CHAPTER 1

THE NATURE OF LIGHT

1.1 INTRODUCTION

Fiber has been the long-haul transmission medium of choice for several years as well as for metropolitan area networks (MAN) in inner-city and inner-campus applications. Based on a demand by end customers for higher bandwidth, fiber penetration in the loop plant starts becoming noticeable as well.

Synchronous optical network/synchronous digital hierarchy (SONET/SDH) technologies have paved the fiberway for ultrahigh bit rates and ultra bandwidths. Many thousands of kilometers of fiber are installed each year around the world. Advances in solid-state and photonic technology have transformed what once "could not be done" (i.e., bit rates at 40 Gb/s over many kilometers of single-mode fiber) into a reality.

In addition to traditional time division multiplexing (TDM) services (e.g., voice, low-speed data), new services (e.g., Internet, high-speed data, video, wireless, etc.) have triggered a voracious appetite for bandwidth that legacy communications networks have a hard time delivering. Currently, voice traffic is increasing at a rate of 10% per year. Data traffic increases at a rate of 80% per year.

New communications systems have been designed and new standards have been recommended that promise prompt and reliable delivery of large volume of customer bits. However, although new systems are able to process a large quantity of data, the network must be able to transport and manage the increasing traffic, as well as the communication conduits that pass bits from one system to another. Therefore, a question arises: As the bandwidth keeps increasing, how do we assure that the transmission medium has a scalable bandwidth capacity? There are two approaches:

1. Install more fiber.
2. Increase the transportable bandwidth of an existing fiber.

Currently, depending on technology and economics, both choices are pursued. We examine the second.

1.2 INCREASING THE TRANSPORTABLE BANDWIDTH OF A FIBER

There are two methods of increasing the bandwidth in a single fiber:

1. *Increase the bit rate.* An increase to 10 Gb/s and up to 40 Gb/s is currently feasible for transporting SONET/SDH optical carrier-192 (OC-192) and optical carrier-768 (OC-768) signals, or their aggregate equivalent. However, the electronic circuitry (transmitters, receivers, etc.) that makes this possible is neither trivial nor cost-effective. In addition, transmitting a reliable error-free signal beyond 40 Gb/s is a technology currently in experimental phase, and it does not seem likely that it will be incorporated into commercial systems soon.
2. *Increase the number of wavelengths in the same fiber.* This is a viable solution that capitalizes on advances in solid-state and photonic technology. Several wavelengths, each transporting data at 10 or 40 Gb/s would increase the transportable bandwidth by a factor as large as the number of wavelengths. Systems with 40, 80, and 128 wavelengths per fiber have been designed, and systems with more wavelengths are in planning or experimental phase.

1.3 WHAT IS DWDM?

Wavelength division multiplexing (WDM) is an optical technology that couples many wavelengths in the same fiber, thus effectively increasing the aggregate bandwidth per fiber to the sum of the bit rates of each wavelength. For example, by using 40 wavelengths at 10 Gb/s per wavelength in the same fiber, we can raise the aggregate bandwidth to 400 Gb/s. Astonishing aggregate bandwidths at several terabits per second (Tb/s) are also a reality.

Dense WDM (DWDM) is a technology with a larger (denser) number of wavelengths (> 40) coupled into a fiber than WDM. However, as the number of wavelengths increases, several issues need attention, such as channel width and channel spacing, total optical power launched in fiber, nonlinear effects, cross-talk, span of fiber, and amplification (we define these terms in subsequent sections). An earlier WDM technology with a small number of wavelengths (<10), larger channel width, and channel spacing is termed *coarse WDM* (CWDM). Here, we use the terms WDM and DWDM interchangeably.

DWDM technology was made possible with the realization of several optical components. Components that were previously an experimenter's curiosity are now compact, of a high quality, commercially available, and increasingly inexpensive. It is also expected that several optical functions will soon be integrated to offer complex functionality at a cost per function comparable to electronic implementation. The following provides a snapshot of what has enabled the DWDM technology to become reality.

- Optical fiber has been produced that exhibits low loss and better optical transmission performance over the spectrum windows of 1.3–1.6 μm.
- Optical amplifiers with flat gain over a range of wavelengths and coupled in line with the transmitting fiber boost the optical signal, thus eliminating the need for regenerators.
- Integrated solid-state optical filters are compact and can be integrated with other optical components on the same substrate.
- Integrated solid-state laser sources and photodetectors offer compact designs.
- Optical multiplexers and demultiplexers are based on passive optical diffraction.
- Wavelength-selectable (tunable) filters can be used as optical add-drop multiplexers.
- Optical add–drop multiplexer (OADM) components have made DWDM possible in MAN ring-type and long-haul networks.
- Optical cross-connect (OXC) components, implemented with a variety of technologies (e.g., lithium niobate), have made optical switching possible.

In addition, standards have been developed so that interoperable systems can be offered by many vendors. As DWDM technology evolves, existing standards are updated or new ones are introduced to address emerging issues.

DWDM finds applications in ultra-high bandwidth long haul as well as in ultra-high-speed metropolitan or inner-city networks, and at the edge of other networks: SONET, Internet protocol (IP), and asynchronous transfer mode (ATM).

As DWDM deployment becomes more ubiquitous, DWDM technology cost decreases, primarily owing to increased optical component volume. Consequently, DWDM is also expected to become a low-cost technology in many access-type networks, such as fiber to the home (FTTH) and fiber-to-the-desktop PC (FTTPC).

1.4 WHAT IS OFDM?

Optical frequency-division multiplexing (FDM or OFDM) is an earlier acronym for WDM. However, the term FDM was already in use by designers of nonoptical systems (e.g., radio systems), whereas the terms WDM and DWDM have been exclusively used in optical communications systems. There is also an unofficial, subtle difference between the two: in WDM systems the spacing between wavelengths is in the order of 1 nm, whereas in (optical) FDM is in the order of the bit rate of the signal.

In DWDM, each channel represents a bit stream that is carried over a different wavelength (λ_i). Different channels may carry data at different bit rates and of different services (e.g., voice, data, video, IP, ATM, SONET, etc.). An end-to-end simplistic view of a DWDM system with an optical amplifier is shown in Figure 1.1.

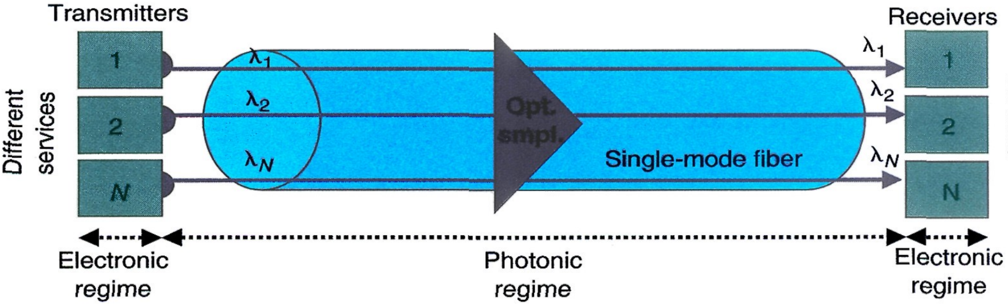


Figure 1.1 A conceptual DWDM system with many wavelength channels in the same fiber.

1.5 OPAQUE VERSUS TRANSPARENT WDM SYSTEMS

There are two types of WDM system. *Opaque* systems receive photonic information from the fiber; they photonically demultiplex each wavelength channel, and then each photonic channel is converted into electronic. Within the system, signal processing for each channel (payload multiplexing/demultiplexing, error control, routing, switching, etc.) takes place electronically. At the output port of the system, electronic information is converted back to photonic, wavelengths are multiplexed, and the WDM signal is launched into the fiber. Thus, from an observer's viewpoint, photons do not go through the system; hence the term *opaque.*

Optical devices are used throughout *transparent* systems. That is, received photons are never converted into electrons, including functions such as switching, multiplexing, and demultiplexing. Thus, from an observer's viewpoint, photons go through the system; hence the term *transparent.*

1.6 DWDM DEVICES

DWDM technology requires specialized optical devices that are based on properties of light and on the optical, electrical, and mechanical properties of semiconductor materials. Such devices must provide the equivalent functionality of electrical/electronic (opaque) communications systems. These devices include optical transmitters, optical receivers, optical filters, optical modulators, optical amplifiers, OADM, and OXC. A quick review of the nature and properties of light both in free space and in transparent material is therefore critical to a better understanding of WDM components, technology, and networks.

1.7 FUNDAMENTALS OF LIGHT

Light possesses two natures, a wave nature and a particle nature.

1.7.1 The Wave Nature of Light

Like radio waves or X-rays, light is electromagnetic radiation that is subject to reflection, refraction, diffraction, interference, polarization, fading, loss, and so on. Light of a single frequency is termed *monochromatic,* or single color. Light is described by the Maxwell's plane wave equations in vacuum:

$$\nabla^2 E = \left(\frac{1}{\mathrm{c}^2}\right)\left(\frac{\partial^2 E}{\partial t^2}\right), \quad \nabla^2 H = \left(\frac{1}{\mathrm{c}^2}\right)\left(\frac{\partial^2 H}{\partial t^2}\right), \quad \nabla D = \rho, \quad \text{and} \quad \nabla B = 0,$$

where ∇ is the Laplacian operator, c is the speed of the wave in vacuum, E and H are the electric and magnetic fields, respectively, D is the electric displacement vector, B is the magnetic induction vector, and ρ is the charge density.

The four field vectors are related by:

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

where ϵ_0 is the dielectric permitivity, μ_0 is the permeability, P is the electric polarization and M is the magnetic polarization. Note that Maxwell's equations refer to monochromatic light.

Light as a wave is characterized by frequency (and wavelength), phase, and propagation speed. *Frequency* is the number of waves in a second, and *wavelength* is the distance of a complete wave (e.g., peak to peak) in a medium or in vacuum. Frequency is described in cycles per second or hertz, and wavelength in nanometers (nm) or micrometers (μm). Another unit occasionally encountered is the angstrom; an *angstrom* (Å) is 10^{-10} meter.

1.7.2 The Particle Nature of Light

Like all moving particles, light too can exert pressure and cause a wheel to spin (Compton's experiment). Thus, light is also described in number of particles. 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, $6.6260755 \times 10^{-34}$ joule-second, and ν is the frequency of light.

Light (from an incandescent lightbulb) consists of a continuum of wavelengths that spans the complete optical spectrum from deep red (700 nm) to deep violet-blue (400 nm), as shown in Figure 1.2.

Figure 1.2 The visible spectrum is in the range from 0.7 μm (700 nm) to 0.4 μm (400 nm). The yellow light of a sodium lamp has a wavelength of 589 nm.

Light does not travel at the same speed in all media. In vacuum, it travels in a straight path at a constant maximum speed defined by Einstein's equation

$$E = mc^2,$$

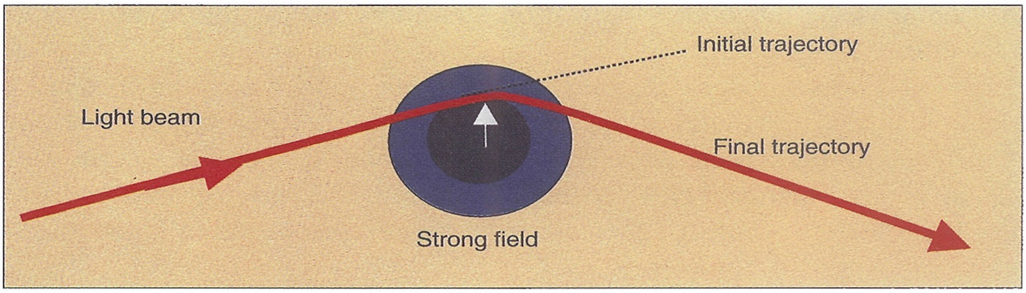
where $c = 2.99792458 \times 10^5$ km/s, or ~30 cm/ns.

The relationship between frequency, speed of light and wavelength is given by

$$\nu = c/\lambda$$

From the two energy relations $E = mc^2 = h\nu$, and the last one, certain interesting relationships are obtained, such as the frequency in terms of photon equivalent mass and speed ($\nu = mc^2/h$), and the equivalent mass of a photon ($m = h\nu/c^2$), a truly controversial issue.

When light passes by a very strong gravitational field, it interacts with it and its trajectory changes direction. The stronger the field, the larger the change (Figure 1.3).



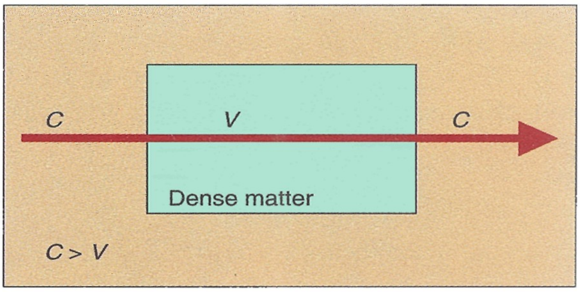


Figure 1.3 Light passing by a strong electromagnetic field, and light traveling through optically denser (than vacuum) medium (e.g., water, glass, transparent plastic).

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

1.8 PHOTOMETRIC TERMS: FLUX, ILLUMINANCE, AND LUMINANCE

When one is looking at two light sources or two illuminated objects, by comparison, it is possible to determine which is brighter. Although such comparisons are useful, absolute units of the brightness of light sources are very important. In the following, we list some key definitions.

The rate of optical energy flow (or number of photons per second) that is emitted by a point light source in all directions is known as the (total) *luminous flux,* Φ, measured in *lumens* (lm). In radiometric terms this is known as power, measured in watts.

Most known sources of light do not emit at the same rate in all directions. The rate emitted in a solid angle of a spherical surface area equal to its radius (e.g., radius = 1 m, surface area = 1 m^2) is known as *luminous intensity, I.* Luminous intensity is measured in *candelas* or *candles* (cd). The luminous intensity of a sphere is $\Phi/4\pi$.

The flux density at an area A (m^2), or the luminous flux per unit area, is defined as *illuminance, E,* and it is measured in *lux* (lx). The illuminance at a point of a spherical surface is $E = \Phi/4\pi R^2$. Because 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* (Figure 1.4).

Illuminance refers to light received by a surface. The amount of optical energy emitted by a lighted surface per unit of time, per unit of solid angle, and per unit of projected area is known as *luminance, B.* Luminance is measured in candelas per

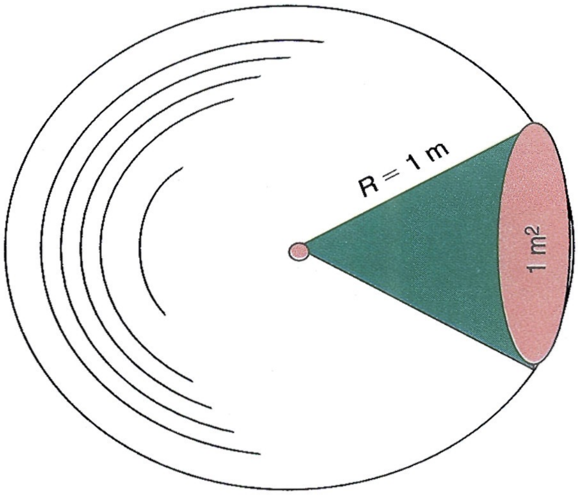


Figure 1.4 Definition of luminous (or candle) intensity.

square meter 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 1.1 summarizes photometric units that are used in optics and optical communications, their measuring units, and their dimensions.

Table 1.1 Summary of Photometric Units

Definition	Photometric Unit	Dimensions*[1]
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 (lm/m^2 or lambert)	MT^{-3}
Flux per unit solid angle	Luminous intensity (lms/sr)	ML^2T^{-3}
Flux per unit solid angle per unit projected area	Luminance (cd/m^2)	MT^{-3}
Flux input per unit area	Illuminance (m-cd)	MT^{-3}
Ratio of reflected to incident flux	Luminous reflectance	
Ratio of incident flux to output flux	Luminous transmittance	
Ratio of absorbed to incident flux	Luminous absorptance	

[1]*M = mass, T = time, L = length.

EXERCISES

1. Two nodes are linked with a 50-km single-mode fiber cable and communicate at a bit rate of 1 Gb/s. The wavelength over which data is carried is 1310 nm. The two nodes are upgraded to 10 Gb/s. The fiber capacity must be increased to 10 Gb/s. What would you recommend if:
   (a) The fiber is part of a seven-fiber cable (not all used) routed via an underground 10-cm diameter pipe?
   (b) The fiber is part of a seven-fiber cable (all used) routed via an underground 10-cm diameter pipe?
   (c) The fiber is part of a seven-fiber aerial cable (all used)?
2. A glass plate has blue color. Is it transparent or opaque?
3. A glass plate has blue color. A red glass plate is placed on top of it. A flashlight is placed behind the two plates. What color do you expect to see?
4. A surface is made such that half is covered with aluminum foil and the other half is painted black. If the surface is exposed to the sun, what do you expect to find after 1 hour?