Computational Science:
Computational Methods in Engineering

Slab Waveguide Analysis

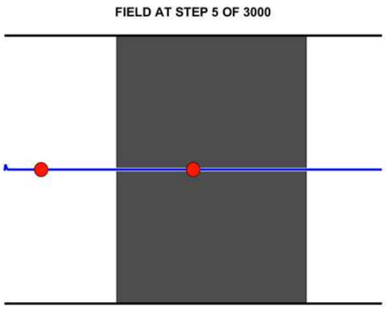
Outline

- Slab Waveguides
- Formulation
- Solution
- Implementation in MATLAB
- More About Resolution and Spacer Regions

Slab Waveguides

Refractive Index n

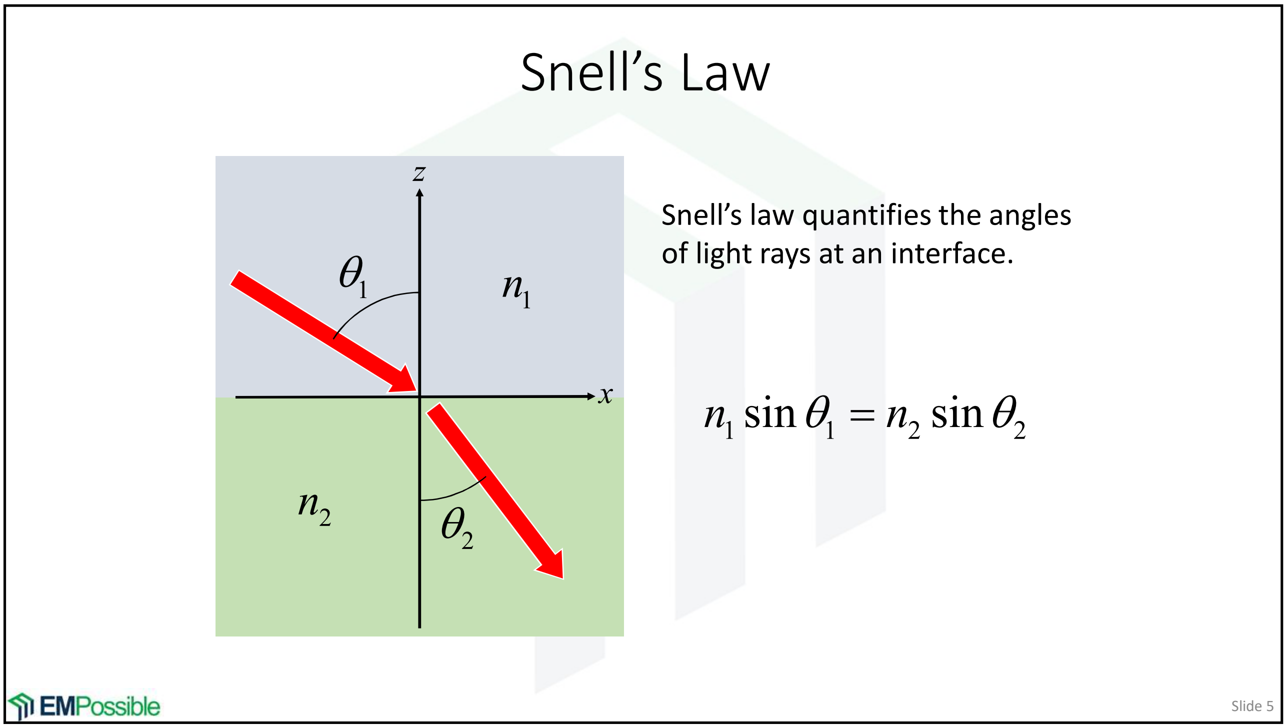
Light travels at different speeds when it is inside different materials.



Frequency is constant.
Speed changes.
Wavelength changes.

The factor by which light slows down is called the *refractive index*.

$$n = \frac{c}{v}$$

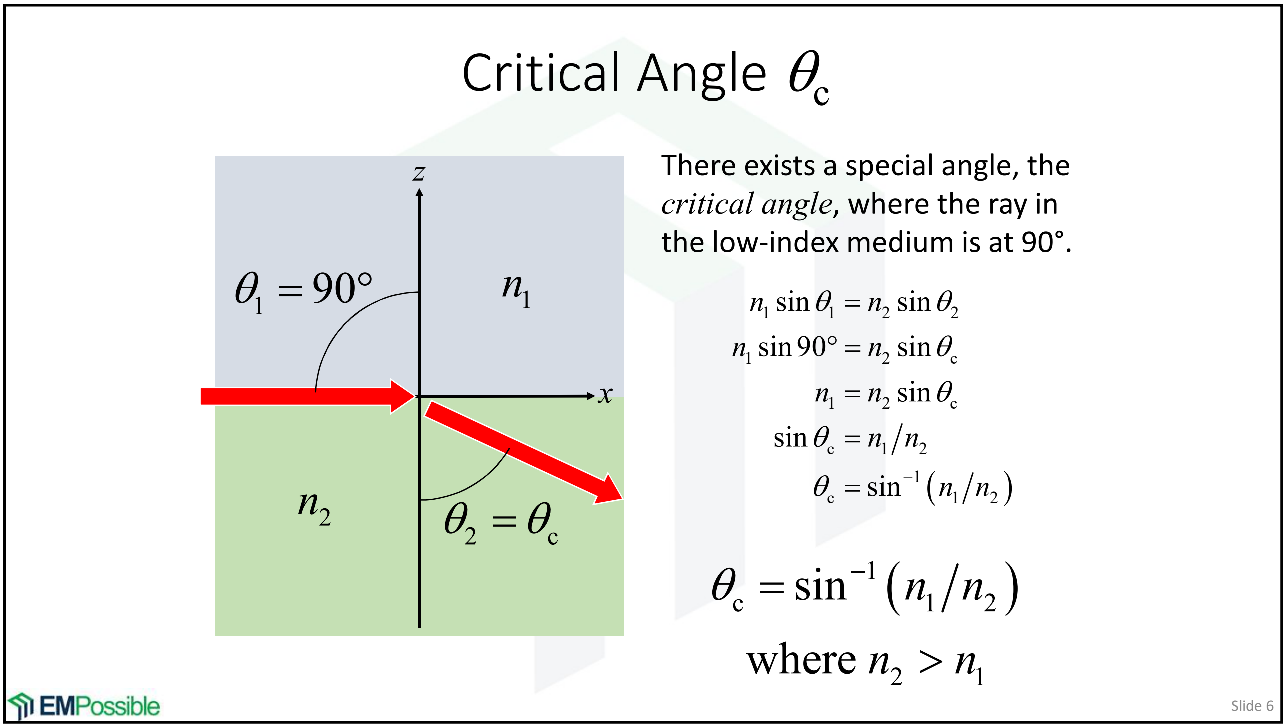


Snell's Law

Snell's law quantifies the angles of light rays at an interface.

$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

EMPossible



Critical Angle θ_c

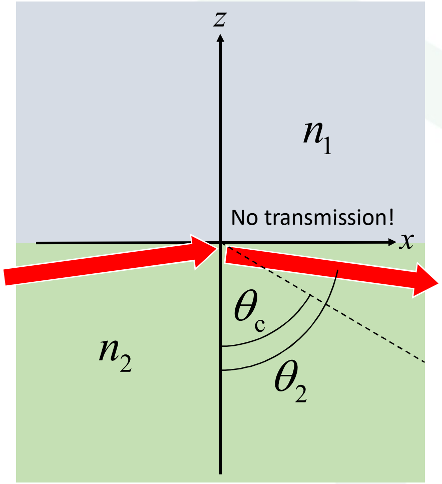
There exists a special angle, the *critical angle*, where the ray in the low-index medium is at 90°.

$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$
$$n_1 \sin 90° = n_2 \sin\theta_c$$
$$n_1 = n_2 \sin\theta_c$$
$$\sin\theta_c = n_1 / n_2$$
$$\theta_c = \sin^{-1}\left(n_1 / n_2\right)$$

$$\theta_c = \sin^{-1}\left(n_1 / n_2\right)$$
$$\text{where } n_2 > n_1$$

EMPossible

Total Internal Reflection (TIR)



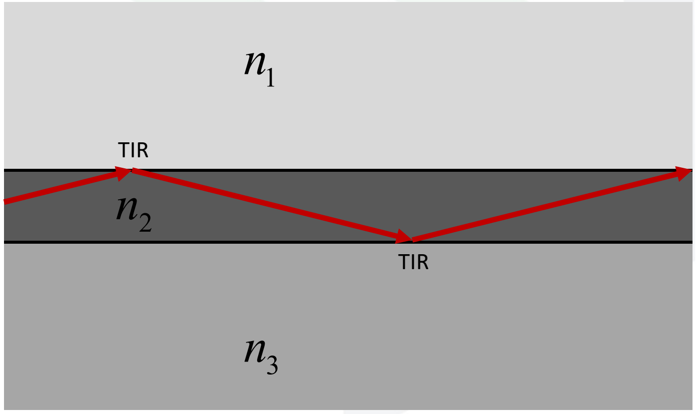
When a light ray is incident onto an interface at an angle greater than the critical angle, the light completely reflects and no light is transmitted.

This is called *total internal reflection* (TIR).

$$\theta_2 > \theta_c$$

The Slab Waveguide

If we “sandwich” a slab of high-index material between two materials with lower refractive index, we form a slab waveguide.

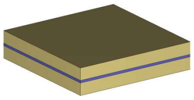


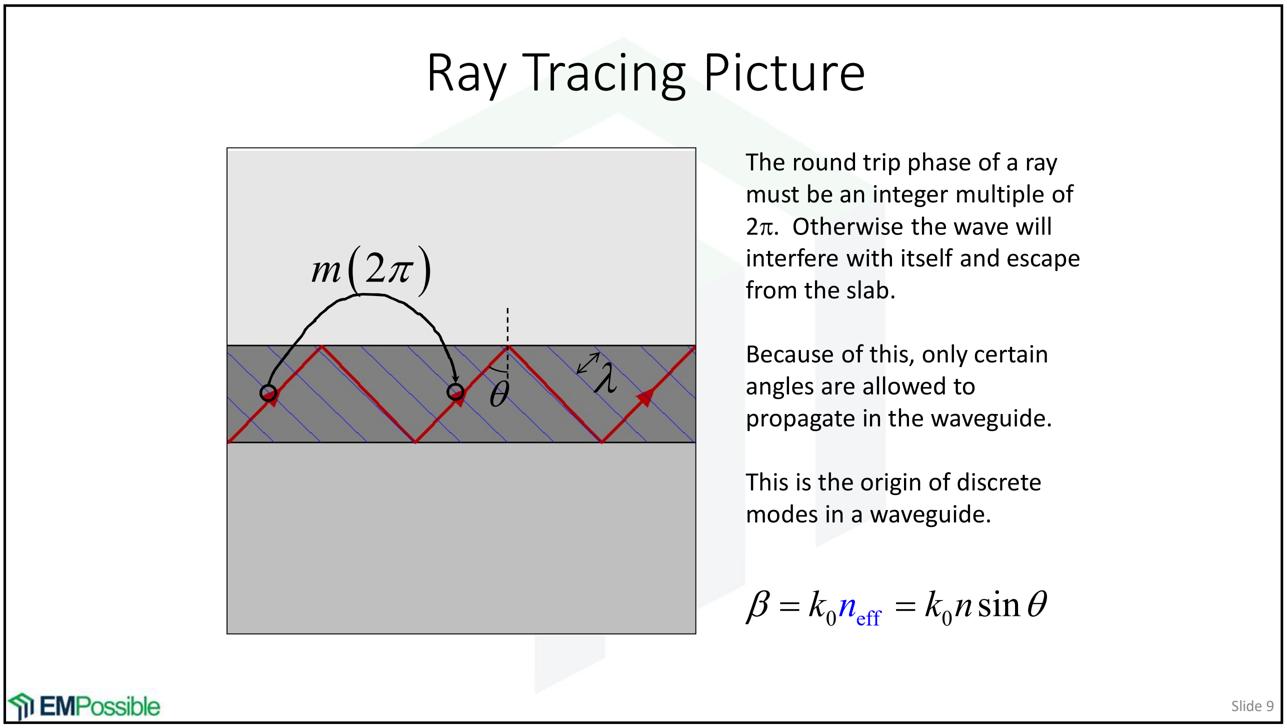
Conditions

$n_2 > n_1$

and

$n_2 > n_3$





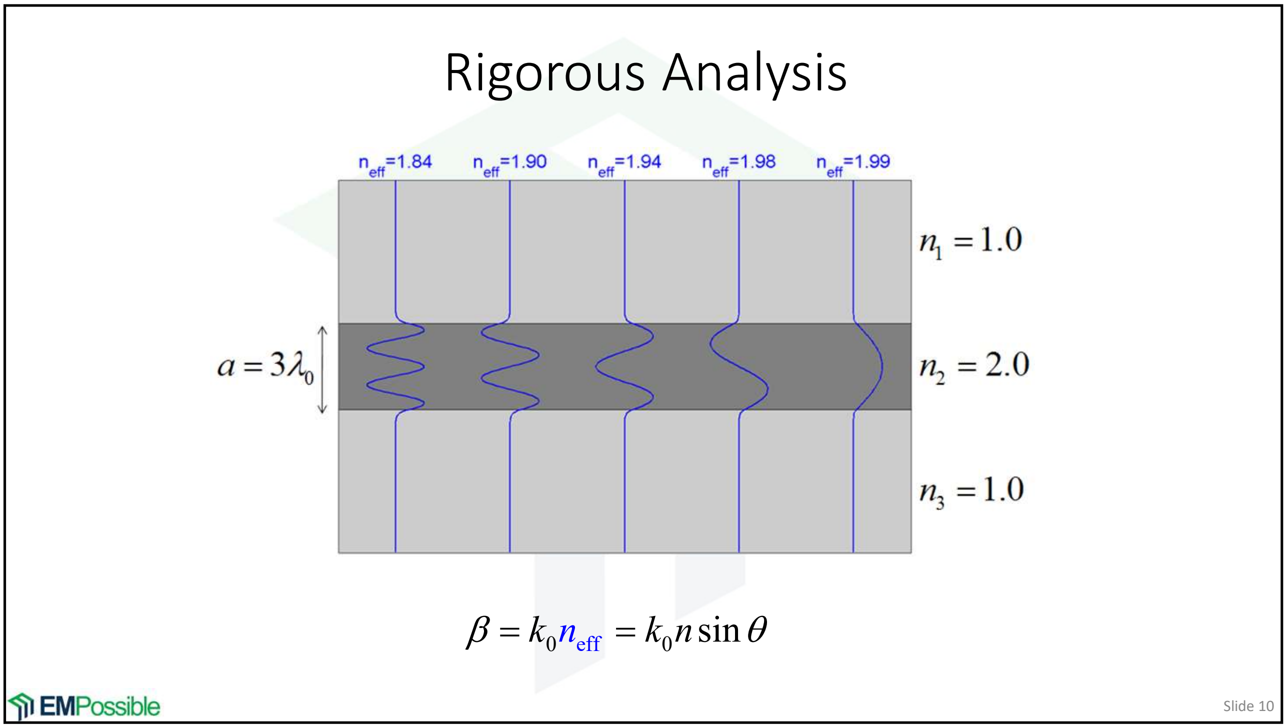
Ray Tracing Picture

The round trip phase of a ray must be an integer multiple of 2π. Otherwise the wave will interfere with itself and escape from the slab.

Because of this, only certain angles are allowed to propagate in the waveguide.

This is the origin of discrete modes in a waveguide.

$$\beta = k_0 n_{\text{eff}} = k_0 n \sin\theta$$



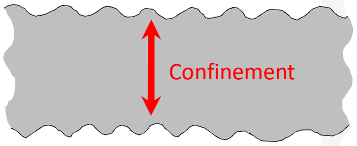
Rigorous Analysis

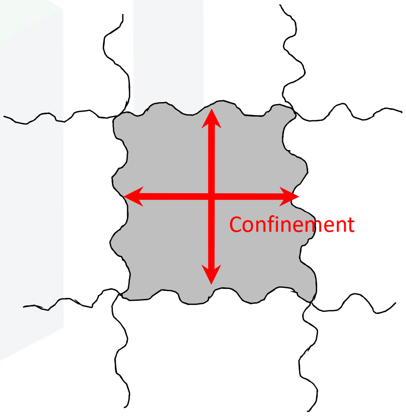
$$\beta = k_0 n_{\text{eff}} = k_0 n \sin\theta$$

Slab Vs. Channel Waveguides

Slab waveguides confine energy in only one transverse direction.

Channel waveguides confine energy in both transverse directions.

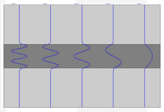


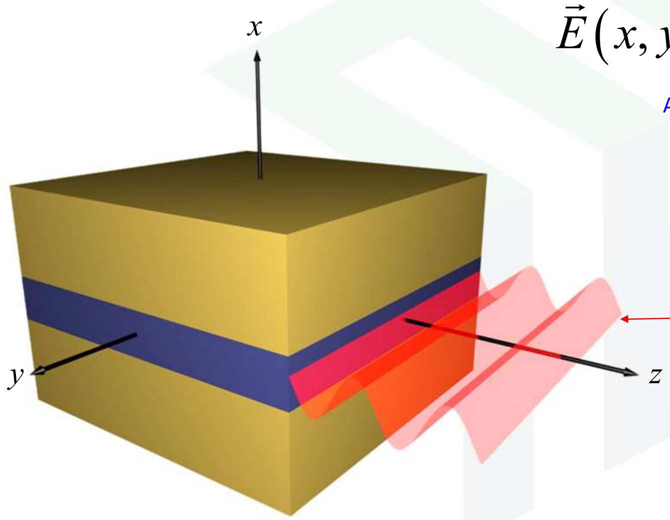


Mathematical Form of Solution

$$\vec{E}(x,y,z)=\vec{A}(x)e^{-j\beta z}$$

Amplitude Profile





Wave oscillations

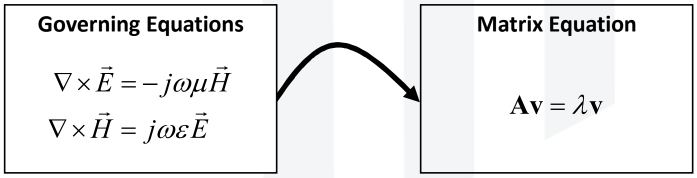
$\beta \equiv$ phase constant

Formulation

What is Formulation?

Formulation is the initial analytical work we do before implementing a computer code.

Usually we start with the governing equation(s) and end with the matrix equation to be solved.



Governing Equations

$$\nabla \times \vec{E} = -j\omega\mu\vec{H}$$
$$\nabla \times \vec{H} = j\omega\varepsilon\vec{E}$$

Matrix Equation

$$\mathbf{A}\mathbf{v} = \lambda\mathbf{v}$$

Governing Equations

Since this is an electrodynamics problem, we start with Maxwell's curl equations.

$$\nabla \times \vec{E} = -j\omega\mu\vec{H}$$
$$\nabla \times \vec{H} = j\omega\varepsilon\vec{E}$$

Vector Curl

The curl of a vector is a measure of the vector field's tendency to circulate about an axis. The curl quantity is directly along this axis and the magnitude measures the strength of the circulation.

$$\nabla \times \vec{A} = \left(\frac{\partial A_z}{\partial y} - \frac{\partial A_y}{\partial z}\right)\hat{a}_x + \left(\frac{\partial A_x}{\partial z} - \frac{\partial A_z}{\partial x}\right)\hat{a}_y + \left(\frac{\partial A_y}{\partial x} - \frac{\partial A_x}{\partial y}\right)\hat{a}_z$$

Expand Governing Equations
(1 of 2)

If we expand the first equation into its vector components, we get

$$\nabla \times \vec{E} = -j\omega\mu\vec{H}$$

$$\left(\frac{\partial E_z}{\partial y} - \frac{\partial E_y}{\partial z}\right)\hat{a}_x + \left(\frac{\partial E_x}{\partial z} - \frac{\partial E_z}{\partial x}\right)\hat{a}_y + \left(\frac{\partial E_y}{\partial x} - \frac{\partial E_x}{\partial y}\right)\hat{a}_z = -j\omega\mu\left(H_x\hat{a}_x + H_y\hat{a}_y + H_z\hat{a}_z\right)$$

The vector components on each side must be equal.

$$x\text{-component:}\quad \frac{\partial E_z}{\partial y} - \frac{\partial E_y}{\partial z} = -j\omega\mu H_x$$

$$y\text{-component:}\quad \frac{\partial E_x}{\partial z} - \frac{\partial E_z}{\partial x} = -j\omega\mu H_y$$

$$z\text{-component:}\quad \frac{\partial E_y}{\partial x} - \frac{\partial E_x}{\partial y} = -j\omega\mu H_z$$

Expand Governing Equations (2 of 2)

There are now six equations.

$$\nabla \times \vec{E} = -j\omega\mu\vec{H}$$

$$\frac{\partial E_z}{\partial y} - \frac{\partial E_y}{\partial z} = -j\omega\mu H_x$$

$$\frac{\partial E_x}{\partial z} - \frac{\partial E_z}{\partial x} = -j\omega\mu H_y$$

$$\frac{\partial E_y}{\partial x} - \frac{\partial E_x}{\partial y} = -j\omega\mu H_z$$

$$\nabla \times \vec{H} = j\omega\varepsilon\vec{E}$$

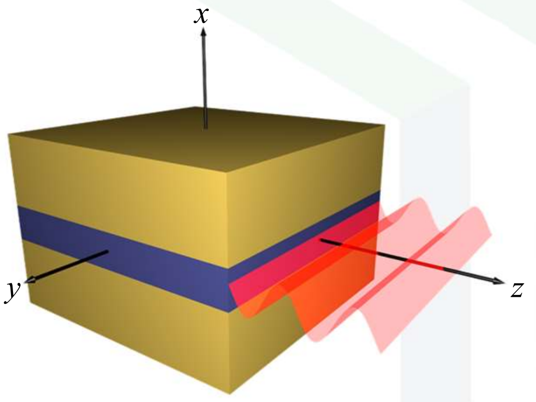
$$\frac{\partial H_z}{\partial y} - \frac{\partial H_y}{\partial z} = j\omega\varepsilon E_x$$

$$\frac{\partial H_x}{\partial z} - \frac{\partial H_z}{\partial x} = j\omega\varepsilon E_y$$

$$\frac{\partial H_y}{\partial x} - \frac{\partial H_x}{\partial y} = j\omega\varepsilon E_z$$

How to Reduce Dimensions

It is always good practice to minimize the number of dimensions utilized in a numerical analysis.



x
Material changes as a function of x. The mode profile will change as a function of x. We must retain this dimension.

y
Device is uniform. Wave does not propagate in this direction. Mode profile is uniform.

$$\frac{\partial}{\partial y} = 0$$

z
Device is uniform. Wave propagates in this direction so wave phase is increasing.

$$\frac{\partial}{\partial z} = -j\beta$$

$\partial/\partial y = 0$ Apply

Since nothing is changing in the y direction, any derivative with respect to y must be zero.

$$\begin{aligned} \cancel{\frac{\partial E_z}{\partial y}} - \frac{\partial E_y}{\partial z} &= -j\omega\mu H_x \\ \frac{\partial E_x}{\partial z} - \frac{\partial E_z}{\partial x} &= -j\omega\mu H_y \\ \frac{\partial E_y}{\partial x} - \cancel{\frac{\partial E_x}{\partial y}} &= -j\omega\mu H_z \end{aligned} \quad \Longrightarrow \quad \begin{aligned} -\frac{\partial E_y}{\partial z} &= -j\omega\mu H_x \\ \frac{\partial E_x}{\partial z} - \frac{\partial E_z}{\partial x} &= -j\omega\mu H_y \\ \frac{\partial E_y}{\partial x} &= -j\omega\mu H_z \end{aligned}$$

$$\begin{aligned} \cancel{\frac{\partial H_z}{\partial y}} - \frac{\partial H_y}{\partial z} &= j\omega\varepsilon E_x \\ \frac{\partial H_x}{\partial z} - \frac{\partial H_z}{\partial x} &= j\omega\varepsilon E_y \\ \frac{\partial H_y}{\partial x} - \cancel{\frac{\partial H_x}{\partial y}} &= j\omega\varepsilon E_z \end{aligned} \quad \Longrightarrow \quad \begin{aligned} -\frac{\partial H_y}{\partial z} &= j\omega\varepsilon E_x \\ \frac{\partial H_x}{\partial z} - \frac{\partial H_z}{\partial x} &= j\omega\varepsilon E_y \\ \frac{\partial H_y}{\partial x} &= j\omega\varepsilon E_z \end{aligned}$$

Two Distinct Mode Types

Our revised governing equations have separated into two distinct mode types.

$$-\frac{\partial E_y}{\partial z} = -j\omega\mu H_x$$
$$\frac{\partial E_x}{\partial z} - \frac{\partial E_z}{\partial x} = -j\omega\mu H_y$$
$$\frac{\partial E_y}{\partial x} = -j\omega\mu H_z$$

$$-\frac{\partial H_y}{\partial z} = j\omega\varepsilon E_x$$
$$\frac{\partial H_x}{\partial z} - \frac{\partial H_z}{\partial x} = j\omega\varepsilon E_y$$
$$\frac{\partial H_y}{\partial x} = j\omega\varepsilon E_z$$

We will analyze the Ey mode

Mode Type 1 – Ey Mode

$$\frac{\partial H_x}{\partial z} - \frac{\partial H_z}{\partial x} = j\omega\varepsilon E_y$$
$$-\frac{\partial E_y}{\partial z} = -j\omega\mu H_x$$
$$\frac{\partial E_y}{\partial x} = -j\omega\mu H_z$$

Mode Type 2 – Hy Mode

$$\frac{\partial E_x}{\partial z} - \frac{\partial E_z}{\partial x} = -j\omega\mu H_y$$
$$-\frac{\partial H_y}{\partial z} = j\omega\varepsilon E_x$$
$$\frac{\partial H_y}{\partial x} = j\omega\varepsilon E_z$$

What About $\partial/\partial z$?

The guided mode has the following mathematical form

$$\vec{E}(x,y,z) = \vec{A}(x)e^{-j\beta z}$$

Now calculate the partial derivative with respect to z and see what happens.

$$\frac{\partial}{\partial z}\vec{E}(x,y,z) = \frac{\partial}{\partial z}\left[\vec{A}(x)e^{-j\beta z}\right] = \vec{A}(x)\frac{\partial}{\partial z}e^{-j\beta z} + \cancel{e^{-j\beta z}\frac{\partial}{\partial z}\vec{A}(x)}$$

$$= -j\beta\underbrace{\vec{A}(x)e^{-j\beta z}}_{\vec{E}(x,y,z)} = -j\beta\vec{E}(x,y,z)$$

It can be concluded that for this slab waveguide analysis,

$$\frac{\partial}{\partial z} = -j\beta$$

1D Governing Equations

The equations for the Ey mode were

$$\frac{\partial}{\partial z}H_x - \frac{\partial H_z}{\partial x} = j\omega\varepsilon E_y$$

$$-\frac{\partial}{\partial z}E_y = -j\omega\mu H_x$$

$$\frac{\partial E_y}{\partial x} = -j\omega\mu H_z$$

These equations were derived simply replacing $\partial/\partial z$ with $-j\beta$.

$$-j\beta H_x - \frac{dH_z}{dx} = j\omega\varepsilon E_y$$

$$j\beta E_y = -j\omega\mu H_x$$

$$\frac{dE_y}{dx} = -j\omega\mu H_z$$

The partial derivative has become an ordinary derivative because there is only one independent variable remaining.

Normalize the Parameters

Before converting our equations to matrix form, we should normalize the spatial coordinate x to put it in terms of wavelength in some manner.

$$\tilde{x} \overset{???}{=} \frac{x}{\lambda_0}$$

Additionally, it will be mathematically convenient to normalize by multiplying x by the free space wave number k_0.

$$\tilde{x} = k_0 x \qquad k_0 = \frac{2\pi}{\lambda_0} = \frac{\omega\sqrt{\mu\varepsilon}}{n}$$

Normalizing Maxwell's Equations

Start with the following equation,

$$-j\beta H_x - \frac{dH_z}{dx} = j\omega\varepsilon E_y$$

and replace x with $\tilde{x}/k_0$.

$$-j\beta H_x - k_0\frac{dH_z}{d\tilde{x}} = j\omega\varepsilon E_y$$

Next, divide both sides of the equation by k_0.

$$-j\frac{\beta}{k_0}H_x - \frac{dH_z}{d\tilde{x}} = \frac{j\omega\varepsilon}{k_0}E_y$$

Recognizing that $\beta = k_0 n_{\text{eff}}$, this equation becomes

$$-jn_{\text{eff}}H_x - \frac{dH_z}{d\tilde{x}} = \frac{j\omega\varepsilon}{k_0}E_y$$

$$= \frac{j\omega\varepsilon_0\varepsilon_{\text{r}}}{\omega\sqrt{\mu_0\varepsilon_0}}E_y = j\sqrt{\frac{\varepsilon_0}{\mu_0}}\varepsilon_{\text{r}}E_y$$

Normalized Equations

Applying the normalizations to all equations to get

$$-jn_{\text{eff}}H_x-\frac{dH_z}{d\tilde{x}}=j\sqrt{\frac{\varepsilon_0}{\mu_0}}\varepsilon_{\text{r}}E_y$$

$$jn_{\text{eff}}E_y=-j\sqrt{\frac{\mu_0}{\varepsilon_0}}\mu_{\text{r}}H_x$$

$$\frac{dE_y}{d\tilde{x}}=-j\sqrt{\frac{\mu_0}{\varepsilon_0}}\mu_{\text{r}}H_z$$

Last, at optical frequencies, the magnetic response is negligible so $\mu_{\text{r}}=1$.

$$-jn_{\text{eff}}H_x-\frac{dH_z}{d\tilde{x}}=j\sqrt{\frac{\varepsilon_0}{\mu_0}}\varepsilon_{\text{r}}E_y$$

$$jn_{\text{eff}}E_y=-j\sqrt{\frac{\mu_0}{\varepsilon_0}}H_x$$

$$\frac{dE_y}{d\tilde{x}}=-j\sqrt{\frac{\mu_0}{\varepsilon_0}}H_z$$

Final Governing Equation

Solve the last two equations for H_x and H_z.

$$-jn_{\text{eff}}H_x-\frac{dH_z}{d\tilde{x}}=j\sqrt{\frac{\varepsilon_0}{\mu_0}}\varepsilon_{\text{r}}E_y$$

$$jn_{\text{eff}}E_y=-j\sqrt{\frac{\mu_0}{\varepsilon_0}}H_x \quad\rightarrow\quad H_x=-n_{\text{eff}}\sqrt{\frac{\varepsilon_0}{\mu_0}}E_y$$

$$\frac{dE_y}{d\tilde{x}}=-j\sqrt{\frac{\mu_0}{\varepsilon_0}}H_z \quad\rightarrow\quad H_z=j\sqrt{\frac{\varepsilon_0}{\mu_0}}\frac{dE_y}{d\tilde{x}}$$

These are substituted into the first equation to get a single equation containing only E_y. This is why it was called the E_y mode.

$$-jn_{\text{eff}}H_x-\frac{dH_z}{d\tilde{x}}=j\sqrt{\frac{\varepsilon_0}{\mu_0}}\varepsilon_{\text{r}}E_y$$

$$-jn_{\text{eff}}\left(-n_{\text{eff}}\sqrt{\frac{\varepsilon_0}{\mu_0}}E_y\right)-\frac{d}{d\tilde{x}}\left(j\sqrt{\frac{\varepsilon_0}{\mu_0}}\frac{dE_y}{d\tilde{x}}\right)=j\sqrt{\frac{\varepsilon_0}{\mu_0}}\varepsilon_{\text{r}}E_y$$

$$n_{\text{eff}}^2E_y-\frac{d^2E_y}{d\tilde{x}^2}=\varepsilon_{\text{r}}E_y \xrightarrow{\qquad} \frac{d^2E_y}{d\tilde{x}^2}+\varepsilon_{\text{r}}E_y=n_{\text{eff}}^2E_y$$

Eigen-Value Problem

For optical problems, people like to put everything in terms of refractive index. This is related to the relative permittivity through $\varepsilon_\mathrm{r} = n^2$.

$$\frac{d^2 E_y}{d\tilde{x}^2} + n^2 E_y = n_\mathrm{eff}^2 E_y$$

The governing equation can be rearranged to the form of a standard eigen-value problem $\mathbf{A}\mathbf{x} = \lambda \mathbf{x}$.

$$\boxed{\left[\frac{d^2}{d\tilde{x}^2} + n^2(x)\right] E_y(x) = n_\mathrm{eff}^2 E_y(x)}$$

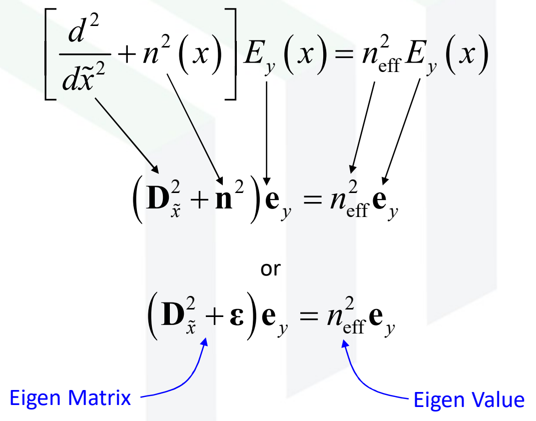
$\mathbf{A} = \frac{d^2}{d\tilde{x}^2} + n^2(x)$

$\mathbf{x} = E_y(x)$

$\lambda = n_\mathrm{eff}^2$

Matrix Form

We go term-by-term to write the equation in matrix form.



$$\left[\frac{d^2}{d\tilde{x}^2} + n^2(x)\right] E_y(x) = n_\mathrm{eff}^2 E_y(x)$$

$$\left(\mathbf{D}_{\tilde{x}}^2 + \mathbf{n}^2\right)\mathbf{e}_y = n_\mathrm{eff}^2 \mathbf{e}_y$$

or

$$\left(\mathbf{D}_{\tilde{x}}^2 + \boldsymbol{\varepsilon}\right)\mathbf{e}_y = n_\mathrm{eff}^2 \mathbf{e}_y$$

Eigen Matrix

Eigen Value

Solution

Solving the Eigen-Value Problem

$$\left(\mathbf{D}_{\tilde{x}}^{2}+\boldsymbol{\varepsilon}\right)\mathbf{e}_{y}=n_{\text{eff}}^{2}\mathbf{e}_{y} \quad \rightarrow$$

$\mathbf{V} \equiv$ Eigen-vector matrix

$\boldsymbol{\lambda} \equiv$ Eigen-value matrix

$$\mathbf{V}=\left[\begin{bmatrix} e_y^{(1)}(1) \\ e_y^{(1)}(2) \\ e_y^{(1)}(3) \\ \vdots \\ e_y^{(1)}(N_x-1) \\ e_y^{(1)}(N_x) \end{bmatrix} \quad \begin{bmatrix} e_y^{(2)}(1) \\ e_y^{(2)}(2) \\ e_y^{(2)}(3) \\ \vdots \\ e_y^{(2)}(N_x-1) \\ e_y^{(2)}(N_x) \end{bmatrix} \quad \cdots \quad \begin{bmatrix} e_y^{(M)}(1) \\ e_y^{(M)}(2) \\ e_y^{(M)}(3) \\ \vdots \\ e_y^{(M)}(N_x-1) \\ e_y^{(M)}(N_x) \end{bmatrix}\right]$$

M = # modes

Usually $M = N_x$

$$\mathbf{D}_{\tilde{x}}=\begin{bmatrix} \left(n_{\text{eff}}^{(1)}\right)^{2} & & & \\ & \left(n_{\text{eff}}^{(2)}\right)^{2} & & \\ & & \ddots & \\ & & & \left(n_{\text{eff}}^{(M)}\right)^{2} \end{bmatrix}$$

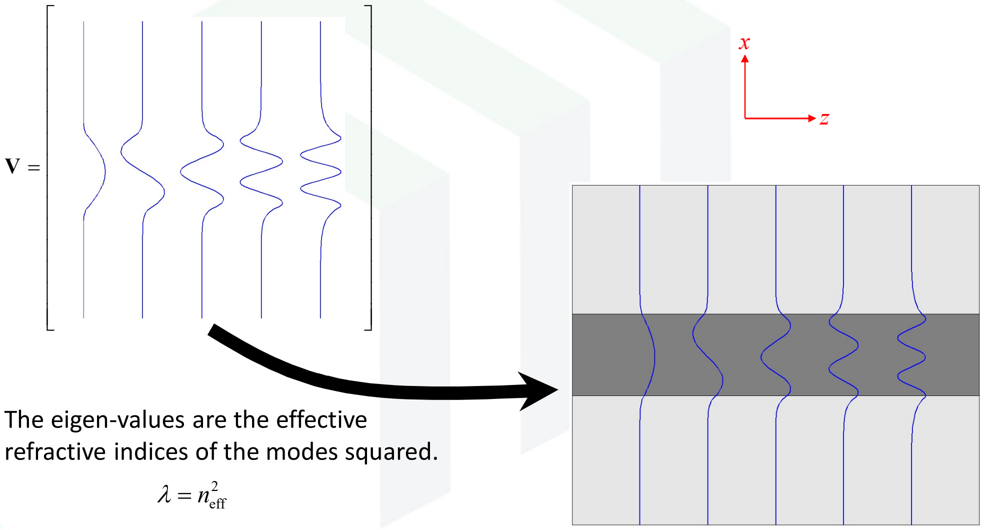
Eigen-vectors and eigen-values come in pairs.

Do not mix up their pairing!

EMPossible

Visualizing the Solution

The columns of the eigen-vector matrix are pictures of the modes.



The eigen-values are the effective refractive indices of the modes squared.

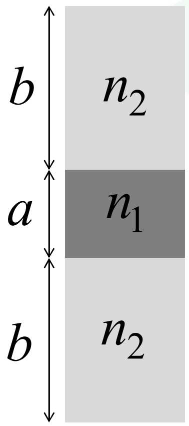
$$\lambda = n_{\text{eff}}^2$$

Implementation in MATLAB

Implementation Outline

1. Initialize MATLAB
2. Dashboard (materials, dimensions, etc.)
3. Calculate Grid
4. Build Device on Grid
5. Perform Finite-Difference Analysis
6. Visualize the Results

Dashboard



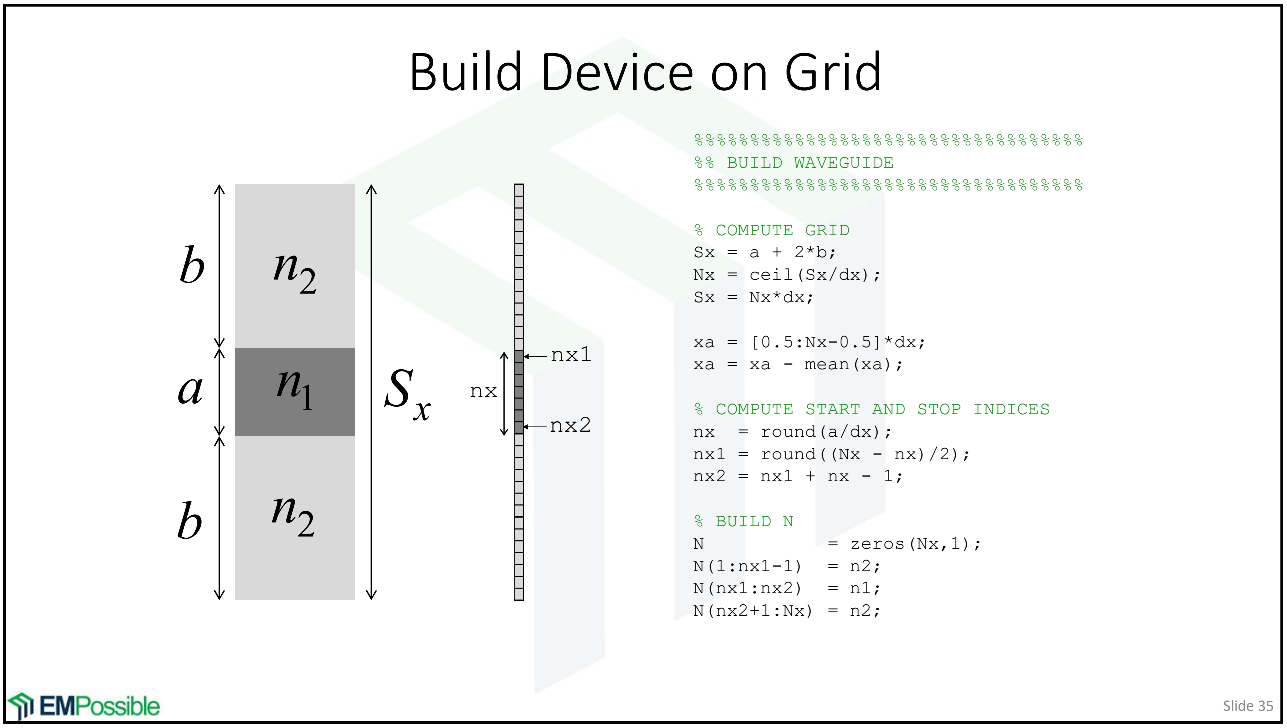
How big should we make b?

→ Enough to allow the mode to decay to zero before reaching the boundary.

What grid resolution should we use?

→ Convergence

```
% slabdemo.m

% INITIALIZE MATLAB
close all;
clc;
clear all;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% DASHBOARD
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% FREE SPACE WAVELENGTH
lam0 = 1.0;

% SLAB PARAMETERS
n1 = 2.0;
n2 = 1.0;
a  = 3*lam0;

% GRID
b    = 5*lam0;
NRES = 10;
dx   = lam0/NRES;

% NUMBER OF MODES TO CALCULATE
M = 5;
```



Build Device on Grid

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% BUILD WAVEGUIDE
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% COMPUTE GRID
Sx = a + 2*b;
Nx = ceil(Sx/dx);
Sx = Nx*dx;

xa = [0.5:Nx-0.5]*dx;
xa = xa - mean(xa);

% COMPUTE START AND STOP INDICES
nx  = round(a/dx);
nx1 = round((Nx - nx)/2);
nx2 = nx1 + nx - 1;

% BUILD N
N            = zeros(Nx,1);
N(1:nx1-1)   = n2;
N(nx1:nx2)   = n1;
N(nx2+1:Nx)  = n2;
```

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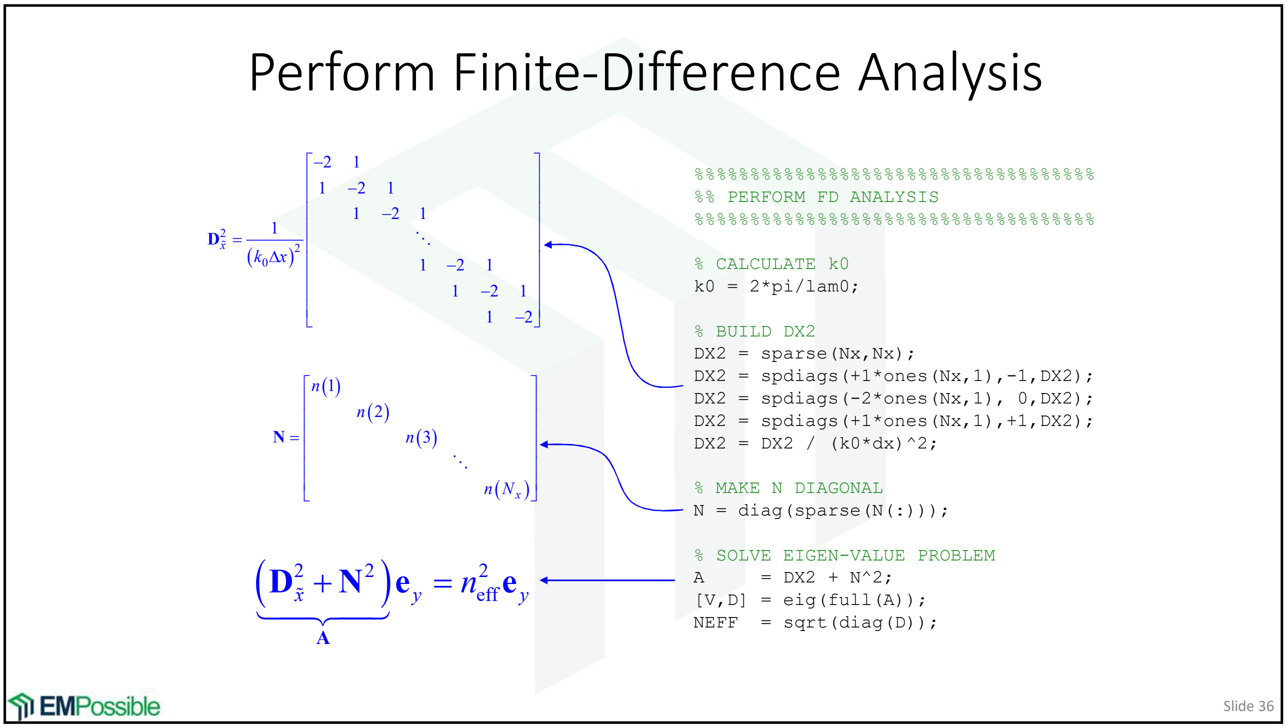


Perform Finite-Difference Analysis

$$\mathbf{D}_{\tilde{x}}^2 = \frac{1}{(k_0\Delta x)^2}\begin{bmatrix} -2 & 1 & & & & & \\ 1 & -2 & 1 & & & & \\ & 1 & -2 & 1 & & & \\ & & & \ddots & & & \\ & & & 1 & -2 & 1 & \\ & & & & 1 & -2 & 1 \\ & & & & & 1 & -2 \end{bmatrix}$$

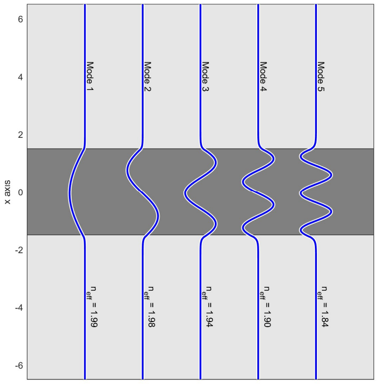
$$\mathbf{N} = \begin{bmatrix} n(1) & & & & \\ & n(2) & & & \\ & & n(3) & & \\ & & & \ddots & \\ & & & & n(N_x) \end{bmatrix}$$

$$\underbrace{\left(\mathbf{D}_{\tilde{x}}^2 + \mathbf{N}^2\right)}_{\mathbf{A}}\mathbf{e}_y = n_{\text{eff}}^2\mathbf{e}_y$$

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% PERFORM FD ANALYSIS
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% CALCULATE k0
k0 = 2*pi/lam0;

% BUILD DX2
DX2 = sparse(Nx,Nx);
DX2 = spdiags(+1*ones(Nx,1),-1,DX2);
DX2 = spdiags(-2*ones(Nx,1), 0,DX2);
DX2 = spdiags(+1*ones(Nx,1),+1,DX2);
DX2 = DX2 / (k0*dx)^2;

% MAKE N DIAGONAL
N = diag(sparse(N(:)));

% SOLVE EIGEN-VALUE PROBLEM
A     = DX2 + N^2;
[V,D] = eig(full(A));
NEFF  = sqrt(diag(D));
```

Slide 36

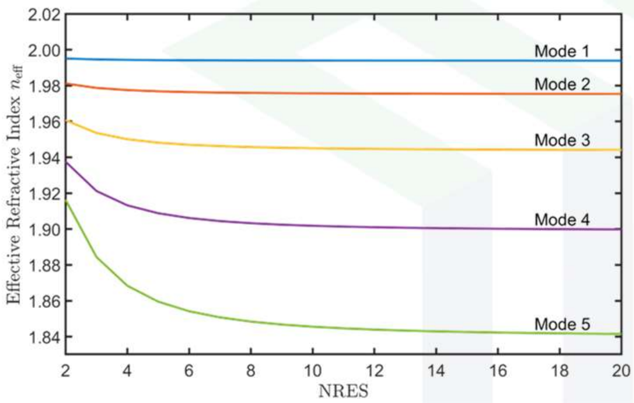
Visualize the Results



```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% VISUALIZE
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% SORT MODES
[~,ind] = sort(real(NEFF),'descend');
V       = V(:,ind);
NEFF    = NEFF(ind);

% OPEN FIGURE WINDOW
figure('Color','w');
hold on;

% DRAW SLAB WAVEGUIDE
x = [0 2*(M+1) 2*(M+1) 0 0];
y = [ -b-a/2 -b-a/2 b+a/2 b+a/2 -b-a/2 ];
fill(x,y,0.9*[1 1 1]);
y = [ -a/2 -a/2 a/2 a/2 -a/2 ];
fill(x,y,0.5*[1 1 1]);

% DRAW AND LABEL MODES
for m = 1 : M
    x0 = 2*m;
    y0 = (a + b)/2;
    x = x0 + 3*V(:,m);
    y = linspace(-b-a/2,b+a/2,Nx);
    line(x,y,'Color','w','LineWidth',4);
    h = line(x,y,'Color','b','LineWidth',2);
    text(x0,y0,['Mode ' num2str(m)],'Rotation',-90,...
         'HorizontalAlignment','center','VerticalAlignment','bottom');
    text(x0,-y0,['n_{eff} = ' num2str(NEFF(m),'%4.2f')],'Rotation',-90,...
         'HorizontalAlignment','center','VerticalAlignment','bottom');
end

% SET GRAPHICS VIEW
hold off;
h2 = get(h,'Parent');
set(h2,'XTick',[]);
axis equal tight;
ylabel('x axis');
```

More About Resolution and Spacer Regions

Convergence Study for `NRES`



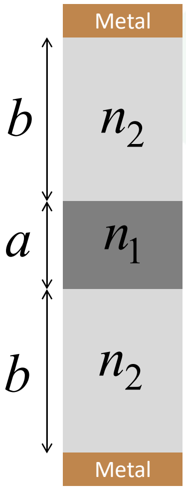
$$\Delta x = \frac{\lambda_0}{\text{NRES}}$$

Notes

- Higher-order modes converge slower.
- Higher-order modes have a smaller n_{eff}.

EMPossible

Spacer Region b



Remember the Dirichlet boundary conditions? Values outside of the grid are forced to zero.

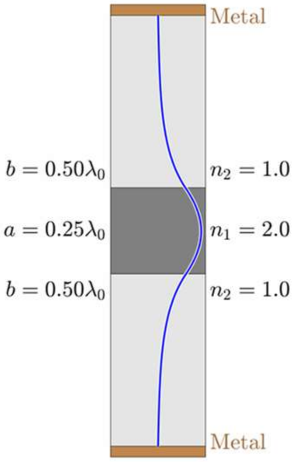
This means we really are simulating a slab waveguide inside of a large metal waveguide.

It is only possible to get an accurate simulation of the slab waveguide when the metal waveguide is large enough.

We must choose b to be large enough to ensure the metal waveguide is insignificant.

EMPossible

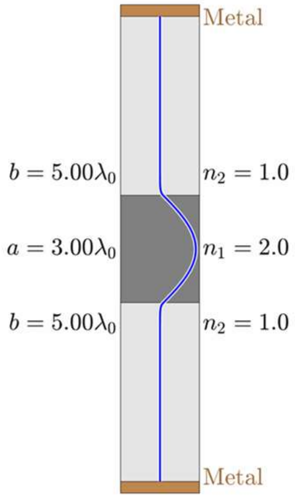
Effect of Spacer Region Size



$n_{\text{eff}} = 1.6622$

If the spacer region b is too small, the outer metal waveguide becomes significant and the results for the slab are not accurate.

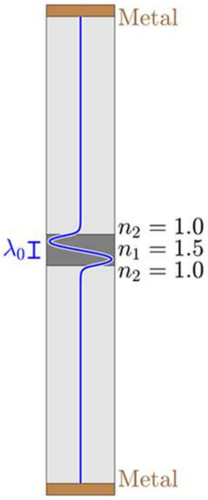
Conditions for Large Evanescent Fields: *Thin Waveguides*



Thin dielectric waveguides have large evanescent fields.

The spacer region b must be big enough to sufficiently encompass the evanescent field in order to give an accurate simulation.

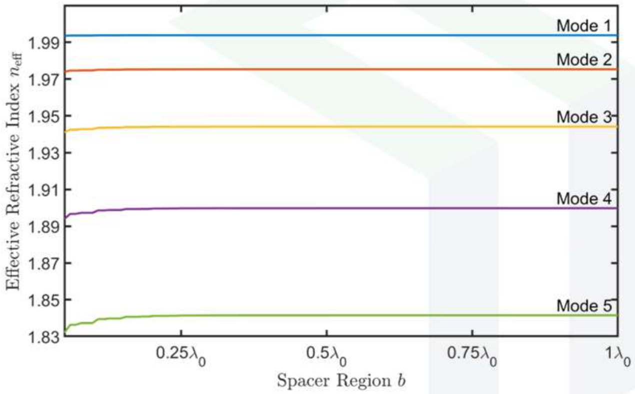
Conditions for Large Evanescent Fields: *Modes Near Cutoff*



Guided modes operating near cutoff have very large evanescent fields.

The spacer region b must be big enough to sufficiently encompass the evanescent field in order to give an accurate simulation.

Convergence Study for Spacer Region b



Notes

- Under normal circumstances, the spacer region size can be ~$0.25\lambda_0$.
- Modes near cutoff require larger spacer regions to resolve.
- Thin waveguides may require larger spacer regions.
- Always check for convergence of spacer region size.