Losses and Dispersion in Waveguides

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Loss Mechanisms

Scattering loss

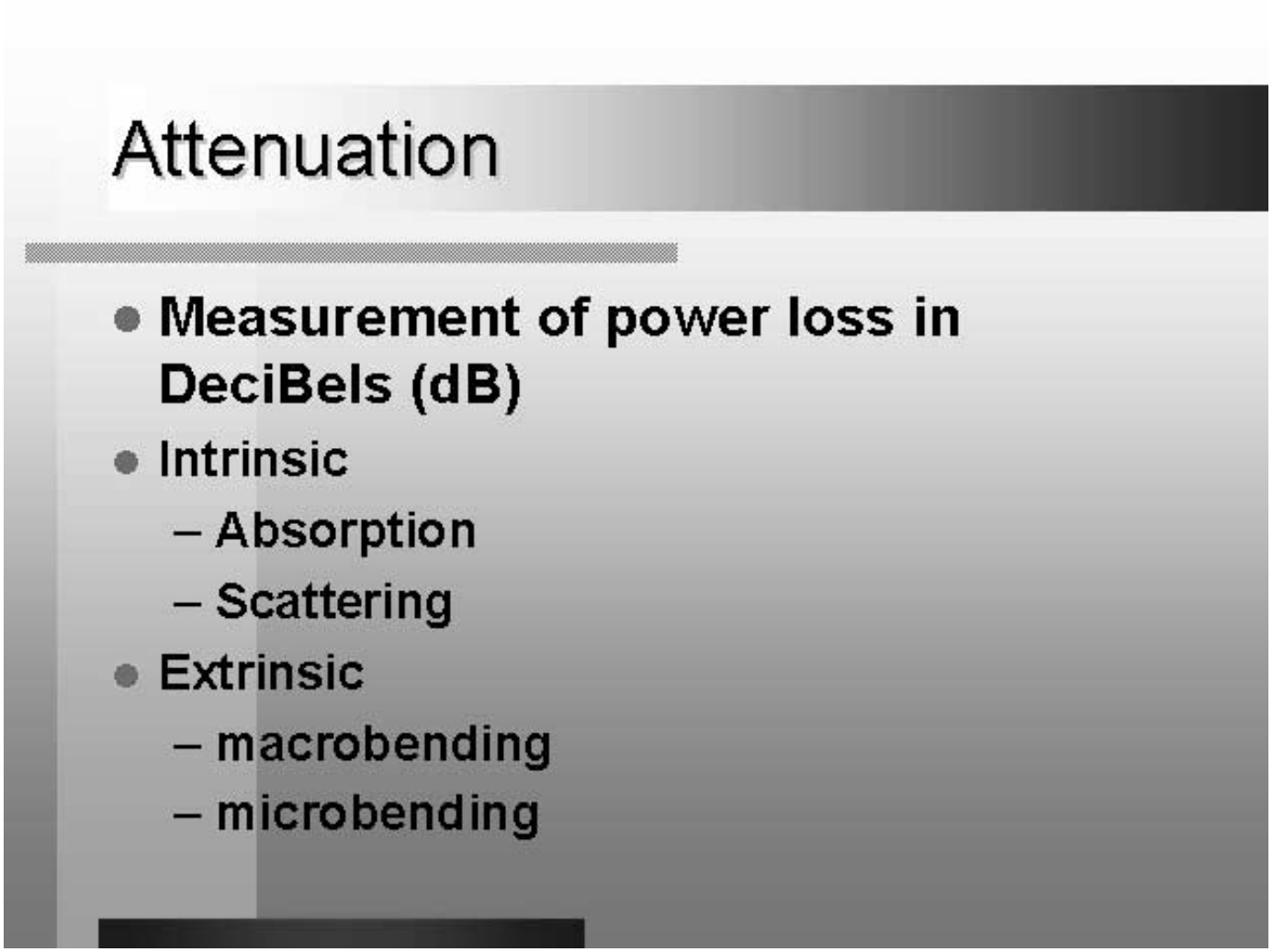
- Predominates in glass or dielectric (such as oxide) waveguides.

Absorption loss

- Most important in semiconductor and other crystalline materials.

Radiation loss

- Significant when waveguides are bent.



- dB is a ratio of the power received verses the power transmitted
  Loss (dB) = 10log (power transmitted / power received)

Surface Scattering Loss (I)

More significant for higher-order modes.

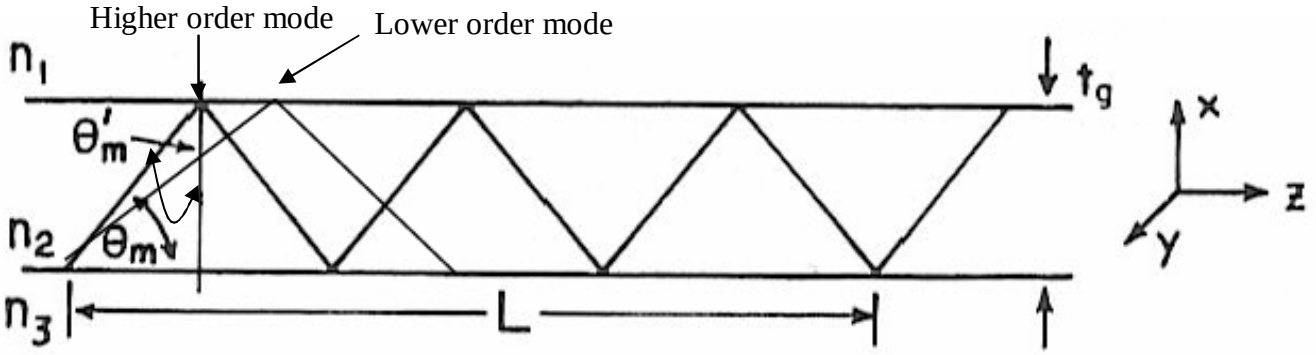


Fig. 6.1. Diagram of a ray optic approach to determination of scattering loss

Number of reflections from each surface: $N_R = \dfrac{L}{2t_g \cot\theta_m}$

$$I(z) = I_0 e^{-\alpha z}$$

$$\mathcal{L}\ \left(\frac{\text{dB}}{\text{cm}}\right) = 4.3\alpha\ (\text{cm}^{-1})$$

Surface Scattering Loss (II)

$$\alpha_s = A^2 \left[\frac{1}{2} \frac{\cos^3 \theta'_m}{\sin \theta'_m} \right] \frac{1}{t_g + 1/\gamma_1 + 1/\gamma_3}$$

$$\gamma_1 = \sqrt{\beta^2 - n_1^2 k^2}, \quad \gamma_3 = \sqrt{\beta^2 - n_3 k^2}$$

$$A \quad \frac{4\pi}{\lambda} (\sigma_{12}^2 + \sigma_{23}^2)^{1/2}$$

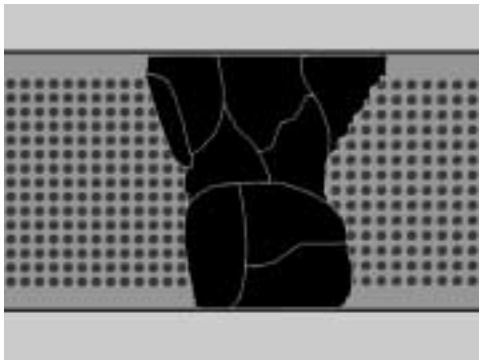
σ^2 : Variances of surface roughness

α_s increases as γ increases.
Higher order mode (smaller θ_m') has higher surface scattering loss.
In dielectric film waveguide, such as glasses and oxides, surface variation ~ 0.1 um -> α_s ~ 0.5-5 dB/cm.
In semiconductor waveguides, thickness variation ~ 0.01 um. Surface scattering loss is negligible compared to absorption loss.

Ref: P.K. Tien, Appl. Opt. V. " 0, 2395 (" 97")

Rayleigh Scattering

The random localized variations of the molecular positions in glass create random inhomogeneities of the refractive index that acts as tiny scattering centers. The amplitude of the scattered field is proportional to ω^2. The intensity is therefore proportional to ω^4 or $1/\lambda^4$



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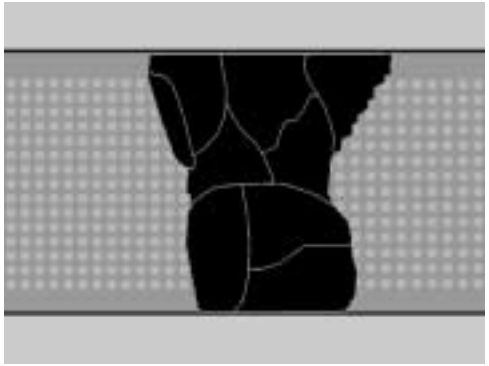

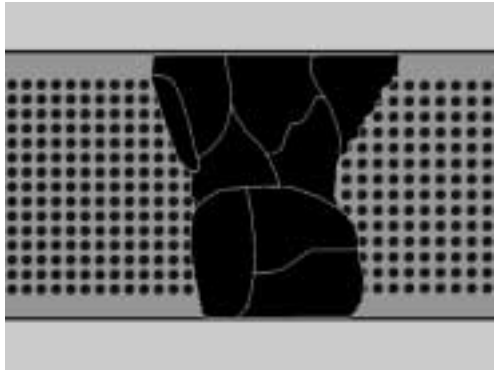

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Absorption Coefficient Due to Rayleigh Scattering

α = **field loss coefficient**

$$2\alpha = \left(8\pi^3/3\lambda^4\right) n_0^8 \rho^2 \beta_T k_\beta T$$

n_0 = average refractive index
ρ = photo elastic coefficient
β_T = isothermal compressibility
k = Boltzmann's constant
T = Temperature (^{0}K) at which the glass solidified

Absorption Coefficient Due to Rayleigh Scattering

$$P(L) = P(L=0)\, e^{-2\alpha L}$$

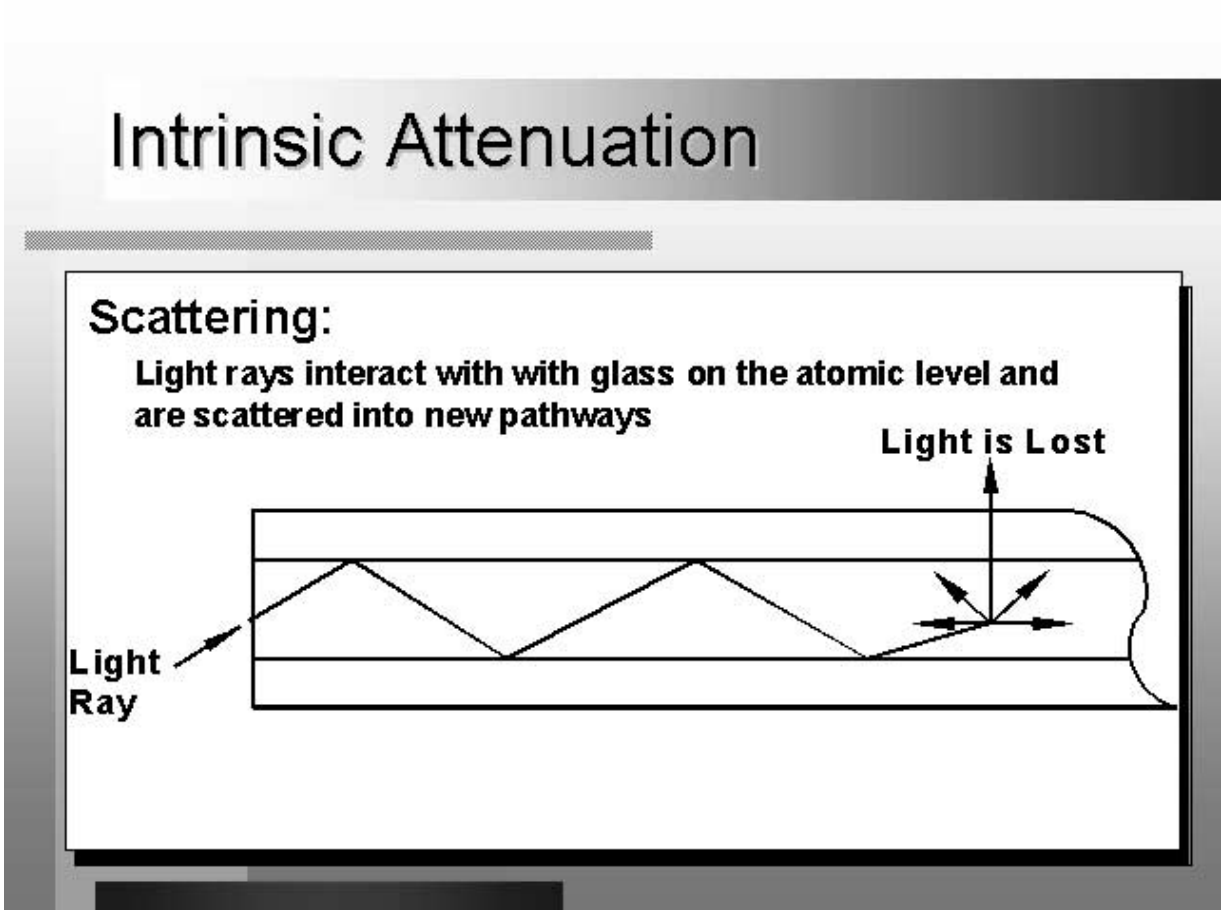
Define L = Loss due to Rayleigh scattering in dB.

$$\frac{L(0.95)}{L\ 1.55} = \frac{1.55^{\ 4}}{0.95^{\ 4}} = 7$$

Motivation for work on "Mid IR" fibers

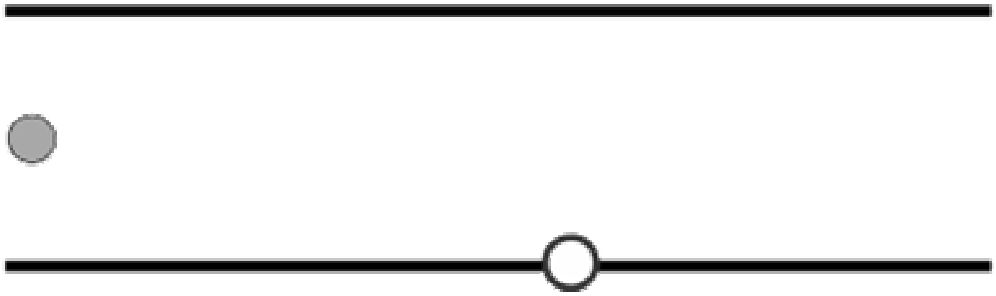
Mie scattering

If the size of the defect is greater than one-tenth of the wavelength of light, the scattering mechanism is called **Mie scattering**. Mie scattering, caused by these large defects in the fiber core, scatters light out of the fiber core. However, in commercial fibers, the effects of Mie scattering are insignificant. Optical fibers are manufactured with very few large defects.



- Light striking the Ge molecules in the core can be scattered into new pathways out of the fiber
- Rayleigh Scattering accounts for 95% of fiber attenuation
- Optical Time Domain Reflectometers (OTDR) use this property to measure loss in a fiber

Absorption



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Interband Absorption

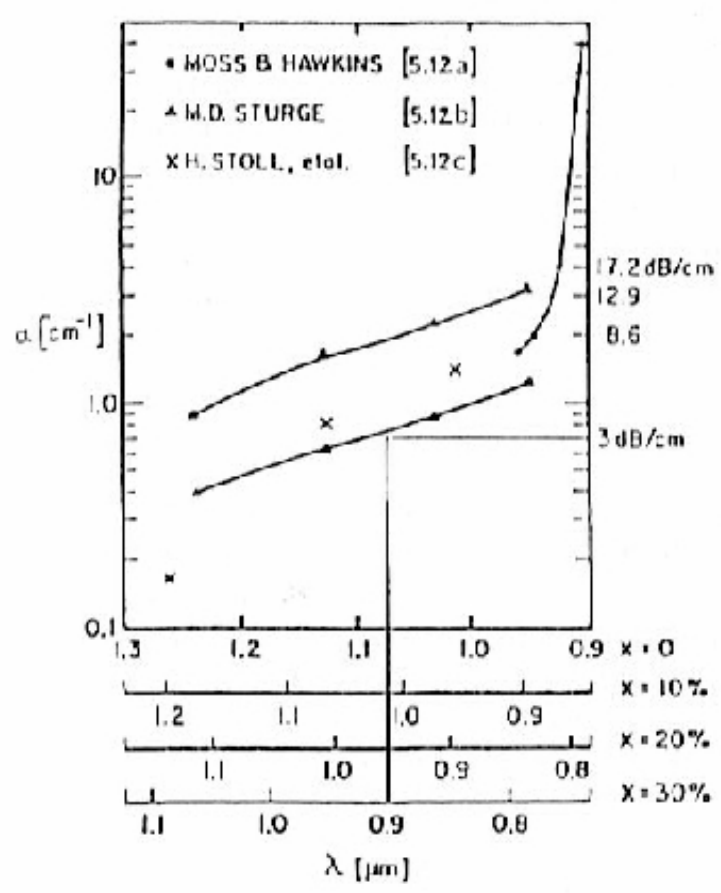

Fig. 6.2. Absorption in the long wavelength tail of the $Ga_{(1-x)}Al_xAs$ bandedge. Abscissa scales are shown for four different concentrations of aluminum (in atomic percent)

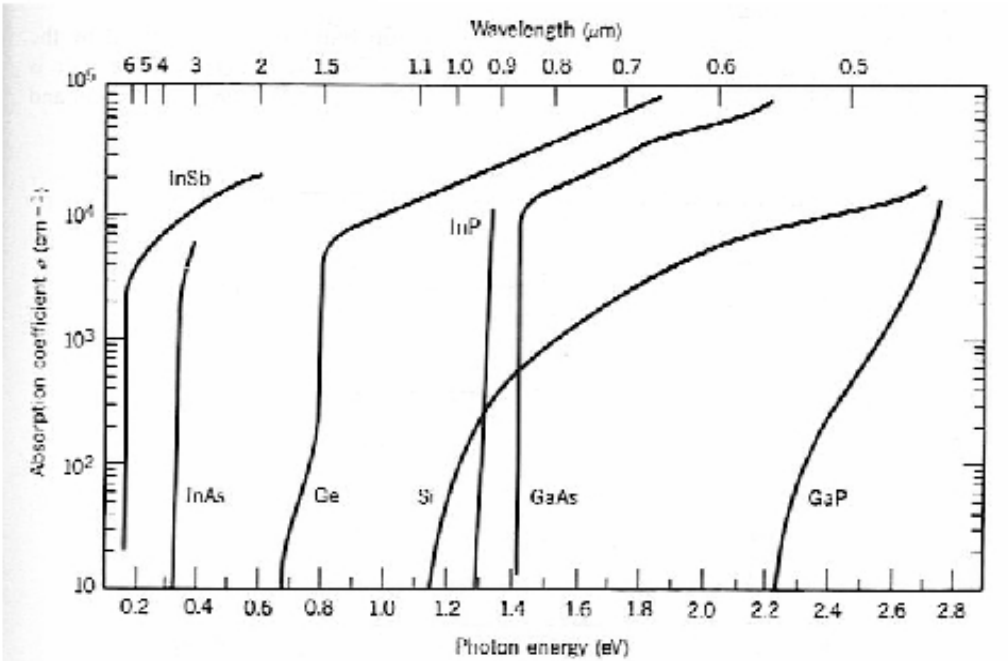

Figure 15.2-3 Absorption coefficient versus photon energy for Ge, Si, GaAs, and selected other III–V binary semiconductors at $T = 300$ K, on an expanded scale (Adapted from G. E. Stillman, V. M. Robbins, and N. Tabatabaie, III–V Compound Semiconductor Devices: Optical Detectors, *IEEE Transactions on Electron Devices*, vol. ED-31, pp. 1643–1655, © 1984 IEEE.)

Design wavguide material compositions so that the operating wavelength lies beyond the tail of the absorption curve to minimize interband absorption.

Loss Coefficient for Free-Carrier Absorption (I)

Motion of the free electrons under an applied electric field $E_0\exp(j\omega t)$

$$x = \frac{eE_0 / m^*}{\omega^2 - j\omega g}\exp(j\omega t)$$

The displacement causes polarization $p_1 = -Nex$

And complex dielectric constant

$$K = n_0^2 - \frac{(Ne^2)/(m^*\varepsilon_0)}{\omega^2 - j\omega g}$$

$$K_r = n_0^2 - \frac{(Ne^2)/(m^*\varepsilon_0)}{2} = n^2$$
$$g^2$$

$$K_i = -\frac{(Ne^2 g)/(m^*\omega\varepsilon_0)}{\omega^2 + g^2}$$

n_0: Index of refraction without the free carriers

For most semiconductor materials, $g = \frac{e}{\mu m^*} << \omega$ μ : Electron mobility

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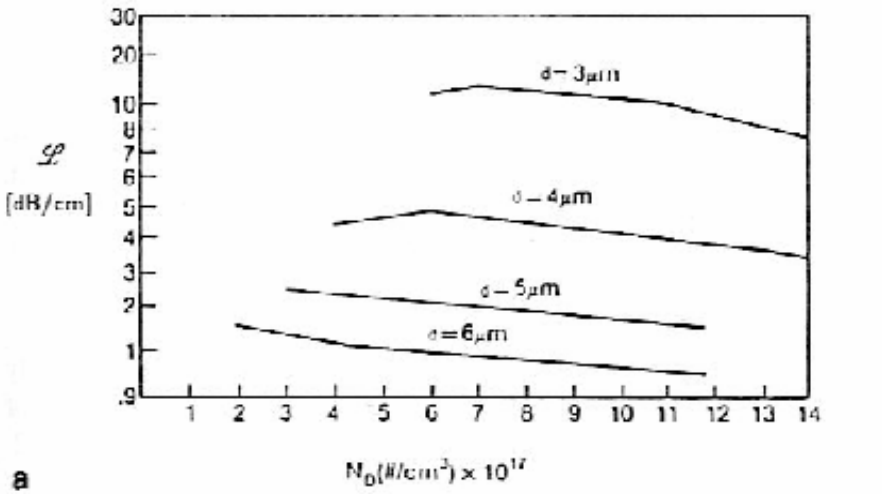
Loss Coefficient for Free-Carrier Absorption (II)



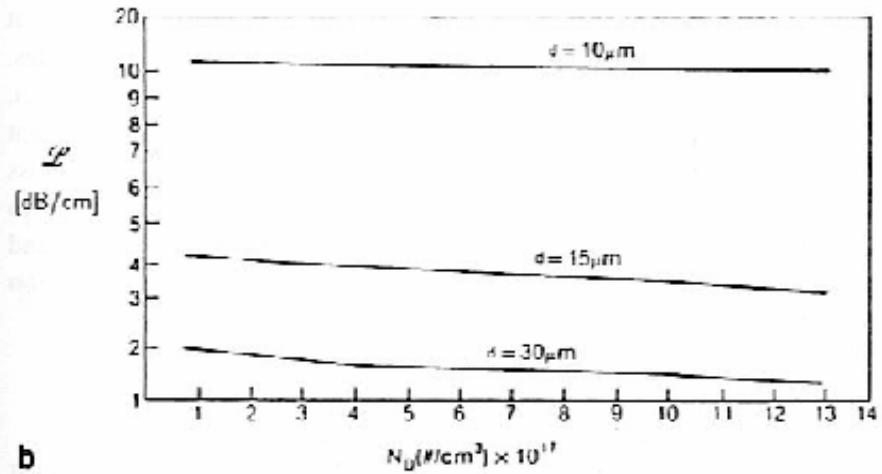


Fig. 6.4a,b. Propagation losses in proton bombarded waveguides (d = waveguide thickness, N_D = substrate doping concentration). a $\lambda_0 = 1.3\,\mu m$ propagation losses versus substrate doping. b $\lambda_0 = 10.6\,\mu m$ propagation losses versus substrate doping

$$\alpha_{fc} = -k\frac{K_i}{\sqrt{K_r}} \sim -\frac{kK_i}{n}$$

$$= \frac{Ne^3\lambda_0^2}{4\ ^2(m^*)^2 n\mu\varepsilon_0 c^3}$$

Example: n-type GaAs at $\lambda = 1.15\,\mu m$

$$\alpha_{fc}\ (\mathrm{cm}^{-1}) \sim 10^{-18} N \quad (N \text{ in } \mathrm{cm}^{-3})$$

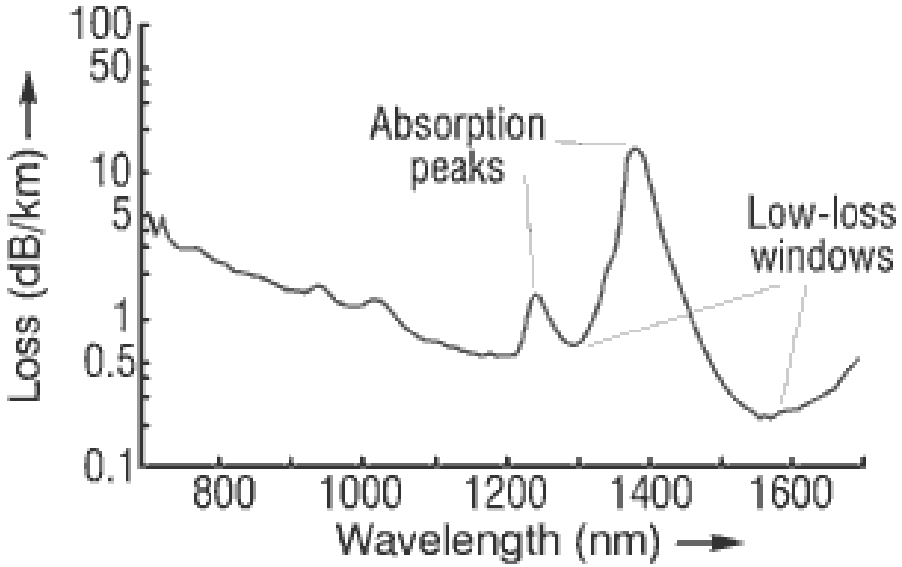
Absorption in Silica based Optical Fiber

- Imperfections in the atomic structure of the fiber material
  - induce absorption by the presence of missing molecules or oxygen defects.

- The intrinsic or basic fiber-material properties
  - UV (due to electronic and molecular transitions)
  - middle-infrared (due to vibrational transitions)

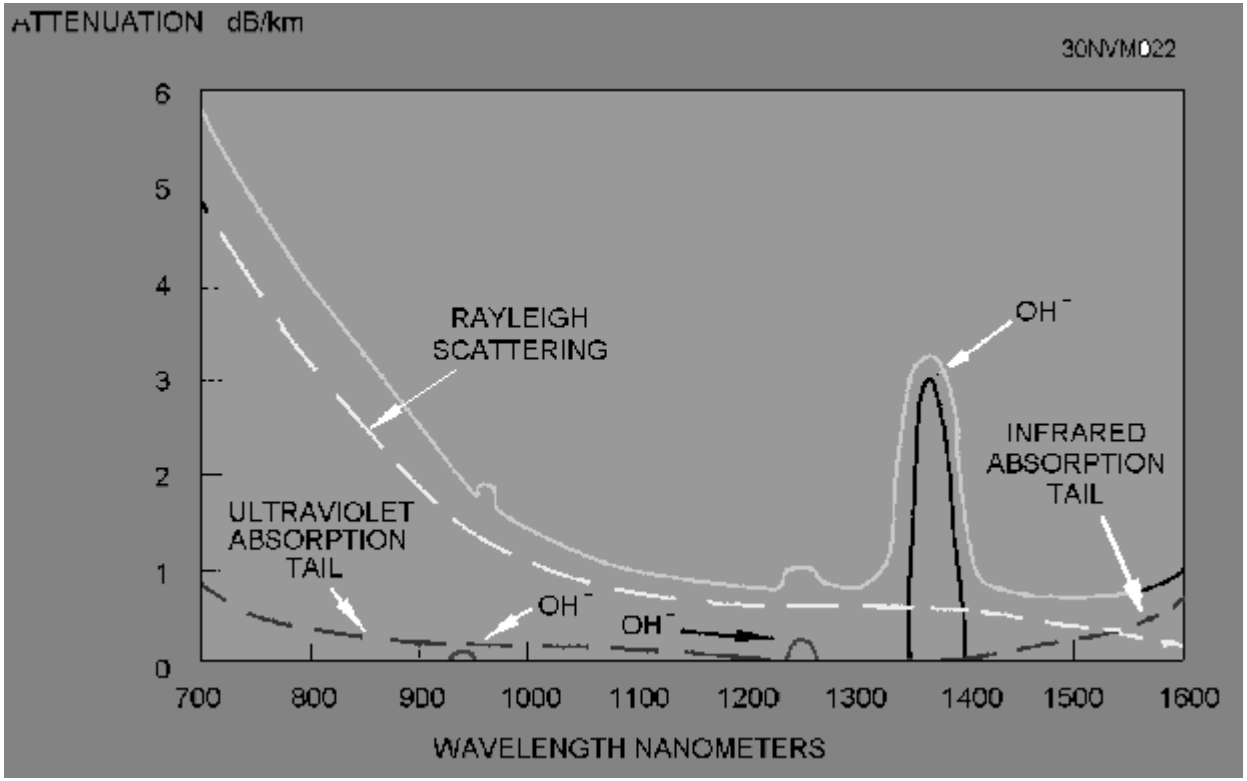
- The extrinsic (presence of impurities) fiber-material properties
  - OH radicals
  - transition metal ions

Dependence of the attenuation coefficient of silica glass on wavelengths



Scientific and Technological Education in Photonics

Silica glass (SiO_2) is strongly dependent on wavelength.



The main cause of **intrinsic absorption** in the infrared region is the characteristic vibration frequency of atomic bonds. In silica glass, absorption is caused by the vibration of silicon-oxygen (Si-O) bonds. The interaction between the vibrating bond and the electromagnetic field of the optical signal causes intrinsic absorption. Light energy is transferred from the electromagnetic field to the bond. The tail of the infrared absorption band is shown in figure.

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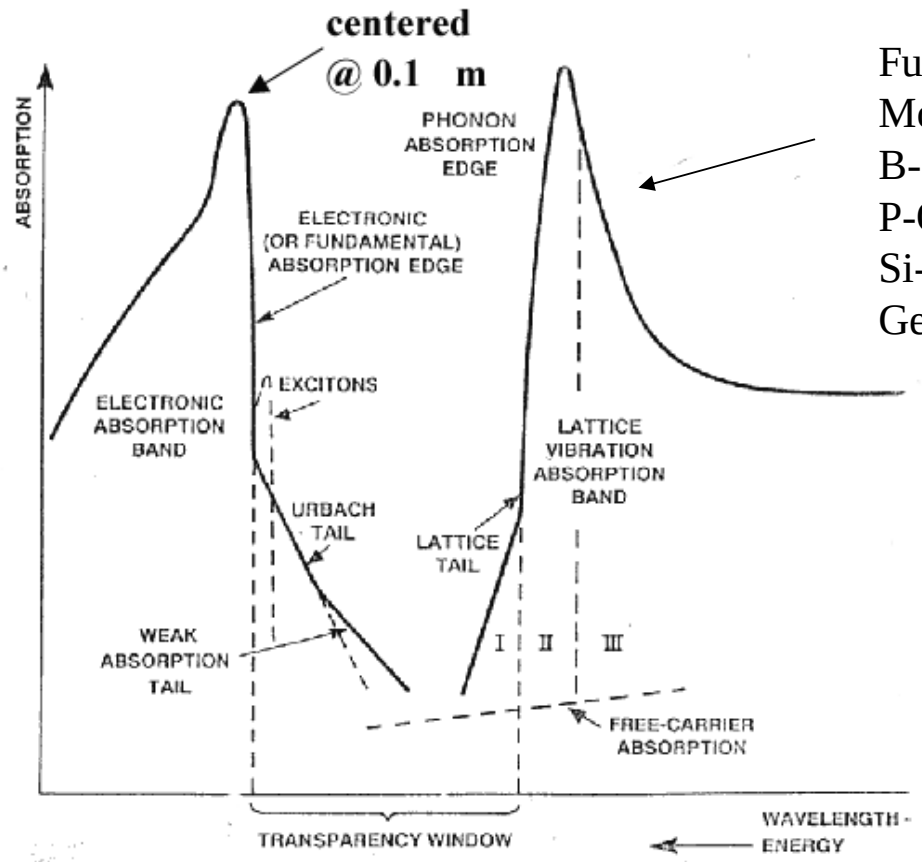
UV- electric transitions associated with bandgap in SiO_2
IR – molecules vibrations (phonons)



Fundamental
Molecular vibration
B-O 7.3 μm
P-O 8.0 μm
Si-O 9.0 μm
Ge-O 11.0 μm

UV and IR Absorption

Urbach Tail: GeO2 shifts to longer wavelength:

$\alpha_{uv} = (1.59/(47g+60))\ e^{4.6/\lambda}$

g= mole function =0.02 (GeO2) small @1.3μm
λ= wavelength in mm
α_{uv} => dB/km

$\alpha_{IR} = A\ e^{\alpha_{\cdot IR/\lambda}}$

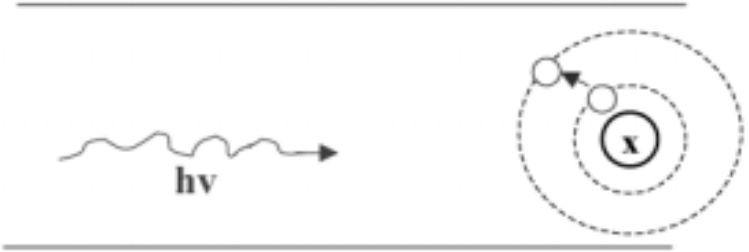
Where A = $8x10^{11}$ dB/km

$\alpha_{\cdot IR/\lambda v} = 48.5\mu m$

Extrinsic Absorption. - Extrinsic absorption is caused by impurities introduced into the fiber material. Trace metal impurities, such as iron, nickel, and chromium, are introduced into the fiber during fabrication. **Extrinsic absorption** is caused by the electronic transition of these metal ions from one energy level to another.
Extrinsic absorption also occurs when hydroxyl ions (OH^-) are introduced into the fiber. Water in silica glass forms a silicon-hydroxyl (Si-OH) bond. This bond has a fundamental absorption at 2700 nm. However, the harmonics or overtones of the fundamental absorption occur in the region of operation. These harmonics increase extrinsic absorption at 1383 nm, 1250 nm, and 950 nm. Last figure shows the presence of the three OH^- harmonics. The level of the OH^- harmonic absorption is also indicated. These absorption peaks define three regions or windows of preferred operation. The first window is centered at **850** nm. The second window is centered at **1300** nm. The third window is centered at **1550** nm. Fiber optic systems operate at wavelengths defined by one of these windows.
The amount of water (OH^-) impurities present in a fiber should be less than a few parts per billion. Fiber attenuation caused by extrinsic absorption is affected by the level of impurities (OH^-) present in the fiber. If the amount of impurities in a fiber is reduced, then fiber attenuation is reduced.

Impurity Absorption

Impurities absorb photons and then reradiate at different angles different 's.
Also phonon emission

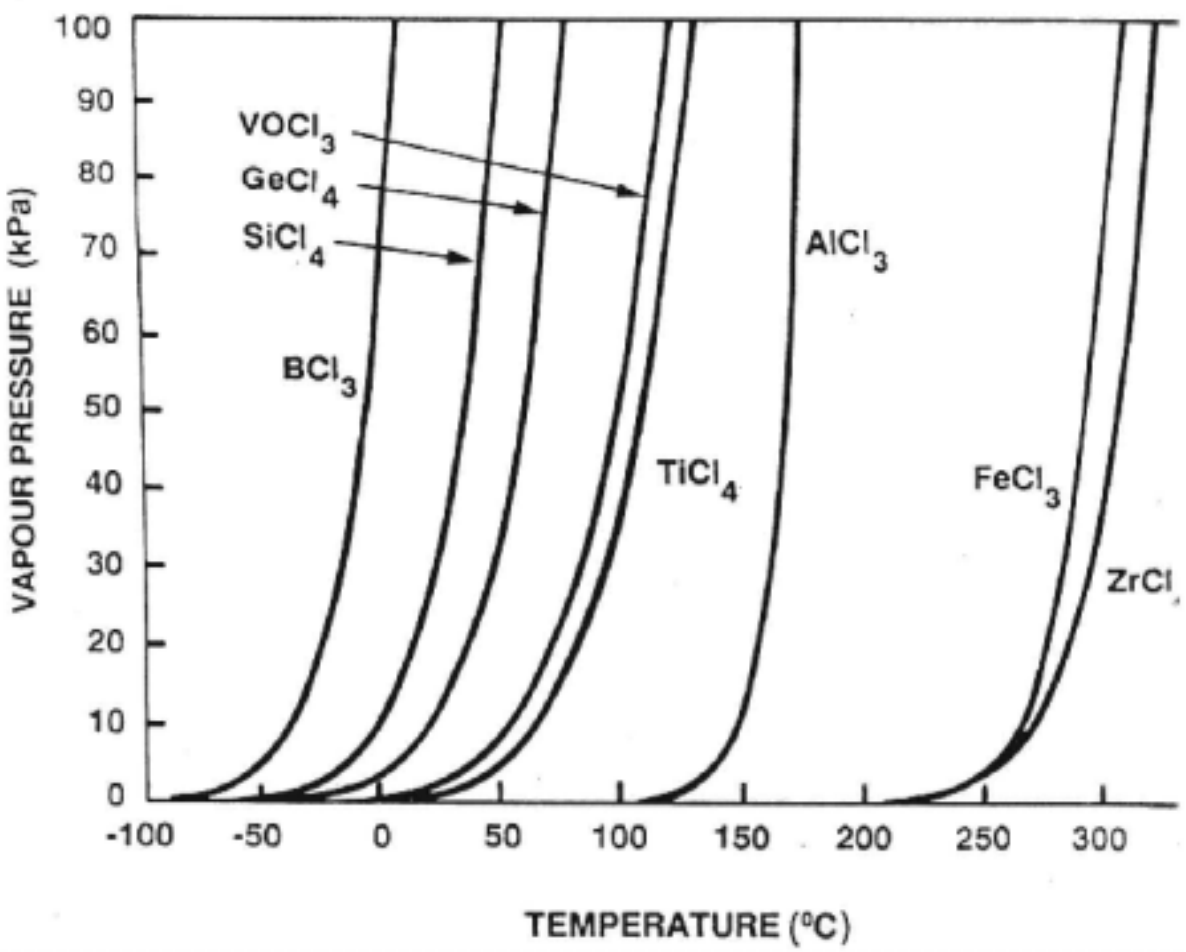


Need to make the glass very pure to minimize impurity absorption

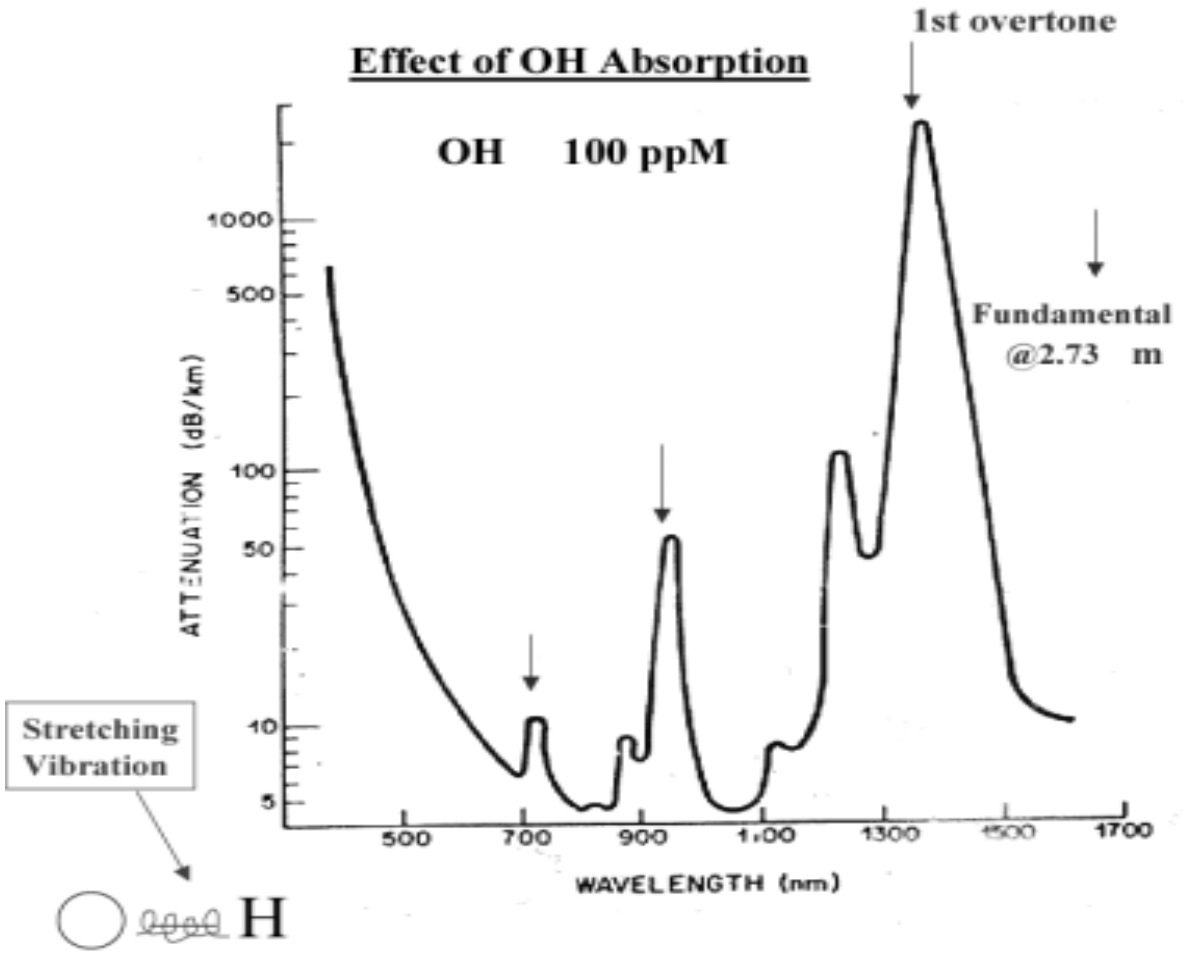
A. Transition Metal Ions

ION	Absorption Peak	Concentration (ppB)
Cu^{++}	0.8 m	0.45
Fe^{++}	1.1 m	0.4
Ni^{++}	0.65 m	0.2
V^{+++}	0.475 m	0.9
Cr^{+++}	0.675 m	0.4
Mn^{+++}	0.5 m	0.9

Cone required to keep an ion's contribution to <1dB/km.
Mid IR: Pr, Nd, Sm, Eu, Tb,Dy



These relative vapor pressures not only have reduced contamination to extremely low levels but have also led to glasses that are purer than the reagents used.



For 1pp Mw @ 1.38 μm
= 48 dB/km
@ 1.24 μm
= 2.5 dB/km
@1.6μm
α < 0.1dB/km

Addition of GeO_2 broadens peaks to long λ side (First overtone at 1.41 μ m).

Addition of P gives broad overtone in 1.5 μ m to 1.6 μ m range.

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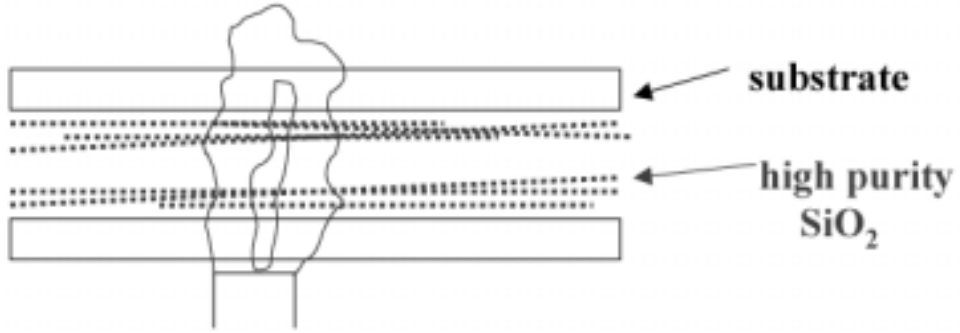
O-H ABSORPTION

Molecular vibration (stretching)

A concentration of 1 ppM => 1.25 dB/km
at $\lambda = 0.95\ \mu m$
(worse at $\lambda = 1.39\ \mu m$)

There are 2 sources of OH in fibers.

1. **Incorporation of hydrogenic impurities from the flowing gases during pre form formation solutions**
   a. **Adjust Cl to O_2 partial pressures to enhance HCl formation at expense of SiOH.**
   ***b. Chemical purification and leak tight delivery systems.**
2. **Thermal diffusion from the substrate**



Solution: Deposit low OH buffer before starting the core region.

Lucent → OFS Fitel AllWave Fiber

This is due to an OFS patented manufactur-ing process that *permanently* removes the water peak defect to ensure low and stable loss performance in the 1400 nm band and over the life-time of the cable. AllWave Zero Water Peak fiber offers the lowest loss of all commercial low water peak (LWP) fibers in the industry.

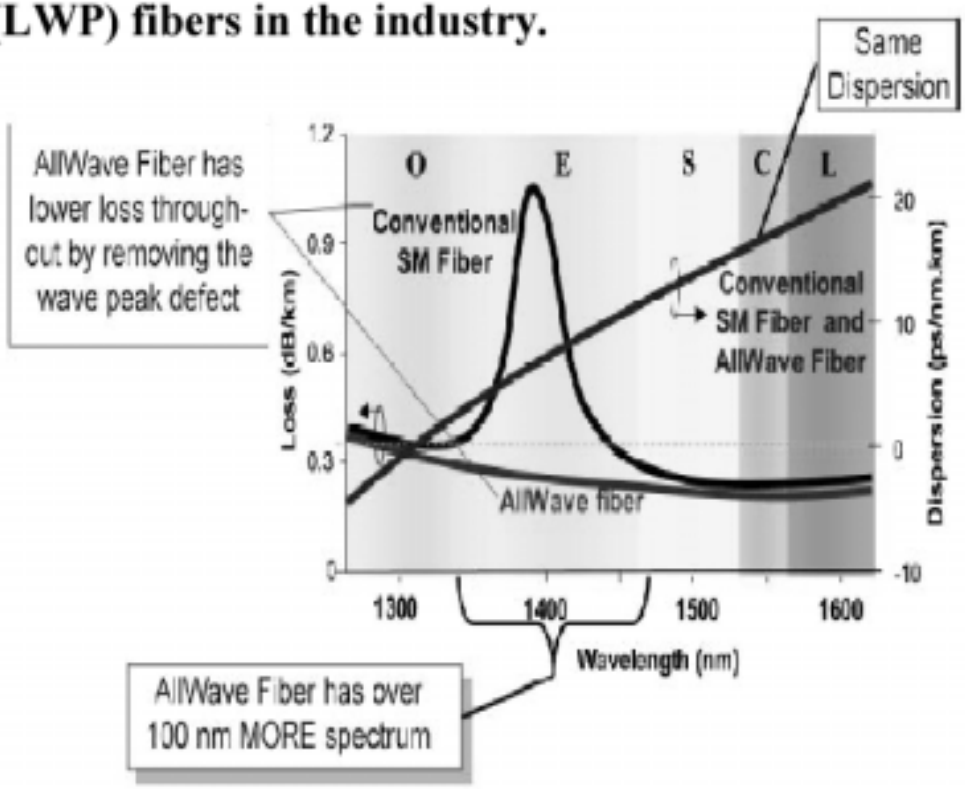


Figure 1. AllWave® Fiber- Compatible with Conventional Single-Mode fiber, but with More Available Spectrum

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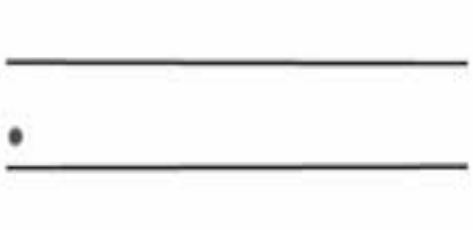
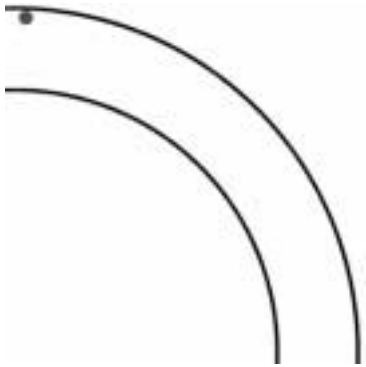
Radiation loss due to bending



straight



Small bend

Large bend

Radiation Loss (I)

To preserve the phase front, the tangential phase velocity must be proportional to the distance from the center of curvature.

$$(R + X_r)\frac{d\theta}{dt} = \frac{\omega}{\beta_0}$$

$$R\frac{d\theta}{dt} = \frac{\omega}{\beta_z}$$

$$X_r = \frac{\beta_z - \beta_0}{\beta_0} R$$

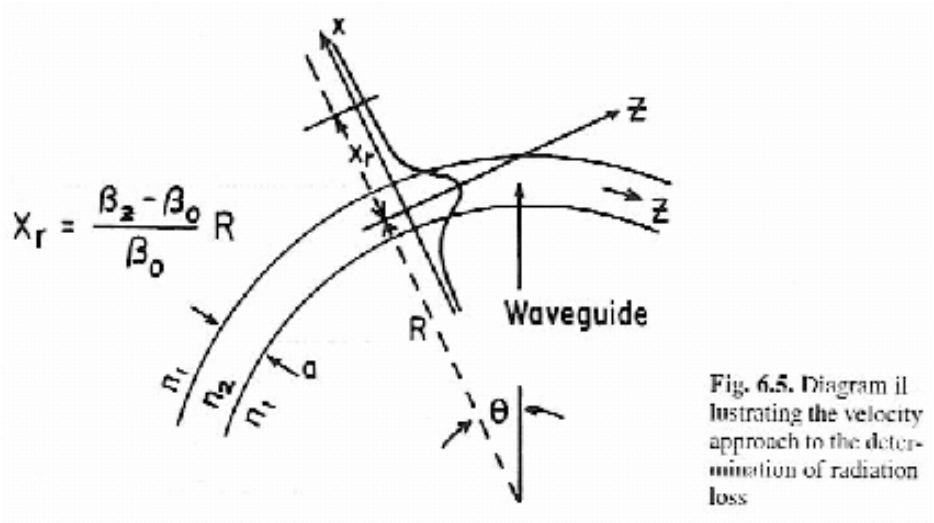


Fig. 6.5. Diagram illustrating the velocity approach to the determination of radiation loss

How far must the photons travel before they can be considered as having been removed from the guided mode?

Coherent length:

$$Z_c = \frac{a}{\phi} \sim \frac{a^2}{2\lambda_1}$$

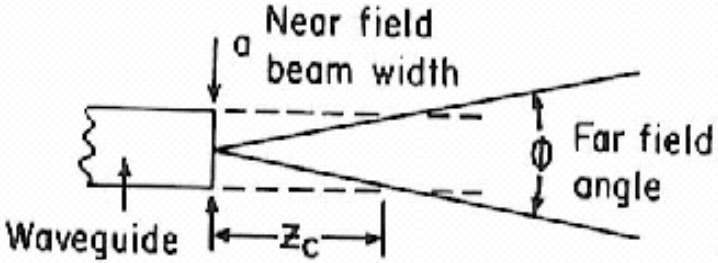


Fig. 6.6. Spread of light emitted from a truncated waveguide

Radiation Loss (II)

$$\alpha = -\frac{1}{P(z)}\frac{dP(z)}{dz} \sim \frac{1}{P_t}\frac{P_1}{Z_c}$$

P_1: Power in the tail of the mode beyond X_r (i.e., the power to be lost by radiation within a length Z_c)
P_t: Total power

$$E(x) = E_0 \cos(hx) \qquad \text{for } -\frac{a}{2} \le x \le \frac{a}{2}$$

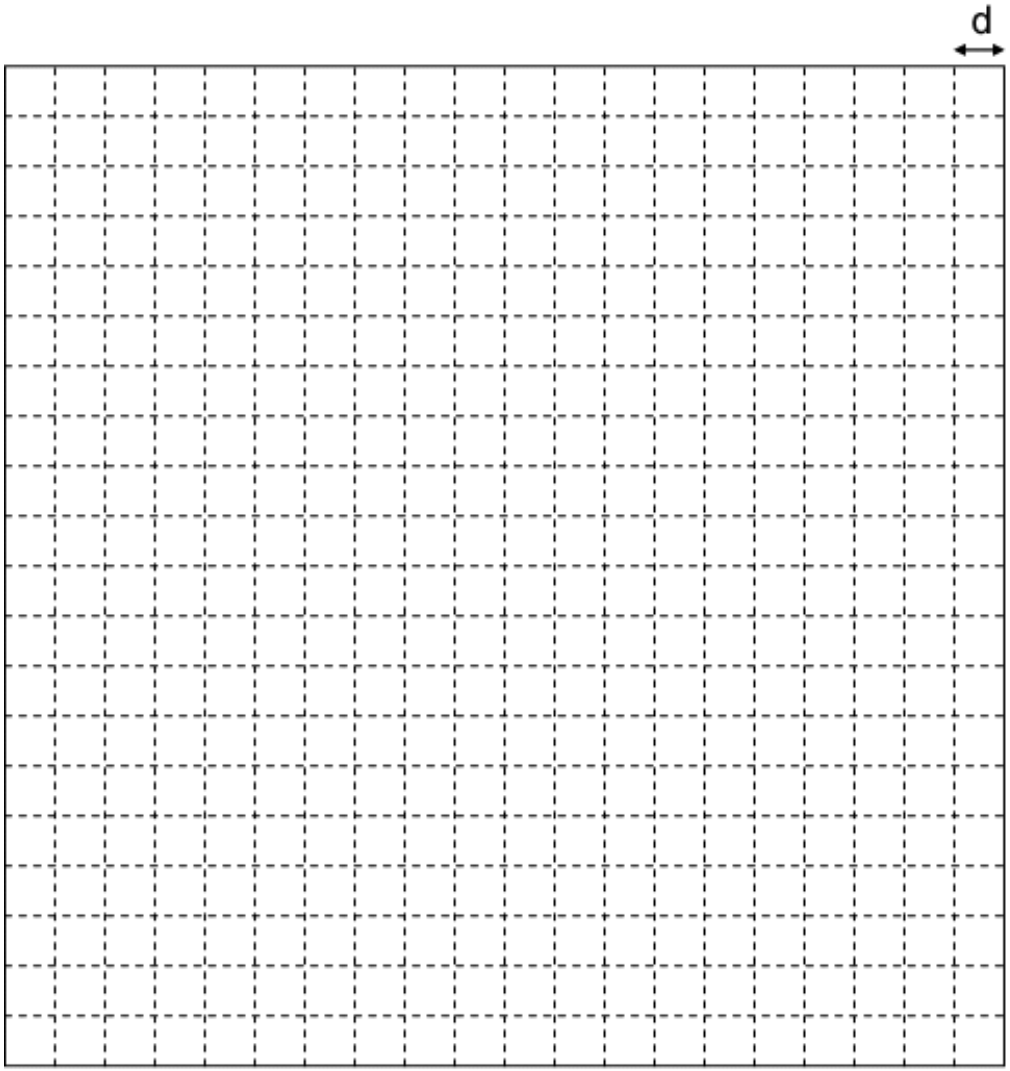
$$E(x) = E_0 \cos(h\frac{a}{2}) \exp[-\frac{|x| - (a/2)}{\gamma}] \text{ for } |x| \ge \frac{a}{2}$$

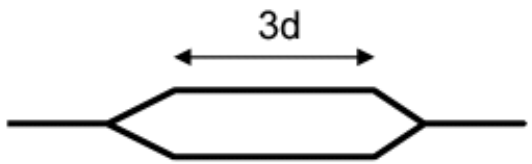
$$\frac{\gamma \cos^2(\frac{ha}{2}) \exp\left(\frac{2}{\gamma}\frac{\beta_z - \beta_0}{\beta_0} R\right) \exp\left(\frac{a}{\gamma}\right) \lambda_1}{\left(\frac{a}{2} + \frac{1}{2h}\sin(ha) + \gamma \cos^2(\frac{ha}{2})\right) a^2} = C_1 \exp(-C_2 R)$$

Table 6.2. Waveguide radiation loss data [6.24, 6.25]

Case	Index of refraction		Width a	C_1	C_2	R
	Waveguide	surrounding	[μm]	[dB/cm]	[cm^{-1}]	for $\alpha = 0.1$ dB/cm
1	1.5	1.00	0.198	2.23×10^5	3.47×10^4	4.21 μm
2	1.5	1.485	1.04	9.03×10^3	1.46×10^2	0.78 mm
3	1.5	1.4985	1.18	4.69×10^2	0.814	10.4 cm

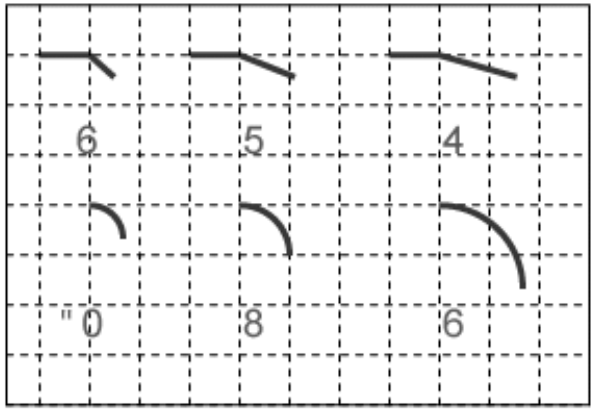
Let's pack 16 stages of modulators





Scattering and absorption loss: " unit per d

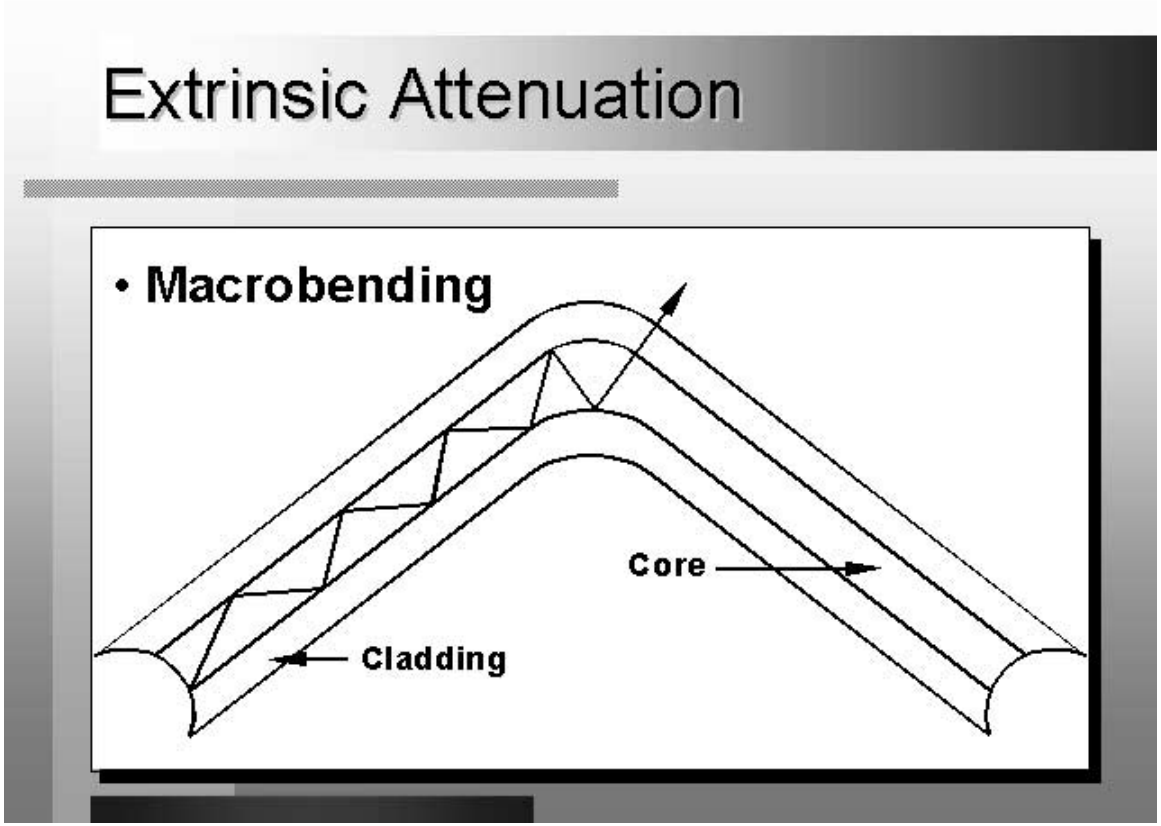
Radiation loss (in units):



Constraints:

- Spacing between waveguides at least d
- Input and output cannot be on the same side

What's the loss you obtain?



Extrinsic attenuation can be controlled by the cable installer

Macrobend loss

Radiation attenuation coefficient is

$$\alpha_t = c_1 exp\ (-c_2 R)$$

Where R is radius of curvature, c_1 *and* c_2 *are constants independent of R*

Large bending loss tends to occurs at critical radius R_c

$$R_c \sim 3n_1^2 \lambda / (4\pi (n_1^2 - n_2^2)^{3/2})$$

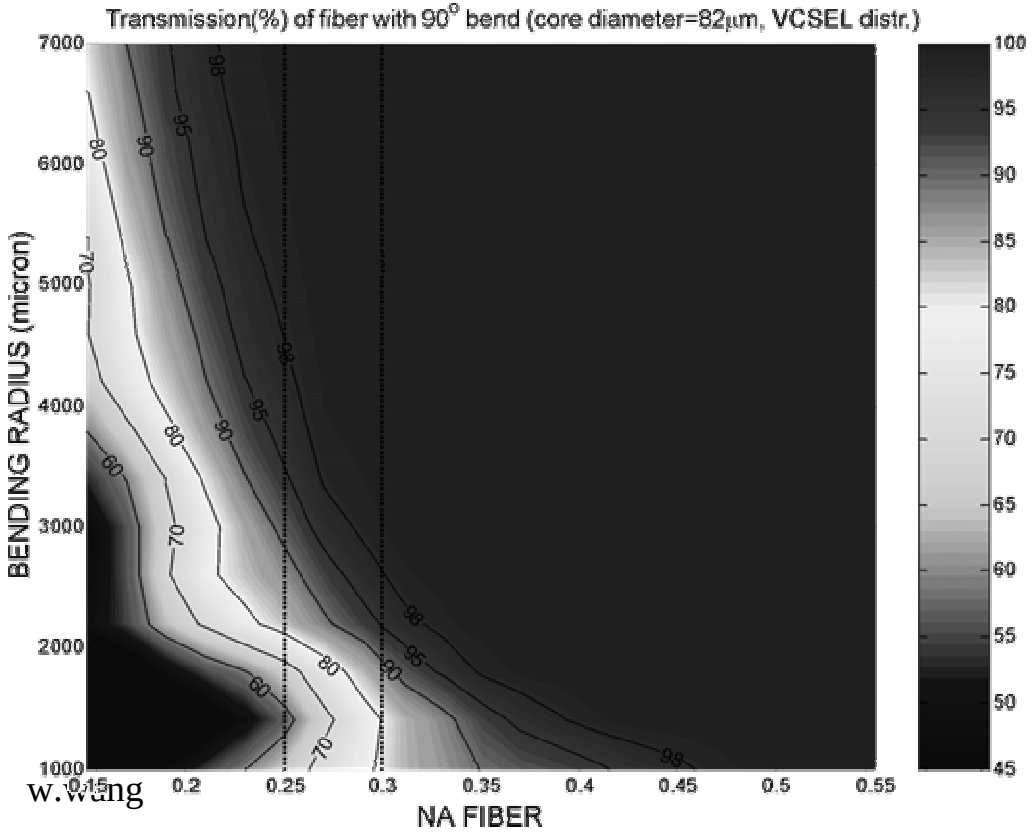
Loss maybe reduced by

-large relative refractive index difference

-Operating at shortest wavelength possible

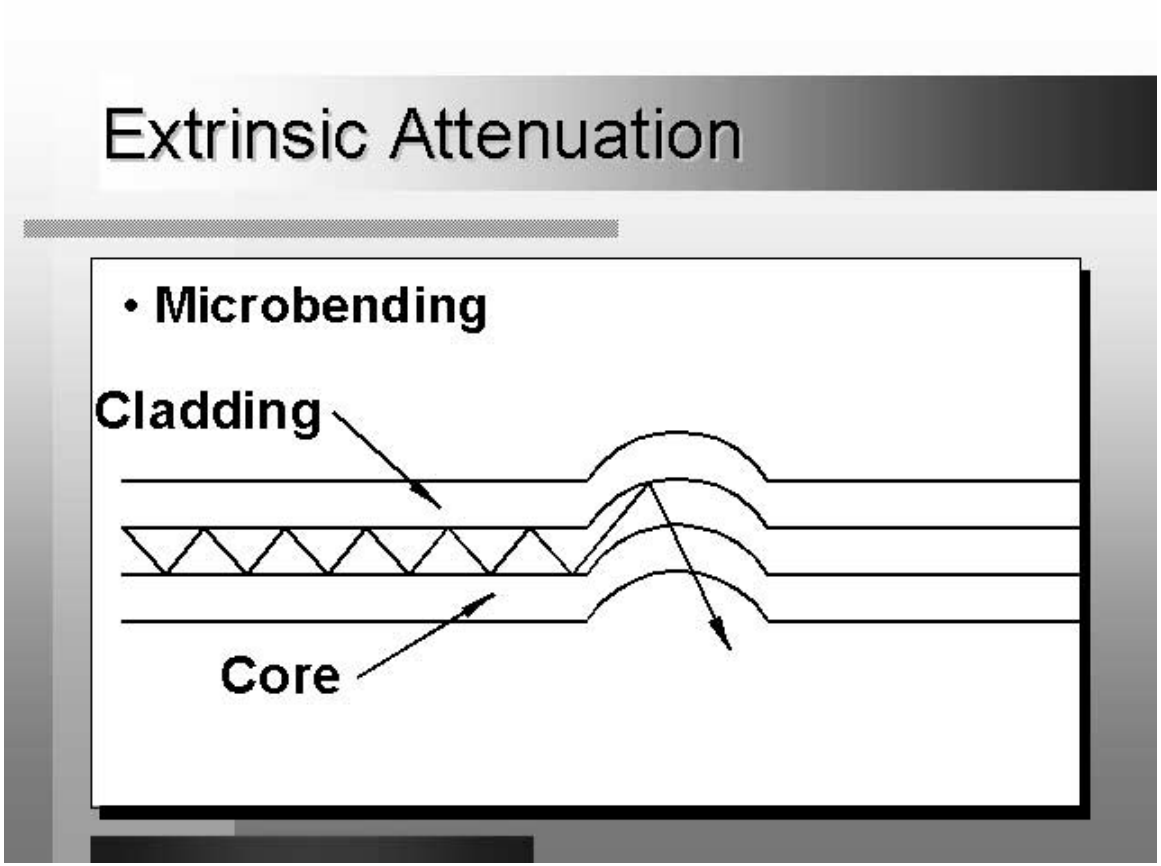
Fiber bend losses

- Bend losses can be approximated using a combination of raytracing results (H. Lambrecht, et.al.)
- Validation through optical path measurements



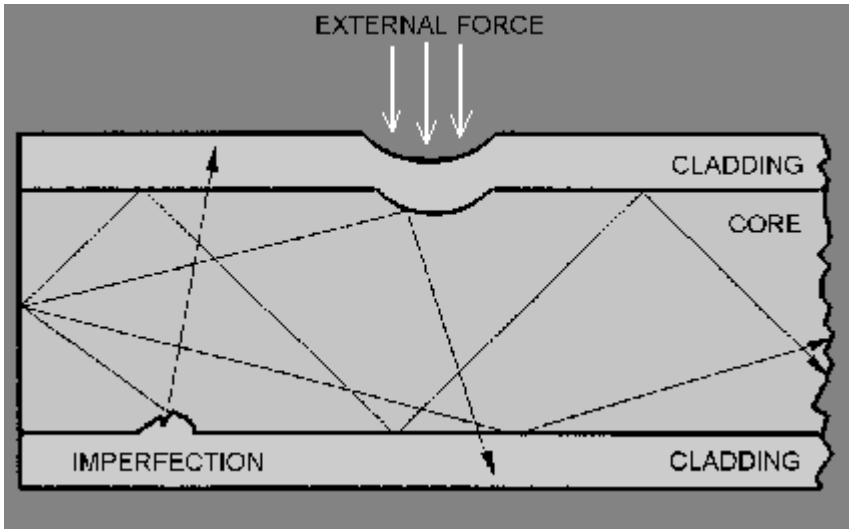
90° bend
X axis: NA fiber
Y axis: bending radius
Blue color = high losses

(source: H. Lambrecht)



- Microbends may not be visible with the naked eye
- Microbends may be:
  - bend related
  - temperature related
  - tensile related
  - crush related

Microbend Loss



Microbends are caused by small discontinuities or imperfections in the fiber. Uneven coating applications and improper cabling procedures increase microbend loss. External forces are also a source of microbends. An external force deforms the cabled jacket surrounding the fiber but causes only a small bend in the fiber. Microbends change the path that propagating modes take, as shown in figure. **Microbend loss** increases attenuation because low-order modes become coupled with high-order modes that are naturally lossy.

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Measurement of Waveguide Losses

End-Fire Coupling to Waveguides of Different Lengths

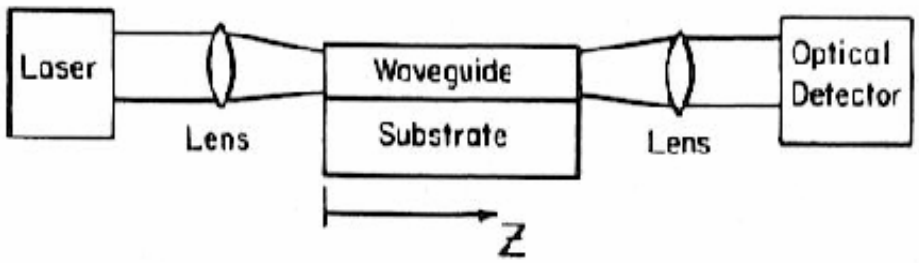


Fig. 6.7. Experimental set-up for measurement of waveguide attenuation employing end-fire coupling

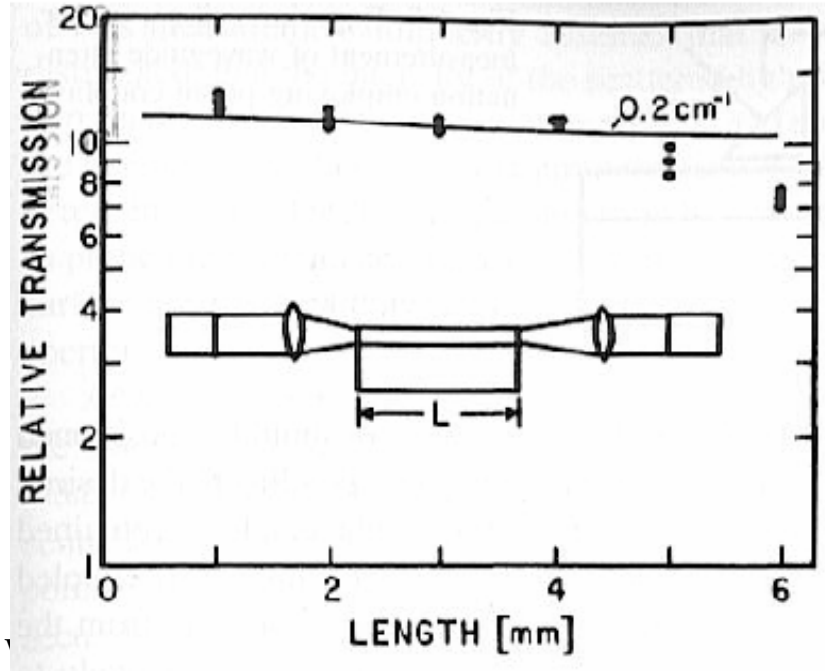


Fig. 6.8. Typical attenuation data. (These data were obtained using the set-up of Fig. 6.7 to measure loss in a Ti diffused waveguide in $LiNbO_3$)

$$\alpha = \frac{\ln(P_1 / P_2)}{Z_2 - Z_1}$$

Cleaving the waveguide

Measurement of Waveguide Losses

Prism-Coupled Loss Measurement

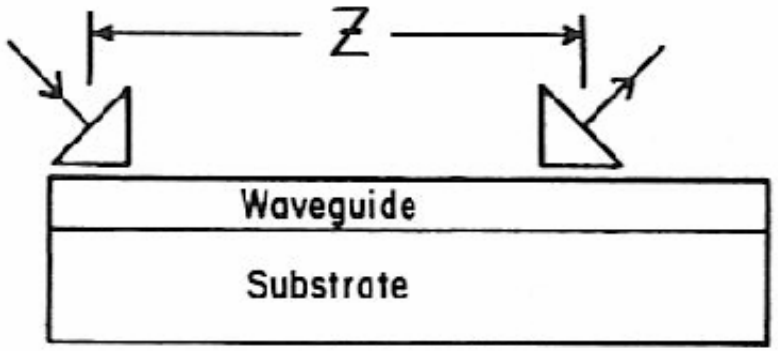


Fig. 6.9. Experimental set-up for measurement of waveguide attenuation employing prism coupling

Measure only overall light loss

Advantages:

- **Non-destructive.**
- **Light can be selectively coupled into each mode by properly choosing the angle of incidence.**

Dispersion

Pollack "Fundamentals of Optoelectronics"

Most optical communication systems utilize pulse modulation and direct detection.

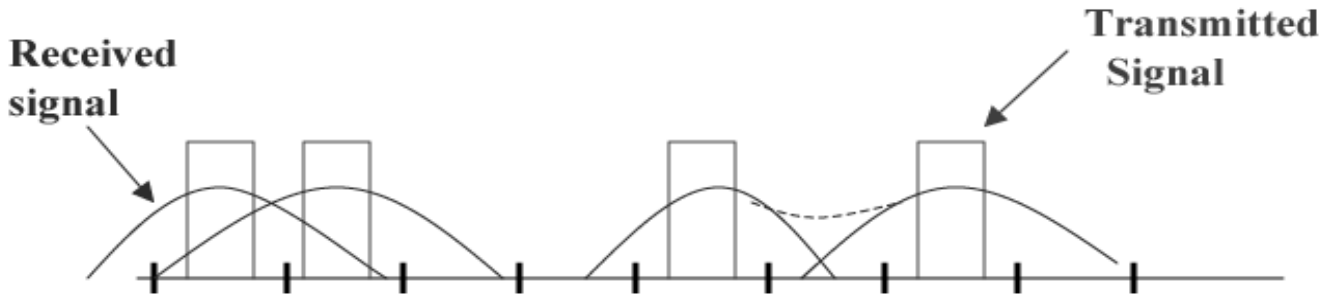
(1) Signals are transmitted in digital format where a light pulse is a "1" and "no light" is a "0".

(2) The receiver looks at each slot and determines whether a "1" or "0" was transmitted. This is achieved with a decision circuit.

(3) If we only have to deal with attenuation, the decisions are determined solely by noise.

Simply move decision level as low as noise permits.

Problem: **Dispersion causes pulses to broaden.**



This pulse broadening can lead to errors

Reduction in distance before signal is reconstructed and retransmitted

More repeaters

Higher cost

Sources of Dispersion

Modal Dispersion (Intermodal)

↓

Present in multimode waveguides

Chromatic Dispersion (Intra-modal)

↓

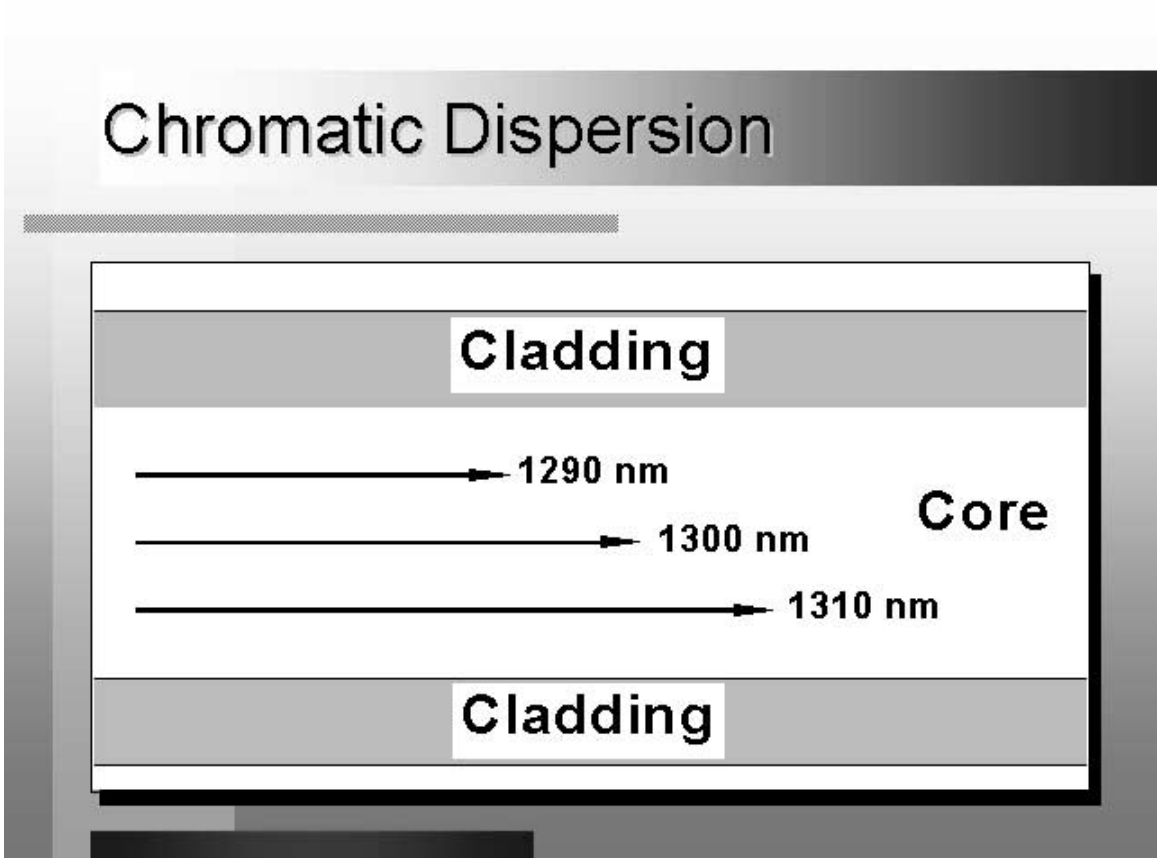
1. Material dispersion
2. Waveguide dispersion

Chromatic (Intramodal) Dispersion

Intramodal, or chromatic, dispersion depends primarily on fiber materials. There are two types of intramodal dispersion:

- Material dispersion
- Waveguide dispersion.

Dispersion occurs in all types of fibers



- Index of refraction is a function of wavelength n(λ)
- Since light velocity is a function of index of refraction
  - light velocity in a given medium is a function of wavelength

Light pulses at different wavelengths will have different propagation times

Material Dispersion

We noted that the velocity of light in a medium is given by

$$v = c/n(\lambda)$$

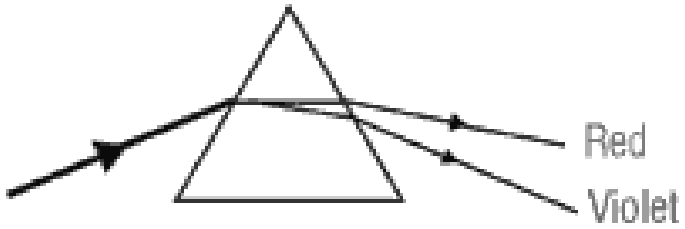
Here n is the refractive index of the medium, which, in general, depends on the wavelength. The dependence of the refractive index on wavelength leads to what is known as *dispersion*

Now, the quantity v defined by above equation is usually referred to as the *phase velocity*. However, a pulse travels with what is known as the *group velocity*, which is given by

$$v_g = c/n_g(\lambda)$$

where n_g is known as the group index and, in most cases its value is slightly larger than n.

Material Dispersion



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Dispersion of white light as it passes through a prism

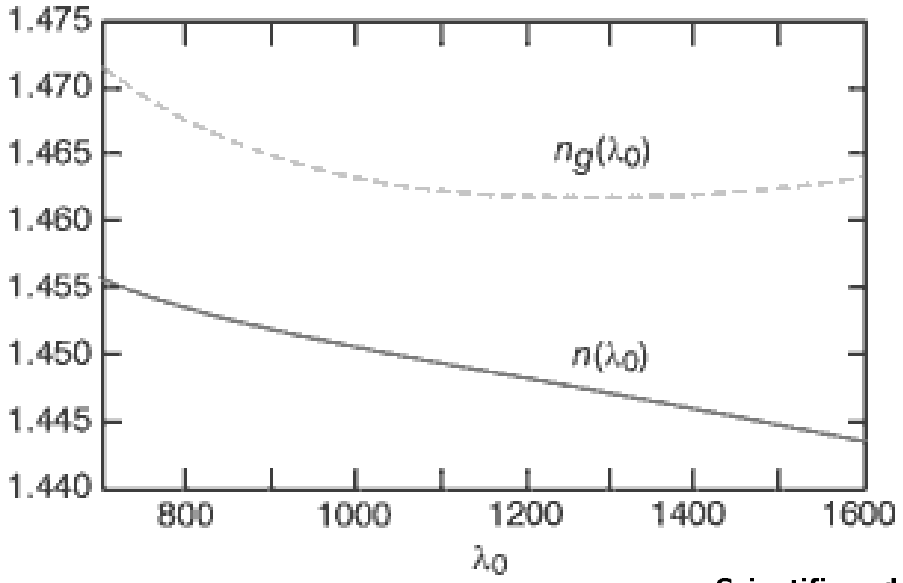
For example, for crown glass the refractive indices at 656.3 nm (orange), 589.0 nm (yellow), and 486.1 nm (green) are respectively given by 1.5244, 1.5270, and 1.5330. Thus, if the angle of incidence $i = 45^{\circ}$ the angle of refraction, r, will be $r = 27.64°$, 27.58°, and 27.47° for the orange, yellow, and blue colors respectively.

group index (n_g): for a given mode propagating in a medium of refractive index n , the velocity of light in vacuum, c, divided by the group velocity of the mode. *Note:* For a plane wave of wavelength , the group index may also be expressed,

$$n_g = n - \lambda(dn/d\lambda)$$

where *n* is the phase index of wavelength , n_g is value is slightly larger than *n*.

Material Dispersion



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Variation of n and n_g with wavelength for pure silica. Notice that n_g has a minimum value of around 1270 nm

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Material Dispersion

Material dispersion occurs because the spreading of a light pulse is dependent on the wavelengths' interaction with the refractive index of the waveguide core,

$$\tau_m = D_m \times L \times \Delta\lambda$$

Where D_m represents the material dispersion in picoseconds per kilometer length of the fiber per nanometer spectral width of the source

Different wavelengths travel at different speeds in the fwaveguide material. Different wavelengths of a light pulse that enter a waveguide at one time exit the waveguide at different times. Material dispersion is a function of the source spectral width. The spectral width specifies the range of wavelengths that can propagate in the waveguide. Material dispersion is less at longer wavelengths.

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λ_0 (nm)	n (λ_0)	n_g (λ_0)	D_m (ps/nm-km)
700	1.45561	1.47154	–172.902
750	1.45456	1.46924	–135.313
800	1.45364	1.46744	–106.609
850	1.45282	1.46601	–84.2077
900	1.45208	1.46489	–66.382
950	1.45139	1.46401	–51.9441
1000	1.45075	1.46332	–40.0577
1050	1.45013	1.46279	–30.1214
1100	1.44954	1.46241	–21.6951
1150	1.44896	1.46214	–14.4511
1200	1.44839	1.46197	–8.14213
1250	1.44783	1.46189	–2.57872
1300	1.44726	1.46189	2.38579
1350	1.44670	1.46196	6.86631
1400	1.44613	1.46209	10.9539
1450	1.44556	1.46229	14.7211
1500	1.44498	1.46253	18.2268
1550	1.44439	1.46283	21.5187
1600	1.44379	1.46318	24.6358

Values of n, n_g, and D_m for pure silica for different values of wavelength lying between 700 nm and 1600 nm

Examples

The LEDs used in early optical communication systems had a spectral width $\Delta\lambda_0$ of about 20 nm around $\lambda_0 = 825$ nm. Using D_m in Table (at 850 nm), such a pulse will broaden by

$$\tau_m = D_m \times L \times \Delta\lambda = 84.2 \text{ (ps/km-nm)} \times 1 \text{ (km)} \times 20 \text{ (nm)} \sim 1700 \text{ ps} = 1.7 \text{ ns}$$

in traversing a 1-km length of the fiber. It is very interesting to note that, if we carry out a similar calculation around $\lambda_0 \approx 1300$ nm, we will obtain a much smaller value of τ_m; thus

$$\tau_m = D_m \times L \times \Delta\lambda = 2.4 \text{ (ps/km-nm)} \times 1 \text{ (km)} \times 20 \text{ (nm)} \sim 0.05 \text{ ns}$$

in traversing 1-km length of the fiber. The very small value of τ_m is due to the fact that n_g is approximately constant around $\lambda_0 = 1300$ nm. Indeed, the wavelength $\lambda_0 \approx 1270$ nm is usually referred to as the zero material dispersion wavelength, and it is because of such low material dispersion that the optical communication systems shifted their operation to around $\lambda_0 \approx 1300$ nm.

In the optical communication systems that are in operation today, one uses laser diodes (LD) with $\lambda_0 \approx 1550$ nm having a spectral width of about 2 nm. Thus, for a 1-km length of the fiber, the material dispersion τ_m becomes

$$\tau_m = D_m \times L \times \Delta\lambda = 21.5 \text{ (ps/km-nm)} \times 1 \text{ (km)} \times 2 \text{ (nm)} \sim 43 \text{ ps}$$

the positive sign indicating that higher wavelengths travel more slowly than lower wavelengths. [Notice from Table that, for $\lambda_0 \geq 1300$ nm, n_g increases with λ_0.]

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Waveguide Dispersion

Waveguide dispersion occurs because the mode propagation constant (β) is a function of the size of the fiber's core relative to the wavelength of operation. Waveguide dispersion also occurs because light propagates differently in the core than in the cladding.

- In multimode fibers, waveguide dispersion and material dispersion are basically separate properties. Multimode waveguide dispersion is generally small compared to material dispersion. Waveguide dispersion is usually neglected.

- However, in single mode fibers, material and waveguide dispersion are interrelated.

- The total dispersion present in single mode fibers may be minimized by trading material and waveguide properties depending on the wavelength of operation.

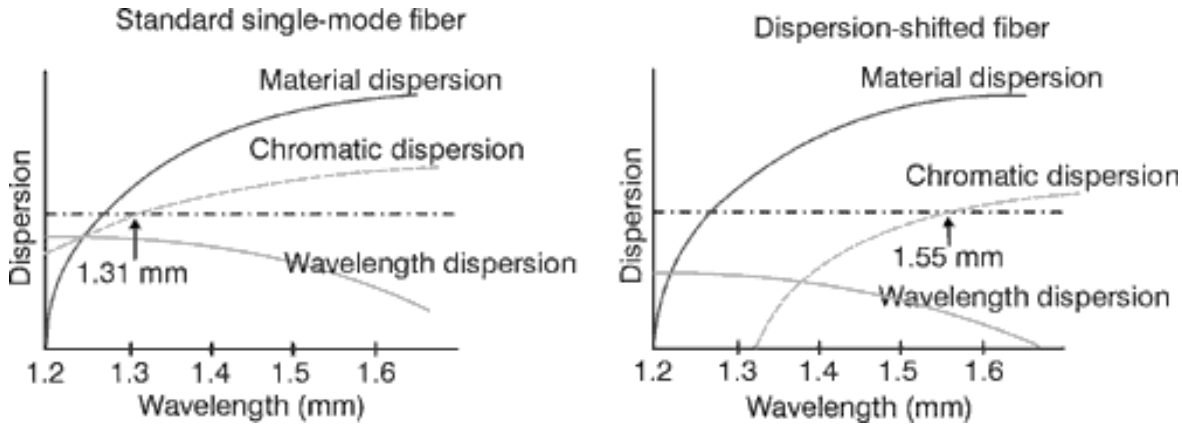
Waveguide Dispersion

we discussed material dispersion that results from the dependence of the refractive index of the fiber on wavelength. Even if we assume the refractive indices n_1 and n_2 to be independent of λ_0, the group velocity of each mode *does* depend on the wavelength. This leads to what is known as *waveguide dispersion*. The detailed theory is rather involved [see, e.g., Chapter 10, Ghatak and Thyagarajan]; we may mention here two important points:

1. The waveguide dispersion is usually negative for a given single-mode fiber. The magnitude increases with an increase in wavelength.

2. If the core radius a (of a single-mode fiber) is made smaller and the value of Δ is made larger, the magnitude of the waveguide dispersion increases. Thus we can tailor the waveguide dispersion by changing the refractive index profile.

We consider the fiber for which $n_2 = 1.447$, $\Delta = 0.003$, and $a = 4.2\ \mu m$. The variations of the waveguide dispersion (τ_w), material dispersion (τ_m), and total dispersion ($\tau_{tot} = \tau_w + \tau_m$) with λ_0 are shown in Figure below. From the figure it can be seen that the total dispersion passes through zero around $\lambda_0 \approx 1300$ nm. This is known as *zero total-dispersion wavelength* and represents an extremely important parameter.



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The variations of τ_m, τ_w, and τ_{tot} with λ_0 for a typical conventional single-mode fiber (CSF) with parameters given in above Example. The total dispersion passes through zero at around $\lambda_0 \approx 1300$ nm, known as zero total dispersion wavelength.

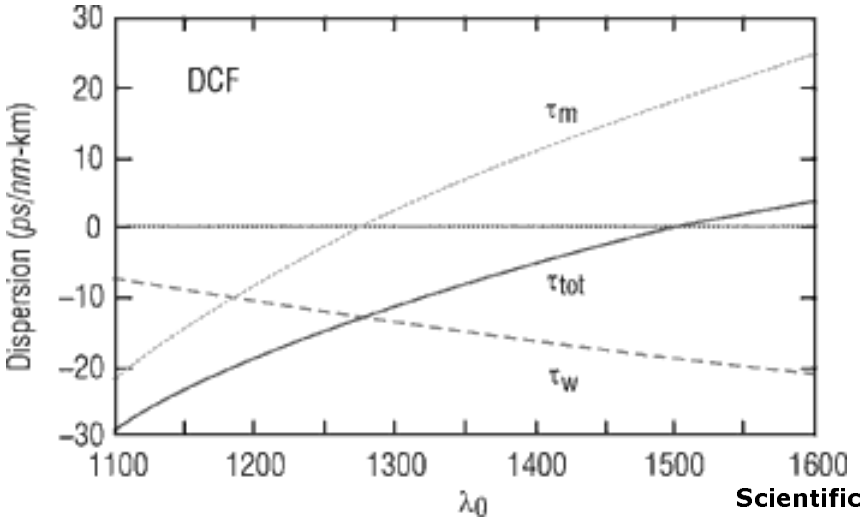
We next consider the fiber for which $n_2 = 1.444$, $\Delta = 0.0075$, and $a = 2.3$ μm. For this fiber, at $\lambda_0 \approx 1550$ nm,

$$\tau_w = -20 \text{ ps/km-nm}$$

On the other hand, the material dispersion at this wavelength—per km and per unit wavelength interval in nm—is given by Table as

`

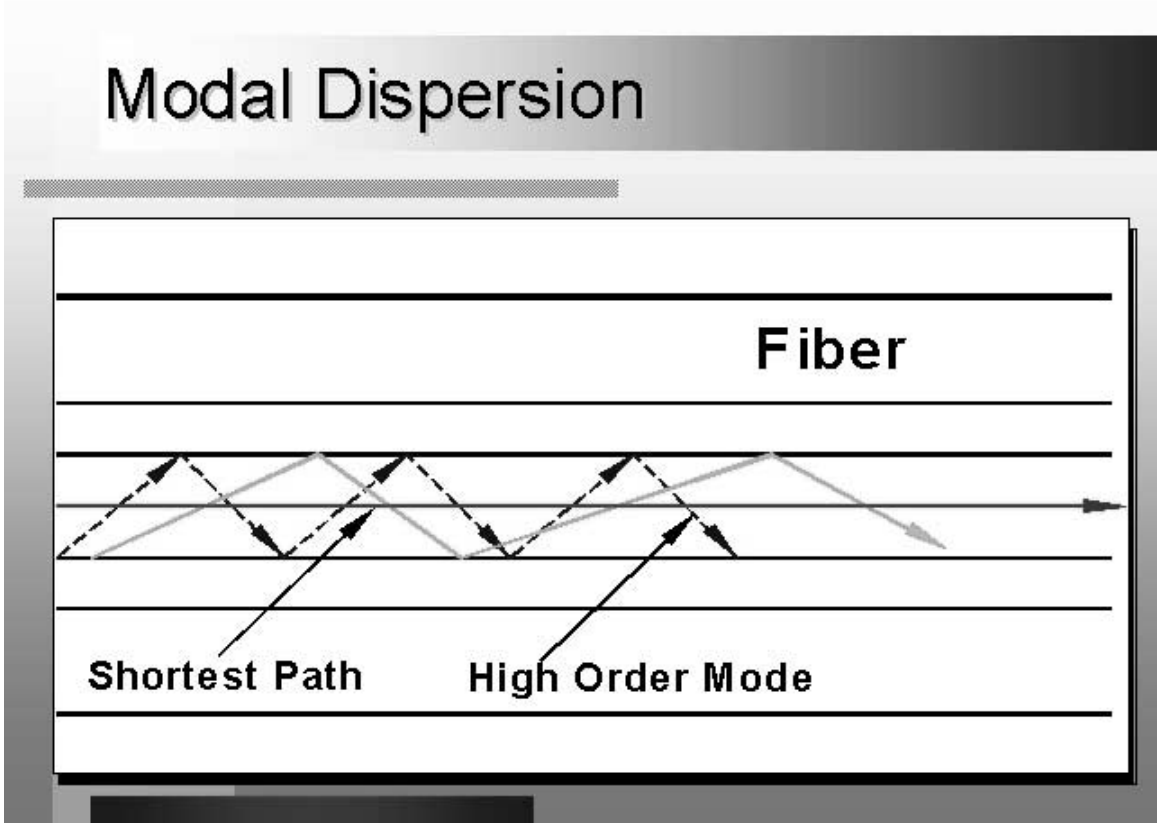
$$D_m = \tau_m = +21 \text{ ps/km-nm}$$



The variations of τ_m, τ_w, and τ_{tot} with λ_0 for a typical dispersion-shifted single-mode fiber (DSF) with parameters given. The total dispersion passes through zero at around $\lambda_0 \approx 1550$ nm.

Dispersion Shift Fibers

Since the lowest loss lies at around $\lambda_0 \approx 1550$ nm, if the zero-dispersion wavelength could be shifted to the $\lambda_0 \approx 1550$-nm region, one could have both minimum loss and very low dispersion. This would lead to very-high-bandwidth systems with very long (~ 100 km) repeater spacings. Apart from this, extremely efficient optical fiber amplifiers capable of amplifying optical signals in the 1550-nm band have also been developed. Thus, shifting the operating wavelength from 1310 nm to 1550 nm would be very advantageous. By reducing the core size and increasing the value of Δ, we can shift the zero-dispersion wavelength to 1550 nm, which represents the low-loss window. Indeed, the current fourth-generation optical communication systems operate at 1550 nm, using dispersion-shifted single-mode fibers with repeater spacing of about 100 km, carrying about 10 Gbit/s of information (equivalent to about 150,000 telephone channels) through one hair-thin single-mode fiber.



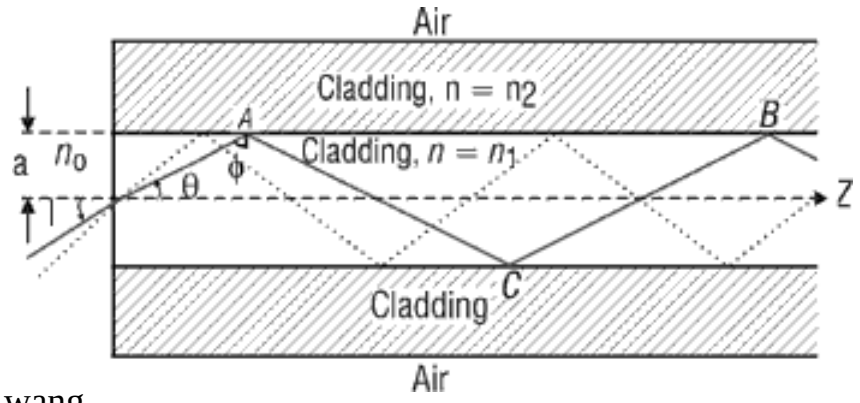
Various modes follow different paths causing pulse broadening

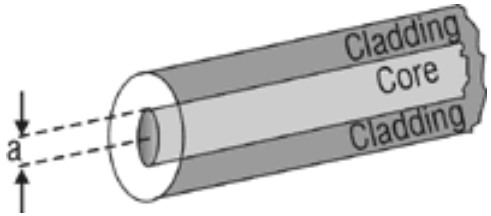
Intermodal Dispersion

For a ray making an angle θ with the axis, the distance *AB* is traversed in time.

$$t_{AB} = \frac{AC + CB}{c / n_1} = \frac{AB / \cos\theta}{c / n_1}$$

$$t_{AB} = \frac{n_{1(AB)}}{c \cos\theta}$$





Intermodal Dispersion

Since the ray path will repeat itself, the time taken by a ray to traverse a length L of the fiber would be

$$t_L = \frac{n_1 L}{c \cos\theta}$$

The above expression shows that the time taken by a ray is a function of the angle θ made by the ray with the *z*-axis (fiber axis), which leads to pulse dispersion.

Intermodal Dispersion

If we assume that all rays lying between $\theta = 0$ and $\theta = \theta_c = \cos^{-1}(n_2/n_1)$, the time taken by the following extreme rays for a fiber of length L would be given by

$$\tau_i = t_{max} - t_{min} = \frac{n_1 L}{c}\left[\frac{n_1}{n_2} - 1\right]$$

corresponding to rays at $\theta = 0$

$$t_{min} = \frac{n_1 L}{c}$$

corresponding to rays at $\theta = \theta_c = \cos^{-1}(n_2/n_1)$

$$t_{max} = \frac{n_1^2 L}{c n_2}$$

Hence, if all the input rays were excited simultaneously, the rays would occupy a time interval at the output end of duration. or, finally, the intermodal dispersion in a multimode Step index fiber (SIF) is

$$\tau_i \cong \frac{n_1 L}{c}\Delta \approx \frac{L}{2 n_1 c}(NA)^2$$

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Assignment

For a typical (multimode) step-index fiber, if we assume $n_1 = 1.5$, $\Delta = 0.01$, $L = 1$ km, we would get

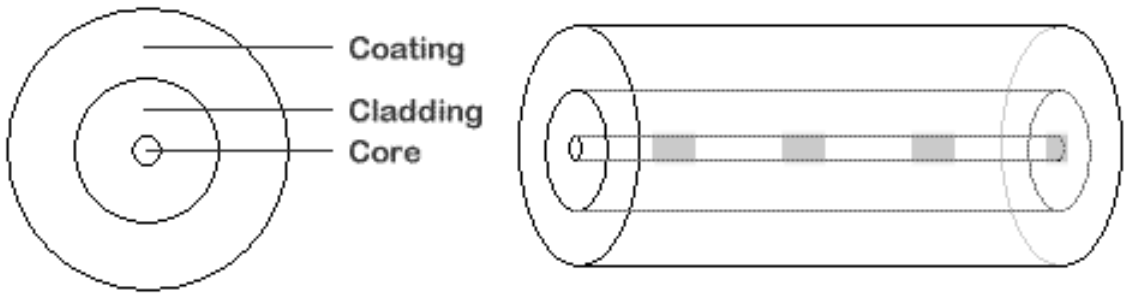
$$\tau_1 = \frac{1.5 \times 1000}{3 \times 10^8} \times 0.01 = 50 \text{ ns/km}$$

That is, a pulse traversing through the fiber of length 1 km will be broadened by 50 ns. Thus, two pulses separated by, say, 500 ns at the input end will be quite resolvable at the end of 1 km of the fiber. However, if consecutive pulses were separated by, say, 10 ns at the input end, they would be absolutely unresolvable at the output end. Hence, in a 1-Mbit/s fiber optic system, where we have one pulse every 10^{-6} s, a 50-ns/km dispersion would require repeaters to be placed every 3 to 4 km. On the other hand, in a 1-Gbit/s fiber optic communication system, which requires the transmission of one pulse every 10^{-9} s, a dispersion of 50 ns/km would result in intolerable broadening even within 50 meters or so. This would be highly inefficient and uneconomical from a system point of view.

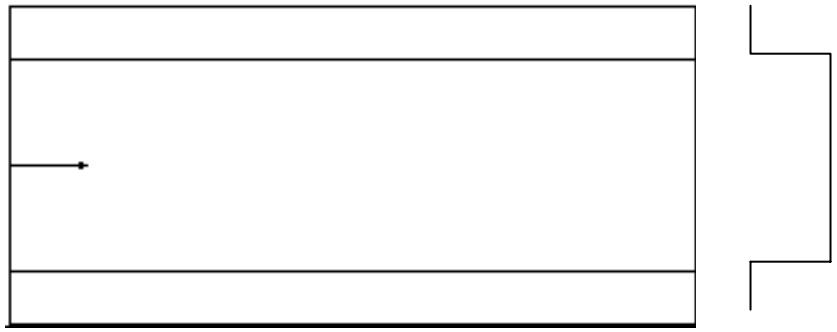
Fiber types

Single mode fiber

Multimode fiber



Step index fiber



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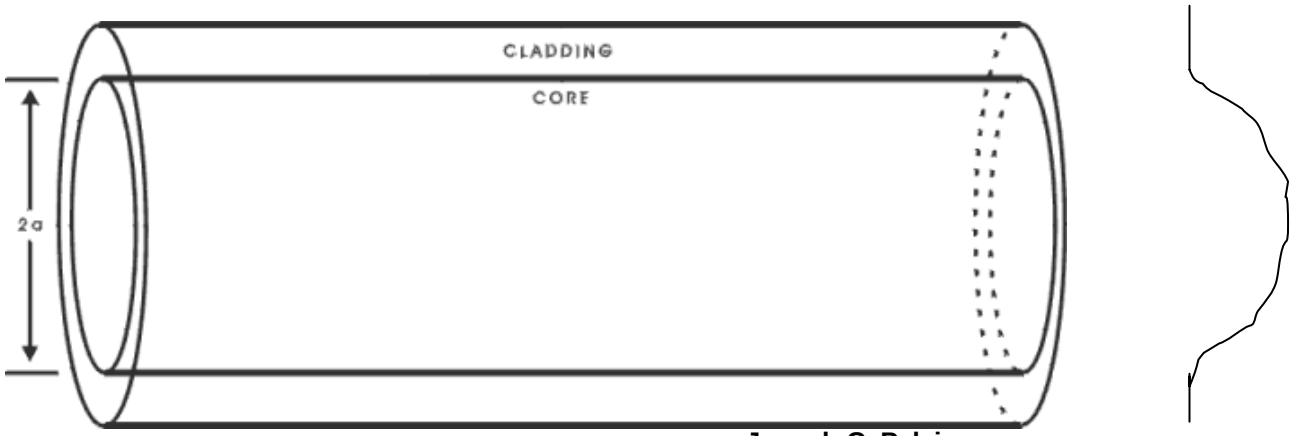
Multimode Step Index Fiber

The delay between these two rays when travels in the core allows Estimation of the pulse broadening resulting from intermodal Dispersion. The minimum time delay travel along given fiber length L is,

$$T_{min} = distance/velocity = L/(c/n_1)$$
$$T_{max} = L/\cos\theta/(c/n_1) = L\, n_1^2/c\, n_2$$
$$\Delta T = T_{max} - T_{min} = (Ln_1^2/c\, n_2)\,((n_1-n_2)/n_1) \sim Ln_1^2\Delta/c\, n_2$$

Graded Index fiber



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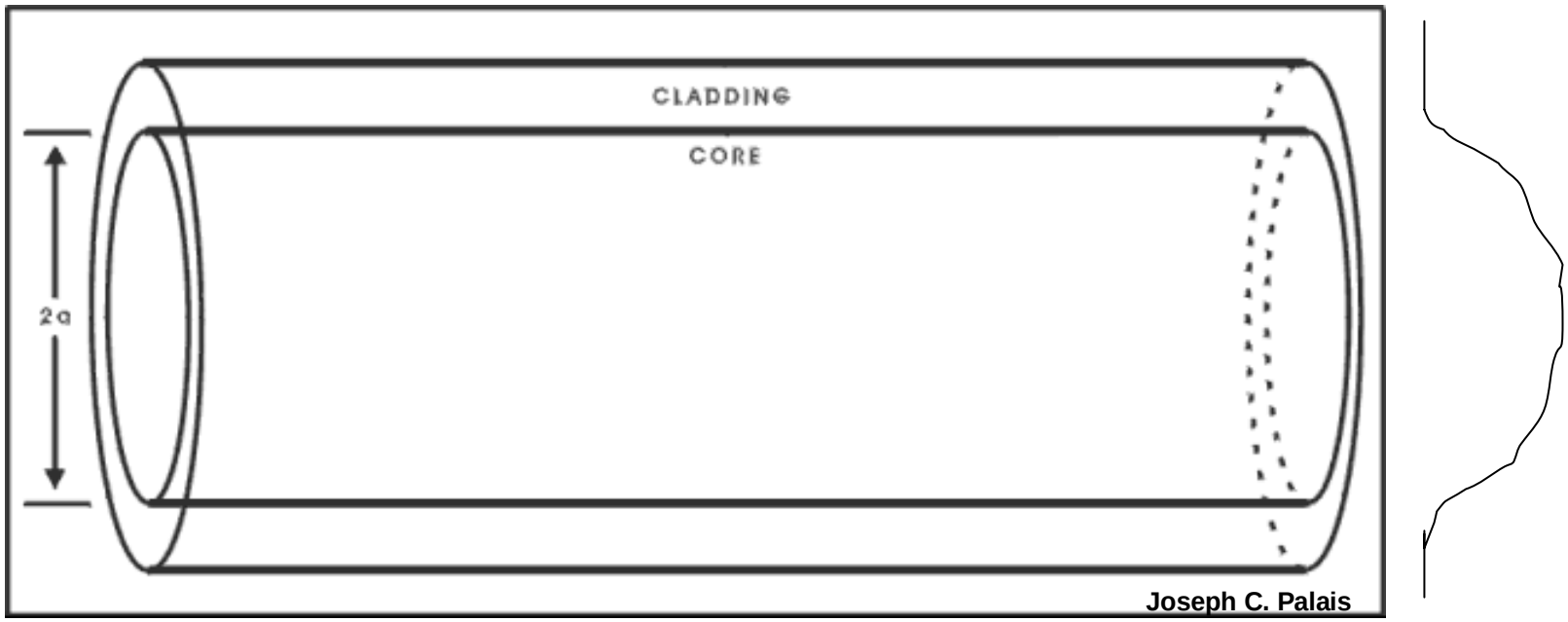
The graded-index(GRIN)fiber has a core material whose reflective index varies with distance from the fiber axis. The light waves in a GRIN travel through the fiber in the ocillatory fashion of the above figure. The changing refractive index causes the rays to be continually redirected toward the fiber axis.



A characteristics of the GRIN fiber is the fact that the order of the wave is irrelevant to the distance it travels. In the above animation this phenomenon is shown, the ray that travels directly along the axis reaches the end of the fiber at the same time as the higher order ray .

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Graded index fibers

Why graded index in multimode fiber?

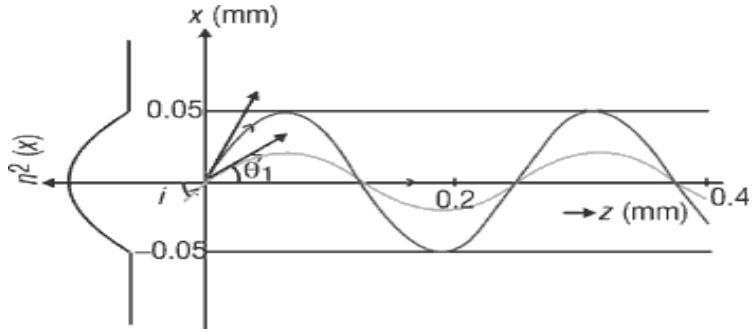
- Multimode graded index fibers exhibits less intermodal dispersion

Parabolic-Index Fibers

In a step-index fiber, the refractive index of the core has a constant value. By contrast, in a parabolic-index fiber, the refractive index in the core decreases continuously (in a quadratic fashion) from a maximum value at the center of the core to a constant value at the core-cladding interface. The refractive index variation is given by

$$n^2(r) = n_1^2\left[1 - 2\Delta\left(\frac{r}{a}\right)^2\right] \qquad 0 < r < a \qquad \text{core}$$

$$n^2(r) = n_2^2 = n_1^2(1 - 2\Delta) \qquad r > a \qquad \text{cladding}$$



with Δ as defined in lecture. For a typical (multimode) parabolic-index silica fiber, $\Delta \approx 0.01$, $n_2 \approx 1.45$, and $a \approx 25$ μm. On the other hand, for a typical plastic fiber, $n_1 \approx 1.49$, $n_2 \approx 1.40$, and $a \approx 500$ μm.

Parabolic-Index Fibers

This follows from Snell's law because the ray continuously encounters a medium of lower refractive index and hence bends continuously away from the normal. Even though rays making larger angles with the fiber axis traverse a longer path, they do so now in a region of lower refractive index (and hence greater speed). The longer path length is almost compensated for by a greater average speed such that all rays take approximately the same amount of time in traversing the fiber. This leads to a much smaller pulse dispersion. The detailed calculations are a bit involved [see, e.g., Chapters 4 and 5, Ghatak and Thyagarajan]. The final result for the intermodal dispersion in a parabolic-index fiber (PIF) is given by

$$\tau_{im} = \frac{n_2 L}{2c}\left(\frac{n_1 - n_2}{n_2}\right)^2 \approx \frac{n_2 L}{2c}\Delta^2 \approx \frac{L}{8cn_1^3}(NA)^4$$

Pulse dispersion in multimode PIF

Note that, as compared to a step-index fiber, the pulse dispersion is proportional to the fourth power of *NA*. For a typical (multimode parabolic-index) fiber with $n_2 \approx 1.45$ and $\Delta \approx 0.01$, we would get

$$\tau_{im} \approx 0.25 \text{ ns/km}$$

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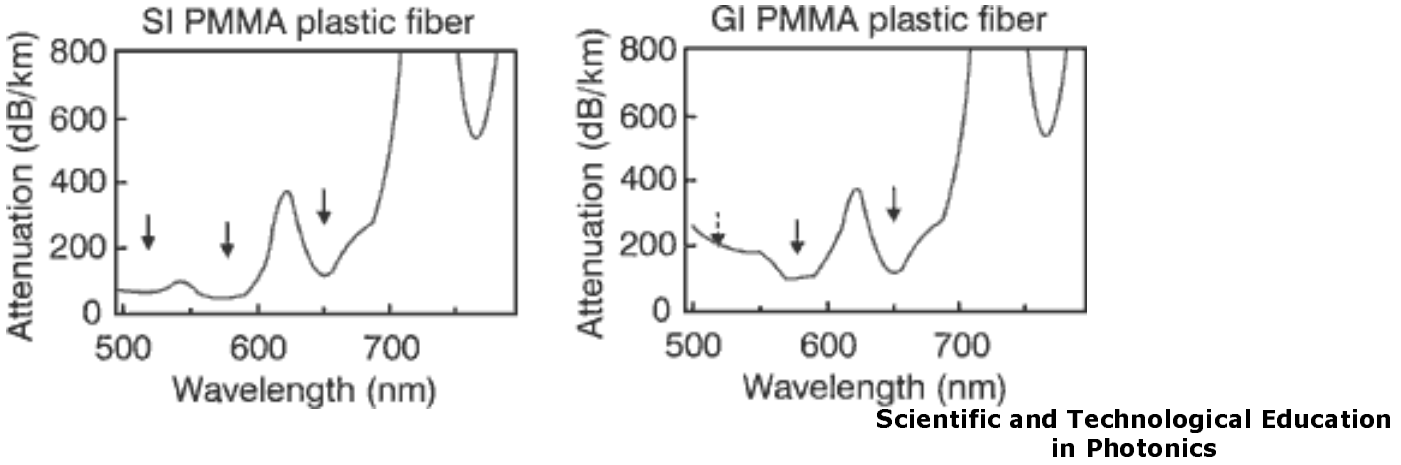
Plastic Optical Fiber

Plastic optical fibers are made from materials such as polymethyl methacrylate PMMA (n = 1.49), polystyrene (n = 1.59), polycarbonates (n = 1.5-1.57), fluorinated polymers, and so on. These fibers share the advantages of glass optical fibers in terms of insensitivity to electromagnetic interference, small size and weight, low cost, and potential capability of carrying information at high rates. The most important attribute of POFs is their large core diameters of around 1 mm as compared to glass fibers with cores of 50 μm or 62.5 μm. Such a large diameter results in easier alignment at joints. They are also more durable and flexible than glass fibers. In addition, they usually have a large *NA*, resulting in larger light-gathering power .

Although glass optical fibers dominate long-distance data communication, POFs are expected to provide *low-cost solutions to short-distance applications* such as local area networks (LAN) and high-speed Internet access. At gigabit rates of transmission, glass fibers are at least 30% more expensive than POFs, while the cost of copper increases dramatically.

Attenuation is one of the important parameters of an optical fiber. Figure shows typical loss spectra of 1-mm-diameter step-index (SI) and graded-index (GI) PMMA-based POF. There are three low-loss windows, at 570 nm, 650 nm, and 780 nm. The loss of SI POF at the 650-nm window is about 110 dB/km. This is, of course, very large compared to silica fibers, which have typical losses of about a few dB/km in this wavelength region. The large losses are due to Rayleigh scattering, intrinsic absorption of the material itself, and impurities and absorption due to vibrational modes of the molecules. Because of the high losses, these fibers are used in only short-distance (~ a few hundred meters) communication links.



Typical attenuation spectra of 1-mm-diameter (a) step-index (SI) and (b) graded-index (GI) PMMA plastic fiber [Adapted from Koeppen, Shi, Chen, and Garito]

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