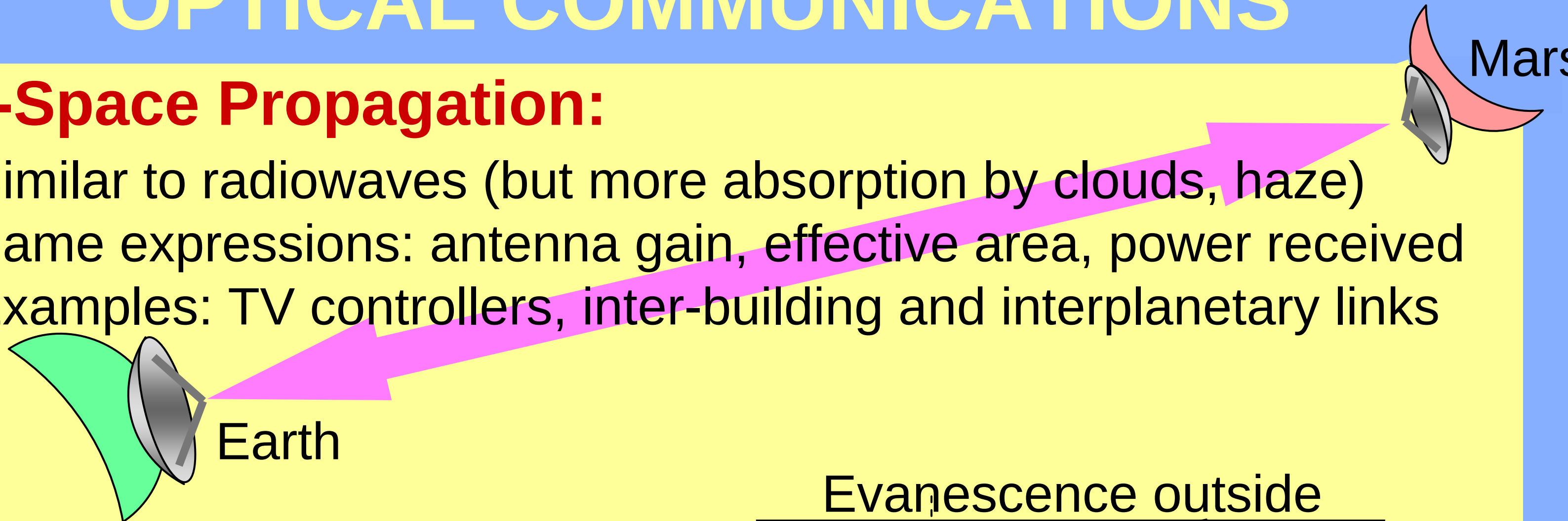
6.013 Electromagnetics and Applications
Spring 2009

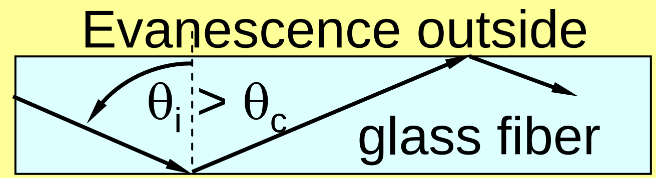
OPTICAL COMMUNICATIONS

Free-Space Propagation:

- Similar to radiowaves (but more absorption by clouds, haze)
- Same expressions: antenna gain, effective area, power received
- Examples: TV controllers, inter-building and interplanetary links



Guided Wave Propagation:



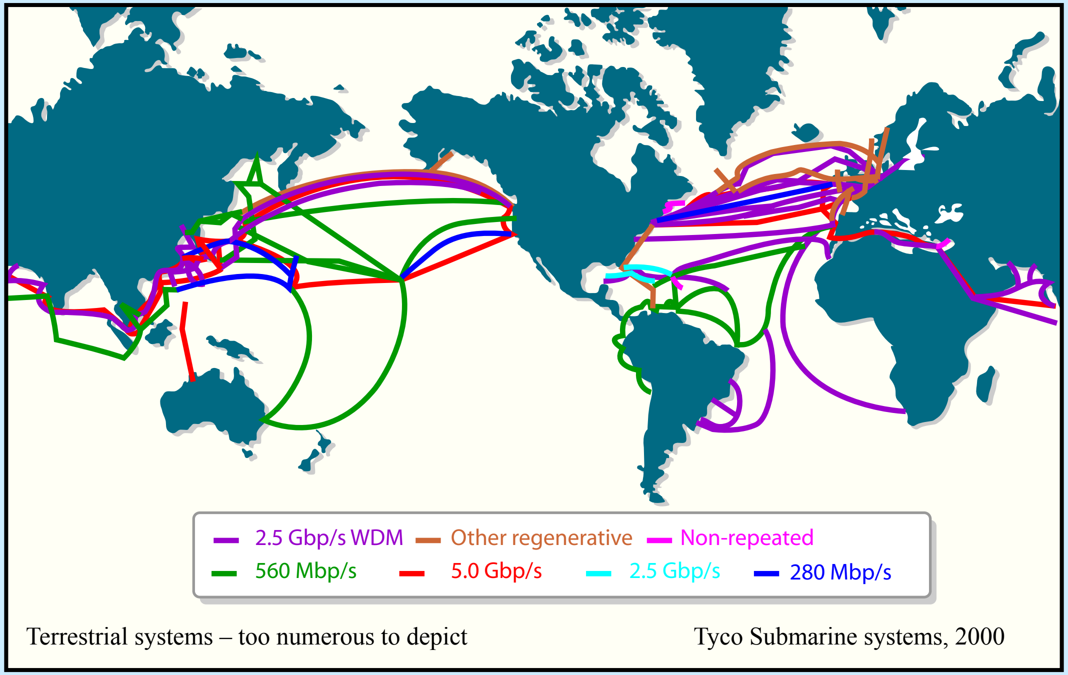
- Optical fibers guide waves
- Rays inside fiber impact wall beyond critical angle
  $\Rightarrow$ total reflection and wave trapping
- Little attenuation $0.5 < \lambda < 2$ microns (can go >100 km)

Devices:

- Detectors: phototubes, photodiodes, avalanche photodiodes
- Sources: LED's, laser diodes, fiber amplifiers, gas lasers
- Modulators: amplitude and frequency, mixers, switches
- Other: filters, spectral multiplexers and combiners

UNDERSEA OPTICAL FIBER CABLES

Fiber Communications Around the Globe



2008: undersea about ×1.5, some are dark

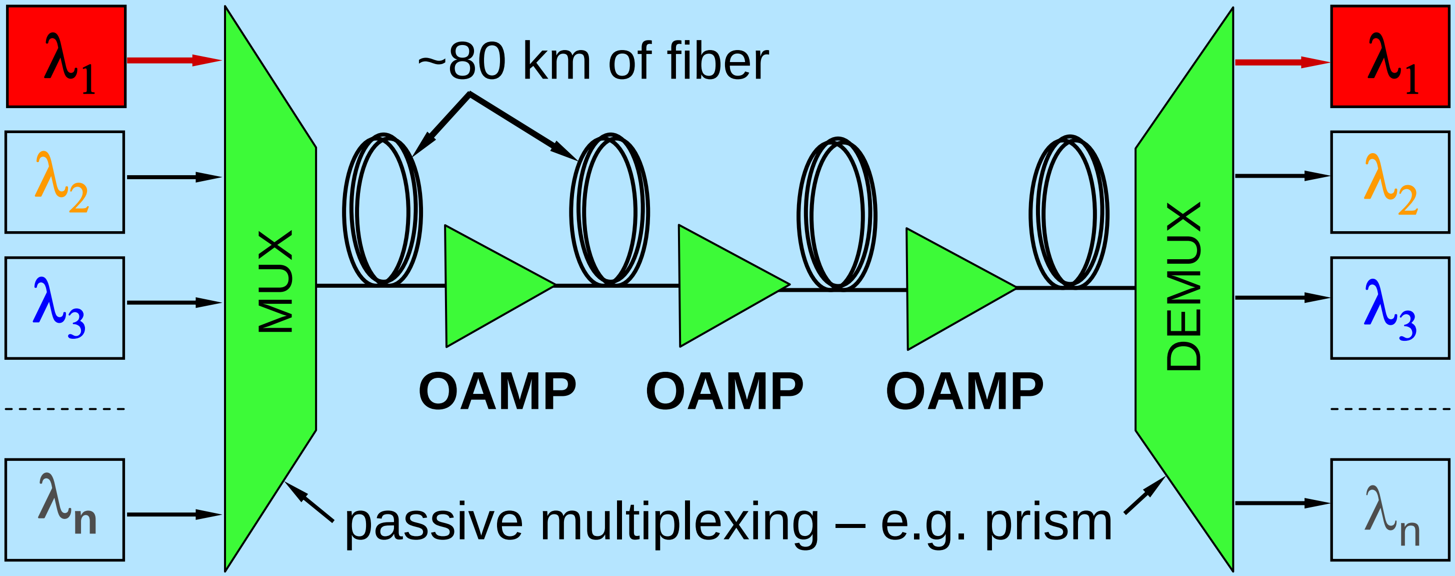
Figure by MIT OpenCourseWare.

- Fiber optics dominates long-distance telecommunications
- In-line Erbium-Doped Fiber Amplifiers (EDFA's) make extremely wideband transoceanic transmission possible without repeaters
- Without fiber communications there would be no World Wide Web

WDM MULTIPLEXED LINK

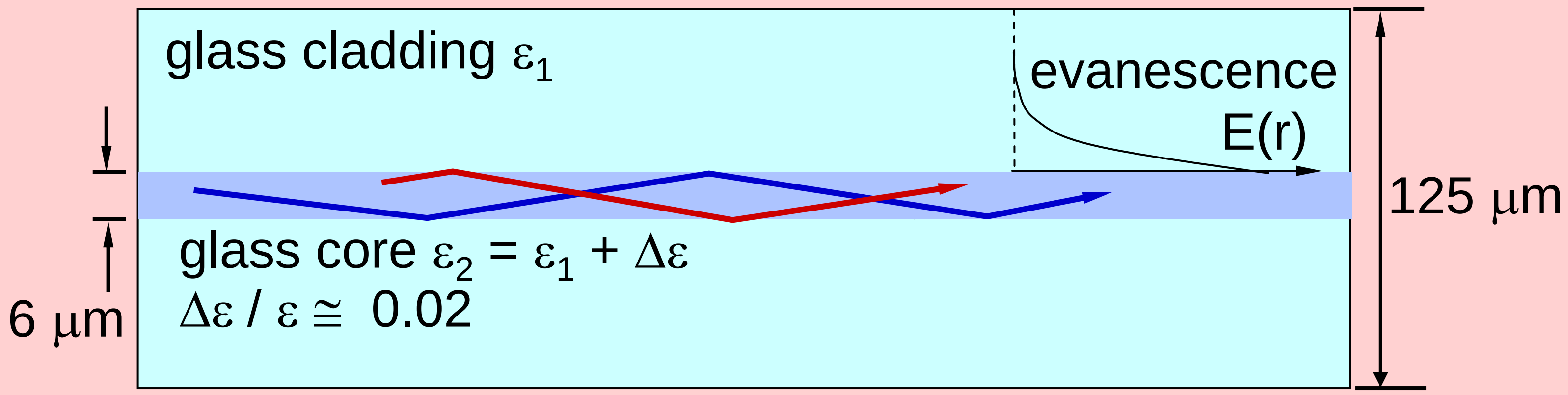
WAVELENGTH DIVISION MULTIPLEXING (WDM):

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



WAVES IN FIBERS

Optical Fiber – Simple Picture:



- Total internal reflection in the higher ε glass core traps light
- Small $\Delta\varepsilon$ $\Rightarrow$ very shallow reflection angles.
- Only certain angles are allowed: waves must interfere constructively
  $\Rightarrow$ modes (characterized by Bessel functions)
- Mode velocity = f(ε's, core size, mode)

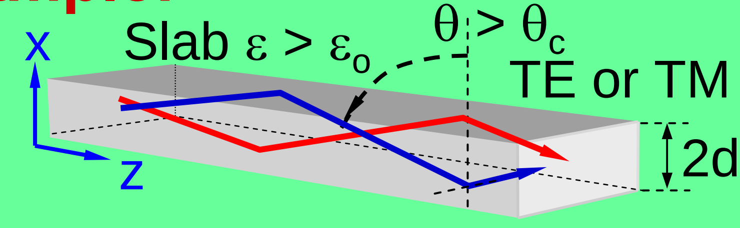
OPTICAL WAVEGUIDES

Dielectric slab waveguide example:

Waves reflect if $\theta_i > \theta_c$

Glass/air $\theta_c = \sin^{-1}(n_g^{-1})$
$n_g \cong 1.5 \quad \Rightarrow \quad \theta_c \cong 41.8°$

Cladding/core $\theta_c = \sim\sin^{-1}(0.98)$
$\Rightarrow \quad \theta_c \cong 78.5°$



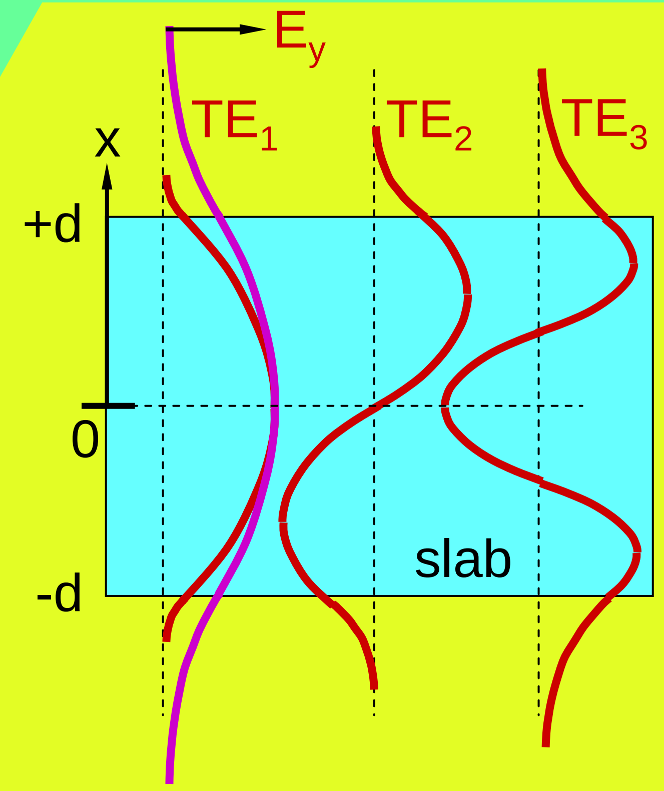
Slab waveguide fields:

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

$\longleftarrow TE_{odd}$

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

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

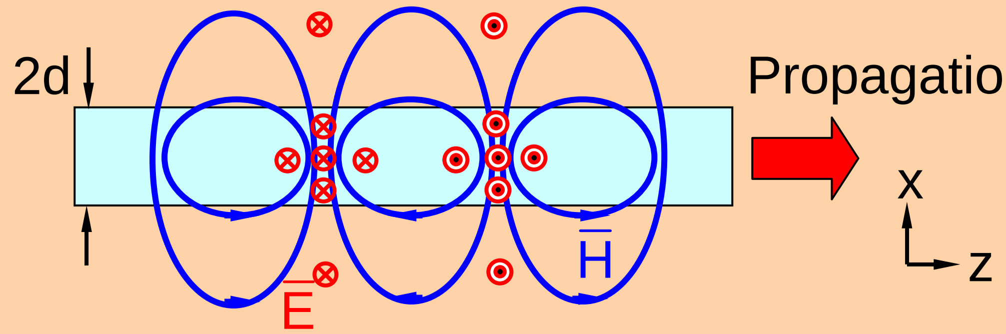


Boundary conditions for TE_n:

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

ELECTROMAGNETIC FIELD DISTRIBUTION

Magnetic Field:



$$\overline{H} = -(\nabla \times \overline{E})/j\omega\mu_o$$

Inside the slab, |x| < d:

$$\overline{H} = (E_o/\omega\mu_o)\left(-\hat{x}k_z \begin{Bmatrix} \sin k_x x \\ \cos k_x x \end{Bmatrix} - \hat{z}jk_x \begin{Bmatrix} -\cos k_x x \\ \sin k_x x \end{Bmatrix}\right) e^{-jk_z z}$$

← TE_{odd}

Outside, x > d: $\overline{H} = (\underline{E}_1/\omega\mu_o)(-\hat{x}k_z - \hat{z}j\alpha)e^{-\alpha x - jk_z z}$

Matching Boundary Conditions at x = d:

Dispersion relations: $k_x^2 + k_z^2 = \omega^2\mu_o\varepsilon$ inside the slab, |x| < d

$-\alpha^2 + k_z^2 = \omega^2\mu_o\varepsilon_o$ outside, |x| > d [let $\mu = \mu_o$]

Continuity of $\overline{E}$: $E_o \cos k_x d\, e^{-jk_z z} = \underline{E}_1 e^{-\alpha d - jk_z z}$ for $TE_{1,3,5...}$

Continuity of $\overline{H}$: $(-jk_x E_o/\omega\mu_o)\sin k_x d\, e^{-jk_z z} = -(j\alpha \underline{E}_1/\omega\mu_o)e^{-\alpha d - jk_z z}$

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

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

DIELECTRIC SLAB WAVEGUIDES $TE_{odd\ n}$

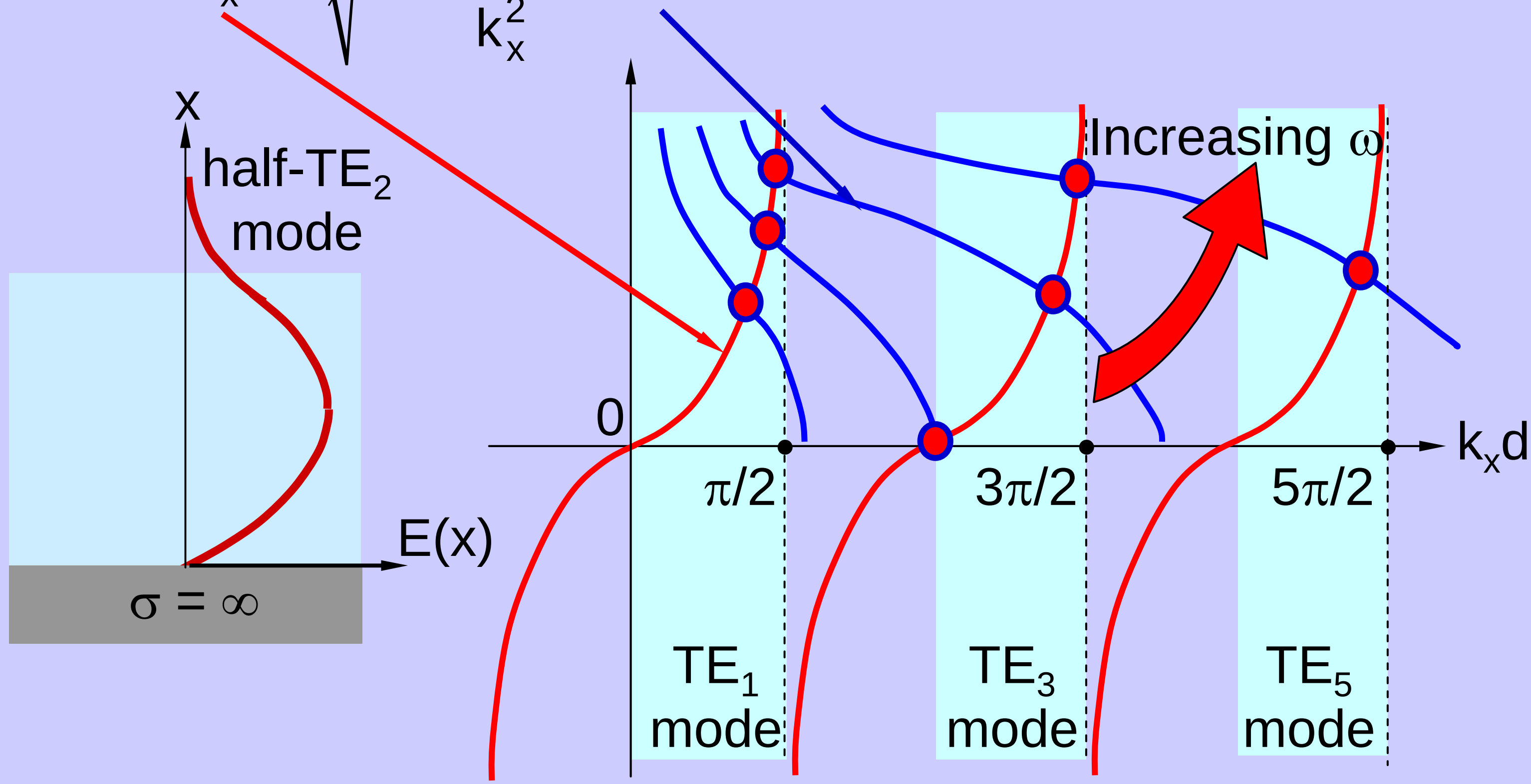
Field continuity equations:

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

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

Transcendental equation, graphical solution:

$$\tan k_x d = \sqrt{\frac{\omega^2 \mu_o (\varepsilon - \varepsilon_o)}{k_x^2} - 1}$$



FIBER WAVEGUIDE DESIGN

Loss mechanisms:

Rayleigh scattering from random density fluctuations
Loss $\propto f^4$ (scattering makes sky blue)
Infrared absorption dominates for λ > ~1.6 microns
Minimum total attenuation $\cong$ 0.2 dB km^{-1}

Fiber structure:

Typical: 10-μm core in 125-μm diameter glass, with 100-μm-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. $Si(Ge)Cl_4 + O_2 = Si(Ge)O_2 + 2Cl_2$)
Architecture: various – single or multimode, polarization-selective