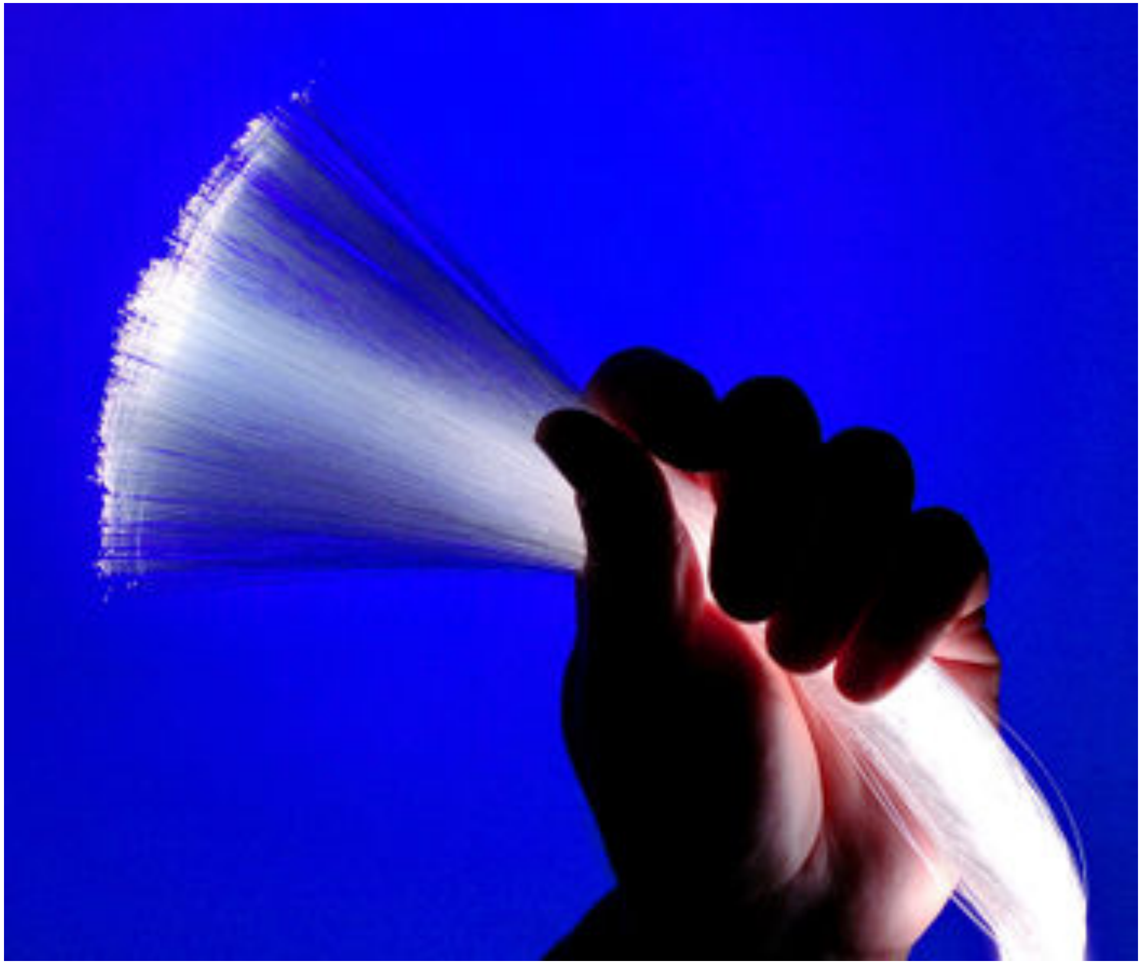
7 – Fiber Optics



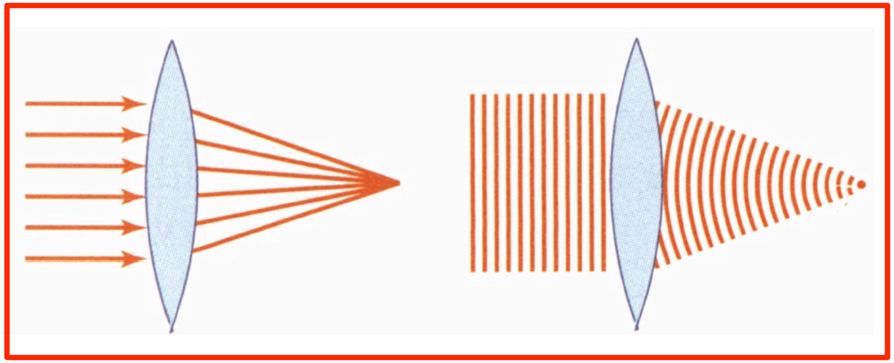
Schedule (1000 pts. total)

- You have two weeks to complete this lab (no lecture next Monday).

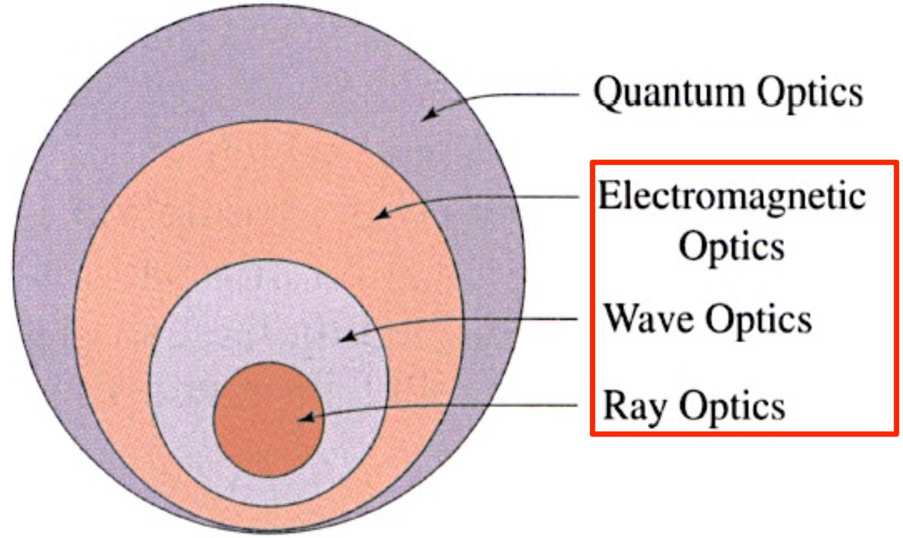
- Reminder: always look on blackboard for the most up to date schedule! The one shown below might not be accurate….

Week	Topic	Pts.	Notes
1	Basic Light Interactions (Refraction, Absorption, etc.)	30	*1st week takes longer…*
2	Lenses, Magnification, & Beam Expanders	40	*2nd week you get faster, better…*
3	Optical Interference	50	*3rd week you are skilled (little wasted time)…*
4	Diffraction	50	
5	Polarization	50	
6	Fourier Optics	50	
7&8	Fiber Optics	80	*You will get two weeks to complete this lab!*
9	Displays	50	
10	Emitters/Detectors	50	
11	Bio-photonics – Lecture / Lab: Part 1	-	*Work on part 1 this week, present next week.*
12	Bio-photonics – Part 1 Presentations / Lab: Part 2	40	*Work on part 2 this week, present next week.*
13	Bio-photonics – Part 2 Presentations / Start Final Proj.	60	*Get approval from Dr. H! Order any parts!*
14	Final Project: informal presentations on design & procedures		*Provide an update to Dr. H on your progress!*
15	Final Project: Demonstrations During The Week	100	*Schedule a demo and presentation with Dr. H.*
16	Quizzes Total	350	*Averaged out at the end to be out of 300 pts. total.*

- Today, we will mainly use a bit of ray, wave, and electromagnetic optics, some content will be hard to visualize and is highly mathematical…



Credit: *Fund. Photonics – Fig. 2.3-1*

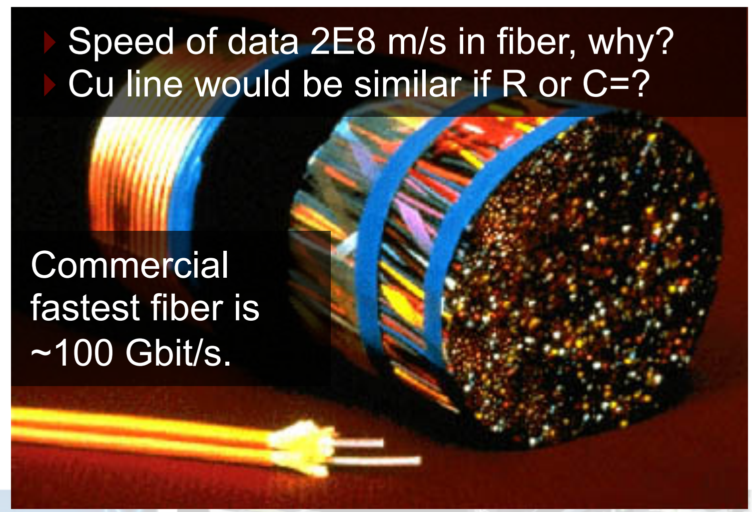


Credit: *Fund. Photonics – Fig. 1.0-1*

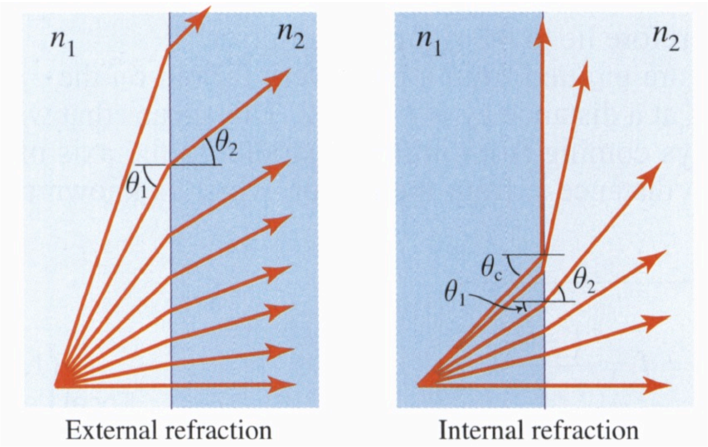
- Topics:

(1) Fiber Optics Basics (Multimode)
(2) Fiber Attenuation
(3) Single or Few Mode Fibers
(4) Dispersion
(5) Fiber Amplifiers

Many of the figures today are from CH8/9 of Fund. of Photonics



- Look at refraction vs. various incidence angles… Look at the case for internal refraction (high index into low index…).



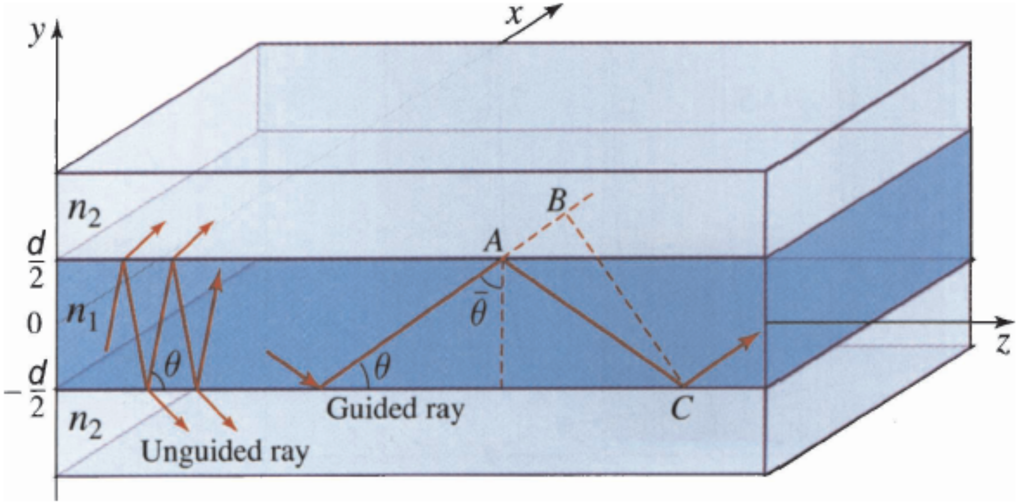
Credit: Fund. Photonics

$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

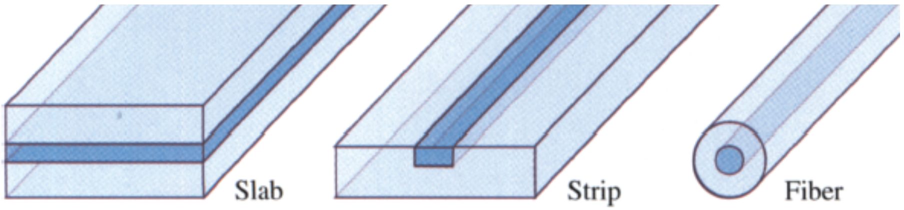
$$n_1 \sin\theta_C = n_2 \sin 90$$

$$\theta_C = \sin^{-1}(n_2 / n_1)$$

- Total internal reflection occurs when you reach the critical angle for the case of $n_1 > n_2$.

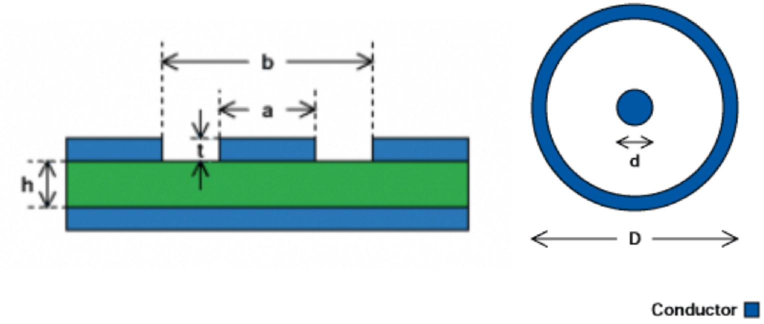


- There are several types of waveguides, not everything is a fiber…

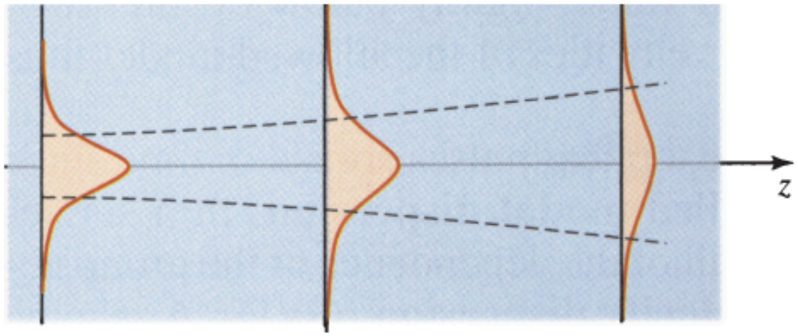


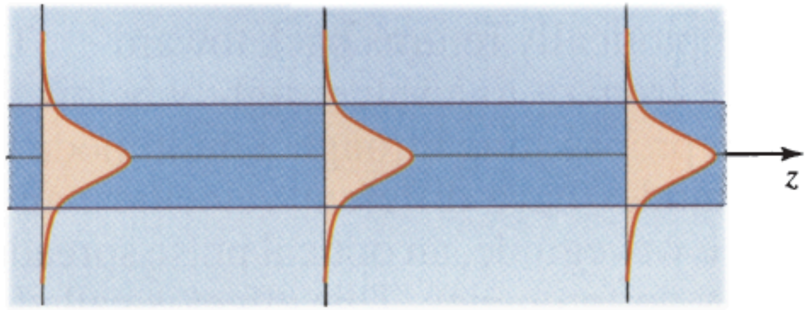
Credit: Fund. Photonics

- Analogs exist in PCB strip lines, coax cabling, etc…



- Light diverges normally (even if a Laser), but the exception is when confined inside a waveguide…





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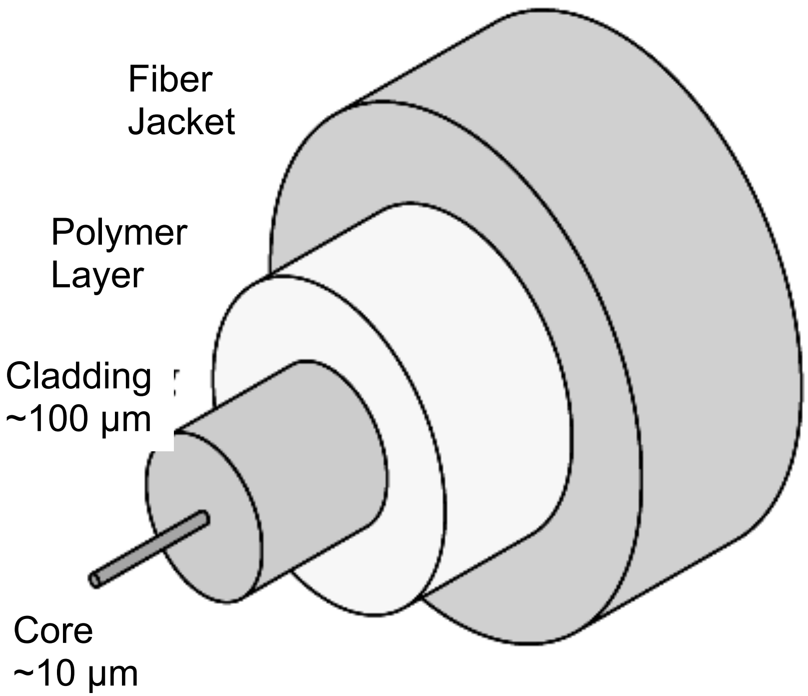
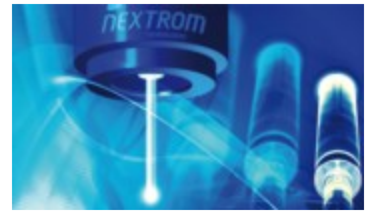
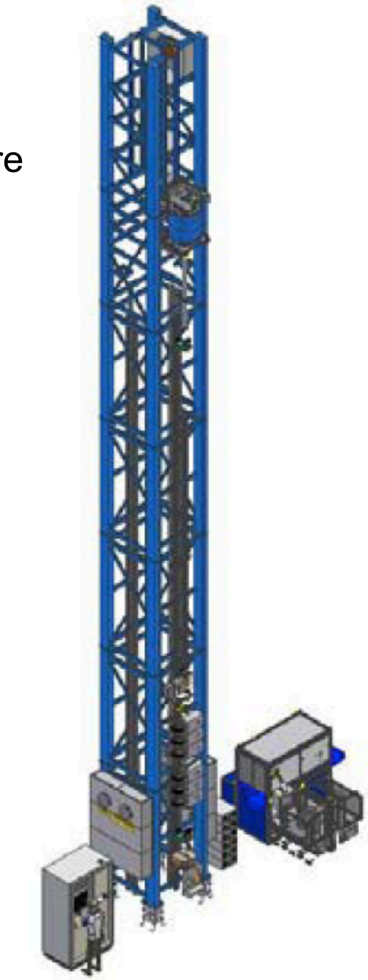
- Typical fiber core n~1.46 (SiO2)
- Cladding is typically ~0.1 to 0.3 lower to support TIR



- Fiber preform has core and cladding, but is ~10 cm wide, heated till soft and then drawn downward to the base where polymer protective layer is added.





Tall OFC 20 Fiber Draw Tower for mass production of Single-Mode optical fiber

- Numerical Aperture can be calculated for ANY optical element… who remembers what it is? We talked about it for lenses…

$$NA = n_0 \sin\theta_a$$

$$n_0 \sin\theta_a = n_1 \sin(90 - \theta_C)$$

$$n_0 \sin\theta_a = n_1 \cos(\theta_C)$$

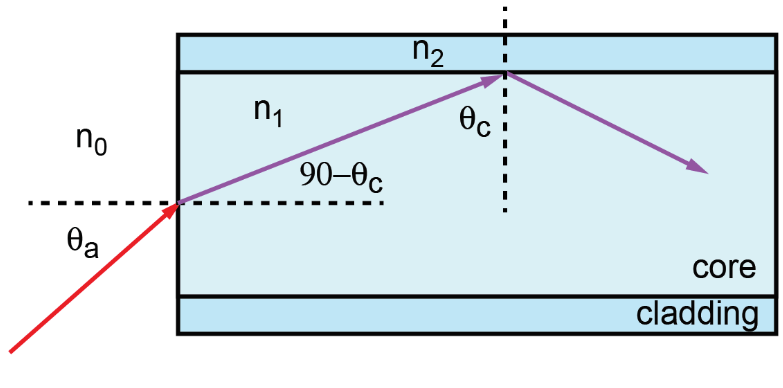
$$n_0 \sin\theta_a = n_1 \sqrt{1 - \sin^2(\theta_C)}$$

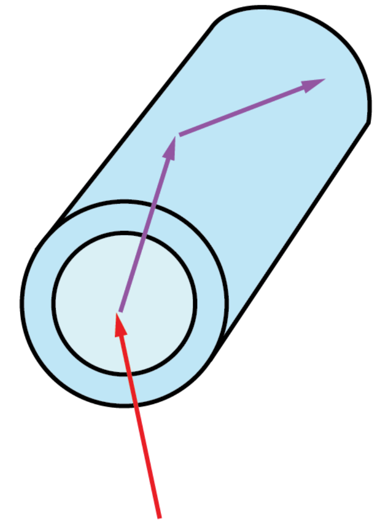
$$n_0 \sin\theta_a = n_1 \sqrt{1 - (n_2 / n_1)^2}$$

$$n_0 \sin\theta_a = \sqrt{n_1^2}\sqrt{1 - (n_2 / n_1)^2}$$

$$n_0 \sin\theta_a = \sqrt{n_1^2 - n_2^2}$$

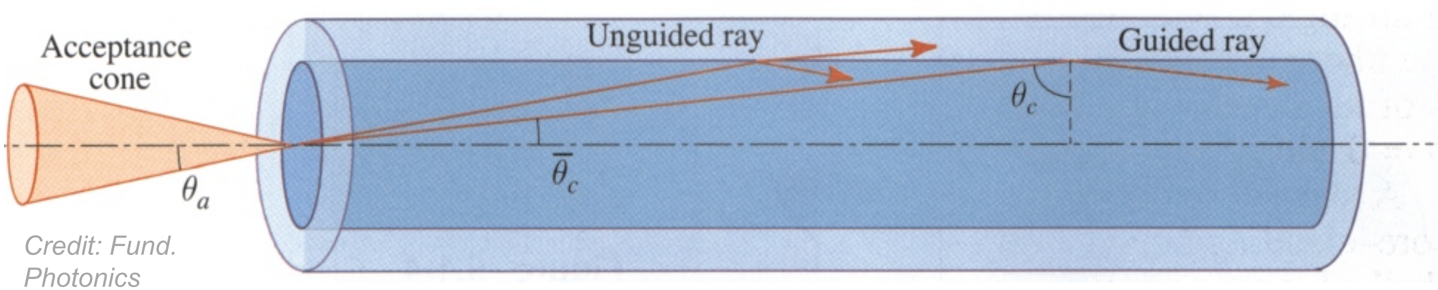
$$NA = n_0 \sin\theta_a = \sqrt{n_1^2 - n_2^2}$$





- NA is the 'light gathering power' or the sine of the maximum angle at which any optical element (fiber, lens, etc…) can capture light!

- Typical θ_α values are ~5-15° since Δn is small. If n_1=1.46 and n_2<1.06 then θ_α = 90 (a bare fiber in air will capture all light onto it!).



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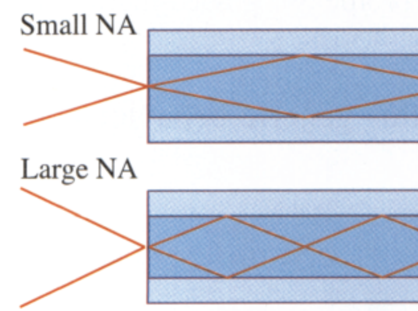


- Which would have the least optical loss:

(a) An optical fiber relying on an external metal reflector coating to confine the light.
(b) An optical fiber with a glass core with refractive index that is less than a glass cladding.
(c) An optical fiber with a glass core with refractive index that is greater than a glass cladding.
(d) All of the above are equal in loss.

- Numerical aperture for a fiber:

(a) Increases as refractive index difference between the core and cladding increases.
(b) Is a measure of the largest size of the a cone of light that could be coupled into the fiber.
(c) Can capture light from all incidence angles (out to 90 degrees) for a bare glass fiber in air.
(d) All the above are true.

- Whew! That's enough. Lets take a break!

- SiO_2 lowest loss due to absorption of light is α~0.15 dB/km for 1.5 μm light.

$$\alpha(dB/km) = \frac{-10\log\left(P(z)/P(0)\right)}{z(km)}$$

$$\frac{P(z)}{P(0)} = 10^{-\alpha z/10} \approx e^{-0.23\alpha z}$$

$$\dots(2.3\times\log X = \ln X)$$

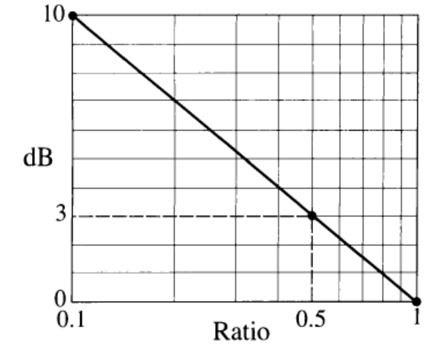
$$if\ \frac{P_z}{P_0} = 0.10, \alpha = 0.15$$

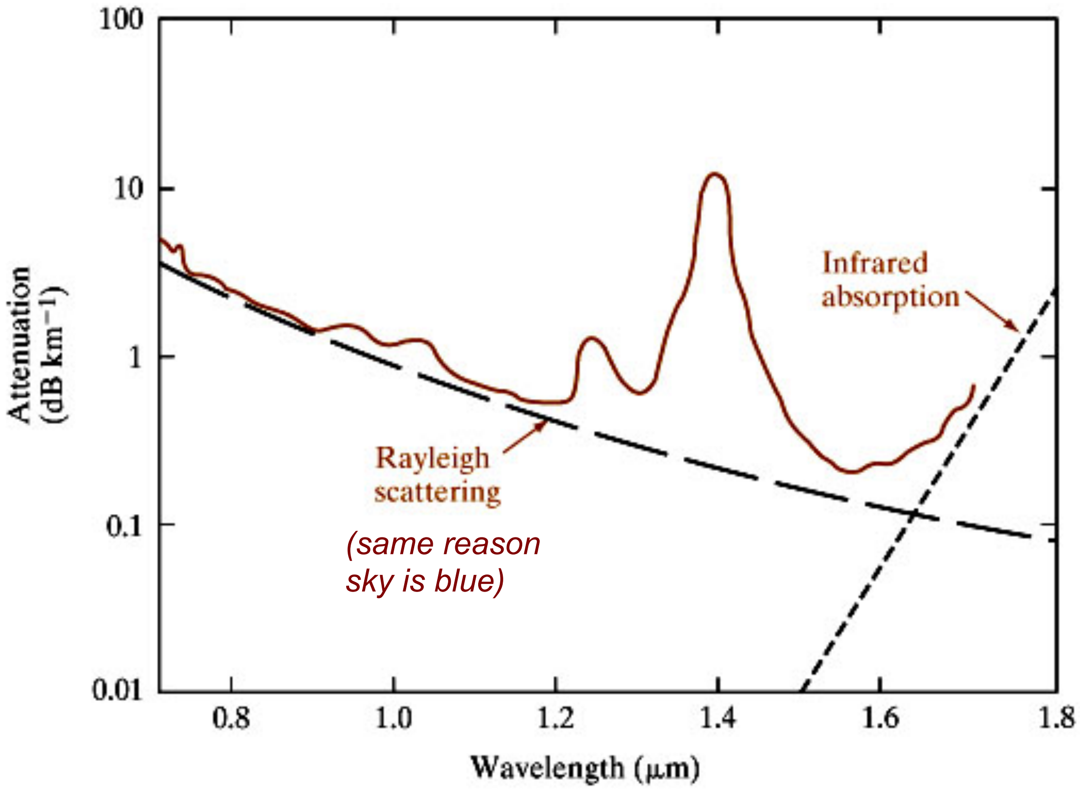
$$then\ z = 67{,}000m \quad (67\,km)$$

- Telecom: 1.5 μm is one of the dominant wavelengths used because of such low loss!

- If dB not the units given, then here is why (is not as popular):

$$\alpha(km^{-1}) = \frac{-1}{z(km)}\ln\left(\frac{P(z)}{P(0)}\right)$$





Credit: Fund. Photonics

Corning® InfiniCor® 62.5 µm Optical Fibers

Product Information

Attenuation

Wavelength (nm)	Maximum Value (dB/km)
850	≤ 2.9
1300	≤ 0.6

No point discontinuity greater than 0.2 dB.

Attenuation at 1380 nm does not exceed the attenuation at 1300 nm by more than 1.0 dB/km.

Induced attenuation from 100 turns around a 75 mm mandrel shall be ≤ 0.5 dB at 850 nm and 1300 nm.

Numerical Aperture

0.275 ± 0.015

Dimensional Specifications

Glass Geometry

Core Diameter	62.5 ± 2.5 µm
Cladding Diameter	125.0 ± 2.0 µm
Core-Clad Concentricity	≤ 1.5 µm
Cladding Non-Circularity	≤ 1.0%
Core Non-Circularity	≤ 5%

Coating Geometry

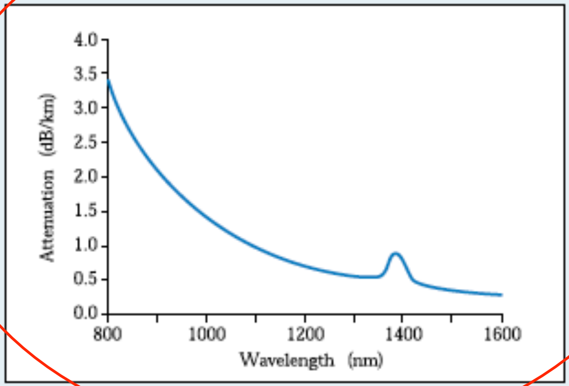
Coating Diameter	242 ± 5 µm
Coating-Cladding Concentricity	< 12 µm

(Gigabit Ethernet) for product-specific bandwidth metrics and values provided in this document.

Refractive Index Difference	2%
Effective Group Index of Refraction (N_{eff})	850 nm: 1.496 1300 nm: 1.491

N_{eff} was empirically derived to the third decimal place using a specific commercially available OTDR.

Spectral Attenuation (Typical Fiber)



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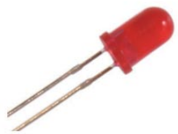
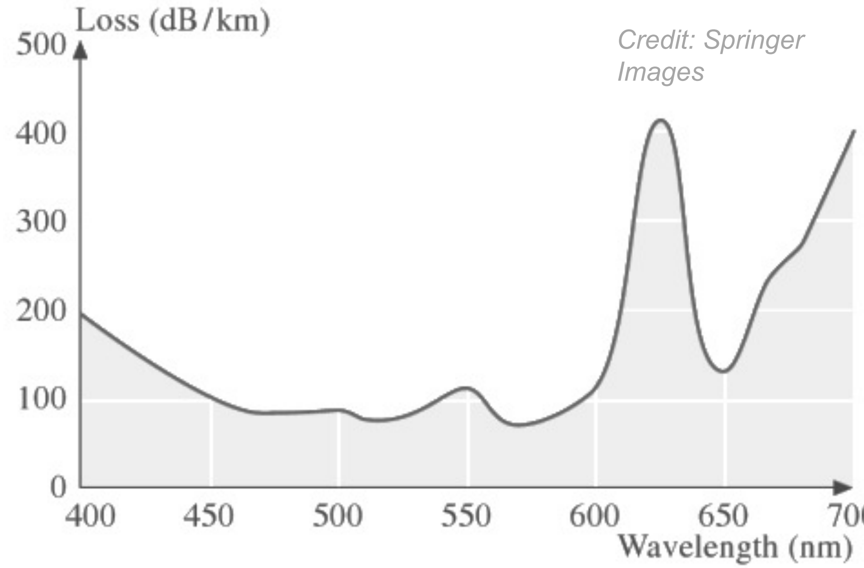
- Plastic Optical Fibers (POF) targets lower cost applications and uses the cheapest LEDs available (red LEDs).

$$\alpha(dB/km) = \frac{-10\log(P_z/P_0)}{z}$$

$$if\ \frac{P_z}{P_0} = 0.10, \alpha = 100$$

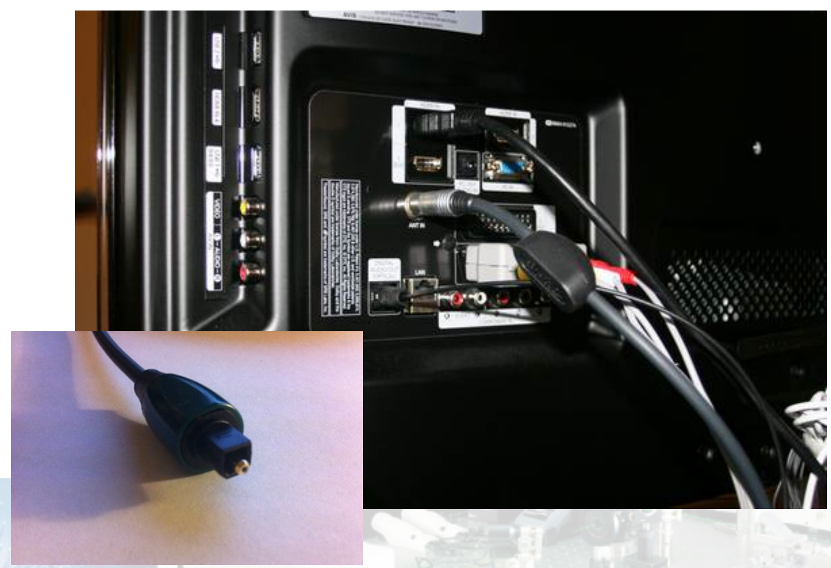
$$then\ z = 0.1\ km \quad (100m)$$





Credit: Springer Images

- Copper wire: 100 Mbps over 100 m
- LEDs / POF: 10 Gbps over 100 m
- Lasers / Glass Fiber: 100 Gbps over 1000's of m !!



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- Optical fibers underneath the sea connecting the fiber networks between continents:

(a) Can be made out of plastic or glass.
(b) Must be made out of plastic.
(c) Must be made out of glass.
(d) Are not made using any of the above materials.

- A good laser wavelength for applications includes (which two of the answers below are correct?):

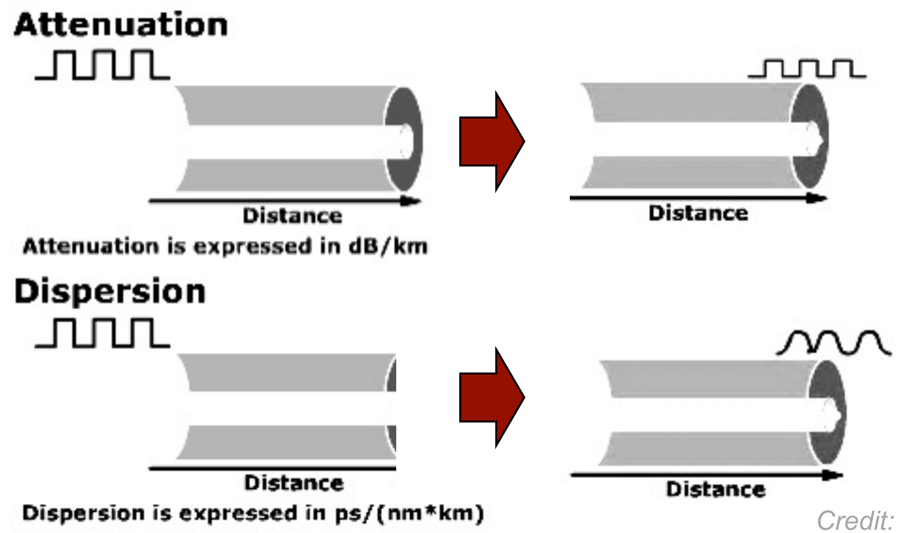
(a) Visible red light for long distance telecom.
(b) Infrared light for fibers in stereos and cars.
(c) Infrared light for long distance telecom.
(d) Visible light for fibers in stereos and cars.

- Whew! That's enough. Lets take a break!

- Optical loss can of course cause you to lose your signal over long distances…

…but typically the loss can be made very low and boosted by amplification (more on that later…

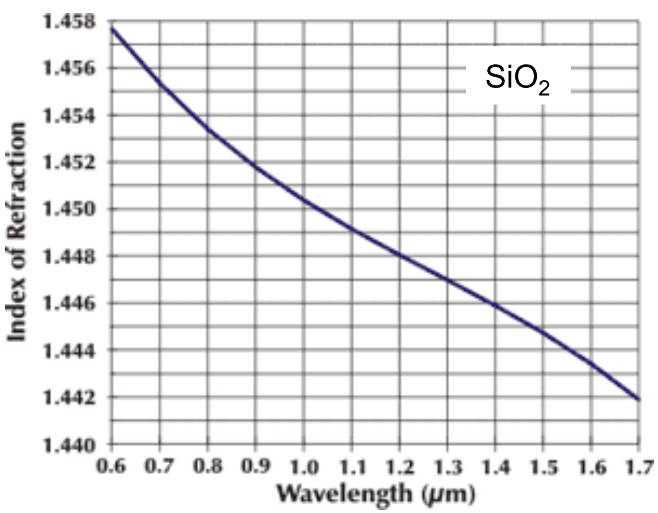
- The big issue is when you go to high data rates with pulses very close to each other… you get pulse broadening due to dispersion which can make it difficult to read the pulses!

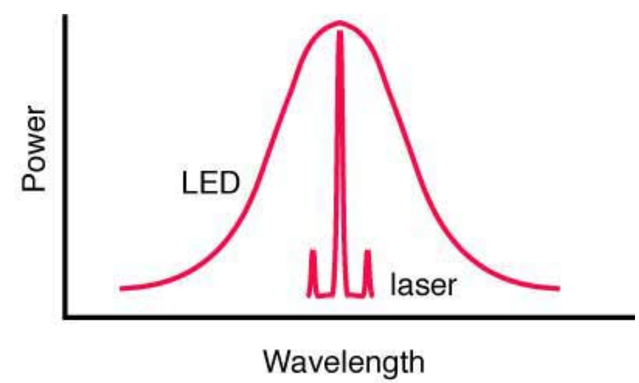


Credit: Corning

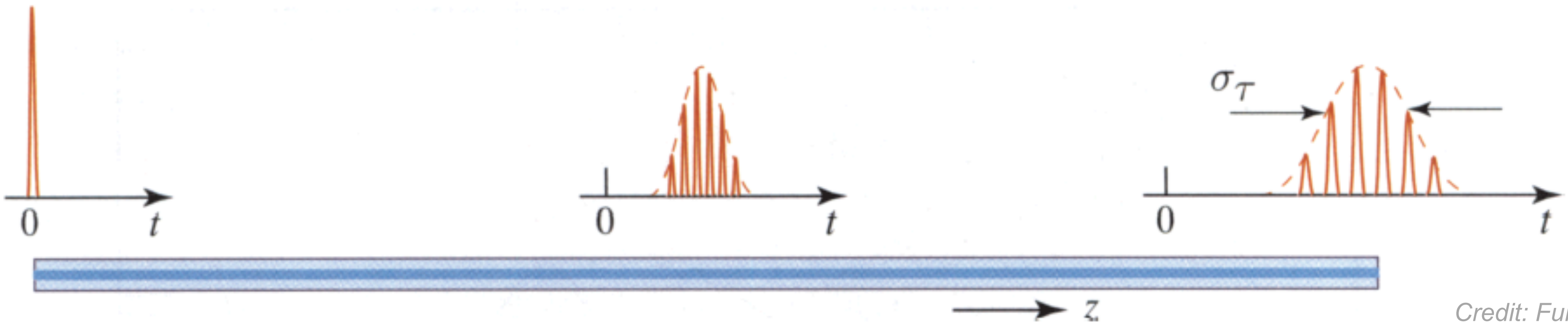
- Dispersion types:

- material dispersion, see →
- waveguide dispersion
- non-linear dispersion
- modal dispersion

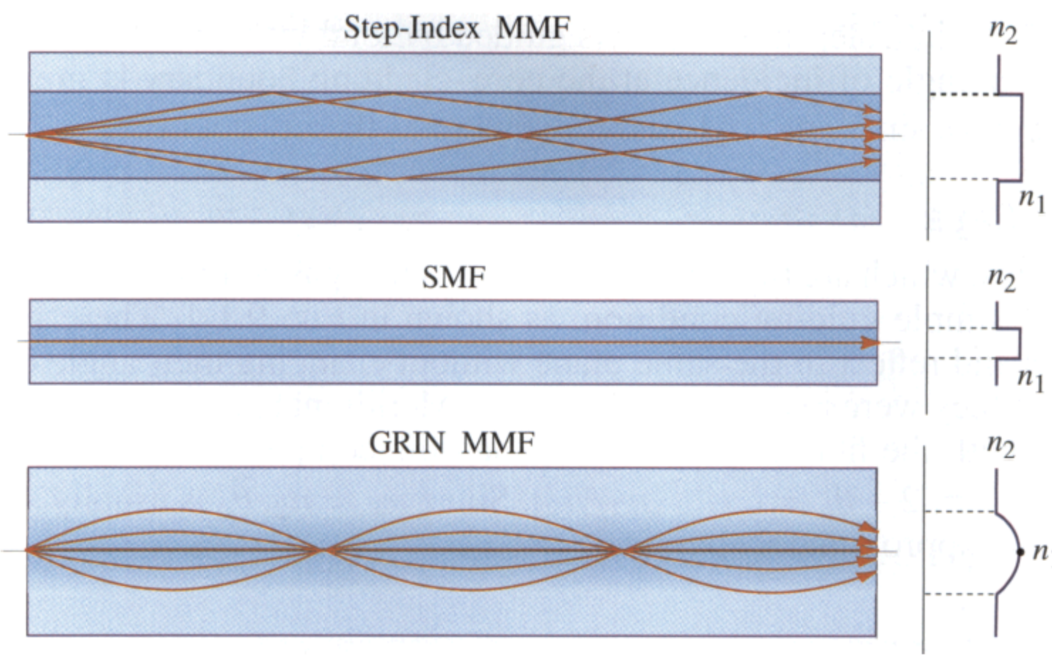




Telecom lasers have 'spectral widths' of only a few nm, but that still is enough that dispersion can be an issue at very high transmission rates!



Credit: Fund. Photonics



- One way to think of modal dispersion is time it takes for different photons to traverse the entire fiber…

For fibers at right, do you see this? Do any of these solve the problem?

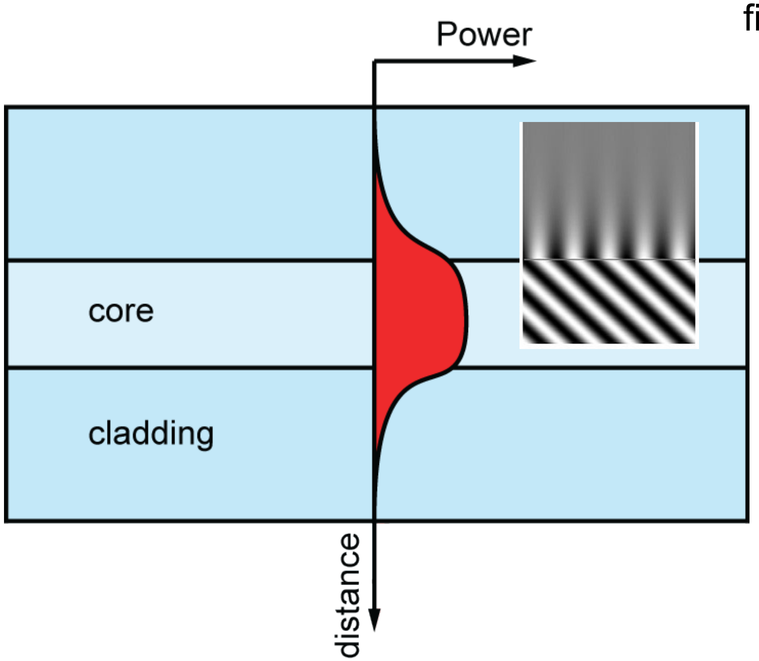
- Sure, the straight path solves the problem… but not completely! Lets examine this on the next slide…

- When we have only a few modes, the light travels in a fairly straight line (no zig zag).

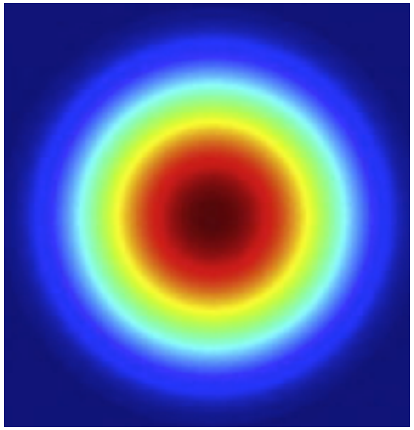
- However we have to also consider how much of the *evanescent* optical field is in the cladding (obviously the E-field of the photon does not disappear right at the core/cladding interface).

- The drop off in evanescent optical field is exponential (short distances only), but enough that it matters for dispersion… why?

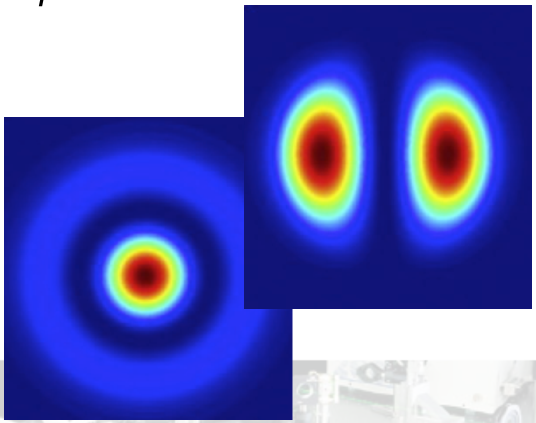
Side view of fiber



Front view: light coming toward you in the fiber (red is peak E-field, dark blue is zero E-field).

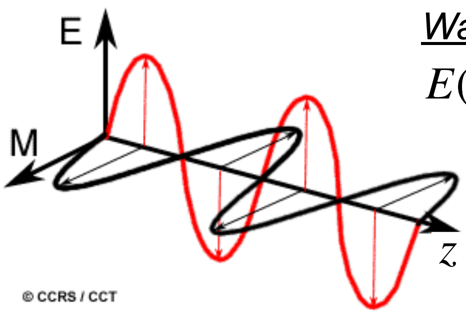


Front view: these also travel 'straight' through the fiber but the E-field distributions represent different modes… *Why would this cause data pulse broadening if we have several of these modes of propagation in our data pulse?*



- How many of you remember this from the Optoelectronics course? How many understand it?

- Let's demystify the mode chart!



Wave equation

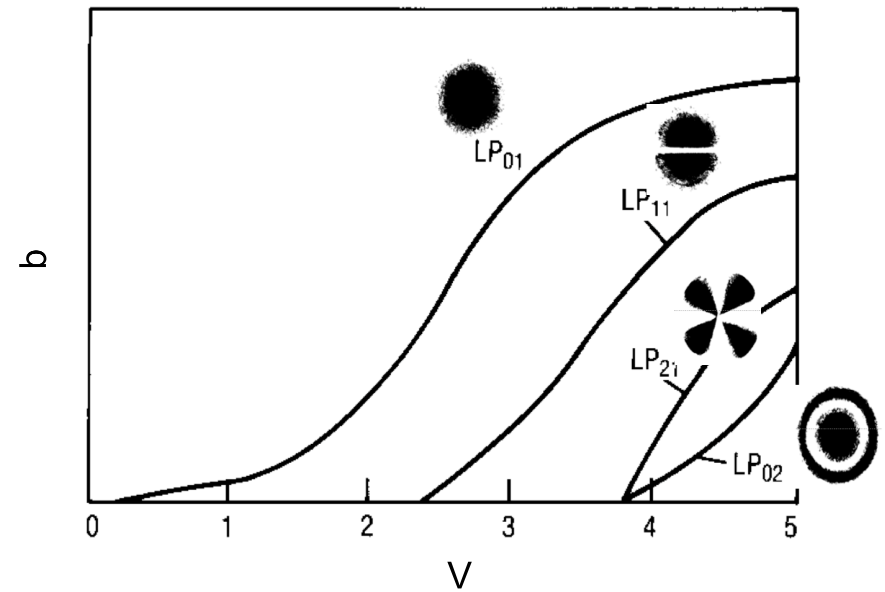
$$E(z,t) = E_0 \cos(wt - kz)$$

Angular frequency

$$w = 2\pi f$$

Wave number or propagation constant

$$k = 2\pi / \lambda$$



$$E(r,\phi,z) = f(r)\ \cos(wt - \beta z + \gamma)\ \cos(q\phi)$$

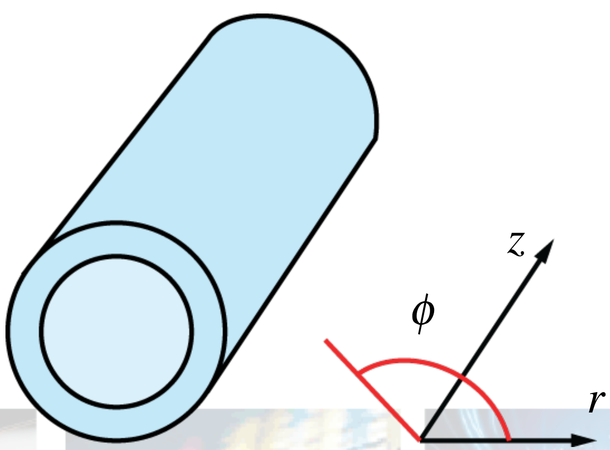
$f(r)$ *Bessel function*

β $2\pi / \lambda$ (*like k but projected onto z*)

γ *just a phase const.*

q *integer*

(1) Solve Maxell's equations for photon propagation in a cylindrical system. Volunteers?



- Take this system, confine it, and we will achieve only a few allowable propagation modes (analogous to a quantum well)

- All the mode chart tells us is what modes exist!

'size' of light
- λ↑ V↓ *less modes!*
- λ↓ V↑ *more modes!*

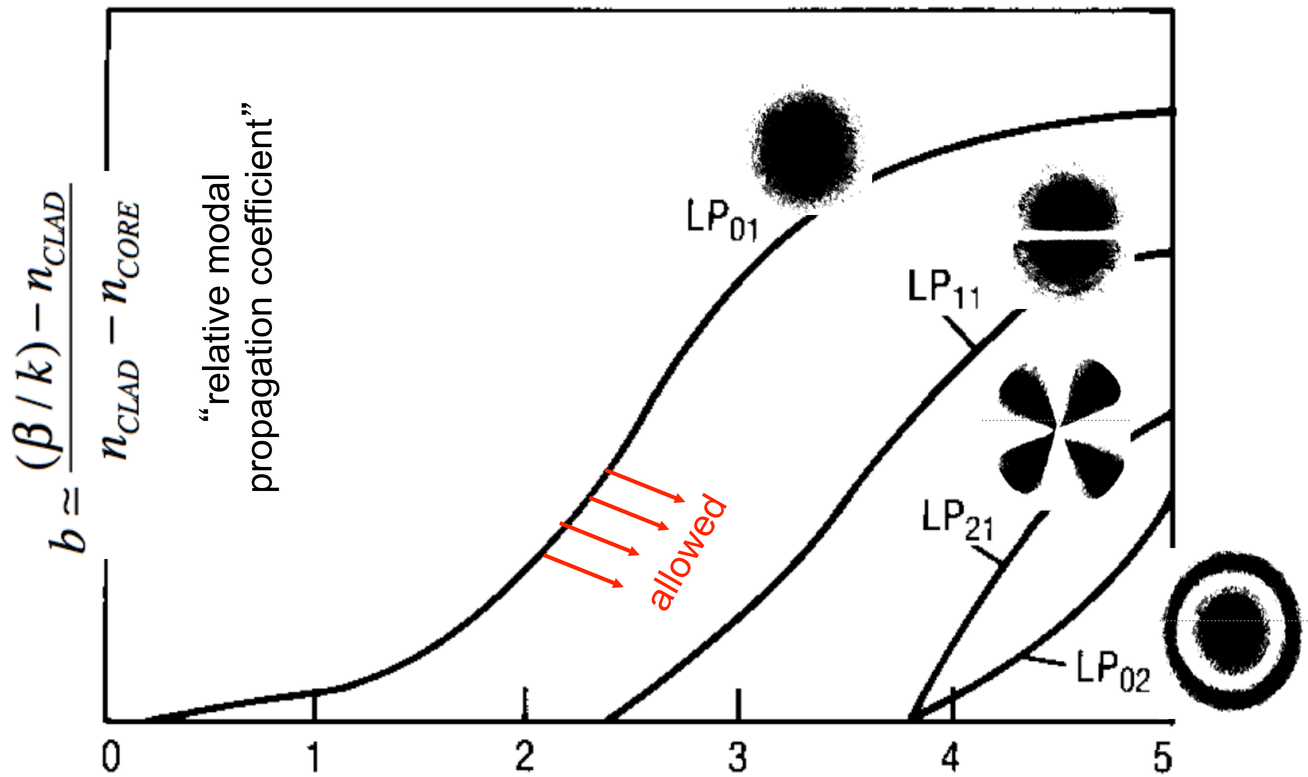
confinement…
- Δn↓ b↑ *less modes!*
- Δn↑ b↓ *more modes!*

…same effect for NA!

core radius (a)…
- a↑ V↑ *more modes!*
- a↓ V↓ *less modes!*

etc…

remember, less modes
= less broadening of data pulse!



$$V = \frac{2\pi}{\lambda_0} \times a \times NA$$

dimensionless "V-number"

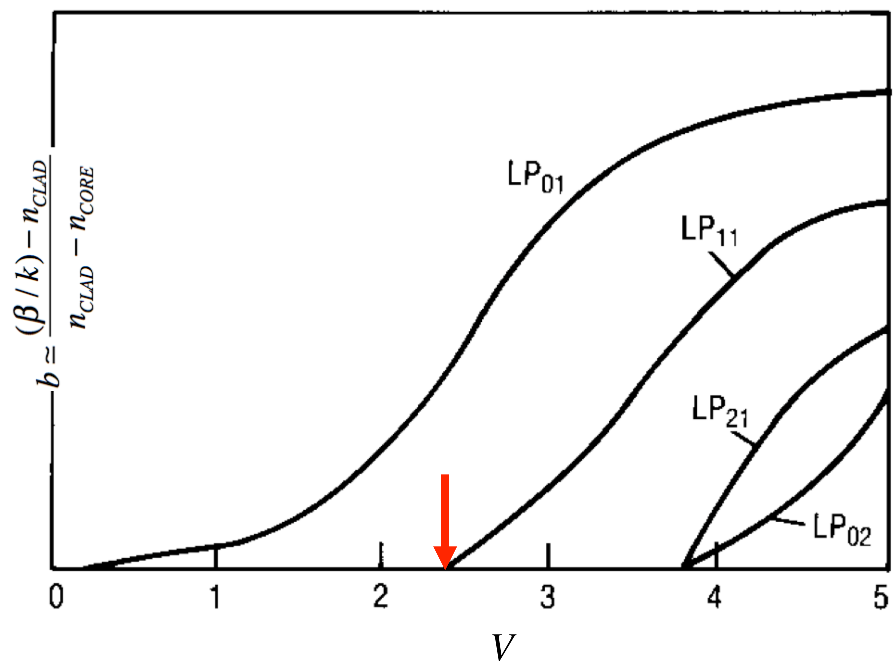
- If there are LOTS of modes (large V), the calculation is quite easy…

$$V = 2\pi \frac{a}{\lambda} NA \qquad M \approx \frac{4V^2}{\pi^2}$$

- Silica fiber n_1=1.452, n_2=1.442, 850 nm Laser, and core radius a=25 μm:

$$NA = \sqrt{n_1^2 - n_2^2} = 0.205$$
$$V = 37.9$$
$$M = 585$$

- Remove the cladding and M>13,800, why?

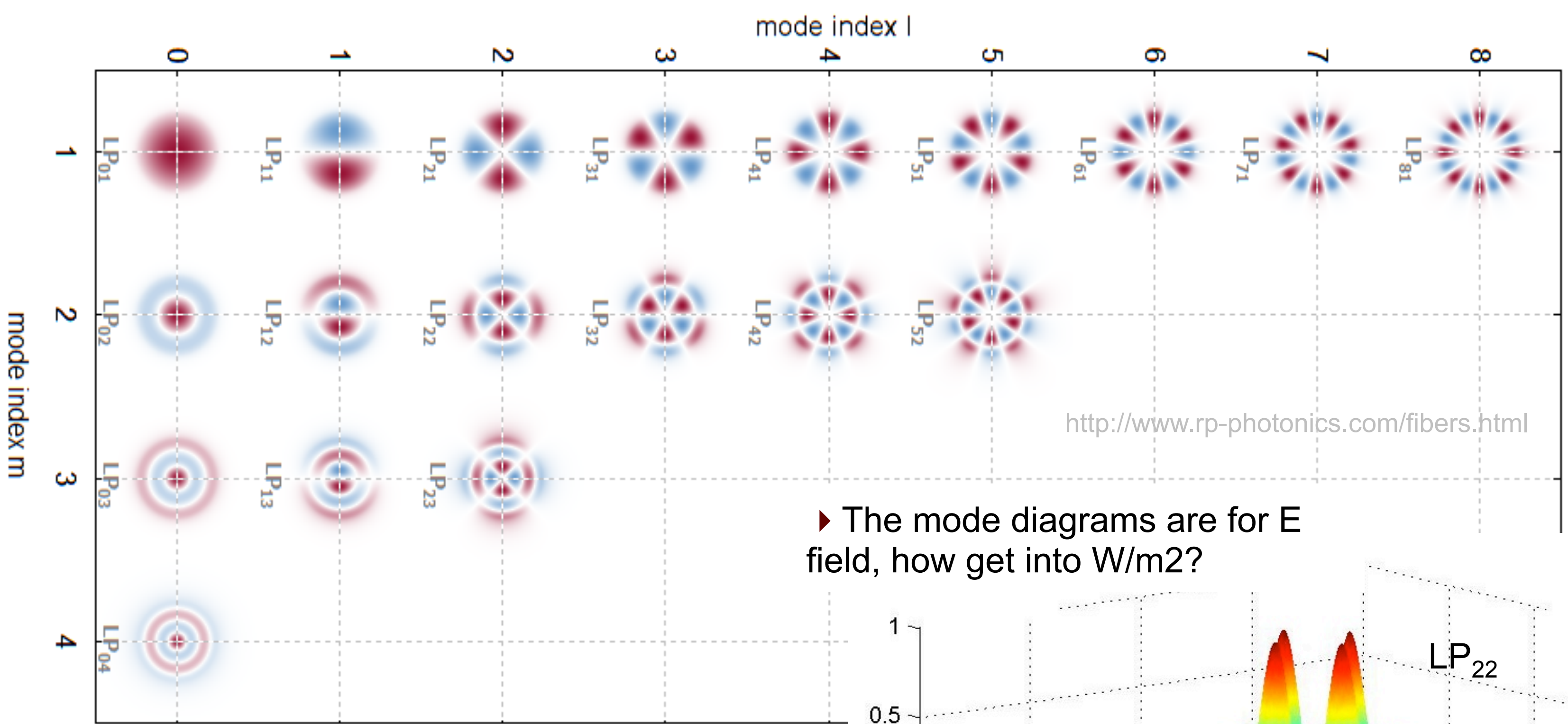


- So, you want a true single mode fiber? That means ONLY the LP_{01} mode which has a V-number cutoff at V<2.405. Lets calculate it…

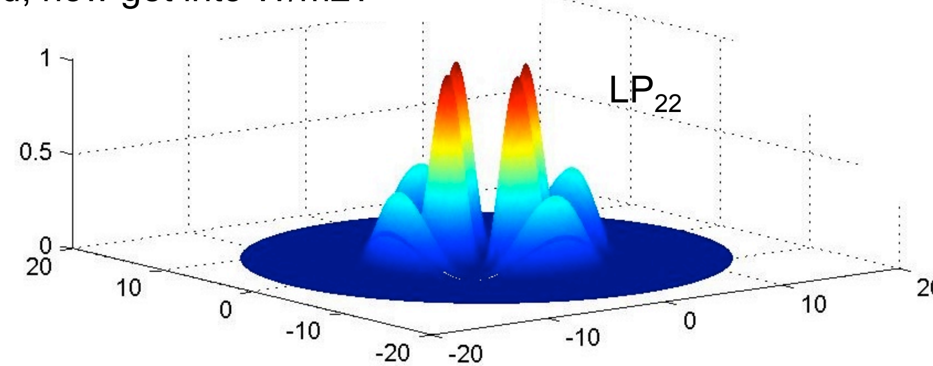
- Silica fiber n_1=1.447, n_2=1.437, 1.3 μm Laser…

$$V = 2\pi \frac{a}{\lambda} NA < 2.405$$
$$2\pi \frac{a}{1.3\ \mu m}(0.205) < 2.405$$
$$a < 4.86\ \mu m$$

- Reduce refractive index difference to 0.0025 (by 4X) and a < 9.72 μm (2X).



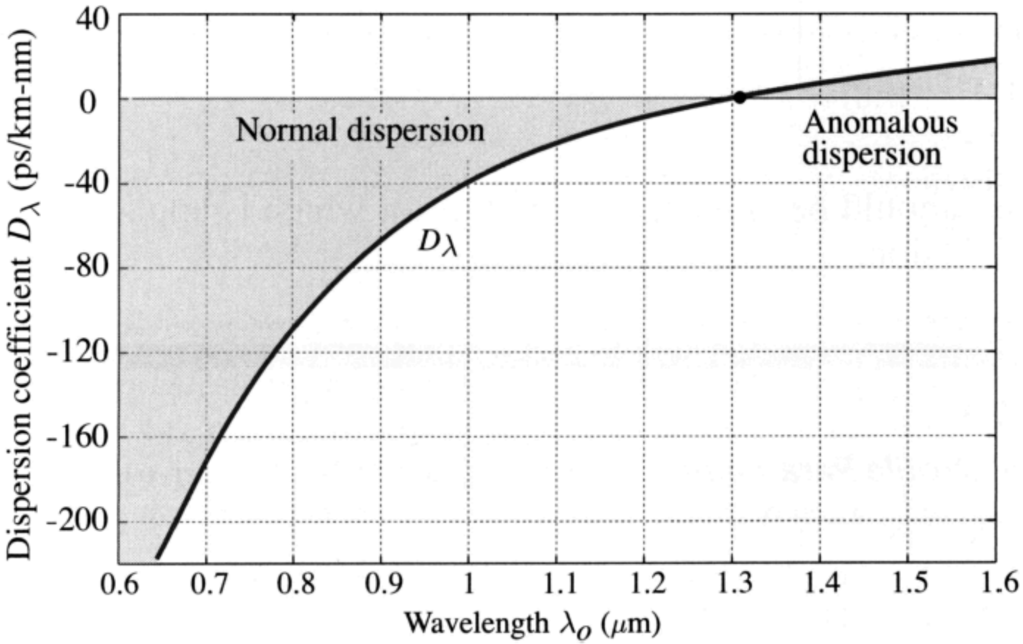
- The mode diagrams are for E field, how get into W/m2?



- The l and m characterize the azimuthal and radial distributions…
- Moreover, each mode can have two polarizations, which matters if detector is polarization dependent…
- Can also get superposition of two or more modes too (will see in lab)
- How often to you get to ‘SEE’ the Fourier transform, or ‘SEE’ the optical equivalent of quantum confinement!

- Standard telecom fibers exhibit zero dispersion at 1.3-μm wavelength. This was convenient for early optical fiber systems.

- However, the 1.5-μm region later became more important, because of lowest loss and because this matches the wavelength of the best fiber amplifiers!



- But what about dispersion???? Dispersion-shifted fibers have been developed, which have modified waveguide dispersion so as to shift the zero dispersion wavelength to 1.5-μm region (see below, look for 'zero' on y-axis).

- This is achieved by modifying the refractive index profile of the core. Common index profiles of dispersion-shifted fibers have a triangular, trapezoidal or Gaussian shape.

http://www.rp-photonics.com/dispersion_shifted_fibers.html

- The number of modes in a fiber increases (which is bad for max data rate!) as:

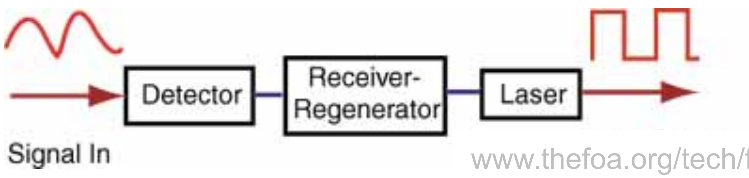
(a) The fiber diameter increases.
(b) The numerical aperture increases (think about this one…).
(c) The wavelength of light decreases.
(d) All the above.

- A photon which has more of its E-field penetrating into the cladding of a fiber will:

(a) Travel faster.
(b) Travel slower.
(c) No change.
(d) All of the above are possible.

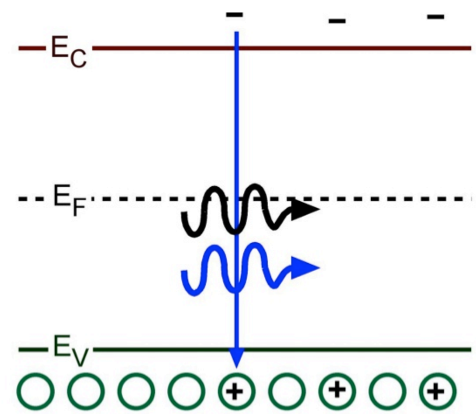
- Whew! That's enough. Lets take a break!

- Last topic, amplification… this approach below is not good, why?

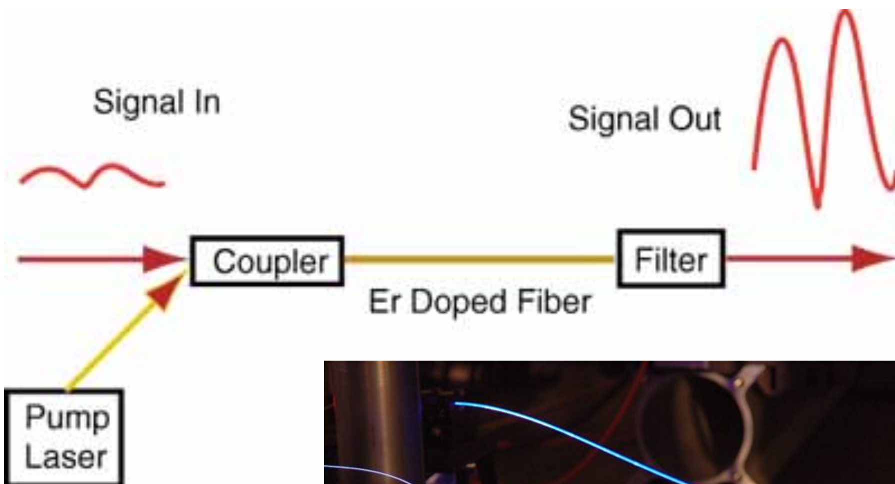


www.thefoa.org/tech/fiberamp.htm

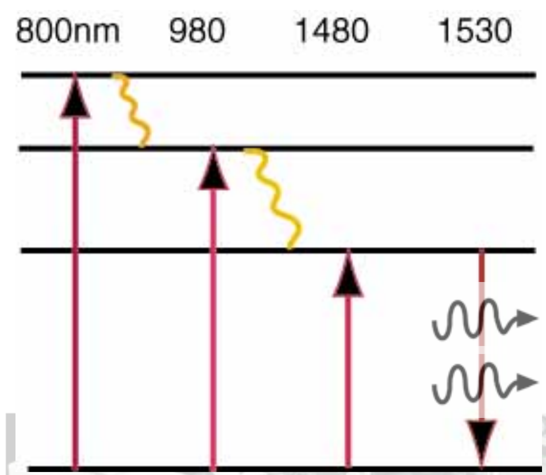
Stimulated emission (semicond.)



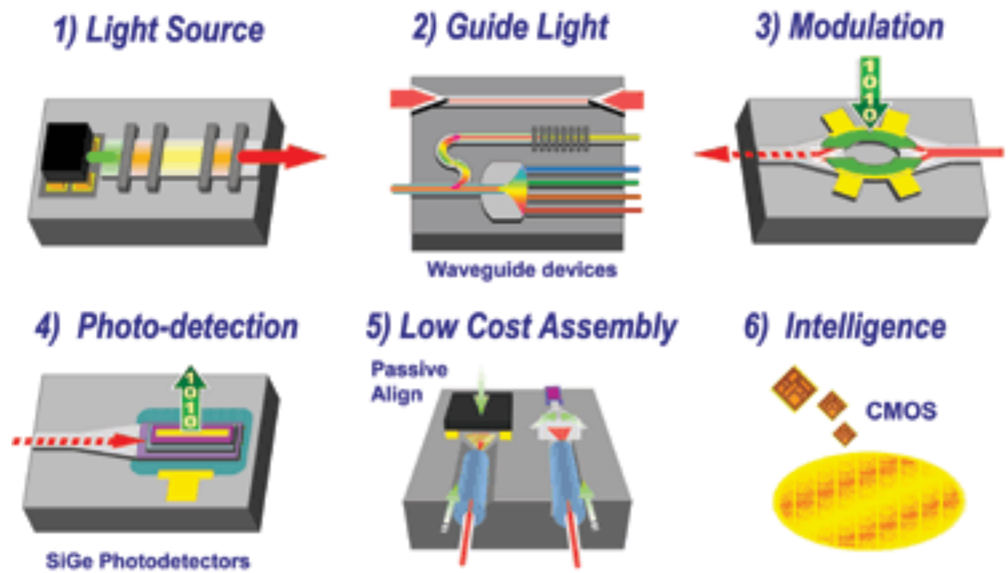
- Need a fiber amplifier! (like a LASER with no mirrors)

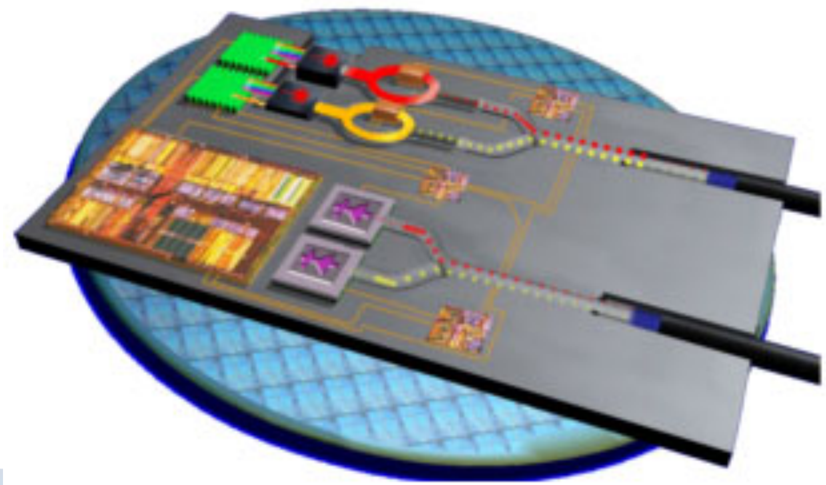


Stimulated emission at 1.5 μm (Erbium)

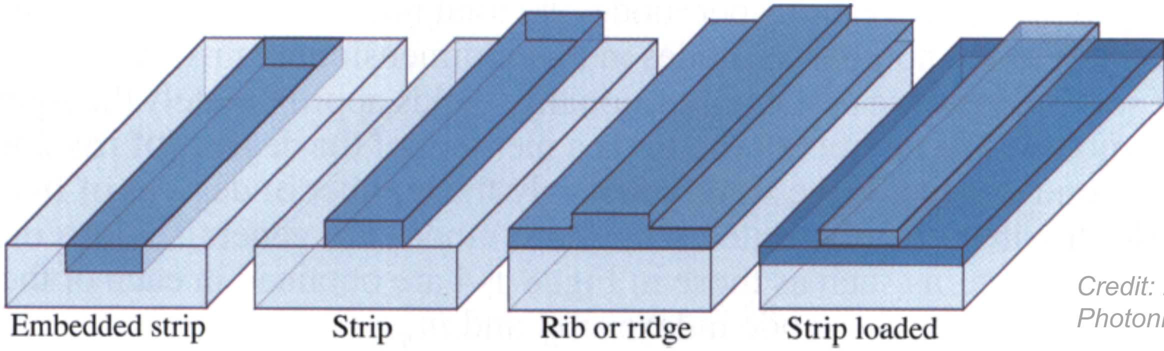


- Silicon Photonics – can you bring more ‘speed of light’ functionality onto Si chips?!





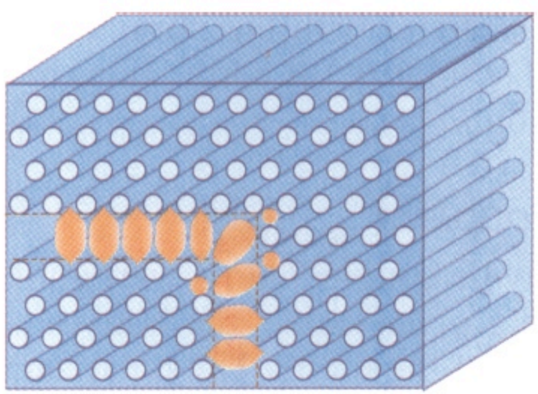
- You can make waveguides that work great, without them being circular, just need higher refractive index region where you want to propagate, or near where you want to propagate!



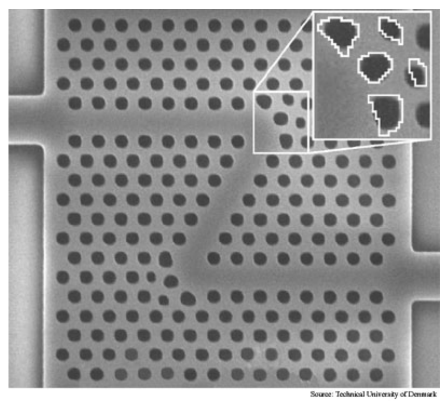
Credit: Fund. Photonics

- *For a high density circuit, what is the major issue though?*

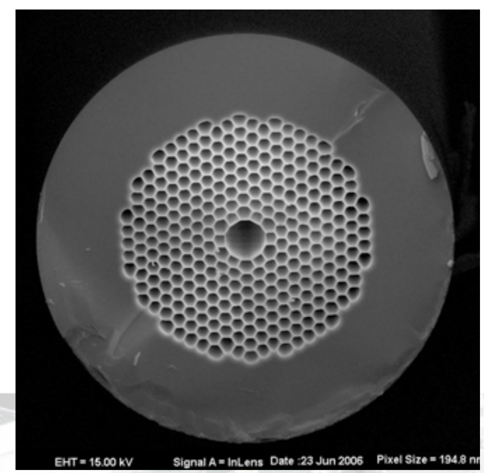
- However, in a circuit, you need to turn 90 degree corners (can exceed TIR, bend loss), so you really need Photonic Crystal waveguides… (100% based on interference).



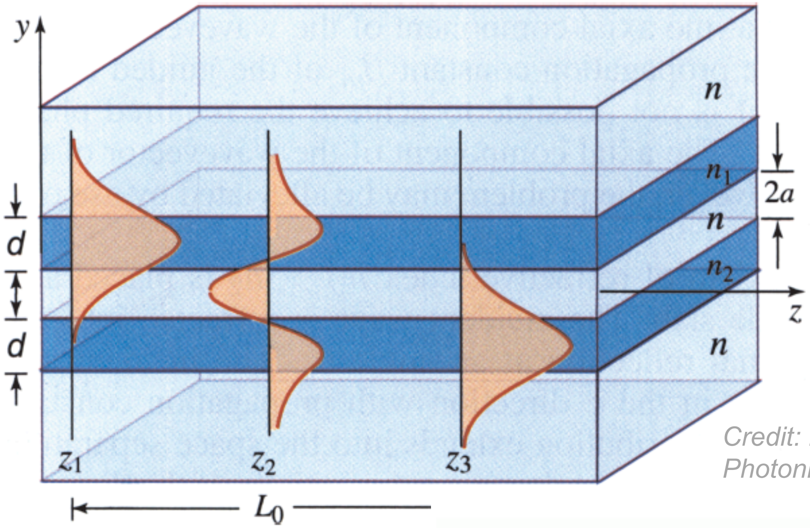
Credit: Fund. Photonics



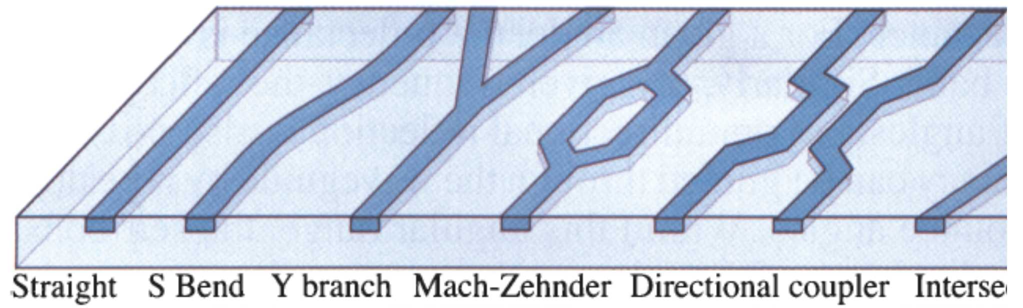
- *Check this out! They use this to reduce fiber dispersion… how?*



- Evanescent optical field penetration into an adjacent waveguide can transfer the optical mode over to that waveguide… (directional coupler).



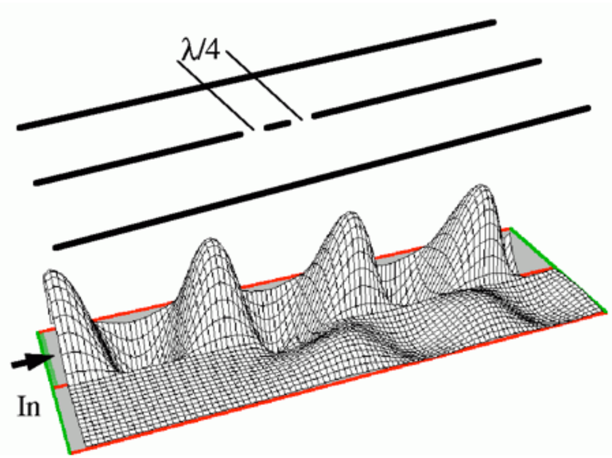
Credit: Fund. Photonics

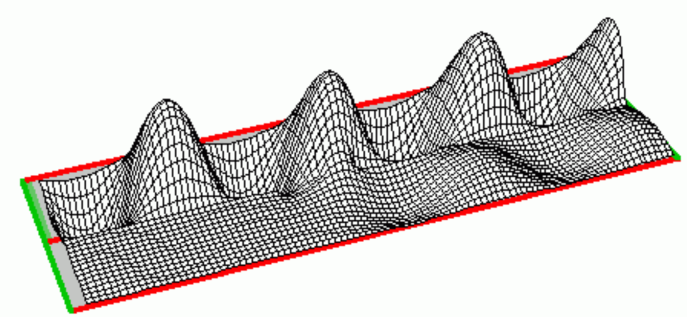


- The Mach-Zhender Inteferometer is a great way to modulate an optical signal (10101110..), put electrodes on one 'arm' to slightly change n, how does it work?

- Here is a μ-wave directional coupler in action… if want full power transfer, what to do?

Note: is animated in powerpoint version.





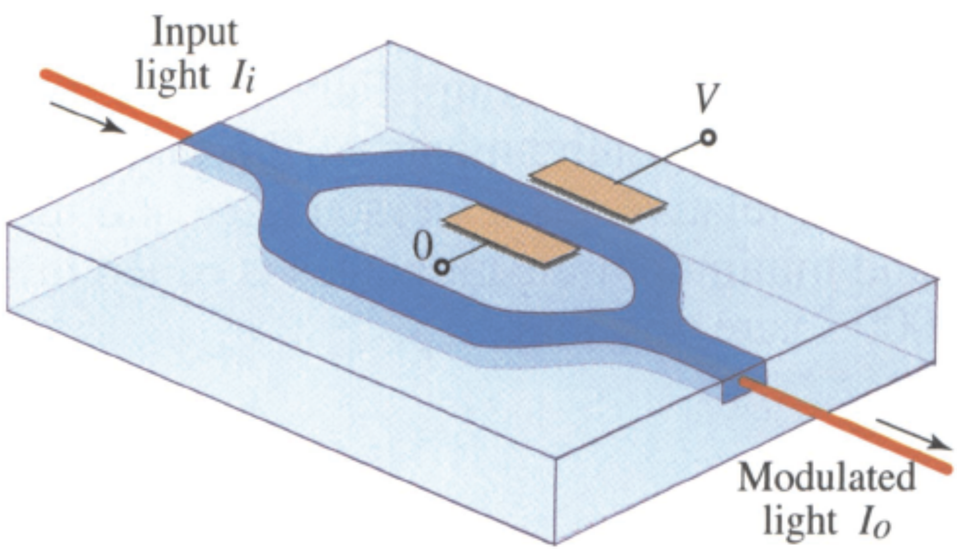
Wolfgang Menzel, Fellow, IEEE

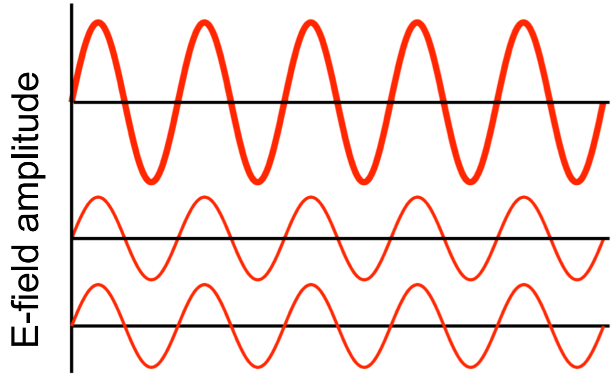
Microwave Techniques, University of Ulm

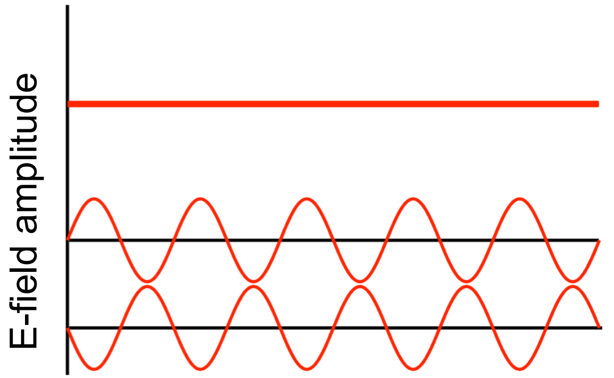
- How to create a stream of optical 1's and 0's?

- You could try to turn the laser ON and OFF really fast, but because of capacitance and other delays, you typically can't switch the laser as fast as you want…

- Instead a Mach-Zhender waveguide inteferometer is a great way to modulate an optical signal (10101110..), put electrodes on one 'arm' to slightly change n, how does it work?







- An optical amplifier is often used for boosting an attenuated optical signal because:

(a) It is able to fix any dispersion in the light.
(b) It amplifies at the speed of light with no delay.
(c) be utilized to 'clean up' imperfections created on a laser beam by sharp features such as scratches on lenses and mirrors, etc..
(d) all the above.

- The highest speed optical data is typically created by:

(a) Switching an LED on and off.
(b) Switching an Laser on and off.
(c) Feeding an Laser into a waveguide interferometer.
(d) Wiggling a fiber with your hand in and out of the path of an incoming laser beam

- We are now done!

- See table at right, WDMs are the fastest, what are they??

Hint, note the number of 'channels' and Google search for 'Wavelength Division Multiplexing'.

Year	Organization	Effective speed	WDM channels	Per channel speed	Distance
2009	Alcatel-Lucent[7]	15 Tbit/s	155	100 Gbit/s	90 km
2010	NTT[8]	69.1 Tbit/s	432	171 Gbit/s	240 km
2011	KIT[9]	26 Tbit/s	1	26 Tbit/s	50 km
2011	NEC[10]	101 Tbit/s	370	273 Gbit/s	165 km
2012	NEC, Corning[11]	1.05 Petabit/s	12 core fiber		52.4 km