

Optical Waveguide Theory (F)



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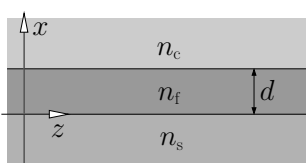
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Course overview

Optical waveguide theory

- A Photonics / integrated optics; theory, motto; phenomena, introductory examples.
- B Brush up on mathematical tools.
- C Maxwell equations, different formulations, interfaces, energy and power flow.
- D Classes of simulation tasks: scattering problems, mode analysis, resonance problems.
- E Normal modes of dielectric optical waveguides, mode interference.
- F Examples for dielectric optical waveguides.
- G Waveguide discontinuities & circuits, scattering matrices, reciprocal circuits.
- H Bent optical waveguides; whispering gallery resonances; circular microresonators.
- I Coupled mode theory, perturbation theory.
 - Hybrid analytical / numerical coupled mode theory.
- J A touch of photonic crystals; a touch of plasmonics.
 - Oblique semi-guided waves: 2-D integrated optics.
 - Summary, concluding remarks.

2-D waveguide configurations



$\epsilon \in \mathbb{R}, \mu = 1, \sim \exp(i\omega t)$ (FD)

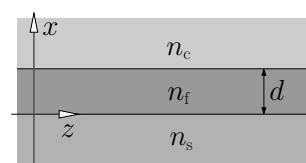
- 2-D waveguide, 1-D cross section.
- Permittivity $\epsilon = n^2$, refractive index $n(x)$. (1-D waveguide)

- $\partial_y \epsilon = 0 \iff \partial_y \mathbf{E} = 0, \partial_y \mathbf{H} = 0$, 2-D TE/TM setting.
- $\partial_z \epsilon = 0 \iff$ Modal solutions that vary harmonically with z :

$$\begin{pmatrix} \mathbf{E} \\ \mathbf{H} \end{pmatrix} (x, z) = \begin{pmatrix} \bar{\mathbf{E}} \\ \bar{\mathbf{H}} \end{pmatrix} (x) e^{-i\beta z}, \quad \begin{array}{l} \text{mode profile } \bar{\mathbf{E}}, \bar{\mathbf{H}}, \\ \text{propagation constant } \beta, \\ \text{effective index } n_{\text{eff}} = \beta/k. \end{array}$$

(TE): principal component \bar{E}_y , $\partial_x^2 \bar{E}_y + (k^2 \epsilon - \beta^2) \bar{E}_y = 0$,
 $\bar{E}_x = 0, \bar{E}_z = 0, \bar{H}_x = \frac{-\beta}{\omega \mu_0} \bar{E}_y, \bar{H}_y = 0, \bar{H}_z = \frac{i}{\omega \mu_0} \partial_x \bar{E}_y$,
 \bar{E}_y & $\partial_x \bar{E}_y$ continuous at dielectric interfaces.

2-D waveguide configurations



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(TM): principal component \bar{H}_y , $\epsilon \partial_x \frac{1}{\epsilon} \partial_x \bar{H}_y + (k^2 \epsilon - \beta^2) \bar{H}_y = 0$,
 $\bar{E}_x = \frac{\beta}{\omega \epsilon_0 \epsilon} \bar{H}_y, \bar{E}_y = 0, \bar{E}_z = \frac{-i}{\omega \epsilon_0 \epsilon} \partial_x \bar{H}_y, \bar{H}_x = 0, \bar{H}_z = 0$,
 \bar{H}_y & $\epsilon^{-1} \partial_x \bar{H}_y$ continuous at dielectric interfaces.

Guided 2-D TE/TM modes, orthogonality properties

- A set (index m) of guided modes of a 2-D waveguide (ϵ), (→ Exercise.)
 $\psi_m^p = (\bar{\mathbf{E}}_m, \bar{\mathbf{H}}_m)$, $p=\text{TE, TM}$ & β_m , $\beta_m \neq \beta_l$, if $l \neq m$.
- $(\mathbf{E}_1, \mathbf{H}_1; \mathbf{E}_2, \mathbf{H}_2) := \frac{1}{4} \int (E_{1x}^* H_{2y} - E_{1y}^* H_{2x} + H_{1y}^* E_{2x} - H_{1x}^* E_{2y}) dx$.
- Power P_m per lateral (y) unit length carried by mode ψ_m^p , β_m :

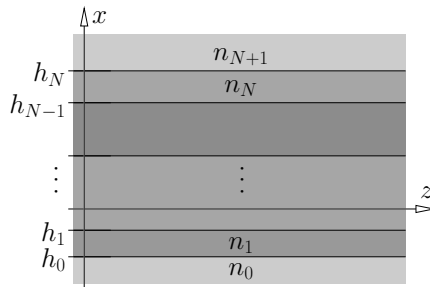
$$P_m := \int S_z dx = (\psi_m^p; \psi_m^p) = \begin{cases} \frac{\beta_m}{2\omega\mu_0} \int |E_{m,y}|^2 dx, & \text{if } p = \text{TE}, \\ \frac{\beta_m}{2\omega\epsilon_0} \int \frac{1}{\epsilon} |H_{m,y}|^2 dx, & \text{if } p = \text{TM}. \end{cases}$$

$$(\psi_l^{\text{TE}}; \psi_m^{\text{TM}}) = 0, \quad (\psi_l^{\text{TE}}; \psi_m^{\text{TE}}) = \frac{\beta_m}{2\omega\mu_0} \int E_{l,y}^* E_{m,y} dx = \delta_{lm} P_m,$$

$$(\psi_l^{\text{TM}}; \psi_m^{\text{TE}}) = 0, \quad (\psi_l^{\text{TM}}; \psi_m^{\text{TM}}) = \frac{\beta_m}{2\omega\epsilon_0} \int \frac{1}{\epsilon} H_{l,y}^* H_{m,y} dx = \delta_{lm} P_m.$$

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Dielectric multilayer slab waveguide



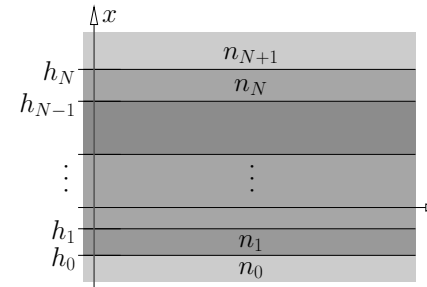
- Interior layer l ,
 $h_{l-1} < x < h_l$,
 local refractive index n_l ,
- $\partial_x^2 \phi = (\beta^2 - k^2 n_l^2) \phi$.
- Consider a trial value $\beta^2 \in \mathbb{R}$.

- $\beta^2 < k^2 n_l^2 \rightsquigarrow \partial_x^2 \phi = -\kappa_l^2 \phi$, $\kappa_l := \sqrt{k^2 n_l^2 - \beta^2}$,
 $\phi(x) = A_l \sin(\kappa_l x) + B_l \cos(\kappa_l x)$.
- $\beta^2 > k^2 n_l^2 \rightsquigarrow \partial_x^2 \phi = \kappa_l^2 \phi$, $\kappa_l := \sqrt{\beta^2 - k^2 n_l^2}$,
 $\phi(x) = A_l e^{\kappa_l x} + B_l e^{-\kappa_l x}$.

- Unknowns $A_l, B_l \in \mathbb{C}$. (Local coordinate offsets required to cope with the exponentials.)

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Dielectric multilayer slab waveguide



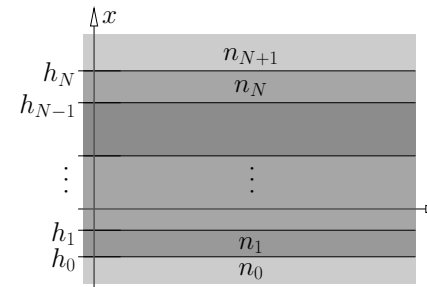
$\epsilon \in \mathbb{R}$, $\mu = 1$, $\sim \exp(i\omega t)$ (2-D, FD)

- N interior layers,
 piecewise constant $\epsilon = n^2$:

$$n(x) = \begin{cases} n_{N+1} & \text{if } h_N < x, \\ n_l & \text{if } h_{l-1} < x < h_l, \\ n_0 & \text{if } x < h_0. \end{cases}$$
- Principal component $\phi(x)$ (TE: $\phi = \bar{E}_y$, TM: $\phi = \bar{H}_y$).
- $\partial_x^2 \phi + (k^2 n_l^2 - \beta^2) \phi = 0$, $x \in \text{layer } l$, $l = 0, \dots, N+1$
(Half-infinite substrate ($l = 0$) and cover ($l = N+1$) layers.)
- ϕ & $\eta \partial_x \phi$ continuous at $x = h_l$, (TE: $\eta = 1$, TM: $\eta = n^{-2}$).

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Dielectric multilayer slab waveguide, guided modes



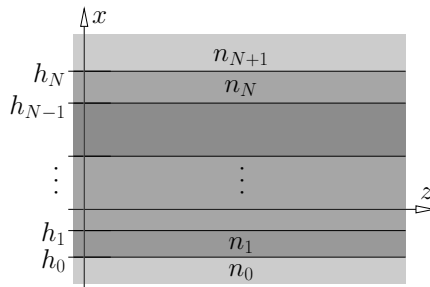
- Substrate region,
 $x < h_0$,
 local refractive index n_0 ,
- $\partial_x^2 \phi = (\beta^2 - k^2 n_0^2) \phi$.
- Consider a trial value $\beta^2 \in \mathbb{R}$.

- $\beta^2 < k^2 n_0^2 \rightsquigarrow \partial_x^2 \phi = -\kappa_0^2 \phi$, $\kappa_0 := \sqrt{k^2 n_0^2 - \beta^2}$,
 $\phi(x) = A_0 \sin(\kappa_0 x) + B_0 \cos(-\kappa_0 x)$.
- $\beta^2 > k^2 n_0^2 \rightsquigarrow \partial_x^2 \phi = \kappa_0^2 \phi$, $\kappa_0 := \sqrt{\beta^2 - k^2 n_0^2}$,
 $\phi(x) = A_0 e^{\kappa_0 x} + B_0 e^{-\kappa_0 x}$.

- Unknown $A_0 \in \mathbb{C}$. **Guided modes: $n_{\text{eff}} = \beta/k > n_0$.**

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Dielectric multilayer slab waveguide, guided modes



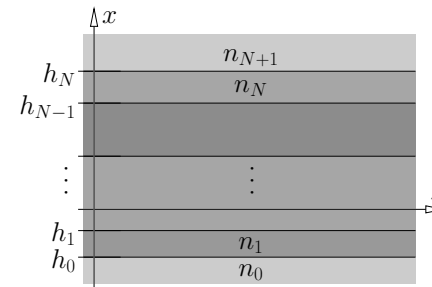
- Cover region, $h_N < x$, local refractive index n_{N+1} ,
- $\partial_x^2 \phi = (\beta^2 - k^2 n_{N+1}^2) \phi$.
- Consider a trial value $\beta^2 \in \mathbb{R}$.

- $\beta^2 < k^2 n_{N+1}^2 \rightsquigarrow \partial_x^2 \phi = -\kappa_{N+1}^2 \phi$, $\kappa_{N+1} := \sqrt{k^2 n_{N+1}^2 - \beta^2}$,
 $\phi(x) = A_{N+1} \sin(\kappa_{N+1} x) + B_{N+1} \cos(\kappa_{N+1} x)$.
- $\beta^2 > k^2 n_{N+1}^2 \rightsquigarrow \partial_x^2 \phi = \kappa_{N+1}^2 \phi$, $\kappa_{N+1} := \sqrt{\beta^2 - k^2 n_{N+1}^2}$,
 $\phi(x) = A_{N+1} e^{\kappa_{N+1} x} + B_{N+1} e^{-\kappa_{N+1} x}$.
- Unknown $B_{N+1} \in \mathbb{C}$. Guided modes: $n_{\text{eff}} = \beta/k > n_{N+1}$.

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Dielectric multilayer slab waveguide



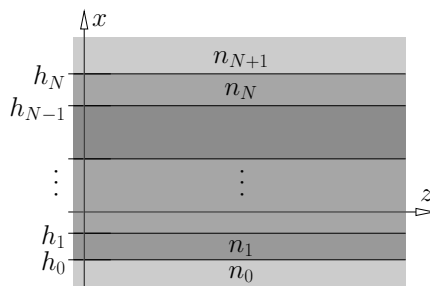
- Trial value $\beta^2 \in \mathbb{R}$,
- $\beta/k > n_0, n_{N+1}$,
- $\rightsquigarrow \kappa_l$, $l = 0, \dots, N+1$.

$$\phi(x) = \begin{cases} B_{N+1} e^{-\kappa_{N+1} x}, & \text{for } h_N < x, \\ \begin{cases} A_l \sin(\kappa_l x) + B_l \cos(\kappa_l x), & \text{if } \beta^2 < k^2 n_l^2, \\ A_l e^{\kappa_l x} + B_l e^{-\kappa_l x}, & \text{if } \beta^2 > k^2 n_l^2, \end{cases} & \text{for } h_{l-1} < x < h_l, \\ A_0 e^{\kappa_0 x}, & \text{for } x < h_0. \end{cases}$$

- $2N + 2$ unknowns $A_0, A_1, B_1, \dots, A_N, B_N, B_{N+1}$.
- Continuity of $\phi, \eta \partial_x \phi$ at $N + 1$ interfaces $\rightsquigarrow 2N + 2$ equations.

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Dielectric multilayer slab waveguide



- Trial value $\beta^2 \in \mathbb{R}$,
- $\beta/k > n_0, n_{N+1}$.

- $2N + 2$ unknowns $A_0, A_1, B_1, \dots, A_N, B_N, B_{N+1}$.
- Continuity of $\phi, \eta \partial_x \phi$ at $N + 1$ interfaces $\rightsquigarrow 2N + 2$ equations.
- Arrange as linear system of equations $\mathbf{M}(\beta^2) (A_0, \dots, B_{N+1})^T = 0$.
- Identify propagation constants where $\mathbf{M}(\beta^2)$ becomes singular.

(Equations relate to the series of interfaces \leftrightarrow A transfer-matrix technique can be applied.)

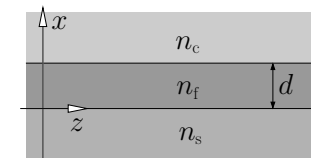
- Choose e.g. $A_0 = 1$, fill A_1, \dots, B_{N+1} , normalize. (\dots, \dots)

Guided modes $\{\beta_m, (\vec{E}_m, \vec{H}_m)\}$.

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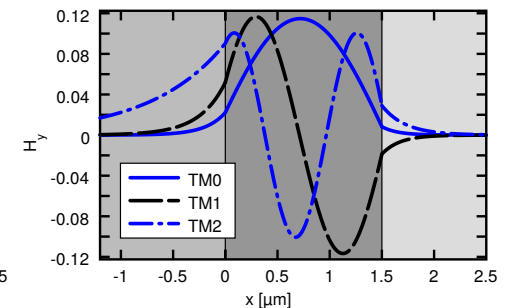
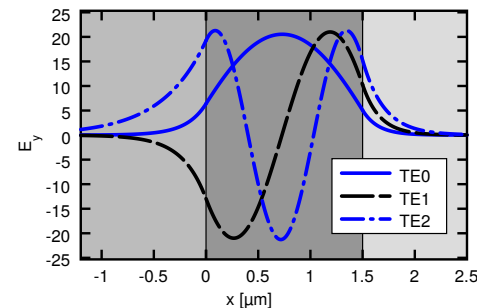
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A nonsymmetric 3-layer slab waveguide



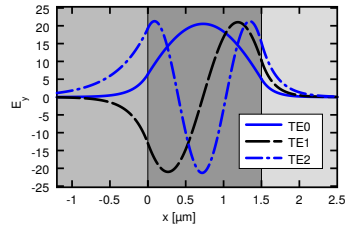
$n_s = 1.45$, $n_f = 1.99$, $n_c = 1.0$,
 $d = 1.5 \mu\text{m}$, $\lambda = 1.55 \mu\text{m}$.

TE₀: $n_{\text{eff}} = 1.944$, TM₀: $n_{\text{eff}} = 1.933$,
 TE₁: $n_{\text{eff}} = 1.804$, TM₁: $n_{\text{eff}} = 1.759$,
 TE₂: $n_{\text{eff}} = 1.562$, TM₂: $n_{\text{eff}} = 1.490$.



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Dielectric multilayer slab waveguide, nodal properties



(Fixed polarization, TE/TM.)

$$\partial_x(\partial_x\phi) = -(k^2 n^2 - \beta^2)\phi.$$

$k^2 n^2 - \beta^2$ determines the rate of change of the slope of ϕ .

Imagine a numerical ODE algorithm of "shooting-type".



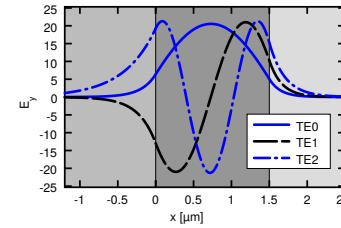
- Guided modes with a growing number of nodes (x with $\phi(x) = 0$) with decreasing effective indices

↔ mode indices = number of nodes in ϕ .

"Quantum numbers".

- A **fundamental mode** with zero nodes and highest effective index.
- Modes of the same polarization are **non-degenerate**.

Dielectric multilayer slab waveguide, nodal properties



(Fixed polarization, TE/TM.)

$$\partial_x(\partial_x\phi) = -(k^2 n^2 - \beta^2)\phi.$$

$k^2 n^2 - \beta^2$ determines the rate of change of the slope of ϕ .

Imagine a numerical ODE algorithm of "shooting-type".

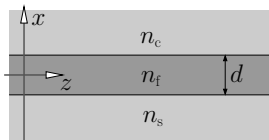


- A sign change of $\partial_x\phi$ is required to form a guided mode
 ↳ There must be some region (layer) with $k^2 n^2 - \beta^2 > 0$.

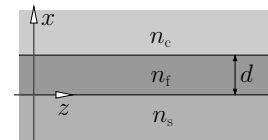
Interval for effective indices n_{eff} of guided modes:

$$\max\{n_0, n_{N+1}\} < n_{\text{eff}} < \max\{n_l\}.$$

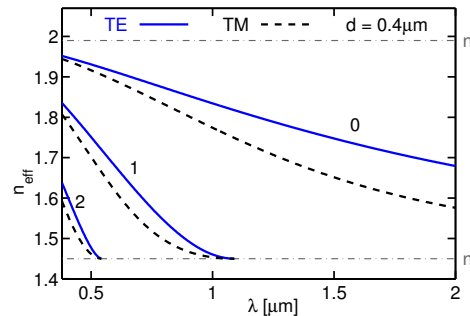
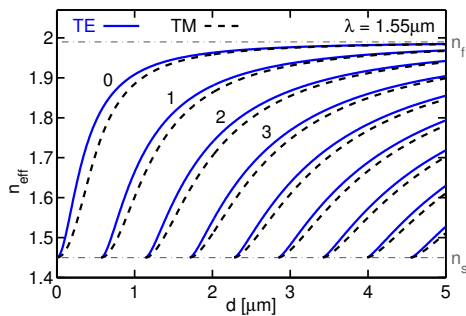
3-layer slab waveguide, dispersion curves



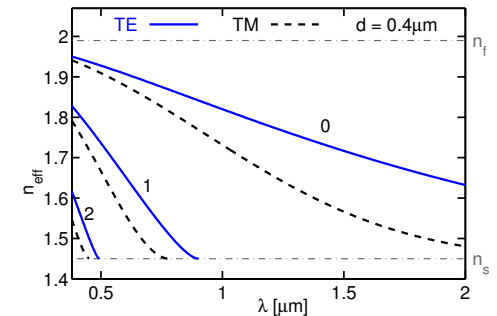
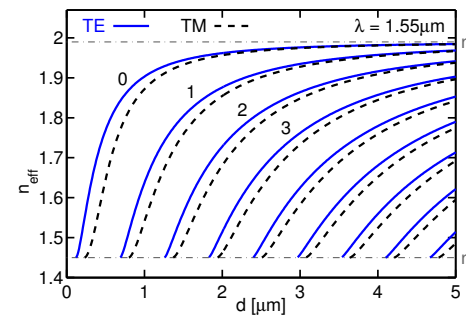
Symmetric waveguide, moderate refractive index contrast, $n_s = 1.45$, $n_f = 1.99$, $n_c = 1.45$.



Nonsymmetric waveguide, moderate refractive index contrast, $n_s = 1.45$, $n_f = 1.99$, $n_c = 1.0$.

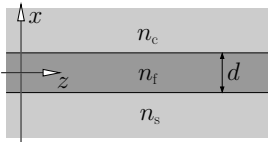


(Caution: $\partial_\lambda \epsilon = 0$ assumed!)

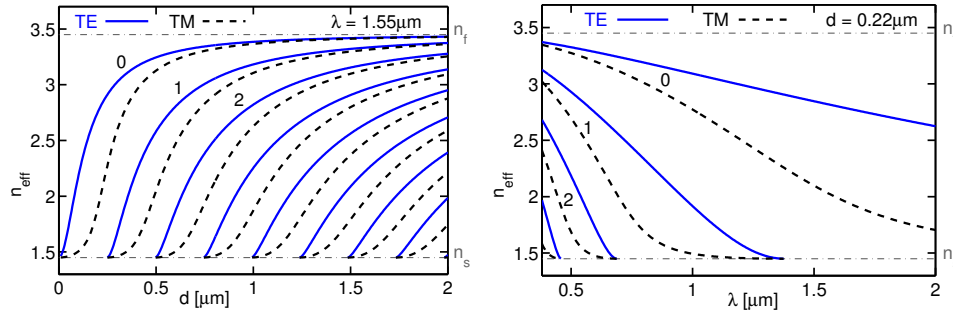


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3-layer slab waveguide, dispersion curves

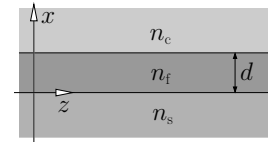


Symmetric waveguide,
high refractive index contrast,
 $n_s = 1.45, n_f = 3.45, n_c = 1.45$.

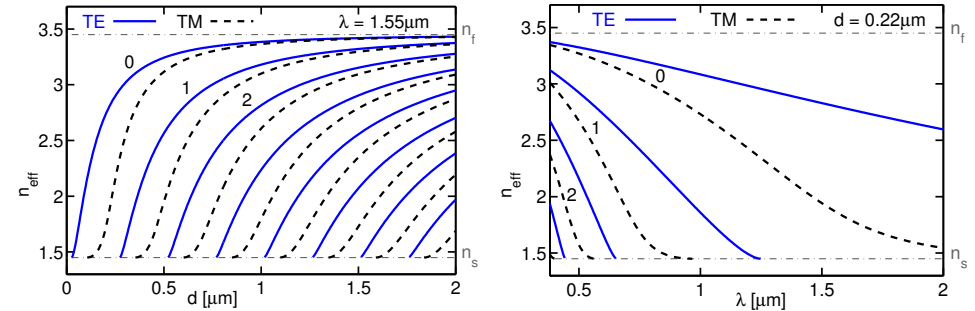


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3-layer slab waveguide, dispersion curves



Nonsymmetric waveguide,
high refractive index contrast,
 $n_s = 1.45, n_f = 3.45, n_c = 1.0$.



(Caution: $\partial_\lambda \epsilon = 0$ assumed!)

3-layer slab waveguide, dispersion curves

Remarks / observations:

- At large core thicknesses, or short wavelengths, for all modes: n_{eff} approaches the level n_f of bulk waves in the core material.
- Modes of higher order at the same n_{eff} supported by waveguides with thickness increased by specific distances.

Guided mode, layer l with $\kappa_l^2 = (k^2 n^2 - \beta^2) > 0$, field $\phi(x) \sim \cos(\kappa_l x + \chi)$ for $x \in$ layer l ;
increase layer thickness by $\Delta x = \pi / \kappa_l$, such that $\kappa_l(x + \Delta x) = \kappa_l x + \pi$
→ the thicker waveguide supports a mode of order $+1$ with the same propagation constant.

- Cutoff thicknesses at fixed wavelength.

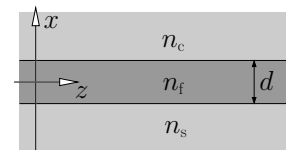
Nonsymmetric 3-layer waveguide $n_s \neq n_c$: There exist cutoff thicknesses for all modes.
Symmetric 3-layer waveguide $n_s = n_c$: Cutoff thicknesses exist for all modes of order ≥ 1 ,
no cutoff thickness for the fundamental TE/TM modes.

- λ is the “length-defining” quantity; wavelength scaling, factor a :
 $n_{\text{eff}}(\lambda, d) = n_{\text{eff}}(a\lambda, ad)$, $\beta(\lambda, d) = a^{-1} \beta(a\lambda, ad)$.

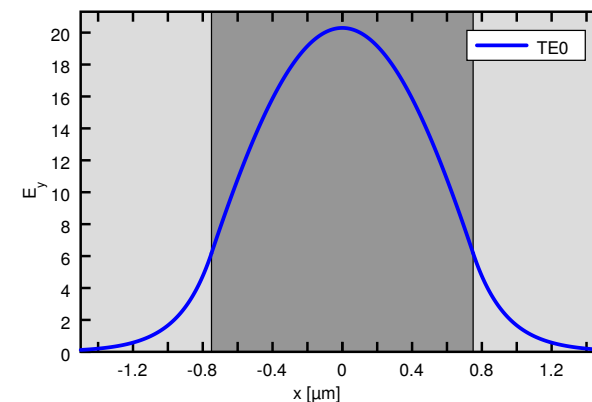
- Cutoff wavelengths for waveguides with fixed thickness.

For all modes; exception: no cutoff wavelength for the fundamental TE/TM modes in a symmetric 3-layer waveguide.

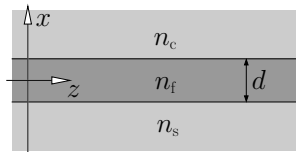
3-layer slab waveguide, mode confinement



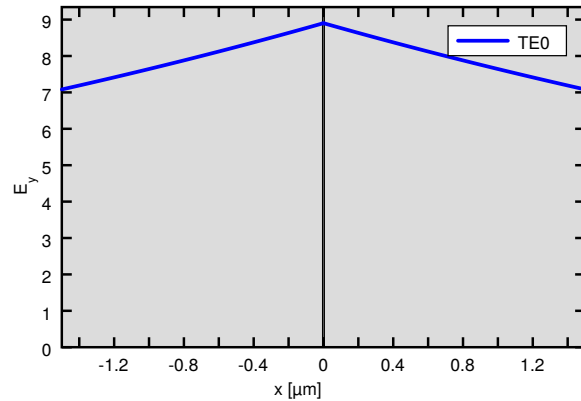
Symmetric waveguide,
moderate refractive index contrast,
 $n_s = 1.45, n_f = 1.99, n_c = 1.45, \lambda = 1.55 \mu\text{m}$,
 $d = 1.50 \mu\text{m}$, TE₀: $n_{\text{eff}} = 1.946$.



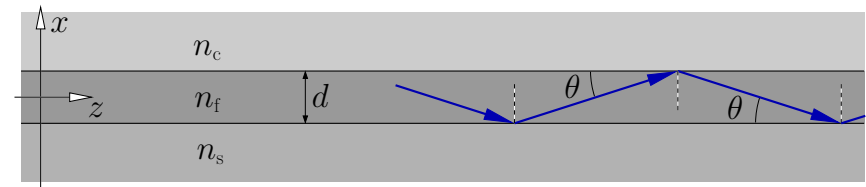
3-layer slab waveguide, mode confinement



Symmetric waveguide, moderate refractive index contrast, $n_s = 1.45$, $n_f = 1.99$, $n_c = 1.45$, $\lambda = 1.55 \mu\text{m}$, $d = 0.01 \mu\text{m}$, TE₀: $n_{\text{eff}} = 1.450$.



3-layer slab waveguide, ray model



Field in the core:

$$\sim a_u e^{-i(\kappa x + \beta z)} + a_d e^{-i(-\kappa x + \beta z)}, \quad k^2 n_f^2 = \beta^2 + \kappa^2$$

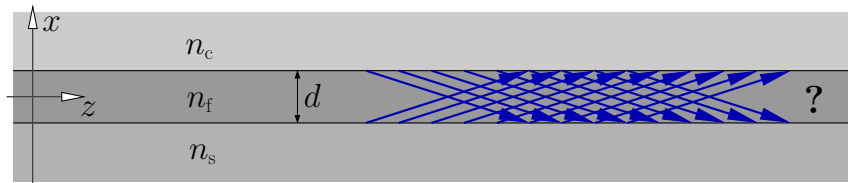
propagation angle θ with $\beta = kn_f \cos \theta$, $\kappa = kn_f \sin \theta$.

Guided mode formation:

- Repeated total internal reflection of waves in the core at upper and lower interfaces
- Calculate optical phase gain, including phase jumps for reflection at interfaces (polarization dependent).
- Phase gain of 2π for one "round trip", "transverse resonance condition" \longleftrightarrow constructive interference of waves.

(A frequently encountered intuitive model . . . of very limited applicability.)

3-layer slab waveguide, ray model



Field in the core:

$$\sim a_u e^{-i(\kappa x + \beta z)} + a_d e^{-i(-\kappa x + \beta z)}, \quad k^2 n_f^2 = \beta^2 + \kappa^2$$

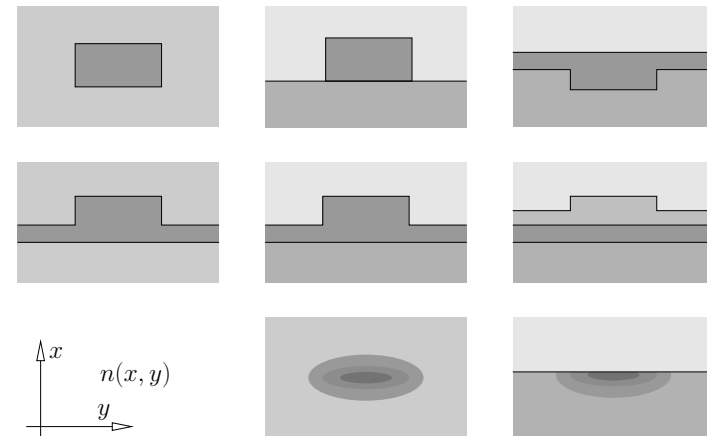
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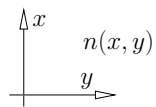
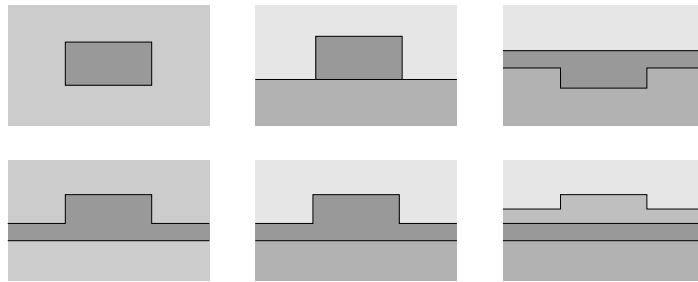
(A frequently encountered intuitive model . . . of very limited applicability.)

3-D waveguides



Cross sections (2-D) of typical integrated-optical waveguides.

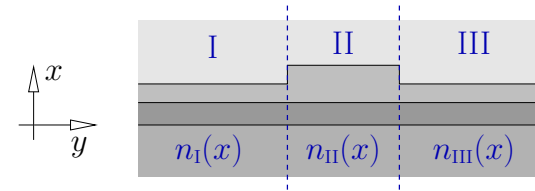
3-D rectangular waveguides



No analytical solutions:

- numerical mode solvers.
- approximations.

Effective index method



Outline:

- Divide into slices $\rho = I, II, III$: $n(x, y) = n_\rho(x)$, if $y \in \text{slice } \rho$.
- Compute polarized modes $X_\rho(x), \beta_\rho$, $X_\rho'' + (k^2 n_\rho^2 - \beta_\rho^2)X_\rho = 0$, $N_\rho = \beta_\rho/k$.
- Consider a scalar mode equation for the principal component Ψ of the 3-D waveguide

$$\partial_x^2 \Psi + \partial_y^2 \Psi + (k^2 n^2 - \beta^2)\Psi = 0, \quad \Psi = E_y \text{ (TE)}, \quad \Psi = H_y \text{ (TM)}.$$

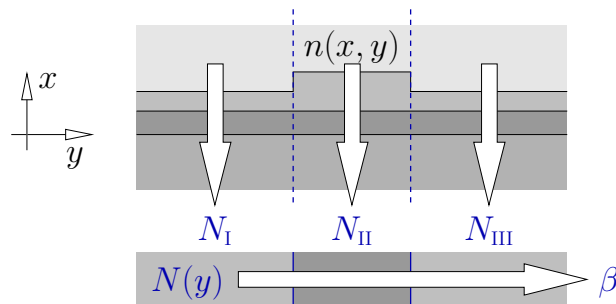
- Ansatz: $\Psi(x, y) = X_\rho(x) Y(y)$, if $y \in \text{slice } \rho$; require continuity of Y and Y' .
- **Effective index profile:** $N(y) := N_\rho$, if $y \in \text{slice } \rho$.

$$Y'' + (k^2 N^2 - \beta^2)Y = 0,$$

a 1-D mode equation for Y, β with the effective index profile N in place of the refractive indices.

(!)

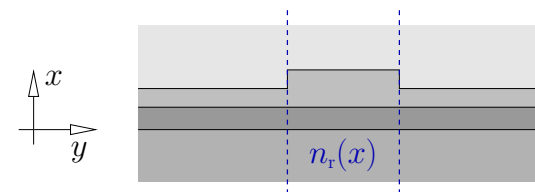
Effective index method, schematically



Remarks / issues:

- A popular, quite intuitive method.
- Frequently an (often informal) basis for discussion of waveguide properties.
- \leftrightarrow Relevance of the slab waveguide model.
- Manifold variants / ways of improvements exist.
- What if a slice does not support a guided slab mode?
- What about higher order modes?
- How to evaluate modal fields? What about other than principal components?
- ...

Variational effective index method



Outline:

- Identify a reference slice, refractive index profile $n_r(x)$.
- Compute polarized guided slab modes $(\bar{E}, \bar{H})_r, \beta_r$ for the reference slice.
- For each each reference slab mode: ...
- Choose an ansatz:

$$\begin{pmatrix} E_x, E_y, E_z \\ H_x, H_y, H_z \end{pmatrix} (x, y, z) = \begin{pmatrix} 0, & \bar{E}_{r,y}(x)Y^{E_y}(y), & \bar{E}_{r,y}(x)Y^{E_z}(y) \\ \bar{H}_{r,x}(x)Y^{H_x}(y), & \bar{H}_{r,z}(x)Y^{H_y}(y), & \bar{H}_{r,z}(x)Y^{H_z}(y) \end{pmatrix} \quad \text{(TE)}$$

$$\begin{pmatrix} E_x, E_y, E_z \\ H_x, H_y, H_z \end{pmatrix} (x, y, z) = \begin{pmatrix} \bar{E}_{r,x}(x)Y^{E_x}(y), & \bar{E}_{r,z}(x)Y^{E_y}(y), & \bar{E}_{r,z}(x)Y^{E_z}(y) \\ 0, & \bar{H}_{r,y}(x)Y^{H_y}(y), & \bar{H}_{r,y}(x)Y^{H_z}(y) \end{pmatrix} \quad \text{(TM)}$$

$$Y \cdot (y) = ?$$

(!)

(VEIM)

A functional for guided modes of 3-D dielectric waveguides

(→ Exercise.)

$$\bullet \begin{pmatrix} \mathbf{E} \\ \mathbf{H} \end{pmatrix} (x, y, z) = \begin{pmatrix} \bar{\mathbf{E}} \\ \bar{\mathbf{H}} \end{pmatrix} (x, y) e^{-i\beta z}, \quad \beta \in \mathbb{R}, \\ \bar{\mathbf{E}}, \bar{\mathbf{H}} \rightarrow 0 \text{ for } x, y \rightarrow \pm\infty.$$

$$\bullet (\mathbf{C} + i\beta\mathbf{R})\bar{\mathbf{E}} = -i\omega\mu_0\bar{\mathbf{H}}, \quad (\mathbf{C} + i\beta\mathbf{R})\bar{\mathbf{H}} = i\omega\epsilon_0\bar{\mathbf{E}},$$

$$\mathbf{R} = \begin{pmatrix} 0 & 1 & 0 \\ -1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \quad \mathbf{C} = \begin{pmatrix} 0 & 0 & \partial_y \\ 0 & 0 & -\partial_x \\ -\partial_y & \partial_x & 0 \end{pmatrix}.$$

$$\bullet \mathcal{B}(\mathbf{E}, \mathbf{H}) := \frac{\omega\epsilon_0\langle \mathbf{E}, \epsilon\mathbf{E} \rangle + \omega\mu_0\langle \mathbf{H}, \mathbf{H} \rangle + i\langle \mathbf{E}, \mathbf{C}\mathbf{H} \rangle - i\langle \mathbf{H}, \mathbf{C}\mathbf{E} \rangle}{\langle \mathbf{E}, \mathbf{R}\mathbf{H} \rangle - \langle \mathbf{H}, \mathbf{R}\mathbf{E} \rangle}, \\ \langle \mathbf{F}, \mathbf{G} \rangle = \iint \mathbf{F}^* \cdot \mathbf{G} \, dx \, dy.$$

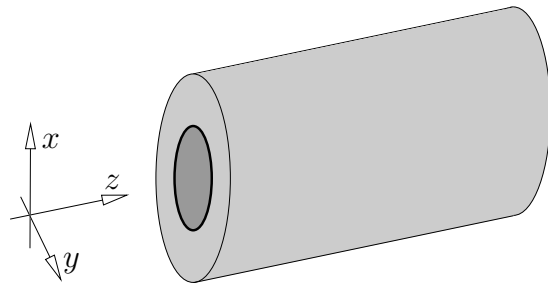
$$\mathcal{B}(\bar{\mathbf{E}}, \bar{\mathbf{H}}) = \beta, \quad \left. \frac{d}{ds} \mathcal{B}(\bar{\mathbf{E}} + s\delta\bar{\mathbf{E}}, \bar{\mathbf{H}} + s\delta\bar{\mathbf{H}}) \right|_{s=0} = 0$$

at valid mode fields $\bar{\mathbf{E}}, \bar{\mathbf{H}}$, for arbitrary $\delta\bar{\mathbf{E}}, \delta\bar{\mathbf{H}}$.

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Optical fibers

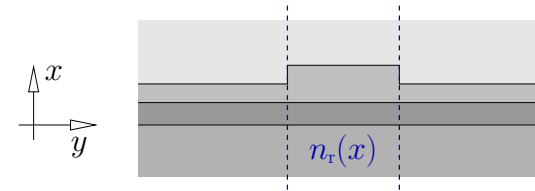


[Optical Communication A-D]

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Variational effective index method



Outline, continued:

• Restrict \mathcal{B} to the VEIM ansatz, require stationarity with respect to the $\{Y\}$.

↪ 1-D mode ("s-like") equations for principal unknowns Y^{H_x} (TE) and Y^{E_x} (TM) with effective quantities in place of refractive indices, all other Y can be computed.

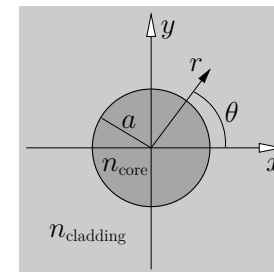
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Circular step index optical fibers



(FD)

Circular symmetry

↔ cylindrical coordinates r, θ, z .

$$\epsilon = n^2, \quad n(r) = \begin{cases} n_{\text{core}}, & r \leq a, \\ n_{\text{cladding}}, & r > a. \end{cases}$$

Circular and axial symmetry:

$$\hookrightarrow \begin{pmatrix} \mathbf{E} \\ \mathbf{H} \end{pmatrix} (r, \theta, z) = \begin{pmatrix} \bar{\mathbf{E}} \\ \bar{\mathbf{H}} \end{pmatrix} (r) e^{-il\theta - i\beta z}, \quad l \in \mathbb{Z}, \beta \in \mathbb{R}. \\ \text{(} E_r, E_\theta, E_z, H_r, H_\theta, H_z \text{)}$$

Where $\partial\epsilon = 0$: $\Delta\psi + k^2 n^2 \psi = 0, \quad \psi \in \{E_r, \dots, H_z\}$.

$$\hookrightarrow \partial_r^2 \phi + \frac{1}{r} \partial_r \phi + (k^2 n^2 - \beta^2 - \frac{l^2}{r^2}) \phi = 0, \quad \phi \in \{\bar{E}_r, \dots, \bar{H}_z\} \\ \text{(An ODE of Bessel type.)}$$

& vectorial interface conditions at $r = a$. (Alternatively: Scalar theory, LP modes.)

(...)



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Next lectures:

- Waveguide discontinuities & circuits, scattering matrices, reciprocal circuits.
- Bent optical waveguides; whispering gallery resonances; circular microresonators.
- Coupled mode theory, perturbation theory.

