Lecture 17 - Rectangular Waveguides/Photonic Crystals and Radiative Recombination - Outline

- **Dielectric optics** (continuing discussion in Lecture 16)
  - Rectangular waveguides
  - Coupled rectangular waveguide structures
    - Couplers, Filters, Switches
- **Photonic crystals**
  - History: Optical bandgaps and Eli Yablonovich, to the present
  - One-dimensional photonic crystals
    - Distributed Bragg reflectors
    - Photonic fibers; perfect mirrors
  - Two-dimensional photonic crystals
    - Guided wave optics structures
    - Defect levels
  - Three-dimensional photonic crystals
- **Recombination Processes** (preparation for LEDs and LDs)
  - Radiative vs. non-radiative
  - Relative carrier lifetimes

Absorption in semiconductors - indirect-gap band-to-band

- The phonon modes involved indirect band gap absorption
- Dispersion curves for acoustic and optical phonons

Approximate optical phonon energies for several semiconductors

Ge:	37 meV
Si:	63 meV
GaAs:	36 meV

(Swaminathan and Macrander)

Slab dielectric waveguides

- **Nature of TE-modes (E-field has only a y-component). For the j-th mode of the slab, the electric field is given by:**

$$E_{y,j} = X_j(x)\,\mathrm{Re}\left[e^{-j(\beta_j z - \omega t)}\right]$$

In this equation:

ω: frequency/energy of the light

$$2\pi\omega = \nu = c/\lambda_o$$

λ_o: free space wavelength

β_j: propagation constant of the j-th mode

$X_j(x)$: mode profile normal to the slab.
satisfies

$$\frac{d^2 X_j}{dx^2} + \left(n_i^2 k_o^2 - \beta_j^2\right) X_j = 0$$

where:

n_i: refractive index in region i

k_o: propagation constant in free space

$$k_o = 2\pi/\lambda_o$$

Slab dielectric waveguides

- In approaching a slab waveguide problem, we typically take the dimensions and indices in the various regions and the free space wavelength or frequency of the light as the "givens" and the unknown is β, the propagation constant in the slab.
- We find that there are only discrete values for β that yield a solution for X(x). Each value corresponds to a mode of the slab.
- For a guided solution we want solutions with β_j's such that

$$\left(n_i^2 k_o^2 - \beta_j^2\right) \leq 0$$

  in the regions above and below the slab, and

$$\left(n_i^2 k_o^2 - \beta_j^2\right) \geq 0$$

  in the slab.
- If these conditions are satisfied, $X_j(x)$ will be an exponential function decaying away for the slab in the outer regions and a sinusoidal function in the slab, and the mode will be guided.

Slab dielectric waveguides

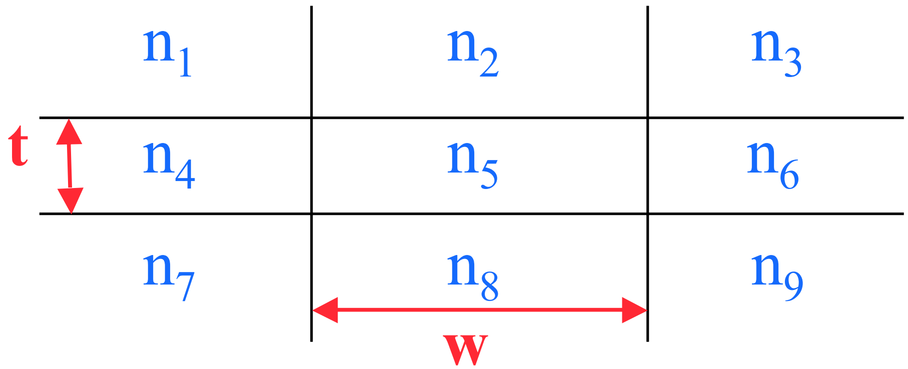
- **Mode patterns and charts for symmetric and asymmetric slabs**

(Images deleted)

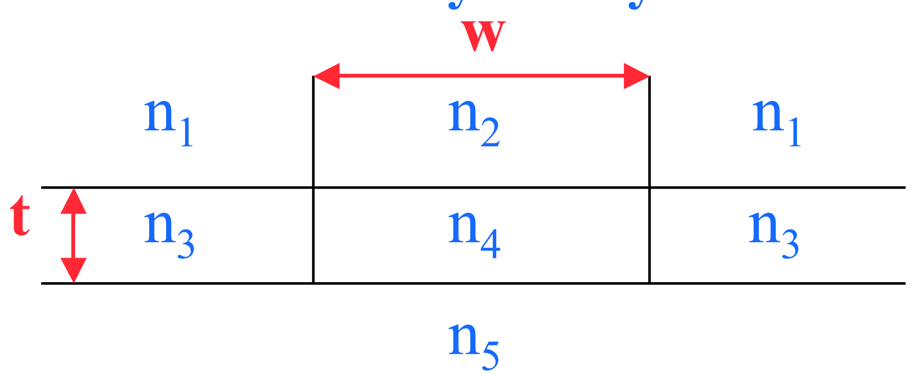
See Figures 4-5, 4-7, 4-8, and 4-9 in Palais, Joseph C. *Fiber Optic Communications.* 4th ed. Upper Saddle River, N.J. : Prentice Hall, 1998.

Rectangular dielectric waveguides - modeling issues

- It is in general not possible to get a closed-form analytical solution to the field problem in an arbitrary rectangular guide, and an interative computer solution must be done:



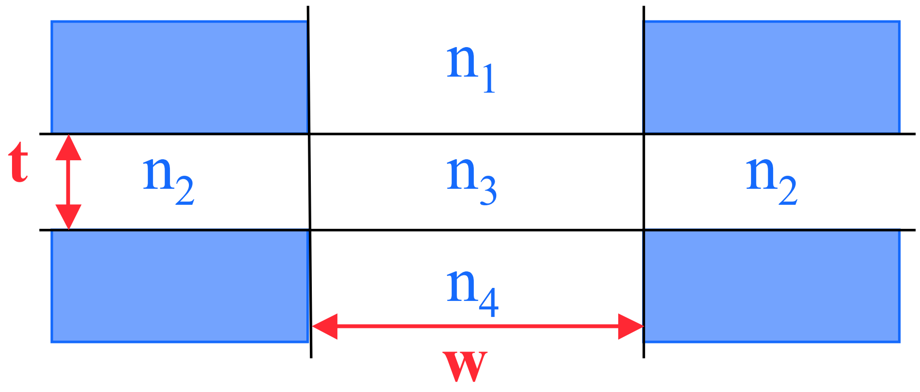
- A realistic guide, however, will typically be built on a slab and will have horizontal symmetry.



- Still, the problem is difficult to analyze.

Rectangular dielectric waveguides - modeling issues

- One route to a more managable problem is to ignor the corner regions:



in this case solutions can be found if $n_1 = n_4$, but this is a very restrictive condition.

- The most common and intuitively helpful approximate solution is what is called the "effective index" method. In this approximation we decompose the problem into three slab guide problems, first, two vertical slab guides, and, finally, one horizontal slab problem.

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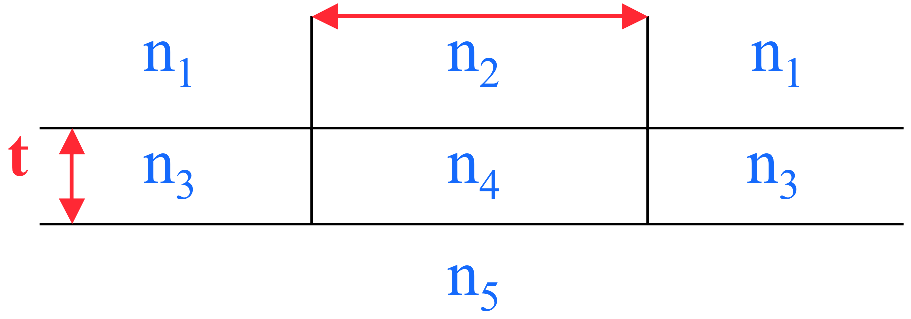
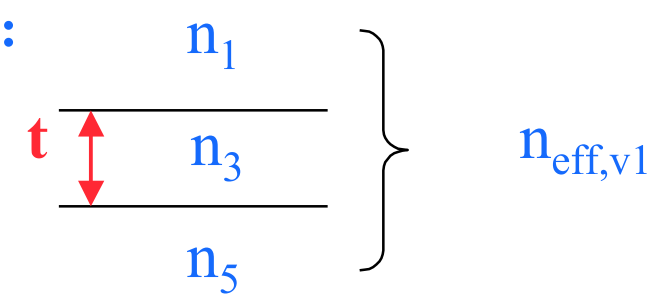
Rectangular dielectric waveguides - Effective index method

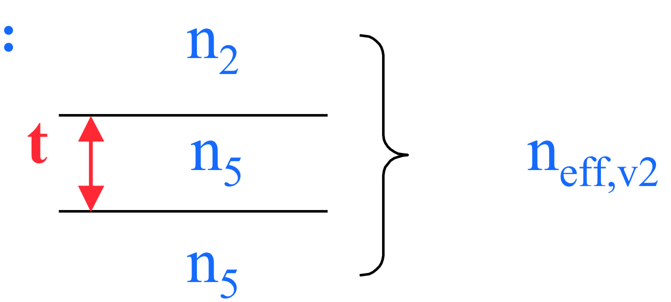
- We look at the rectangular guide as being formed from two different slab guides, and calculate the effective indices for modes propagating in each: w



- Vertical slab 1:

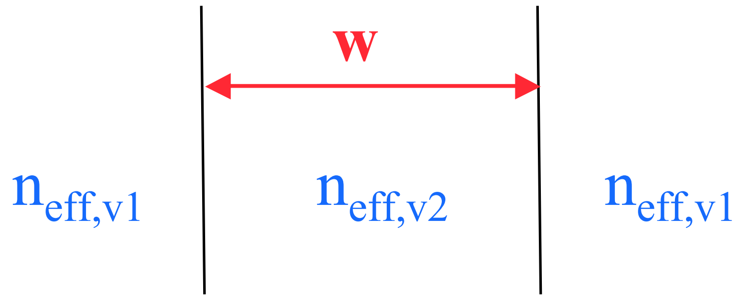


- Vertical slab 2:



<u>Rectangular dielectric waveguides</u> - Effective index method, cont.

- Then we build our third horizontal slab from these "layers", bounding layer 2 on either side by layers 1, and for each layer we use the appropriate effective refractive index:



- This is a symmetric slab guide and the solutions for this geometry are well known and fully tabulated*. The same is true of the solutions for asymmetric slab guides (the vertical problems on the previous slide)

  * See Appendices 7 and 8 in P. Bhattacharya, <u>Semiconductor Optical Devices</u> ISBN 0-13-805748-6, TK8320.B52 1994.

- This method gives usefully accurate results, and is extremely intuitive and helpful when thinking about real guides

Rectangular dielectric waveguides - useful structures

- Numerous useful structures and devices can be built from rectangular dielectric waveguides:

  Passive structures
  - Bends
  - Corners
  - Splitters/combiners
  - Couplers
  - In-line filters
  - Add-drop filters

  Active structures
  - Switches
  - Modulators

- We will look at each of these, some more extensively than others (and the active devices more later on)

Rectangular dielectric waveguides - bends

- **If a rectangular dielectric wave-guide curves there must be some radiation loss, as seen on the right:**

(Image deleted)

See Coldren, L.A., Corzine, S. W. *Diode Lasers and Photonic Integrated Circuits*, Editor Kai Chang, Wiley, pg. 335, Fig. 7.24.

- **The goal is to make the curve gradual enough so the loss is small. In doing this there is a direct trade-off between the level of confinement (Δn) and the bending radius. We find:**

$$\alpha_{curve} \approx C_1 e^{-C_2 R}$$

The constants are related to the waveguide structure as:

$$C_1 = \frac{\cos^2(k_{xg} w)\lambda_o e^{2k_{xL} w}}{4k_{xL} n_L w^2 \left[w + \frac{1}{2k_{xg}} \sin(2wk_{xg}) + \frac{1}{k_{xL}} \cos^2(wk_{xg}) \right]}, \quad C_2 = 2k_{xL}\left(\frac{\lambda_o \beta}{2\pi n_L} - 1 \right)$$

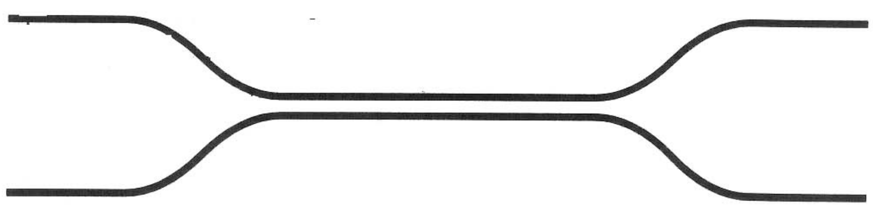
(continued on the next slide)

Rectangular dielectric waveguides - bends, cont.

- In these equations the following quantities appear:

  β: z-directed propagation constant for guide
  k_{xg}: x-directed propagation constant in guide
  k_{xL}: decay constant in regions on outside of guide
  $2w$: width of guide
  n_g: refractive index in guide
  n_L: refractive index outside of guide

- Because of the difficulty of making sharp bends, optical waveguide layouts tend to look more like railroad switch yards, rather than city streets and intersections.



Rectangular dielectric waveguides - edge roughness loss

- Tighter confinement of the light to the guide, i.e., larger Δn, means there is less bending loss for a given curve radius,

  but it also means

  1. single modes guides have to be narrower
  2. the guides will be more susceptible to edge scattering losses

- Tien [Appl. Opt. 10 (1971) 2395] found

$$\alpha_{edge} \approx \frac{\cos^3\theta}{2w_{eff}\sin\theta}\left(\frac{4\pi\, n_{eff}\Delta w}{\lambda_o}\right)^2$$

If we are modeling side-wall roughness the parameters are:

n_{eff}: effective index of the mode in the guide

w_{eff}: effective width of the guide, defined as $w + 2k_{xL}^{-1}$

θ: angle of incidence of the mode on the boundary

If are interested in the loss due to substrate and surface roughness, the width is replaced by the thickness, and t_{eff} is $t + k_{ysub}^{-1} + ky_{surf}^{-1}$.

Rectangular dielectric waveguides

- **The issue of the trade-offs between bend radius, scattering loss, guide dimension, and index step**

(Image deleted)

See Kimmerling. *MARCO Review.* October 2002.

Achieving compact rectangular waveguide layouts

- **Bends**

Calculated transmisson:

a. 30%

b. 60%

c. 98.5%

d. 98%

(Image deleted)

See C. Manolatou, S.G. Johnson, S. Fan, P.R. Villeneuve, H.A. Haus, and J.D. Joanopolous, "High-Density Integrated Optics," IEEE J. Lightwave Technology, 17 (1999) 1682-1692.

<u>Rectangular dielectric waveguides</u> - splitters, combiners

- Another useful structue is one where a signal is split into two signals, typically of equal strength

Notice that the guide widens before the split to become multi-mode. Lowest order mode widens, and the energy in it must be coupled into the much narrower lowest order modes of the two branch waveguides. This is an obvious recipe for loss.

It is possible to make the splitting loss from becoming too significant if the angle between the branches, ϕ, is kept small:

$$\phi < \cos^{-1}\left(\frac{n_L}{n_g}\right) - \tan^{-1}\left(\frac{k_{xg}}{\beta}\right)$$

Equation and figure from Zappe, p. 210. Eq. Ref: M. Kuznetsov, "Radiation Losses in Dielectric Waveguide Y-Branch Structures, IEEE J. Lightwave Tech. <u>LT-3</u> (1985) 674-6777.

Achieving compact rectangular waveguide layouts

- **Splitting Tees**

Calculated transmisson:

**a. 30%
(15 %/side)**

**b. 99%
(> 49%/side)**

(Image deleted)

See C. Manolatou, S.G. Johnson, S. Fan, P.R. Villeneuve, H.A. Haus, and J.D. Joanopolous, "High-Density Integrated Optics," IEEE J. Lightwave Technology, 17 (1999) 1682-1692.

Rectangular dielectric waveguides - waveguide couplers

- **Another method of splitting a signal into two parts, as well as to make switches is to use what is called a waveguide coupler. This structure exploits the fact that the light is not totally confined to the waveguides:**

(Images deleted)

See Figures 7.29, 6.9b, and 6.21 in Coldren, L. A., and S. W. Corzine. *Diode Lasers and Photonic Integrated Circuits.* New York: Wiley Interscience, 1995.

Rectangular dielectric waveguides - waveguide couplers

- There are two lowest order modes for the combined pair of guides, and they travel down the guide with slightly different velocities.

Planar waveguide integrated optics components

- **Resonant ring couplers and channel dropping filters**

Then

Now

(Image deleted)

See B.E. Little et al, "Vertically Coupled Glass Microring Resonator Channel Dropping Filters," IEEE Photonics Tech. Lett. 11 (1999) 215.

(Images deleted)

See Figs. 1 and 12 in E.A.J. Marcatili, "Bends in Optical Dielectric Guides," Bell Syst. Tech. J. 48 (1969) 2103-2132.

(Image deleted)

See S.T. Chu et al, "An Eight-Channel Add-Drop Filter Using Vertically Coupled Microring Resonators over a Cross Grid," IEEE Photonics Tech. Lett. 11 (1999) 691.

<u>Photonic crystals</u> - Yablonvich's original proposals

- **3-dimensional structures with optical bandgaps:** solids that totally reflect light in band of energy

<u>Photonic crystals</u> - Axel Scherer

- **Rectangular dielectric waveguide structures:**

example of making bends using phtonic bandgap concepts

Right: structure and fabrication sequence

Below: performance

(Images deleted)

See Fig. 4 and Table II in Cheng, C. C., and A. Scherer. "Lithographic Band Gap Tuning in Photonic Bandgap Crystals." J. Vac. Sci. Technol. B 14 (1996): 4110-4114.