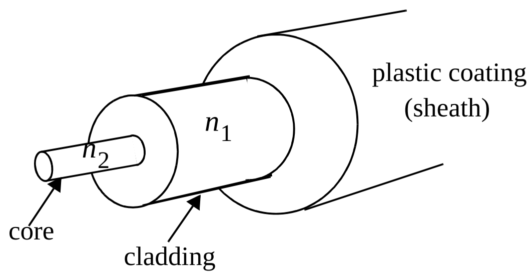
Chapter 9
GUIDED WAVE OPTICS

[Reading Assignment, Hecht 5.6]

Optical fibers

The step index circular waveguide is the most common fiber design for optical communications

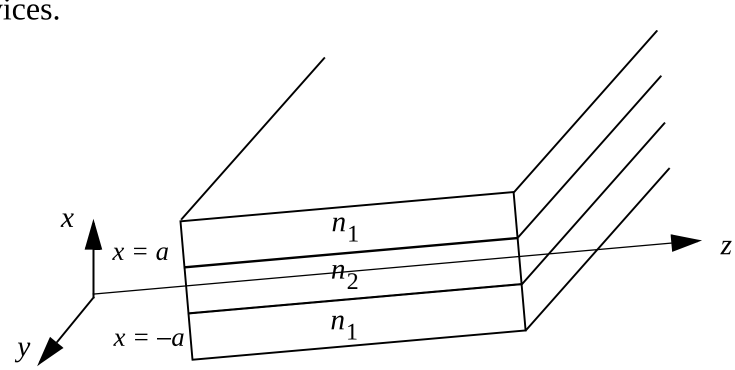


For guiding to occur, we will see that the necessary condition is that $\boxed{}$.

For communications, optical fibers offer extraordinary advantages over either free-space radio, or coaxial cable as a transmission medium:

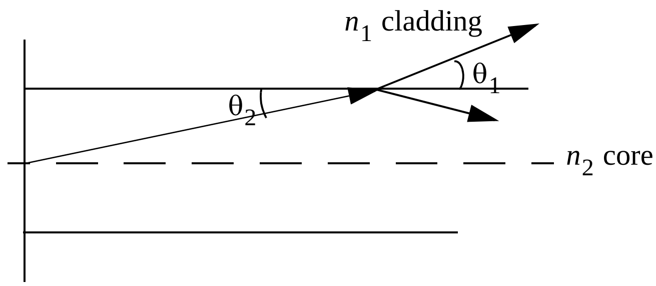
1. low loss
2. no crosstalk between fibers
3. no electromagnetic interference
4. small, light, flexible
5. huge bandwidth

For analysis simplicity – we consider an infinite slab waveguide. This allows us to perform a simpler 2D analysis in Cartesian coordinates. However, this planar waveguide configuration is not just academic - this is the structure used in double-heterostructure laser diodes and other integrated optical devices.



Consider 2D analysis
(infinite in y-direction)

<u>We first consider a ray optics analysis:</u>



By Snell's law Note: not our usual definition of the angles

Note the use of the grazing angle (angle with respect to the surface) instead of the incidence angle (angle with respect to the normal). This leads to the cosine instead of the sine form of Snell's law.

If $n_2 > n_1$, then at the critical angle θ_c

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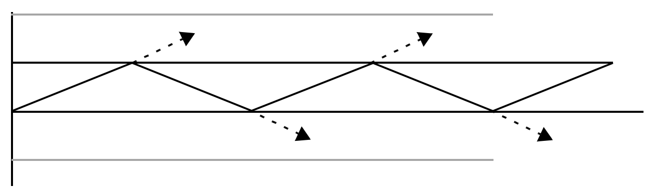
For $\theta_2 < \theta_c$, there is no refracted ray due to total internal reflection.

The ray then reaches opposite interface at same θ_2, and is reflected again:

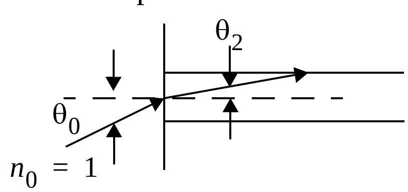


For $\theta_2 < \theta_c$, there is never a transmitted ray at the interface, so there is no loss.

But for $\theta_2 > \theta_c$, light leaks out to the cladding, and there is rapid attenuation along z.

This shows us that the input rays should be at a small angle to be guided.

What about refraction at the input face?



Snell's law at the input face:

For guiding to occur, we then see that there is the following condition on the input angle:

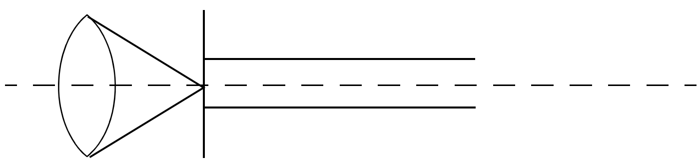
$$\begin{aligned}\sin\theta_0 &< n_2 \sin\theta_c \\ &< n_2(1-\cos\theta_c^2)^{1/2} \\ \sin\theta_0 &< (n_2^2 - n_1^2)^{1/2}\end{aligned}$$

For optical fiber, we also use the concept of numerical aperture, $\mathrm{NA} = \sin\theta_{\max}$. So the NA of the fiber is given simply by: $\boxed{\qquad\qquad\qquad}$.

Example: $n_2 = 1.5 \qquad n_1 = 1.4$

$$\mathrm{NA} = \sqrt{(1.5^2 - 1.4^2)} = 0.54$$

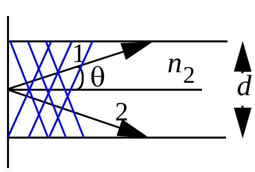
$$\theta_{\max} = 32°$$



The usefulness of this definition is that we can see how large the lens NA should be to efficiently couple light into the fiber.

<u>Wave picture</u>

We can capture much of the wave physics of fibers and waveguides by considering a wave guide with perfectly reflecting walls. The boundary condition on the wall is that the electric field must be zero. The wave equation solutions are then cosines in the transverse direction with an integer number of half-wavelengths between the walls. Different “modes” correspond to varying numbers of these half-wavelengths.



The interference pattern between rays 1 and 2 gives a sinusoidal fringe pattern. This fringe pattern must contain an integer number of half-waves to satisfy the BC.

From the above diagram, we can see the correspondence between the various transverse modes and the propagation angle for the corresponding rays. This can be expressed as

$$2d\sin\theta_m = \frac{(m+1)\lambda}{n_2} \qquad m = 0, 1, \ldots$$

Low order modes propagate at shallower angles than higher order modes. The cutoff angle imposed by θ_c then imposes a mode cutoff. Mode numbers below the cutoff will propagate with low loss, while higher order modes are lost. For reasons we will discuss in a moment, it is often desirable to design the guide such that only the very lowest order mode will propagate, and all higher order modes will be lost. The condition for the second mode (m = 1) to be lost is that $\theta_1 > \theta_c$

The condition for single mode operation is then

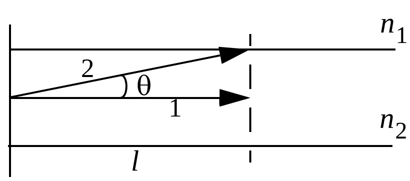
Take $\lambda = 1.3\mu m$, $n_2 = 1.45$, $n_1 = 1.4$

$\theta_c = 0.26$ rad, $d < 3.4\mu m$

Modal dispersion

One of the main advantages of single-mode fiber is that modal dispersion is eliminated. The "effective" speed of propagation of light in fibers varies for different modes because the total optical path traversed in a given length of fiber by diferent modes is different.

The amount of modal dispersion in multi-mode fiber can be estimated as follows:



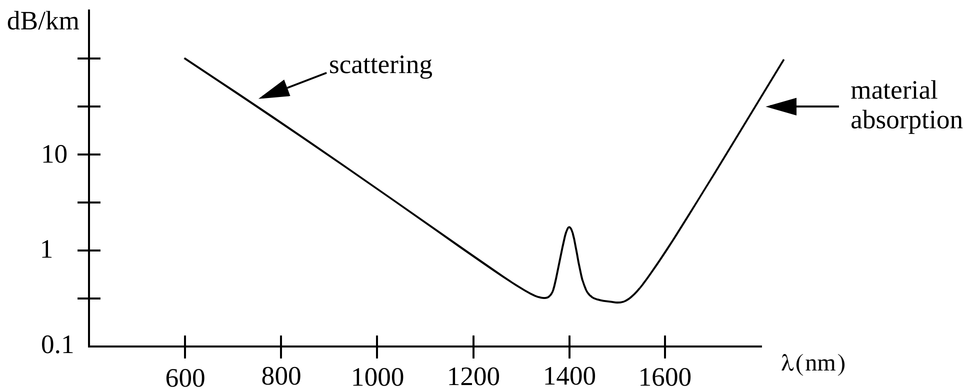
The shortest path through the fiber is taken by ray 1. The longest path is taken by the ray with maximum θ, which is θ_c, where

The path length for ray 2 is $l/\cos\theta$. So the difference in path length is $l/\cos\theta_c = \frac{n_2}{n_1}l$

The propagation velocity is approximately c/n_2, so the time dispersion in a fiber of length L is

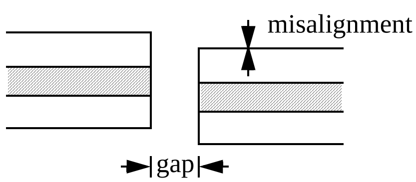
Take $n_2 = 1.45$, $n_1 = 1.4$, $L = 1\ \text{km}$, then $\Delta T = 173\ \text{nsec}$! Today's fiber communication systems are transmitting data at rates up to 10 GHz. If multi-mode fiber is used, then data pulses would become hopelessly spread out by such a large spread in propagation delay down the fiber.

Fiber loss



<u>Fiber optical components</u>

Splices and connectors: Joining 2 fibers (particularly challenging for single-mode fiber)

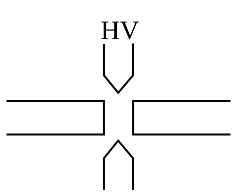


To achieve low loss, the 2 fiber ends must be well-aligned, flat, and parallel.

Cleaver: Score and break fiber end to get flat, or *grind and polish*. Both are commercially available

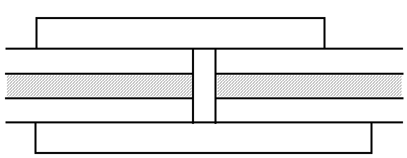
<u>To splice</u>:

fusion splice:

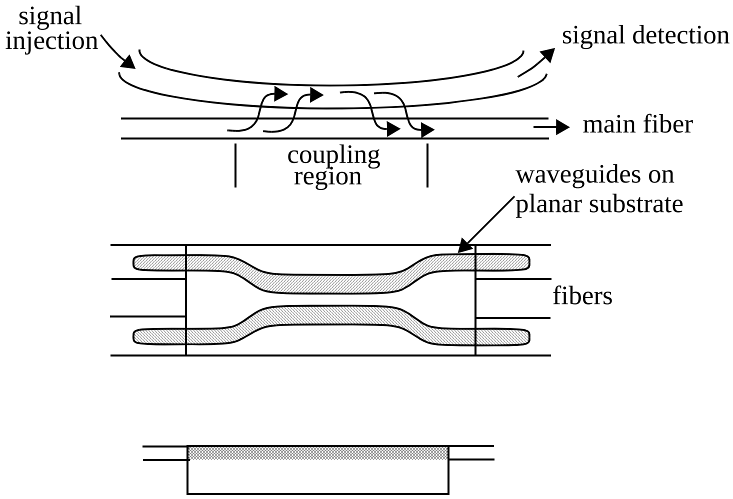


1. align fiber ends
2. fuse by quick melting using a HV arc

Connectors

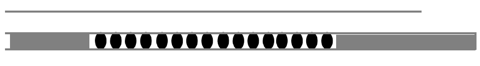


Couplers and waveguide devices

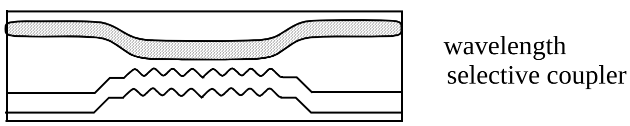


(similar to a free-space beamsplitter)

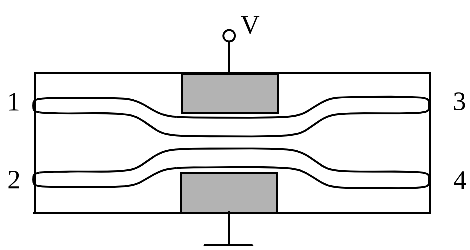
Fiber-grating



Acts as a waveguide-selective element that can be used in planar waveguide devices too.



Switch

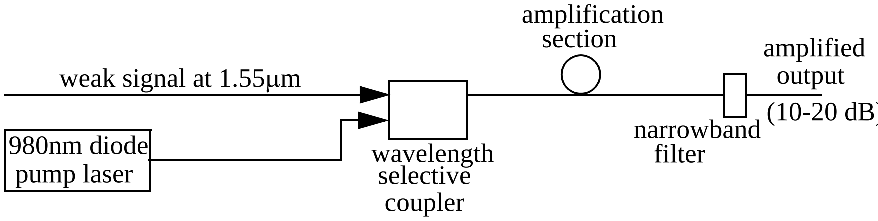


$LiNbO_3$ lithium niobate

electro-optic: index can be varied by application of E-field

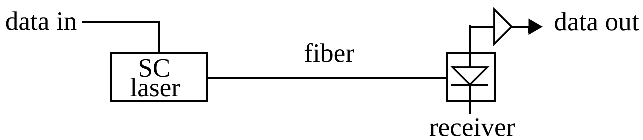
By manipulating the voltage input, 1 can be routed to 3 or 4. Similarly for input 2.

Erbium-doped fiber amplifiers (EDFA)

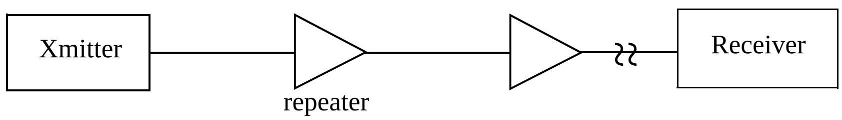


Amplifier uses Er^+ ions doped in the fiber, several meters in length. Pump laser power is 200-300 mW.

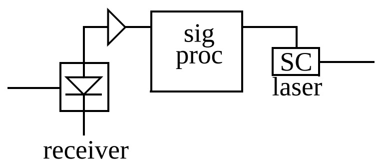
Optical Data Link (ODL)



Long-haul links (e.g., undersea trans-oceanic)

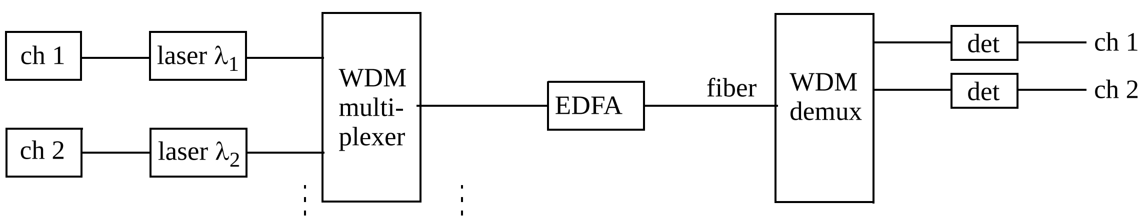


80’s systems – Repeater:

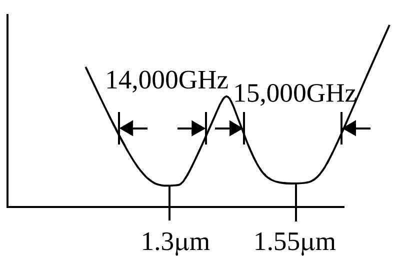


90’s systems: *EDFA repeaters*

Wavelength division multiplexing – Increase bandwidth of installed fiber 1



Fiber loss



Dense WDM (DWDM) wavelength channels ~ 1nm separation.

Current systems: 40 channels, 10 Gbit/sec each!

Future ~ 200 channels

Internet growth fuels demand for DWDM.