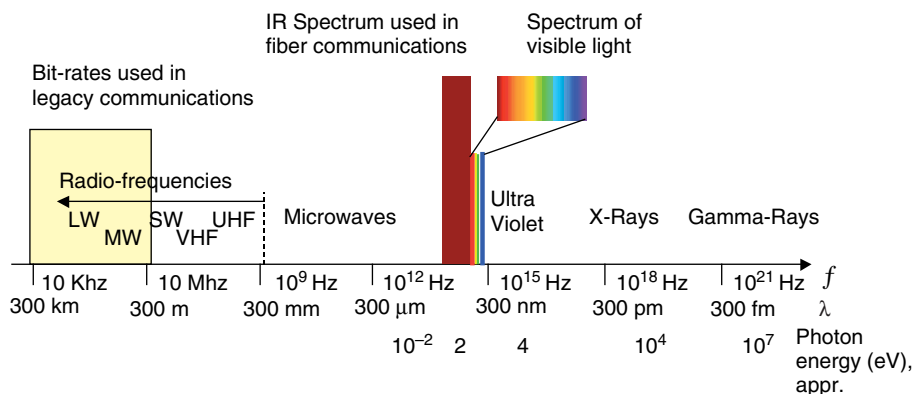


Figure 1.4 The visible spectrum is in the range from 0.7 μ m (700 nm) to 0.4 μ m (400 nm). The spectrum used in fiber communications is beyond the red.

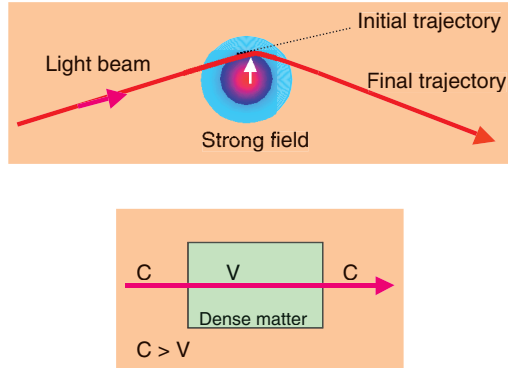


Figure 1.5 Light travels in a straight path but it “bends” when it crosses a strong field.

In free space, light (of all wavelengths) travels in a straight path at a constant maximum speed. However, the speed of light changes when it travels in a medium, and this change is not the same for all media or for all wavelengths. By free space it is meant space that is free from matter (vacuum) and/or free from electromagnetic fields. Thus, the speed of light in free space is defined by Einstein’s equation:

$$E = mc^2$$

Frequency, ν , speed of light in free space, c , and wavelength, λ , are interrelated by:

$$\nu = c/\lambda$$

From the energy relationships $E = mc^2 = h\nu$ and the last one, an interesting relationship is obtained, the equivalent mass of a photon (which is a controversial issue among scientists)

$$m = h\nu/c^2$$

When light is in the vicinity of a strong electromagnetic field, it interacts with it. From this interaction and other influences, its trajectory changes direction (Fig. 1.5). In fact, in the presence of gravitational fields of cosmic proportions, the trajectory change of light causes a phenomenon known as *gravitational lensing*, which is used in astrophysics to detect dark matter and distant galaxies.

1.2.3 Huygens–Fresnel Principle

When light from a monochromatic point source impinges on a screen having a small round hole on the order of the wavelength, the hole behaves like a light source of the same wavelength and phase (Fig. 1.6). This is known as the *Huygens–Fresnel principle*, and it is a key principle in the study of *interference of light*.

1.2.4 Interference

1.2.4.1 Classical Interference

Consider the optical setup of Figure 1.7 with a monochromatic light source, a screen with two pinholes equidistant from the axis of symmetry, and a second screen behind

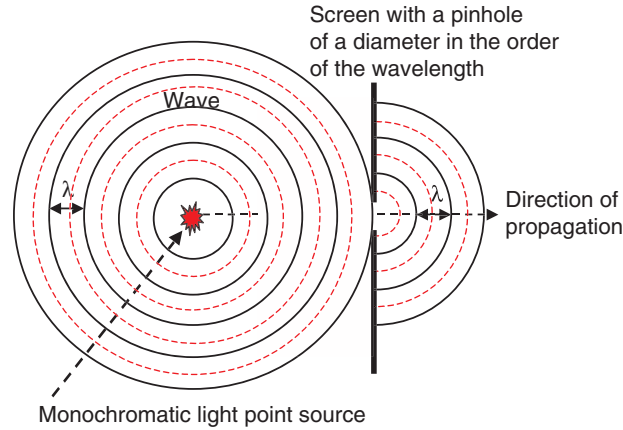


Figure 1.6 Principle of Huygens-Fresnel.

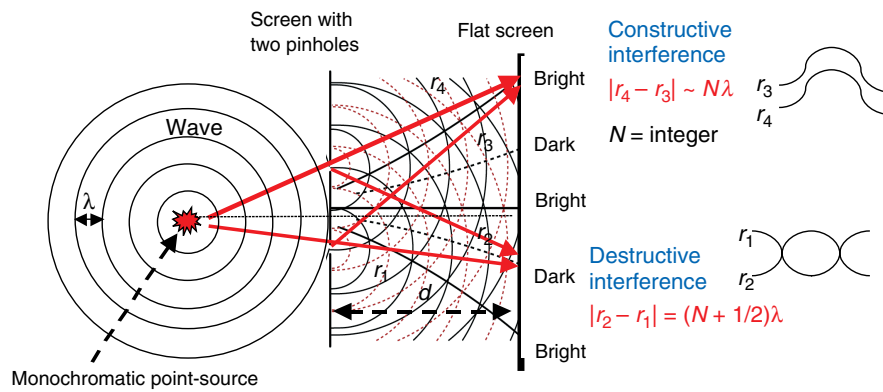


Figure 1.7 Interference of two coherent sources of the same wavelength.

the first and parallel to it. Based on the Huygens-Fresnel principle, the pinholes become two sources of coherent light. Then, alternating bright and dark zones, or fringes, are seen on the second screen. The bright or dark state of a fringe depends on the absolute difference of the optical paths, which is equal to the variation of the product $n \times r$, where n is the refractive index of the medium and r is a vector, the magnitude of which equals the travel distance. In the setup of Figure 1.7, the medium is free space and thus $n = 1$. Thus, the variation of the optical path is equal to the variation of the travel distance, which is closely related to wave phase difference between the rays r_1 , r_2 , r_3 , and r_4 :

$$\Delta = |r_2 - r_1| \quad \text{or} \quad \Delta = |r_4 - r_3|$$

Bright zones (*constructive interference*) are formed when the path difference is an integer multiple of λ (i.e., $k\lambda$, $k = 1, 2, 3 \dots$), and dark zones (*destructive interference*) are formed when the travel difference between the two rays is half-integer multiple of λ [i.e., $(k + 1/2)\lambda$, $k = 0, 1, 2, 3 \dots$].

Interferometric fringes can easily be formed when a collimated laser beam impinges on a transparent plate. As monochromatic light reflects back and forth within the two surfaces of the plate, the emerging rays interfere among them to form zones of maxima and minima of light intensity, or fringes. The shape of fringes depends on the plate thickness and its refractive index. Thus, interferometry is also used to measure surface, thickness, and refractive index uniformity; when the plate is under stress, both thickness and refractive index change, and interferometric techniques measure nonintrusively and remotely the distribution of stress or temperature on plates. Typically, there are two well-known methods, the Fizeau method and the Twyman–Green method. Based on interferometric techniques, only surface variations up to $\lambda/40$ can be measurable; this determines the accuracy of the method and also its limits. For example, if red laser light ($\lambda = 600$ nm) is used, then accuracy is within 15 nm, and if ultraviolet (UV) light ($\lambda \sim 300$ nm) is used, then it is within approximately 7.5 nm. Clearly, the shorter the wavelength, the higher the accuracy, and the more complex the method. Consequently, as we move into the realm of subnanometer accuracy, more advanced technologies are needed with a fine subatomic scale resolution. In this category, the phase-shifting interferometric microscope (PSIM) provides a resolution of approximately a tenth of a nanometer and the Nomarski interferometric technique can be as good as 10 times that of the PSIM and of the atomic force microscope (AFM).

1.2.4.2 Quantum Interference

Consider an atom with only one electron at the outer orbit (e.g., Na), being at the ground energy level or state S_1 . Then, when a photon of energy E_{12} is absorbed, the electron “jumps” to a higher energy level S_2 . While at level S_2 , the electron may absorb another photon of energy E_{23} to “jump” to energy level S_3 .

Photon absorption by an electron (or an atom) implies that the atom is “opaque” for that frequency (or wavelength) to which the photon corresponds. Photons that are not absorbed travel through it, and thus the material is “transparent.”

Thus, when the atom is at level S_1 , it is transparent to energy E_{23} and opaque to E_{12} ; and when the atom is at level S_2 it is transparent to energy E_{12} and opaque to E_{23} . At some random time, and while at energy level S_2 , the atom may jump down to ground energy level S_1 , releasing photonic energy.

Consider a “cloud” of such atoms illuminated with both E_{12} and E_{23} . However, since all atoms in the cloud are not excited by photons at the same time and atoms are not synchronized, jumping from one state to another becomes a random process. Therefore, statistically there will be a time when a mix of both states will exist, S_1 and S_2 . It turns out that, under a specific mix of states S_1 and S_2 and intensity of E_{12} and E_{23} , the “cloud” seems to be transparent to both photonic energies. Macroscopically, this seems like a destructive interferometric action at the quantum (atomic energy) level, hence quantum interferometry. Quantum interferometry is an area of current research. More findings and developments are expected to be announced in the near future.

1.2.5 Holography

Holography is an interferometric method by which, using coherent light (laser light), the phase and amplitude characteristics of diffracted light by a three-dimensional (3-D) object is captured on a two-dimensional photographic plate.

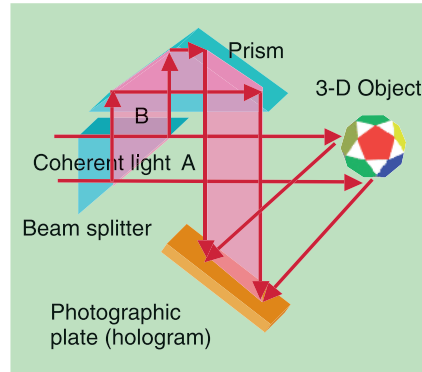


Figure 1.8 Principles of holography; generating a hologram.

Consider the following experiment illustrated in Figure 1.8: a monochromatic coherent light source is split into two beams, A and B. Beam A impinges on a three-dimensional object and is diffracted onto a photographic film. A prism reflects beam B such that it too impinges on the photographic plate. At the plate, beams A and B interfere and depending on the travel difference of each ray in the two beams, because of the three-dimensionality of the object, the amplitude and phase difference from each point of the object are recorded on the photographic plate. The end result is an incomprehensible image of dense stripes and whorls on the plate. This exposed plate is known as a *hologram*.

Based on “diffraction at infinity,” the phase and amplitude information of a 3-D object have been recorded in a myriad of locations of a hologram. Thus, each small segment of the hologram contains all phase and amplitude information of the 3-D object.

To recreate an image of the 3-D object, the hologram must be illuminated with coherent light. The dense stripes and whorls in the plate (acting like a diffraction grating) interact with the incident coherent beam, decoding phase and amplitude, and recreate a replica image of the object (Fig. 1.9).

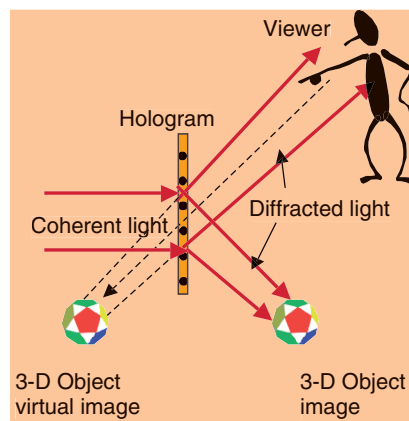


Figure 1.9 Principles of holography; creating a holographic image.

1.2.6 Optical Correlators and Storage

Among the applications that holography has found are optical storage, image recognition, and pattern correlation. When coherent light passes through a transparent plate with a set of images and then passes through the hologram of an object, if there is a match, two conjugate inverted images appear on a screen matching the one in the hologram; if there is no match, a blurred dot appears.

Thousands of holograms may be contained in a square millimeter of a holographic plate. Thus, many thousands of different images may be stored in few square millimeters of a holographic plate. The storage capacity of a hologram, C_{store} , is in the terabit range and is theoretically limited to the hologram volume, V_{hol} , divided by the cube of the source wavelength, λ :

$$C_{\text{store}} = V_{\text{hol}}/\lambda^3$$

It has been reported that 160,000 holograms have been stored and successfully reconstructed in a single crystal.

Optical correlators work by comparing the Fourier transform of two patterns or images that are combined with holographic methods to retrieve an optical pattern and recognize an image fast. Hence, holographic methods promise very large capacity optical storage applicable in many areas including communications.

Among these applications, Fe-doped LiNbO_3 crystals and organic photopolymers have been used in write once read many times (WORM) memories. The write capability is accomplished with high-power low-cost semiconductor lasers, and the read capability, or desired holographic frame, is selected by activating a micromirror in a matrix (see MEMS).

Among other applications, holography may be used in the creation of 3-D crystals. In this case, 3-D molds, such as photonics crystals, gratings, and integrated optics, may be rapidly designed and reproduced. It may also be used in 3-D spatiotemporal storage.

1.2.7 Light Attributes

The attributes of light and their significance, of interest in this book, are listed in Table 1.3.

Table 1.3 Attributes of light

Attribute	Significance
Dual nature	Electromagnetic wave and particle ($E = h\nu = mc^2$)
Consists of many λ s	Wide and continuous spectrum
Polarization*	Circular, elliptic, linear (TE_{nm} , TM_{nm}); affected by fields and matter
Optical power	Wide range (from μW to MW); affected by matter
Propagation	In free space in straight path; in matter it is affected differently (absorbed, scattered, through); in optical waveguides (fiber) it follows its bends
Propagation speed	In free space $c \sim 10^{10}$ cm/sec, in matter c/n ; different wavelengths travel at different speed
Phase	Affected by variations in fields and matter

*Polarization is discussed in subsequent sections.

1.3 OPTICAL MATERIALS

When light enters matter, its electromagnetic field interacts with localized electromagnetic fields. The result is a change in the characteristics of light and in certain cases a change in the properties of matter as well. The strength of the field of light, its wavelength, its polarization state, and matter determine how light will be affected. Moreover, external temperature, pressure, and fields (electrical, magnetic, and gravitational) influence the interaction of light with matter. Such interactions may degrade propagation of light, and thus they are undesirable but they are also used to advantage in the design of optical components.

1.3.1 Transparent Versus Opaque Matter

- Some matter allows most optical energy (all photons) to propagate through it and is called *optically transparent*. In contrast, some dense matter absorbs light within the first few atomic layers and is called *nonoptically transparent* or *opaque* matter (it scatters and/or absorbs it). **Example:** compare clear glass or water with a sheet of metal.
- Some matter passes a portion of optical energy through it and absorbs part of it (typically $\sim 50\%$), and is called *semitransparent* matter. Such matter attenuates the optical power of light and may be used in optical devices known as *optical attenuators*. **Example:** most transparent matter, semitransparent mirrors.
- Some matter allows selected frequencies to propagate through and is called an *optical filter*. **Example:** red, green, yellow, or blue glass (each allows a selected range of frequencies to be propagated through it).
- Some matter in an ionized state absorbs selected frequencies and passes all others. **Example:** the sun's ionized surface or the hot vapors of sulfur.
- Some matter permits rays with certain polarization to propagate through and absorbs or reflects the others; it is called a *polarizing filter*. **Example:** polarizing sunglasses.
- Some matter emits photons when in intense electric field and some matter emits photons of specific wavelengths when it is illuminated with light of another shorter wavelength. **Example:** most minerals under UV light; fluorescent substances, erbium, and so on.

1.3.2 Homogeneity and Heterogeneity

A *homogeneous* optically transparent medium has the same consistency (chemical, mechanical, electrical, magnetic, or crystallographic) throughout its volume and in all directions. A *heterogeneous* optically transparent medium does not have the same consistency (chemical, mechanical, electrical, magnetic, or crystallographic) throughout its volume.

1.3.3 Isotropy and Anisotropy

Isotropic optically transparent materials have the same index of refraction, same polarization state, and same propagation constant in every direction throughout the

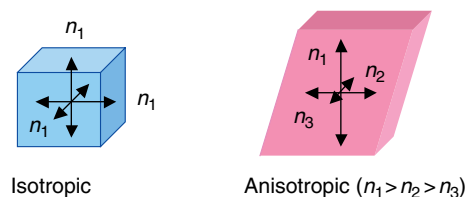


Figure 1.10 Principle of isotropic and anisotropic materials.

material. Materials that do not exhibit all these properties are known as *anisotropic* (Fig. 1.10).

Anisotropy is explained as follows: the electrons of certain crystals, such as calcite- CaCO_3 , move with a different amount of freedom in selective directions of the crystal, and the dielectric constant as well as the refractive index of the crystal is different in these selective directions. As a result, as photons enter the crystal, their electromagnetic field interacts differently in one direction than in another and this affects their propagation pattern in the crystal.

1.3.4 Organic Materials

Besides inorganic compounds such as traditional crystals and oxides, there is a growing interest in organic compounds. Organics promise components that can be easily manufacturable in large quantities and thus at low cost. Certain compounds can be deposited to virtually any type of other material such as glass, plastic, and treated paper. For example, consider organic compounds that can be made into optical organic thin films (OTF). Then, based on fluorescence properties, when a voltage excites their molecular state, they emit light of a specific wavelength, known as *exciton*. The duration of light emission of such compounds is on the order of many microseconds. Among these compounds is *perylene*, which emits blue light; *coumarin-6*, which emits green light; and other compounds that emit different colors. These compounds have high luminescent efficiency at a wide angle. Thus, OTFs may find several optoelectric applications, such as flat thin displays with transparent electrical contacts made of titanium oxides or indium tin oxide (ITO) by deposition.

Other organic compounds, such as *pentacene*, have electrical properties that are suitable for producing field-effect transistors. Pentacene is a simple molecule made of five connected *benzene* rings that form crystals. These compounds may be applicable to portable devices, communications, electronic identification, and others.

In a different endeavor, organic matter is used to extract compounds that can be used in optical and semiconductor fields. For example, corn is used to extract compounds that can be turned into plastic films. Rice hull or coconuts are rich in silicon dioxide, or silica, which can be used for semiconductors or in devices with specific properties. Obviously, the world of organics holds many secrets for the near future.

1.3.5 Photochromaticity

Photochromaticity is the property of some clear materials, either in solution or in plastic film, or in organic crystals (e.g., diarylethene), to change their color upon irradiation

with ultraviolet (UV) light. Photochromic materials return to their clear state upon exposure to visible light.

Of particular importance are certain organic crystals, such as diarylethene, that change not only their color but also their size. It has been found that when diarylethene molecules are irradiated with UV light, each molecule changes by a fraction of a nanometer. However, if several molecules comprise a layer, then the change in thickness of the layer is proportional to the number of molecules, and thus nanometer variation is easily achieved by manipulating the layer thickness.

1.4 LIGHT MEETS MATTER

When light meets matter, its electromagnetic field interacts with the near fields of ions and electrons, and depending on consistency and the structural details of matter interactions take place that may affect the light properties, the material properties, or both. In fact, in many cases light affects matter, which in turn affects light.

1.4.1 Reflection and Refraction: Snell's Law

When a ray impinges on an angle the planar interface of two homogeneous transparent media (e.g., free space and glass), a portion of it will be reflected and the remainder will be refracted (Fig. 1.11).

The *index of refraction* of a transparent medium (n_{med}) is defined as the ratio of the speed of monochromatic light in free space, c , over the speed of the same monochromatic light in a medium (v_{med}):

$$n_{\text{med}} = c/v_{\text{med}}$$

Then, between two mediums (1 and 2), the relationships are true:

$$n_2/n_1 = v_1/v_2$$

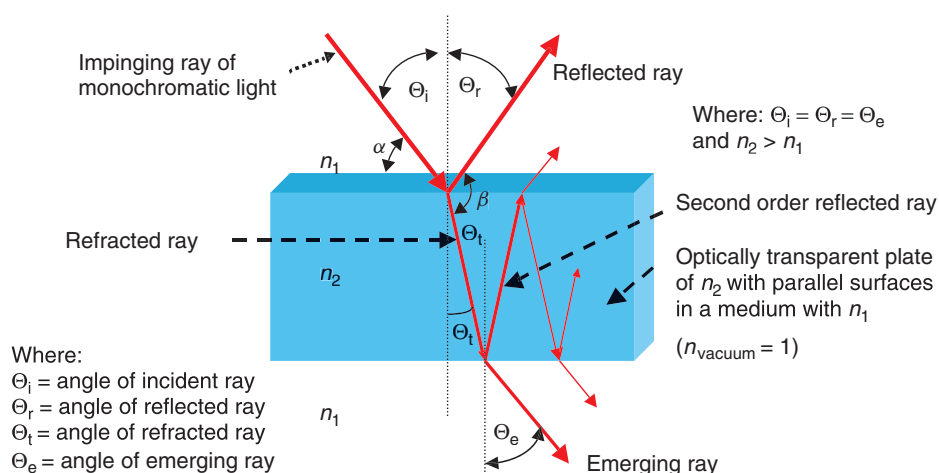


Figure 1.11 Reflection and refraction.

and

$$n_1 \cos \beta = n_2 \cos \alpha$$

where n_1 , v_1 , and n_2 , v_2 are the index of refraction and the speed of light in the two media, and α and β are the angle of incidence and the angle of refraction with respect to the surface of incidence, respectively.

When the angle of incidence is very small, $\cos \alpha = 1 - \alpha^2/2$ and the cosine equation becomes

$$n_1(1 - \beta^2/2) = n_2(1 - \alpha^2/2)$$

The index of refraction, or *refractive index*, for free space has the numerical value of 1, whereas for other materials it is typically between 1 and 2, and in some cases it is greater than 2 or 3.

The reflected portion of monochromatic light is known as Fresnel reflection. The amount of reflected power and the polarization state of the reflected light depend on the polarization state of the incident light, the angle of incidence, and the refractive index difference.

For normal incidence on a single surface, the reflectivity, ρ , is given by the Fresnel equation

$$\rho = (n - 1)^2 / (n + 1)^2$$

If the absorption of the material over a length d is A , which is calculated from the absorption coefficient (absorbed power per cm) α , then the internal material transmittance, τ_i , is defined as the inverse of the material absorption. For internal transmittance τ_i , the external input–output transmittance (taking into account the reflectivity, ρ by the surface) is given by

$$\tau = [(1 - \rho)^2 \tau_i] / [1 - \rho^2 \tau_i^2]$$

The following basic relationships are also useful:

Speed of light in free space:	$c = \lambda f$
Speed of light in medium:	$v_{\text{med}} = \lambda_{\text{med}} f$
Index of refraction:	$n_1/n_2 = \lambda_2/\lambda_1$

where f is the frequency of light and λ is its wavelength. Both the letter f and the Greek ν are used for frequency. Here we use f to eliminate confusion between v (for speed) and ν (for frequency).

Snell's law relates the ratio of index of refraction with the angle of the incident (Θ_i) and with the refracted (Θ_t) rays (Fig. 1.11):

$$n_2/n_1 = \sin \Theta_i / \sin \Theta_t$$

1.4.2 Critical Angle

Critical angle, Θ_{critical} , is the (maximum) angle of incidence of light (from a material with high to low refractive index) at which light stops being refracted and is totally reflected (Fig. 1.12). As the angle of incidence approaches the critical angle, the refracted ray becomes parallel to the surface (and without added phase shift) and

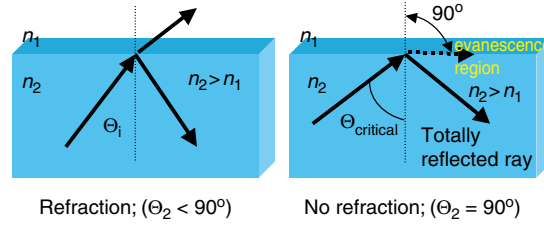


Figure 1.12 Definition of critical angle.

is termed *evanescent*. Beyond that point, there is no refracted ray. The critical angle depends on the refractive index and the wavelength of light.

$$\sin \Theta_{\text{critical}} = n_1/n_2$$

for $n_1 = 1$ (air), then

$$\sin \Theta_{\text{critical}} = 1/n_2$$

In certain cases, a gradual variation of refractive index may take place. When light rays enter from one side, rays are refracted such that they may emerge from the same side they entered. This is the case of the natural phenomenon known as a *mirage*.

Although to this day the index of refraction has been considered to be only positive and greater than +1, the value of vacuum, researchers and theoreticians have been trying to learn, what would have happen to light if there were materials with negative values. Materials with negative values would solve several issues in optics and would find several important applications in the optics and photonic areas.

1.4.3 Antireflection

In optical communications, it usually is desirable to have all optical power of a signal coupled in the fiber or an optical component and to have zero or minimal reflected power. This is accomplished by using *antireflection coatings* at the interface air–component.

Antireflection coatings consist of one or more thin layers (film) of material, each layer having a specific thickness and a specific refractive index. A transition from one layer to another represents an index of refraction discontinuity. Thus, as a beam of light travels through the layers, it is partially reflected by the refractive index discontinuities. These reflections, on their way back interfere destructively, canceling each other out, and thus no reflection emerges from the layers.

For example, to minimize the reflected optical power of incident light on glass, the layer that interfaces glass with air has a low refractive index.

In an arrangement of a single antireflection thin film, two requirements must be satisfied:

$$n_2 d_2 = m\lambda/4$$

and

$$n_2 = \text{sqrt}(n_1 \cdot n_3)$$

where d_2 is the film thickness and m is an odd integer (1,3,5, ...).

In practice, it is very difficult to find materials with a refractive index n_2 , as calculated by the last relationship; if n_1 is for air ($=1$) and n_3 is for standard glass ($=1.52$), then n_2 is calculated to be 1.23. However, it is very difficult to find a material with this exact value, and the closest to it is cryolite with a refractive index at 1.35; consequently, the cryolite film will also be partially reflective. As a result, complex structures with more layers are used (approximately 40–50 layers) to construct antireflective films.

As an example of an antireflecting film, consider the two-layer structure that consists of a first layer of MgF_2 ($n = 1.38$) and a second layer of PbF_2 ($n = 1.7$) deposited on a glass plate ($n = 1.5$). In this structure, each layer has a thickness of a quarter-wavelength such that rays reflected by each layer interfere destructively. As a consequence, the *extinction of reflection* at the designed wavelength is very high. This means that the antireflection coating is also wavelength-selective. Because of the wavelength selectivity of antireflecting films, they are also used as optical filters (see Filters).

1.4.4 Prisms and Superprisms

Consider that two planes of a plate intersect each other at an angle Θ_2 to form a *prism*. When a polychromatic narrow beam of light impinges on one of the prism surfaces, each frequency component is refracted at different angle. As each frequency reaches the other surface, it is also refracted at a different angle again. Thus, the output from the second surface of the prism consists of frequency components separated by a small angle.

The angle of each frequency component with the original composite beam is known as the *angle of deflection*, ε ; that is, the angle of deflection varies with frequency (Fig. 1.13).

In Figure 1.13, note that when $n_1 = 1$, then

$$n_2 = \{\sin[(\Theta_2 + \varepsilon)/2]\} / \sin(\Theta_2/2)$$

The following prism laws hold (see figure 1.17 for Θ_λ):

- The angle Θ_λ increases as the index of refraction increases.
- The angle Θ_λ increases as the prism angle Θ_2 increases.

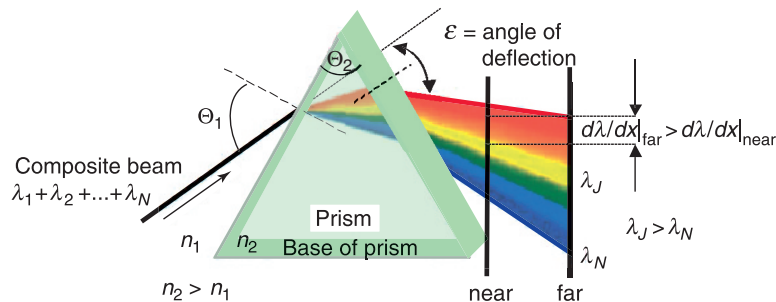


Figure 1.13 The angular deflection varies with optical frequency. With common prisms, an acceptable resolution is achieved only at impractical far distances.

- The angle Θ_λ increases as the angle of incidence Θ_1 increases.
- The angle Θ_λ increases as the frequency of light increases (or the wavelength decreases).

When the angle of incidence Θ_1 varies, so does the angle of deflection ε and in a nonlinear manner. For a given wavelength and prism, it is noted that (Fig. 1.14):

- There is a minimum angle of deflection below which no light emerges.
- The deflection angle ε is the same for two different values of angle of incidence Θ_1 .

The angular separation of each frequency component is known as *angular dispersion* and is given by

$$d\theta/d\lambda = [(d\theta/dn)(dn/d\lambda)]$$

where n is the index of refraction and λ is the wavelength.

The first factor of the latter product depends on the geometry of the prism, whereas the second factor depends on the material.

Amici prisms are right-angle prisms that have an interesting property used in many optical instruments and experimental apparatus; they cause image inversion as in Figure 1.15.

The angular dispersion of common prisms is not substantial enough to be used to advantage in optical components for communications. However, certain artificial crystalline structures, known as *superprisms*, promise to remedy this. Superprisms consist of an artificial optic structure known as a *photonic crystalline* structure. Photonic crystalline optics, a relatively new field, is a periodic dielectric lattice structure fabricated

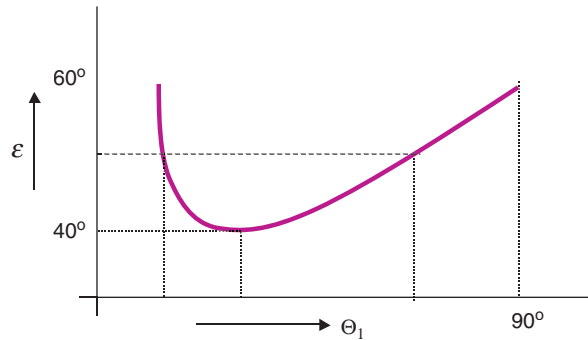


Figure 1.14 Variation of angle of deflection ε versus angle of incidence Θ_1 .

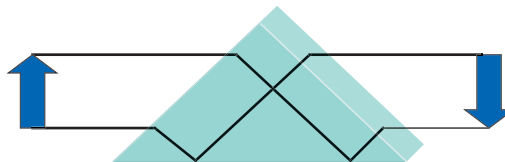


Figure 1.15 Principles of the Amici prism.

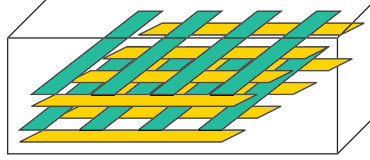


Figure 1.16 Photonic crystalline optics are based on three-dimensional periodic lattices. This lattice emulates the exoskeleton structure (and the iridescent properties) of certain fishes and butterflies.

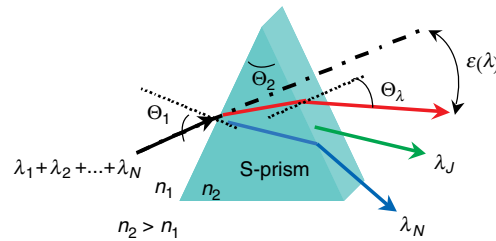


Figure 1.17 Prisms made with photonic crystalline optics exhibit angle of deflection 500 times that of ordinary prisms.

on Si using nanotechnology (Fig. 1.16). The periodicity of the crystalline lattice is three-dimensional and is several tens of nm (reported at 180 nm). This periodicity consists of three-dimensionally distributed bands and gaps. Depending on periodicity, an optical frequency range is defined within which optical frequencies (wavelengths) are or are not permitted to propagate.

Photonic crystalline structures may act as energy band-gap filters (i.e., filters that do not pass photons within certain energy range). They also may act as highly dispersive structures.

Photonic crystalline structures are solid-state grown epitaxially (such as SiO₂ on Si); they are very small and have superb diffraction properties. Formed like a prism, photonic crystalline structures exhibit an angular dispersion that is approximately 500 times that of conventional prisms (Fig. 1.17). Their structure is the result of close examination of the iridescent hairlike spines of the sea mouse (genus *Aphrodita*), as well as of certain butterflies and caterpillars. Therefore, even though we claim that photonic crystals are synthetic, in reality nature was first, millions of years ago.

In addition to solid-state materials, other materials such as block copolymers and polystyrene have been used on an experimental basis.

1.4.5 Propagation of Light

As already described, when light enters matter, it is reflected by its surface, it is refracted by the matter, and its velocity changes as well as its wavelength, but not its frequency. This is important to remember throughout this book.

1.4.5.1 Phase Velocity

A monochromatic (single ω or λ) wave that travels along the fiber axis is described by

$$E(t, x) = A \exp[j(\omega t - \beta x)]$$

where A is the amplitude of the field, $\omega = 2\pi f$, and β is the propagation constant.

Phase velocity, v_ϕ , is defined as the velocity of an observer that maintains constant phase with the traveling field (i.e., $\omega t - \beta x = \text{constant}$).

Replacing the traveled distance x within time t , $x = v_\phi t$, the phase velocity of the monochromatic light in the medium is

$$v_\phi = \omega/\beta$$

1.4.5.2 Group Velocity

When a signal is transmitted in a dispersive medium, it is necessary to know its speed of propagation. A continuous sine wave does not provide any meaningful information because a real optical signal consists of a band of frequencies in a narrow spectrum. Moreover, each frequency component in the band travels (in the medium) at a slightly different phase. This is explained mathematically as follows:

Consider an amplitude-modulated optical signal, e_{AM} , traveling along the fiber

$$e_{\text{AM}}(t) = E[1 + m \cos(\omega_1 t)] \cos(\omega_c t)$$

where E is the electric field, m is the modulation depth, ω_1 is the modulation frequency, ω_c is the frequency of light (or carrier frequency), and $\omega_1 \ll \omega_c$.

Trigonometric expansion of this expression results in three frequency components with arguments:

$$\omega_c, \quad \omega_c - \omega_1, \quad \text{and} \quad \omega_c + \omega_1$$

Each component travels along the fiber at a slightly different phase velocity (β_c , $\beta_c - \Delta\beta$, $\beta_c + \Delta\beta$, respectively) accruing a different phase shift. Eventually, all three components form a spreading envelope that travels along the fiber with a phase velocity

$$\beta(\omega) = \beta_c + (\eta\beta/\eta\omega \mid \omega = \omega_c)\Delta\omega = \beta_c + \beta' \Delta\omega$$

Group velocity, $v_g = c/n_g$, is defined as the velocity of an observer that maintains constant phase with the group traveling envelope (i.e., $\omega t - (\Delta\beta)x = \text{constant}$).

Replacing x by $v_g t$, the group velocity is expressed by

$$v_g = \omega/\Delta\beta = \eta\omega/\eta\beta = 1/\beta'$$

where β is the propagation constant and β' is the first partial derivative with respect to ω (remember that in this case ω is not purely monochromatic, and thus the derivative of ω is not zero).

1.4.5.3 Impact of Impurities

Impurity is the presence of unwanted elements or compounds in matter. During the purification process of matter, certain undesired elements cannot be completely removed and traces remain. These undesired elements alter the optical characteristics of transparent materials, such as fiber, causing an absorptive or scattering effect that amounts to optical throughput loss.

A similar effect is caused by small fluctuations of the refractive index, which is on the order of the wavelength of light through it. This effect is known as *Rayleigh scattering*.

Iron, copper, cobalt, and oxides are some examples of impurities that affect optical absorption. For instance, blue glass is the result of cobalt or copper in glass (it looks blue because it absorbs all wavelengths except the blue). Another “impurity” is the OH^- , which is responsible for increased fiber absorption at approximately 1400 nm.

In special cases, specific elements are intentionally introduced to modify the optical propagation and/or excitation properties of matter, such as dispersive fibers, fiber amplifiers, and so on.

1.4.5.4 Impact of Microcracks

Microcracks may be viewed as abrupt discontinuities in the index of refraction of the material and with surfaces that are not necessarily plane or parallel. Microcracks in the crystallized matrix of matter or in amorphous solid matter are generated as a result of stresses (mechanical or thermal) or material aging.

Microcracks may have an adverse effect on the propagation of light as well as on the strength of the material. In fact, if the crack gap (the distance between the crack surfaces) increases because of tensile forces on the order of a wavelength ($\lambda/4$, $\lambda/2$), it may act as an uninvited filter, which may not be what light would expect to encounter.

1.4.5.5 Impact of Mechanical Pressure

When mechanical pressure is applied on matter, its internal microstructure is disturbed, which causes a variation of the refractive index with a distribution determined by the distribution of pressure. This variation affects the propagation of light in matter, and in general pressure points are undesirable points of optical disturbance. Similarly, when fiber is bent, the outer periphery experiences stretching and the inner periphery undergoes compression, and this also affects optical propagation. Thus, the safe bend radius recommended by ITU-T is 37.5 mm (ITU-T G.652, para. 5.5, note 2).

1.4.5.6 Impact of Temperature Variation

Temperature variations affect the properties of any material. They affect its physical, mechanical, electrical, magnetic, chemical, and crystalline (if any) properties. As a result, the index of refraction also is affected, which impacts the propagation characteristics of light. Clearly, temperature variations are undesirable in optical communications, although there are cases where they have been used productively to control the refractive index of optical devices.

1.4.6 Diffraction

Consider a screen having a small hole with sharp edges at the periphery and dimensions comparable to those of wavelength light (this may be an aperture, a slit, or a grating). Consider also a parallel (collimated) and monochromatic beam, known as *light from a source at infinity*, directed to this screen (or diaphragm) and a second screen behind it at distance d (Fig. 1.18). Since light travels straight in free space and a small round projection is expected, D_{EXP} , a wider projection is seen instead, D_{ACT} , with concentric rings around it. The smaller the diameter of the hole, the wider the projection. This phenomenon is attributed to interference at each edge point of the hole, which acts like a secondary source resulting in *diffraction*; this is also known as the *phenomenon of*

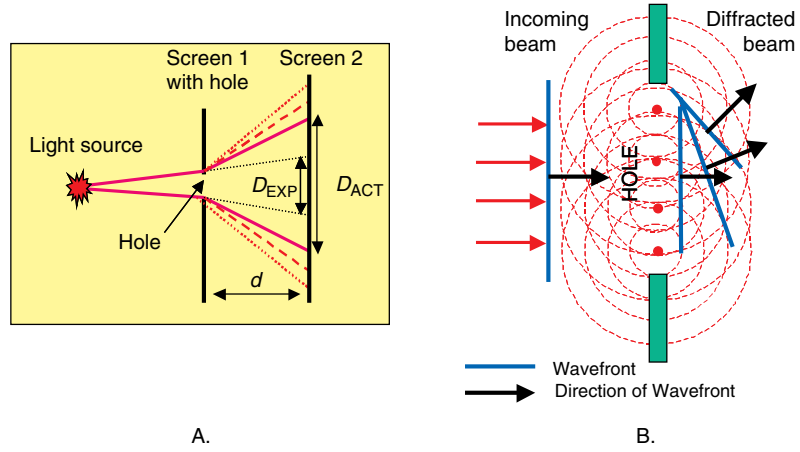


Figure 1.18 Diffraction by a hole in the order of wavelength; A. Experiment, and B. Based on the Huygens–Fresnel principle, secondary sources form a multiplicity of possible waveforms at specific angles.

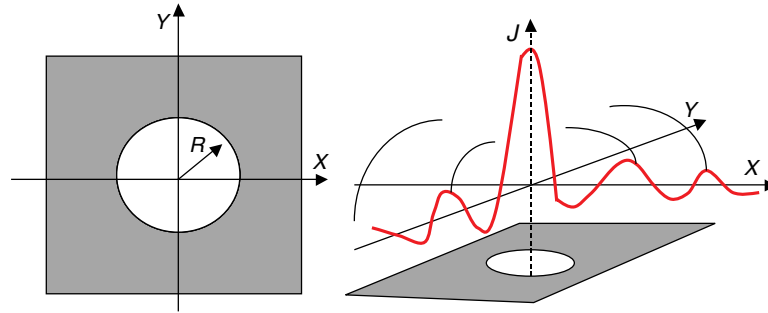


Figure 1.19 Intensity distribution of diffracted light by a round hole (the formed rings on a screen are known as “Airy rings”).

Fresnel. Moreover, the intensity of rings, J , decreases with distance from the center of the projection (Fig. 1.19). This pattern is also known as *Fraunhofer diffraction*.

According to Huygens’s principle, the incident wave excites coherent secondary waves at each point of the wavefront. All these waves interfere with each other and cause the diffraction pattern. The pure mathematical analysis of diffraction is studied by approximating the scalar Helmholtz equation in which the wavefront is a spherical function; this analysis is quite involved and it beyond the scope of this book. However, to illustrate this point, if a plane wave is incident on an aperture, then the radiant intensity per unit of projected area of the source viewed from that direction (i.e., the radiance, L), is described by

$$L(\alpha, \beta - \beta_0) = \gamma_0(\lambda^2/A)[F\{U(x, y, z = 0) \exp(i2\pi\beta_0 y)\}]^2 (\text{W/sr-m}^2)$$

where α , β , and γ are propagation vectors in the x , y , and z directions, respectively; A is the area of the diffracting aperture; λ is the wavelength; F is the Fourier transform; and U is the complex amplitude distribution emerging from the aperture (hence $z = 0$).

Integrating the above, invoking the conservation of energy theorem and using Parseval's (or Rayleigh's) theorem, which converts the integral of the squared modulus of a function $f(x)$ to the integral of the squared modulus of its Fourier transform $f(\omega)$,

$$\int |f(x)|^2 dx = (1/2\pi) \int |f(\omega)|^2 d\omega$$

where the integrals are from $-$ to $+$ infinity, then the radiance is expressed by

$$L(\alpha, \beta - \beta_0) = K \gamma_0 (\lambda^2 / A) |F\{U(x, y, z = 0) \exp(i2\pi\beta_0 y)\}|^2 \text{ for } a^2 + b^2 \leq 1$$

$$L(\alpha, \beta - \beta_0) = 0 \text{ for } a^2 + b^2 > 1$$

where K is a normalization constant.

Now let us consider that the aperture is not round but a narrow rectangular slit of height h and width w . In this case, the monochromatic collimated beam passes through it and due to refraction, the projection on a screen is a rectangle rotated by 90° ; that is, the refracted pattern is narrow in the direction in which the aperture is wide. Moreover, because of two-dimensional Fourier expansion, the refracted light forms many secondary rectangles in the X-Y plane of the screen, with intensity fading away from the axis of symmetry (Fig. 1.20). This is also known as *Fraunhofer diffraction* of a rectangular aperture. The condition for these rectangles on the screen is

$$R(x, y) = \text{Rect}(x/w_0) \text{Rect}(y/h_0) = 1, \quad \text{for } |x| < w_0/2 \text{ and } |y| < h_0/2,$$

and

$$R(x, y) = 0 \text{ elsewhere.}$$

Theoretically speaking, when a diffracting aperture is illuminated by a uniform monochromatic plane wave, λ , the total radiant power, P_{TR} , emanating from the diffracting aperture is calculated using Rayleigh's theorem and Fourier transforms:

$$P_{\text{TR}} = \lambda^2 \iint |U_0(x, y; 0) \exp(i2\pi\beta y)|^2 dx dy$$

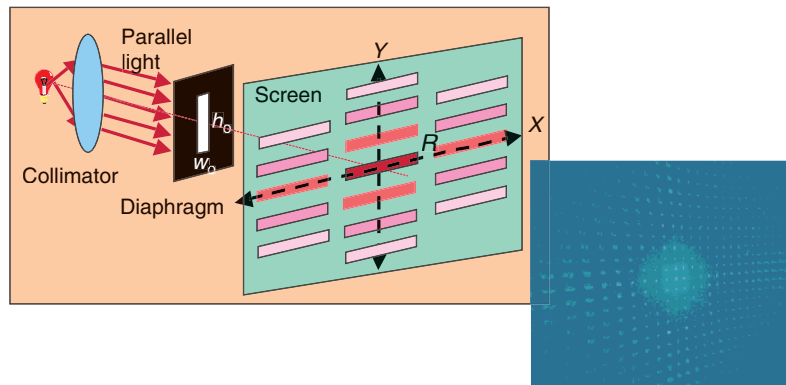


Figure 1.20 Diffraction at infinity.

where U_0 is the function of the complex amplitude distribution emerging from the diffracting aperture, β is the propagating vector, and $\{x, y\}$ are the Cartesian coordinates; both integrals are from $-\infty$ to $+\infty$.

This discussion applies to monochromatic light. If light were polychromatic, then each color (frequency) component would be diffracted differently (i.e., at a different angle). Then, fringes on the screen would be of different color but overlapping. The corollary is that the angle of diffraction depends on the frequency (color) of light.

If in the preceding experiment, instead of one slit or hole there was an array of parallel slits, then light would be diffracted in certain angles due to interference among the slits. This diffraction of light is known as *diffraction by transmission*. Interesting phenomena take place when slits are positioned in a matrix configuration. Diffraction then takes place in a two-dimensional plane and the fringe pattern depends on the size, shape, density, and topological arrangement of the slits.

If in the preceding discussion, instead of slits in the diaphragm there are parallel grooves each at a width comparable to wavelength, then the above discussion of diffraction, as well as the same theory, applies. Instead, now light does not pass through but it diffracts back at certain angles that depend, among other factors, on the wavelength. All other factors being equal, each wavelength diffracts at different angles. This is known as *diffraction by reflection*.

We have discussed slits, holes, and grooves. What it really means to light when it encounters them is a periodic variation of the refractive index, in the case of a slit or hole the refractive index is 1 as opposed to the refractive index of the diaphragm, which is >1 or infinity. Having said that, one can then take a transparent plate and form on it parallel strips of another transparent material but of a different refractive index. A diffraction pattern is still observed. All these slotted, grooved, or stripped plates are known as gratings.

A simple, quick, and convincing experiment, which I often demonstrate in lectures, involves a CD-ROM. When light impinges in an angle on the CD-ROM surface, one sees many colors as a result of diffraction of ambient light in the visible spectrum by the “grooves” of the CD-ROM.

1.4.7 Polarization

Polarization Vector. If we examine the electrical state of matter on a microscopic level, we discover that it consists of charges, the distribution of which depends on the presence or absence of external fields. If we assume that for every positive charge there is a negative charge, then we may think that each positive–negative charge constitutes an electric dipole. The electric moment of a dipole at some distance is a function of distance and charge density. For a distribution of electric dipoles, *the electric dipole moment per unit volume is defined as the polarization vector P .*

Transverse Wave. Two relationships describe the propagation of light in nonconducting media:

$$E(r, t) = \varepsilon_1 E_0 e^{-j(\omega t - k \cdot r)}$$

and

$$H(r, t) = \varepsilon_2 H_0 e^{-j(\omega t - k \cdot r)}$$

where ε_1 and ε_2 are two constant unit vectors that define the direction of each field, k is the unit vector in the direction of propagation, and E_o and H_o are complex amplitudes, which are constant in space and time.

Assuming a wave propagating in a medium without charges, then $\nabla E = 0$ and $\nabla H = 0$. Based on this, the product of unit vectors is:

$$\varepsilon_1 \cdot k = 0 \quad \text{and} \quad \varepsilon_2 \cdot k = 0$$

That is, the electric (E) field and the magnetic (H) field are perpendicular to the direction of propagation k (Fig. 1.2). Such a wave is called a *transverse wave*.

Circular, Elliptical, and Linear Polarization. Polarization of electromagnetic waves is a complex subject, particularly when light propagates in a medium with a different refractive index in different directions. As light propagates through a medium, it enters the fields of nearby dipoles and field interaction takes place. This interaction may affect the strength of the electric and/or magnetic fields of light differently in certain directions so that the end result may be a complex field with an elliptical field distribution or a linear field distribution.

For example, the electric field E becomes the linear combination of two complex fields E_{ox} and E_{oy} , the two components in the x and y directions of a Cartesian coordinate system, such that

$$E(r, t) = (\varepsilon_x E_{ox} + \varepsilon_y E_{oy}) e^{-j(\omega t - k \cdot r)}$$

This relationship implies that the two components, E_{ox} and E_{oy} , vary sinusoidally; they are perpendicular to each other; and there may be a phase between them, ϕ . From this relationship, a vector is defined, which is known as the *Jones vector*; the Jones vector $J = [J_1, J_2]$ is related to the radiation aspects of the wave:

$$J = \begin{bmatrix} E_{ox} & e^{j\phi_x} \\ E_{oy} & e^{j\phi_y} \end{bmatrix}$$

In this case, the dielectric quantity ε is described by a tensor that generally has different values in the three axes:

$$\varepsilon = \begin{bmatrix} \varepsilon_x & 0 & 0 \\ 0 & \varepsilon_y & 0 \\ 0 & 0 & \varepsilon_z \end{bmatrix} = \varepsilon_o \begin{bmatrix} n_x^2 & 0 & 0 \\ 0 & n_y^2 & 0 \\ 0 & 0 & n_z^2 \end{bmatrix}$$

Now, from

$$\nabla^2 E = (1/v^2)(\partial^2 E / \partial t^2)$$

and

$$E(r, t) = \varepsilon E_o e^{-j(\omega t - k \cdot r)}$$

one obtains

$$k \times (k \times E_o) + \mu_o \varepsilon \omega^2 E_o = 0$$

or

$$[k \times (k \times I) + \mu_0 \varepsilon \omega^2][E_0] = 0$$

where I is the identity matrix. The latter is a vector equation equivalent to a set of three homogeneous linear equations with unknowns the components of E_0 , E_{0x} , E_{0y} and E_{0z} . In a typical case, the component E_{0z} along the axis of propagation is equal to zero.

This vector equation determines a relationship between the vector k (k_x, k_y, k_z), the angular frequency ω , and the dielectric constant ε ($\varepsilon_x, \varepsilon_y, \varepsilon_z$), as well as the polarization state of the plane wave.

The term $[k \times (k \times I) + \mu_0 \varepsilon \omega^2]$ describes a three-dimensional surface. As the (complex) electric field is separated into its constituent components, each component may propagate in the medium at a different phase. The phase relationship as well as the magnitude of each vector define the *mode of polarization*.

If E_{0x} and E_{0y} have the same magnitude and are in phase, then the wave is called *linearly polarized*.

If E_{0x} and E_{0y} have a phase difference (other than 90°), then the wave is called *elliptically polarized*.

If E_{0x} and E_{0y} have the same magnitude, but differ in phase by 90° , then the wave is called *circularly polarized*.

For example, in circularly polarized light the wave equation (propagating in the z direction) becomes:

$$E(r, t) = E_0(\varepsilon_x \pm j\varepsilon_y) e^{-j(\omega t - k \cdot r)}$$

Then, the two real components (in the x and in the y directions) are:

$$E_x(r, t) = E_0 \cos(k \cdot r - \omega t)$$

and

$$E_y(r, t) = \pm E_0 \cos(k \cdot r - \omega t)$$

These equations indicate that at a fixed point in space the fields are such that the electric vector is constant in magnitude but rotates in a circular motion at a frequency ω . The term $\varepsilon_x + j\varepsilon_y$ indicates a counterclockwise rotation (when facing the oncoming wave), and this wave is called a *left circularly polarized* wave or a wave with *positive helicity*. The term $\varepsilon_x - j\varepsilon_y$ indicates a clockwise rotation (when facing the oncoming wave), and this wave is called a *right circularly polarized* wave or a wave with *negative helicity*.

Using the notion of positive and negative helicity, E can be rewritten as

$$E(r, t) = (\varepsilon_+ E_+ + \varepsilon_- E_-) e^{-j(\omega t - k \cdot r)}$$

where E_+ and E_- are complex amplitudes denoting the direction of rotation.

If E_+ and E_- are in phase but have different amplitude, the last relationship represents an *elliptically polarized* wave with principal axes of the ellipse in the directions ε_x and ε_y .

Then, the ratio semimajor-to-semiminor axis is $(1+r)/(1-r)$, where $E_-/E_+ = r$.

If the amplitudes E_+ and E_- have a difference between them, $E_-/E_+ = r e^{j\alpha}$, then the ellipse traced out by the vector E has its axes rotated by an angle $\phi/2$.

When $E_-/E_+ = r = \pm 1$, the wave is *linearly polarized*.

Thus, we have come to the same definition of polarization modes. This discussion for the electric field E can also be repeated for the magnetic field H .

In a mathematical analysis, it is shown that the displacement vector yields a vector equation similar to the one above, which also yields a refractive index with an ellipsoidal distribution or an ellipsoid of revolution around the z axis (the axis of propagation). The ellipsoidal distribution is a mathematical result from the analysis of the displacement vector D and the electric field E that is related by

$$D = \varepsilon_0 \varepsilon E$$

where ε is a tensor (a 3×3 matrix with elements $\varepsilon_{xx}, \varepsilon_{xy}, \varepsilon_{xz}, \varepsilon_{yx}, \varepsilon_{yy}, \varepsilon_{yz}, \varepsilon_{zx}, \varepsilon_{zy}, \varepsilon_{zz}$). Because of the conservation of energy, the tensor is symmetric, that is, $\varepsilon_{xy} = \varepsilon_{yx}$, $\varepsilon_{xz} = \varepsilon_{zx}$, and $\varepsilon_{yz} = \varepsilon_{zy}$, which greatly simplifies the mathematical derivation of the tensor expression in the three displacement components:

$$D_x = \varepsilon_0 \varepsilon_x E_x, D_y = \varepsilon_0 \varepsilon_y E_y, \text{ and } D_z = \varepsilon_0 \varepsilon_z E_z$$

Based on this, the energy, W , stored in the electric field is then expressed by

$$W = (1/2)DE = \varepsilon_0(D_x^2/\varepsilon_x + D_y^2/\varepsilon_y + D_z^2/\varepsilon_z)$$

In this relationship, the parenthesis is of the form $(x^2/a + y^2/b + z^2/c)$, which defines an ellipsoid, and hence the name of the ellipsoidal refractive index of nonlinear optical crystals. Remember that a cross section through the center of an ellipsoid can yield an ellipse or a circle. In addition, a sphere for which $a = b = c$ is a special case of an ellipsoid (this is also the definition of isotropy).

In simple terms, the electromagnetic wave nature of monochromatic light implies that the electric field and the magnetic field are in quadrature and time phase. When created light propagates in free space, the two fields change sinusoidally, and each one lies on one of two perpendicularly to each other planes, as in Figure 1.2. When light enters matter, then depending on the displacement vector distribution in matter (and hence the dielectric and the refractive index), light (its electric and/or magnetic field) will interact with it in different ways. If the two planes (of the electric or magnetic field) are in a Cartesian coordinate system and fixed, then light is *linearly polarized*. If on the other hand, the planes keep changing in a circular (corkscrew-like) motion and the (vectorial) fields remain at the same intensity, then light is *circularly polarized*. If in addition to it, the intensity of the field changes monotonically, then light is *elliptically polarized*. Figure 1.21 illustrates some polarization distributions around the axis of propagation of an electromagnetic plane wave.

If we consider that light is separated into two components, one linearly polarized, I_P , and one unpolarized, I_U , the degree of polarization, P , is defined as

$$P = I_P/(I_P + I_U)$$

Light may be polarized when it is reflected, refracted, or scattered. In polarization by reflection, the degree of polarization depends on the angle of incidence and the

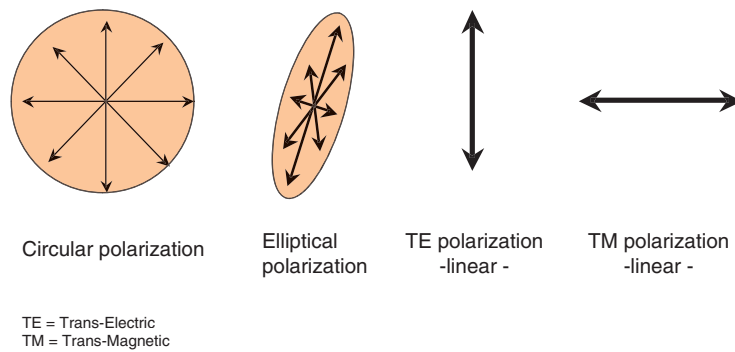


Figure 1.21 Examples of polarization modes of an E - M wave (direction of light is perpendicular to page).

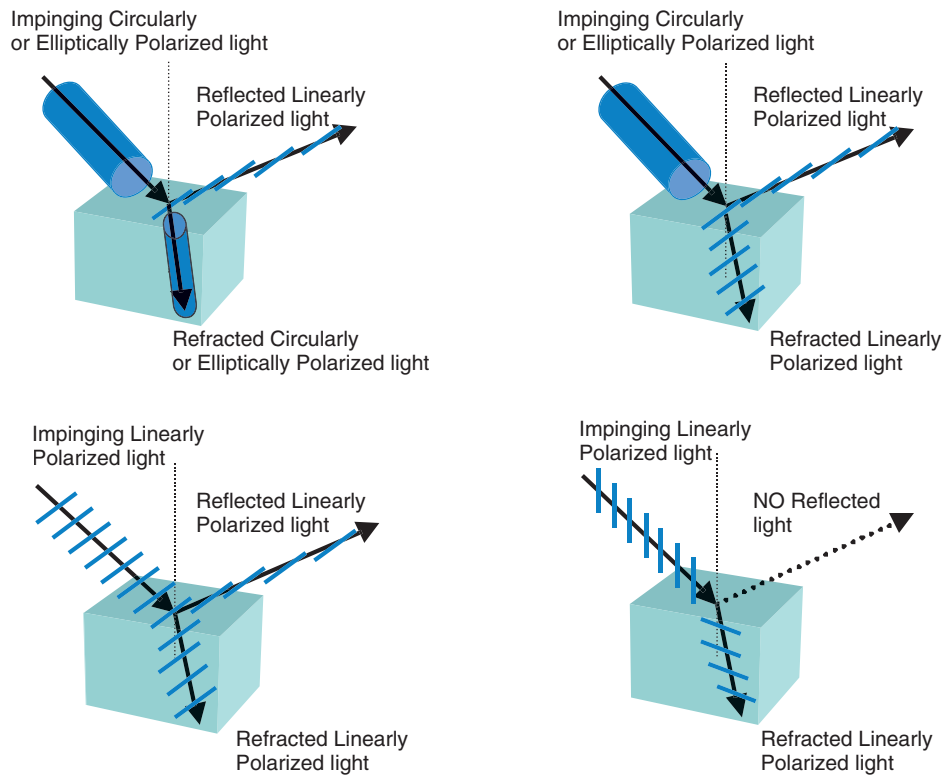


Figure 1.22 Four examples of polarization by reflection and refraction.

refractive index of the material, given by *Brewster's law*:

$$\tan(I_P) = n$$

where n is the refractive index and I_P is the polarizing angle. Figure 1.22 illustrates some examples of reflected and refracted polarization.

The Stokes Vector. The Jones vector describes the polarized radiation components of the E - M wave. However, in the general case, the propagating wave may consist of a polarized component and a nonpolarized component. This is described by the Stokes vector $S = [S_0, S_1, S_2, S_3]$ in which each of the four parameters is defined in terms of the two component fields E_{ox} and E_{oy} and the phase difference ϕ , as

$$\begin{aligned} S_0 &= E_{ox}^2 + E_{oy}^2 \\ S_1 &= E_{ox}^2 - E_{oy}^2 \\ S_2 &= 2E_{ox}E_{oy} \cos \phi \\ S_3 &= 2E_{ox}E_{oy} \sin \phi \end{aligned}$$

and are related between them as

$$S_0^2 = S_1^2 + S_2^2 + S_3^2$$

Based on this definition, light intensity, degree of polarization, ellipticity, amplitude ratio of the field components in the x and y directions and their phase difference, and polarization azimuth are expressed in terms of the Stokes parameters as

$$\begin{aligned} I(\text{intensity}) &= S_0 \\ P(\text{degree of polarization}) &= \sqrt{S_1^2 + S_2^2 + S_3^2}/S_0 \\ \varepsilon(\text{ellipticity}) &= \frac{1}{2} \arctan S_3 / \sqrt{S_1^2 + S_2^2} \\ E_{oy}/E_{ox}(\text{amplitude ratio}) &= \sqrt{(S_0 - S_1)/(S_0 + S_1)} \\ \phi(\text{phase difference}) &= \phi_y - \phi_x = \arccos[S_2/(S_0^2 - S_1^2)] \\ \alpha(\text{azimuth}) &= \frac{1}{2} \arctan(S_2/S_1) \end{aligned}$$

Relationship between Jones and Stokes Vectors. The relationship for specific polarization states of the Jones and Stokes vectors are:

$$\begin{aligned} \text{Unpolarized light: } J &= [\text{not defined}], S = [1, 0, 0, 0] \\ \text{Circular polarized right: } J &= \sqrt{2}^{-1} [1, i], S = [1, 0, 0, 1] \\ \text{Circular polarized left: } J &= \sqrt{2}^{-1} [1, -i], S = [1, 0, 0, -1] \\ \text{Linear polarization horizontal: } J &= [1, 0], S = [1, 1, 0, 0] \\ \text{Linear polarization vertical: } J &= [0, 1], S = [1, -1, 0, 0] \\ \text{Linear polarization } +45^\circ : J &= \sqrt{2}^{-1} [1, 1], S = [1, 0, 1, 0] \\ \text{Linear polarization } -45^\circ : J &= \sqrt{2}^{-1} [1, -1], S = [1, 0, -1, 0] \end{aligned}$$

1.4.7.1 The Faraday Effect

Certain materials exhibit a particularly optical nonlinear behavior manifested by a polarization phenomenon known as *photorefraction*. Photorefraction is the phenomenon by which the polarization plane of light is caused to rotate (Fig. 1.23). This phenomenon is also known as the *Faraday effect*. Devices based on the Faraday effect are known as *rotators*. The rotation of polarization is also known as *polarization mode shift*, θ . This is explained as follows:

Plane-polarized light upon entrance in the *photorefractive* medium is decomposed in two circularly polarized waves rotating in opposite directions and traveling in the

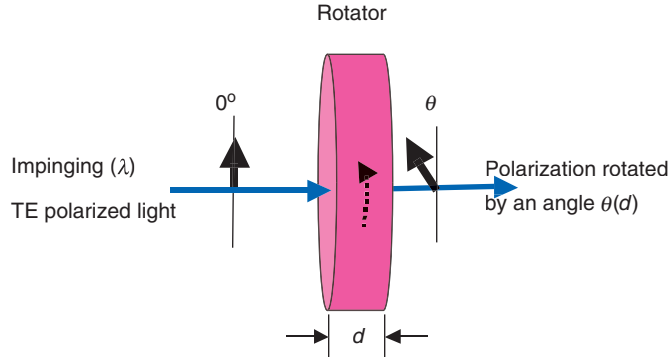


Figure 1.23 Principle of polarization rotator — The Faraday effect.

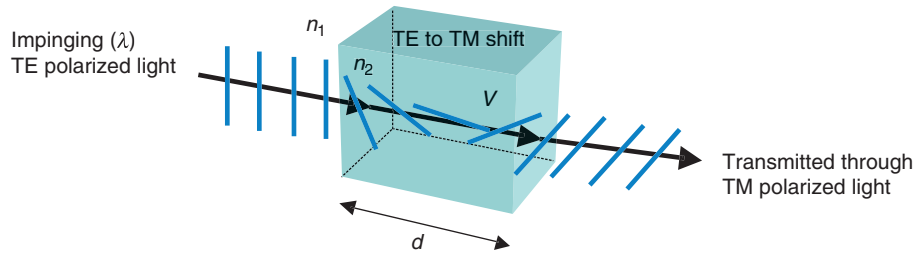


Figure 1.24 Polarization shift from TE to TM mode.

medium at different speeds. Thus, a phase between the two is created, increasing linearly the more it travels in the medium. The two waves recombine upon exiting the medium, producing a wave but with a polarization plane shifted (or rotated) by an angle relative to its polarization at the entrance. The amount of mode shift depends on the thickness of the medium, d (cm), on the magnetic field H (Oersted), and a material constant V , known as the *Verdet constant* (min/cm-Oe), expressed by:

$$\theta = V H d$$

Based on the above, devices of material with a large Verdet constant and a large thickness may be made such that when in a strong magnetic field can shift the polarization mode from TE to TM (Fig. 1.24).

Among solid photorefractive materials are the α -quartz and crystallized *sodium chlorate*. Among liquid photorefractive materials is the water solution of *cane sugar*, and among gaseous materials is *camphor* vapor.

1.4.7.2 The Poincare Sphere

The interaction of light with matter affects the state (or states) of polarization (SoP). In general, a state of polarization (SoP) with azimuth α and ellipticity ε is expressed by

$$\text{SoP} = \begin{vmatrix} 1 + \cos(2\alpha) \cos(2\varepsilon) \\ \cos(2\alpha) \sin(2\varepsilon) + i \sin(2\alpha) \end{vmatrix}$$

Under certain circumstances, the SoP of a wave changes (rotates) as it travels through a medium; such change is associated with delay. When the rotation is 90° , it results in two orthogonal SoPs (one before and one after the rotation). Two mutually orthogonal SoPs, both at equal intensity, result in a depolarized field.

Described in terms of the Stokes parameters, the unpolarized part $S_0 - \sqrt{(S_1^2 + S_2^2 + S_3^2)}$ in the Poincare sphere is left out and only the polarized part is considered. The three Stokes' parameters on terms of the azimuth ε and ellipticity α are expressed by:

$$S_1 = \cos(2\varepsilon) \cos(2\alpha)$$

$$S_2 = \cos(2\varepsilon) \sin(2\alpha)$$

$$S_3 = \sin 2\varepsilon$$

The Poincare sphere is a graphical representation of all possible SoPs; each point on the sphere's surface is a SoP defined by S . As the SoP changes, the point S on the surface defines a trajectory on the Poincare sphere; the trajectory is directly related to the retardation experienced by the field components. If the sphere is defined by the three axes x , y , and z , then a linear retardation without axis rotation moves S on a circle with plane perpendicular to the x -axis; the arc traveled on the circle due to polarization rotation equals the amount of linear retardation. A linear retardation with axis rotation by θ moves S on a circle with plane perpendicular to an axis x -axis, which is in an angle 2θ with the x -axis. Similarly, a circular retardation moves S along a circle on a plane perpendicular to the y -axis. In this case, the rotation angle is equal to the amount of circular retardation. In conclusion, think of the Poincare sphere as the sphere of the Earth; then the equator of the sphere represents linear polarizations states; the poles (north and south) represent the left and right circular polarizations states, respectively; and any other point on the sphere represents elliptical polarization states, Figure 1.25.

1.4.7.3 Polarization-Dependent Loss

When light travels through matter, it suffers loss of power. The contributors to power loss are many, one of them being polarization.

Virtually all optically transparent materials interact with light and affect to some degree its polarization state, some more and some less. In general, optically transparent

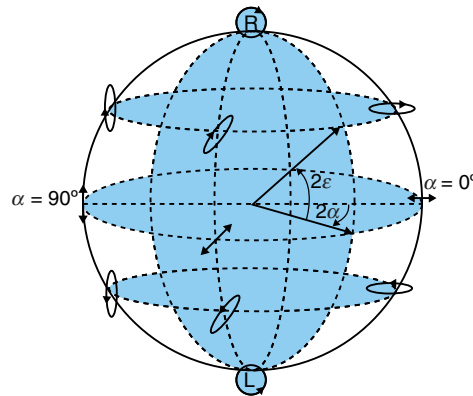


Figure 1.25 Poincare sphere.

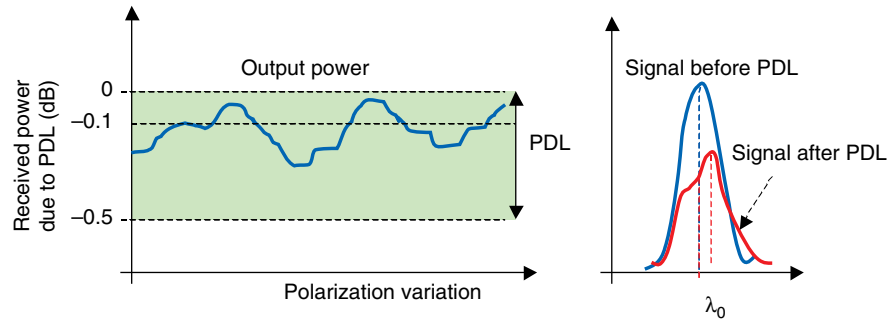


Figure 1.26 Polarization dependence loss.

materials exhibit a spatial polarization distribution. As an optical signal passes through it, due to spatial polarization interaction it suffers selective power reduction, or optical power loss, in specific directions; this power loss due to local polarization influences is wavelength-dependent. This is known as *polarization-dependent loss* (PDL) and is measured in decibels (dB); that is, the polarization loss (L_{PDL}) has been calculated based on $10 \log(L_{\text{PDL}})$. Power loss affects system performance and therefore the power loss of all contributors should be considered.

At low data rates, PDL as compared to IL is a minor contributor to loss; at data rates of 10 Gb/s and above PDL becomes as important as IL. Therefore, when operating at high bit rates, PDL must be carefully examined. The surprising result here is that over a span there may be several contributors in PDL, so the total loss due to PDL is not the algebraic sum. To explain this, consider two cascaded PDL elements, A and B. Element A will attenuate the optical signal due to partial polarization rotation. This signal then will enter element B, which has a random polarization axis and properties with element A. Therefore, the partially polarized light exiting element A and entering element B undergoes another stage of polarization distortion and loss, which now depends on the polarization orientation and characteristics between the two elements A and B, as well as the polarization state of light at the entrances and exits. As a simple example, if the two elements have parallel orientations and similar characteristics, the total PDL is $L_{\text{PDL},1-2} = [L_{\text{PDL},1} + L_{\text{PDL},2}] / [1 + L_{\text{PDL},1} L_{\text{PDL},2}]$.

The power loss due to polarization of the received signal may vary by approximately 0.5 dB (Fig. 1.26). In worst-case optical transmission design, the maximum loss level (as much as -0.5 dB) should be used, whereas in typical performance design an average level (typically at about -0.1 dB). This value does not change with respect to the center wavelength of the received signal. However, asymmetric spectral polarization loss causes asymmetric amplitude signal distortions, and the signal may appear with shifted center wavelength.

1.4.8 Extinction Ratio

Consider polarized light traveling through a polarizer. The maximum transmittance, T_1 , is termed *major principal transmittance*, and the minimum transmittance, T_2 , is termed *minor principal transmittance*. The ratio of major to minor is known as *principal transmittance*. The inverse, minimum to maximum, is known as the *extinction ratio*.

Consider two polarizers in tandem, one behind the other with parallel surfaces. Then, if their polarization axes are parallel, the transmittance is $T_1^2/2$. If their axes are crossed (perpendicular), the transmittance is $2T_2/T_1$. This is also (but erroneously) termed the *extinction ratio*.

In optical communications, the term *extinction ratio* is defined slightly differently. It describes the modulation efficiency in the optical medium, considering that the source (laser) is always continuous and it is externally modulated on–off (i.e., on–off keying modulation). In this case, the extinction ratio is defined as the ratio of the transmitted optical power of a logic 1 (ON), P_1 , over the transmitted optical power of a logic 0, P_0 , and it is measured in decibels,

$$\text{Extinction ratio} = 10 \times \log(P_1/P_0) \text{ (dB)}$$

Or, in percentage

$$\text{Extinction ratio} = (P_1/P_0) \times 100 \text{ (\%)}$$

1.4.9 Phase Shift

In contrast to polarization rotation some dielectric materials, shift the phase of transmitted light through it (Fig. 1.27). The amount of phase shift $\Delta\phi$ depends on the wavelength λ , the dielectric constant ϵ , the refractive index ratio n_1/n_2 , and the optical path (thickness) of material.

1.4.10 Birefringence

Anisotropic materials have a different index of refraction in specific directions. As such, when a beam of monochromatic unpolarized light enters the material at a specific angle and travels through it, it is refracted differently in the directions of different indices (Fig. 1.28). That is, when an unpolarized ray enters the material, it is separated

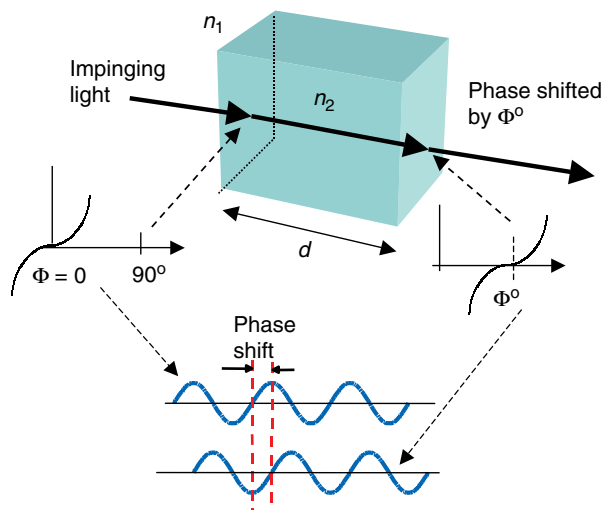


Figure 1.27 Principle of phase angle shift.

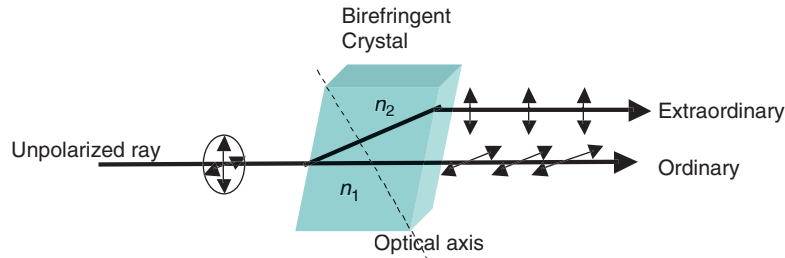


Figure 1.28 Birefringent materials split the incident beam in the ordinary and extraordinary rays, each with different polarization.

into two rays, each with a different polarization, a different direction, and a different propagation constant; one is called an *ordinary* ray (O) and the other is called an *extraordinary* ray (E). In these directions, the refracted index is similarly called *ordinary index*, n_o , and *extraordinary index*, n_e , respectively. This property of crystals is known as *birefringence*. In general, all optically transparent crystals have some degree of birefringence (some have more than others), unless they belong to the cubic system or they are amorphous.

Some birefringent crystals are:

- Calcite (CaCO_3) with $n_e = 1.477$ and $n_o = 1.644$ measured at 1,500 nm. Calcite has a spectral transmission range of 0.2 to 3.2 μm , is nonhygroscopic but is a soft crystal.
- Quartz (SiO_2) with $n_e = 1.537$ and $n_o = 1.529$ measured at 1,500 nm. Natural or synthetic quartz is used. Quartz has a spectral transmission range of approximately 0.2 to 2.6 μm .
- Titanium dioxide (rutile) has an index of refraction difference (index of birefringence) $n_o - n_e = 0.27$. The spectral transmission is in the range of 0.45 to 6.2 μm .

Certain optically transparent isotropic materials become anisotropic when under stress. Stress may be exerted due to mechanical forces (pulling, bending, twisting), thermal forces (ambient temperature variations), and electrical fields. Under such conditions, the index of refraction, polarization, and propagation characteristics become different in certain directions within the material. Figure 1.29 illustrates an unpolarized light ray traversing a birefringent plate, and Figure 1.30 shows the optical effect of a birefringent crystal plate.

Clearly, birefringence in fiber alters the polarization state of the characteristics of the propagating optical signal in an undesirable manner. Consequently, birefringence in fiber is highly undesirable. Therefore, several steps have been taken to minimize fiber birefringence. First, because the major contributor to fiber birefringence is due to geometry imperfections (core not exactly circular) and variations in the refractive index, serious manufacturing steps have been taken to resolve these issues. Additionally, several techniques are applied to minimize residual birefringence. One technique that monitors and controls the polarization at the receiver is accomplished by using polarization-maintaining fibers. Another technique uses transmitting and receiving strategies to “immunize” the system from fiber polarization

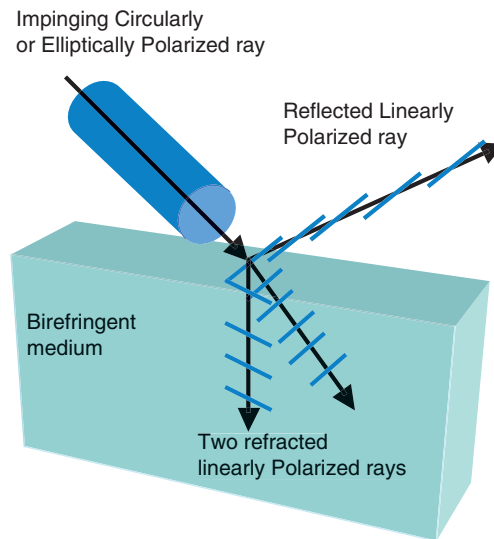


Figure 1.29 Example of birefringence on a nonpolarized beam before and after.

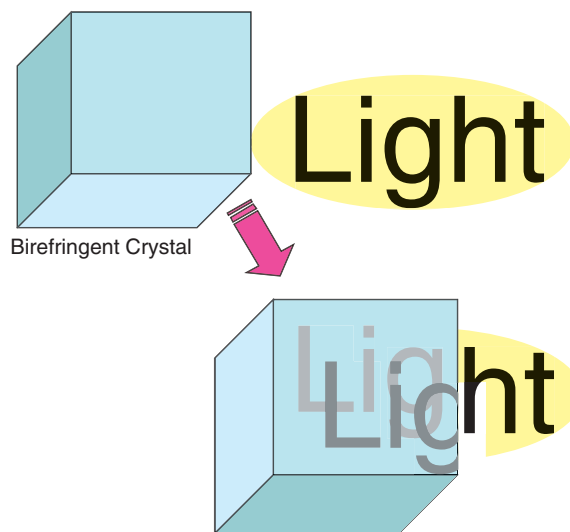


Figure 1.30 Effect of a birefringence crystal.

variations, such techniques are *polarization spreading* (polarization scrambling, data-induced polarization) or *polarization diversity*.

On the other side, birefringence has also been used to construct filters that function as wavelength multiplexers and as demultiplexers (see filters).

1.4.10.1 Quarter-Wavelength Plates

A birefringent plate of a quarter-wavelength ($\lambda/4$) thickness and with surfaces parallel to the optic axis has important effects on polarized light.

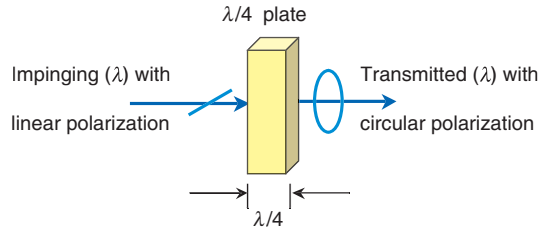


Figure 1.31 Effect of a quarter-wavelength plate.

If light is linearly polarized and at 45° to the fast optical axis, it is transformed into circularly polarized light and vice versa (Fig. 1.31).

If light is linearly polarized and parallel to the fast or slow axis, it remains unchanged.

If light is linearly polarized and is at any other angle to the optical axis, it is transformed into elliptical light and vice versa.

If the plate consists of quartz or mica, the thickness, d , is related to wavelength by the relationship

$$d = (R \cdot \lambda) / \Delta n$$

where $\Delta n = n_e - n_o$ is the refractive index difference of the extraordinary and ordinary paths and R is a constant real number.

The phase difference, δ , is related to R by

$$\delta = 2\pi R$$

For $\lambda/4$ plates, $R = \pm 0.25$.

1.4.10.2 Half-Wavelength Plate

A birefringent plate of a half-wavelength ($\lambda/2$) thickness and with the surfaces parallel to the optic axis has other important effects on polarized light than the quarter-wavelength plate.

If light is linear-polarized and at an angle θ with the fast optical axis, it remains linear but the orientation is rotated by 2θ degrees. Thus, if the angle is 45° , the linear polarization is rotated by 90° (Fig. 1.32).

For $\lambda/2$ plates, $R = \pm 0.5$.

1.4.11 Material Dispersion

The refractive index of matter is related to the dielectric coefficient and to the characteristic resonance frequency of its dipoles, which interact stronger with and

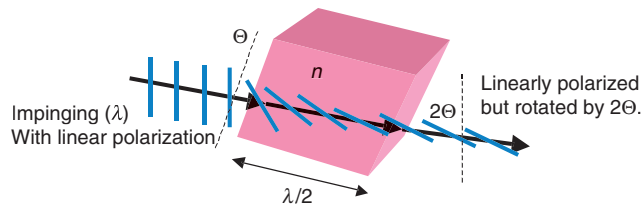


Figure 1.32 Effect of half-wavelength plate.

absorb more optical energy closer to their resonance frequency. Consequently, the refractive index $n(\omega)$ depends on the optical frequency ω . This dependency is termed *material dispersion* and is measured in ps/nm. Dispersion is easier to explain if one considers an optical signal that consists of a narrow band of frequencies. Then, dispersion represents a time delay difference per nanometer of frequency spectrally distributed in an optical signal. That is, a 100-nsec delay over a 10-frequency spectrum is different from a 20-nsec delay over the same spectrum.

Silica, a key ingredient of optical fiber cable, has a refractive index that varies with optical frequency. Thus, dispersion plays a significant role in fiber-optic communications.

The polarization of an E-M wave, P , induced in the electric dipoles of a medium by an electric field, E , is proportional to susceptibility, χ :

$$P = \epsilon_o[\chi^1 \cdot E + \chi^2 \cdot E \cdot E + \chi^3 \cdot E \cdot E \cdot E + \dots]$$

where ϵ_o is the permittivity of free space.

For an isotropic medium, the first-order term expresses the linear behavior of matter. The second-order term is orthogonal and thus it vanishes; for anisotropic media the second order still holds. Higher order terms are negligible (in optical communications, this may not be true for long fiber lengths or for ultrahigh bit rates).

Thus, for an isotropic medium the above series relationship is simplified to $P = \epsilon_o \chi \cdot E$. However, nature is not as simple, and most materials are either anisotropic or become anisotropic under certain conditions. In this case, higher-order terms should also be considered. In particular, the third-order term becomes significant and results in nonlinear effects that may affect and limit optical transmission.

The most influential nonlinear effects in optical transmission, particularly when many wavelengths at high optical power are transmitted over the same medium (e.g., DWDM), are *four-wave mixing* (FWM), *stimulated Raman scattering* (SRC), and *Brillouin scattering* (BS).

1.4.12 Electro-Optic Effects

Electro-optic effects refer to variation of material optical properties when in an electric field. When matter is in an electric field, it influences its electron motions in the atoms or molecules, or it influences the crystal structure and thus its refractive index distribution and its optical properties. For example, the application of an electric field may cause an isotropic crystal (e.g., GaAs) to become nonisotropic (birefringent). In general, the refractive index n^* (after a field is applied) is a function of the applied electric field and may be expanded in a series (similar arguments hold when a magnetic field, and in some cases a gravitational field, is applied):

$$n^* = n + a_1 E^1 + a_2 E^2 + \dots$$

where n^* and n are the refractive indices after and before the application of the electric field, and a_1 and a_2 are known as the first-order and second-order electro-optic coefficients.

This expansion assumes an isotropic medium. In a general case, this expansion is very involved because the applied electric field on a crystal will yield different series expansions for each crystallographic axis, a problem that is studied with tensors having

a matrix notation. Thus, if a crystal had three indices (n_1, n_2, n_3) in three directions, then the applied field would affect each one differently (thus adding a second subscript to keep track). Moreover, if the direction of the field changed, then this would be further complicated (thus adding a third subscript). Furthermore, if the field also changed in the time domain, then one realizes the complexities in studying the electro-optic effect of a complex crystal.

1.4.12.1 The Pockels Effect

In the previous expansion (repeated for convenience), consider only the first (linear) term:

$$n^* = n + a_1 E^1 + [a_2 E^2 + \dots]$$

Then, the difference in refractive index is

$$\Delta n = n^* - n = a_1 E$$

This relationship characterizes the Pockels effect. However, the coefficient a_1 is not nonzero for all materials. In fact, it is zero ($a_1 = 0$) for all liquids and noncrystals, as well as for all crystals that have a symmetric structure. Thus, glasses and NaCl, exhibit no Pockels effect, but GaAs, LiNbO₃, and KDP (KH₂PO₄-potassium dihydrogen phosphate) do.

If an electric field E_a is applied to an isotropic crystal (n_0) with nonzero a_1 coefficient (e.g., GaAs), then birefringence is induced that changes the refractive index to two n_1 and n_2 . The new refractive indices are given by

$$n_1 = n_0 + (1/2)n_0^3 r_{22} E_a$$

and

$$n_2 = n_0 - (1/2)n_0^3 r_{22} E_a$$

where the constant r_{22} is called the Pockels coefficient, measured in m/V, which depends on the material and the crystal structure. In fact, even the Pockels coefficient is not the same for all directions in the crystal; the Pockels coefficient along the propagation axis is denoted r_{13} .

Typical Pockels coefficient values of LiNbO₃ (measured at 500 nm) are $r_{13} = 8.6 \times 10^{-12}$ m/V, and $r_{22} = 3.4 \times 10^{-12}$ m/V.

As the electric field is applied and birefringence is induced, a propagating optical monochromatic beam through the crystal is polarized differently in two directions; two beams are formed, each propagating at a different speed, and thus they have a phase difference. As the electric field changes, so does the phase difference (Fig. 1.33). This is known as a phase modulator or a *Pockels cell*.

Consider that a voltage V is applied across a Pockels cell of thickness d and length L , and in a direction (y -axis) perpendicular to optical transmission (z -axis). Then, the field across the cell is $E = V/d$. Because of the induced birefringence, an optical beam is separated into two polarized beams. After length L , the first beam will have a phase ϕ_1 and the second beam ϕ_2 :

$$\phi_1 = (2\pi n_1 L)/\lambda = [2\pi L/\lambda][n_0 + (1/2)n_0^3 r_{22} V/d]$$

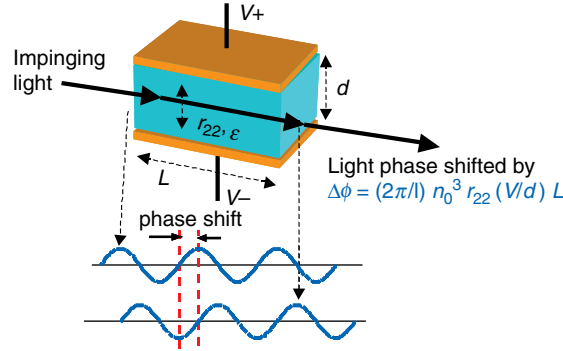


Figure 1.33 Principle of Pockels cell. In the Kerr cell the field is much stronger.

and

$$\phi_2 = (2\pi n_1 L)/\lambda = [2\pi L/\lambda][n_0 - (1/2)n_0^3 r_{22} V/d]$$

Thus, the phase difference is

$$\Delta\phi = \phi_1 - \phi_2 = (2\pi\lambda)n_0^3 r_{22} (V/d) L$$

This relationship indicates that the phase difference is proportional to the field (V/d) and to the length of the cell. Thus, if more phase difference is required, the length of the cell may be increased and the thickness d of the Pockels cell may be decreased. Pockels cells are applicable to phase modulators or polarization modulators.

1.4.12.2 Kerr Effect

In the refractive index expansion (repeated for convenience), consider only the second-order (nonlinear) term:

$$n^* = n + a_2 E^2$$

In this case, the refractive index difference is

$$\Delta n = n^* - n = a_2 E^2 = (\lambda K) E^2$$

where K is the Kerr coefficient, measured in m/V^2 . It is noteworthy that K depends on the wavelength.

In contrast to the Pockels effect (according to which only some materials have a nonzero a_1 coefficient), all materials have a nonzero a_2 coefficient, and thus all materials, including glass exhibit the Kerr effect to some degree.

The Kerr effect is very similar to the Pockels effect in that it induces birefringence and thus causes two polarized optical beams and a phase difference. However, the Kerr effect is a second-order phenomenon and therefore it is significant when the applied field is strong. In addition, certain crystals exhibit a Kerr effect with a response time on the order of picoseconds or less, and this is what makes them suitable as ultrafast modulators at bit rates exceeding 10 Gbps. A typical value for the Kerr coefficient of glass is $3 \times 10^{-15} \text{ m/V}^2$.

1.4.13 Material Attributes

The attributes of material and their significance, of interest in DWDM, are:

- Refractive index (n): is a function of molecular structure of matter;
is a function of optical frequency $\{n(\omega)\}$,
is a function of optical intensity;
determines optical propagation properties of each λ ;
may not be distributed equally in all directions;
is affected by external temperature, pressure,
and fields;
- Reflectivity (R): it is a function of geometry, λ and n
material surface reflects optical power;
changes polarization of incident optical wave;
changes phase of incident optical wave
- Transparency (T): depends on matter consistency;
- Scattering: due to molecular matrix disorders
- Absorption (A): due to ion presence in matrix
- Polarization (P): due to X–Y uneven E-M fields (light–matter interaction)
- Birefringence (B): due to nonuniform distribution of n in all directions.
- Phase shift ($\Delta\Phi$): due to wave propagation property of light through matter
- Ions act like dipoles: exhibit eigen frequencies;
exhibit antenna characteristics (receiver/transmitter)

1.5 THE FIBER AS AN OPTICAL TRANSMISSION MEDIUM

The first work that dealt with the propagation of electromagnetic waves in dielectric rods was published in 1910. Since then, this seminal work evolved to take the form of optical transmission in dielectric fibers.

A single fiber strand consists of an ultrapure silica glass SiO_2 (70–95 wt%), several kilometers long, mixed with specific elements such as germanium, fluorine, phosphorus, and boron, which are known as *dopants*. Dopants are added to adjust the refractive index of fiber and its light propagation characteristics. The purity of glass fiber is measured by its very low loss, about 0.35 dB/Km at 1,310 nm and 0.25 dB at 1,550 nm.

The fiber strand consists of several concentric layers. The innermost layer is the silica *core*; in optical communications, this is where the photonic signal propagates. The core is covered by another layer of silica with a different mix of dopants, known as *cladding*; it has a lower refractive index than the core. The cladding is covered with a buffer *coating* to absorb mechanical stresses, and this is covered with a strong material such as Kevlar (Kevlar is a trademark of E.I. du Pont & Co.). Finally, an external layer of plastic material covers this. The final fiber including coating is standardized to 245 μm diameter for compatibility reasons. Fiber cables used in long-haul communications consist of a bundle of fiber strands, and depending on cable and manufacturer, they may incorporate 432 or even more than 1,000 strands.

Fiber is made by vertically drawing a cylindrical *preform* (also known as a *blank*), which is made of ultrapure SiO_2 and in which a number of dopants (e.g., GeO_2) have been added. Dopants are homogeneously distributed in a tubular fashion in controlled

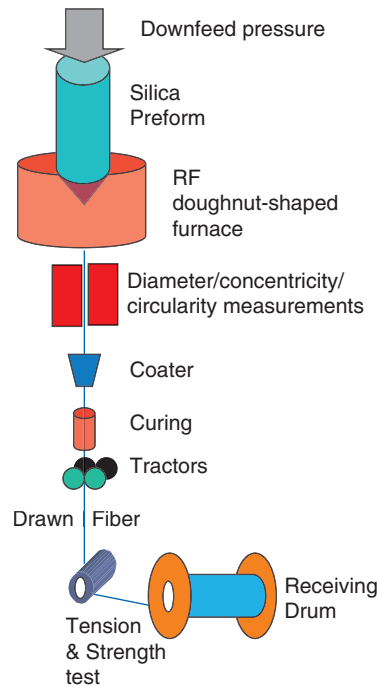


Figure 1.34 Making a fiber (a conceptual simplified diagram).

quantities to determine the distribution of the refractive index in the core or the fiber *refractive index profile*.

The preform blank has been immersed in a high-frequency doughnut-shaped furnace such that the base of the blank is heated at 2000°C . At this temperature the base of the blank starts melting and becomes viscous (Fig. 1.34). Then the lower tip of the molten blank forms a *gob* that starts falling from the blank, thus pulling a thin fiber behind it. The gob is cutoff, and the fiber is threaded into a tractor assembly and is drawn. The diameter of the drawn fiber is continuously monitored, and minute adjustments are made (via an automatic control mechanism) to the drawing rate so that a produced fiber complies with the diameter tolerance specified by ITU-T standards. The various coatings are also applied during the drawing process.

The cylindrical preform is made with one of several proprietary methods. Such methods are the vapor-phase axial deposition (VAD); the outer vapor deposition (OVD); and the modified chemical deposition (MCVD), which was invented in 1970 by scientists at Bell Laboratories. The cylindrical preform starts with the manufacture of a hollow tube of highly pure silica. One of the methods to produce the tube is Lucent Technologies' *sol gel* method (described and illustrated in <http://www.bell-labs.com/org/physicalsciences/projects/solgel>, 1999).

Based on the MCVD method, the silica hollow tube is placed horizontally on a lathe and oxygen and vaporized ultrapure oxides (such as SiCl_4 , GeCl_4) enter the rotating tube in a specified sequence. The rotating tube is kept at a high and constant temperature such that the inner walls of the silica tube chemically interact with the oxides in a controlled manner, evenly depositing elements such as Ge, P, B, and F. In

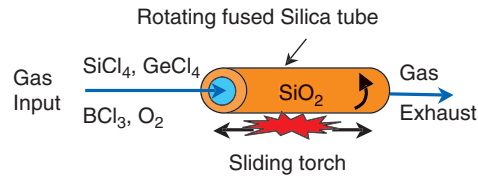
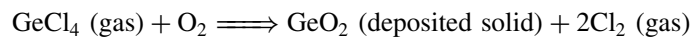
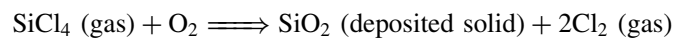


Figure 1.35 Making the preform.

this case, the chemical reaction of oxides with oxygen is



As deposition takes place, the opening of the tube is closing in (Fig. 1.35). The radial deposition of dopants in the preform determines the profile of the index of refraction of the fiber.

Application-specific optical fiber (ASOF) can be custom-made by modifying, with any of the methods mentioned, the sequence and concentration of dopants of the fiber core and/or the geometry of the fiber. According to this, fibers with specific properties for specific applications can be made.

One would think that glass fiber is fragile “like glass.” However, what is important in communications fiber is the tensile strength of the fiber cable, which indeed is higher than that of copper. In fact, the tensile strength of copper is 100 pounds per square inch, whereas that of glass fiber is theoretically 2 million pounds per square inch. However, due to surface microcracks that exist in any glass fiber, it is about 800,000 pounds per square inch. In addition to high strength, glass fiber has a long service lifetime of well above 20 years.

ITU-T has defined parameters specific to many optical components but not to fiber. Here we provide a list of parameters that pertain to fibers; in the following sections, we elaborate on these parameters, and it will become evident that indeed the fiber is one of the most important components in optical communications.

- fiber type (multimode, single mode, dispersion-compensating)
- forward attenuation per kilometer
- backward attenuation per kilometer (if asymmetric)
- polarization mode dispersion
- polarization-dependent loss (PDL)
- birefringence
- dispersion (chromatic and material)
- zero-dispersion wavelength
- dispersion flatness over spectrum range
- birefringence
- cutoff wavelength

1.5.1 Composite Refractive Indices

Each element and each compound are characterized by their own refractive index. Certain compounds have a low index and some others high (Chalcogenides) and when combined they produce a different refractive index value. However, there is no exact relationship that predicts what the end refractive index value will be based on a specific mix of elements or compounds; the refractive index is merely measured after a new compound is produced. As such, the value of many diffractive indices has been derived experimentally, and experimental graphs may aid in predicting the refractive index.

Polymers (e.g., polysterene, vinyl) have a high index of refraction. As a consequence, polymers have started making inroads in applications ranging from optical components to ultra-short-haul (very short distance) fiber communication.

Some refractive indices of certain materials are listed in Table 1.4 (note that the refractive index is a function of the wavelength for which it is measured and thus the tabulated numbers are approximate, indicating only a relative degree of magnitude):

1.5.2 Fiber Modes

When monochromatic light travels in an optical waveguide, transmission takes place through specific guided modes. These modes are determined from the *eigenvalues* of second-order differential equations and their boundary conditions, a similar analysis to propagation of electromagnetic waves in cylindrical waveguides. The solution of these equations determines the modes of propagation in the waveguide, as well as the *cutoff frequency* beyond which the fiber does not support transmission.

The propagation characteristics of light in silica fiber depend on the chemical consistency (silica + dopants) and the cross-sectional dimensions of core and cladding.

Table 1.4 Approximate refractive index of certain materials

Material	Refractive Index
SiO ₂ (0.8 wt% F)	1.65
CaF ₂	1.56
CsBr	1.67
BaF ₂	1.47
MgF ₂	1.37
KBr	1.53
NaCl	1.52
GeO ₂ (at 2 mol%)	1.46
P ₂ O ₅ (at 2 mol%)	1.46
B ₂ O ₃ (at 8 mol%)	1.46
CdTe	2.70
Diamond	2.40
Si	3.43
Fused silica	1.41
GaAs	3.31
Ge	4.02
Polyurethane	1.46
Polysterene	1.59
N-vinyl carbazol	1.68
PMMA aczylic (red)	1.49

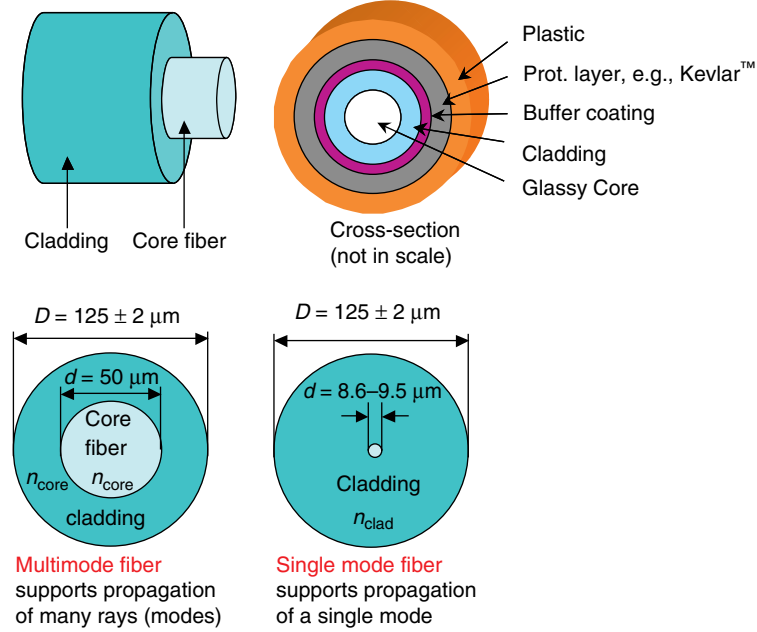


Figure 1.36 Anatomy of a multi-mode and single-mode fiber.

Typically, core and cladding have a diameter of about $125 \mu\text{m}$, but the core itself comes in two sizes, depending on the application for which the fiber is intended. Fiber with a core diameter of about $50 \mu\text{m}$ supports many modes of propagation, and thus it is known as *multimode* fiber, whereas fiber with a core diameter of about 8.6 to $9.5 \mu\text{m}$ (theoretically) supports one mode of propagation and is known as *single-mode* fiber (per ITU-T G.652) (Fig. 1.36).

1.5.2.1 Cutoff Wavelength

When electromagnetic waves propagate in a guided medium (i.e., fiber), the guide puts a limit on the shortest wavelength (highest frequency) that can pass through. Propagation in rectangular waveguides is studied using simple boundary conditions and Cartesian coordinates and is used in circular waveguides using Bessel functions.

The actual number of modes, M , supported by a fiber depends on fiber geometry (core diameter), the refractive index of core and cladding (or the numerical aperture), and the wavelength of the optical signal. These fiber parameters are combined in a normalized parameter known as the M number, expressed by

$$M = \frac{1}{2} \left\{ (4\pi/\lambda)d \sqrt{(n_{\text{clad}}^2 - n_{\text{core}}^2)} \right\}^2$$

where λ is the wavelength and d is the core diameter. Note that a fiber supports fewer modes at shorter frequencies and more modes at higher frequencies.

The square root in this relationship is also known as the *numerical aperture*, NA, of the step index fiber, i.e.,

$$NA = \sqrt{(n_{\text{clad}}^2 - n_{\text{core}}^2)}$$

In optical fibers with complex refractive index profiles, the theoretical calculation of numerical aperture and cutoff wavelength is complex and is only determined using approximate models with acceptable accuracy. In general, if the wavelength at free space is λ , the wavelength in the guide is λ_g and the cutoff wavelength λ_c is provided by

$$(1/\lambda_c^2) = (1/\lambda^2) - (1/\lambda_g^2)$$

In terms of the M number, the condition for single mode transmission is

$$M < M_{\text{cutoff}} = \sim 2.4$$

The wavelength below which a single-mode fiber allows multiple modes is expressed as

$$\lambda \geq \lambda_{\text{cutoff}} = \sim 2.6r(NA)$$

where r is the core radius and NA is the numerical aperture of the fiber.

The cutoff wavelength, per ITU-T G.650, is defined as the wavelength that experiences by the waveguide a “fundamental mode power decrease to less than 0.1 dB.” ITU-T G.650 also elaborates that in this case when many modes are equally excited “the second-order (LP_{11}) mode undergoes 19.3 dB more attenuation than the fundamental (LP_{01})” mode.

Propagation modes are labeled as TE_{MN} or TM_{MN} (where M and N are integers), depending on the magnitude of the *transverse electric* field ($E_z = 0$) or the *transverse magnetic* field ($H_z = 0$) at the surface of the fiber core (the boundary) in the transverse direction.

Figure 1.37 graphically illustrates certain modes of standard circular waveguides. The theoretical critical wavelengths for the three modes, and for a waveguide of diameter D , are provided by the relationship

$$\lambda_c = \pi D/s$$

where s is the Bessel function constant. The theoretical values are listed in Table 1.5.

Based on dielectric constant and dimensions, the optical fiber supports the fundamental mode TE_{11} (also known as HE_{11} or H_{11}) or higher modes. A fiber that supports many modes is known as a *multimode* fiber, and a fiber that supports only one mode

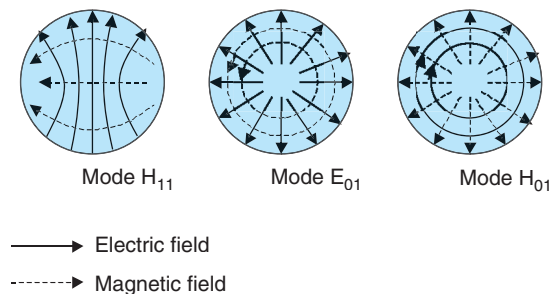


Figure 1.37 Graphical representation of the distribution of electro-magnetic fields in circular waveguide for certain modes (shown cross-section).

Table 1.5 Critical wavelengths for three modes

Mode	λ_c
H_{11}	1.71D
E_{01}	1.31D
H_{01}	0.82D

(the HE_{11}) is known as a *single-mode* fiber. A single-mode fiber supports transmission along its longitudinal axis (H_{11}).

Multimode fibers and single-mode fibers have different refractive index profiles, different cross-sectional dimensions, and therefore different transmission characteristics. Consequently, different fiber types are used in different network applications, such as multimode fibers in access communication and single-mode fibers in long-haul communication.

The propagation of light in matter is typically illustrated by using the ray technique. This is a graphical and visual technique that shows the paths of optical rays as they travel through matter and through the fiber, depicting diffraction, refraction, polarization, and birefringence. Figure 1.38 shows two cases of light propagating in a step index fiber and in a graded index fiber using the ray technique. This technique is used extensively throughout this book.

1.5.2.2 Multimode Fiber Graded Index Characteristics

A list of the salient characteristics of multimode fiber graded index (MMF GRIN) follows:

- It minimizes delay spread, but is still significant in long lengths.
- One percent index difference between core and cladding amounts to 1–5 ns/Km delay spread (compare with step index that has about 50 ns/Km)
- Easier to splice and easier to couple light into it
- Bit rate is limited; up to 100 Mb/s for lengths up to 40 Km; higher bit rates for shorter lengths

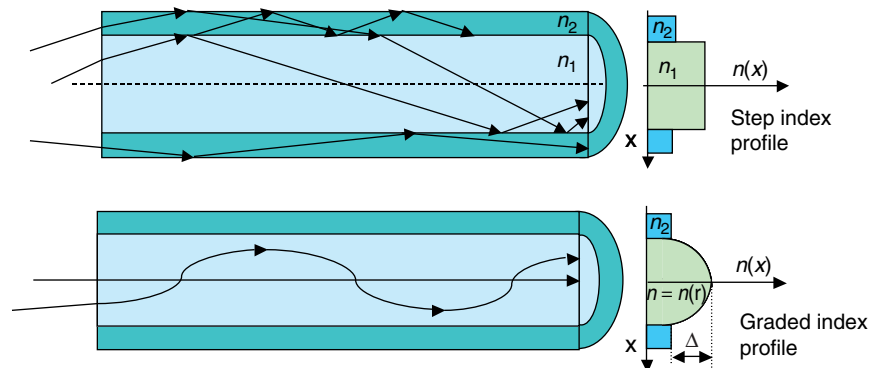


Figure 1.38 Propagation of light rays in step and in graded index fibers (shown cross-section along the axis).

- Fiber span without amplification is limited; up to 40 Km at 100 Mb/s (extended to Gbps for shorter distances for graded index)
- Dispersion effects for long lengths and high bit rates is a limiting factor

1.5.2.3 Single-Mode Characteristics

A list of the salient characteristics of standard single-mode fiber (SSMF) follows:

- It (almost) eliminates delay spread
- More difficult to splice (than multimode) due to critical core alignment requirements
- More difficult to couple all photonic energy from a source into it.
- Difficult to study propagation with ray theory; it requires Maxwell's equations
- Suitable for transmitting modulated signals at 40 Gb/s (or higher) and up to 200 km without amplification
- Long lengths and bit rates greater than 10 Gb/s bring forth a number of issues due to residual nonlinearity/birefringence of the fiber
- Fiber temperature for long lengths and bit rates greater than 10 Gb/s becomes significant

1.5.2.4 Critical Cone and Exit Cone

Critical cone, also known as *acceptance cone*, is a cone of an angle within which all rays that are launched into the core are reflected at the core-cladding interface at or beyond the critical angle (Fig. 1.39). The half angle of the critical cone, also known as *numerical aperture*, depends on the refractive index distribution function in the core and cladding and is independent of the core diameter. For a step index fiber, the numerical aperture is

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

where n_1 is for the core and n_2 is for the cladding.

When light emerges from the far end of the fiber, it does so in a cone, which is known as the *emerging cone* or the *exit cone*. In single-mode fiber, the exit cone is approximately the same as the acceptance cone. Clearly, for best coupling results, the acceptance cone and the exit cone should be as acute as possible.

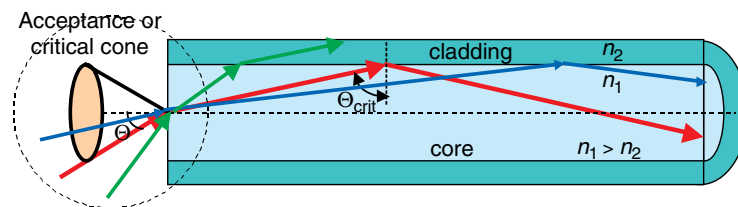


Figure 1.39 Illustrative definition of acceptance or critical cone (shown cross-section along the axis).

1.5.3 Fiber Attenuation and Power Loss

Fiber consists of optically transparent matter that, like any other matter, absorbs and scatters part of the optical power of light. This is termed *attenuation*. The more light travels in matter, the more it is attenuated. Fiber attenuation depends on scattering and fluctuations of the refractive index, on the imperfection in the fiber, and on impurities. Metal ions and OH radicals have a particular effect, particularly in the range of 1.4 μm , although fiber cable, almost free of OH radicals, has been successfully manufactured.

However, there are more mechanisms that contribute to optical power loss in the presence of matter. This sum of all power lost due to all contributors is clearly measured by subtracting the power out from the power in the fiber. This is termed *fiber loss* (many times used synonymously with *power attenuation*). Power loss is a very important transmission characteristic that imposes a limiting effect on the fiber length. Fiber loss, for a given optical power, $P(0)$, launched into fiber affects the total power arrived at the receiver, P_r . Based on this, fiber loss limits the fiber span, L_{max} , without amplification, and/or determines the required amplification gain.

For a fiber with optical power attenuation constant $\alpha(\lambda)$, the optical power attenuation at a length L is expressed as

$$P(L) = P(0)10^{-\alpha(\lambda)L/10}$$

In this relationship, if we replace $P(L)$ with the minimum acceptable power at the receiver, P_r , then the (ideal) maximum fiber length is

$$L_{\text{max}} = [10/\alpha(\lambda)] \log_{10}[P(0)/P_r]$$

In subsequent sections, we will see that there are additional limiting factors (e.g., dispersion and bit rate) that further limit the (ideal) maximum fiber length.

In general, the optical power attenuation constant, $\alpha(\lambda)$, is nonlinear and depends on the wavelength

$$\alpha(\lambda) = C_1/\lambda^4 + C_2 + A(\lambda)$$

where C_1 is a constant (due to Rayleigh scattering), C_2 is a constant due to fiber imperfections, and $A(\lambda)$ is a function that describes fiber impurity absorption as a function of wavelength.

The optical power attenuation constant of a fiber (measured in dB/km) is typically plotted as a function of the wavelength (Fig. 1.40).

Conventional single-mode fibers have two low attenuation ranges, one at about 1.3 μm and another at about 1.55 μm . Between these two ranges, and at about 1.4 μm , there is a high attenuation range (1,350–1,450 nm), due to the OH radical with a peak at 1,385 nm, known as the “fifth window.”

If the OH radical could be eliminated from the fiber material, then the high attenuation region at about 1.4 μm also could be used in DWDM communications. The AllWaveTM is a low water peak fiber (LWPF) with minimum attenuation over the entire spectrum between 1,310 nm and 1,625 nm, increasing the number of optical channels by over 50%, as compared with the conventional single mode fiber (CSMF); this corresponds to about 500 channels with 100 GHz channel spacing. This fiber is suitable for metropolitan area network applications.

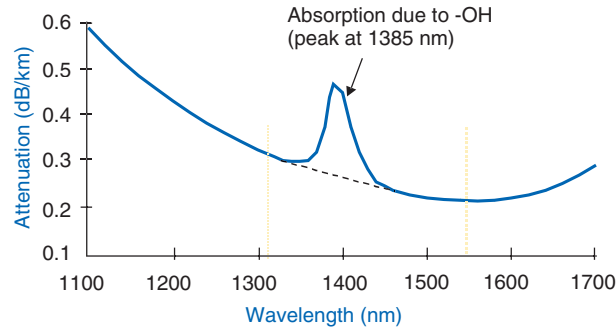


Figure 1.40 Attenuation as a function of wavelength for single mode fiber.

Fiber attenuation is measured in dB per kilometer. ITU-T G.652 recommends losses below 0.5 dB/km in the region 1,310 nm, and below 0.4 dB/km in the region 1,500 nm.

1.5.3.1 The Decibel Unit

Optical power, power attenuation, and optical loss are measured in decibel (dB) units. Power in dB units is defined as 10 times the logarithm (base 10) of power (in watts):

$$\text{Power (dB)} = 10 \log_{10}[P \text{ (watts)}]$$

In communications, the transmitted optical signal is at extremely low power, on the order of milliwatts. To denote that the reference power point is in milliwatts, the dB unit is expressed in dBm:

$$\text{Power (dBm)} = 10 \log[P \text{ (mWatts)}] = 10 \log[P \times 10^{-3} \text{ (W)}]$$

Here, a few properties of logarithms are recalled (Table 1.6), because they play a key role in the understanding of dos and don'ts when dealing with decibels.

When adding or subtracting dBs and dBms, certain cautions should be taken regarding the mix-and-match of units. Decibel units are additive if their argument

Table 1.6 Properties of logarithms

1. $\log(AB) = \log A + \log B$
2. $\log(A/B) = \log A - \log B$
3. $\log(A^N) = N \log A$
4. $\log\{N \text{ root}(A)\} = (1/N) \log A$
5. $\log 10 = 1$
6. $\log 1 = 0$
7. $\log A = \log(e) \ln A$
8. $\log(e) = \log(2.71828+) = 0.434294$
9. $\ln 10 = 2.30258+$
10. $\ln 2.71828 = 1$
11. $\log A = + \log A$, where $A > 1$
12. $\log A = - \log |A|$, where $0 < A < 1$
13. $\log(A + B)$ not equal to $\log A + \log B$

is multiplicative, and therefore, if the dB units are not handled correctly, one may make a serious erroneous calculation.

For example, $1 \text{ dBm} = 10 \log[10 \text{ mW}]$, but $1 \text{ dBm} + 1 \text{ dBm}$ is *not* 2 dBm because this is not the result of $10 \log(10 \text{ mW} \times 10 \text{ mW})$, as a result of property #1 in Table 1.6. If it were, however, then $10 \text{ mW} \times 10 \text{ mW}$ is $100 \times 10^{-6} \text{ W} = 10^{-4} \text{ W}$, and hence $10 \log 10^{-4} = -40 \text{ dB}$! As a consequence:

- dBms cannot be added.
- dBms can be subtracted (as a result of property #2 in Table 1.6); the result is in dBs (not in dBms) since a dBm difference implies a power ratio.
- dBs can be added; the result is in dBm.
- a dB can be added to a dBm; the result is in dBm.

Power attenuation or power loss is also expressed in dB units. In this case, it is (10 times) the logarithm of the ratio of received power over transmitted power, both expressed in the same units, and thus the ratio is dimensionless. Hence, the attenuation over a fiber span is expressed in dB units, regardless of whether the power is in W or mW units):

$$\alpha\lambda = 10 \log P_1/P_2 \text{ (dB)}$$

For example, a power ratio of 1,000 is 30 dB, of 10 is 10 dB, of ~ 3 is 5 dB, of 2 is ~ 3 dB, and a ratio of 0.1 is -10 dB . To the untrained eye and mind, loss or gain in dBs is very abstract because we are trained to think of loss and gain in ratios, such as, for example, 100 times less or 100 times more versus 20 dB. However, a dB is a more convenient unit and is widely used in optical communications; Figure 1.41 illustrates how a 5-dB loss of a signal is seen at the receiver.

Besides decibels, power loss is provided as a percentage of power transmitted compared with that received, such as 60%, and so on. That is, if 100 units of power were transmitted and 60 units were received, the loss is $100 - 60 = 40$ and in percentage it is $(100 - 60)/100$. The correspondence of dB to percentage is easy to calculate. For example, 90% power loss corresponds to $10 \log\{(100 - 90)/100\} = -10 \text{ dB}$, 50% corresponds to $10 \log 0.5 = -3 \text{ dB}$ and 2% to $10 \log 0.98 = -0.01 \text{ dB}$. Table 1.7 lists a conversion table from dB loss to percentage loss and percentage loss to dB loss.

Another power ratio that is widely used in communications is the signal-to-noise ratio (SNR), which is also expressed in dB units.

Example #1: Convert -1 dBm optical power in mWatts.

From the definition of dB: $-1 \text{ dBm} = 10 \log(0.1 \text{ mW}) \text{ dBm}$

$\Rightarrow$ The optical power is: $P = 0.1 \text{ mW} = 10^{-4} \text{ W}$



Figure 1.41 Perceived 5 dB loss of optical signal.

Table 1.7 dB loss and percent loss

dB Loss	%Loss	%Loss	dB Loss
0	0	0	0
-0.1	-2.3	-0.5	-0.02
-0.5	-10.9	-1	-0.04
-1	-20.6	-5	-0.22
-2	-36.9	-10	-0.46
-5	-68.4	-40	-2.22
-10	-90.0	-90	-10.00
-20	-99.0	-99	-20.00

Example #2: Convert -1 dBm in optical power density (W/cm^2) if -1 dBm is launched in a fiber core with diameter $D = 10 \mu\text{m}$

$$\Rightarrow \text{The cross-sectional area of fiber is: } A = (\pi/4)D^2 = (3.14/4)[10 \times 10^{-4}]^2 \text{ cm}^2 = 0.785 \times 10^{-6} \text{ cm}^2$$

$$\Rightarrow \text{The optical power density is } P/A = 10^{-4} \text{ W}/[0.785 \times 10^{-6}] \text{ cm}^2 = 10^2/0.785 \text{ (W/cm}^2\text{)} = 127 \text{ (W/cm}^2\text{)}$$

Example #3: Calculate the optical loss for a laser beam with a step intensity distribution and a diameter of $12 \mu\text{m}$ if the reflectivity of the fiber surface is 5%.

$\Rightarrow$ There are two loss contributions, A. due to cross-sectional area mismatch between beam and fiber core, and B. due to reflectivity.

$$\Rightarrow \text{A. the cross section of the beam is } A = (\pi/4)D_2^2 = (3.14/4)[12 \times 10^{-4}]^2 \text{ cm}^2 = 0.785[1.44 \times 10^{-6}] \text{ cm}^2 = 1.130 \times 10^{-6} \text{ cm}^2.$$

Thus, the part of optical power impinging on the core is calculated from:

$$[D/D_2]P = [0.785 \times 10^{-6}/1.130 \times 10^{-6}]10^{-4} \text{ W} = 0.69 \times 10^{-4} \text{ W}$$

$\Rightarrow$ B. From the optical power impinging on the fiber core 95% is coupled in and 5% is lost due to reflectivity. Thus, the power launched in the fiber is:

$$0.95 \times 0.69 \times 10^{-4} \text{ W} = 0.66 \times 10^{-4} \text{ W} = \underline{0.066 \text{ mW}}$$

The latter is expressed in dBm as follows:

$$10 \log(0.066 \text{ mW}) = 10 \log(0.066) \text{ dBm} = 10(-1.18) \text{ dBm} = \underline{-10.18 \text{ dBm}}$$

Here we have assumed a laser beam with circular and step distribution intensity. In practice, the beam has a distribution such as Gaussian, Poisson's, Maxwellian, and so on. In addition, the near-field or far-field positioning of the fiber from the beam source may be considered as well as any beam transformations (corrective and/or focusing lens).

1.5.3.2 Fiber Spectrum Utilization

The spectral low-loss of fiber has been distinguished in ranges such as:

The S-band (also known as short wavelength or second window) is defined as the range 1,280 nm to 1,350 nm. The S-band was the first band to be used in high-speed

long-haul applications. The S-band and C-band have found applications in WDM metropolitan networks.

The “new band” (also known as the fifth window) is defined as the range from 1,350 nm to 1,450 nm; perhaps we should call it the N-band for new band, or the W-band for water band (from the well-known fiber water-peak absorption), or the M-band for middleband. The window in the range from 1,450 to 1,528 nm (also part of the fifth window) is used in single-mode fiber short-distance networks, such as MAN, that do not require erbium-doped fiber amplifiers (EDFA); perhaps we should call it the M-band for medium band.

The C-band (also known as the conventional or third window) is defined as the range from 1,528 nm to 1,565 nm. This is subdivided into the “blue band” (1,528–1,545 nm), and the “red band” (1,545–1,561 nm).

The L-band (also known as the long wavelength or fourth window) is defined as the range from 1,561 nm to 1,660 nm. This band, in conjunction with dispersion shifted fiber (DSF) was first bands deployed in DWDM applications in Japan.

The C-bands and L-bands have found applications in ultra-high-speed (10–40 Gbps) DWDM communications. The C-band is currently popular in the United States and elsewhere, and the L-band is popular in Japan and elsewhere. The L-band takes advantage of the dispersion-compensating fiber. Recently, the L-band has been extended to 1,625 nm to a band known as UL (for ultra-L). In fact, the 1,650-nm wavelength is used for maintenance and testing.

Finally, the first window refers to the wavelength range from 820 nm to below 900 nm, which is popular in multimode-fiber applications. Ultraviolet wavelengths are not used in communications.

Table 1.8 summarizes the frequency bands, and Figure 1.42 illustrates the channel-grid in the C-band spectral range.

1.5.3.3 Limits of Optical Power in Fiber

The maximum acceptable optical power density is the amount of optical power that a fiber can support without being damaged. Power density is the ratio of laser beam

Table 1.8 Summary of frequency utilization for fiber applications

Window	Label	Range	Fiber-type	Applications
1st	—	820–900 nm	MMF	
2nd	S	1280–1350 nm	SMF	Single- λ
3rd	C	1528–1561 nm	SMF	DWDM
4th	L	1561–1620 nm	DSF	DWDM
5th	—	1350–1450 nm	SMF AllWave™	DWDM
5th	—	1450–1528 nm	SMF	DWDM/MAN

Note: Wavelengths are measured in free-space

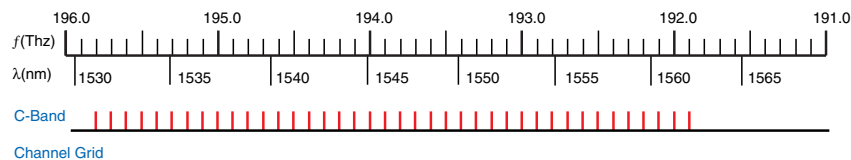


Figure 1.42 100 GHz channel grid in the C-band.

power over the cross-sectional area of the laser beam. Because the cross-sectional areas are very small, low powers may have large densities. For example, a 10-mW power beam with a 6- μm diameter produces a power density of

$$\begin{aligned} P/A &= 10 \times 10^{-3} / \pi (3 \times 10^{-4})^2 \text{ W/cm}^2 \\ &= 10 \times 10^{-3} / 28.26 \times 10^{-8} = 35 \text{ kW/cm}^2 \end{aligned}$$

In communications, the optical signal is modulated in the form of pulses. A pulse is typically characterized by duration (in psec or nsec) and energy per pulse in millijoules. In this case, to calculate the power density of the pulse, the energy over time must first be converted into power and then into power density. Thus, a pulse of 10 mJ for 1 nsec is equivalent to a power

$$\begin{aligned} P &= 10 \times 10^{-3} / 10^{-9} \text{ J/s} \\ &= 10 \text{ megawatts} \end{aligned}$$

1.5.4 Fiber Birefringence

The ideal single-mode fiber would support two orthogonally polarized modes or *states*, one along the x -axis and one along the y -axis (the z -axis is along the fiber). However, since there are only real fibers, they have a small amount of birefringence which in some applications is considered negligible, but in other applications (long spans and high bit rate) is significant. The *degree of fiber birefringence* is defined by

$$B = |n_x - n_y|$$

where n_x and n_y are indices for the polarized fiber modes in the axes x and y (z is the axis of propagation).

Fiber birefringence causes power exchange between the two polarization states in a continuous manner, changing the polarization from linear to elliptical, to circular, and finally back to linear. The length of birefringent fiber over which a complete revolution of polarization takes place is defined as *beat length* (Fig. 1.43). The beat length is given by

$$L_B = \lambda / B$$

For $\lambda = 1,550 \text{ nm}$ and $B \sim 10^{-7}$, $L_B \sim 15 \text{ meters}$.

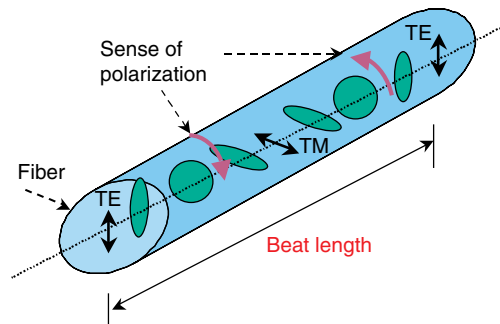


Figure 1.43 Polarization evolution and beat-length.

In optical communications, the receiver detects total photonic intensity directly, and fiber birefringence may not be a serious problem. However, in coherent communications, where a specific polarization at the receiver is expected, or when polarization-sensitive components are used, birefringence may be of concern.

Polarization-preserving fibers (PPF) is used to minimize the effects of fiber birefringence; polarization-preserving fibers exhibit a very strong degree of birefringence ($B \sim 10^{-4}$). Thus, when the signal enters the PPF, the birefringence induced by the fiber is so strong that it “overshadows” other sources of birefringence, which are negligible by comparison.

1.5.5 Dispersion

In an ideal world of propagating monochromatic signals chromatic dispersion has no meaning, with the exception of a dispersion type that depends on the geometry of the medium or its polarization state. Aside from this, in the real world there are no monochromatic signals, but polychromatic signals with a bundle of frequencies in a narrow band. This reality raises many issues, most of which are undesirable. In the following sections, we examine dispersion types, their issues, and their countermeasures.

1.5.5.1 Modal Dispersion

An optical signal launched into a fiber may be considered as a bundle of rays. Although a serious effort is made to launch all rays parallel into the fiber, due to imperfections of optical devices, rays are transmitted within a small cone. The nonparallelism of the rays in the fiber affects transmission.

Consider a modulated optical signal consisting of various rays of the same wavelength coupled into the fiber (Fig. 1.44); here we make a simplification of this effect by assuming ideal monochromaticity. Because the rays are not parallel they travel different paths along the fiber in different zigzag paths, as electromagnetic waves travel in waveguides; each zigzag path represents a different *mode*. Thus, ray A travels in a straight path along the core of the fiber (one mode), whereas ray B travels in an angle bouncing off the cladding (another mode). Thus, as each ray travels a different distance, it arrives at a distant point of the fiber at a different time. As a result, due to

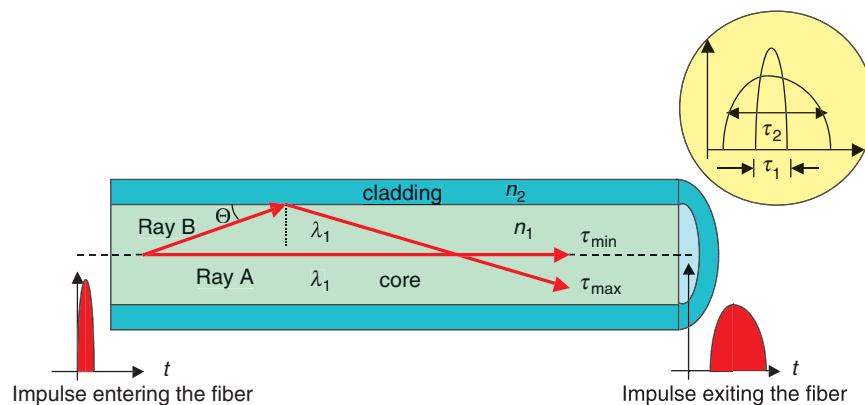


Figure 1.44 Modal dispersion causes a narrow pulse to widen.

modal delays the initial narrow pulse spreads out. This is known as *modal dispersion*; modal dispersion is particularly important in multimode fibers.

Thus, as a pulse spreads out, at some point it starts overlapping the pulse that follows it. Obviously, in ultrafast digital transmission where pulses are as narrow as a few tens of picoseconds, this is highly undesirable.

In digital transmission, a rule of thumb for acceptable dispersion (of any type) is

$$\Delta\tau < T/k$$

and the bit rate information limit is expressed by

$$R_b < 1/(k\Delta\tau)$$

where $\Delta\tau = \tau_2 - \tau_1$, R_b is the information (bit) rate, T is the bit period, k is the dispersion factor (a transmission design parameter, typically selected to $k = 4$). If $k = 5$, then less dispersion is acceptable, and if $k = 3$, then more dispersion is acceptable.

The travel time of the two rays is expressed as

$$\tau_{\min} = (Ln_1)/v$$

and

$$\tau_{\max} = (Ln_1)/v \cos \Theta$$

for $\Theta = \Theta_{\text{crit}}$ (total reflection) and from Snell's law

$$\cos \Theta_{\text{crit}} = n_1/n_2$$

The difference in travel time (assuming total reflection) is

$$\Delta\tau = \tau_{\max} - \tau_{\min} = \{(Ln_1)/v\} \Delta n/n_1$$

Hence, the maximum bit rate, R_b , is calculated from

$$R_b < 1/(4\Delta\tau) = (1/4)(v/Ln_1)(n_1/\Delta n)$$

Consider the case of two connected multimode fibers. Clearly, the connection point of the two fibers represents a perturbation or a discontinuity in the optical path. When light rays reach the end of the first fiber, they are launched into the second fiber. However, since there are many modes (i.e., different rays travel in different angles), each ray enters the second fiber at a different angle and thus is refracted differently, changing from one mode to another mode. This is known as *mode mixing*, and it occurs only in interconnected multimode fibers.

Mode mixing affects the actual transmitted bandwidth (BW_{act}) over the multimode fiber length (L), defining an effective bandwidth. To distinguish the effect of mode mixing on bandwidth, an empirical *scaling factor*, γ , has been devised, defining the effective bandwidth as

$$BW_{\text{eff}} = BW_{\text{act}}/L^\gamma$$

where γ is between 0.7 and 1.0.

The difference in travel time (assuming total reflection) is improved if a graded index fiber is used, with a graded index refraction profile $n(r)$. In this case, the fiber dispersion is improved if the condition holds:

$$R_b = / < 2v_g / (n_g L \Delta^2)$$

where n_g is the group refractive index, Δ is the maximum relative index between core and cladding, and v_g is the group velocity in the medium.

Fibers with various graded index profiles have been made. An example of a profile is:

$$n(r) = n_1 \theta \{1 - 2\Delta(r/a)^\alpha\}, \quad \text{for } r < a$$

1.5.5.2 Chromatic Dispersion

The refractive index and the propagation constant of the fiber medium are functions of wavelength. Thus, the travel time of each wavelength over a unit length of fiber depends on these two parameters. In addition, a real optical pulse is not purely monochromatic but consists of a narrow band of wavelengths. Thus, each wavelength in the band travels at a different speed, creating a relative delay among them. The end result of this is that the pulse broadens as it travels in the medium. This is termed *chromatic dispersion*. Thus, chromatic dispersion is the rate of change of the group delay with wavelength.

In terms of the propagation constant, β_o , if it is expanded in a Taylor series, then

$$\beta(\omega) = \beta_o + \beta_1(\omega - \omega_o) + 0.5\beta_2(\omega - \omega_o)^2 + \dots$$

In the series, the term β_1 is the inverse of the group velocity and β_2 is the group velocity dispersion, which causes pulse broadening.

Chromatic dispersion consists of two contributions, *material dispersion* and *wavelength dispersion*; by some sources it is also termed *waveguide dispersion*. Dispersion is measured in ps/nm-Km (i.e., delay per wavelength variation and per fiber length).

In general, the photonic impulse response, $H(t)$, of a dispersive material can be expressed by

$$H(t) = \exp[(i\pi t^2)/(2\beta''z)]$$

where z is the optical path distance in the dispersive medium, and β'' is the second derivative of the propagation constant with respect to frequency ω (or second-order dispersion coefficient).

Material dispersion is due to the dependence of the dielectric constant, ϵ , or the refractive index, n , on frequency, ω . Thus, the propagation characteristics of each wavelength in a fiber are different. Different wavelengths travel at different speeds in the fiber, which results in dispersion due to material.

Material dispersion is the most significant and is characterized by a parameter M , defined as the derivative of group index, N , with respect to wavelength, λ

$$M(\lambda) = -(1/c)(dN/d\lambda) = (\lambda/c)(d^2n/d\lambda^2)$$

where n is the refractive index, λ is the wavelength, c is the speed of light in free space, and $N = n - \lambda(dn/d\lambda)$.

Consider a medium with a region in which the distribution of n changes nonlinearly; then the group and phase velocity change accordingly. If a narrow light pulse that consists of a narrow range of wavelengths is launched in a medium, each individual wavelength arrives at the end of the fiber at a different time. The result is a dispersed pulse due to *material dispersion*.

Waveguide dispersion or *wavelength dispersion* is the contribution due to nonlinear dependence of the propagation constant on frequency, ω . Wavelength dispersion is explained as follows.

Assume a narrow optical impulse that consists of a narrow spectral range. Consider two wavelengths, λ_1 and λ_2 , in the same impulse. We assume that both wavelengths travel (along the core of the fiber) in a straight path, but λ_1 travels faster than λ_2 ($\lambda_1 < \lambda_2$) because of nonlinear dependence of the propagation constant on frequency ω (and on wavelength).

Wavelength dispersion has different sign than material dispersion (Fig. 1.45), although material dispersion is the major contributor. The counteracting action of wavelength dispersion to material dispersion slightly ameliorates the combined effect. Negative dispersion implies that shorter wavelengths travel slower than longer wavelengths. As a consequence, fiber with negative dispersion can be used to compensate for positive dispersion (see Dispersion Compensation).

The travel time t for a group velocity v_g over a length of fiber L is

$$\tau = L/v_g$$

or

$$\tau = L\beta' = L\{\eta\beta/\eta\omega\}$$

where β is the propagation constant, β' is the first derivative with respect to ω , and η is the partial derivative.

The variation of τ with respect to ω , $(\eta\tau/\eta\omega)$, is

$$\eta\tau/\eta\omega = L\eta(1/v_g)/\eta\omega = L\eta^2(\beta)/\eta\omega^2 = L\beta''$$

where β'' is the second derivative with respect to ω .

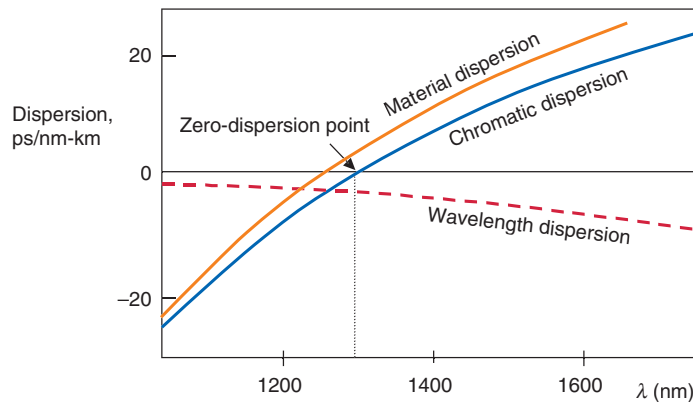


Figure 1.45 Chromatic dispersion components for single mode fiber.

For a signal with a spectral width $\Delta\omega$, then

$$\Delta\tau = (\beta'')L\Delta\omega$$

That is, the pulse spread $\Delta\tau$ (chromatic dispersion) depends on the second derivative with respect to ω , β'' and is proportional to the length of the fiber, L , and the spectral range, $\Delta\omega$.

Based on this, a *group velocity dispersion* (GVD) coefficient, D , is defined as the variation of travel time due to the wavelength variation per unit length of fiber, L

$$D = (1/L)(\eta\tau/\eta\lambda)$$

The coefficient D is also known as the *chromatic dispersion coefficient*; it gives a measure of the *group delay rate change* with wavelength. Consequently, in communications, the chromatic dispersion of a fiber can be found by measuring the time delay of wavelength components that constitute an optical pulse.

It follows that

$$D = (1/L)(\eta\tau/\eta\omega)(\eta\omega/\eta\lambda)$$

However,

$$\eta\tau/\eta\omega = L\beta''$$

and

$$\eta\omega/\eta\lambda = -2\pi v/\lambda^2$$

and thus

$$D = -(2\pi v/\lambda^2)\beta''$$

and

$$\Delta\tau = DL\{-1/(2\pi v/\lambda^2)\}\Delta\omega$$

Finally, the pulse spread, or chromatic dispersion (where η has been replaced by Δ) is expressed by

$$\Delta\tau = |D|L\Delta\lambda$$

where $\Delta\lambda$ is the optical spectral width of the signal (in nm units); occasionally, the chromatic dispersion is also denoted by the Greek letter σ .

Clearly, the pulse spread due to dispersion imposes a limitation on the maximum bit rate; this is also viewed as penalty due to dispersion, which is measured in dB. The dispersion penalty is related to the maximum allowable delay (a fraction ε of the bit period T) before severe signal degradation and unacceptable bit error rate (BER) occurs. From the definition of decibel, a 1-dB penalty corresponds to a bit period fraction approximately 0.5. At ultrahigh bit rates, $0.5T$ may be few picoseconds.

Figure 1.46 illustrates the various actions of chromatic dispersion.

1.5.5.3 Chromatic Dispersion Limits: ITU-T

The maximum *chromatic dispersion coefficient* (CDC), $D(\lambda)$, is specified by ITU-T G.652, G.653, and G.655.

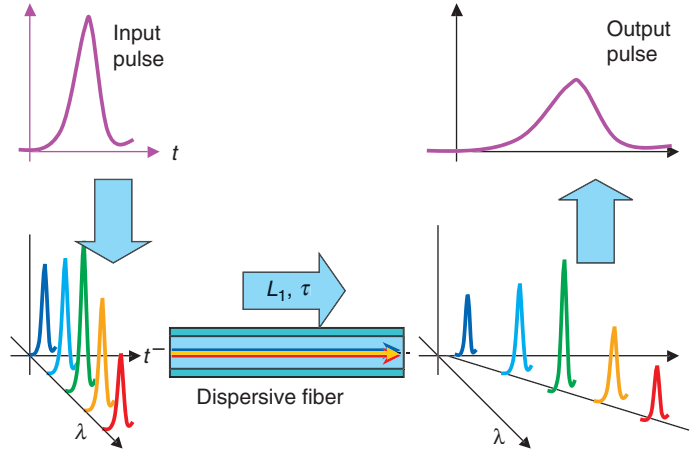


Figure 1.46 Chromatic dispersion: How it works.

ITU-T G.652 recommends the limits of CDC for single-mode fiber and for wavelengths in the range of 1,260 to 1,360 nm. In this case, the CDC limits are calculated by

$$D_1(\lambda) = (S_{0\max}/4)[\lambda - (\lambda_{0\min}^4/\lambda^3)]$$

and

$$D_2(\lambda) = (S_{0\max}/4)[\lambda - (\lambda_{0\max}^4/\lambda^3)]$$

where $S_{0\max}$ is the maximum *zero-dispersion slope* set at $S_{0\max} = -0.093$ ps/(nm²·km), $\lambda_{0\max} = 1,300$ nm, and $\lambda_{0\min} = 1,324$ nm.

ITU-T G.653 recommends the chromatic dispersion coefficients for dispersion-shifted fiber cables. In this case, the CDC is calculated by

$$D(\lambda) = S_0(\lambda - \lambda_0)$$

where S_0 is the zero-dispersion slope [typically equal to or less than 0.085 ps/(nm²·km)], λ_0 is the zero-dispersion wavelength in nm, and λ is the wavelength of interest. Assuming a zero-dispersion fiber at $\lambda_0 = 1,550$ and λ within the range of 1,525 to 1,575 nm, then $D < 3.5$ ps/(nm·km).

ITU-T G.655 recommends the chromatic dispersion coefficients for nonzero dispersion-shifted fiber cables. In this case, the CDC should be within the range specified by

$$D_{\min} = < |D_{\min}(\lambda)| = < D_{\max}, \quad \text{for } \lambda_{\min} = < \lambda = < \lambda_{\max}$$

where 0.1 ps/(nm·km) = $< D_{\min} = < D_{\max} = < 6$ ps/(nm·km), and $1,530$ nm = $< \lambda_{\min} = < \lambda_{\max} = < 1,565$ nm.

Fiber cable manufacturers provide chromatic dispersion coefficients by wavelength regions and for each cable type.

The total dispersion over a fiber span is calculated assuming a linear dependence on length; that is, the coefficient is multiplied by the fiber length in Km.

1.5.5.4 Dispersion-Shifted Fibers and Dispersion-Flattened Fibers

The dependency of the refractive index of silica fiber is nonlinear. As such, at some wavelength, the derivative $d^2\{n(\omega)\}/d\lambda^2$ becomes zero, that is, the material dispersion parameter is given by

$$M(\lambda) = -(dN/d\lambda)/c = (\lambda/c)(d^2n/d\lambda^2)$$

The value λ_0 for which M becomes zero is known as the *zero-dispersion wavelength*. Then, for $\lambda > \lambda_0$ M is positive and for $\lambda < \lambda_0$ M is negative.

In certain cases, the wavelength dispersion and the chromatic dispersion within a spectral (wavelength) range may be of opposite sign, and they may either cancel each other or greatly minimize the net effect. In this case, the effective zero-dispersion wavelength moves to a longer wavelengths. The wavelength range over which this may take place depends on the dispersion slope, given by

$$dD(\lambda)/d\lambda \approx (\lambda/c)(d^3n/d\lambda^3)$$

In general, the operating point on the dispersion curve is not exactly at the zero wavelength point. A small dispersion, enough to ensure that the overall pulse width is still acceptable, is desirable to minimize nonlinear interactions that result in pulse-shape distortion and thus noise generation. When the laser source is expected to increase in frequency, such as for example when the temperature rises (a phenomenon known as *positive chirping*), then the operating point is below the zero wavelength; that is, a small negative dispersion is desirable *as it starts at the outset with pulse compression*.

The amount of desirable dispersion is a function of both the data rate and the modulation method (return-to-zero versus nonreturn-to-zero). As the data rate increases, the pulse width narrows and pulse distortions become more pronounced. Similarly, reducing the optical power density (power per cm^2 of fiber core cross section) reduces nonlinear effects. Consequently, increasing the effective area of the fiber core is desirable as well.

A conventional single-mode fiber with a core diameter of about $8.3 \mu\text{m}$ and an index of refraction variation of about 0.37% has a zero-dispersion at about $1.3 \mu\text{m}$. Below this point, wavelength dispersion is negative, and above this point it is positive.

A fiber with a zero-dispersion point shifted at $1,550 \text{ nm}$ ($1.55 \mu\text{m}$) (i.e., where the minimum absorption for silica fiber is) is called a *dispersion-shifted fiber* (DSF). Such fibers are compatible with optical amplifiers that perform best at around $1,550 \text{ nm}$.

DSF with low loss in the L-band range ($1,570\text{--}1,610 \text{ nm}$) provides a wide range of wavelengths, making it suitable for DWDM applications. For example, DSF fiber has been installed extensively in Japan.

Another fiber with near-zero dispersion in the range from $1.3 \mu\text{m}$ to $1.55 \mu\text{m}$ is called *dispersion-flattened fiber* (DFF). In this category, depending on the slope of the DFF, there is *positive DFF* and *negative DFF*.

To address dispersion effects and to improve optical transmission, a variety of specialty fibers have been engineered, such as the *dispersion-compensated fiber* (DCF), the *dispersion-flattened compensated fiber* (DFCF), the *dispersion-slope compensated fiber* (DSCF), the *dispersion-shift compensated fiber* (DSCF), the *nonzero-dispersion-shifted fiber* (NZDSF), and others. Figure 1.47 illustrates the relative zero-dispersion wavelength between standard single-mode fiber (SSMF), DSF, and NZDSF.

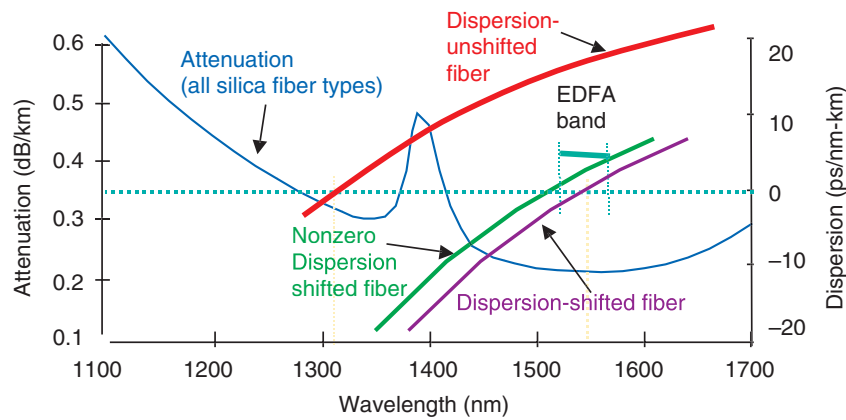


Figure 1.47 SSMF, DSF and NZDSF fibers.

Certain fibers with improved optical transmission characteristics bear tradenames such as *Large Effective Area Fiber* (LEAFTM) and *MetroCor*TM by Corning Inc., *TrueWave*TM and *AllWave*TM by Lucent Technologies, Inc., and others. In general, although dispersion is undesirable, it turns out that operation at the zero-dispersion wavelength may seriously degrade certain channels. Therefore, it is recommended that frequencies passed the zero-dispersion point are used; that is, a small amount of positive or negative dispersion is desirable. Figure 1.48 illustrates the dispersion of several commercial fibers, also indicating the undesirable region (+1 to -1 ps/nm-km), and Table 1.9 tabulates their parameters.

For example: MetroCorTM is a negative-dispersion fiber designed for applications to transport 10 Gb/s C-band WDM signals generated by a distributed feedback laser and for spans in the range of 70 to 100 km. To explain the merits of this fiber, assume that a 1,550-nm signal in a positive dispersion fiber matches its dispersion zero-wavelength. However, assume that the laser source has a positive-frequency chirp (such as a DFB); that is, as the signal travels in the fiber, the wavelength

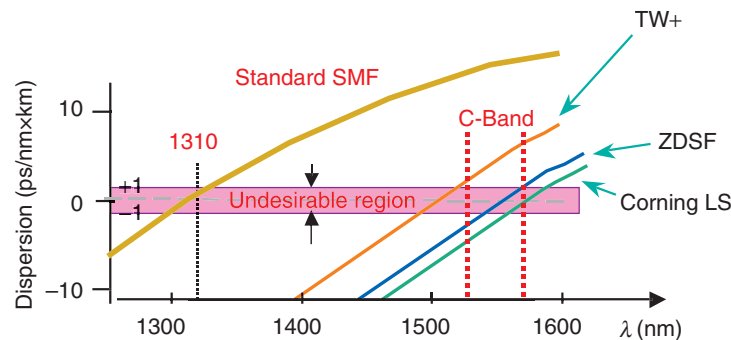


Figure 1.48 Chromatic dispersion (approximate) and zero-dispersion wavelength for different fiber types.

Table 1.9 Fiber parameters

Fiber	D (ps/nm-Km)	S (ps/nm ² -Km)	A_{eff} (μm^2)	Loss (dB/Km)
TWRS	4.4	0.045	55	0.21
TWRS+	4.4	0.030	55	0.21
LEAF	4.0	0.09	72	0.21
SSMF	17	0.056	80	0.21
TeraLight	8	0.058	65	0.21
DCF	-100	-0.33	20	0.5

 D = chromatic dispersion coefficient S = dispersion slope A_{eff} = fiber core effective area

of the leading end of the signal shortens (shifts to the blue) and the wavelength of the trailing edge elongates (shifts to the red). As more wavelengths in the same band propagate in the fiber, nonlinear effects and chirp affect the quality of signal permitting reliable transmission over a fiber span to about 10 km. The MetroCor negative-dispersion fiber minimizes the chirp effect allowing for a fiber length in the range of 70 to 100 km.

TrueWave™ is a two-member fiber family of nonzero-dispersion fibers optimized for WDM applications over long fiber spans (i.e., long haul). This type of fiber is made so that a segment of positive dispersion alternates with an equal length of negative dispersion. Thus, the total dispersion adds up to almost zero. TrueWave comes in different flavors. The TrueWave reduced slope or TW-RS member is optimized for minimal dispersion to minimize cross talk. It introduces only small dispersion (3–7 ps/nm-km) that over a broad spectrum including both the C-bands and L-bands, thus making it suitable for DWDM applications. In addition, the total dispersion over a span of 800 km has less residual dispersion than other fibers with competing specifications. The TrueWave XL is optimized for high-power DWDM signals suitable for undersea long spans and at rates up to 10 Gbps per wavelength.

For example, the TW-RS fiber is specified with:

- maximum noncabled fiber attenuation coefficient (loss) of less than or equal to 0.25 dB/km at 1,550 and 1,600 nm
- maximum attenuation fluctuation in the range of 1,525 to 1,625 nm is no more than 0.05 dB/km greater than the attenuation at 1,550 nm
- chromatic dispersion in
 - the 3rd window (1,530–1,565 nm) is from 2.6 to 6.0 ps/nm-km
 - the 4th window (1,565–1,625 nm) is from 4.0 to 8.9 ps/nm-km
- typical dispersion slope at 1,550 nm is equal to 0.045 ps/nm²-km
- effective group index of refraction at 1,310, 1,550, and 1,625 nm is equal to 1.470
- cabled polarization mode dispersion at 1,550 nm is equal to or less than 0.05 ps/sqrt(km)
- fiber weight per km is 64 grams
- fiber can be cut at lengths of 6.4, 12.6, 19.2, 25, and 38.2 km

Some typical dispersion values, measured at 1,550 nm, are:

Standard single-mode fiber (SSMF) = 16.9

TrueWave RS (TWRS) = 4.41

E-LEAF = 4.32

Numerical Example: Single-Mode Chromatic Dispersion Calculations

The following is an approximate example of dispersion calculations over a fiber link.

Optical fiber manufacturer model:	“XYZ, Inc”, model X-F145X	
Bit rate:	1.2 Gb/s	
Maximum allowable dispersion:	220 ps	
Transmitter wavelength (nominal):	λ_{nom}	1,310 (± 20) nm
Total fiber span length:	L	45 Km
Zero dispersion wavelength:	λ_0	1,310 nm
Dispersion slope at nominal wavelength:	S_0	0.1 ps/nm ² -km
Source spectral line width:	$\Delta\lambda$	0.5 nm
Chromatic dispersion coefficient @ λ_{max} : (provided by manufacturer or calculated by equation: $D(\lambda) = [S_0\lambda/4][1 - (\lambda_0^4/\lambda^4)]$)	$D(\lambda_{\text{max}})$	2.9 ps/nm-km
Chromatic dispersion (calculated):	σ	$\Delta\lambda * D * L = 0.5 * 2.9 * 45$ $= 65.25$ ps

Conclusion: The calculated chromatic dispersion 65.25 ps is within the system manufacturer’s allowable dispersion of 200 ps.

1.5.5.5 Chromatic Dispersion Compensation

Dispersion was not a serious issue for bit rates up to 2.5 Gb/s over SMF fiber lengths less than 500 km. However, at higher bit rates, the bit period decreases and chromatic dispersion dramatically increases, having an adverse effect on the integrity of optical signal. It turns out that the bad effect dispersion has on the signal integrity increases as the square of the data rate.

For example, increasing the bit rate four times, from 2.5 to 10 Gb/s, the effect of chromatic dispersion increases 16 times, and increases by the same factor when increasing from 10 to 40 Gb/s. Similarly, over the same length of fiber the tolerable dispersion at 2.5 Gb/s is 16,000 ps, at 10 Gb/s it is 1000 ps, and at 40 Gb/s is only 60 ps. As another example, at 10 Gb/s a 33% return-to-zero (RZ) pulse has a width of ~ 33 ps, at 40 Gb/s a width of ~ 8 ps and at 160 Gb/s a width of ~ 2.1 ps. It is not difficult to calculate the maximum allowed dispersion before sequential pulses broaden and interfere among them (e.g., at 40 Gb/s it should be ± 12 ps from the center wavelength).

In fiber communications, an increase in dispersion means a decrease in fiber length, as dispersion is cumulative, and for all practical purposes linearly increasing over the length of SMF fiber (the dispersion coefficient is given in ps/nm-km and for SMF it is about 1 ps/nm-Km). Thus, due to dispersion, although at 2.5 Gb/s a fiber length of 500 km may be reasonable, at 10 Gbps it is not, and the length must be 80 km or less. One can easily extrapolate what the fiber length should be at 40 or 160 Gb/s. Nevertheless, the situation is not hopeless. There are dispersion-compensating methods that can spectrally shrink (compensate for) dispersed pulses and allow them to travel over longer fiber lengths.

Because of the sensitivity of the transmitted optical signal to dispersion, particularly at bit rates of 40 Gb/s and beyond, even temperature variations of the fiber must be considered, as the refractive index and hence dispersion are affected. For example, if the dispersion variation per degree Celsius is $0.0025 \text{ ps/nm-km-}^\circ\text{C}$ (for a NZ-DSF fiber type), for a span of 500 Km and for temperature variation of $\Delta T \sim 50^\circ\text{C}$, the total dispersion is calculated to be about 50 ps. Such dispersion puts a limit on high bit rates greater than 10 Gb/s.

1.5.5.6 Dispersion Compensation Methods and Figure of Merit

Chromatic dispersion compensation may be achieved by several methods; we describe two.

A popular method is the *dispersion-compensating fiber* (DCF). A DCF is a fiber with a diffractive index profile that has an opposite dispersive effect than conventional fibers. For instance, because most of the SMF deployed have a positive dispersion effect, whereby longer wavelengths travel slower than shorter wavelengths, DCF is made with negative dispersion over a specific range of wavelengths (Fig. 1.49).

The core of a DCF fiber is heavily doped with germanium and the cladding with fluoride to control the difference of index of refraction between cladding and core, and between silica and germanium, so that, with a proper geometry of index profile, a negative dispersion is achieved. In addition, the DCF's core has an effective aperture three to four times and a refractive index about five times than that of standard SMF. Figure 1.50 illustrates DCF's effect if it is placed after a dispersive fiber (SSMF).

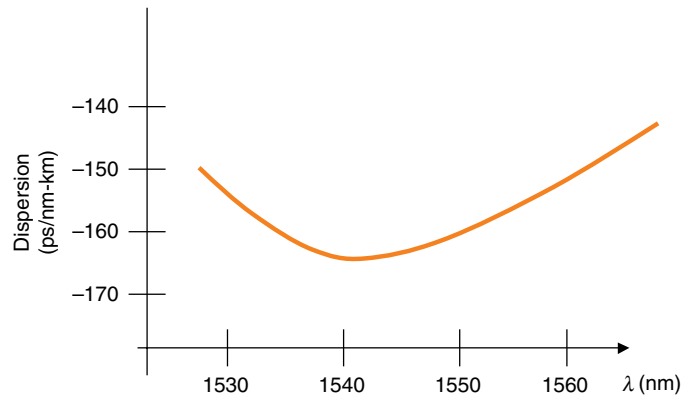


Figure 1.49 Dispersion for DCF (approximate).

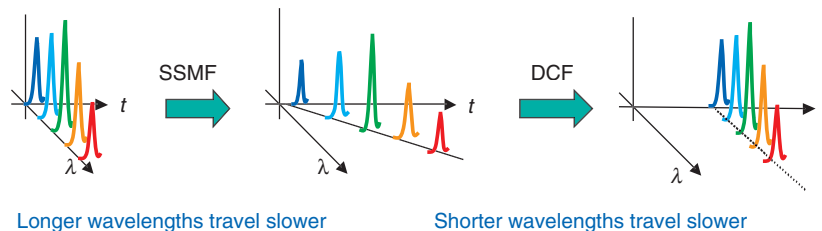


Figure 1.50 Dispersion compensation action for an optical channel.

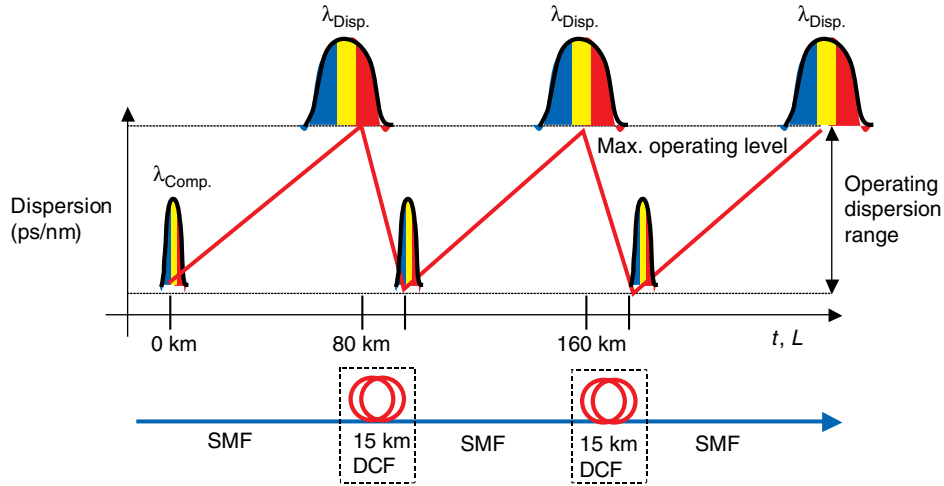


Figure 1.51 Dispersion compensation action for several fiber links (propagation from left to right).

Thus, if standard SMF and DCF fiber are alternating over the complete length, the dispersion induced by the SMF is undone by the DCF. In fact, every 80 km of SMF a spool of about 15 km DCF fiber is connected (this spool is in a central office or in a cabinet). Thus, when a DCF fiber is coupled to the transmitting (conventional) fiber, chromatic dispersion is compensated for the group of wavelengths the DCF is best designed for. DCFs are attractive for DWDM applications in the C-band (with zero dispersion at 1,550 nm), particularly when there are plans for EDFA optical amplification (Fig. 1.51).

However, although this method seems simplistic in its application, it has two “watch outs.” First, it affects the optical transmission loss budget as DCF exhibits twice the loss of standard SMF (clearly this impacts the overall optical amplification plan as well). Second, SMF and DCF are not exactly spectrally balanced; that is, in DWDM whereas one wavelength (optical channel) is exactly compensated, the remaining wavelengths in the band are not, longer wavelengths have a negative residual dispersion and shorter wavelengths a positive, and thus there is a residual dispersion. The variation from positive to negative residual is known as *dispersion slope mismatch* (Fig. 1.52).

When the silica fiber is heavily doped with germanium and the cladding with fluoride to create negative dispersion slope (i.e., a DCF) at an operating wavelength, the doping creates an unpleasant and anomalous increase in optical loss. In DCFs, a figure of merit (FOM) is defined as the ratio of the absolute value of chromatic dispersion to transmission loss, at the wavelength of interest (e.g., 1,550 nm) (Fig. 1.53). Here, two additional parameters are of interest, the difference of the refractive index between cladding (in this case, fluorine-doped) and silica core (germanium-doped), Δ^- , and the difference of the refractive index of germanium and silica, Δ^+ .

Chromatic dispersion is also compensated by using chirped in-fiber Bragg gratings. According to this, adjacent wavelengths in a channel are reflected at different depths of the FBG, thus compensating for the travel time variation. However, this type of arrangement accounts for single wavelength compensation; for a band of frequencies, an equal amount of gratings is required. Another method is to have several gratings

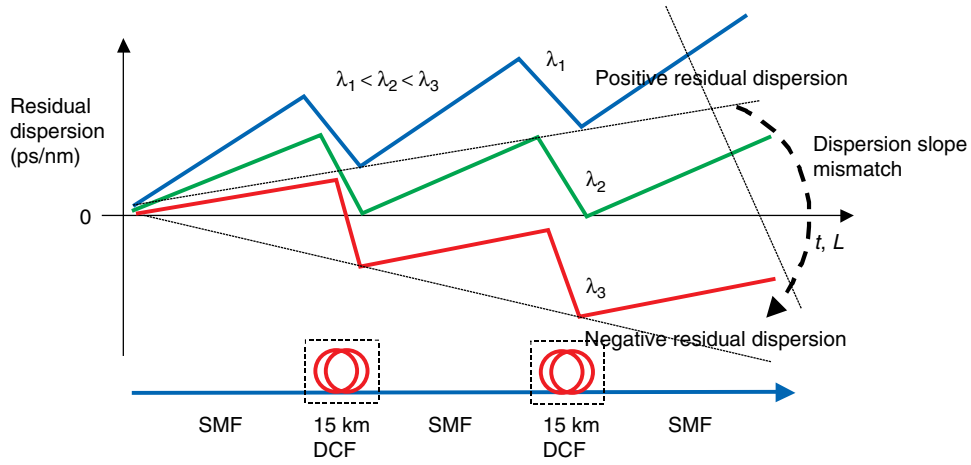


Figure 1.52 Residual dispersion in dispersion compensation.

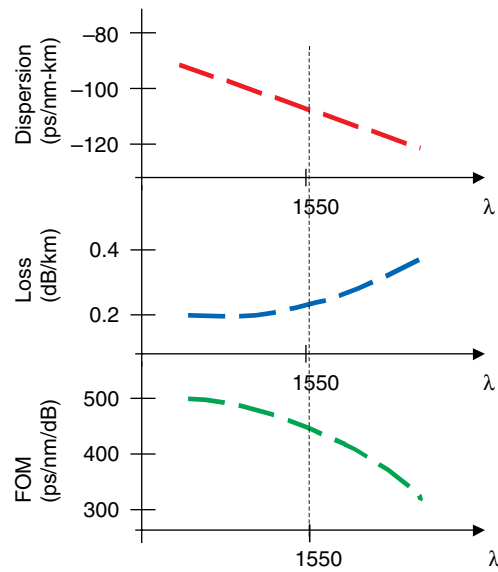


Figure 1.53 Approximate figure of merit for DCF.

written in a longer fiber (on the order of a meter), or having a pattern written in a shorter fiber (on the order of several centimeters) emanating from a sampling function. The Fourier transform of a sampling function results in many replicas, each at a different frequency. Thus, the sampling function creates different gratings with negative dispersion, each operating at different frequencies.

Another promising method for compensating dispersion is using an interferometer-based on *nonlinear optical loop mirrors* (NOLM). A NOLM is made with a 50/50 splitter and a loop of dispersion-shifted fiber (see Resonant Ring) to construct a two-port device, with each of the ports being a possible output. Typically, light is reflected

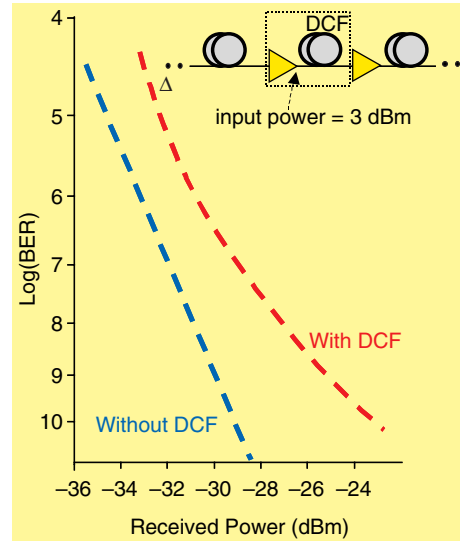


Figure 1.54 Improvement of BER using DCF.

back to the fiber input. However, because of self-phase modulation in the nonlinear fiber, a phase-shift occurs that causes an interference fringe shift that changes the direction of propagation and light propagates onward. Switching from one input to the other in a NOLM is a very fast process, on the order of picoseconds, and thus this technique is suitable in soliton transmission.

Compensation at very high bit rates is very critical. Hence, dispersion-compensating modules (DCM), that incorporate a dispersion-compensating technology have been developed to allow for dispersion management. As such, DCMs monitor the dispersion of each optical channel at a receiving terminal of a DWDM system and individually compensate each channel for dispersion. In general, DCMs improve dispersion and thus the bit error rate (BER) of the signal(s) allowing for longer fiber length (Fig. 1.54). Therefore, at high bit rates, and particularly in DWDM transmission, they provide a very important function.

The (ideal) salient characteristics of DCMs are:

- uniform dispersion compensation over the spectral range of interest
- uniform insertion loss over the spectral range of interest
- zero polarization
- zero birefringence
- small package and low cost

1.5.5.7 Polarization Mode Dispersion

All fibers have some degree of birefringence and have a core that is not perfectly circular over their entire length. Fiber birefringence and core noncircularity causes an optical (monochromatic) signal to be separated into two orthogonally polarized signals, or principal states of polarization (PSP), each traveling at different speed and phase. The same occurs to each pulse of a modulated optical signal; the pulse is

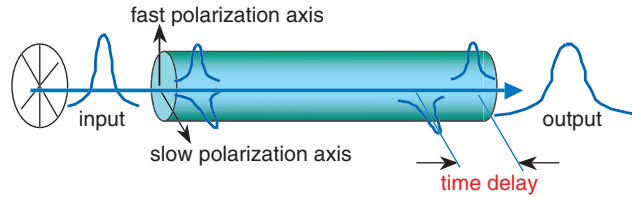


Figure 1.55 Polarization-mode dispersion.

separated into two pulses, each traveling at a different speed. Thus, when the two signals recombine, because of the variation in time of arrival, a pulse spreading occurs (Fig. 1.55). This phenomenon is particularly noticeable in single-mode fiber transmission at ultrahigh bit rates (above 2.5 Gbps) and is known as *polarization mode dispersion* (PMD).

By definition (see ITU-T G.650), PMD is measured by the average differential group delay time (DGD) over wavelength between two orthogonally polarized modes (measured in ps). PMD is maximized if both PSPs are equally and maximally excited resulting in maximum DGD and pulse spreading. Conversely, PMD vanishes or is greatly minimized if only one of the two states is excited. Similarly, the *polarization mode dispersion coefficient* is defined as the PMD divided by the square root of fiber length (measured in ps/ $\sqrt{\text{km}}$). Optical fibers have a polarization mode dispersion coefficient of less than 0.5 ps/ $\sqrt{\text{km}}$ (see ITU-T G.650, G.652, G.653, and G.655).

Another phenomenon, experimentally demonstrated but not fully explained theoretically, is also attributed to PMD. According to this phenomenon, when a stream of very narrow (few picoseconds) orthogonally polarized pulses with separation of few tens of picoseconds is transmitted in a fiber, then two sequential (orthogonally polarized) pulses interact and generate two pulses at lower amplitude and different polarization. Thus, two consecutive pulses, one polarized at $+45^\circ$ and the other at -45° produce a third linearly polarized signal at lower amplitude (Fig. 1.56). It has been shown that as the separation between the two pulses increases, this PMD generated signal decreases.

As a consequence of the DGD definition, if DGD is measured by the average difference of time arrival, $\Delta\tau$, between the two orthogonally polarized modes, and that the two polarized modes are related to the birefringence of the fiber, Δn_g , then DGD is measured by

$$Dt = (\Delta n_g L)/c$$

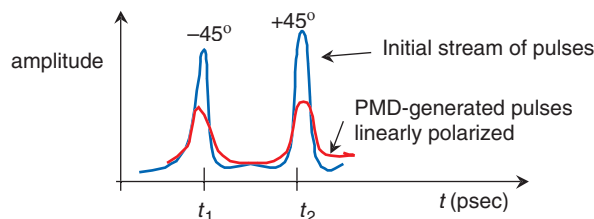


Figure 1.56 In polarization mode dispersion, sequential orthogonally polarized pulses interact to generate another stream of linearly polarized pulses.

where c is the speed of light, L is the length of the fiber, and Δn_g is the refractive index variation corresponding to the group velocity of the orthogonal polarization states.

PMD has been phenomenologically explained by extensive vectorial analysis that considers the propagation of principle states of polarization. In a graphical representation of polarization states, see Poincare' sphere (Figure 1.25), PSPs are located in diametrically opposite points on the sphere's surface; points on the equator of the sphere represent linear polarization, polar points represent circular, and points on the hemispheres represent elliptical polarizations states (the northern hemisphere represents right-handed and the southern hemisphere represents left-handed).

As the noncircularity of a fiber core causes PSPs, each polarization state at different speed and phase, an issue emerges at the connecting point of two fibers where in most practical cases core noncircularity is not matched. Hence, slow and fast states from one segment are coupled into another core with different orientations of polarization. Thus, at the interface as the polarization states from one fiber are coupled into the next, input PSPs are transformed into different output PSPs. This is known as *polarization mode coupling* (PMC). As a consequence, over a fiber span with several connections, PMC becomes a random event that affects DGD and PSPs randomly to further complicate PMD compensation.

In reality, the fiber core is not perfect (free from geometrical imperfections) but it varies between circular and elliptical and in a nonuniform manner. Moreover, the optical channel is not purely monochromatic. Therefore, as an optical channel propagates in the fiber core, PMD is the unavoidable result of fiber core birefringence and channel nonmonochromaticity. As a consequence, as two orthogonal (principle) states propagate in the fiber core, they reexperience a variability in polarization (due to nonuniform fluctuation of imperfections), known as Stokes noise, and due to optical channel wavelength content, known as chromatic jitter. In this case, the square of the relative DGD noise ($d(\Delta\tau)/\Delta\tau$) is the sum of squares of each noise component (the Stokes-related and the jitter-related components):

$$[d(\Delta\tau)/\Delta\tau]^2 = [d(\Delta S)/\Delta S]^2 + [d(\Delta\varpi)/\Delta\varpi]^2$$

where $\Delta\varpi$ is the frequency (or wavelength), d is the differential operator, and ΔS is the polarization state variability at the output of the fiber; the inverse of the latter is also known as the "bandwidth efficiency factor," α :

$$\alpha = 1/d(\Delta S)$$

The bandwidth efficiency factor is characteristic of the measuring method (it may have a value from less than 1 to more than 200), and it is related to the signal-to-noise ratio (SNR) of the optical signal in the following sense:

$$\text{SNR} = \alpha \Delta\tau \Delta\varpi$$

That is, given the value of α , and measuring $\Delta\tau$ and $\Delta\varpi$, the potential maximum SNR is calculated from which the potential amount of noise is determined.

In summary, the key fiber PMD parameters are the differential group delay, the beat length, and the correlation length. PMD adds to the fiber dispersion characteristics and puts additional limits on both fiber span and optical received power (Fig. 1.57).

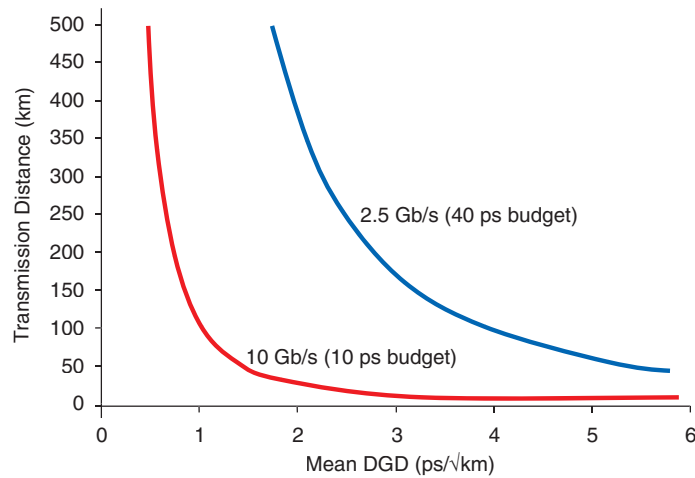


Figure 1.57 Transmission distance as a function of fiber differential group delay; at higher data rates PMD becomes more significant as it effectively shortens the fiber length (actual graph depends on fiber).

Currently, there are several methods under development aiming to compensate for PMD. For an STS-192/STM-64 signal (~ 10 Gbps), this PMD coefficient value limits the fiber length to 400 km.

1.5.5.8 Fiber Polarization-Dependent Loss

Virtually all optically transparent materials, including fiber, exhibit some degree of polarization sensitivity. That is, optical power passes without power reduction selectively in certain polarized states while with reduced power in others. As a result, optical power suffers loss. This is termed fiber *polarization-dependent loss* (PDL), and it represents the peak-to-peak optical power variation measured in decibels (dB). Clearly, linear polarizers have strong PDL values (e.g. > 30 dB), whereas SMF very little (< 0.02 dB).

In DWDM, PDL becomes critical when the bit rate is high (greater than 10 Gb/s) and the number of optical channels (wavelengths) gets dense, with a narrow linewidth, at or less than 0.05 nm at full-width half maximum (FWHM); such narrow linewidths become highly polarized. Strong PDL adds to IL and cross talk. An issue with polarization dependence is that a source may change its polarization state randomly, and thus PDL, complicating power budget calculations, degrading the quality of signal and service and system performance.

PDL, like PMD, has been phenomenologically explained by extensive vectorial analysis and considering the propagation of principle states of polarization.

1.5.5.9 Polarization Mode Dispersion Compensation

Fibers are specified by an average *differential group delay* (DGD) in ps or a mean DGD coefficient in $\text{ps}/\sqrt{\text{km}}$. Thus, for a low PMD fiber, the mean DGD coefficient is less than $0.1 \text{ ps}/\sqrt{\text{km}}$, for a high PMD is $\sim 2 \text{ ps}/\sqrt{\text{km}}$. Thus, for a fiber length of 625 km the average DGD for low PMD fiber is about 2.5 ps whereas for high PMD fiber is about 50 ps ($2 \times \sqrt{625} = 2 \times 25 = 50$). In terms of decibels, the receiver sensitivity penalty for avg DGD of 50 ps is less than 0.1 dB at 2.5 Gb/s, and greater than 4 dB at 10 Gb/s. Extrapolating to 40 Gb/s, the receiver penalty clearly becomes very severe.

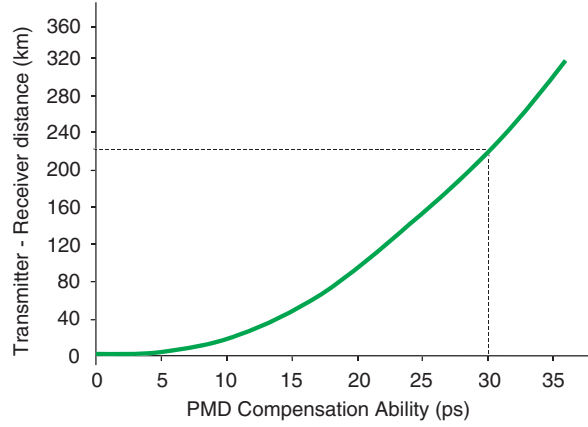


Figure 1.58 PMD compensation increases the transmitter-receiver fiber span; e.g., 30 ps compensation corresponds to more than 200 km (actual graph depends on fiber).

Consequently, PMD becomes a main contributor to dispersion as the bit rate approaches and exceeds 40 Gb/s, necessitating the need for PMD compensation. However, compared with chromatic dispersion, PMD is much more difficult to compensate for, and for the time being there are no easy and inexpensive solutions. Clearly, this presents an opportunity, and substantial research is being conducted in this area. As the bit rate keeps increasing, and PMD compensation will improve the length of the fiber; the distance between transmitter and receiver versus the PMD compensation ability is illustrated in Figure 1.58 for a fiber with *polarization mode dispersion coefficient* ~ 2 ps/sqrt(km).

1.5.6 Spectral Broadening

The refractive index of many materials depends on the amplitude of the electrical field. Thus, as the electrical field changes, so does the refractive index. Thus, as an almost monochromatic light pulse travels in a transparent medium, its amplitude variation causes *phase change* and *spectral broadening*.

The *phase change* is given by

$$\Delta\Phi = [2\pi(\Delta n)L]/\lambda$$

where L is the fiber length and Δn is the refractive index variation,

$$\Delta n = n(\lambda, E) - n_1(\lambda)$$

Phase variations are equivalent to frequency modulation or to “chirping.”

The *spectral broadening* is given by

$$\delta\omega = -d(\Delta\Phi)/dt$$

For a *Gaussian* shaped pulse, spectral broadening is

$$\delta\omega = 0.86\Delta\omega\Delta\Phi_m$$

where $\Delta\omega$ is the spectral width and $\Delta\Phi_m$ is the maximum phase shift in radians.

Spectral broadening appears as if one half of the pulse is frequency downshifted (known as *red shift*) and the other half is frequency upshifted (known as *blue shift*). Such shifts are also expected in pulses that consist of a narrow range of wavelengths that are centered on the zero-dispersion wavelength. Below the zero-dispersion point *wavelength dispersion is negative and above it positive*. Significant spectral broadening is observed when $\Delta\Phi_m$ is equal to or greater than 2.

1.5.7 Self-Phase Modulation

The dynamic characteristics of a propagating optical pulse in fiber, due to the Kerr effect of the medium, result in modulation of its own phase. This nonlinear phenomenon, which is known as *self-phase modulation*, causes spectral broadening, the principles of which are illustrated in Figure 1.59.

If the wavelength of the pulse is below the zero-dispersion point (known as *normal dispersion regime*), then spectral broadening causes temporal broadening of the pulse as it propagates. If the wavelength is above the zero-dispersion wavelength of the fiber (the *anomalous dispersion regime*), then chromatic dispersion compensates self-phase modulation reducing temporal broadening.

1.5.8 Self-Modulation or Modulation Instability

When a single pulse of an almost monochromatic light has a wavelength above the zero-dispersion wavelength of the fiber (known as the anomalous dispersion regime), another phenomenon occurs that degrades the width of the pulse. That is, two side lobes are symmetrically generated at either side of the pulse (Fig. 1.60), thus adding to the noise content of the signal. This is known as *self-modulation* or *modulation instability*.

Modulation instability depends on material dispersion, the optical traveled path (or fiber length) and the optical channel power. Modulation instability is considered a special four-wave mixing case that affects the signal-to-noise ratio.

Modulation instability is reduced by operating at low energy levels and/or at wavelengths below the zero-dispersion wavelength.

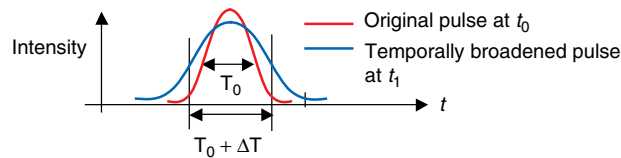


Figure 1.59 The dynamic propagating characteristics of a light-pulse in fiber result in modulating its own phase causing pulse broadening.

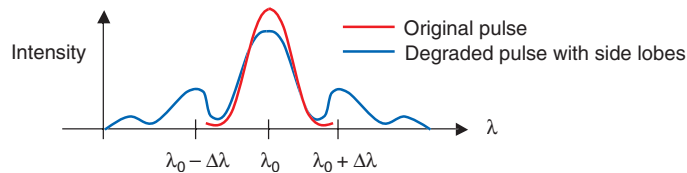


Figure 1.60 When an optical channel operates above the zero-dispersion point, two side lobes are symmetrically generated at a pulse, a phenomenon known as self-modulation or modulation instability.

1.5.9 Effect of Pulse Broadening on Bit Error Rate

The type of fiber used in optical communications is extremely important and different fiber type, based on standards (such as ITU-T G.652, G.653, and G.655) is selected for each application. As an example, according to Chinese officials (presented at the Asian-Pacific Optical Communications Conference in Beijing, November 2001) China will invest \$300 billion in communications infrastructure in the period 2001–2005, becoming that “largest network in the world” with more than 400 million lines and more than 1259 million Km fiber; the average projected growth per year will be 60 million lines for the next five years (China with an excess of 1 billion people had only 10 million lines in 1990). This is a significant decision if one considers that the China optical network requires fiber with high dispersion point (G.652) only for currently existing systems, next generation fiber (G.655) with large A_{eff} , and improved dispersion and dispersion slope to be deployed in high-traffic density networks, whereas discontinuing the DSF (G.653) fiber.

The various forms of dispersion cause pulse broadening that degrades the quality of the signal and increases the *bit error rate* (BER); BER is a measure of the signal quality and is measured in number of errored bits in 1000 received bits. To counterbalance BER increase one needs to shorten the fiber span, which in long-haul communications is highly undesirable; in later sections we will also examine other methods such as the *forward error correction* (FEC). Notice that BER is not defined in the unit of time as this would not be a good metric if we consider that in communications there is a large variety of bit rates ranging from 64 Kb/s to 40 Gb/s; if the unit of time were used instead, then 5 errored bits in one second could be 5 of 64,000 or 5 of 40 billion bits, and clearly this is not a good-quality metric.

One of the factors that causes BERs is pulse broadening which may be the combined effect of many degradation mechanisms as already examined. As pulses broaden, they spread in adjacent bit periods. If in a bit period a logic “zero” should be, spreading of optical power may raise the level such that the receiver may “see” it as a logic “one” (Fig. 1.61). In Chapter 2 we examine how BER can be predicted and what defense mechanisms can be built to restore the degraded signal quality.

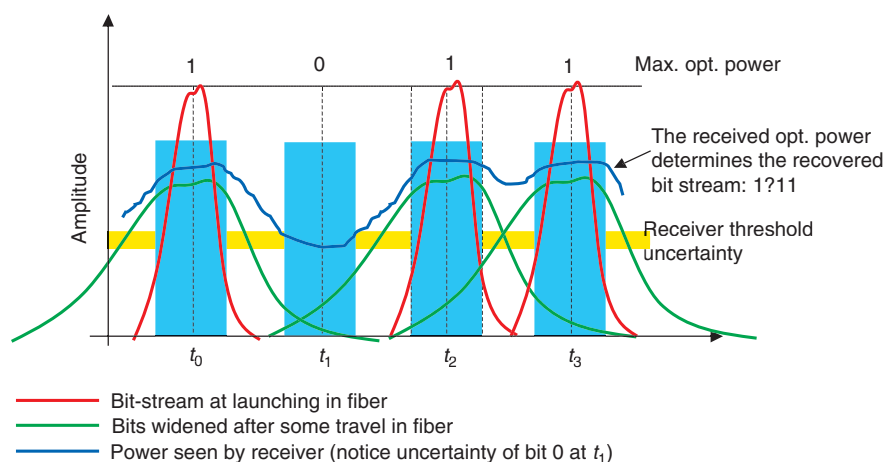


Figure 1.61 Effect of excessive pulse-widening on ISI and BER.

1.6 NONLINEAR PHENOMENA

When light enters matter, photons interact with atoms, and under certain circumstances photons may be absorbed by atoms and excite them to higher energy levels. Many atoms in an excited state become metastable (they cannot remain at that level for a short time, in the range of ns to μ s). However, while in the excited state, certain photons may trigger them (or stimulate them) to come down to their initial lower energy level by releasing energy, *photons*, and/or *phonons* (acoustic quantum energy).

In addition to the phenomena from the photon–atom interaction, there are also photon–atom–photon interactions that result in some complex phenomena, some of which are not well understood yet. These interactions, known as nonlinear phenomena, are best described by quantum theory, and thus we provide only a quantitative description. They are distinguished in *forward scattering* and *backward scattering* (Raman and Brillouin scattering) as well as in *four-wave (or four-photon) mixing*. The direction (forward and backward) is with respect to the direction of the excitation light with respect to the direction of the stimulated light. Backward scattering is due mostly to reflected light at the end face (or other discontinuities) of the fiber.

In optical systems, nonlinear phenomena are viewed as both advantageous and degrading.

- *Advantageous* because lasers, optical amplifiers, and dispersion compensation are based on them.
- *Degrading* because signal losses, noise, cross talk, and pulse broadening are caused by them.

In general, the input–output relationship of a system is expressed by

$$O = k^1 \cdot I + k^2 \cdot I \cdot I + k^3 \cdot I \cdot I \cdot I + \dots$$

where k^n is a higher-order system coefficient, O is the output, and I is the input vector.

The first term ($n = 1$) describes the linear behavior of the system, whereas other terms ($n > 1$) describe higher-order nonlinear behavior.

The response of any dielectric (such as glass fiber) to optical power is nonlinear; the behavior of dielectric to optical power is like that of a dipole. It is the dipole nature of dielectric that interacts harmonically with electromagnetic waves such as light.

When the optical power is low, it results in small oscillations, and the first term of the series approximates the photon–fiber system behavior (i.e., a linear system). However, when the optical power is large, the oscillations are such that higher-order terms (nonlinear behavior) become significant.

Similarly, the polarization of an electromagnetic wave, P , induced in the electric dipoles of a medium by an electric field, E , is proportional to *susceptibility*, χ :

$$P = e_o[\chi^1 \cdot E + \chi^2 \cdot E \cdot E + \chi^3 \cdot E \cdot E \cdot E + \dots]$$

where e_o is the permittivity of free space.

Here again, the first term ($n = 1$) describes the linear behavior of the system whereas other terms ($n > 1$) describe higher-order nonlinear behavior.

For an *isotropic* medium, the second-order is orthogonal and thus it vanishes (or is negligible). Zero second-order nonlinearity implies no second-order nonlinear processes or electro-optic variability (modulation). Silica glass, unlike quartz crystals, is amorphous with macroscopic inversion symmetry. Thus, it too has zero (or near zero) second-order nonlinearity. However, the third-order term produces nonlinear effects that may be significant. Among the nonlinearities, in the following, we examine four-wave mixing, stimulated Raman scattering, and stimulated Brillouin scattering.

If silica fiber with nonzero second-order could be made, and hence with a linear electro-optic coefficient, then it would be possible to manufacture active fibers that could be used as wavelength converters, parametric oscillators, electrically tunable Bragg gratings, optical switches, frequency doubling, optical storage, and so on. Currently, stoichiometric LiNbO_3 and TiTaO_3 with reportedly superior nonlinear and electro-optic coefficients than ordinary congruent crystals have been produced, and it is expected that they soon will be applicable to nonlinear parametric devices.

1.6.1 Stimulated Raman Scattering

Consider a short-wavelength intense source (source A) and a longer-wavelength (by about 80 nm) weak source (source B) propagating within the same medium.

The short-wavelength high-energy (~ 500 mW) source A (known as a pump) excites atoms to a high-energy level. Then, due to some weak nonlinear properties of the medium, excited atoms “drop” after some short time to an intermediate energy level releasing light energy at a wavelength longer than the pump source A. Eventually, all atoms at the intermediate level will “drop” to their initially low (or ground) energy level by releasing the remaining energy in the form of (optical) phonons (Fig. 1.62). This is known as *stimulated Raman scattering* (SRS). In general, when an ion falls from an energy level E_{high} to a lower energy level E_{low} the emitted photon frequency (or wavelength) is determined by the relationship $E = h\nu$:

$$\nu = [E_{\text{high}} - E_{\text{low}}]/h$$

If the excited atoms are stimulated by the photons of the weak source B, the stimulated atoms emit photons of the same wavelength with the stimulating source and under the right conditions signal B is amplified; this is known as *Raman amplification* (more

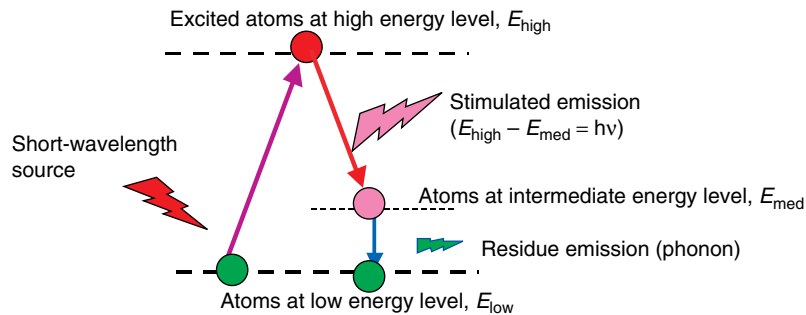


Figure 1.62 A short-wavelength source excites atoms to a higher-energy level. When the atom is stimulated, it releases photonic energy of a longer wavelength.

of this later). In theory, Raman lines are generated, known as Stokes lines) according to relationship $f - n\Delta f$, where for single mode fiber Δf is 70 nm at 1310 nm and 102 nm at 1550 nm.

Thus, because of Raman scattering, energy from the pump is transferred to atoms and it is downshifted (wavelength becomes longer) and it is transferred to the weak signal. Raman scattering occurs in either direction (forward or backward) with respect to the direction of the signal (see also Raman Amplification).

1.6.2 Stimulated Brillouin Scattering

Stimulated Brillouin scattering (SBS), in contrast to Raman scattering, produces stimulated emission while a photon–acoustic phonon interaction takes place. Although stimulated emission is in both directions, the part that is in the same direction with the original signal interacts with acoustical phonons and is scattered, and the part that is in the opposite direction is guided by the fiber. In this case, the stimulated light is at a shorter wavelength (downshifted by 11.1 GHz at 1550 nm, or 13.2 GHz at 1310 nm, although upshifting has also been predicted). If another optical signal at the downshifted wavelength propagates in the fiber in the direction opposite to the original signal, it will be mixed with the transferred energy. This may increase signal cross talk.

It has been experimentally determined that SBS is dominant when the spectral power (brightness) of the source is large and it abruptly increases when the launched power reaches a threshold value. Several factors determine the actual threshold value of launched power, such as the fiber material, the linewidth of the source light, the fiber length, the fiber-core effective cross-section area, and the bit rate of the signal.

Threshold values for SBS in fiber systems are in the range of 5 to 10 mW of launched power (for externally modulated narrow linewidths) and 20 to 30 mW for directly modulated lasers (ITU-T G.663).

Brillouin scattering, like Raman scattering, restricts the launched power per channel. However, SBS also may be advantageously used in optical amplification, where the backward signal may be the pump and the forward signal the one to be amplified.

1.6.3 Four-Wave Mixing

Consider three lightwave frequencies, f_1 , f_2 , and f_3 , closely spaced (in terms of wavelength). Then, from the interaction of the three, a fourth lightwave frequency is generated, f_{fwm} , such that $f_{\text{fwm}} = f_1 + f_2 - f_3$. This is known as *four-wave mixing* (FWM) or *four-photon mixing*. The order of lightwave frequencies is f_1 , f_{fwm} , f_3 , and f_2 (Fig. 1.63). In fact, TU-T defines the generated FWM component as $f_{\text{fwm}} =$

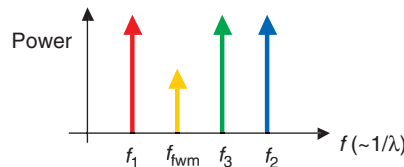


Figure 1.63 In four-wave mixing, three optical frequencies, f_1 , f_2 , and f_3 may interact to produce a fourth frequency, f_{fwm} , $f_{\text{fwm}} = f_1 + f_2 - f_3$.

$f_1 \pm f_2 \pm f_3$. FWM is a nonlinear effect that is described by a nonlinear equation. The FWM component, E_{FWM} , at the output of a fiber segment, L , generated by the three components E_1 , E_2 , and E_3 , with angular frequency ω , refractive index n , nonlinear refractive index χ and loss α is described by

$$E_{\text{FWM}} = j[(2\pi\omega)/nc]d\chi E_1 E_2 E_3 e^{-\alpha(L/2)} F(\alpha, L, \Delta\beta)$$

where $F(\alpha, L, \Delta\beta)$ is a function of fiber loss, fiber length, and propagation variation (phase mismatch) related to channel spacing and dispersion.

The output power of the f_{fwm} and the efficiency of four-wave mixing depend on several factors. These factors are:

- the wavelength mismatch or channel spacing, D_b , or Δf
- the power intensity of the contributing frequencies f_1 , f_2 , and f_3
- the chromatic dispersion of the fiber
- the refractive index
- the fiber length
- higher-order polarization properties of the material (nonlinear Kerr coefficient)

Four-wave mixing (FWM) may also occur with two signals at different wavelengths if their intensity and wavelengths are in a specific relationship. In this case, the fiber refractive index is modulated at the beat frequency of the two wavelengths. The phase modulation in this case creates two sidebands (at frequencies given by this difference) the intensity of which is weak as compared with the intensity of the mixing products from three signals.

The effect of FWM on optical transmission and in single mode fiber is:

- cross talk, due to superposition of uncorrelated data from the contributing channels
- signal power depletion as a result of signal power sharing among the contributing channels to the FWM generated channel
- signal-to-noise degradation, due to superposition of noise and random data from the contributing frequencies

As the signal input power of f_1 , f_2 , and f_3 increases, or as the channel spacing decreases (due to more wavelength-channels in the same fiber), the FWM output term f_{fwm} increases. ITU-T (G.663) recommends that the critical optical power for FWM is greater than 10 mW, although this depends on channel spacing. At 200 GHz channel spacing, it has been experimentally verified that the FWM effect is drastically decreased as compared with 100 GHz or less spacing.

The current trend (caused by bandwidth demand) is to fit more channels into the same spectrum; as a result of this, the channel spacing decreases to less than 100 GHz (50 GHz for 80 channels in the C-band going down to 25 GHz) and thus FWM cross talk becomes more significant. A widely used formula for FWM-induced cross talk is given by

$$P_{ijk}(L) = (\eta/9)D^2\gamma^2 P_i P_j P_k e^{-\alpha L} \{[1 - \exp^{-\alpha L}]^2 / \alpha^2\}$$

where P_i , P_j , and P_k are the input powers of the three input signals f_1 , f_2 , and f_3 ; L is the optical traveled length (i.e., fiber length); α is the attenuation coefficient; η is the FWM efficiency; D is a degenerative factor (equal to 3 for degenerative FWM or 6 for nondegenerative FWM); and γ is a nonlinear coefficient (for the fiber medium) given by

$$\gamma = (2\pi n_2)/(\lambda A_{\text{eff}})$$

where λ is the wavelength in free space, and A_{eff} and n_2 are the effective area and the nonlinear refractive index of the fiber, respectively.

The nonlinear refractive index is related to nonlinear susceptibility χ_{1111} of the optical medium and to the refractive index of the core n of the fiber given by

$$n_2 = [(48\pi^2)/(cn^2)]\chi_{1111}$$

The FWM efficiency factor depends, among other parameters, on a phase matching factor, which depends on fiber dispersion and channel spacing. In fact, at the zero-dispersion wavelength, FWM is at its best performance; this is one of the reasons that in DWDM communications the zero-dispersion wavelength is avoided and the wavelength operating point is preferably positive and slightly above the zero-dispersion wavelength. Thus, four-wave mixing, as opposed to Raman scattering, requires strong phase matching of coincident energy from all three wavelengths. Moreover, both chromatic dispersion and length of fiber reduce the intensity of the FWM product.

In short, the FWM efficiency depends on material dispersion, channel separation, optical traveled path (or fiber length) and on optical power level of each contributing channel. The resultant FWM component affects the quality of the signal in terms of cross talk and bit error rate and thus FWM limits the channel capacity of a fiber system.

As a side note, it is of interest to note that the same mechanism that causes FWM also causes modulation instability.

1.6.4 Temporal FWM, Near-End and Far-End

Consider a narrow light pulse at a wavelength traveling along a fiber segment. Think of the light pulse as a sliding window along the fiber with constant speed. As the light pulse slides along the fiber, it influences the electric dipoles of the fiber segment for as long as they are in it. If at the same time, there are two more pulses on adjacent wavelength channels, overlapping in time, then in this segment FWM occurs. Since the signal power at the *near-end* of the fiber (close to the source) is at its maximum, the FWM product also is at its highest intensity. This is a consequence from the discussion on the FWM efficiency factor and the strong phase matching required for FWM.

Similarly, when the three light pulses arrive at a *far-end* segment of a fiber that is several kilometers long, due to dispersion and attenuation of the pulses, the FWM product at that segment is at its lowest intensity. Figure 1.64 qualitatively illustrates the contribution of FWM at the near-end and at the far-end of a fiber. Clearly, FWM occurs in a time-continuous manner, and although at the near-end it has a maximum

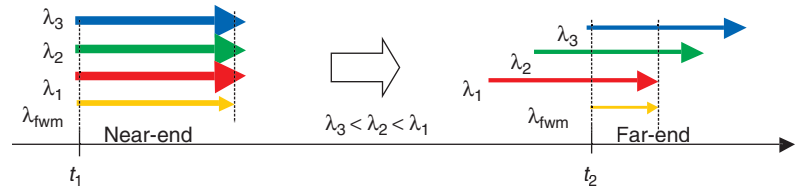


Figure 1.64 The effect of FWM is strongest at the near-end of synchronized channels, and it is diminished at the far-end where channels are weakest due to attenuation and dispersion.

effect, its cumulative strength diminishes as the pulses travel along the fiber. The study of FWM in the time domain is termed *temporal FWM* (tFWM).

1.6.5 Impact of FWM on DWDM Transmission Systems

As the density of wavelengths (channels) in DWDM systems increases, cross talk increases in importance.

- If the optical power of each channel is increased, FWM becomes more intense.
- If the launched optical power of each channel is lowered, then the actual fiber length is decreased to ensure that the arriving signal can be detected reliably. This may necessitate optical amplification to extend the fiber path (optical amplification increases the cost).
- If the channel (wavelength) density increases, or if the channels are spaced very close to each other, FWM becomes more intense.
- If the channels are spaced farther apart, then fewer wavelength channels can fit into the fiber.

1.6.6 Countermeasures to Reduce FWM

Four-wave mixing is a phenomenon that cannot be entirely eliminated. However, it can be greatly minimized so that its effect is not destructive. Several countermeasures and design approaches may aid to suppress the FWM contribution.

- Channels are spaced unevenly.
- Channel spacing is increased.
- The launched power into the fiber is reduced.
- Segments of fibers with opposing nonzero dispersion characteristics after long spans of standard fiber cable are used to maintain a near-zero net chromatic dispersion.

1.7 SOLITONS

Self-modulation (red shift and blue shift) depends on pulse shape. Under specific conditions (very short pulses with a specific power spectrum), spectral broadening due to self-modulation can be compensated for by fiber dispersion. In this case, assuming an ideal fiber, pulses preserve their input shape and are stable over the entire length of the fiber. Pulses that preserve their shape, amplitude, and width are known as *solitons*, and the conditions for generation and sustained propagation are known as the *soliton regime*.

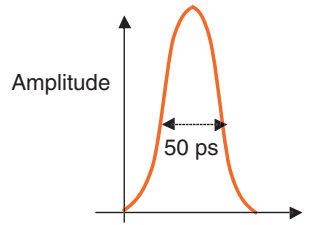


Figure 1.65 Self-modulation of very narrow pulses can be compensated for by fiber dispersion thus preserving the pulse shape; such pulses, known as solitons, have the ability to travel for thousands of kilometers.

The *soliton regime* involves parameters such as “input optical power” (derived from a *hyperbolic secant* function), “effective area and cross section of the fiber core,” “dielectric constant” of fiber and of free space ($\epsilon_0 = 8.854 \cdot 10^{-12}$ F/m), and fiber type. Similarly, a rigorous theoretical analysis of soliton generation and propagation entails solving a homogeneous Shrödinger-type equation. Any optical pulse within an area of $A = \sqrt{1.6} W^{1/2}$ ps ($\pm 50\%$) can reach the soliton regime in a typical single-mode fiber. Typical solitons are about 50 ps wide or less (Fig 1.65).

Solving Shrödinger’s equation is beyond the scope of this book (many textbooks have dealt with this); it is more appropriate, however, to provide a qualitative description of the soliton.

When a narrow pulse is launched into a fiber, its initial pulse shape oscillates temporarily as two competing effects act on it, spectral broadening and compensation by dispersion. Finally, this oscillation, at some time later and after some fiber length, reaches an equilibrium compensating state and the soliton takes a shape very close to its initial form. However, the shape of a soliton is also affected by other effects, such as third-order dispersion effects may cause the soliton to change its velocity and thus its shape, and fiber losses that may cause the soliton to lose amplitude and broaden. For example, 15 Km travel in standard single-mode fiber doubles the soliton width, but a low-loss single mode fiber with low third-order dispersion characteristics enables solitons to travel much longer distances (on the order of a few thousand kilometers) without amplification and because of the narrowness of pulses allow for very high bit rates.

When solitons are used in DWDM systems collision among solitons that belong to different optical channels also may take place. Collision may take place over a fiber length for which solitons overlap; this length is known as the *collision length*, L_{coll} . The collision length depends on fiber parameters, channel spacing, channel wavelength, and the bit rate of the colliding channels; L_{coll} can be 10 Km or even 100 Km.

It has been shown that an exchange of energy takes place during soliton collision. As a result, there is a soliton frequency and temporal phase-shift that cause residual effects. At the receiver, because of the *collision-induced temporal shift* and because 1s and 0s in the bit stream are random (timing) *jitter* is induced. Only transitions from 1 to 0 or from 0 to 1 would cause this as a contiguous string of ones would cause the same shift from bit to bit and thus no jitter. When the collision length becomes comparable to the amplifier spacing, the residual shift (jitter) may be about 0.1 GHz, which is an unacceptable value since jitter is cumulative.

Soliton generation in long-haul and particularly transoceanic transmission systems using dispersion managed fibers promise a technology that exhibits reduced nonlinear effects, high spectral efficiency, RZ modulation, ultrahigh bit rates, and fiber spans at very long lengths (many hundreds of kilometers) without regeneration or amplification. Yet the soliton integrity must be maintained over a path despite path diversity, temperature variations, and the addition or removal of splices, connectors, and fiber type over time; and this is what slows down the soliton deployment in fiber paths that in practice cannot remain unchanged. Soliton applicability in medium-haul and short-haul land network is, for the time being, cost-prohibitive but they are promising in submarine cross-Atlantic deployment.

1.8 SUMMARY OF NONLINEAR PHENOMENA

Briefly, the most important nonlinear phenomena in optical communication are:

- Stimulated Raman scattering (SRS): OChs with optical power above a threshold may behave as a pump for longer wavelengths or cause photonic spontaneous emission in either direction that degrades the signal to noise ratio. There is no well-known controlling mechanism for SRS.
- Stimulated Brillouin scattering (SBS): Similar to SRS, dominant in the backward direction, and the threshold is from ~ 5 to 10 mW for external modulation, and from ~ 20 to 30 mW for direct modulation. SBS is controlled by lowering the signal intensity, or by making the source linewidth wider than the Brillouin bandwidth.
- Four-wave mixing (FWM): Created sidebands that deplete the optical power of contributing signals. Channel spacing and optical power management controls FWM.
- Modulation instability (MI): MI may degrades the signal to noise ratio due to created sidebands and thus decrease the optical power level.
- Self-phase modulation (SPM): Changes in optical intensity cause variation in the phase of the optical signal; this broadens the signal spectrum (and pulse width). Operating in the anomalous dispersion region, chromatic dispersion and SPM compensate each other. However, this may result in spontaneous formation of Solitons.
- Cross-phase modulation (XPM): Interacting adjacent optical channels induce phase changes and thus pulse broadening. This is controlled by channel spacing selection.

1.9 FACTORS THAT AFFECT MATTER AND LIGHT

We have discussed the parameters that influence light, the parameters that influence matter, and the interactions that take place when light meets matter. In this section, we summarize these effects, what causes them, and how they are measured. Table 1.10 tabulates the effects and what causes them, and Table 1.11 lists the parameters and the measuring methods.

For more details, see ITU-T recommendations G.650, G.652, G.653, and G.654.

Table 1.10 Cause and effect

Cause	Effect
λ interacts with λ	Interference
λ s interact with matter	Linear and nonlinear effects: absorption, scattering, birefringence, phase shift, reflection, refraction, diffraction, polarization, polarization shift, PDL, modulation, self-phase modulation, etc.
λ -matter- λ interaction	FWM, issues, SRS, SBS, OFA
Nonmonochromatic channel	Pulse broadening, finite number of channels within available band.
Refractive index variation (n)	Affects propagation of light
Transparency variation	Affects amount of light through matter;
Scattering	optical power loss (attenuation)
Reflectivity	Affects polarization of reflected optical wave;
	Affects phase of reflected optical wave
Ions in matter	Dipoles interacting selectively with λ s;
	Energy absorption or exchange;
	Affect refractive index;

Table 1.11 Parameters and measuring methods

Parameter (Symbol, Unit)	Measuring Method
Attenuation $\{A(\lambda), \text{-dB}\}$	$A(\lambda) = 10 \log[P_{\text{out}}(\lambda)/P_{\text{in}}(\lambda)]$, $P_{\text{in}} > P_{\text{out}}$
Attenuation coefficient $\{\alpha(\lambda), \text{dB/km}\}$	$\alpha(\lambda) = A(\lambda)/L$
Insertion Loss, (IL, -dB) between port i and port j	$IL_{ij} = P_j - P_i$, or $IL_{ij} = -10 \log_{10} t_{ij}$, (where $t_{ij} = I/O$ power transfer matrix)
Amplification gain (g, dB)	$g(\lambda) = 10 \log[P_{\text{out}}(\lambda)/P_{\text{in}}(\lambda)]$, $P_{\text{in}} < P_{\text{out}}$
Birefringence	P_O/P_E ; indirectly (BER, X-talk)
Extinction ratio	P_B/P_F ; indirectly from IL & $A(\lambda)$
Pulse spreading (ps)	$\Delta\tau_{\text{OUT}} - \Delta\tau_{\text{IN}}$ (indirectly from BER, X-talk, eye diagram)
Group delay (ps) ⁺	$\tau(\lambda) = \tau_0 + (S_0/2)(\lambda - \lambda_0)^2$ (see G.653)
Diff. group delay (DGD, ps)	(see ITU-T G.650 for procedure)
Chromatic disp. coeff. (D, psec/nm-km)	$D(\lambda) = S_0(\lambda - \lambda_0)^*$ (see G.653)
Chromatic disp. slope (S, psec/nm ² -km)	it requires laboratory optical setup
Polarization mode dispersion (PMD, ps)	it requires laboratory optical setup
Phase shift ($\Delta\phi$, °, rad):	it requires interferometric setup
Polarization mode shift (Θ , °, rad)	it requires laboratory optical setup

1.10 REGARDING OPTICAL FIBER

Optical fiber is one of the most important parts of the communications network because it impacts the quality of signal, cost, and maintenance. Therefore, a tremendous effort is consumed to select the right fiber for the application at hand and to engineer the fiber span, because once the fiber type has been selected, the span has been engineered, and the cable has been installed, the cost to make changes is not trivial.

1.10.1 Ideal Fiber Versus Real Fiber

To design a fiber, one starts with a mathematical fiber model, which (in theory) is ideal. However, when the real fiber is manufactured, based on this model, it turns out that its theoretical model is only a good approximation. For example, the physical dimensions of fiber are not exact and uniform over its length, although they may be contained within the ITU-T–defined limits, its refractive index is not exactly uniform, and it is not absolutely stress-free (stress causes birefringence). As a consequence:

- The diameter of the core and of the cladding varies.
- The refractive distribution over length varies.
- The radial refractive distribution (refractive index profile) varies.
- The density of contaminants or dopants over length varies.
- Birefringence varies.
- Polarization varies.
- Many other parameters also vary.

These imperfections affect the quality of the signal and they are either manifested as power loss, polarization state variation, noise, and other linear and nonlinear effects. Fiber manufacturers are aware of these imperfections and strive to produce the most uniform fiber with the most desired propagation characteristics. In general, good fiber should have the same characteristics in every kilometer of its length.

1.10.2 The Evolving Bandwidth-Span Product

Although current fiber meets the bandwidth needs and spans in optical networking, it is clear that fiber is continuously evolving and improving in both transmission performance and cost. When the first SMF, optimized for 1310 nm, made its debut in 1983, announcing that it supports optical transmission at 2.5 Gb/s for up to 640 km without amplification (or 10 Gb/s up to ~ 100 km), it was in the news. Recent SMF transports the same optical signal (2.5 Gb/s) to over 4,400 km (or 10 Gb/s up to ~ 500 km) without amplification. With a simple extrapolation, it is reasonable to expect in the next decade that new fiber will further push the envelope to $\sim 2,000$ km for 10 Gb/s signals and to 500 km for 40 Gb/s, and 2.5 Gb/s will be used in lower network layers (Metro and Access) and not in long-haul applications.

Based on this data rate trend, for 2.5 Gb/s the transportable bandwidth-span product without amplification has increased (per channel) from 1600 to 11,000, and for 10 Gb/s it has increased from 1,000 to 5,000 and projected to approximately 20,000.

In DWDM, the aggregate bandwidth-span product is calculated by multiplying the bandwidth-span product by the number of optical channels; for 10 Gb/s and for 160 channels, this is projected to 3,200,000!

1.10.3 Fiber Amplifiers and Spectral Continuum

Transmitting photonic signals over very long fiber spans (tens or hundreds of kilometers) it requires optical signal amplification due to fiber loss (unless in the special case where optical transmission is in the soliton regime). Unfortunately, a single amplifier

type does not perform over the entire 1,300 to 1,600 nm spectrum but only within a narrow band, as already discussed.

Although a more comprehensive presentation of optical fiber amplifiers is in the next chapter, here, it is important to identify some doped fiber amplifiers.

Praseodymium-doped fluoride fiber amplifiers (PDFFA) promise acceptable performance in the 1,310 nm range. Thorium-doped fiber amplifiers (ThDFA) promise to fill the need of photonic amplification in the 1,350 to 1,450 nm range and Thulium-doped fiber amplifiers (TmDFA) in the range 1,450–1,530 nm.

Erbium-doped fiber amplifiers (EDFA) have been extensively used for optical signal amplification. The 1,550 nm range is the first to be used extensively in DWDM applications, and for which standards have been drafted. In the L-band, modified tellurium-erbium-doped fluoride fiber amplifiers (Te-EDFA) extend this range from 1532 to 1608 nm, which is suitable for long-reach network applications.

Currently, Raman amplifiers have made inroads in fiber amplification as they efficiently address an extended spectrum using standard single-mode fiber. Other fiber amplifiers, better suited in short-wavelength ranges, take advantage of optical parametric properties of fibers. Figure 1.66 illustrates the diversity in optical amplification and the range that each covers.

1.10.4 New Fibers

New fiber types are a matter of intense research and development. Application-specific optical fiber (ASOF) is custom-made by modifying the sequence and concentration of dopants of the fiber core and/or the geometry of the fiber. According to this, fibers with specific properties for specific applications are made. A new type of fiber, currently in experimental phase, is known as *photonic crystal fiber* (PCF) promising improved propagation properties suitable to DWDM applications.

PCFs consist of a bundle of microscopic silica tubes, about one micrometer in diameter (Fig. 1.67). To construct this, one starts with filling a larger silica tube with many smaller silica tubes (like a bundle of thin spaghetti) about 1 millimeter in diameter. This is fused and drawn into long lengths with conventional fiber manufacturing techniques reducing the air hole of each tube to a micrometer scale. The end result is a fiber that when viewed under a microscope consists of microscopic hollow capillary tubes. Light coupled in PCF fiber is confined by the walls of capillary tubes, which guide it

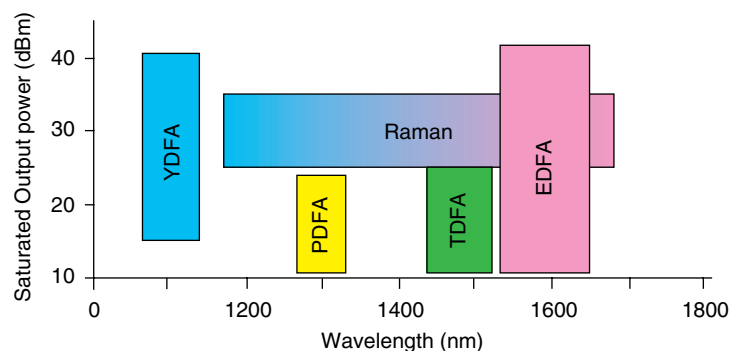


Figure 1.66 Optical amplifiers are many, each suitable for a different spectral range.

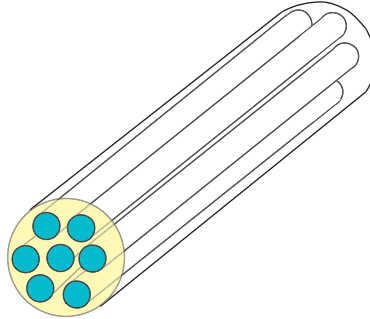


Figure 1.67 Hollow nano-tube optical waveguides (light may travel in each tube for ultra long distances, many hundreds of Km).

through the (photonic) air gap confinement of airholes. The (photonic) air gaps turn out to be in a specific relationship with particular wavelengths, and thus only certain of them are transmitted through the PCF. This implies that there is spectral selectivity or iridescence (a similar iridescence effect is observed in the fibrous feathers of birds and butterflies), and also that all propagating wavelengths in PCF have the same propagation characteristics. Moreover, since the tube is hollow (no dielectric) light propagates in air with virtually no loss, it does not suffer from dispersion and thus it can travel for ultralong distances (many hundreds of kilometers).

PCFs are still in the experimental phase, but they promise customization to guide multiwavelength light in single mode, with uniform characteristics and low attenuation. Thus, it is projected that PCFs will find a variety of applications in communication, amplifiers, sensors, and others.

1.10.5 How Strong Is Fiber?

In communications, it is important that cables are flexible as well as strong when they are pulled. One would think that glass fiber is fragile “like glass,” yet it is flexible enough and its tensile strength is stronger than copper. In fact, the tensile strength of copper is 100 pounds per square inch, whereas that of glass fiber is theoretically 2 million pounds per square inch. However, due to surface microcracks, in practice it is about 800,000 pounds per square inch, still much stronger than copper. In addition to high strength, glass fiber does not corrode, is immune to external electromagnetic interference, is waterproof, and has a long service lifetime of well above 20 years.

1.11 FIBER CONNECTIVITY

Copper wire may be installed in segments, each segment connected with one or more segments by simply bringing the copper ends into physical contact by any means. Consequently, no special treatment of the two copper ends is required other than removing possible contaminants.

Unlike copper wire, fiber requires specialized treatment. Two fiber ends placed one next to the other represent a discontinuity and imperfections. For example, the two fibers may be of different type and different refractive index profile; each fiber may

have been supplied by a different manufacturer or in a different time. Moreover, the glassy end-faces may be flat or not, parallel or not, of good optical quality (with minor imperfections on the faces) or not, and between the end-faces there may be a minute but finite air-gap. Thus, photons traveling from one fiber to the other must overcome this discontinuity and the imperfections with minimal loss. Consequently, certain special precautions must be taken to minimize power loss as photons travel through it.

- The two fiber ends to be connected should be treated so that the end-faces are flat, perpendicular to the fiber's longitudinal axis, and highly polished (or the faces may be formed into a spherical lens, a specialized operation that requires more specialized personnel and equipment).
- The two end-faces should be treated with antireflecting coatings.
- The two fiber-cores should be in perfect alignment.
- The two end-faces should be brought to close (small fraction of λ) proximity.
- In some cases, a refractive index matching fluid may be used.

The first two precautions are related to the treatment of fiber ends and it is accomplished with specialized abrasive materials and coatings. The third is related to how precisely the fiber circular core is at the center of the fiber and how precisely the interconnecting devices align the cores. Concerning A, the concentricity error of a single-mode fiber (based on ITU-T G.652) should be less than $1\text{ }\mu\text{m}$, and concerning B, the cores are precisely aligned with biconical self-aligned connectors or with aligned grooves. The fourth item is related to the flatness and perpendicularity of the two end-surfaces and on the accuracy of the connectors.

Another fiber interconnecting method does not use connectors, but it splices two fibers by fusing them permanently. This operation requires specialized splicing equipments with which the two fiber ends are first stripped from their cladding and then are fused together and re-treated to yield a continuous fiber. Clearly, this process does not require end-face treatment, antireflection coatings.

Splicing is preferred when fiber connectivity is permanent (i.e., repairing broken cables) and in the field (aerial or buried cable). Connectors are preferred in central offices, cabinets and huts where connectors are protected and disconnecting and reconnecting may be expected. However, core alignment of the two fibers and polarization issues are still relevant.

In either case, connector optical power loss is taken into serious account when estimating the overall power loss of an optical link, and it should be a small fraction of a dB per connector or splice. Because of stringent power loss budget, fibers preferably are installed in long (many km) segments to minimize a large number of interconnecting devices. However, unforeseen fiber breakage is reality and an estimated amount of loss due to future splices/connectors should be included in the power budget.

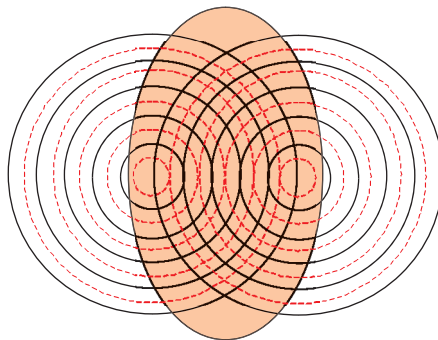
1.12 OPTICAL PWBs

As communications systems become more “optical,” the optical transmission medium between system plug-in units also should be optical; today, this is accomplished by using connectorized fiber cables. The “old days,” a similar approach was used with

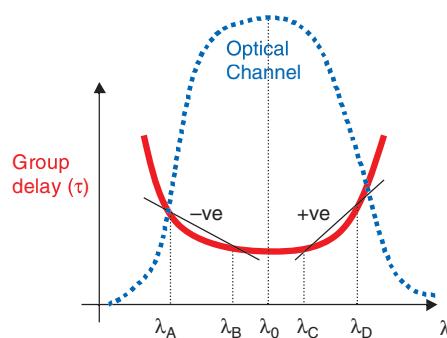
copper cables; individual cables interconnected the various plug-ins forming such a cable-clattered space that deservingly was known as the “rat nest.” However, multilayered printed wiring boards (PWB) with vias and connectors eliminated this and greatly simplified the nightmare of cable management. Today, the optical cabling “rat nest” has once more revived, and an interim solution is given using flat ribbon fiber cables. However, the solution of a true “optical PWB” is still awaited (in this case, W stands for waveguide), although currently there is substantial research in this direction. Optical PWBs will provide a compact and cost-effective solution.

EXERCISES

1. Calculate the distance traveled by light in 10 picoseconds and in free space.
2. When monochromatic light of frequency f transverses the boundary from matter into free space, its speed changes but its energy is preserved. What does it change?
3. A stream of bits at 100 Gb/s propagate in free space. How many bits could fit in a distance of 1 meter (round off the number)?
4. Calculate the energy of a 157-nm wavelength photon (in eV). The electron charge is $e = 1.6 \times 10^{-19}$ coulomb.
5. Could n be smaller than 1?
6. Could n be negative?
7. If, in Figure 1.11, Θ_i is zero (i.e., ray is perpendicular to surface) then:
 - a. would there be a reflected ray?
 - b. would there be a refractive ray? If yes, what would the refractive angle be?
8. A coin lies on the bottom of a pond that appears to be 3 feet deep. We try to reach the coin with a 3.5-foot long stick, but we discover that we cannot reach it. Why?
9. A pulse of almost monochromatic light enters matter in which it propagates. If we compare the phase with the group velocity, which is faster? Or are they the same?
10. Two coherent light sources impinge on a screen as shown. Identify points of intensity maxima in the highlighted area.



11. Could a moving photon in space be stopped, captured, and stored?
12. What happens when a photon interacts with an atom?
13. Consider two coherent sources (at the same long wavelength) interfering and forming fringes on a screen. The density of fringes on the screen depends on the distance and other factors. If we keep the distance fixed but change the wavelength to short, what can you tell about the fringe density?
14. Consider a fiber, 1 km long, with a refractive index $n = 1.5$. Consider also a source with a data rate at 10 Gbps. Calculate the number of bits at any time in the fiber, or the fiber bit capacity (approximate the group velocity by $v = c/n$).
15. In a step index fiber, the core has $n_1 = 1.48$ and the cladding $n_2 = 1.46$. Calculate the numerical aperture (NA) or the critical cone for the fiber.
16. An optical link consists of three fiber segments; the first is 10 km long, the second is 30 km, and the third is 20 km. The fiber attenuation is 0.1 dB/km. The segments are connected with connectors at 0.1 dB loss each. Calculate the total loss due to fiber and connectors over the link.
17. An amplifier of gain 8 amplifies an optical signal of 3 mW. Calculate the amplified signal in dBm units.
18. One source of 5 dBm and another source of 9 dBm combine. Is the total power 14 dBm? If not, explain why.
19. For an optical channel, the group delay is as shown in the following figure. With respect to chromatic dispersion and for λ_0 at the zero dispersion wavelength:
 - a. what can you say for wavelengths λ_A and λ_B ?
 - b. what can you say for wavelengths λ_C and λ_D ?
 - c. what can you say for wavelengths λ_A and λ_D ?
 - d. after some travel time, what would the original pulse look like?



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