CHAPTER 1

PROPERTIES OF LIGHT AND MATTER

1.1 INTRODUCTION

Fiber has been the transmission medium of choice for several years. Its use has been in long-haul applications, in metropolitan area networks (MAN), in inner city and inner campus, as well as accessing the last or first mile, such as fiber to the curb (FTTC) and fiber to the home (FTTH), whereas fiber from computer to computer is already reality.

New optical systems and networks assure that the transmission medium has a scalable transportable bandwidth capacity and that the network is scalable and flexible to pass different types of traffic at increasing capacity. Scalability is achieved by installing more fiber (or activating dark fiber), by increasing the bit rate (from 2.5 to 10 Gbps and to 40 Gbps and beyond), and by increasing the number of wavelengths per fiber [dense wavelength-division multiplexing (DWDM)]. Clearly, this implies that switching nodes in the network are able to receive scalable bandwidths, different types of traffic, and that they too have a scalable switching capacity.

As different network strategies are considered to cope with the explosive bandwidth demand, the quality of the optical signal must be maintained at a level that assures reliable and error-free (or acceptable error rate) transmission and that the availability of service must be warrantied with miniscule downtime. To achieve this, one has to first comprehend the properties of light, how light interacts with matter and with itself, and how it propagates in the fiber. In addition, one must understand how various optical components work, their degradation and failure mechanisms, how they affect the quality of the optical signal, and how we can predict or locate faults and initiate consequent remedial actions. In this chapter we examine the properties of light and how it interacts with optical materials.

1.2 NATURE OF LIGHT

Light is electromagnetic radiation that possesses two natures, a wave nature and a particle nature.

1.2.1 Wave Nature of Light

Like radio waves and X-rays, light is also electromagnetic radiation subject to reflection, refraction, diffraction, interference, polarization, fading, loss, and so on.

Light, as a wave, is characterized by frequency (and wavelength) with phase and propagation speed. The unit for frequency is cycles per second, or hertz, and the unit for wavelength is the nanometer (nm) or micrometer (μm). Another unit that occasionally is encountered is the angstrom; 1 Å $= 10^{-10}$ meters.

Light of a single frequency is termed *monochromatic,* or single color. To simplify the mathematical description of light and avoid spherical equations, we consider that the electromagnetic waves are planar. Then, monochromatic light is described by Maxwell's electromagnetic plane-wave equations:

$$\nabla^2\mathbf{E} = \frac{1}{c^2}\frac{\partial^2\mathbf{E}}{\partial t^2}, \qquad \nabla^2\mathbf{H} = \frac{1}{c^2}\frac{\partial^2\mathbf{H}}{\partial t^2}, \qquad \nabla\mathbf{D} = \rho, \qquad \nabla\mathbf{B} = 0$$

where ∇ is the Laplacian operator; c is a constant (the maximum speed of the wave in free space, $c = 2.99792458 \times 10^5$ km/s, or ~30 cm/ns); $\mathbf{E}$ and $\mathbf{H}$ are the electric and magnetic fields, respectively; $\mathbf{D}$ is the electric displacement vector; $\mathbf{B}$ is the magnetic induction vector; and ρ is the charge density. In practice, it is impossible to produce pure monochromatic light (i.e., a single wavelength), and this creates a number of issues that we will address later on. For theoretical analysis, however, we may consider monochromatic light.

The four field vector relations are connected with the relations

$$\mathbf{D} = \epsilon_0\mathbf{E} + \mathbf{P} \quad \text{and} \quad \mathbf{B} = \mu_0\mathbf{H} + \mathbf{M}$$

where ϵ_0 is the dielectric permittivity and μ_0 is the permeability, both constants of the vacuum, $\mathbf{P}$ is the electric polarization, and $\mathbf{M}$ is the magnetic polarization of the wave.

When a wave propagates through a linear medium (e.g., noncrystalline), the electric polarization is

$$\mathbf{P} = \epsilon_0\chi\mathbf{E}$$

where χ is the electric susceptibility of the medium (in nonlinear medium this is expressed as a tensor). It turns out that the dielectric constant ϵ of the material is connected with the above medium constants by $\epsilon = \epsilon_0(1 + \chi)$.

The monochromatic plane wave has a velocity $\mathbf{v}$ in a medium that is expressed by

$$\mathbf{v} = \frac{\omega}{k} = \frac{1}{\sqrt{\mu_0\epsilon_0}}$$

where k is a constant.

In vacuum it has a maximum constant speed c (since μ_0 and ϵ_0 are constants)

$$c = \frac{\omega}{k} = \frac{1}{\sqrt{\mu_0\epsilon_0}}$$

From the previous relationships we establish that there are indeed dependencies between speed of light and wavelength, between speed of light and dielectric constant, and between frequency of light and dielectric constant.

1.2.2 Particle Nature of Light

The smallest quantity of monochromatic light, known as a *photon*, is described by the energy (E) equation:

$$E = h\nu$$

where h is Planck's constant, equal to $6.6260755 \times 10^{-34}$ J-s and ν is the frequency of light.

Light (from an incandescent lightbulb) consists of a continuum of wavelengths that span the entire optical spectrum from deep red (700 nm) to deep violet-blue (400 nm).

Light does not travel at the same speed in all media. In addition, each frequency travels at different speed in the same medium. In vacuum, light travels in a straight path at a constant maximum speed c defined by Einstein's equation (and also present in Maxwell's equations):

$$E = mc^2$$

The relationship between frequency ν, speed of light in free space c, and wavelength λ is given by

$$\nu = \frac{c}{\lambda}$$

When light travels in an optically denser (than free-space) medium (e.g., water, glass, transparent plastic), then its speed becomes slower.

1.3 REFLECTION, REFRACTION, AND DIFFRACTION

When light enters matter, its electromagnetic field reacts with the near fields of its atoms. In dense matter, light is quickly absorbed within the first few atomic layers, and since it does not emerge from it, that matter is termed *non(optically) transparent.* In contrast to this, some types of matter do not completely absorb light, letting it propagate through it and emerge from it. This is termed *optically transparent* matter. Examples of such matter are water and clear glass.

1.3.1 Reflection and Refraction: Index of Refraction

The *index of refraction* of a transparent medium (n_{med}) is defined as the ratio of the speed of light in vacuum (c) over the speed of light in the medium (v_{med}).

1.3.2 Diffraction

Almost any obstacle with sharp edges in the path of light, such as an aperture, a slit, or a grating (with dimensions comparable to wavelength), will cause diffraction.

According to Huygen's principle, incident waves excite secondary coherent waves at each point of the wavefront. All these waves interfere with each other and cause a diffraction pattern (i.e., each wave is diffracted at a different angle). A pure mathematical analysis of diffraction is quite involved, and it is studied by approximating the scalar Helmholz equation in which the wavefront is a spherical function. The degree of diffraction (the angle by which a ray is diffracted) depends on the wavelength. This gives rise to diffraction gratings. Although the phenomenon of diffraction is used to construct diffraction gratings, it may also be considered undesirable as causing unwanted spread of a light beam in certain optical devices and thus optical power decrease per unit area.

1.3.3 Gaussian Beams

In theory it is assumed that a beam of light has a uniform cross-sectional distribution of intensity. In reality, most beams have a radial distribution, intense in the center of the beam and reducing radially away from the center, closely matching a Gaussian distribution. Because of this intensity distribution, even if the beam is initially parallel, it does not remain so due to spatial diffraction within the beam that causes the beam to first narrow and then diverge at an angle Θ. The narrowest point in the beam is known as the *waist* of the beam (Figure 1.1).

The reality of nonuniform radial distribution introduces certain degradations that only by proper design can be compensated for.

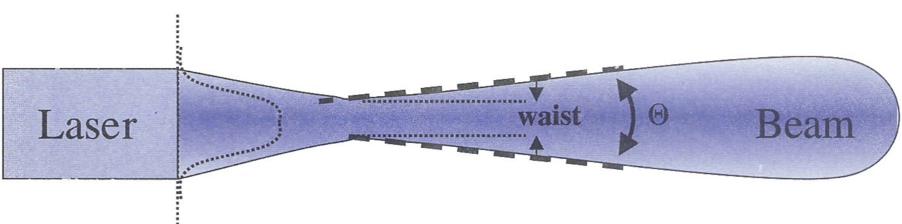

Figure 1.1 Gaussian beam.

1.4 POLARIZATION OF LIGHT

If we examine the electrical state of matter on a microscopic level, we find out that it consists of electrical charges, the distribution of which depends on the presence or absence of external fields. If we consider that for every positive charge there is a negative, then we may think that each positive-negative pair constitues an electric dipole. The electric moment of a dipole is a function of distance and charge density. Now, if we consider a distribution of electric dipoles, then *the electric dipole moment per unit volume is termed the polarization vector* **P**.

Polarization of electromagnetic waves is, mathematically speaking, a complex subject, particularly when light propagates in a medium with different refractive indices in different directions (e.g., crystallographic axes) in it. As light propagates through a medium, it enters the fields of nearby dipoles and field interaction takes place. This interaction may affect the strength distribution of the electric and/or magnetic fields of the propagating light differently in certain directions so that the end result may be a complex field with an elliptical or a linear field distribution.

Consequently, any external or internal influences that affect the charge density distribution of the material will also affect the propagating and polarization properties of light through it.

1.4.1 Faraday Effect

Some photorefractive solid materials (e.g., α-quartz, crystallized sodium chlorate) cause a rotation of the polarization plane as light travels through it. Certain liquids (cane sugar solution) and gases (camphor) also cause such rotation. This rotation is also known as the *Faraday effect.* Devices based on the Faraday effect are known as *rotators.*

In actuality, polarization rotation is explained as follows: Upon entrance in the medium, plane polarized light is decomposed into two circularly polarized waves rotating in opposite directions. Each of the two waves travels in the medium at different speed, and thus an increasing phase difference between the two is generated. Upon exiting the medium, the two waves recombine to produce a polarized wave with its polarization plane rotated by an angle, with reference to the initial polarization of the wave.

The amount of the rotation angle or *mode shift,* θ, depends on the distance traveled in the medium or on the thickness of material d (in centimeters), the magnetic field **H** (in oersteds), and a constant V, known as Verdet constant (measured in minutes per centimeter-oersted). The amount of rotation, or *mode shift,* is expressed by

$$\theta = V\mathbf{H}d$$

Clearly, any external influences that affect the constant V will also affect the amount of mode shift, θ.

1.5 PROPAGATION OF LIGHT

When light travels in a fiber, we assume that it is purely monochromatic. In general, this is a bad assumption since there is no light source that can generate a pure single optical frequency. In fact, no matter how close to perfect a monochromatic source is, there is a near-Gaussian distribution of wavelengths around a center wavelength. This is one of several reasons that optical channels in DWDM have a finite width. As a consequence, the study of optical propagation in a waveguide (optical fiber) requires the study of propagation of a group of frequencies. Two definitions are important here, the *phase velocity* and the *group velocity*.

1.5.1 Phase Velocity

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

$$\mathbf{E}(t, x) = Ae^{j(\omega t - \beta x)}$$

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

Phase velocity $\mathbf{v}_\phi$ is defined as the velocity of an observer that maintains constant phase with the traveling field, that is, $\omega t - \beta x = \text{const.}$

Replacing the traveled distance x within time t by $x = \mathbf{v}_\phi t$, the phase velocity of the monochromatic light in the medium is

$$\mathbf{v}_\phi = \frac{\omega}{\beta}$$

1.5.2 Group Velocity

In optical communications, an optical channel does not consist of only one wavelength; that is, it is not purely monochromatic. Consequently, if we assume that an optical pulse is propagating in the fiber, we may think of it as the result of a modulated optical signal that contains frequency components within a group of optical frequencies, the optical channel. The optical modulated signal is expressed by

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

where $\mathbf{E}$ 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 $\omega_1 << \omega_c$.

However, each frequency component in the group travels in the fiber with slightly different velocity forming a traveling envelope of frequencies.

Group velocity $\mathbf{v}_g = c/n_g$ is defined as the velocity of an observer that maintains constant phase with the group traveling envelope. The group velocity is mathematically defined as the inverse of the first derivative of the propagation constant β:

$$\mathbf{v}_g = \frac{1}{\beta'}$$

When light travels in a region of anomalous refractive index, the group and phase velocities undergo distortions (Figure 1.2).

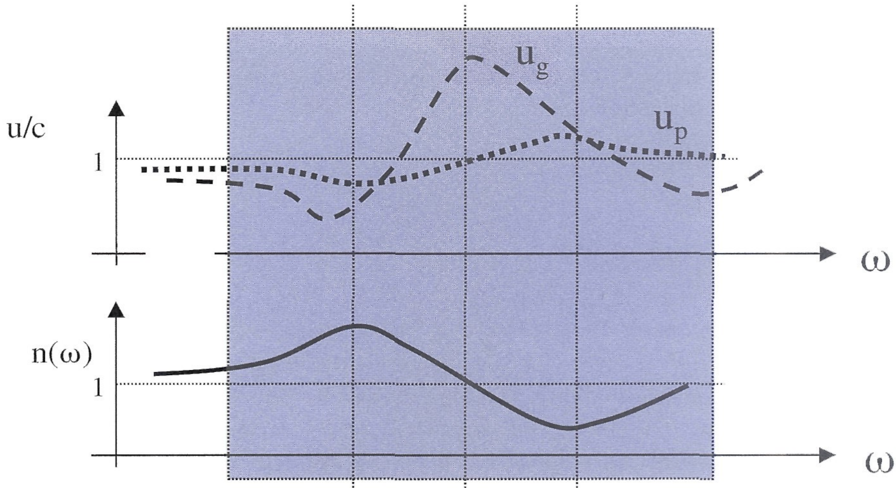

Figure 1.2 Group (u_g) and phase (u_p) velocity in a region of anomalous refractive index.

1.6 FIBER BIREFRINGENCE AND POLARIZATION

Anisotropic (crystalline) materials have a different index of refraction in specific directions within them. As such, when a beam of monochromatic unpolarized light enters such a material, it is refracted differently along the directions of different indices, and it travels along these directions at a different speed and polarization. This property of anisotropic (crystalline) materials is known as *birefringence*. Thus, an unpolarized ray that enters a birefringent material is separated into two rays, each with different polarization and different propagation constant. One ray is called *ordinary* (O) and the other *extraordinary* (E). In these two directions the refracted index is also called ordinary, n_o, and extraordinary, n_e, respectively. For example, the n_e and n_o for some birefringent crystals (measured at 1500 nm) are as follows:

Crystal	n_e	n_o
Calcite ($CaCO_3$)	1.477	1.644
Quartz (SiO_2)	1.537	1.529
Magnesium fluoride (MgF_2)	1.384	1.372

When under stress, some optically transparent isotropic materials become anisotropic as well. Stress may be exerted due to mechanical forces (pull, pressure, bend, and twist), due to thermal forces and due to strong electrical external fields. Under such conditions, the polarization and the propagation characteristics of light will be affected.

Clearly, birefringence in transmission fiber is undesirable because it alters the polarization and propagating characteristics of the optical signal.

1.7 DISPERSION

1.7.1 Modal

An optical signal propagating in 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, the rays that comprise a narrow pulse are transmitted within a small cone. As a result, each ray in the cone (known as *mode*) travels a different path and each ray arrives at a distant point of the fiber at a different time. Thus, an initial narrow pulse will spread out due to modal delays. This is known as *modal dispersion.* Obviously, this is highly undesirable in ultrafast digital transmission, where pulses may be as narrow as a few tens of picoseconds. The difference in travel time is improved if, for example, a single mode graded-index fiber is used.

1.7.2 Chromatic Dispersion

The refractive index of the material is related to the dielectric coefficient ϵ and to the characteristic resonant frequencies of its dipoles. Thus, the dipoles interact stronger with optical frequencies that are closer to their resonant frequencies. Consequently, the refractive index $n(\omega)$ is optical frequency dependent, and it affects the propagation characteristics of each frequency (or wavelength) in the signal differently.

An optical signal is not strictly monochromatic, but it consists of a continuum of wavelengths in a narrow spectral range. The propagation characteristics of each wavelength in the optical signal depend on the refractive index of the medium and the nonlinearity of the propagation constant. These dependencies affect the travel time of each wavelength in the signal through a fiber medium. As a result, an initially narrow pulse is widened because the pulse is not monochromatic but in reality it consists of a group of wavelengths (Figure 1.3). This is termed *chromatic dispersion.*

Silica, a key ingredient of optical fiber cable, has a refractive index that varies with optical frequency. Therefore, dispersion plays a significant role in fiber-optic communications. The dependence on wavelength λ also causes dispersion known as *wavelength dispersion.* The part of chromatic dispersion that depends on the dielectric constant ϵ is known as *material dispersion.* Material dispersion is the most significant. Dispersion is measured in picoseconds per nanometer-kilometer (i.e., delay per wavelength variation and fiber length).

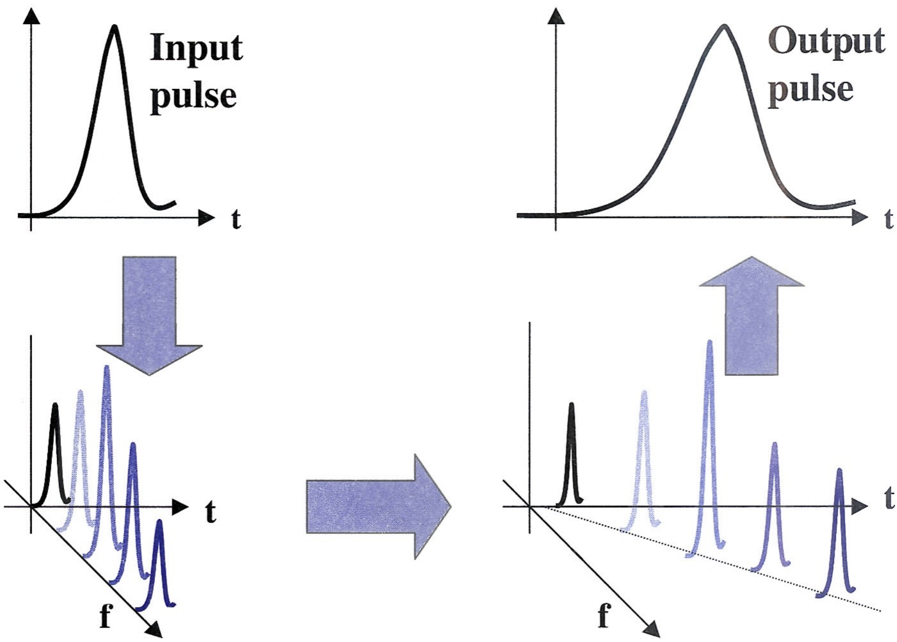

Figure 1.3 Chromatic dispersion: from input to output pulse.

1.7.3 Polarization Mode Dispersion

As already discussed, birefringence causes an optical (monochromatic) signal to be separated in two orthogonally polarized signals, each traveling at different speed. The same occurs if an optical pulse of a modulated optical signal travels in a birefringent fiber or in a birefringent component; the pulse is separated into two pulses, each traveling at different speeds with different polarization. Thus, when the two signals recombine, because of the variation in time of arrival, a pulse spreading occurs. This phenomenon is known as *polarization mode dispersion* (PMD) and is noticeable in ultrahigh bit rates (above 2.5 Gbps).

Optical fibers have a polarization mode dispersion coefficient of less than 0.5 ps/km$^{1/2}$ (see ITU-T G.652, G.653, and G.655). For an STS-192/STM-64 signal (~10 Gbps), this PMD coefficient value limits the fiber length to 400 km.

1.8 FIBER ATTENUATION AND LOSS

Optical loss of a fiber, also known as *fiber attenuation*, is a very important transmission characteristic that has a limiting effect on the fiber span, as it imposes power *loss* on the optical signal. That is, for a given launched optical power $P(0)$

into the fiber, attenuation affects the total power P_r arrived at the receiver and, in order to meet the specified signal quality level, it limits the fiber span L_{max} if there is no amplification.

Fiber attenuation depends on scattering mechanisms, on fluctuations of the refractive index, on fiber imperfections, and on impurities. Conventional single-mode fibers have two low attenuation ranges, one about 1.3 μm and another about 1.55 μm. Metal ions and OH radicals have a particular attenuation effect at about 1.4 μm, although fiber almost free of OH radicals has been successfully manufactured. The AllWave(TM) fiber by Lucent Technologies has a low water peak (LWPF) with minimum attenuation over the entire spectrum between 1310 and 1625 nm. In DWDM, this corresponds to about 500 channels with 100 GHz channel spacing.

Fiber attenuation is measured in decibels per kilometer. ITU-T G.652 recommends losses below 0.5 dB/km in the region 1310 nm and below 0.4 dB/km in the region 1500 nm. Some typical values are 0.4 dB/km at about 1310 nm and 0.2 dB/km at about 1550 nm.

1.9 FIBER SPECTRUM UTILIZATION

1.9.1 Spectral Bands

Based on optical power loss in fiber and the spectral performance of optical devices, a number of spectrum ranges have been characterized for compatibility purposes with light sources, receivers, and optical components, including the fiber. Thus, the low-loss spectrum for conventional single-mode fibers has been subdivided into three usable regions as follows:

Band	Wavelength Range (nm)
S-band (short wavelength or second window)	1280–1350
C-band (conventional or third window)	1528–1561
L-band (long wavelength or fourth window)	1561–1660

1.9.2 ITU-T C-Band Nominal Center Frequencies

ITU-T G.692 (October 1998) has recommended 81 optical channels in the C-band with the first channel centered at 196.10 THz (1528.77 nm). Subsequent channels are determined by decrementing by 50 GHz (or incrementing by 0.39 nm). The last channel is centered at 192.10 THz (1560.61 nm). These frequencies are determined from a reference frequency set at 193.10 THz (or 1552.52 nm).

For a channel spacing of 100 GHz, the nominal frequencies are those that start with the first channel in the table (196.10 THz) and continue every other one; similarly, for channel spacing of 200 GHz is every four channels and for 400 GHz is every eight.

The nominal frequency of each channel in the range 196.10–192.10 THz is calculated according to

$$F = 196.10 - ms \qquad \text{(THz)}$$

where $m = 1,2, \ldots$ and $s = 0.050, 0.100, 0.200, 0.400$ THz, or

$$F = 193.10 \pm ms \qquad \text{(THz)}$$

where $m = 0, 1, 2, \ldots$ and $s = 0.050, 0.100, 0.200, 0.400$ THz.

1.10 NONLINEAR PHENOMENA

When light enters matter, photons and atoms interact, and under certain circumstances, photons may be absorbed by atoms and excite them to higher energy levels.

When atoms are excited to a higher state, they do not remain stable. Photons passing by may stimulate them to come down to their initial lower energy level by releasing energy, *photons* and *phonons* (the acoustic quantum equivalent of light).

The behavior of dielectric molecules to optical power is like a dipole. It is the dipole nature of a dielectric that interacts harmonically with electromagnetic waves such as light. When the optical power is low, it results in small oscillations that approximate the photon-fiber system linear behavior. However, when the optical power is large, the oscillations are such that higher order terms (nonlinear behavior) become significant.

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 them not well understood yet. These interactions are distinguished in *forward scattering* and in *backward scattering* [Raman scattering (SRS) and Brillouin (SBS) scattering] as well as in *four-wave (or four-photon) mixing* (FWM). The direction (forward and backward) is with respect to the direction of the excitation light.

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

1.11 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. However, refractive index variations impact the transmission characteristics of the signal itself.

As an almost monochromatic light pulse travels through a fiber, its amplitude variation causes *phase change* and *spectral broadening*. Phase variations are equivalent to frequency modulation or "chirping." Spectral broadening appears as if one-half of the frequency is downshifted (known as *red shift*) and as if the other half is upshifted (known as *blue shift*). Such shifts are also expected in pulses that consist of a narrow range of wavelengths and are centered at the zero-dispersion wavelength. Below the zero-dispersion point *wavelength dispersion is negative and above it is positive.* Because of this, the zero-dispersion point is avoided and the operating point is preferred to be in the positive or in the negative dispersion area.

1.12 SELF-PHASE MODULATION

The dynamic characteristics of a propagating light pulse in a fiber result in modulation of its own phase, due to the Kerr effect of the fiber medium. According to this phenomenon, known as *self-phase modulation,* spectral broadening may also take place.

Specifically, 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, on the other hand, the wavelength is above the zero-dispersion wavelength of the fiber (the *anomalous dispersion regime*), then chromatic dispersion and self-phase modulation compensate for each other, thus reducing temporal broadening.

1.13 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 (the anomalous dispersion regime), another phenomenon occurs that degrades the width of the pulse, known as *self-modulation* or *modulation instability.* According to this, two side-lobe pulses are symmetrically generated at either side of the original pulse.

Modulation instability affects the signal-to-noise ratio, and it is considered a special FWM case. Modulation instability is reduced by operating at low energy levels and/or at wavelengths below the zero-dispersion wavelength.

1.14 EFFECTS OF TEMPERATURE ON MATTER AND LIGHT

The properties of materials vary as temperature varies. In addition to changing its physical properties, the optical, electrical, magnetic, and chemical properties change as well. As a result, the crystaline structure of matter is affected as well as its dielectric constant and the index of refraction. Clearly, in optical communications, adverse changes on the propagation parameters affect the optical signal and its quality, its signal-to-noise ratio, and thus the bit error rate (BER). Therefore, temperature variations are undesirable, although there are cases where this has been used productively to control optical devices by varying the temperature and thus the refractive index. In subsequent chapters we study the effect of parametric changes on the quality of the optical signal.

1.15 LIGHT ATTRIBUTES

Light consists of many frequencies. Its power may be split, coupled, reflected, refracted, diffracted, absorbed, scattered, and polarized. Light interacts with matter, and it even interacts with itself. Light is immune to radio frequency (RF) electromagnetic interference (EMI). The attributes of light are given below:

Light Attributes	Comments
Dual nature	Electromagnetic wave and particle
Consists of many λ's	Within a very wide and continuous spectrum Under certain circumstances, its frequency may be changed to another
Propagation	Follows a straight path in free space* Follows the bends of optical waveguides Its speed depends on the refractive index of matter Affected by refractive index variations
Polarization	Circular, Elliptic, Linear (TE_{nm}, TM_{nm}) Polarization is affected by fields Polarization is affected by matter
Optical power	Wide range (from less than microwatts to watts)†
Propagation speed	Fastest possible (in free space $c \sim 10^{10}$ cm/s, in matter c/n)
Phase	Affected by field discontinuities Affected by material constants
Optical channel	A narrow band of optical frequencies is modulated Ultrafast modulation (many gigahertz) possible May be contaminated by additive optical spectral noise

*Undisturbed light travels forever. In matter, it travels the shortest possible path.
†Here, we consider optical power in fiber communications.

Cause	Effect
λ's interact among themselves	Interference, new wavelength generation
λ's interact with matter	Range of effects (e.g., absorption, scattering, reflection, refraction, diffraction, polarization, polarization shift) Nonlinear effects (e.g., FWM)
Each λ interacts with matter differently	Range of effects (e.g., dispersion, PMD)
λ-matter-λ interaction	Birefringence, phase shift, modulation issues, SRS, SBS, optical fiber amplifiers (OFAs); possible wavelength conversion
No purely monochromatic (single-λ) channel	Finite number of channels within spectrum

1.16 MATERIAL ATTRIBUTES

Not all optical materials interact with light in the same manner. Materials with specific desirable optical properties have been used to device optical compo-

Material Attributes	Comments
Refractive index (n)	A function of molecular structure of matter A function of optical frequency A function of optical intensity Determines optical propagation properties of each λ Affected by external temperature, pressure, and fields
Flat surface reflectivity (R)	A function of molecular/atomic structure, λ and n Affects the reflected power (also a function of angle) Changes the polarization of incident wave Changes the phase of incident optical wave
Transparency (T)	Depends on material consistency and parameters
Scattering	Mainly due to molecular matrix disorders and contaminants
Absorption (A)	Mainly due to ions in the matrix and other contaminants
Polarization (P)	Due to X-Y uneven electromagnetic (EM) fields (light-matter interaction)
Birefringence (B)	Due to nonuniform distribution of n in all directions
Phase shift ($\Delta\Phi$)	Due to wave property of light through matter
Ions act like dipoles	Exhibit eigenfrequencies Exhibit antenna characteristics (receiver/transmitter)

nents. In some cases, artificially made materials have been manufactured to produce desirable properties. Here we examine certain key atributes of optical materials.

Cause	Effect
Refractive index variation (n)	May not be the same in all directions within matter Affects the propagation of light Responsible for birefringence, dispersion, and dichroism
Transparency variation	Affects the amount of light passing through matter
Scattering	Photonic power loss (attenuation)
Absorption	Photonic power loss, SRS, SBS, OFA
Reflectivity	Material surface reflects optical power Changes polarization of incident optical wave Changes phase of incident optical wave
Polarization	Mode change: circular, elliptic, linear (TE_{nm}, TM_{nm}) Affects power received
Birefringence	Splits light in two different rays and directions (ordinary and extraordinary)
Phase shift (PS)	Optical PS may be desirable or undesirable Undesirable in transmission, desirable when it is controlled
Ions act like EM dipoles	Interact selectively with light waves Responsible for energy absorption or energy exchange Change propagation characteristics (speed, phase) of λ's Affect the refractive index Nonlinear phenomena (SRS, SBS, FWM)

1.17 MEASURABLE PARAMETERS

Optical parameters are measured with instruments, some small and compact and some very complex and impractical, as they are seen from a communications system point of view. In addition, some instruments are beyond conventional knowledge and require extensive and specialized knowledge of optics. Therefore, the in-system optical parameter monitors for detecting degradations and faults may require instrumentation or measuring methods that may or may not be cost-ineffective. However, if many resources share a measuring method, then the added cost per optical channel (OCh) may be low. In addition, when a measuring method requires non-evasive optical monitoring then, the optical power penalty imposed by the method can be minimal.

Photonic Parameters	Detectability*
Center wavelength (λ_0) of an optical channel (nm)	Spectrum analyzer
Line witdth ($\Delta\lambda$, nm, or GHz)	Spectrum analyzer
Line spacing or channel separation ($\Delta\lambda$, GHz, or nm)	Spectrum analyzer
Power amplitude at λ_0 ($P_{\lambda 0}$, mW)	Filter plus photodetector
Launched optical power (P_{launched}, mW)	Backscattered photodetector
Received optical power (P_{received}, mW)	Filter plus photodetector
Insertion loss (L, dB)	Calculate ratio P_O/P_I
Polarization, degree of (DOP, %)	Complex
Polarization-dependent loss (PDL) (dB)	Complex
Direction of propagation (Cartesian or polar coordinates)	Complex
Speed of light (v)	Complex
Group velocity (v_g)	Complex
Propagation constant (β)	Complex

*"Complex" denotes, based on current techniques, a nontrivial optoelectronic set-up.

Parameters Due to Light-Matter Interaction	Calculability/Detectability
Attenuation (−dB)	$A\lambda = 10 \log[P_{\text{out}}(\lambda)/P_{\text{in}}(\lambda)]$, $P_{\text{in}} > P_{\text{out}}$
Attenuation coefficient (dB/km)	$\alpha(\lambda) = A(\lambda)/L$; provided by manufacturer's specifications
Insertion loss (−dB)	$L_{ij} = -10 \log_{10} t_{ij}$ or $L_{ij} = P_j - P_I$; t_{ij} = input/output (I/O) power transfer
Amplification gain (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, cross-talk)
Extinction ratio	P_B/P_F; indirectly from IL and $A(\lambda)$
Pulse spreading (ps)	Indirectly: eye diagram, BER, cross-talk
Group delay (ps)*	$\tau(\lambda) = \tau 0 + (S_0/2)(\lambda - \lambda_0)^{2\dagger}$
Differential group delay (ps/km$^{1/2}$)	See ITU G.650 for procedure
Chromatic dispersion coefficient (ps/nm-km)*	$D(\lambda) = S_0(\lambda - \lambda_0)$
Polarization mode dispersion (ps/km$^{1/2}$)	Requires laboratory optical set-up
Phase shift ($\Delta\,\phi$)	Interferometry
Polarization mode shift	Requires laboratory optical set-up
Dispersion effects	See pulse spreading

Note: P_O and P_E: optical power in the ordinary and extraordinary directions, respectively; P_B and P_F: optical power in the backward and in the forward directions, respectively.
*Relationship depends on fiber type (see ITU-T G.652, G.653, G.654).
$^{\dagger}S_0$ is the zero-dispersion slope.

REFERENCES

[1] M. H. Freeman, *Optics,* 10th ed., Butterworths, London, 1990.

[2] W. H. A. Fincham and M. H. Freeman, *Optics,* Butterworths, London, 1974.

[3] E. B. Brown, *Modern Optics,* Reinhold, New York, 1965.

[4] A. Kastler, *Optique,* 6th ed., Masson & Cie, Paris, 1965.

[5] K. Nassau, *The Physics and Chemistry of Color,* Wiley, New York, 1983.

[6] H. A. Haus, *Waves and Fields in Optoelectronics,* Prentice-Hall, Englewood Cliffs, NJ, 1984.

[7] T. Wildi, *Units and Conversion Charts,* 2nd ed., IEEE Press, New York, 1995.

[8] R. G. Hunsperger, *Integrated Optics: Theory and Technology,* Springer-Verlag, New York, 1984.

[9] L. Desmarais, *Applied Electro-Optics,* Prentice-Hall, Englewood Cliffs, NJ, 1999.

[10] J. Nellist, *Understanding Telecommunications and Lightwave Systems,* IEEE Press, New York, 1996.

[11] J. Hecht, *Understanding Fiber Optics,* Prentice-Hall, Englewood Cliffs, NJ, 1999.

[12] E. B. Carne, *Telecommunications Primer,* Prentice-Hall, Englewood Cliffs, NJ, 1995.

[13] P. S. Henry, "Lightwave Primer," *IEEE J. Quant. Electron.,* vol. QE-21, 1985, pp. 1862–1879.

[14] J. J. Refi, "Optical Fibers for Optical Networking," *Bell Labs. Tech. J.,* vol. 4, no. 1, 1999, pp. 246–261.

[15] L. Kazovsky, S. Benedetto, and A. Willner, *Optical Fiber Communication Systems,* Artech House, Boston, 1996.

[16] B. Mukherjee, *Optical Communication Networks,* McGraw-Hill, New York, 1997.

[17] J. C. Palais, *Fiber Optic Communications,* 3rd ed., Prentice-Hall, Englewood Cliffs, NJ, 1992.

[18] S. V. Kartalopoulos, *Understanding SONET/SDH and ATM: Communications Networks for the Next Millennium,* IEEE Press, New York, 1999.

[19] S. V. Kartalopoulos, *Introduction to DWDM Technology: Data in a Rainbow,* IEEE Press, New York, 2000.

[20] H. Toba and K. Nosu, "Optical Frequency Division Multiplexing System-Review of Key Technologies and Applications," *IEICE Trans. Comm.,* vol. E75-B, no. 4, Apr. 1992, pp. 243–255

[21] J. R. Freer, *Computer Communications and Networks*, IEEE Press, New York, 1996.

[22] S. R. Nagle, "Optical Fiber—The Expanding Medium," *IEEE Circuits Devices Mag.,* vol. 5, no. 2, 1989, pp. 36–45.

[23] R. H. Stolen, "Non-Linear Properties of Optical Fibers," in *Optical Fiber Telecommunications,* S. E. Miller and G. Chynoweth, Eds., Academic, New York, 1979.

[24] F. Ouellette, "All-Fiber for Efficient Dispersion Compensation," *Opt. Lett.,* vol. 16, no. 5, 1991, pp. 303–304.

[25] S. E. Miller, "Coupled-Wave Theory and Waveguide Applications," *Bell Syst. Tech. J.,* vol. 33, 1954, pp. 661–719.

[26] A. Yariv, "Coupled Mode Theory for Guided Wave Optics," *IEEE J. Quant. Electron.*, vol QE-9, 1973, pp. 919–933.

[27] R. Driggers, P. Cox, and T. Edwards, *An Introduction to Infrared and Electro-Optical Systems,* Artech House, Boston, 1999.

[28] N. Shibata, K. Nosu, K. Iwashita, and Y. Azuma, "Transmission Limitations Due to Fiber Nonlinearities in Optical FDM Systems," *IEEE J. Selected Areas Commun.*, vol. 8, no. 6, 1990, pp. 1068–1077.

[29] S. V. Kartalopoulos, "A Plateau of Performance?" Guest Editorial, *IEEE Commun. Mag.*, Sept. 1992, pp. 13–14.

STANDARDS

[1] ANSI/IEEE 812-1984, "Definition of Terms Relating to Fiber Optics," 1984.

[2] IEC Publication 793-2, Part 2, "Optical Fibres—Part 2: Product Specifications," 1992.

[3] ITU-T Recommendation G.652, version 4, "Characteristics of a Single-Mode Optical Fiber Cable," Apr. 1997.

[4] ITU-T Recommendation G.653, version 4, "Characteristics of a Dispersion-Shifted Single-Mode Optical Fiber Cable," Apr. 1997.

[5] ITU-T Recommendation G.654, "Characteristics of a Cut-off Shifted Single-Mode Optical Fibre Cable," 1997.

[6] ITU-T Recommendation G.655, version 10, "Characteristics of a Non-Zero Dispersion-Shifted Single-Mode Optical Fiber Cable," Oct. 1996.

[7] ITU-T Recommendation G.662, "Generic Characteristics of Optical Fiber Amplifier Devices and Sub-Systems," July 1995.

[8] ITU-T Recommendation G.671, "Transmission Characteristics of Passive Optical Components," Nov. 1996.

[9] ITU-T Recommendation G.702, "Digital Hierarchy Bit Rates," 1988.

[10] ITU-T Recommendation G.821, "Error Performance of an International Digital Connection Operating at a Bit Rate Below the Primary Rate and Forming Part of an Integrated Services Digital Network," Aug. 1996.

[11] ITU-T Recommendation G.826, "Error Performance Parameters and Objectives for International, Constant Bit Rate Digital Paths at or Above the Primary Rate," Feb. 1999.

[12] ITU-T Recommendation G.828, "Error Performance Parameters and Objectives for International, Constant Bit Rate Synchronous Digital Paths," Feb. 2000.

[13] Go to http://www.itu.int/ITU-T/index.html, for more information on ITU standards.