Group Velocity and Phase Velocity

- Light speed is really the phase velocity v

$$\omega = vk$$

Where ω = 2πf = angular frequency

k = wave vector =2π/λ

- This is really the velocity of the waves
- However information travels in wave packets
- Wave packets have a frequency variation
- Frequency is modulated by slowly changing δω
- Have ω+δω and ω-δω frequency rang
- This packet moves with wave vector δk
- Thus the group velocity is given by

$$v_g = \frac{d\omega}{dk}$$

- In a vacuum

$$v_g = \frac{d\omega}{dk} = c = \textit{phase velocity}$$

- Each mode in a fiber travels with different group velocity
- Thus get spreading of information packet

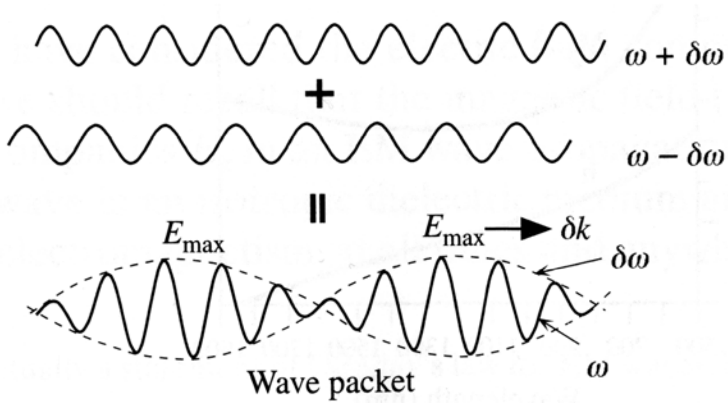


FIGURE 1.6 Two slightly different wavelength waves traveling in the same direction result in a wave packet that has an amplitude variation which travels at the group velocity.

Multi Mode and Single Mode Fiber

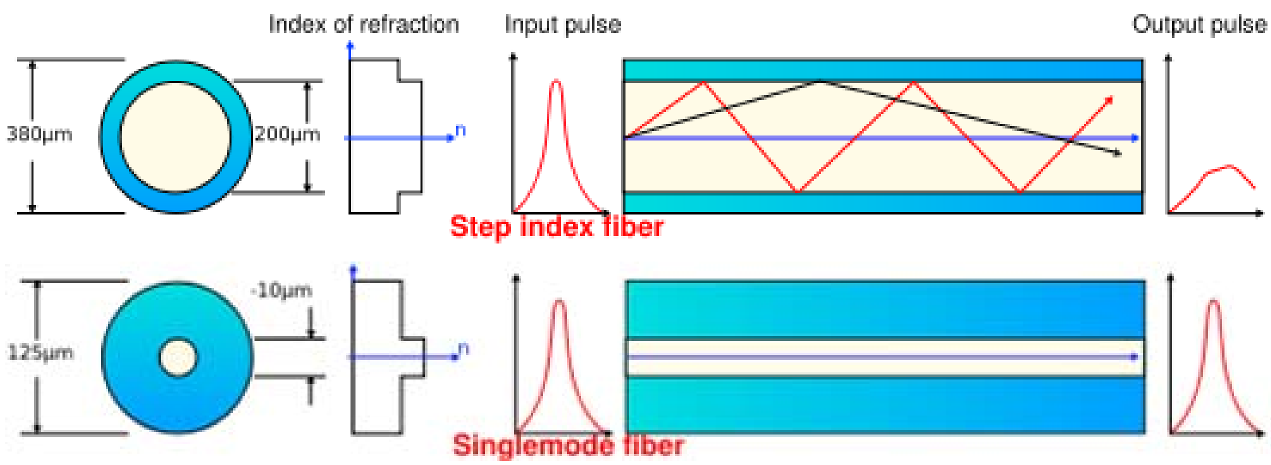
- Multi mode fiber results in spreading of signal
- But number of modes is set by core diameter and index
- Can change number of modes by changing these
- Want a single mode fiber m=0
- Number of modes are set by

$$m \leq \frac{(2V - \phi)}{\pi}$$

- Where V is the V number given by

$$V = \frac{2\pi a}{\lambda}\sqrt{n_1^2 - n_2^2}$$

- Thus get a single mode when $V<\pi/2$
- To create single mode make diameter of core very small
- Result much reduced pulse spreading
- Multi mode fiber 380 μm diameter with 200 μm core
- Single mode 125 μm diameter with 10 μm core
- Also in indexes much smaller



Acceptance Angle and Fibers

- Problem with single mode is harder to get signal into fiber
- Called coupling with the fiber
- Acceptance angle $\theta_a = \alpha_{max}$ max angle light can enter fiber

$$\frac{\sin(\theta_a)}{\sin(90^o - \theta_c)} = \frac{n_1}{n_0} \qquad \sin(\theta_c) = \frac{n_2}{n_1}$$

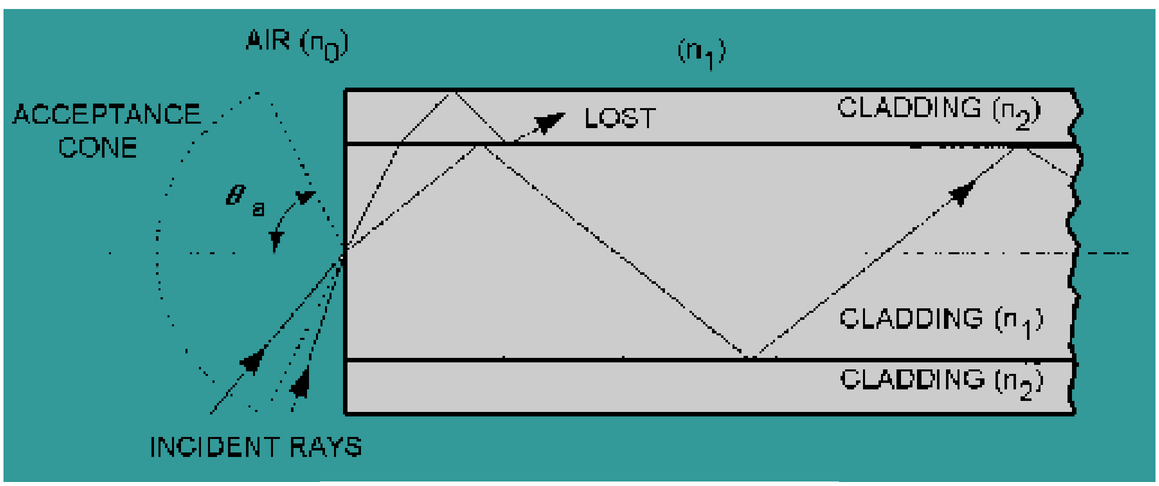
- Thus

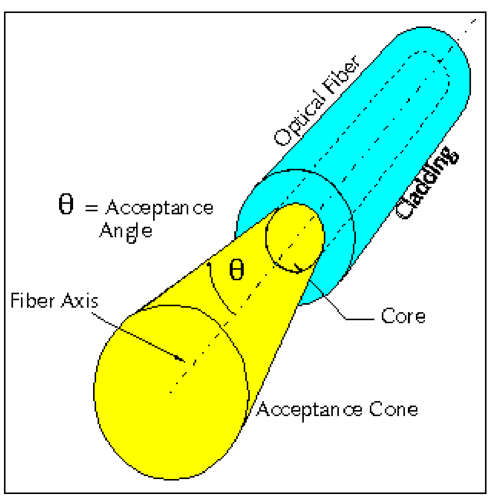
$$\sin(\theta_a) = \frac{\sqrt{n_1^2 - n_2^2}}{n_0} = \frac{NA}{n_o}$$

- The fiber's Numerical Aperture is

$$NA = \sqrt{n_1^2 - n_2^2}$$

- Total Acceptance Angle is $2\theta_a$





acceptance cone

Single & Multi-Mode Fiber Acceptance

- Multimode fiber example
- n_1=1.480, n_2 = 1.460 with a core of 200 μm

$$NA = \sqrt{n_1^2 - n_2^2} = \sqrt{1.480^2 - 1.460^2} = 0.2425$$

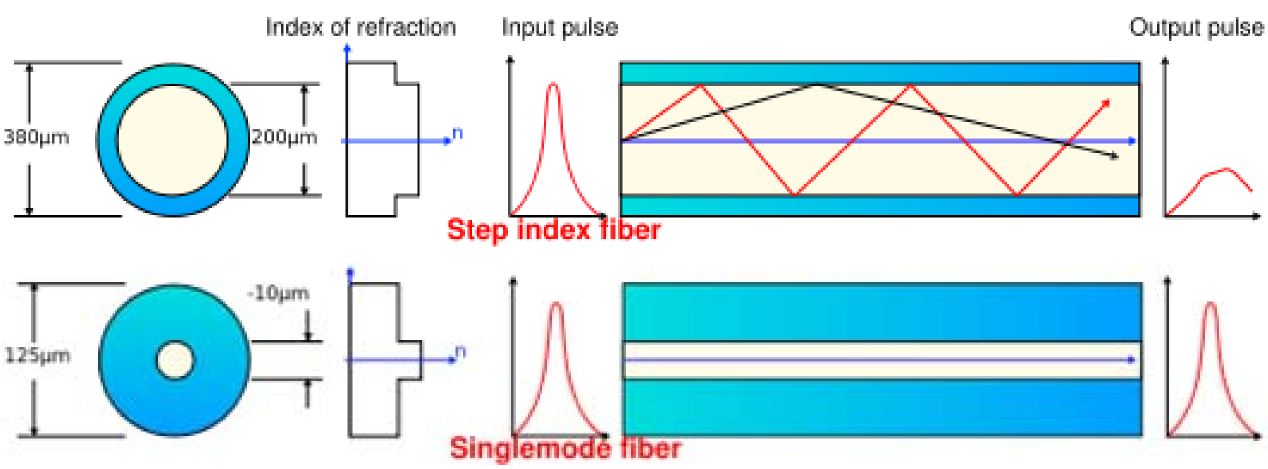
$$\theta_a = arcsin\left(\frac{NA}{n_o}\right) = arcsin\left(\frac{0.2425}{1}\right) = 14^o$$

- And total acceptance angle is 28^o
- Now consider a single mode fiber
- n_1=1.460, n_2 = 1.464 (only 0.3% larger) with a core of 10 μm

$$NA = \sqrt{n_1^2 - n_2^2} = \sqrt{1.460^2 - 1.464^2} = 0.0.113$$

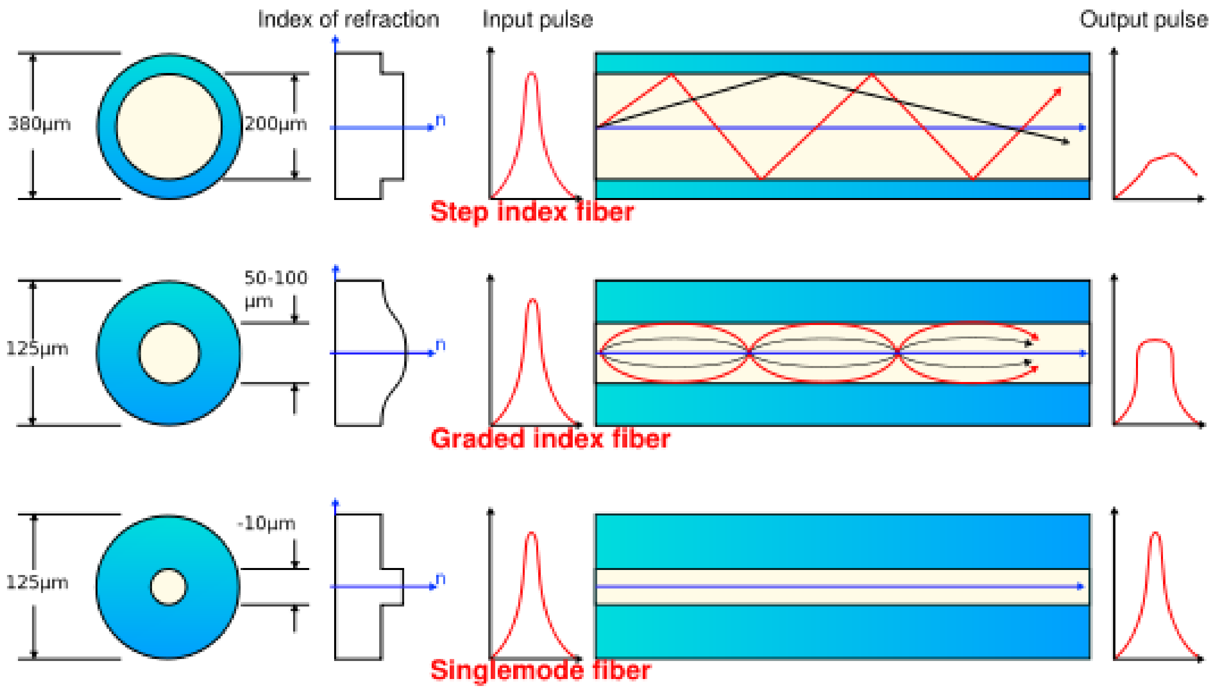
$$\theta_a = arcsin\left(\frac{NA}{n_o}\right) = arcsin\left(\frac{0.113}{1}\right) = 6.5^o$$

- Thus much harder to couple light



Graded Index (GRIN) Fiber

- Due to small acceptance angle want alternative to single mode
- Uuse a GRaded INdex in the core (GRIN)
- Made by doping fiber with material that varies with postion
- Light now bends rather than reflects
- Get acceptance angle close to multimode
- But bit rate much higher than multimode



Fiber Dispersion and Bit Rate

- Dispersion of pulse in fiber sets the limit of bit rate
- Look at the Full Width Half Power (FWHP) of signal $\Delta\tau_{1/2}$
- Two pulse must be at least $2\Delta\tau_{1/2}$ apart to be separated
- Bit rate is thus

$$B \cong \frac{1}{2\Delta\tau_{1/2}}$$

- $\Delta\tau_{1/2}$ increase with distance so measure
- Dispersion = Bandwidth x distance

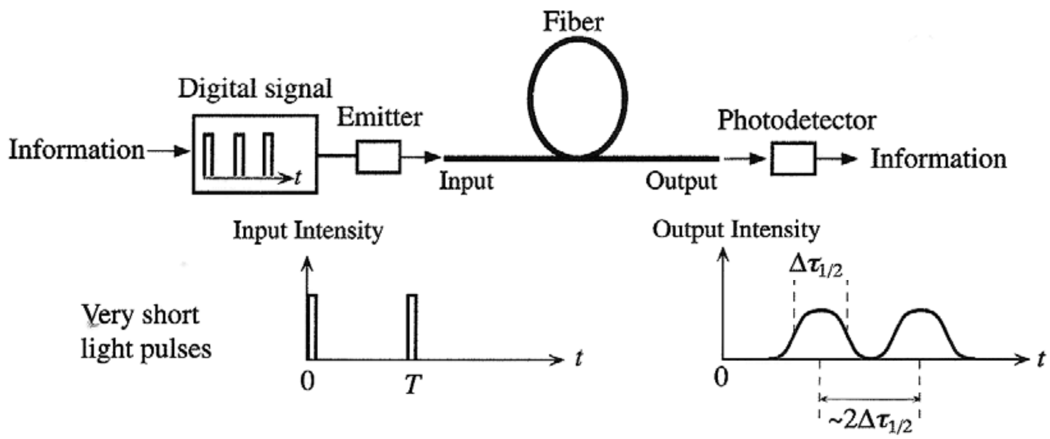
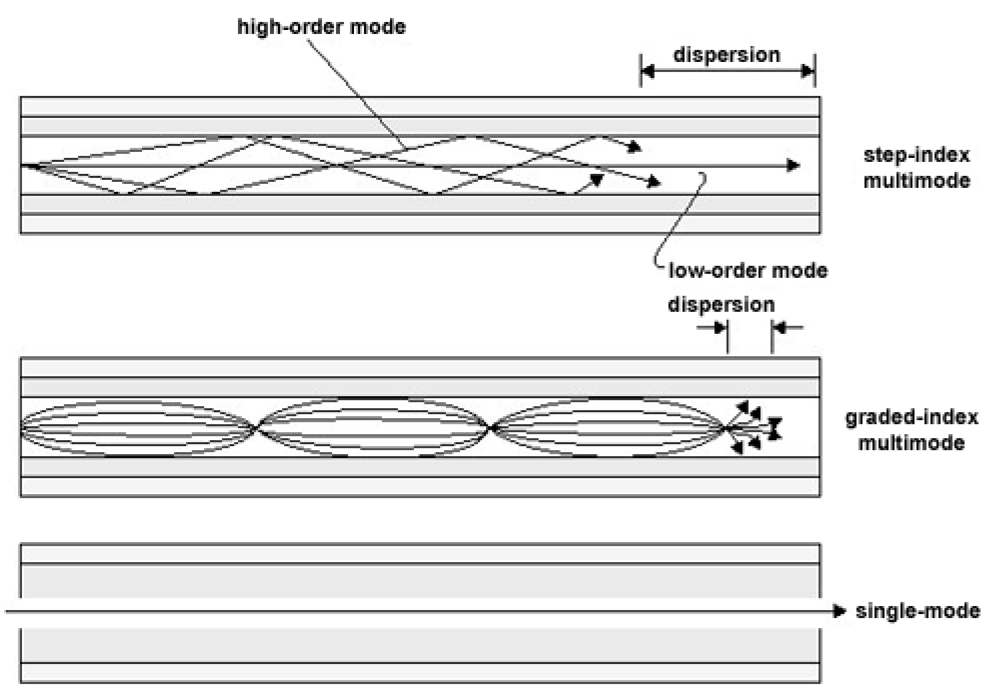


FIGURE 2.22 An optical fiber link for transmitting digital information and the effect of dispersion in the fiber on the output pulses.



Comparison of Multimode, GRIN and Single Mode

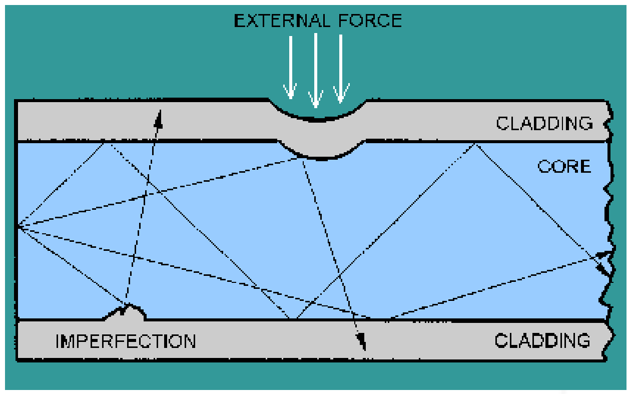
- **Multi mode:** high acceptance angle
- High dispersion ~20-100 Mhz km bandwidth product
- Can use LED's for emitters
- Easy to install – used for short distance networks
- **GRIN** acceptance angle near multimode: easy to connect
- Medium dispersion ~300 MHz km bandwidth product
- LED or lasers as emitters
- Medium distance networks
- **Single mode** small acceptance angle
- Thus harder to interconnect fibers
- Low dispersion 100 GB/s in field
- Laser diodes needed for narrow wavelength

TABLE 2.3 Comparison of typical characteristics of multimode step-index, single-mode step-index, and graded-index fibers. (Typical values combined from various sources.)

Property	Multimode step-index fiber	Single-mode step-index fiber	Graded index fiber
$\Delta = (n_1 - n_2)/n_1$	0.02	0.003	0.015
Core diameter (μm)	100	8.3 (MFD = 9.3 μm)	62.5
Cladding diameter (μm)	140	125	125
NA	0.3	0.1	0.26
Bandwidth × distance or Dispersion	20 − 100 MHz km.	$<$3.5 ps km^{-1} nm^{-1} at 1.3 μm $>$100 Gb s^{-1} km in common use	300 MHz km − 3 GHz km at 1.3 μm at 1.3 μm
Attenuation of light	4 − 6 dB km^{-1} at 850 nm 0.7 − 1 dB km^{-1} at 1.3 μm	1.8 dB km^{-1} at 850 nm 0.34 dB km^{-1} at 1.3 μm 0.2 dB km^{-1} at 1.55 μm	3 dB km^{-1} at 850 nm 0.6 − 1 dB km^{-1} at 1.3 μm 0.3 dB km^{-1} at 1.55 μm
Typical light source	Light emitting diode (LED)	Lasers, single mode injection lasers	LED, lasers
Typical applications	Short haul or subscriber local network communications	Long haul communications	Local and wide-area networks. Medium haul communications

Fiber Bending Loses

- When fiber is bent or has imperfection get increased loss
- Due to change in light angle to below critical angle
- Lose Total Internal Reflection
- The effective absorption coefficient α_B increases greatly
- Smaller radius of curvature, larger the light leaking out



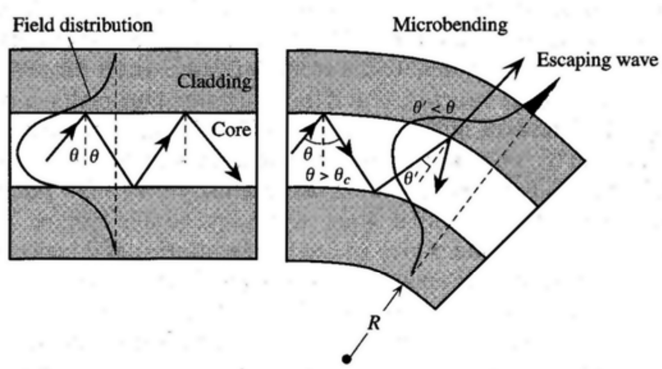


FIGURE 2.32 Sharp bends change the local waveguide geometry that can lead to waves escaping. The zigzagging ray suddenly finds itself with an incidence angle θ' that gives rise to either a transmitted wave, or to a greater cladding penetration; the field reaches the outside medium and some light energy is lost.

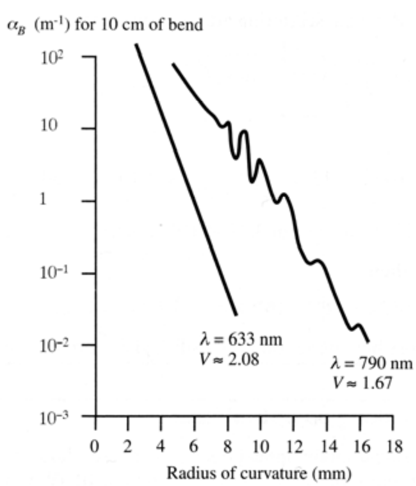


FIGURE 2.33 Measured microbending loss for a 10 cm fiber bent by different amounts of radius of curvature R. Single mode fiber with a core diameter of 3.9 μm, cladding radius 48 μm, $\Delta = 0.004$, $NA = 0.11$, $V \approx 1.67$ and 2.08 (Data extracted and replotted with Δ correction from, A.J. Harris and P.F. Castle, *IEEE J. Light Wave Technology*, Vol. LT14, pp. 34–40, 1986; see original article for discussion of peaks in α_B vs. R at 790 nm.)

How Fiber is Made

- Fiber starts with rod of core and cladding
- Heated in drawing furnace- often rotated to make even
- Pulled into a narrow fiber
- Monitor fiber diameter – adjusted with pull rate
- Add plastic coating on outside
- Rolled into spool