ELECTROMAGNETIC WAVES

- Light consists of an electric field and a magnetic field that oscillate at very high rates, of the order of **10^{14} Hz**.
- These fields travel in **wavelike fashion** at very high speeds. A picture of an electromagnetic wave' traveling along the z direction appears in Fig. 3-1.
- The electric field is plotted at three times, **showing the progress** of the wave.
- At any fixed location, the field **amplitude varies** at the optic frequency.
- The amplitude repeats itself after **one period** of the oscillation.
- The wave repeats itself in space, at a fixed time, after a distance λ. This distance is the ***wavelength.***
- Its reciprocal, $1/\lambda$, is the ***wave number****.*

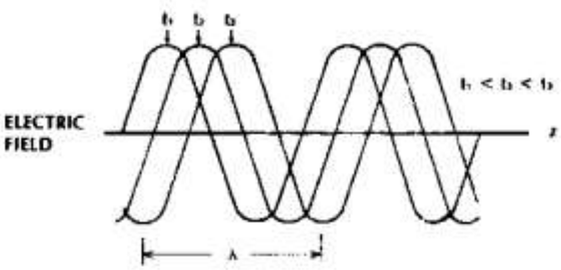

Figure 3-1 Electric field for a wave traveling in the **z** direction. The field is drawn at three different times to illustrate the **motion** of the wave in the direction of travel.

The electric field for the wave sketched in Fig. 3-1 can be written as

$$E = E_0 \sin(\omega t - kz) \qquad (3\text{-}1)$$

where ***E_0*** is the **peak amplitude**,

w = 2 πfr/s The factor ***w*** is called the ***radian frequency****.*

f is the **frequency** in hertz.

$$k = \frac{\omega}{v} \qquad (3\text{-}2)$$

The term ***k*** is the ***propagation factor****.* It is given by where ***v*** is the **phase velocity** of the wave.

The factor **w*t* - *kz*** is the ***phase*** of the wave,

while ***kz*** is the ***phase shift*** owing to travel over length ***z.***

- A ***plane wave*** is one whose phase is the same over a planar surface.
- In the present example, the phase is the same over any plane defined by a fixed value of **z**, so that Eq. (3-1) represents a plane wave.
- If **time** is held **constant**, then Eq. (3-1) shows the sinusoidal spatial variation of the field.

For example, if t = 0,

then $E = E_0 \sin(-kz)$

$= -E_0 \sin kz.$

- On the other hand, if the position is fixed, then Eq. (3-1) shows the sinusoidal time variation of the field.
- Taking the fixed position as the origin, $z = 0$, yields $E = E_0 \sin wt$, illustrating this point.

In terms of the refractive index *n,* the velocity is $v = c/n,$ so that

$$k = \frac{\omega n}{c} \qquad (3\text{-}3)$$

The propagation constant in free space will be denoted by k_o. Since $n = 1$ in free space,

$$k_0 = \frac{\omega}{c} \qquad (3\text{-}4)$$

Combining Eqs. (3-3) and (3-4), the propagation constant in any medium can be given in terms of the free-space propagation value by

$$k = k_0 n \qquad (3\text{-}5)$$

According to Eq. (1-3), $\lambda = v/f$. Substituting this into E.q. (3-2) yields

$$k = \frac{2\pi}{\lambda} \qquad (3\text{-}6)$$

This equation relates the propagation constant in a medium to the wavelength in that medium.

The free-space wavelength **is λ_0 = v/f** and the wavelength in any medium is λ = *v/f,* so that

$$\frac{\lambda_0}{\lambda} = \frac{c}{v} = n \qquad (3\text{-}7)$$

The wavelength in a medium is **shorter** than in free space, because the **refractive index is greater** than unity.

- The power in an optic beam is proportional to the light ***intensity*** (defined as the square of the electric field).
- Intensity is proportional to *irradiance,* the **power density**.
- The **units** of ir-radiance(power density) are **watts per square meter**.
- Sometimes intensity is used to describe the **total power** in a wave. This use, although **not accurate**, is common.

- If a wave **does not lose energy** as it propagates, then Eq. (3-1) and Fig. 3-1 provide appropriate descriptions.
- If **attenuation** is important, than the equation and the figure must be modified. The corrected equation is

$$E = E_o e^{-\alpha z} \sin(\omega t - kz) \qquad (3\text{-}8)$$

where *w* and *k* have the same meaning as in Eq. (3-1).

- The term α is the ***attenuation coefficient***. Its value determines the rate at which the electric field **diminishes** as it travels through the lossy medium.
- Although the decay is exponential, the attenuation coefficient is so small for quality fibers that there is little attenuation (maybe just a few decibels), even over long, paths.

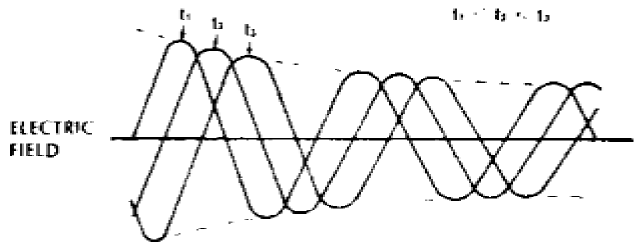

Figure 3-2 Attenuation of a traveling wave.

- In a lossy medium, the field appears as shown in Fig. 3-2, The dashed line on the figure is a curve of the factor exp (- αz), describing the loss in Eq. (3-8).

- The intensity of a light beam is proportional to the square of its electric field. Therefore, the power in the beam corresponding to Eq. (3-8) diminishes as exp (-2 αz).

- For a path of length L, the ratio of the output power to the input power is exp *(*-2 αL*).*

- The power reduction in decibels is thus

$$dB = 10 \log_{10} \exp(-2\alpha L)$$

- This will turn out to be a negative number for propagation through a lossy medium.
- From this last expression, we can find the relationship between the attenuation coefficient and the power change in dB/km.
- The result is

$$db/km = -8.685\alpha$$

where α is given in units of km^{-1}.

Still another useful relationship between the input and output powers and the transmission loss is the following, known as *Beer's law:*

$$P_{out} / P_{in} = 10^{yL/10}$$

where L is the path length and *y* is the power change in dB/km. According to our sign convention, losses correspond to positive values of *α* and negative values of y.

3-2 DISPERSION, PULSE DISTORTION, AND INFORMATION RATE

- Up to this point we have been assuming that optic sources in fiber systems emit light at single wavelength (or, equivalently, at a single frequency). This is never true in practice. Real sources produce radiation over a range wavelengths.
- This range is the source *linewidth* or *spectral width.* The smaller the linewidth, the more *coherent* the source.
- A perfectly coherent source emits light at a sine wavelength. Thus, it has zero linewidth and perfectly *monochromatic.*
- Typical line width of common sources are listed in Table 3-1.The conversion between spectral width wavelengths Δ λ and bandwidth in frequency Δ f is

$$\frac{\Delta f}{f} = \frac{\Delta \lambda}{\lambda} \qquad (3\text{-}$$

where f is the center frequency,

λ is the center wavelength, and

Δ f is the range of frequency radiated.

This conversion is simply the mathematical statement that the fractional emission width is the same whether computed on the basis of wavelength spread or frequency spread.

TABLE 3-1. Typical Source Spectral Widths

Source	**Linewidth (Δλ) (nm)**
Light-emitting diode	20-100
Laser diode	1 - 5
Nd:YAG laser	0.1
HeNe laser	0.002

Figure 3-3 illustrates some of the preceding points. It is a plot of the wavelength distribution of power radiated by a representative LED.

The wavelength, or frequency, content of a signal is called its *spectrum.*

- For the LED in the figure, the center wavelength is 820 nm (0.82) *µm.*
- The linewidth is normally taken to be the width to the half-power points: so, in this example, Δλ = 30nm (805-835 nm). The fractional bandwidth is 30/820 = 0.037, or 3.7*%.*
- According to Table 3-1, laser diodes are more coherent than LEDs.
- The solid state neodymium yttrium-aluminum-garnet laser (Nd:YAG) and the helium-neon gas laser (HeNe) are even better.
- However, the small size and low power requirements of the LED and LD sources make them the most practical for fiber systems, even though they have much greater line widths than other laser emitters.

At this point it is natural to ask: Do we consider a source to have negligible bandwidth (that is, treat it as a perfectly coherent source), or do we need to consider its lack of coherence?

In the discussion that follows, we will examine how the source's spectral width limns the information capacity of a fiber system. If the limiting capacity is higher than needed then the non-coherence can be ignored

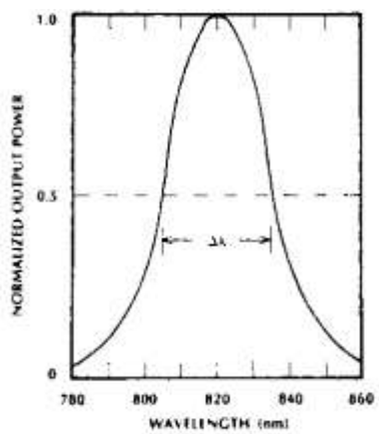

Figure 3-3 Spectrum of a light-emitting diode.

Material Dispersion and Pulse Distortion

- In Section 2-1 we related the wave velocity *r* to the refractive index *n* by the equation $v = c/n$.
- For the glasses used in optic fibers, the refractive index varies with wavelength. Therefore, the wave velocity also varies with wavelength.
- ***Dispersion*** is the name given to the property of velocity variation with wave-length.
- When, as in the present example, the velocity variation is caused by some property of the material, the effect is called ***material dispersion***.
- Consider what happens when a real source (nonzero bandwidth) emits a pulse of light into a dispersive glass fiber.
- The initial pulse consists of a sum of pulses that are identical, except for their wavelengths.
- This is illustrated in Fig. 3-4 for a few of the source wavelengths.

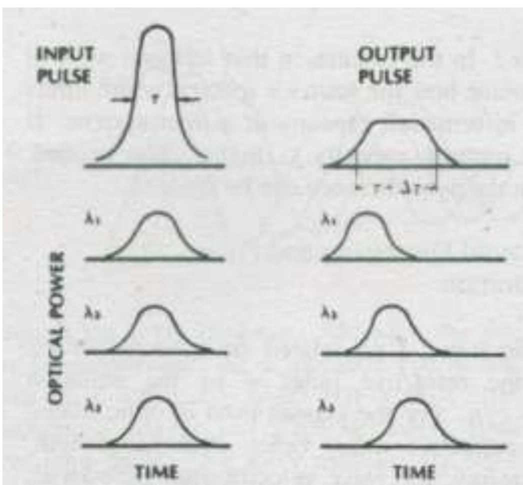

Figure 3-4 Pulse spreading caused by propagation through a dispersive material. The complete pulse contains wavelengths A_1, A_2, and A_3, each traveling at a different speed.

- The several pulses travel at different velocities, reaching the end of the fiber at slightly different times.
- When summed at the output, the slightly displaced pulses add together, yielding an output that is **lengthened**, or **spread**, relative to the input signal.
- This illustrates how dispersion creates **pulse distortion**.
- The farther the pulse travel, the greater the spreading.
- Dispersion will also distort an analog signal. Figure 3-5 shows an analog wave shape propagated at three different wavelengths.

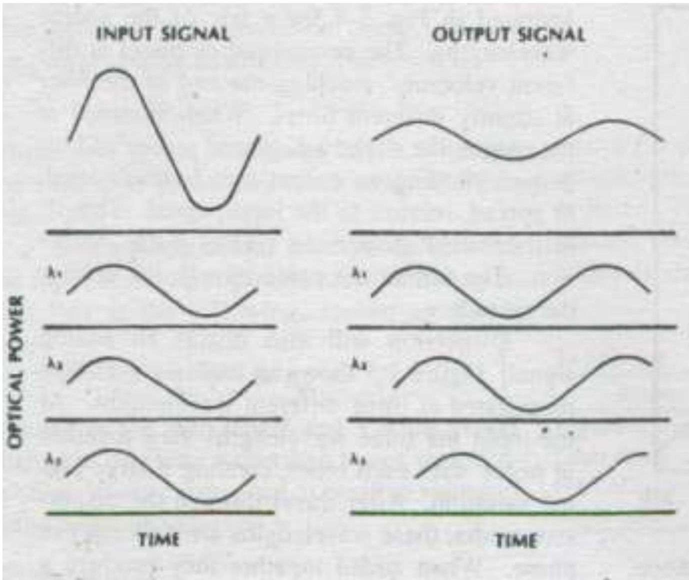

Figure 3-5 Dispersion causes loss amplitude of an analog signal.

At the input the three wavelengths vary together in phase with each other, creating a large signal variation.

After travel through the dispersive media, these wavelengths are no longer in phase! When added together they produce a signal variation lower in amplitude than the input signal variation.

Dispersion does not change the average power or the modulation frequencies, but it does lower the signal variation. The transmitted information is contained in this variation, so its attenuation is troublesome.

We may think of this result as broadening the signal peak (lowering its amplitude and filling in the valley (raising its level), Excessive broadening will cause loss of the signal variation altogether.

- Distortion caused by material (or wave guide) dispersion can be reduced by us sources with smaller bandwidths i.e., using more coherent emitters.
- A laser diode has the advantage over an LED in this respect.
- In principle, dispersive distortion could be reduced by filtering the optic beam at the transmitter or receiver, allowing only a very narrow band of wavelengths to reach the photodetector. This technique has two drawbacks:
  - Fill cannot be constructed with passbands narrow enough to be effective,
  - a narrowband filter would greatly reduce the optic power by eliminating the light at the unwanted wavelength.
- Dispersion in glass is easily observed. We have all seen the results of dispersion when a glass prism separates white light into its component colors.
- This experiment is explained by the wavelength dependence the refractive index of glass. The incident light rays are bent according to Snell's 1aw.

Solutions of above

- Pulse spreading reduces the bandwidth and data capacity of a fiber communications link in the manner described later in this section.
- Because of this, many techniques for minimizing pulse spreading have been pursued.
- A few that we already know about are:
    1. operating at the zero-dispersion wavelength and
    2. choosing very coherent (small spectral width) light sources.
- These solutions (often applied together) have been common since the mid-1980s.
- Improvements now take the form of shifting the fiber's zero-dispersion point to wavelengths of lower fiber attenuation and producing more coherent laser sources.
- Another technique that shows promise for reducing pulse spreading is the production of *solitons.*
- A soliton is a pulse that travels along a fiber without changing shape.
- How can this happen. The actual procedure is fairly complicated, but some insight into soliton propagation can be easily developed.
- Pulses broaden because dispersion causes some wavelengths emitted by the light source to travel faster than other wavelengths.
- All we need do is find some property of the fiber that counters this tendency.
- It turns out that such a property does exist. It is a fiber nonlinearity where the index of refraction depends upon the intensity of the light beam.
- Since the pulse velocity depends on the index of refraction, it is clear that the intensity of the beam can itself influence the speed of the various wavelengths propagating along the fiber.
- Usually this phenomenon is not observed, because it is quite small and requires a moderately large amount of optical power before becoming significant.
- To form a soliton, the initial pulse must have a particular peak energy and pulse shape,
- To be specific, the product of pulse energy and pulse width must be a constant.
- The value of the constant depends on the magnitudes of the dispersion and the nonlinearity.
- With too little power, the nonlinearity is too weak to be effective in

compensating for dispersion.

- If the power is too great, then the pulse may actually continually change widths as it travels, owing to imperfect (and distance-dependent) compensation.
- In addition, the nonlinear compensation is such that solitons are produced only at wavelengths longer than the zero-dispersion wavelength in glass fibers.
- That is, the nonlinearity acts with dispersion to further broaden pulses at the shorter wavelengths and only compensates at the longer ones.
- We conclude that soliton pulses can be expected in silica fibers only when operating in the 1300- to 1600-nm range.
- Although solitons retain pulse widths during propagation, solitons do attenuate just like other waves.
- It will be imperative for long systems that the optical beam be amplified periodically so that the pulse energy not fall below that required for soliton maintenance.
- Various optical amplifiers (to be described in Section 6-7) are candidates for the amplification process.
- Soliton widths of a few picoseconds are realizable.
- The corresponding data rates (the inverse of the soliton widths) are over 10 Gbps.
- Multigigabit-per-second systems covering many thousand kilometers with amplifier spacings of several tens of kilometers can be designed with soliton pulses.
- The product of data rate and fiber path length for such systems is far greater than can be achieved by more conventional fiber techniques.

Information Rate

- Pulse spreading limits the information capacity of any transmission system in the manner described in what follows.
- For numerical calculations we will use the spreads generated by material dispersion.
- The equations developed apply regardless of the cause of the distortion. We will investigate the limits on both analog and digital links.
- Without long and complex derivations, exact results cannot be obtained.
- Reasonable limits can be developed based on approximate intuitive analyses.
- The results obtained will be useful in first-order design and will deepen understanding of the ability of fiber links to carry information.

- First, consider a sinusoidally modulated beam of light (like that shown in Fig. 3-5).
- The modulation frequency is / and the period is *T* = I//. Suppose that the source radiates optic wavelengths between A! and A_2.
- How much delay between the fastest and slowest wavelength is acceptable? Figure 3-9 shows the received power at Aj and A_2 when the delay is equal to half the modulation period; that is,

$$\Delta\tau = \frac{T}{2} \qquad (3\text{-}15)$$

With this amount of delay, the modulation cancels out completely when the two waves are added. Modulated power carried at wavdengths between \{ and A_2 will have delays smaller than *T/2* and will partially cancel, resulting in a small signal variation at the receiver. If we take Eq. (3-15) as the maximum

terns in the shorter-wavelength range 0,8-0.9 /im; so they are used only when necessary to achieve higher performance. The tabulated rates are fairly high. They will be lower in some systems because of additional pulse spreading caused by modal distortion, as described in Section 5-6.

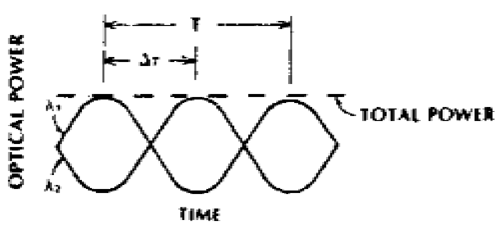

Figure 3-9 Canceling of the modulation when two carrier wavelengths have a delay of half the modulation period. $\Delta\tau = T/2$.

The information limits in Eqs. (3-16), (3-19), (3-20), and (3-21) apply whether the pulse spread is due to material dispersion or other causes. These results are approximate because of the assumptions made in developing them. They do, however, yield reasonable values for initial system design. They are also important because they show the relationships between pulse spreading and the allowed digital data rates and analog modulation frequencies.

3-3 POLARIZATION

- The electric field of a light beam has several directions associated with it.
- One of these, the direction of travel, has already been discussed with regard to phase shift, wavelength, velocity, and attenuation of the propagating wave.
- The other direction is that of the electric-field vector itself. Figure 3-13 shows the relationship between the vector £ and the direction of travel for a simple plane wave.
- The wave travels in the *z* direction, and the electric-field vector points in the *x* direction.
- An electric field that points in just one direction is said to be *linearly polarized,* because it always points along the same single line.

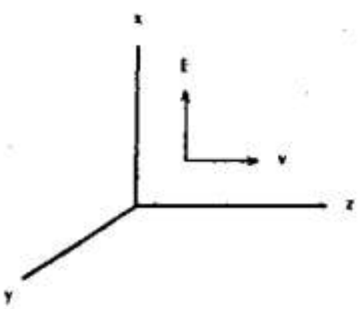

Figure 3-13 Wave traveling in the *z* direction having its electric field polarized in the *x* direction.

- The electric vector is always perpendicular to the direction of travel for a plane wave in an unbounded medium.
- This being so, the field in Fig. 3-13 could also point in the v direction while traveling in the *z* direction.
- The actual direction of polarization is determined by the polarization of the light source and by any polarization-sensitive elements through which the beam passes.
- It is also possible for two waves to simultaneously travel in the *z* direction, one polarized in the *x* direction and one polarized in the v direction.
- These two waves would be independent of each other because of their orthogonal polarization.
- The term *mode* refers to the different ways a wave can travel in a given direction.
- The two independent waves just described are the two plane-wave modes of an unbounded medium.
- It might occur that other modes are possible, having polarizations in the *xy*

plane at some angle to the *x* or *y* axis.

- Any electric-field vector can be decomposed into its *x* and *y* components, so that such a field is simply the combination of the two modes already described.
- A wave is *unpolarized* if its electric vector varies randomly in direction. Waves in most optic fibers are unpolarized,
- In a guided structure, such as an optic fiber, many modes can exist. Polarization is just one of the differences among modes in a waveguide.
- Modes will be investigated in Chapters 4 and 5. They play an extremely important part in determining the design and capabilities of an optic communications system.

3-4 RESONANT CAVITIES

- A radio-frequency oscillator consists of
    - an amplifier,
    - a tuned circuit, and
    - a feedback mechanism.
- The feedback connects the amplifier output to its input, causing the signal to increase as it periodically passes through the amplifier.
- A short time after being turned on, a **steady state** is reached where the system losses are just made up by the gain through the amplifier.
- Now oscillator maintains a constant output power. The tuned circuit determines the oscillation frequency.
- A laser is a very-high-frequency oscillator. It may correctly be referred to as an ***optic oscillator***.
- Its components have functions paralleling those of lower-frequency oscillators.
- The laser sketched in Fig. 3-14 consists of a cylindrically shaped medium with mirrors attached at each end.

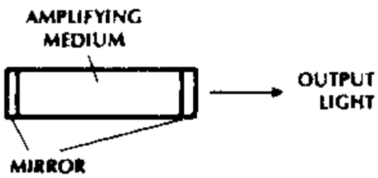

Figure 3-14 A laser consists of an amplifying medium and two end mirrors.

- The medium provides the amplification. Light is amplified in this material by the mechanism described in Chapter 6.
- Properties of the medium determine the output frequency and spectral width of the laser.
- In this section we are primarily interested in the **purpose of the mirrors**. The mirrors provide feedback for the light oscillator, reflecting the light back and forth through the amplifying medium.
- Power exits the laser through one of the mirrors, which is partially transmitting.
- In some lasers, both mirrors transmit, allowing power to be obtained from both ends of the device.
- This construction is valuable for laser diodes in fiber systems.
- Light from one emitting end is coupled to the transmitting fiber, and light from the other end is measured to monitor the source status.
- Fluctuations in source power are quickly determined, and automatic corrections in the drive circuit return the laser to the required output level.

- The two mirrors in Fig. 3-14 form a cavity (called a *Fabry-Perot* resonator) within which two waves exist, one moving to the right and one moving to the left.
- These waves are drawn at various times in Fig. 3-15 for a cavity of length *L.*

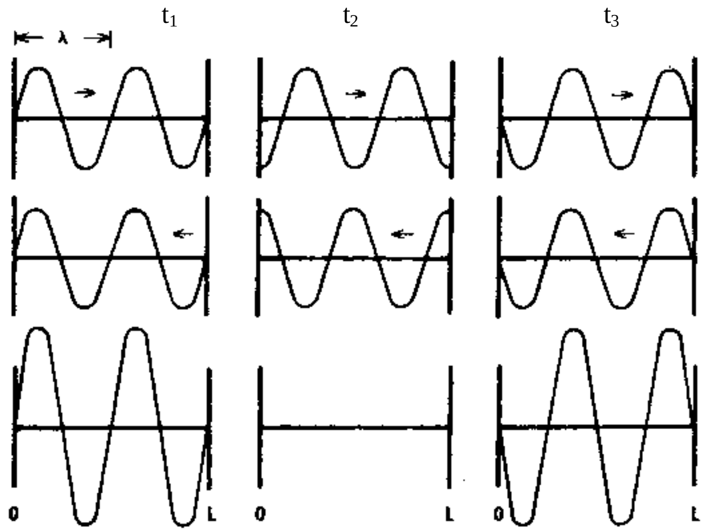

Figure 3-15 Optical waves in a cavity of length *L* at various times: $t_3 > t_2 > t_1$. The top figures portray the wave moving to the right; the middle ones, the wave moving to the left; the bottom ones, the total wave.

-
- The top figures show the wave moving to the right, and the middle ones show the wave moving to the left.
- The total field in the cavity is the sum of the two moving waves and is shown in the bottom figure at the times indicated.
- These drawings illustrate the ways in which electromagnetic waves can interfere with each other.
- When waves have the same phase, they add ***constructively.*** This is the condition at times t_1 and t_3 on the figure.
- The total field is greater than either of its components. When waves are 180° out of phase, as at time t_2, they interfere ***destructively.***
- The total field is **zero** when waves of equal amplitude interfere **destructively**. This is an example of the **wavelike behavior of light**.
- If we draw the total wave for all periods of time on the same figure, we find a repeating pattern of **peaks** and **nulls**.

3-5 REFLECTION AT A PLANE BOUNDARY

- Problem concerning the amount of light reflected at a boundary between two dielectrics are an important part of the study and practice of optics.

Figure 3-19 Reflecting surfaces in a fiber system. Light rays are reflected at the input (A), at the core interface (B), and at the boundaries of an air gap formed at a connector or splice (C or D).

- These problems are particularly critical in the design and analysis of fiber systems. Reflecting surfaces occur in the situations illustrated in Fig. 3-19. These are:
    1. The air-to-glass boundary where light is coupled from a source into a fiber
    2. The interface between the fiber core and its surrounding layer
    3. The two air-glass boundaries where there is an air gap between two fibers being connected
- Light reflected at the input and at the connector gap should be small, because these reflections reduce the power being transmitted.
- Include these losses in calculations of the total system power budget.
- On the other hand, the internal reflection at the core boundary (point B in Fig. 3-19) should be high to keep the light inside the fiber.
- We will determine the amounts of reflection in this section.
- The simplest computations for reflection loss are those for which the incident beam is traveling normal to the boundary, as in Fig. 3-20.
- The *reflection coefficient p* is the ratio of the reflected electric field to the incident electric field. For normal incidence, it is

$$\rho = \frac{n_1 - n_2}{n_1 + n_2} \qquad (3\text{-}27)$$

where n_1 is the refractive index in the incident region and n_2 is the index in the transmitted region.

If n_2 >. N_1, then the reflection coefficient becomes negative. This indicates a 180° phase shift between the incident and reflected electric fields.

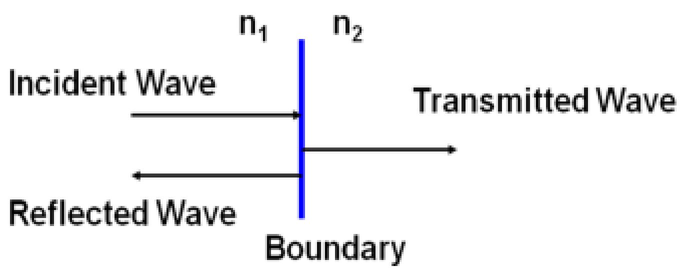

Fig 3-20 A Wave incident on a plane boundary between two dielectrics (refractive indices n1 & n2) is partially transmitted and partially reflected.

The *reflectance R* is the ratio of the reflected-beam intensity to the incident-beam intensity. Because the intensity in an optic beam is proportional to the square of its electric field, the reflectance is equal to the square of the reflection coefficient.

Thus

$$R = \left(\frac{n_1 - n_2}{n_1 + n_2}\right)^2 \qquad (3\text{-}28)$$

3-6 CRITICAL-ANGLE REFLECTIONS

- As drawn in Fig. 3-23, there is total reflection for incident angles greater than a particular value, labeled θ_c.
- θ_c is called the *critical angle.*
- It is easily determined from Eqs. (3-29) and (3-30) by noting that $|p_p| = 1$ and $|p_s| = 1$, when $n_2^2 - n_1^2 \sin^2 \theta_i = 0$. The angle satisfying this equation is the critical angle, so that

$$\sin \theta_c = \frac{n_2}{n_1} \qquad (3\text{-}34)$$

- Because the sine of an angle is never greater than 1,
- it is clear that critical-angle reflections occur only when $n_1 > n_2$, that is, when a wave travels from a region of **higher** refractive index i**nto** a region of **lower** index.
- This explains the occurrence of a critical angle in Fig. 3-23 (glass-to-air boundary), but not in Fig. 3-22 (air-to-glass boundary).
- An alternative and instructive development of total reflection involves Snells law.
- We will consider a glass-to-air boundary and find the angle of transmission for all incident angles from Eq. (2-3), sin 0, = (n_l/n_2) sin 0,.
- The result is plotted in Fig. 3-26. As shown in the figure, the transmission angle increases faster than the incident angle.
- It reaches 90° when $\sin \theta_t = n_2/n_1$, precisely the critical-angle condition, Eq. (3-34).

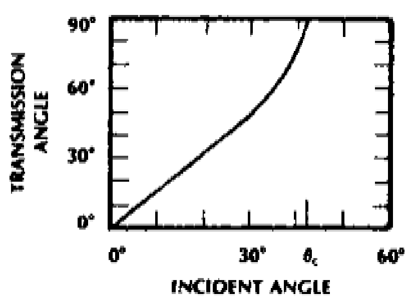

Figure 3-26 Transmission angle for a glass-to-air interface. $n_1 = 1.5$, $n_2 = 1.0$.

- By referring to Fig. 3-27, the meaning of a 90° transmission angle is clear. The transmitted wave no longer propagates into the second medium.
- We conclude that all the light must reflect back into the first medium. Perfect reflection at a dielectric-dielectric boundary is called ***total internal reflection***.

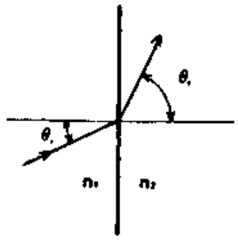

Figure 3-27 As θ_i increases, θ_t approaches 90° if $n_1 > n_2$.

- Critical angles, computed from Eq. (3-34) for several combinations of materials, are listed in Table 3-3.
- The plastic-plastic boundary in the table is typical of an all-plastic fiber whose core and surrounding cladding have different refractive indices.
- The glass-plastic entry corresponds to a fiber having a glass core surrounded by plastic.
- The glass-glass boundary is typical of an all-glass fiber in which the core and cladding have slightly different compositions and, thus, slightly different refractive indices.
- These fibers guide light by totally reflecting the rays that strike their boundaries.
- The rays must be at, or beyond, the critical angle to be guided without loss, however.

TABLE 3-3. Critical Angles

Boundary	**n_1**	**n_2**	**Θ_c**
Glass-air	1.5	1.0	41.8°
Plastic-plastic -	1.49	1.39	68.9°
Glass-plastic	1.46	1.4	73.5°
Glass-glass	1.48	1.46	80.6°

Assignment no 3

Q 1.Discuss the following:

1. **Resonant cavities**
2. **Critical-angle reflections**
3. **Reflection at a plane boundary**

Q2. Discuss dispersion, pulse distortion, and information rate.