6.014 Lecture 18:
Optical Communications

A. Overview

Optical communications is as old as smoke signals, modulated campfires, and mirrors reflecting sunlight. Today it is even more important, particularly for long-haul communications. Optical fibers now carry the great majority of all intercontinental communications, although microwave satellites still provide deployable backup because they can switch capacity from terminal to terminal to address transient shortfalls or failures, or geographically isolated users such as those on ships. Fibers have also been widely installed for intrastate communications, and are beginning to migrate down into the local loop and eventually to 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 through-the-air line-of-sight optical links that provide extreme bandwidths for dedicated point-to-point communications. For example, companies can link between buildings using beams of light, or can quickly bypass inadequate or failed wire links connecting them to the global network, as happened after 911 in New York City. Such links also have great potential for very broadband inter-satellite or space-probe-to-earth communications because small telescopes easily focus their antenna beams (beamwidths of 5-inch apertures are typically one arc second [1 arc second is 1/60 arc minutes, $1/60^2$ degrees, $2\pi/360\times60^2$ radians, or 1/60 of the largest apparent diameters of Venus or Jupiter in the night sky].

The main issues in fiber communications are the fiber links themselves and the devices that manipulate the optical signals, such as sources, detectors (discussed in the first recitation), amplifiers (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. An example of a typical subsystem is pictured in L18-3 where 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 before requiring amplification in an optical amplifier (OAMP). OAMPs are typically erbium-doped fiber amplifiers (EFDA's) spaced about 50 miles apart. At the far end the wavelengths can be separated using a de-multiplexer (DEMUX) into the original user bands for local distribution. Without EFDA's the optical signals would have to be 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 Slab Waveguides

In its simplest form a typical glass optical fiber transmission line is perhaps 125 microns in diameter with a core having diameter ~10 microns. 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

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

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.

A more rigorous, but approximate, way to analyze fiber-optic modes is suggested in Slide L18-5 where a dielectric slab waveguide in vacuum is analyzed. A similar analysis is presented in Section 7.2 of the text. If we start by assuming that the +z-propagating TE waves inside the slab, which is assumed to be infinite in the lateral (y) direction, 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 θ_c, the fields decay exponentially away from the boundary outside. That is, outside $\overline{E} = \hat{y}\underline{E}_1 e^{-ax-jk_z z}$ for x > d, where d marks the upper boundary of the slab.

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 L18-5 are consistent with both E_y and its derivative being continuous across the boundaries at $x = \pm d$.

Once the form of the electric field inside and outside the slab is known, $\overline{H}$ can be immediately found using Faradays law, i.e., by computing $\overline{H} = -(\nabla \times \overline{E})/j\omega\mu$. The resulting magnetic and electric field distributions are suggested in the figure on L18-6, or in Figure 4.12 in the text. At the boundary x = d the electric and magnetic files inside and outside the slab for $TE_{1,3,5,\ldots}$ are:

$$E_o \cos k_x d \; e^{-jk_z z} = E_1 e^{-ad-jk_z z} \tag{2}$$

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

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

The ratio of these two equations that require continuity in parallel $\overline{E}$ (Eqn. 2) and $\overline{H}$ (Eqn. 3) at the boundaries can be computed to yield $k_x d \tan k_x d = \mu\alpha d/\mu_o$. We also know from the dispersion relations:

$$k_z^2 + k_x^2 = \omega^2\mu\varepsilon \text{ inside}, \qquad k_z^2 - \alpha^2 = \omega^2\mu_o\varepsilon_o \text{ outside}, \tag{4}$$

that:

$$k_x^2 + \alpha^2 = \omega^2(\mu\varepsilon - \mu_o\varepsilon_o) \tag{5}$$

Substituting the expression for k_x that comes from the dispersion relation (5) into the first equation we obtain a transcendental equation:

$$\tan k_x d = (\mu/\mu_o)([\omega^2(\mu\varepsilon - \mu_o\varepsilon_o)d^2/k_x^2d^2] - 1)^{0.5} \tag{4}$$

This can be solved graphically, as shown in L18-7. The left-hand side is a tangent function in $k_x d$, and the right-hand side is a curve that depends on $k_x d$ and ω; the solutions are where the two curves cross.

For $\omega \rightarrow 0$ there is only one solution, but it is valid for all ω; this is the TE_1 mode. At low frequencies this slab can propagate waves with small values of α that decay very slowly away from the slab ($\alpha\rightarrow 0$ as $\omega\rightarrow 0$; see (5) as both $k_x d$ and $\omega \rightarrow 0$). 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 ($0<k_x d<\pi/2$) and TE_3 ($\pi<k_x d<3\pi/2$) modes can propagate, as illustrated. As $\omega\rightarrow\infty$, 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.

Slide L18-7 shows three forms of optical fiber. One has a thicker core that can propagate multiple modes, while the other has a core so small that only one mode can propagate. In this case, however, both vertically and horizontally polarized modes can propagate independently and therefore interfere with each other. By making the fiber 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.

Designing 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 was a particularly difficult problem because one of its harmonics fell in the region where attenuation in glass was otherwise minimum, as suggested in Slide L18-8. 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.

At wavelengths longer than ~1.5 microns the wings of absorption lines at lower frequencies begin to dominate. This absorption is associated principally with vibration spectra of inter-atomic bonds, and is unavoidable. The low-attenuation band centered near 1.5-microns 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.

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. The group velocity v_g is the slope of the ω vs k relation ($v_g = (\partial k/\partial\omega)^{-1}$) For example, a square pulse can be fourier-transformed to an equivalent series of frequencies, the higher frequencies being associated with the sharper edges of the waveform, as suggested in Slide L18-9. This set of lower frequencies associated with the modulation envelope of the optical carrier wave is then convolved with the carrier spectrum to produce a narrow optical band that slowly spreads and distorts as it propagates. A dispersive line eventually transforms such a 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 $\varepsilon(r)$ in the fiber, and the center frequency ω_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.

This natural fiber dispersion can, however, help solve the problem of fiber nonlinearity. Since attenuation is always present, 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 amplifier nonlinearities are not triggered.