6.013 Lecture 22:
Optical Communications

A. Overview

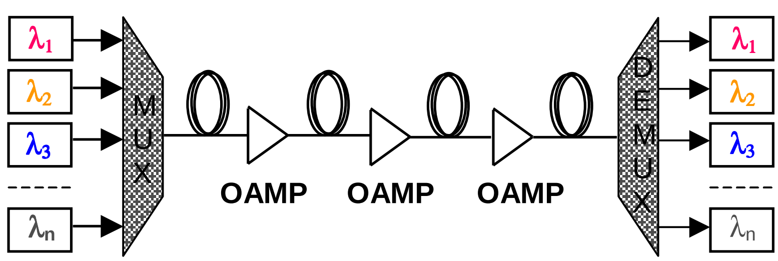
Optical communications is as old as smoke signals and mirrors reflecting sunlight. Today it is particularly important for long-haul and extremely wideband communications. Optical fibers now convey most intercontinental communications, although microwave satellites still serve geographically isolated users such as those on ships. Satellites also provide moveable capacity that can address transient shortfalls or failures across the globe; they simply point their antenna beams at the new users. Fibers have also been widely installed for both interstate and intrastate communications, and are beginning to migrate down into the local loop and to small businesses and homes. Extreme data rates are now also being conveyed between and within computers and even chips, although wires still have advantages of cost and simplicity for most ultra-short applications.

A significant niche market also exists for local line-of-sight optical links that provide extreme bandwidths for dedicated point-to-point communications. For example, companies can link laser beams between buildings and can quickly bypass inadequate or failed wire links connecting them to the global network, as happened after 9/11 in New York City.

Optical links also have great potential for very broadband inter-satellite or satellite-earth communications because small telescopes easily provide highly focused antenna beams. For example, beamwidths of telescopes with 5-inch apertures are typically one arc-second [1 arc-second is 1/60 arc-minutes, $1/60^2$ degrees, $1/(57.3\times60^2)$ radians, or 1/60 of the largest apparent diameters of Venus or Jupiter in the night sky].

The major components in fiber communications systems are the fibers themselves and the optoelectronic devices that manipulate the optical signals, such as detectors (discussed in the second recitation), amplifiers and sources (discussed in next lecture), modulators, mixers, switches (which can be MEMS-controlled mirrors, shutters, or gratings), filters, multiplexers, directional couplers, and others. These are assembled to create useful communications or computing systems. A typical wave-division multiplexed (WDM) amplified long fiber system is pictured in Figure 22-1.

Figure 22-1.
Wave-division multiplexed amplifier



In the system of Figure 22-1 different users transmit modulated signals at n optical wavelengths to a multiplexer (MUX) that losslessly combines them into a single broadband beam near 1.5-micron wavelength that can propagate long distances through a glass fiber before requiring amplification in an optical amplifier (OAMP). OAMPs are typically erbium-doped fiber amplifiers (EFDA's) spaced about 50 miles apart; thus Figure 22-1 represents a ~200-mile link. At the far end the wavelengths can be separated using a de-multiplexer (DEMUX) into the original user bands for local distribution. Without very broad band EFDA's the optical signals at each wavelength would have to be separately amplified, or detected and then regenerated by a new transmitter, for each of the n optical channels that could otherwise be amplified by a single EFDA.

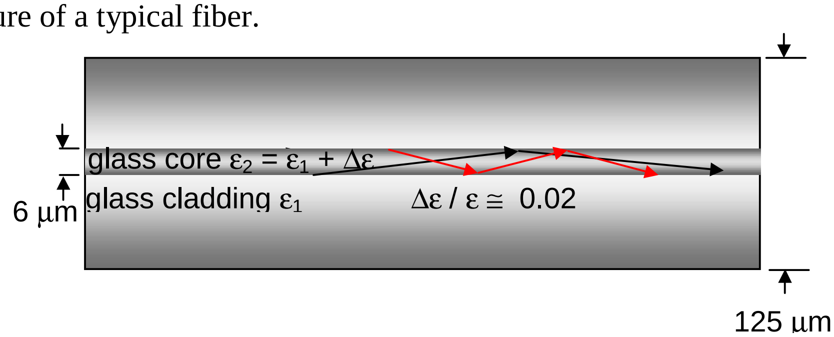
B. Optical Fibers and Dielectric Slab Waveguides

A typical glass optical fiber transmission line is perhaps 125 microns in diameter with a glass core having diameter ~10 microns; the fiber is surrounded by layers providing physical protection. The core permittivity ε is typically ~2 percent greater than that of the cladding so as to trap most of the energy. If the light beams in the core impact the cladding beyond the critical angle

$$\theta_c = \sin^{-1}(\varepsilon/(\varepsilon+\Delta\varepsilon)) \qquad (1)$$

then they are perfectly reflected and thereby trapped within the core. Only evanescent waves exist inside the cladding, and they decay approximately exponentially away from the core to negligible values at the outer cladding boundary, which is often encased in plastic about 0.1 mm thick. Some fibers propagate more than one mode; these multiple modes generally travel at different velocities and can confuse or limit information extraction (data rate). Multiple fibers are usually bundled inside a single cable. Figure 22-2 suggests the structure of a typical fiber.

Figure 22-2.
Optical fiber



A more rigorous but approximate way to analyze fiber-optic modes is suggested in Figure 22-3 where a dielectric slab waveguide in vacuum is analyzed; it is assumed to be infinite in the lateral (y) direction. A similar analysis is presented in Section 7.2 of the text. If we assume that the +z-propagating TE waves inside the slab are standing waves in the x direction, then $\overline{E}$ is some linear combination of even (cosine) or odd (sine) modes proportional to cos $k_x x$ or sin $k_x x$, and to e^{-jkz}. We also know that for plane waves incident at a dielectric interface beyond the critical angle θ_c, the fields decay exponentially away from the boundary outside. That is, outside the slab $\overline{E}$ =

$\hat{y}\underline{E}_1 e^{-\alpha x - jk_z z}$ for x > d, where d marks the upper boundary of the slab, as sketched in Figure 22-3b.

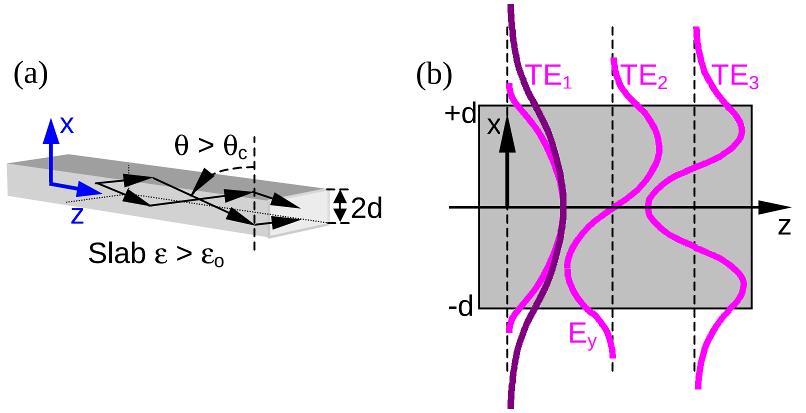


Figure 22-3. Dielectric slab waveguide

Boundary conditions for TE waves say that $\overline{E}_{//}$ must be continuous across the boundary, and also $\partial E_y/\partial x$. The derivative $\partial E_y/\partial x$ must be continuous because we know that $\nabla \times \overline{E} = -\partial \overline{H}/\partial t$ (Faraday's law), where both $\overline{H}$ and $\partial \overline{H}/\partial t$ must be continuous across the same boundary because $H_\perp$ and $H_{//}$ are continuous; thus $\nabla \times \overline{E}$ is continuous too. But $\nabla \times \overline{E} = \hat{z}\,\partial E_y/\partial x - \hat{x}\,\partial E_y/\partial z$, which must therefore also be continuous across the boundary. The field distributions for various modes pictured in Figure 22-3b are consistent with both E_y and its derivative being continuous across the boundaries at x = ±d.

Once the form of the electric field inside and outside the slab is known, $\overline{H}$ can be immediately found using Faraday's law, i.e., by computing $\overline{H} = -(\nabla \times \overline{E})/j\omega\mu$. The resulting magnetic and electric field distributions are suggested in Figure 22-4. At the boundary x = d the electric (y direction) and magnetic (z component) fields inside and outside the slab for $TE_{1,3,5,...}$ are:

$$\hat{y}E_o \cos k_x d\; e^{-jk_z z} = \hat{y}E_1\; e^{-\alpha d - jk_z z} \quad (2)$$

$$\left(-jk_x E_o/\omega\mu\right)\sin k_x d\; e^{-jk_z z} = -\left(j\alpha E_1/\omega\mu_o\right)e^{-\alpha d - jk_z z} \quad (3)$$

where E_o is the amplitude associated with the trapped fields, and E_1 is associated with the evanescent fields.

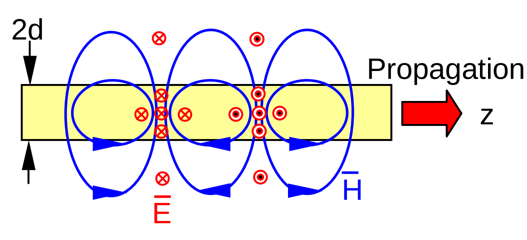


Figure 22-4. Electric and magnetic fields in a dielectric slab waveguide

The ratio of these two equations that require continuity in parallel $\overline{E}$ (Equation 2) and $\overline{H}$ (Equation 3) at the boundaries can be computed to yield:

$$k_x d \tan k_x d = \mu\alpha d/\mu_o \quad (4)$$

The two dispersion relations:

$$k_z^2 + k_x^2 = \omega^2\mu\varepsilon \text{ inside the slab,} \qquad k_z^2 - \alpha^2 = \omega^2\mu_o\varepsilon_o \text{ outside} \tag{5}$$

can be combined by eliminating k_z to yield:

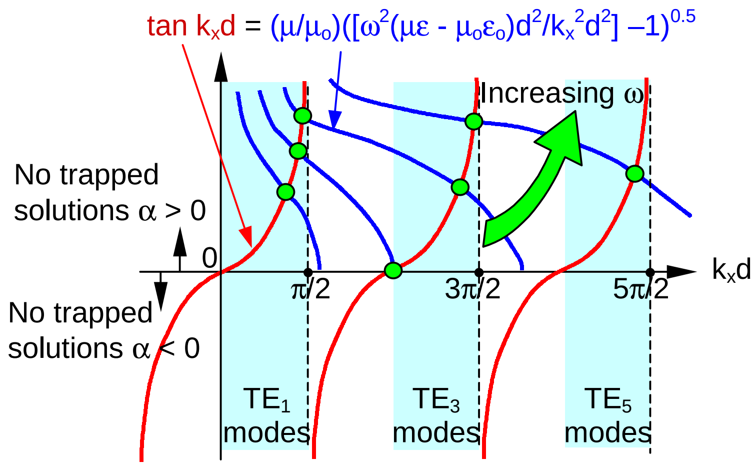
$$k_x^2 + \alpha^2 = \omega^2(\mu\varepsilon - \mu_o\varepsilon_o) \tag{6}$$

Substituting the expression for k_x that comes from the dispersion relation (6) into (4) we obtain a transcendental equation:

$$\tan k_x d = (\mu/\mu_o)([\omega^2(\mu\varepsilon - \mu_o\varepsilon_o)d^2/k_x^2d^2] - 1)^{0.5} \tag{7}$$

This transcendental equation (7) can be solved graphically, as shown in Figure 22-5. The left-hand side is a tangent function in k_xd, and the right-hand side is a curve that depends on k_xd and ω; the solutions for k_xd are where the two curves cross.

Figure 22-5. TE modes for a dielectric slab waveguide

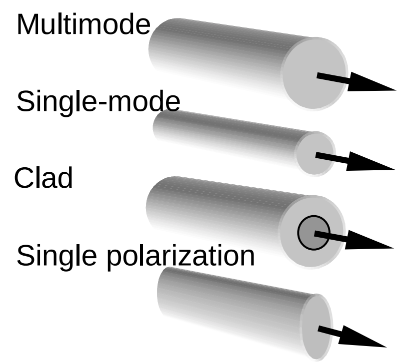


For $\omega \to 0$ only the TE_1 mode is allowed, but it can propagate at all ω. At low frequencies this slab propagates waves with small values of α that decay very slowly away from the slab ($\alpha \to 0$ as $\omega \to 0$; see (6) as both k_xd and $\omega \to 0$). In this low-frequency limit most of the wave energy is actually propagating outside the slab but parallel to it. At sufficiently high frequencies both the TE_1 ($0 < k_xd < \pi/2$) and TE_3 ($\pi < k_xd < 3\pi/2$) modes can propagate, as illustrated. As $\omega \to \infty$, the figure suggests that the number of propagating odd TE modes also approaches infinity. Not shown here are the TM modes and the even TE modes.

These solutions for dielectric-slab wavequides are similar to the solutions for optical fibers, which instead take the form of Bessel functions because of the cylindrical geometry of fibers. In both cases we have lateral standing waves propagating inside and evanescent waves propagating outside.

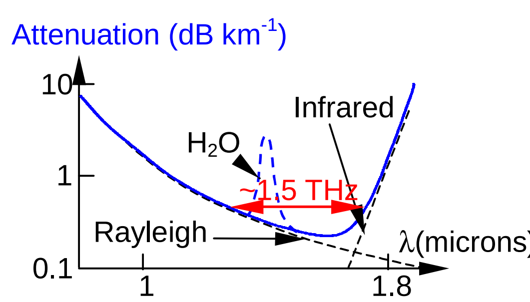
Figure 22-6 shows four forms of optical fiber. One is thicker and can propagate multiple modes, while the other is so small that only one mode can propagate. Since it is essential that the waves propagate in essentially lossless media (e.g. vacuum or glass) and still be mechanically supported, most fibers are clad and have a glass core with a slightly higher permittivity than its glass cladding (also see Figure 22-5) that can trap the waves. In all three cases, however, both vertically and horizontally polarized modes can propagate independently and therefore interfere with each other. By making the fiber core elliptical, it is possible to eliminate one of these two polarizations so the signal becomes even more pure. That is, one polarization decays more slowly away from the core so that it sees more of the absorbing material that surrounds the cladding. Many fiber types have been invented, but these are some of the most widely used.

Figure 22-5



Designing optical fibers has been a major activity for the past twenty years. The first initial issue was propagation loss. Reducing to negligible levels the losses due to rough fiber walls was relatively easy because drawn glass fibers are so smooth. More serious was the absorption due to very small levels of impurities in the glass. Purification was a significant step forward. Water posed a particularly difficult problem because one of its harmonics fell in the region where attenuation in glass was otherwise minimum, as suggested in Figure 22-6. At wavelengths shorter than ~1.5 microns the losses are dominated by Rayleigh scattering of the waves from the random fluctuations in glass density on atomic scales. These scattered waves exit the fiber at angles less than θ_c. Rayleigh scattering is proportional to f^4 and occurs when the inhomogeneities are small compared to $\lambda/2\pi$; here the inhomogeneities have atomic scales, say 1 nm, whereas the wavelength is more than 1000 times larger. Rayleigh scattering losses are best minimized by minimizing unnecessary inhomogeneities.

Figure 22-6. Loss mechanisms in optical fibers

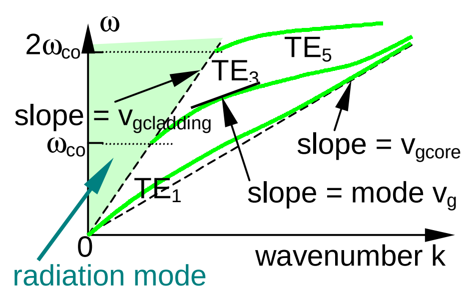


At wavelengths longer than ~1.5 microns the wings of absorption lines at lower frequencies begin to dominate. This absorption is due principally to the vibration spectra of inter-atomic bonds, and is unavoidable. The resulting low-attenuation band centered near 1.5-microns between the Rayleigh and IR attenuating regions is about 1.5 THz wide, enough on one fiber to let each person in the U.S.A. have a private simultaneous bandwidth of $1.5\times10^{12}/2.5\times10^{8}$ = 6 kHz, or a private telephone channel! Most fibers used for local distribution do not operate anywhere close to this limit for lack of demand, although undersea cables are pushing in that direction.

The fibers are usually manufactured first as a preform, which is a glass rod that subsequently can be heated at one end and drawn into a fiber of the desired thickness. Preforms are either solid or hollow. The solid ones are usually made by vapor deposition of SiO_2 and GeO_2 on the outer surface of the initial core rod, which might be a millimeter thick. By varying the mixture of gases, usually $Si(Ge)Cl_4 + O_2 \Rightarrow Si(Ge)O_2 + 2Cl_2$, the permittivity of the deposited glass cladding can be reduced about 2 percent below that of the core. The boundary between core and cladding can be sharp or graded in a controlled way. Alternatively, the preform cladding is large and hollow, and the core is deposited by hot gases from the inside in the same way; upon completion there is still a hole through the middle of the fiber. Since the core is small compared to the cladding, the preforms can be made more rapidly this way. When the preform is drawn into a fiber, any hollow core vanishes. Sometimes the hollow core is an advantage. For example, some newer types of fibers have laterally-periodic longitudinal holes that force more of the energy to propagate within an internal void that is even less lossy than glass.

Another major issue in the design of fibers is dispersion. We want the same group velocity over the entire frequency band so that pulses or other waveforms do not distort as they propagate. If the optical signal is formed by multiplying the optical carrier by a radio-frequency modulation signal, then the optical frequency spectrum is the convolution of the optical carrier spectrum (an impulse) and the radio frequency modulation spectrum. Those outer frequencies farthest from the carrier are generally associated with the sharper edges of the modulation waveform. If v_g varies over this narrow optical band, then the wave will distort if it propagates far enough.

Figure 22-7. Group velocities for optical fiber modes.



The group velocity v_g is the slope of the ω vs k relation ($v_g = (\partial k/\partial\omega)^{-1}$) at the optical frequency of interest, as suggested in Figure 22-7 for three different modes. A dispersive line eventually transforms a square optical pulse into something that looks more like a sine wave of varying frequency. This problem can be minimized by carefully choosing the dispersion n(f) of the glass, the permittivity contour ε(r) in the fiber, and the optical center frequency f_o; the glass dispersion generally dominates. Otherwise we must reduce either the bandwidth of the signal or the length of the fiber. Alternatively, the signal must be detected and regenerated after propagating only very short distances, as was done for the first fiber systems.

This natural fiber dispersion can, however, help solve the problem of fiber nonlinearity. Since attenuation is always present in the fibers, the amplifiers operate at high powers, limited partly by their own nonlinearities and by any fiber nonlinearities. This problem is more severe when the signals are in the form of isolated pulses. By deliberately dispersing and spreading the pulsed signals before introducing them to the fiber, the peak signal amplitudes and resulting nonlinear effects are reduced. This pre-dispersion is made opposite to that of the fiber. That is, if the fiber propagates high frequencies faster, then the pre-dispersion is chosen to delay them correspondingly. Thus the residual fiber dispersion gradually compensates for the pre-dispersion over the full length of the fiber. At the end of the fiber the pulses reappear in their original form, but with peak amplitudes so weak from natural attenuation that the fiber nonlinearities are not triggered.