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 $> \sim 1$ DB/km (depends on fiber architecture, materials, $f$)

UNDERSEA OPTICAL FIBER CABLES

Fiber Communications Around the Globe

- 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
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 \( \theta_c \)

\( \theta_c = \sin^{-1}(\eta_g^{-1}) \) where \( n_g \approx 1.5 \Rightarrow \theta_c \approx 41.8^\circ \)

Standing waves inside guide, evanescent outside:

\[
E = \gamma E_0 \begin{pmatrix} \sin k_x x \\ \cos k_x x \end{pmatrix} e^{-j k_z z} \quad |x| \leq d
\]

and \( E = \gamma E_1 e^{-\alpha x - j k_z z} \) for \( x > d \),

\( E = \pm \gamma E_1 e^{\alpha x - j k_z z} \) for \( x < -d \)

Evanescence region:

Decays more rapidly for lower modes and higher frequencies

Boundary conditions:

\( \nabla \times E = \frac{\varepsilon_0}{\mu_0} \frac{\partial H}{\partial t} \) and \( \partial E_y / \partial x \) continuous for \( E_n \)

ELECTROMAGNETIC FIELD DISTRIBUTION

Magnetic Field Distribution: \( \mathbf{H} = -i(\nabla \times \mathbf{E}) / \omega \mu_0 \) (for \( \text{TE}_1, \text{TE}_2, \text{etc.} \))

Inside the slab:

\[
\mathbf{H} = \left( E_0 / \omega \mu_0 \right) \begin{pmatrix} \sin k_x x \\ \cos k_x x \end{pmatrix} e^{-j k_z z} \quad |x| < d
\]

Outside the slab:

\[
\mathbf{H} = \left( E_1 / \omega \mu_0 \right) \begin{pmatrix} -\sin k_x x \\ \cos k_x x \end{pmatrix} e^{-\alpha x - j k_z z} \quad \text{for} \quad x > d
\]

Matching Boundary Conditions:

Phase:

\( k_x^2 + k_z^2 = \omega^2 \mu_0 \) inside the slab, \( |x| < d \)

\( \alpha_x^2 + k_z^2 = \omega^2 \mu_0 \varepsilon_0 \) outside, \( x > d \)

Continuity of \( E \) at \( x = d \):

\( E_0 \cos k_x x e^{-j k_z z} = E_1 e^{-\alpha x - j k_z z} \) for \( \text{TE}_{1,3,5,...} \)

Continuity of \( H_z \) at \( x = d \):

\( -j k_x E_0 / \omega \mu_0 \sin k_x x e^{-j k_z z} = -j \alpha_1 E_1 / \omega \mu_0 e^{-\alpha x - j k_z z} \)

Therefore:

\( k_z d \tan k_d = \mu d / \mu_0 \) (ratio of continuity equations)

\( k_x^2 + \alpha^2 = \omega^2 (\mu_0 - \mu_0 \varepsilon_0) \) (from dispersion equations)
**SOLUTIONS FOR TE_{odd \, n} DIELECTRIC SLAB WAVEGUIDES**

**Field Continuity Equations:**

\[
\begin{align*}
    k_x d \tan k_y d &= \mu_0 \omega d / \mu_0 \\
    k_x^2 + \omega^2 &= \omega^2 (\mu_0 \varepsilon_0 - \mu_x \varepsilon_x)
\end{align*}
\]

(ratio of continuity equations)  
(from dispersion equations)

**Transcendental Equation:**

\[
\tan k_y d = (\mu_0 \mu_x)[(\omega^2 (\mu_0 \varepsilon_0 - \mu_x \varepsilon_x) d^2 / k_x^2 d^2] - 1)^{0.5}
\]

Graphical solution:

**Optical Fibers:**

- Bessel functions
- Similar modes

No trapped, Solutions \( \alpha > 0 \)

No trapped, Solutions \( \alpha < 0 \)

**FIBER WAVEGUIDE DESIGN**

**Loss Mechanisms:**

- Rayleigh scattering from random density fluctuations
- Loss \( \propto f^4 \) (scattering makes sky blue)
- Infrared absorption dominates for \( \lambda > \sim 1.6 \) microns
- Minimum total attenuation \( \equiv 0.2 \) 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 \( v_g(\omega) = \text{constant} \), so
  - Want flat \( k(\omega) \) \( [n = k/\omega + n_0] \)
- Dispersion: Determined mostly by \( s(\omega) \), modified by \( s(\omega) \) of fiber

Graphs showing attenuation vs. wavelength and group velocity vs. wavenumber.
EFFECTS OF DISPERSION

Pulse Spreading:
Distortion: Square pulse envelope is sum of harmonics—
Want all \( f \) to have same group velocity; \( \Delta \omega \ll \omega_0 \)
Equation: \( k = \beta_0 \omega_0 + \beta_1 (\omega - \omega_0) + \beta_2 (\omega - \omega_0)^2 + \ldots \) where
\[
\beta_0 = k/\omega_0 = v_p^{-1} = n/c \\
\beta_1 = dk/d\omega_0 = v_s^{-1} = (1 + [\omega/n]dn/d\omega)n/c \\
\beta_2 = d^2k/d\omega_0^2 = dv_s^{-1}/d\omega = (2dn/d\omega + \omega d^2n/d\omega^2)/c \{ \text{set to 0 at } \omega_0 \}
\]

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