OPTICAL COMMUNICATIONS

Free-Space Propagation:

- Similar to radiowave propagation
- Antenna gain, effective area, path loss expressions unchanged

Devices:

- Detectors (review first recitation)
- Sources—LED's, lasers (next lecture?), amplifiers
- Modulators—amplitude and frequency, mixers, switches
- Passive filters, spectral multiplexers and combiners

Guided Wave Propagation (including long lines and device interiors):

- Optical fibers trap and guide waves, attenuate little
- Rayleigh scattering is a loss mechanism, $\propto f^4$, favors $\lambda > 1$-micron
- Rays inside fiber impact wall beyond critical angle
  $\Rightarrow$total reflection, totally lossless (for smooth walls; unlike mirrors)
- Attenuation > ~1? DB/km (depends on fiber architecture, materials, f)

UNDERSEA OPTICAL FIBER CABLES

- Virtually all long-distance telecommunication is now by fiber optics

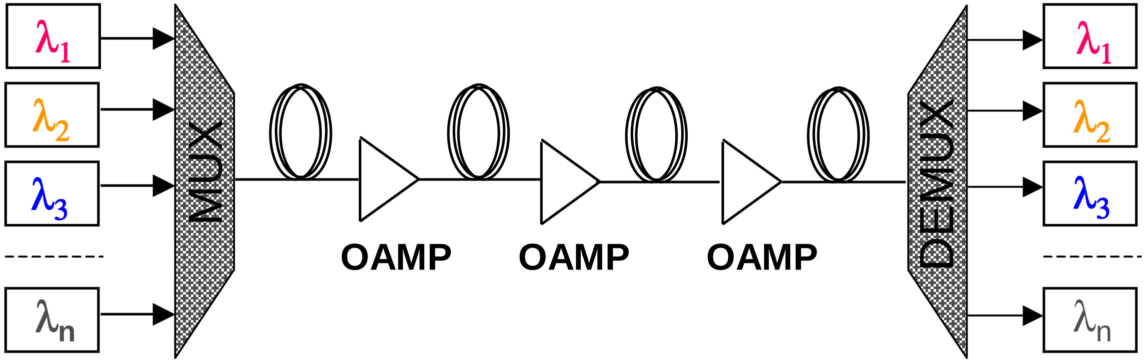
- In-line erbium-doped fiber amplifiers (EDFA’s) make transoceanic transmission possible without repeaters – for many wavelengths at the transmission possible without repeaters – for many wavelengths at the same time in one fiber.

- Without fiber communications there would be no World Wide Web

WDM MULTIPLEXED LINK

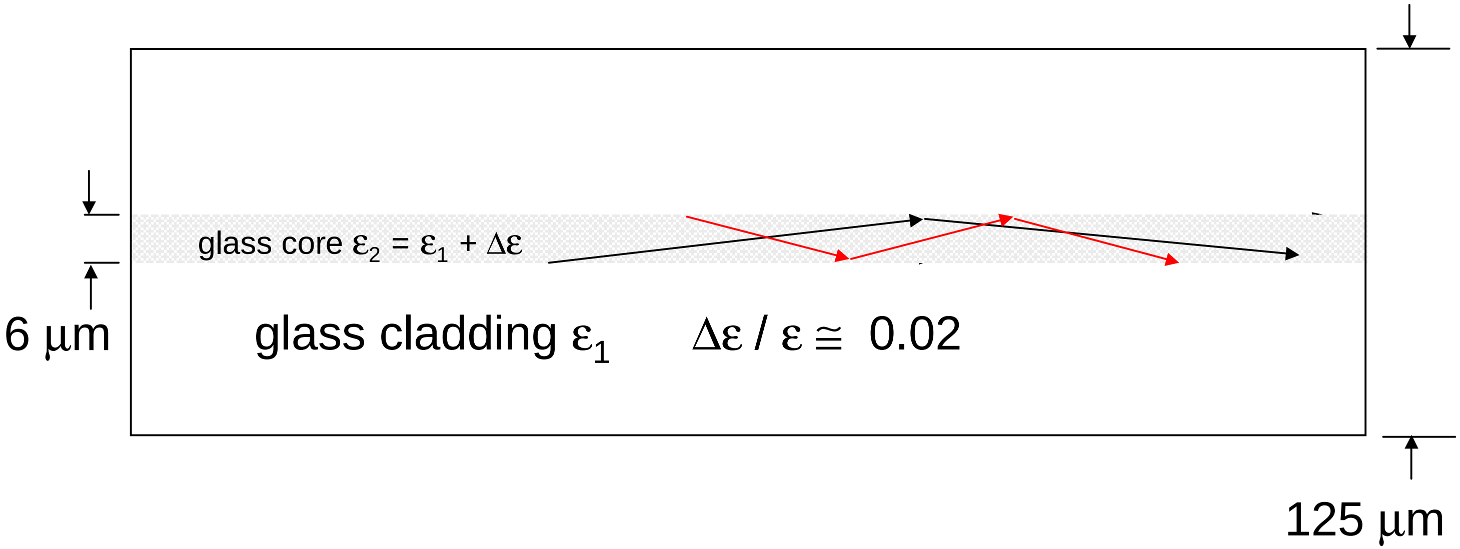
WAVELENGTH DIVISION MULTIPLEXING (WDM):

- Multiple wavelengths combined onto one fiber
- All wavelengths amplified simultaneously and independently in each optical amplifier (OAMP)



WAVES IN FIBERS

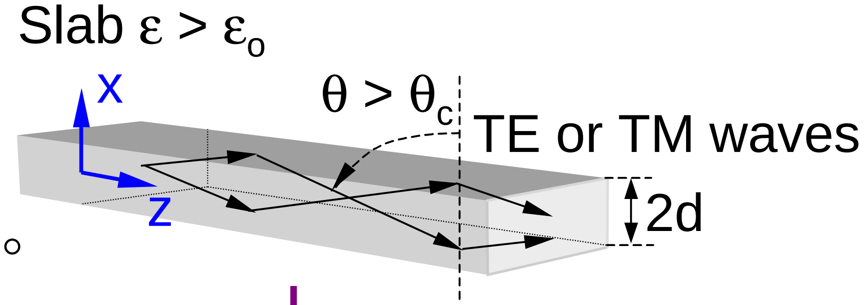
Optical Fiber – Simple Picture:



- Light is trapped by total internal reflection in the higher ε glass core.
- The small difference in ε implies very shallow reflection angles.
- Only certain angles are allowed since the waves must interfere constructively with each reflection => modes.
- Velocity of a mode is determined by the ε's and the core size. (Different modes travel at different velocities.)

OPTICAL WAVEGUIDES

Dielectric slab waveguide example:



Waves reflect beyond critical angle θ_c

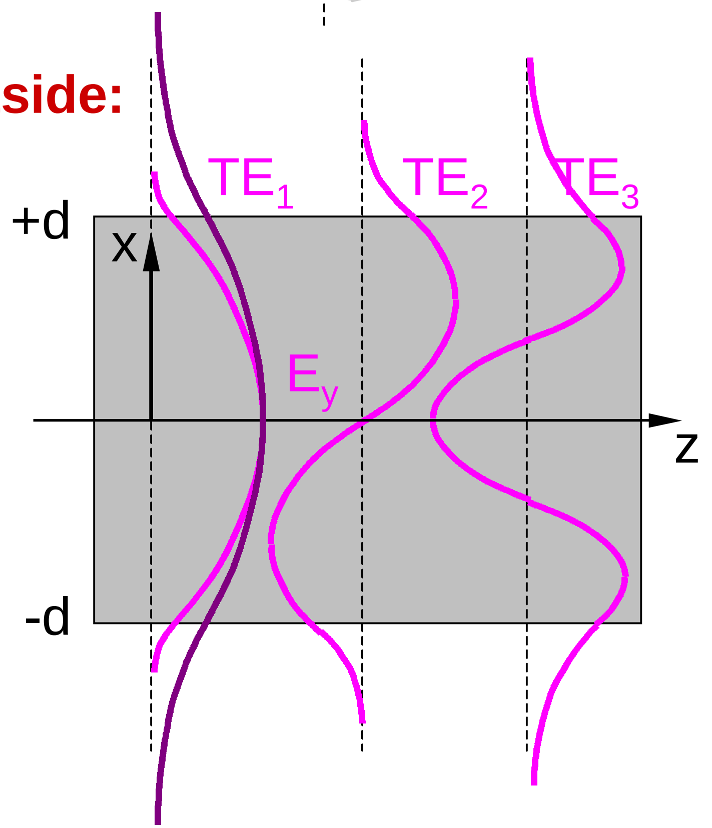
$\theta_c = \sin^{-1}(n_g^{-1})$ where $n_g \cong 1.5 \Rightarrow \theta_c \cong 41.8°$

Standing waves inside guide, evanescent outside:

$$\bar{E} = \hat{y}E_o \begin{Bmatrix} \sin k_x x \\ \cos k_x x \end{Bmatrix} e^{-jk_z z} \qquad |x| \le d$$

and $\bar{E} = \hat{y}\underline{E}_1 e^{-\alpha x - jk_z z}$ for $x > d$,

$\bar{E} = \pm\hat{y}\underline{E}_1 e^{+\alpha x - jk_z z}$ for $x < -d$



Evanescent region:

Decays more rapidly for lower modes and higher frequencies

Boundary conditions:

$\bar{E}_{//}$ and $\partial E_y/\partial x$ continuous for TE$_n$ $\quad \nabla \times \bar{E} = \bar{z}\partial E_y/\partial x - \bar{x}\partial E_y/\partial z = -\partial \bar{H}/\partial t$

ELECTROMAGNETIC FIELD DISTRIBUTION

Magnetic Field Distribution: $\overline{H} = -(\nabla \times \overline{E})/j\omega\mu_o$ (for TE$_1$, TE$_3$, etc.)

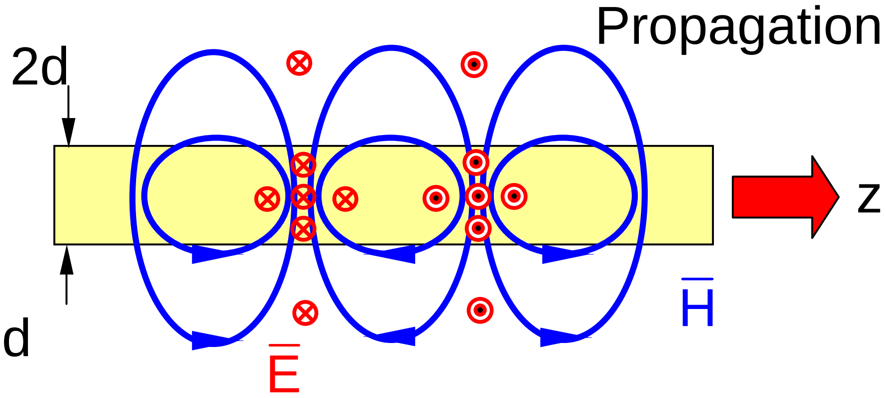
Inside the slab:

$$\overline{H} = (E_o/\omega\mu)\left(-\hat{x}k_z\begin{Bmatrix}\sin k_x x\\ \cos k_x x\end{Bmatrix} - \hat{z}jk_x\begin{Bmatrix}-\cos k_x x\\ \sin k_x x\end{Bmatrix}\right)e^{-jk_z z} \quad \text{for } |x| < d$$

Outside the slab:

$$\overline{H} = (E_1/\omega\mu_o)(-\hat{x}k_z - \hat{z}j\alpha)e^{-\alpha x - jk_z z} \quad \text{for } x > d$$

Matching Boundary Conditions:



Phase: $k_x^2 + k_z^2 = \omega^2\mu\varepsilon$ inside the slab, $|x| < d$

$-\alpha^2 + k_z^2 = \omega^2\mu_o\varepsilon_o$ outside, $x > d$

Continuity of $\overline{E}$ at $x = d$: $E_o \cos k_x d e^{-jk_z z} = E_1 e^{-\alpha d - jk_z z}$ for TE$_{1,3,5...}$

Continuity of H_z at $x = d$: $(-jk_x E_o/\omega\mu)\sin k_x d e^{-jk_z z} = -(j\alpha E_1/\omega\mu_o)e^{-\alpha d - jk_z z}$

Therefore: $k_x d \tan k_x d = \mu\alpha d/\mu_o$ (ratio of continuity equations)

$k_x^2 + \alpha^2 = \omega^2(\mu\varepsilon - \mu_o\varepsilon_o)$ (from dispersion equations)

SOLUTIONS FOR TE$_{\text{odd } n}$ DIELECTRIC SLAB WAVEGUIDES

Field Continuity Equations:

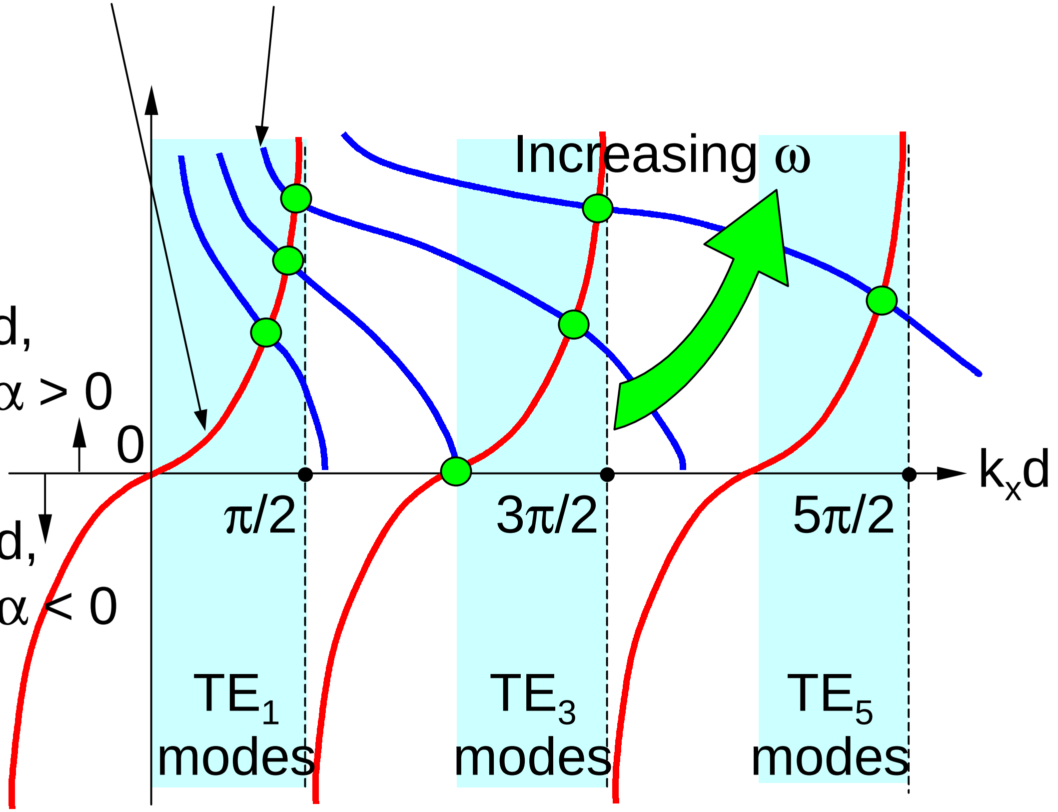
$k_x d \tan k_x d = \mu\alpha d/\mu_o$ (ratio of continuity equations)

$k_x^2 + \alpha^2 = \omega^2(\mu\varepsilon - \mu_o\varepsilon_o)$ (from dispersion equations)

Transendental Equation:

$$\tan k_x d = (\mu/\mu_o)([\omega^2(\mu\varepsilon - \mu_o\varepsilon_o)d^2/k_x^2d^2] - 1)^{0.5}$$

Graphical solution:

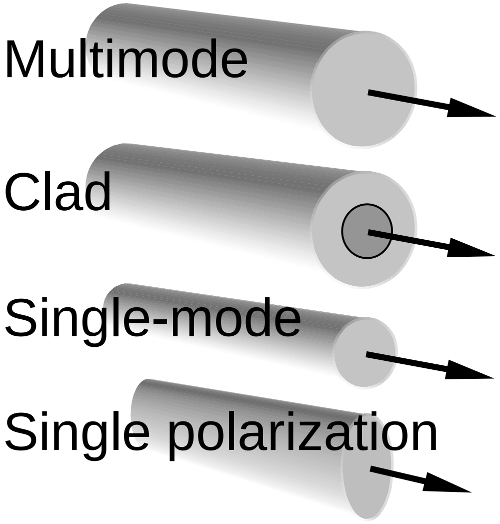


No trapped,
Solutions α > 0

No trapped,
Solutions α < 0

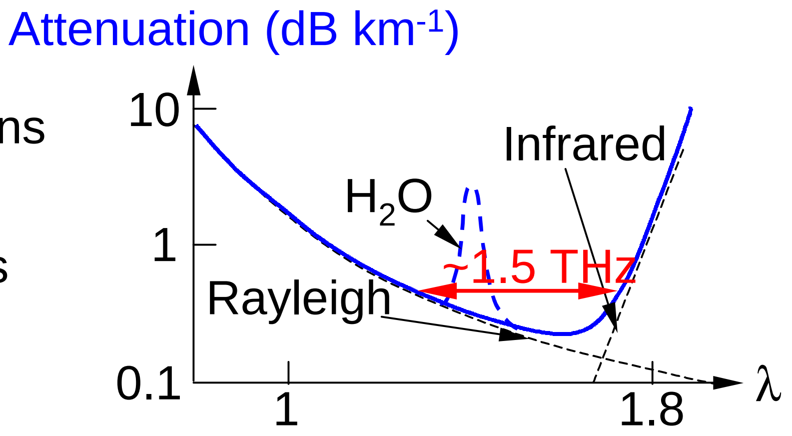
Optical Fibers:

Bessel functions
Similar modes



FIBER WAVEGUIDE DESIGN

Loss Mechanisms:



Rayleigh scattering from random density fluctuations

Loss $\propto f^4$ (scattering makes sky blue)

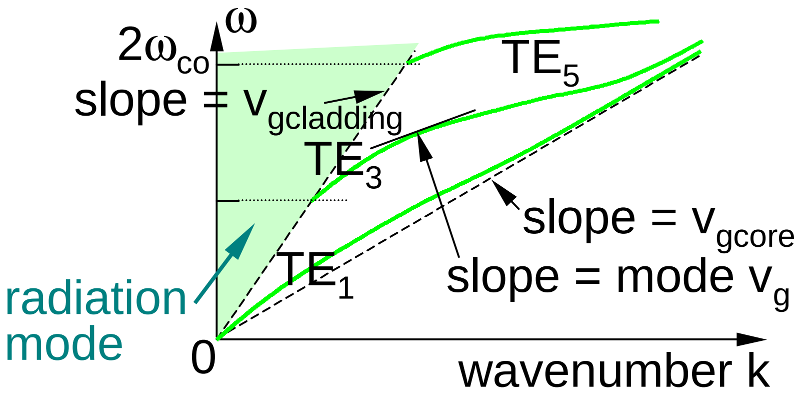
Infrared absorption dominates for $\lambda >$ ~1.6 microns

Minimum total attenuation $\cong$ 0.2 dB km^{-1}

Construction:

Typical:	10-micron core in 125-micron diameter glass, with 100-micron-thick plastic protective cladding (bundled in cables)
Manufacturing:	Solid or hollow preform grown by vapor deposition of SiO_2 and GeO_2 (using e.g. $Si(Ge)Cl_4 + O_2 = Si(Ge)O_2 + 2Cl_2$)

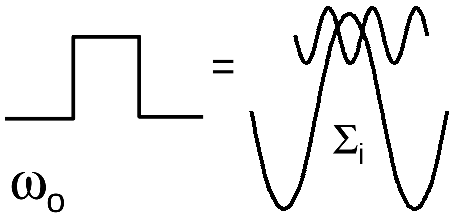
Pulses Spread Due to Dispersion:



Group Velocity:	Want $v_g(f) \cong$ constant, so Want flat $k(\omega)$ [$n = k/\omega + n_o$]
Dispersion:	Determined mostly by $\varepsilon(f)$, modified by $\varepsilon(r)$ of fiber

EFFECTS OF DISPERSION

Pulse Spreading:



Distortion: Square pulse envelope is sum of harmonics--
Want all f_i to have same group velocity; $\Delta\omega << \omega_o$

Equation: $k = \beta_o\omega_o + \beta_1(\omega - \omega_o) + \beta_2(\omega - \omega_o) + \ldots$ where

$$\beta_o = k/\omega_o = v_p^{-1} = n/c$$
$$\beta_1 = dk/d\omega_o = v_g^{-1} = (1 + [\omega/n]dn/d\omega)n/c$$
$$\beta_2 = d^2k/d\omega^2 = dv_g^{-1}/d\omega = (2dn/d\omega + \omega\, d^2n/d\omega^2)/c \ \{\text{set to 0 at } \omega_o\}$$

Non-linearities:

Avoid spikes:	Large amplitudes generate harmonics at nonlinearities
Large amplitudes:	Desired to lengthen distance between amplifiers
Nonlinearities:	Occur in amplifiers and during propagation
One remedy:	Disperse signals initially (e.g. with grating) so fiber dispersion cancel this initialization over its entire length; Spikes reappear at end when signal is weak