# 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

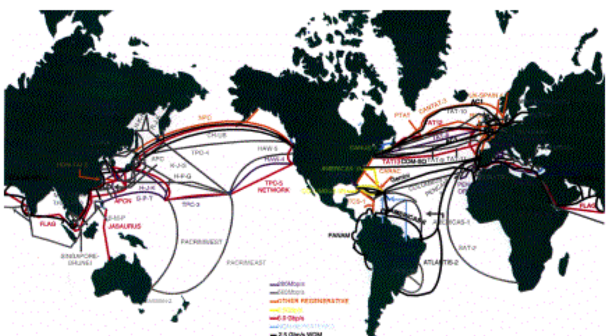
## Guided Wave Propagation (including long lines and device interiors):

- 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)

L18-1

# UNDERSEA OPTICAL FIBER CABLES

Fiber Communications Around the Globe



Terrestrial systems – too numerous to depict Tyco Submarine Systems, 2000

- 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 same time in one fiber.
- Without fiber communications there would be no World Wide Web

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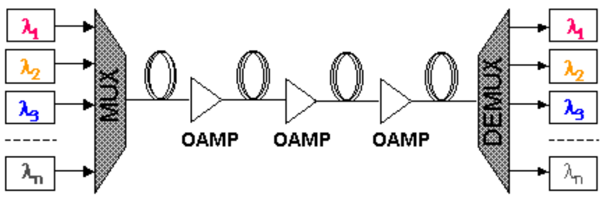
# WDM MULTIPLEXED LINK

## WAVELENGTH DIVISION MULTIPLEXING (WDM):

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

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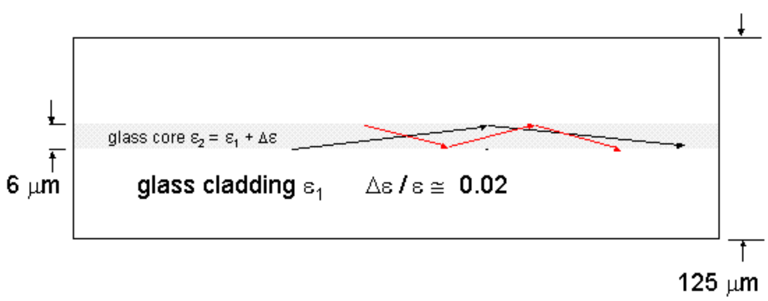
# WAVES IN FIBERS

## Optical Fiber – Simple Picture:




- Light is trapped by total internal reflection in the higher $\varepsilon$ glass core.
- The small difference in $\varepsilon$ 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 $\varepsilon$'s and the core size. (Different modes travel at different velocities.)

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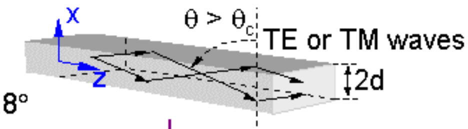
# OPTICAL WAVEGUIDES

**Dielectric slab waveguide example:**

Waves reflect beyond critical angle $\theta_c$

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

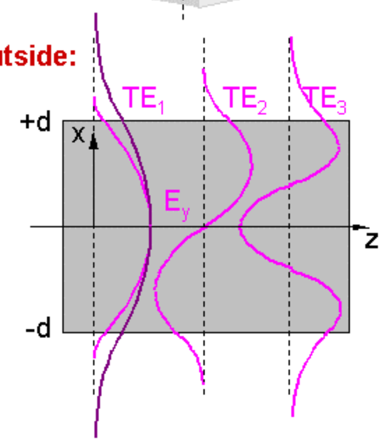



**Standing waves inside guide, evanescent outside:**

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

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

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




**Evanescent region:**

Decays more rapidly for lower modes and higher frequencies

**Boundary conditions:**

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

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# ELECTROMAGNETIC FIELD DISTRIBUTION

**Magnetic Field Distribution:** $\bar{H} = -(\nabla \times \bar{E})/j\omega\mu_o$ (for $TE_1$, $TE_3$, etc.)

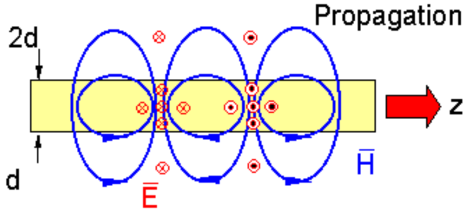
Inside the slab:

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

Outside the slab:

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

**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 $\bar{E}$ 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: $\quad k_x d \tan k_x d = \mu\alpha d/\mu_o$ (ratio of continuity equations)
$\quad k_x^2 + \alpha^2 = \omega^2(\mu\varepsilon - \mu_o\varepsilon_o)$ (from dispersion equations)

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## SOLUTIONS FOR $TE_{odd\ n}$ DIELECTRIC SLAB WAVEGUIDES

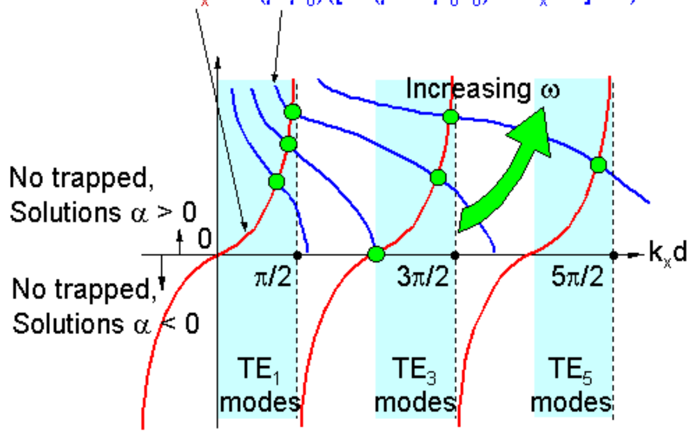
**Field Continuity Equations:**

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

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

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

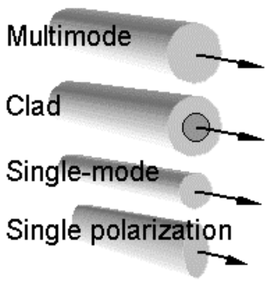
Graphical solution:




**Optical Fibers:**

Bessel functions

Similar modes

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## FIBER WAVEGUIDE DESIGN

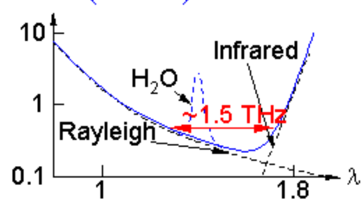
**Loss Mechanisms:**

Rayleigh scattering from random density fluctuations

Loss ∝ $f^4$ (scattering makes sky blue)

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

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




**Construction:**

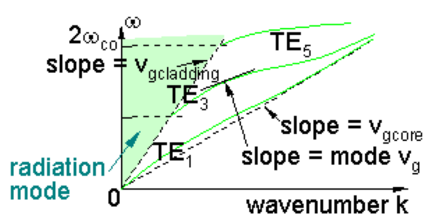
Typical: 10-micron core in 125-micron diameter glass, with 100-micron-thick plastic protective cladding (bundled in cables)

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

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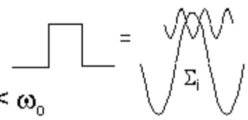
# EFFECTS OF DISPERSION

## 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

$\beta_o = k/\omega_o = v_p^{-1} = n/c$

$\beta_1 = dk/d\omega_o = v_g^{-1} = (1 + [\omega/n]dn/d\omega)n/c$

$\beta_2 = d^2k/d\omega^2 = dv_g^{-1}/d\omega = (2dn/d\omega + \omega\, d^2n/d\omega^2)/c$ {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

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