Optical Components for WDM Lightwave Networks

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Recently, there has been growing interest in developing optical fiber networks to support the increasing bandwidth demands of multimedia applications, such as video conferencing and World Wide Web browsing. One technique for accessing the huge bandwidth available in an optical fiber is wavelength-division multiplexing (WDM). Under WDM, the optical fiber bandwidth is divided into a number of nonoverlapping wavelength bands, each of which may be accessed at peak electronic rates by an end user. By utilizing WDM in optical networks, we can achieve link capacities on the order of 50 THz. The success of WDM networks depends heavily on the available optical device technology. This paper is intended as a tutorial on some of the optical device issues in WDM networks. It discusses the basic principles of optical transmission in fiber and reviews the current state of the art in optical device technology. It introduces some of the basic components in WDM networks, discusses various implementations of these components, and provides insights into their capabilities and limitations. Then, this paper demonstrates how various optical components can be incorporated into WDM optical networks for both local and wide-area applications. Last, the paper provides a brief review of experimental WDM networks that have been implemented.

Keywords*—*Device issues, experimental systems, lightwave network, optical amplifier, optical fiber, switching elements, tunable receiver, tunable transmitter, wavelength converter, wavelength-division multiplexing.

I. INTRODUCTION

Over the past few years, the field of computer and telecommunications networking has experienced tremendous growth. With the rapidly growing popularity of the Internet and the World Wide Web and with the recent deregulation of the telecommunications industry in the United States, this growth can be expected to continue in the foreseeable future. The next decade may bring to the home and office multiple connections of high-definition television, video mail, and digital audio, as well as full Internet connections via user-friendly graphic user interfaces. As more users start to use data networks, and as their usage patterns evolve to include more bandwidth-intensive networking applications, there emerges an acute need for very high bandwidth transport network facilities whose capabilities greatly exceed those of current high-speed networks, such as asynchronous transfer mode (ATM) networks.

The key to the future of networks rests in the relatively young field of fiber optics. Optical fiber provides the huge bandwidth, low loss rate, and cost effectiveness to enable the vision of a "global village." Given that fiber has a potential bandwidth of approximately 50 Tb/s—nearly four orders of magnitude higher than peak electronic data rates—every effort should be made to tap into the capabilities of fiber-optic networks.

Wavelength-division multiplexing (WDM) is one promising approach that can be used to exploit the huge bandwidth of optical fiber. In WDM, the optical transmission spectrum is divided into a number of nonoverlapping wavelength (or frequency) bands, with each wavelength supporting a single communication channel operating at peak electronic speed. Thus, by allowing multiple WDM channels to coexist on a single fiber, we can tap into the huge fiber bandwidth, with the corresponding challenges being the design and development of appropriate network architectures, protocols, and algorithms.

Research and development on optical WDM networks have matured considerably over the past few years, and a number of experimental prototypes have been and are currently being deployed and tested in the United States, Europe, and Japan. It is anticipated that the next generation of the Internet will employ WDM-based optical backbones.

The success of WDM networks relies heavily upon the available optical components. A block diagram of a

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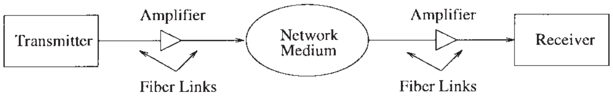

Fig. 1. Block diagram of a WDM transmission system.

WDM communication system is shown in Fig. 1. The network medium may be a simple fiber link, a passive star coupler (PSC) (for a broadcast and select network), or a network of optical or electronic switches and fiber links. The transmitter block consists of one or more optical transmitters, which may be either fixed to a single wavelength or tunable across a range of wavelengths. Each optical transmitter consists of a laser and a laser modulator and may also include an optical filter for tuning purposes. If multiple optical transmitters are used, then a multiplexer or coupler is needed to combine the signals from different laser transmitters onto a single fiber. The receiver block may consist of a tunable filter followed by a photodetector receiver or a demultiplexer followed by an array of photodetectors. Examples of some WDM transmitters and receivers are shown in Fig. 2. Amplifiers may be required in various locations throughout the network to maintain the strength of optical signals.

Designers of next-generation lightwave networks must be aware of the properties and limitations of optical fiber and devices in order for their corresponding protocols and algorithms to take advantage of the full potential of WDM. Often, a network designer may approach the WDM architectures and protocols from an overly simplified, ideal, or traditional-networking point of view. Unfortunately, this may lead an individual to make unrealistic assumptions about the properties of fiber and optical components, and hence may result in an unrealizable or impractical design.

This paper serves as an introduction to WDM device issues. No background in optics or advanced physics is needed. For a more advanced and/or detailed discussion of WDM devices, we refer the interested reader to [1]–[6].

This paper presents an overview of optical fiber and devices such as couplers, optical transmitters, optical receivers and filters, optical amplifiers, optical routers, and switches. It paper attempts to condense the physics behind the principles of optical transmission in fiber in order to provide some background for the novice reader. WDM network-design issues are then discussed in relation to the advantages and limits of optical devices. Last, this paper demonstrates how these optical components can be used to create broadcast networks for local networking applications and wavelength-routed networks for wide-area deployment. The paper concludes with a note on the current status of optical technology and how test networks have used some of the optical devices described in this paper with a reasonable amount of success.

II. Optical Fiber

Fiber possesses many characteristics that make it an excellent physical medium for high-speed networking. Fig. 3 shows the two low-attenuation regions of optical fiber [1]. Centered at approximately 1300 nm is a range of 200 nm in which attenuation is less than 0.5 dB per kilometer. The total bandwidth in this region is about 25 THz. Centered at 1550 nm is a region of similar size with attenuation as low as 0.2 dB per kilometer. Combined, these two regions provide a theoretical upper bound of 50 THz of bandwidth.[1] The dominant loss mechanism in good fibers is Rayleigh scattering, while the peak in loss in the 1400-nm region is due to hydroxyl-ion (OH^-) impurities in the fiber. Other sources of loss include material absorption and radiative loss.

By using these large low-attenuation areas for data transmission, the signal loss for a set of one or more wavelengths can be made very small, thus reducing the number of amplifiers and repeaters needed. In single-channel long-distance experiments, optical signals have been sent over hundreds of kilometers without amplification. Besides its enormous bandwidth and low attenuation, fiber also offers low error rates. Fiber-optic systems typically operate at bit error rates (BER's) of less than 10^{-11}.

The small size and thickness of fiber allows more fiber to occupy the same physical space as copper, a property that is desirable when installing local networks in buildings. Fiber is flexible, difficult to break, reliable in corrosive environments, and deployable at short notice (which makes it particularly favorable for military communications systems). Also, fiber transmission is immune to electromagnetic interference and does not cause interference. Last, fiber is made from one of the cheapest and most readily available substances on earth, sand. This makes fiber environmentally sound; and unlike copper, its use will not deplete natural resources.

A. Optical Transmission in Fiber

Before discussing optical components, it is essential to understand the characteristics of the optical fiber itself. Fiber is essentially a thin filament of glass that acts as a waveguide. A waveguide is a physical medium or path that allows the propagation of electromagnetic waves, such as light. Due to the physical phenomenon of *total internal reflection,* light can propagate the length of a fiber with little loss. Fig. 4 shows the cross section of the two types of fiber most commonly used: multimode and single mode. In order to understand the concept of a mode and to distinguish between these two types of fiber, a diversion into basic optics is needed.

Light travels through vacuum at a speed of $c_{vac} = 3\times10^8$ m/s. Light can also travel through any transparent material, but the speed of light will be slower in the material than in a vacuum. Let c_{mat} be the speed of light for a given material. The ratio of the speed of light in a vacuum to that in a material is known as the material's *refractive index* (n) and is given by $n_{mat} = c_{vac}/c_{mat}$.

When light travels from material of a given refractive index to material of a different refractive index (i.e., when

[1] Usable bandwidth, however, is limited by fiber nonlinearities (see Section II-E).

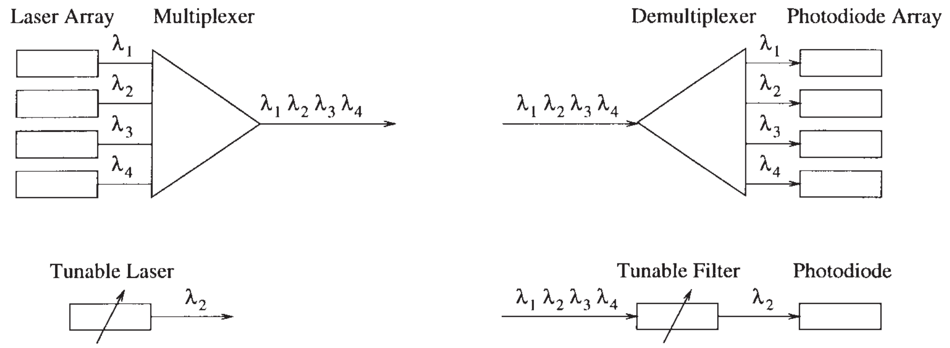

Fig. 2. Transmitter and receiver structures.

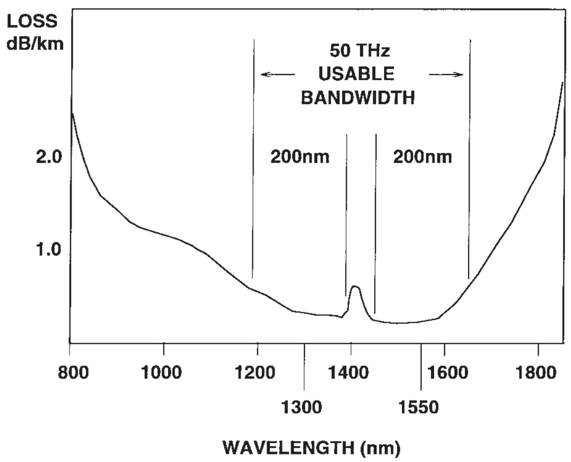

Fig. 3. The low-attenuation regions of an optical fiber.

refraction occurs), the angle at which the light is transmitted in the second material depends on the refractive indexes of the two materials as well as the angle at which light strikes the interface between the two materials. Due to Snell's law, we have $n_a \sin\theta_a = n_b \sin\theta_b$, where n_a and n_b are the refractive indexes of the first substance and the second substance, respectively; θ_a is the angle of incidence, or the angle with respect to normal that light hits the surface between the two materials; and θ_b is the angle of light in the second material. However, if $n_a > n_b$ and θ_a is greater than some critical value and the rays are reflected back into substance a from its boundary with substance b.

Looking again at Fig. 4, we see that the fiber consists of a core completely surrounded by a cladding (both of which consist of glass of different refractive indexes). Let us first consider a *step-index fiber,* in which the change of refractive index at the core-cladding boundary is a step function. If the refractive index of the cladding is less than that of the core, then *total internal reflection* can occur in the core and light can propagate through the fiber (as shown in Fig. 5). The angle above which total internal reflection will take place is known as the *critical angle* and is given by θ_{core}, which corresponds to $\theta_{clad} = 90°$. From Snell's law, we have

$$\sin\theta_{clad} = \frac{n_{core}}{n_{clad}} \sin\theta_{core}.$$

The critical angle is then

$$\theta_{crit} = \sin^{-1}\left(\frac{n_{clad}}{n_{core}}\right). \tag{1}$$

So, for total internal reflection, we require

$$\theta_{crit} > \sin^{-1}\left(\frac{n_{clad}}{n_{core}}\right).$$

In other words, for light to travel down a fiber, the light must be incident on the core-cladding surface at an angle greater than θ_{crit}.

In some cases, the fiber may have a *graded index,* in which the interface between the core and the cladding undergoes a gradual change in refractive index with $n_i > n_{i+1}$ (Fig. 6). A *graded-index* fiber reduces the minimum θ_{crit} required for total internal reflection and also helps to reduce the *intermodal dispersion* in the fiber. Intermodal dispersion will be discussed in the following sections.

For light to enter a fiber, the incoming light should be at an angle such that the refraction at the air-core boundary results in the transmitted light's being at an angle for which total internal reflection can take place at the core-cladding boundary. As shown in Fig. 7, the maximum value of θ_{air} can be derived from

$$\begin{aligned} n_{air}\sin\theta_{air} &= n_{core}\sin(90° - \theta_{crit}) \\ &= n_{core}\sqrt{1 - \sin^2\theta_{crit}}. \end{aligned} \tag{2}$$

From (1), since $\sin\theta_{crit} = n_{clad}/n_{core}$, we can rewrite (2) as

$$n_{air}\sin\theta_{air} = \sqrt{n_{core}^2 - n_{clad}^2}. \tag{3}$$

The quantity $n_{air}\sin\theta_{air}$ is referred to as the *numerical aperture* of the fiber (NA) and θ_{air} is the maximum angle with respect to the normal at the air-core boundary, so that the incident light that enters the core will experience total internal reflection inside the fiber.

B. Multimode Versus Single-Mode Fiber

A mode in an optical fiber corresponds to one of possibly multiple ways in which a wave may propagate through the fiber. It can also be viewed as a standing wave in

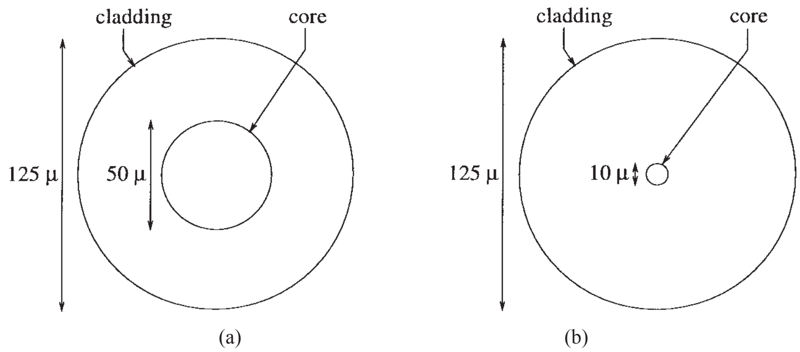

Fig. 4. Multimode and single-mode optical fibers.

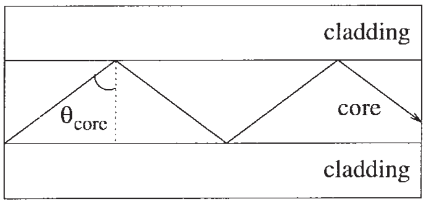

Fig. 5. Light traveling via total internal reflection within a fiber.

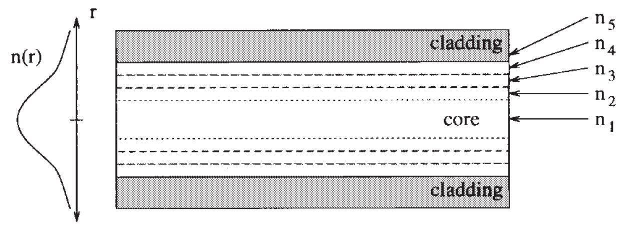

Fig. 6. Graded-index fiber.

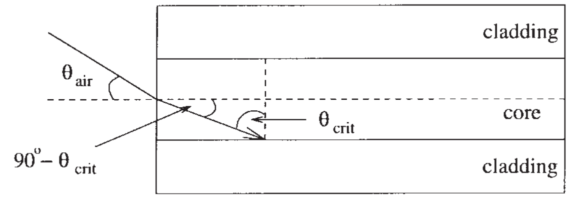

Fig. 7. Numerical aperture of a fiber.

the transverse plane of the fiber. More formally, a mode corresponds to a solution of the wave equation that is derived from Maxwell's equations and subject to boundary conditions imposed by the optical fiber waveguide.

An electromagnetic wave propagating along an optical fiber consists of an electric field vector $\boldsymbol{E}$ and a magnetic field vector $\boldsymbol{H}$. Each field can be broken down into three components. In the cylindrical coordinate system, these components are E_ρ, E_ϕ, E_z, H_ρ, H_ϕ, andH_z, where ρ is the component of the field that is normal to the wall (core-cladding boundary) of the fiber, ϕ is the component of the field that is tangential to the wall of the fiber, and z is the component of the field that is in the direction of propagation. Fiber modes typically are referred to using the notation HE_{xy} (if $H_z > E_z$), or EH_{xy} (if $E_z > H_z$), where x and y are both integers. For the case $x = 0$, the modes are also referred to as transverse-electric (TE), in which case $E_z = 0$, or transverse-magnetic (TM), in which case $H_z = 0$.

Although total internal reflection may occur for any angle θ_{core} that is greater than θ_{crit}, light will not necessarily propagate for all of these angles. For some of these angles, light will not propagate due to destructive interference between the incident light and the reflected light at the core-cladding interface within the fiber. For other angles of incidence, the incident wave and the reflected wave at the core-cladding interface constructively interfere in order to maintain the propagation of the wave. The angles for which waves do propagate correspond to *modes* in a fiber. If more than one mode may propagate through a fiber, the fiber is called multimode. In general, a larger core diameter or high operating frequency allows a greater number of modes to propagate.

The number of modes supported by a multimode optical fiber is related to the normalized frequency V, which is defined as

$$V = k_0 a \sqrt{n_{core}^2 - n_{clad}^2} \tag{4}$$

where $k_0 = 2\pi/\lambda$, a is the radius of the core, and λ is the wavelength of the propagating light in vacuum. In multimode fiber, the number of modes m is given approximately by

$$m \approx \tfrac{1}{2} V^2. \tag{5}$$

The advantage of multimode fiber is that its core diameter is relatively large; as a result, injection of light into the fiber with low coupling loss[2] can be accomplished by using inexpensive, large-area light sources, such as light-emitting diodes (LED's).

The disadvantage of multimode fiber is that it introduces the phenomenon of *intermodal dispersion*. In multimode fiber, each mode propagates at a different velocity due to different angles of incidence at the core-cladding boundary. This effect causes different rays of light from the same source to arrive at the other end of the fiber at different times, resulting in a pulse that is spread out in the time domain. Intermodal dispersion increases with the distance

[2] Coupling loss measures the power loss experienced when attempting to direct light into a fiber.

of propagation. The effect of intermodal dispersion may be reduced through the use of *graded-index* fiber, in which the region between the cladding and the core of the fiber consists of a series of gradual changes in the index of refraction (see Fig. 6). Even with graded-index multimode fiber, however, intermodal dispersion may still limit the bit rate of the transmitted signal and may limit the distance that the signal can travel.

One way to limit intermodal dispersion is to reduce the number of modes. From (4) and (5), we observe that this reduction in the number of modes can be accomplished by reducing the core diameter, reducing the numerical aperture, or increasing the wavelength of the light.

By reducing the fiber core to a sufficiently small diameter and reducing the numerical aperture, it is possible to capture only a single mode in the fiber. This single mode is the HE_{11} mode, also known as the *fundamental mode*. Single-mode fiber usually has a core size of about 10 μm, while multimode fiber typically has a core size of 50–100 μm (see Fig. 4). A step-index fiber will support a single mode if V in (4) is less than 2.4048 [7].

Thus, single-mode fiber eliminates intermodal dispersion and can hence support transmission over much longer distances. However, it introduces the problem of concentrating enough power into a very small core. LED's cannot couple enough light into a single-mode fiber to facilitate long-distance communications. Such a high concentration of light energy may be provided by a semiconductor laser, which can generate a narrow beam of light.

C. Attenuation in Fiber

Attenuation in optical fiber leads to a reduction of the signal power as the signal propagates over some distance. When determining the maximum distance that a signal can propagate for a given transmitter power and receiver sensitivity, one must consider attenuation. Let $P(L)$ be the power of the optical pulse at distance L km from the transmitter and A be the attenuation constant of the fiber (in dB/km). Attenuation is characterized by [2]

$$P(L) = 10^{-AL/10} P(0) \tag{6}$$

where $P(0)$ is the optical power at the transmitter. For a link length of L km, $P(L)$ must be greater than or equal to P_r, the receiver sensitivity. From (6), we get

$$L_{\max} = \frac{10}{A} \log_{10} \frac{P(0)}{P_r}. \tag{7}$$

The maximum distance between the transmitter and the receiver (or the distance between amplifiers)[3] depends more heavily on the constant A than on the optical power launched by the transmitter. Referring back to Fig. 3, we note that the lowest attenuation occurs at approximately 1550 nm.

[3] The amplifier sensitivity is usually equal to the receiver sensitivity, while the amplifier output is usually equal to optical power at a transmitter.

D. Dispersion in Fiber

Dispersion is the widening of a pulse duration as it travels through a fiber. As a pulse widens, it can broaden enough to interfere with neighboring pulses (bits) on the fiber, leading to intersymbol interference. Dispersion thus limits the bit spacing and the maximum transmission rate on a fiber-optic channel.

As mentioned earlier, one form of dispersion is *intermodal dispersion*. This is caused when multiple modes of the same signal propagate at different velocities along the fiber. Intermodal dispersion does not occur in a single-mode fiber.

Another form of dispersion is *material* or *chromatic dispersion*. In a dispersive medium, the index of refraction is a function of the wavelength. Thus, if the transmitted signal consists of more than one wavelength, certain wavelengths will propagate faster than other wavelengths. Since no laser can create a signal consisting of an exact single wavelength, material dispersion will occur in most systems.[4]

A third type of dispersion is *waveguide dispersion*. Waveguide dispersion is caused because the propagation of different wavelengths depends on waveguide characteristics such as the indexes and shape of the fiber core and cladding.

At 1300 nm, material dispersion in a conventional single-mode fiber is near zero. Luckily, this is also a low-attenuation window (although loss is lower at 1550 nm). Through advanced techniques such as *dispersion shifting,* fibers with zero dispersion at a wavelength between 1300–1700 nm can be manufactured [8]. In a dispersion-shifted fiber, the core and cladding are designed such that the waveguide dispersion is negative with respect to the material dispersion, thus canceling the total dispersion. The dispersion will only be zero, however, for a single wavelength.

E. Nonlinearities in Fiber

Nonlinear effects in fiber may potentially have a significant impact on the performance of WDM optical communications systems. Nonlinearities in fiber may lead to attenuation, distortion, and cross-channel interference. In a WDM system, these effects place constraints on the spacing between adjacent wavelength channels, limit the maximum power on any channel, and may also limit the maximum bit rate.

1) Nonlinear Refraction: In optical fiber, the index of refraction depends on the optical intensity of signals propagating through the fiber [9]. Thus, the phase of the light at the receiver will depend on the phase of the light sent by the transmitter, the length of the fiber, and the optical intensity. Two types of nonlinear effects caused by this phenomenon are self-phase modulation (SPM) and cross-phase modulation (XPM).

SPM is caused by variations in the power of an optical signal and results in variations in the phase of the signal.

[4] Even if an unmodulated source consisted of a single wavelength, the process of modulation would cause a spread of wavelengths.

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