

# *Channel Waveguides*

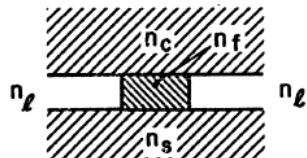
## **Integrated Optics**

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*School of Electrical & Computer Engineering  
National Technical University of Athens*

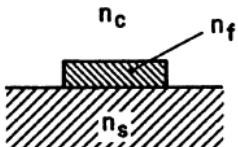
# Channel Waveguides



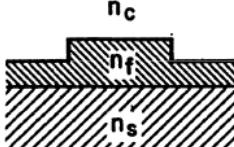
a.) general  
channel guide



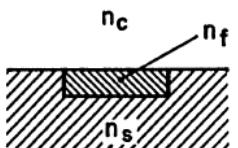
b.) buried channel



c.) raised strip



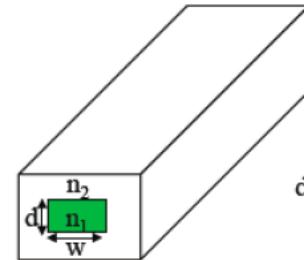
d.) rib guide



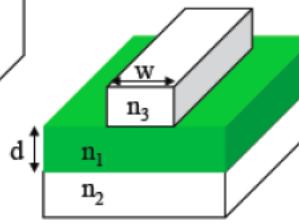
e.) embedded strip



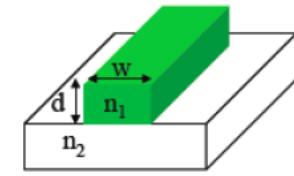
f.) ridge guide



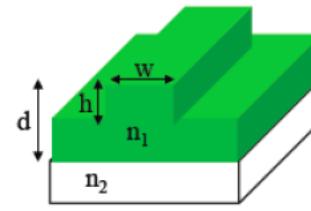
Buried channel  
waveguide



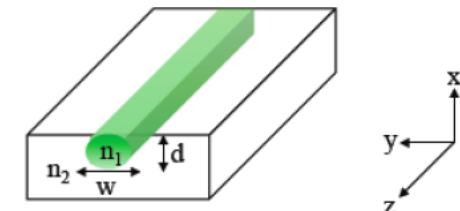
Strip-loaded  
waveguide



Ridge  
waveguide



rib waveguide

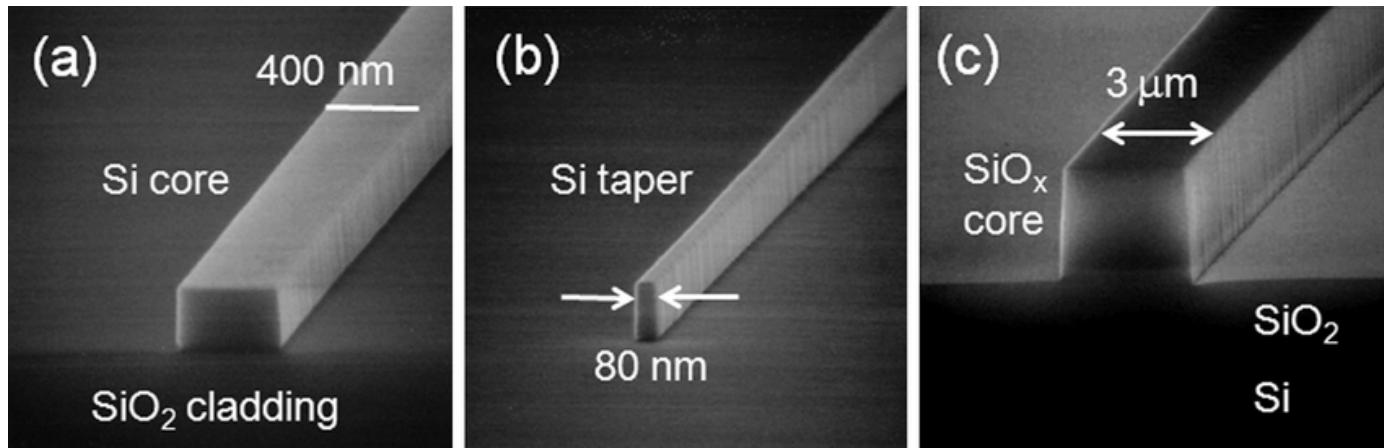


Diffused  
waveguide

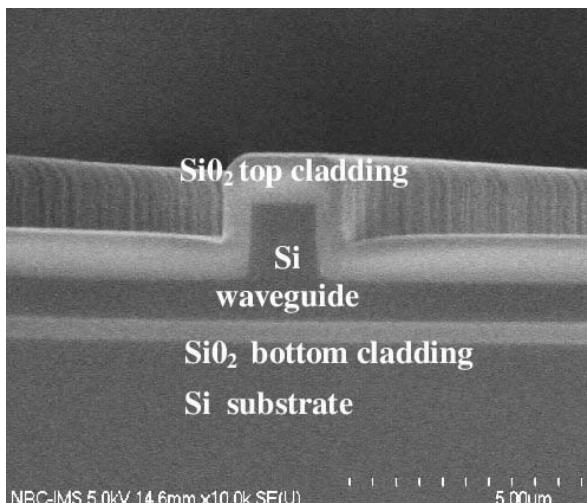
T. Tamir, Ed., "Guided-Wave Optoelectronics", Springer-Verlag, 1988

[https://encrypted-tbn0.gstatic.com/images?q=tbn:ANd9GcSyu68Edp6Tjp8Y2exlv8OYwp2Vb8QQ59cre1dPIFKjvwMG7Ait90\\_tJ4UAM6c4mbczc&usqp=CAU](https://encrypted-tbn0.gstatic.com/images?q=tbn:ANd9GcSyu68Edp6Tjp8Y2exlv8OYwp2Vb8QQ59cre1dPIFKjvwMG7Ait90_tJ4UAM6c4mbczc&usqp=CAU)

# Channel Waveguides Examples



<https://www.researchgate.net/publication/226940484/figure/fig3/AS:670022288568324@1536757170175/SEM-images-of-a-silicon-photonic-wire-waveguide-system-a-Core-of-silicon-photonic-wire.ppm>



[https://www.researchgate.net/profile/Danxia-Xu/publication/228599800/figure/fig2/AS:670016361996294@1536755757463/SEM-image-of-a-typical-waveguide-with-cladding-oxide-fabricated-by-ICP-RIE\\_W640.jpg](https://www.researchgate.net/profile/Danxia-Xu/publication/228599800/figure/fig2/AS:670016361996294@1536755757463/SEM-image-of-a-typical-waveguide-with-cladding-oxide-fabricated-by-ICP-RIE_W640.jpg)

# Channel Waveguides

## 3D-Wave Equations

$$\begin{aligned}\vec{\nabla}^2 \vec{E} + \vec{\nabla} \left( \vec{E} \cdot \vec{\nabla} (\ln \epsilon) \right) + \omega^2 \mu_0 \epsilon \vec{E} &= 0, \\ \vec{\nabla}^2 \vec{H} + \vec{\nabla} (\ln \epsilon) \times \vec{\nabla} \times \vec{H} + \omega^2 \mu_0 \epsilon \vec{H} &= 0.\end{aligned}$$

## Separation of Transverse and Longitudinal Components

$$\begin{aligned}\vec{E} &= \left[ \vec{E}_t(x, y) + \hat{z} E_z(x, y) \right] \exp(-j\beta z), \\ \vec{H} &= \left[ \vec{H}_t(x, y) + \hat{z} H_z(x, y) \right] \exp(-j\beta z),\end{aligned}$$

$$\begin{aligned}\vec{\nabla}_t^2 \vec{E}_t + \vec{\nabla}_t \left( \vec{E}_t \cdot \vec{\nabla}_t (\ln \epsilon) \right) + (\omega^2 \mu_0 \epsilon - \beta^2) \vec{E}_t &= 0, \\ j\beta E_z &= \vec{\nabla}_t \cdot \vec{E}_t + \vec{E}_t \cdot \vec{\nabla}_t (\ln \epsilon)\end{aligned}$$

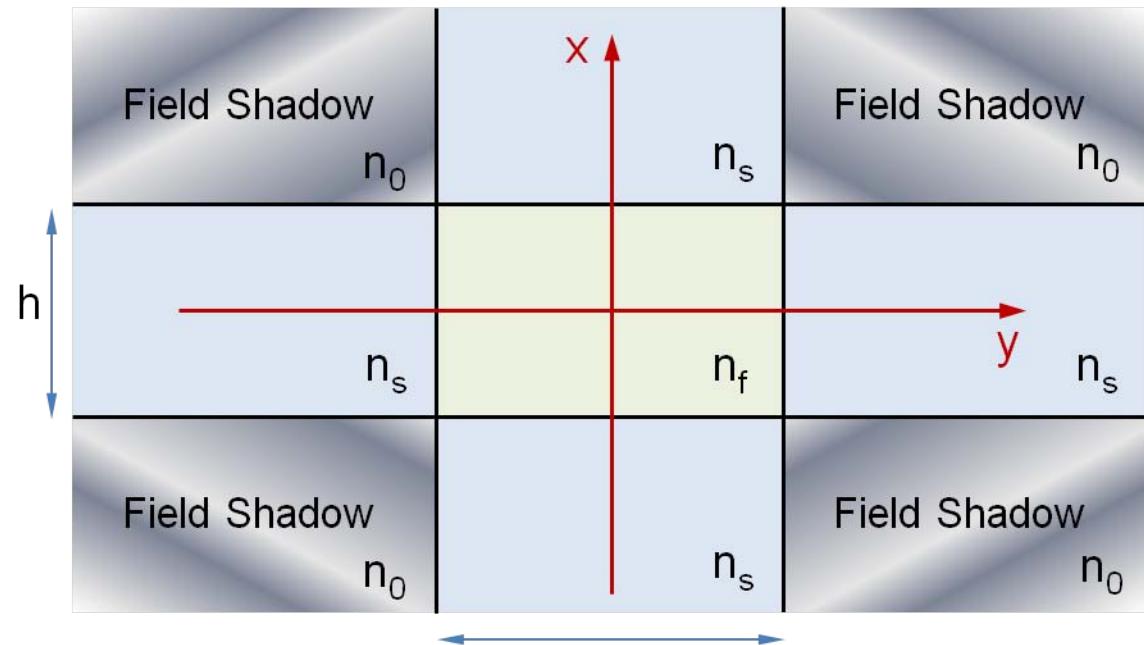
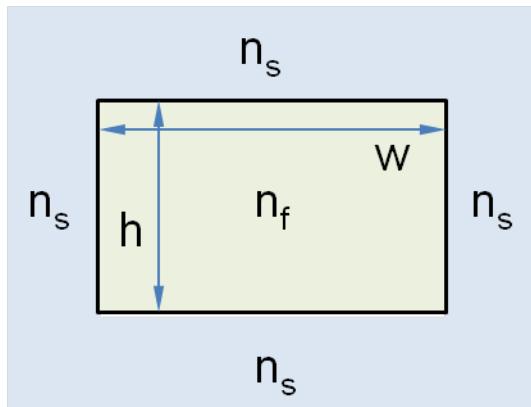
$$\begin{aligned}\vec{\nabla}_t^2 \vec{H}_t + \vec{\nabla}_t (\ln \epsilon) \times \vec{\nabla}_t \times \vec{H}_t + (\omega^2 \mu_0 \epsilon - \beta^2) \vec{H}_t &= 0, \\ j\beta H_z &= \vec{\nabla}_t \cdot \vec{H}_t\end{aligned}$$

# Buried Waveguide

## Method of Field Shadows

After  $xy$ -refractive-index Decomposition Buried Waveguide

Original Buried Waveguide



$$\vec{\nabla}_t^2 \vec{E}_t + \vec{\nabla}_t \left( \vec{E}_t \cdot \vec{\nabla}_t (\ln \epsilon) \right) + (\omega^2 \mu_0 \epsilon - \beta^2) \vec{E}_t = 0,$$

$$\vec{E}_t \simeq \hat{t} E_t(x, y) \exp(-j\beta z),$$

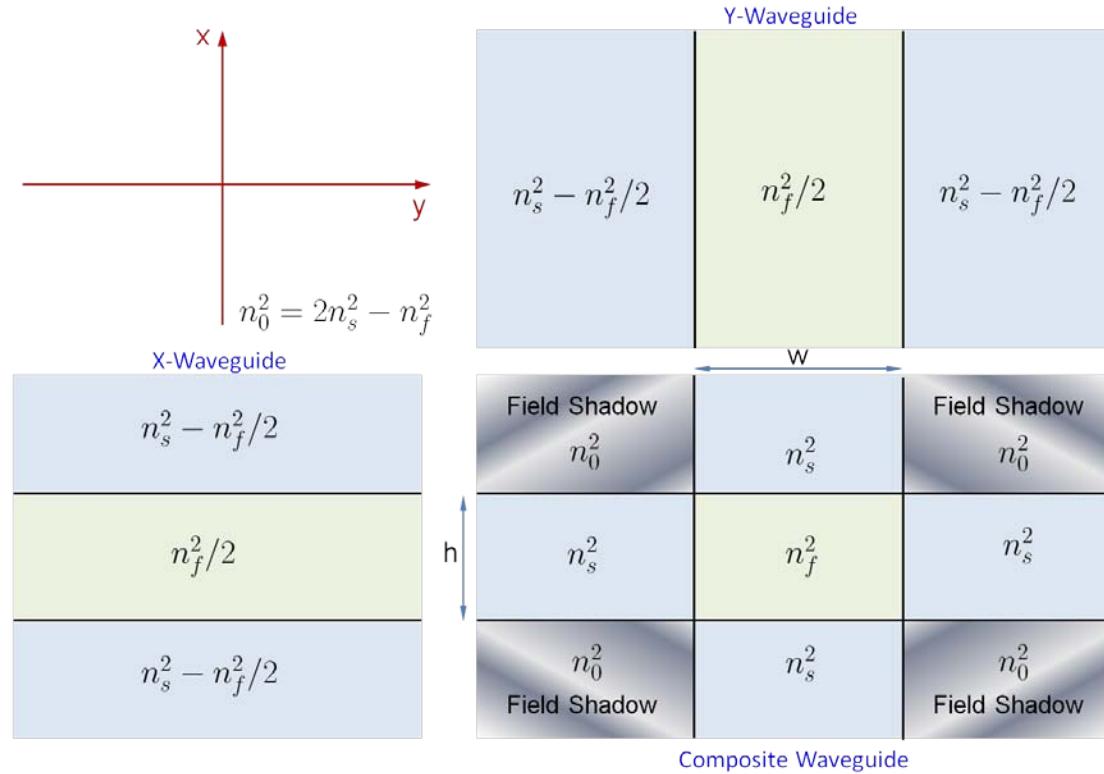
$$\nabla_t^2 E_t + (k_0^2 n^2(x, y) - \beta^2) E_t = 0$$

T. Tamir, Ed., "Guided-Wave Optoelectronics", Springer-Verlag, 1988

Prof. Elias N. Glytsis, School of ECE, NTUA

# Buried Waveguide

## Method of Field Shadows



$$n_x^2(x) = \begin{cases} n_s^2 - \frac{n_f^2}{2}, & x > h/2 \\ \frac{n_f^2}{2}, & -h/2 \leq x \leq h/2 \\ n_s^2 - \frac{n_f^2}{2}, & x < -h/2 \end{cases}, \quad n_y^2(y) = \begin{cases} n_s^2 - \frac{n_f^2}{2}, & y > w/2 \\ \frac{n_f^2}{2}, & -w/2 \leq y \leq w/2 \\ n_s^2 - \frac{n_f^2}{2}, & y < -w/2 \end{cases}$$

# Buried Waveguide

## Method of Field Shadows

$$\vec{E}_t(x, y, z) \simeq \hat{t} E_t(x, y) \exp(-j\beta z),$$

$$E_t(x, y) = X(x)Y(y),$$

$$\frac{1}{X} \frac{d^2 X}{dx^2} + \frac{1}{Y} \frac{d^2 Y}{dy^2} + (k_0^2 n^2(x, y) - \beta^2) = 0$$

$$n^2(x, y) = n_0^2 + n_x^2(x) + n_y^2(y), \quad \beta^2 = \beta_x^2 + \beta_y^2 + k_0^2 n_0^2$$

$$\frac{1}{X} \frac{d^2 X}{dx^2} + [k_0 n_x^2(x) - \beta_x^2] = 0 \implies X(x) = X_p(x),$$

$$\frac{1}{Y} \frac{d^2 Y}{dy^2} + [k_0 n_y^2(y) - \beta_y^2] = 0 \implies Y(y) = Y_q(y),$$

$$\vec{E}_t(x, y, z) \simeq \hat{t} X_p(x) Y_q(y) \exp(-j\beta_{pq} z), \quad \beta_{pq}^2 = \beta_{xp}^2 + \beta_{yq}^2 + k_0^2 n_0^2$$


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$E_{pq}^y$  - TE-like modes  $\longrightarrow \hat{t} = \hat{y}$ :

Dominant  $E_y$  and  $H_x$  Fields

For x-waveguide use TE-mode solution  
For y-waveguide use TM-mode solution

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$E_{pq}^x$  - TM-like modes  $\longrightarrow \hat{t} = \hat{x}$ :

Dominant  $E_x$  and  $H_y$  Fields

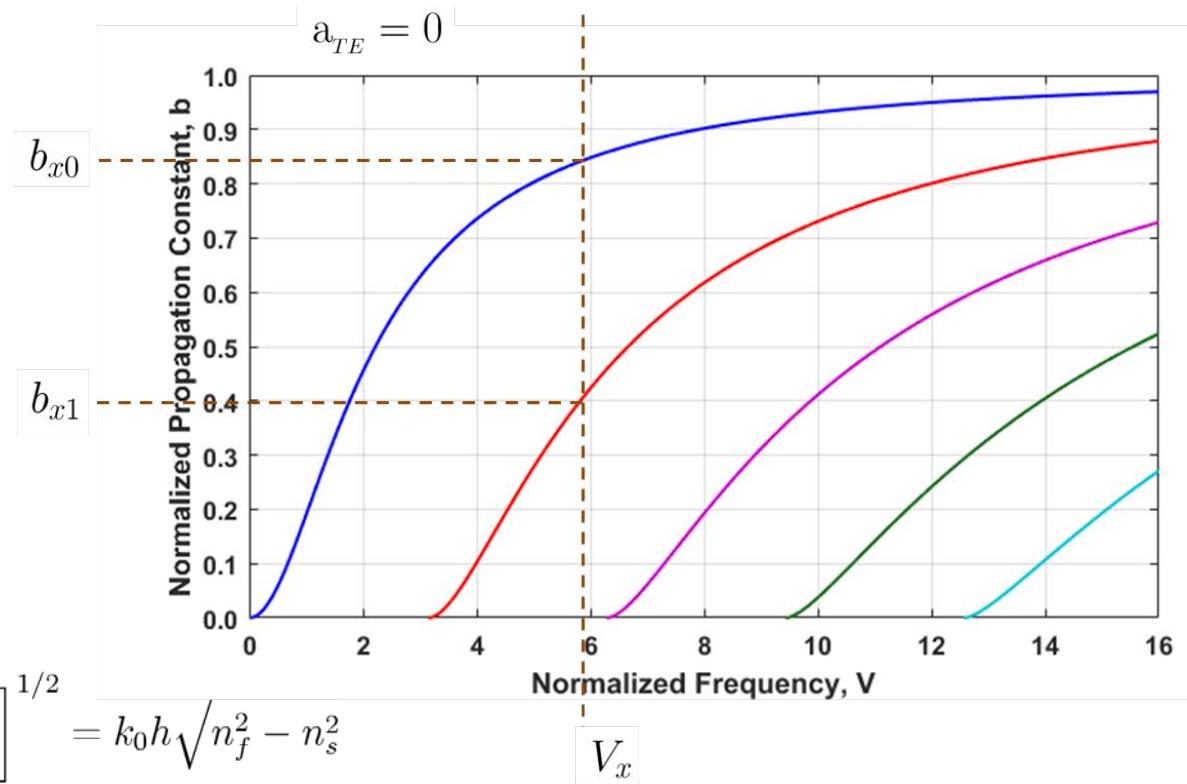
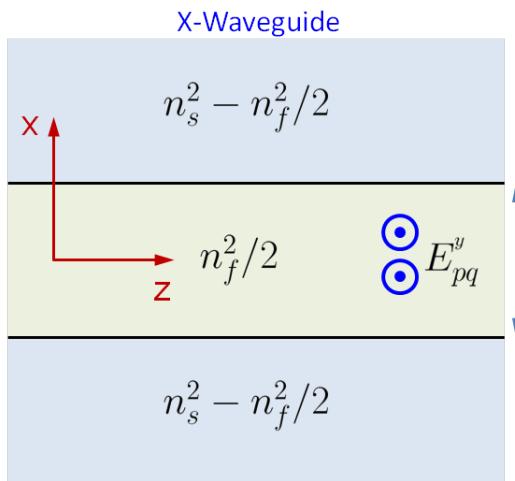
For x-waveguide use TM-mode solution  
For y-waveguide use TE-mode solution

# Buried Waveguide

## Method of Field Shadows

$E_{pq}^y$  - TE-like modes  $\rightarrow \hat{t} = \hat{y}$ :

For x-waveguide use TE-mode solution  
 For y-waveguide use TM-mode solution



$$V_x = k_0 h \left[ \frac{n_f^2}{2} - \left( n_s^2 - \frac{n_f^2}{2} \right) \right]^{1/2} = k_0 h \sqrt{n_f^2 - n_s^2}$$

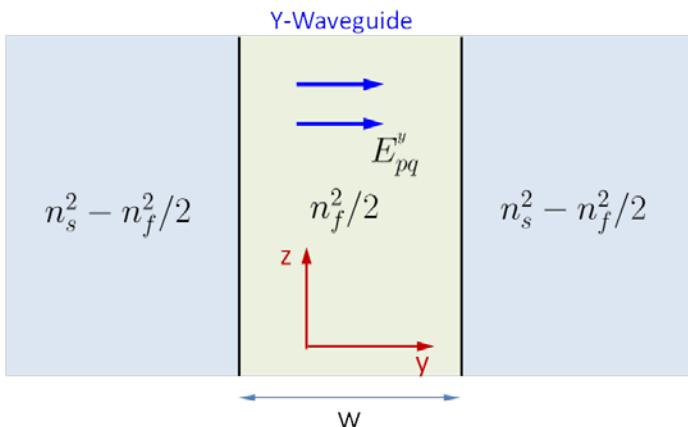
$$b_{xp} = \frac{N_{xp}^2 - \left( n_s^2 - \frac{n_f^2}{2} \right)}{\frac{n_f^2}{2} - \left( n_s^2 - \frac{n_f^2}{2} \right)} = \frac{N_{xp}^2 - \left( n_s^2 - \frac{n_f^2}{2} \right)}{n_f^2 - n_s^2}$$

# Buried Waveguide

## Method of Field Shadows

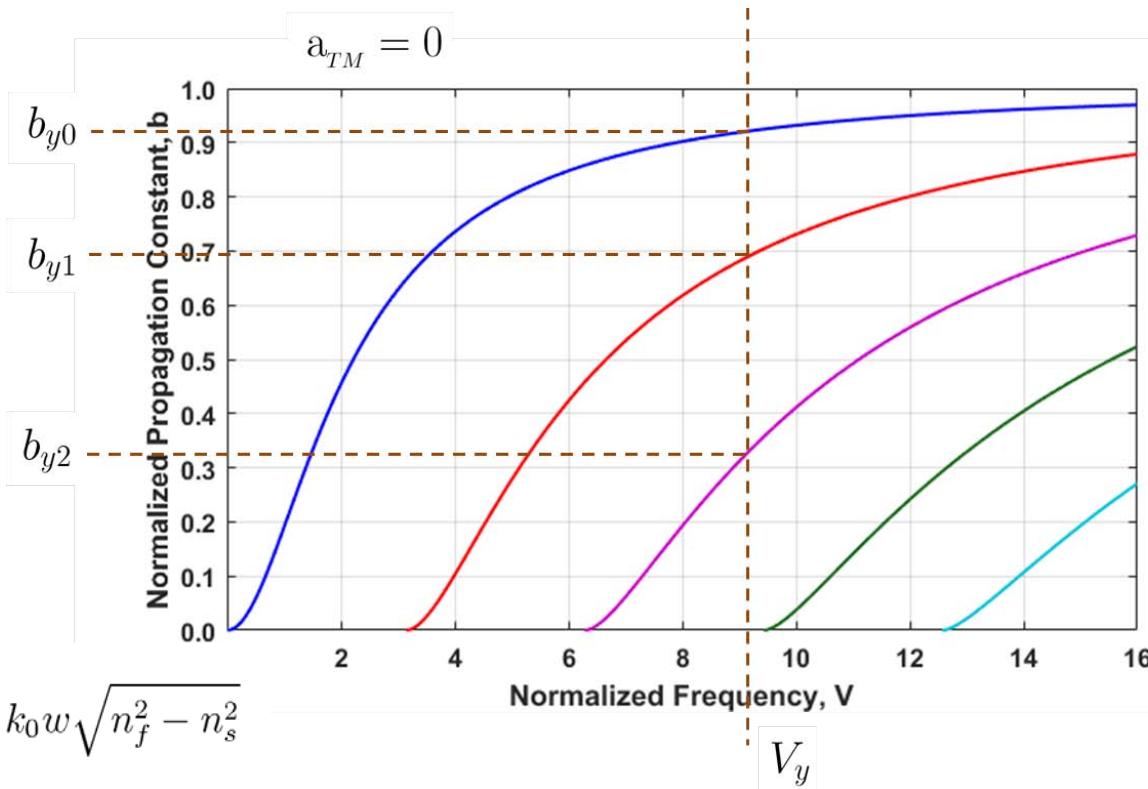
$E_{pq}^y$  - TE-like modes  $\rightarrow \hat{t} = \hat{y}$ :

For x-waveguide use TE-mode solution  
 For y-waveguide use TM-mode solution



$$V_y = k_0 w \left[ \frac{n_f^2}{2} - \left( n_s^2 - \frac{n_f^2}{2} \right) \right]^{1/2} = k_0 w \sqrt{n_f^2 - n_s^2}$$

$$b_{yq} = \frac{N_{yq}^2 - \left( n_s^2 - \frac{n_f^2}{2} \right)}{\frac{n_f^2}{2} - \left( n_s^2 - \frac{n_f^2}{2} \right)} = \frac{N_{yq}^2 - \left( n_s^2 - \frac{n_f^2}{2} \right)}{n_f^2 - n_s^2}$$



# Buried Waveguide

## Method of Field Shadows

$E_{pq}^y$  - TE-like modes  $\longrightarrow \hat{t} = \hat{y}$ :

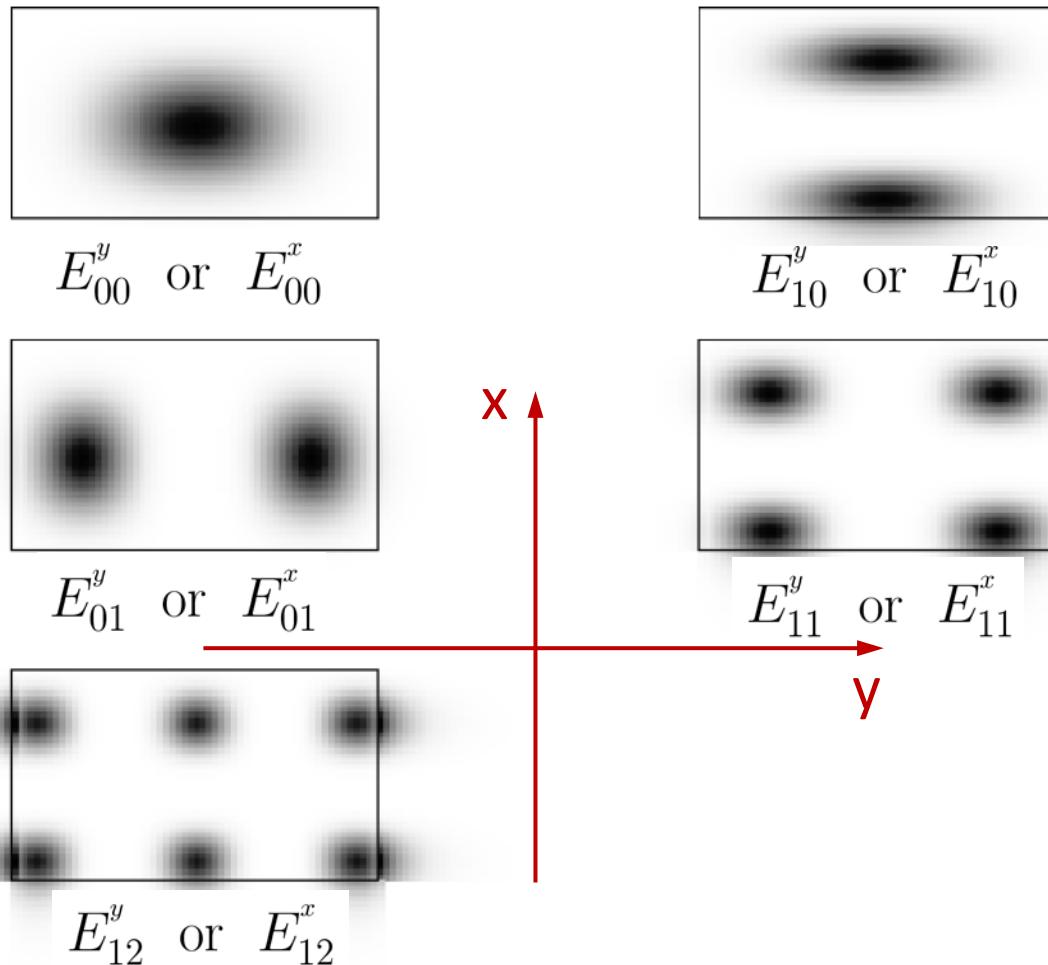
For x-waveguide use TE-mode solution  
For y-waveguide use TM-mode solution

### Field of Shadows Example

$p$	$q$	$b_{pq}$	$N_{pq}$	$E_{pq}^y$
0	0	$b_{00}$	$N_{00}$	$E_{00}^y$
0	1	$b_{01}$	$N_{01}$	$E_{01}^y$
0	2	$b_{02}$	$N_{02}$	$E_{02}^y$
1	0	$b_{10}$	$N_{10}$	$E_{10}^y$
1	1	$b_{11}$	$N_{11}$	$E_{11}^y$
1	2	$b_{12}$	$N_{12}$	$E_{12}^y$

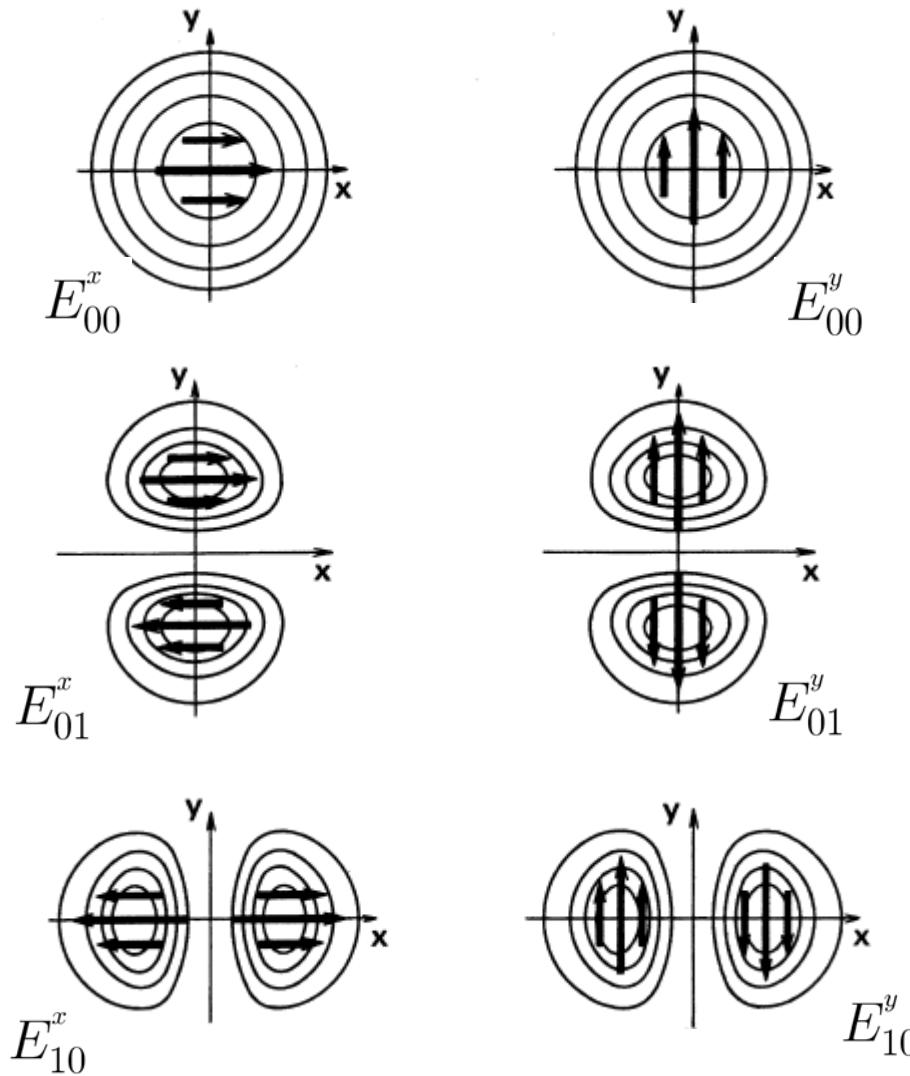
# Buried Waveguide

## Method of Field Shadows



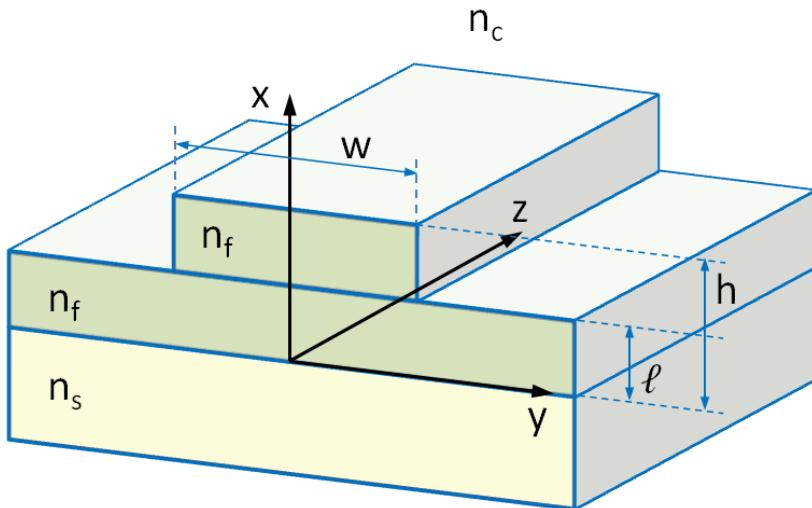
# Buried Waveguide

## Method of Field Shadows



# Rib/Ridge Waveguide

## Effective Index Method



$$E_t(x, y) = \Phi(x, y)Y(y)$$

$$\frac{\partial^2 E_t}{\partial x^2} = Y \frac{\partial^2 \Phi}{\partial x^2}$$

$$\frac{\partial^2 E_t}{\partial y^2} = \frac{d^2 Y}{dy^2} \Phi + 2 \frac{dY}{dy} \frac{\partial \Phi}{\partial y} + Y \frac{\partial^2 \Phi}{\partial y^2}$$

$$\vec{\nabla}_t^2 \vec{E}_t + \vec{\nabla}_t \left( \vec{E}_t \cdot \vec{\nabla}_t (\ln \epsilon) \right) + (\omega^2 \mu_0 \epsilon - \beta^2) \vec{E}_t = 0$$

$$\vec{E}_t \simeq \hat{t} E_t(x, y) \exp(-j\beta z)$$

$$\nabla_t^2 E_t + [k_0^2 n^2(x, y) - \beta^2] E_t = 0$$

$$\frac{\partial^2 E_t}{\partial x^2} + \frac{\partial^2 E_t}{\partial y^2} + [k_0^2 n^2(x, y) - \beta^2] E_t = 0$$

$$\frac{\partial^2 \Phi}{\partial x^2} + [k_0^2 n^2(x, y) - k_0^2 N^2(y)] \Phi(x, y) = 0$$

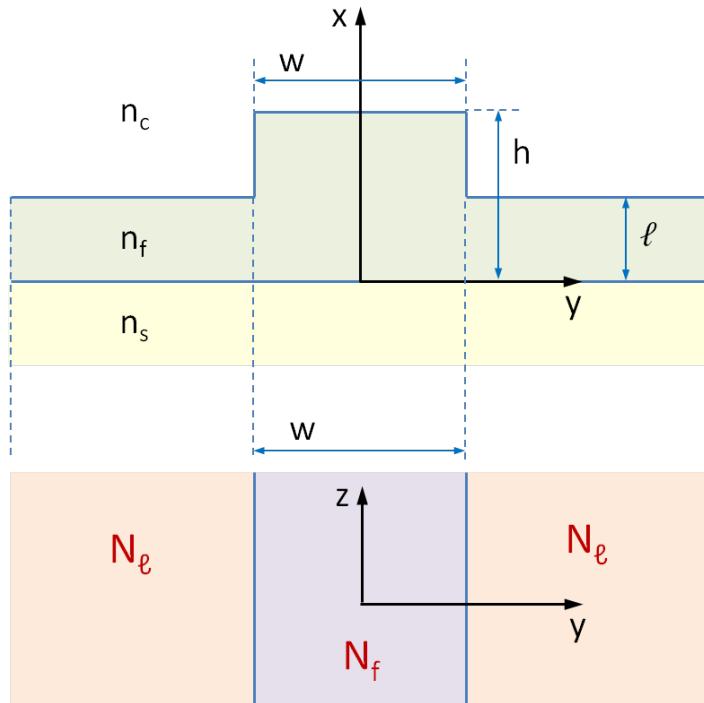
$$\frac{d^2 Y}{dy^2} + \underbrace{\left\{ 2 \frac{dY}{dy} \frac{\partial \Phi}{\partial y} \frac{1}{\Phi} + \frac{Y}{\Phi} \frac{\partial^2 \Phi}{\partial y^2} \right\}}_{\simeq 0} + [k_0^2 N^2(y) - \beta^2] Y = 0$$

$$\frac{d^2 Y}{dy^2} + k_0^2 [N^2(y) - N_{pq}^2] Y = 0$$

$$\beta_{pq} = k_0 N_{pq}$$

# Rib/Ridge Waveguide

## Effective Index Method



$$\frac{\partial^2 \Phi}{\partial x^2} + [k_0^2 n^2(x, y) - k_0^2 N^2(y)] \Phi(x, y) = 0 \implies \Phi(x; y) = \Phi_p(x; y) \quad p = 0, 1, \dots$$

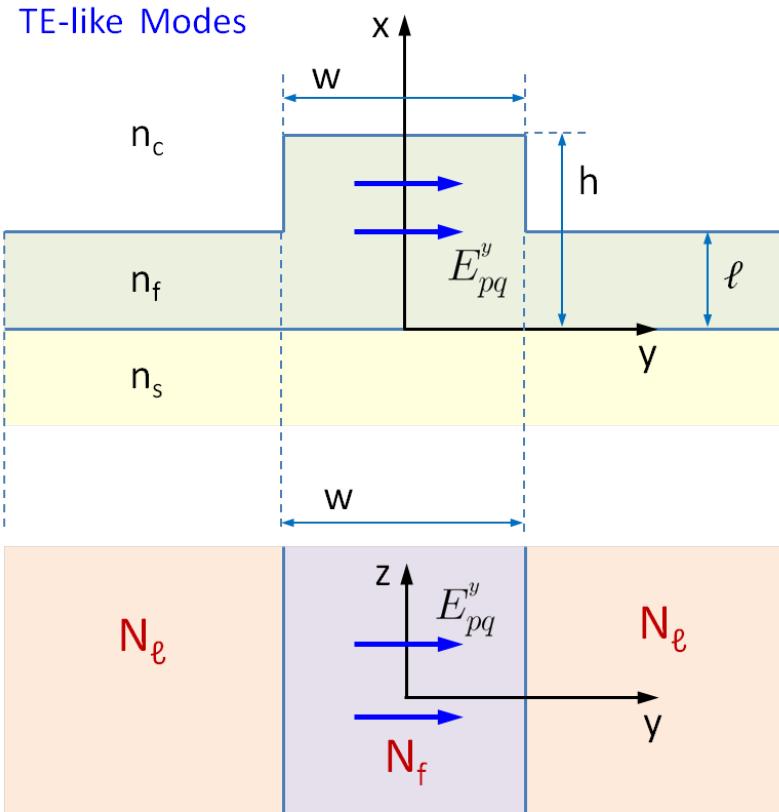
$$\frac{d^2 Y}{dy^2} + k_0^2 [N_p^2(y) - N_{pq}^2] Y = 0 \implies Y(y) = Y_{pq}(y) \quad q = 0, 1, \dots$$

$$\vec{E}_t = \hat{t} \Phi_p(x; y) Y_{pq}(y) \exp[-jk_0 N_{pq} z]$$

$$\beta_{pq} = k_0 N_{pq}$$

# Rib/Ridge Waveguide

## Effective Index Method



$E_{pq}^y$  - TE-like modes  $\longrightarrow \hat{t} = \hat{y}$ :

Dominant  $E_y$  and  $H_x$  Fields

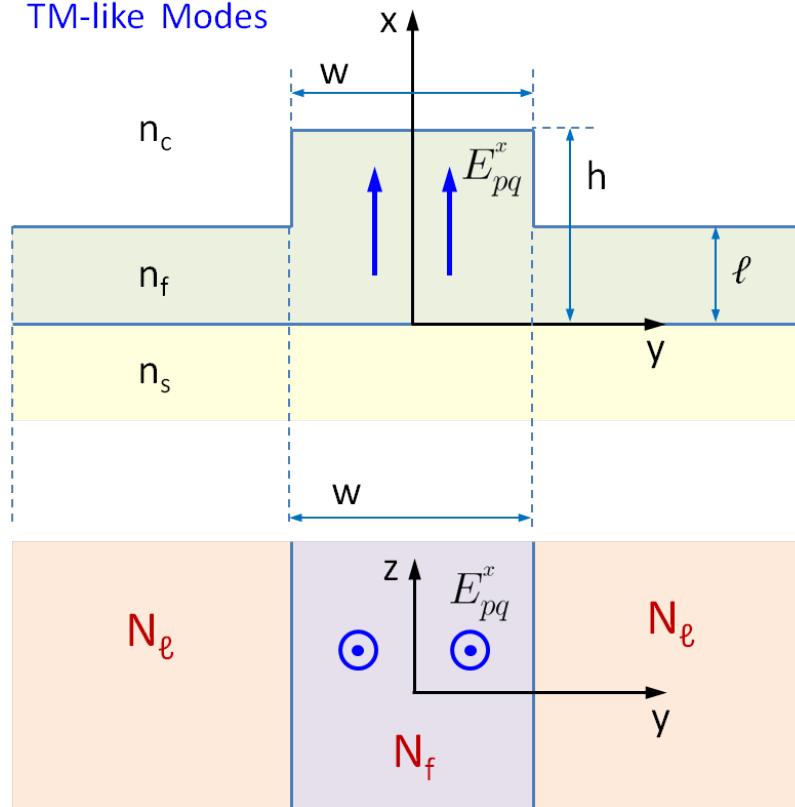
For x-waveguide use TE-mode solution

For y-waveguide use TM-mode solution

# Rib/Ridge Waveguide

## Effective Index Method

TM-like Modes



$E_{pq}^x$  - TM-like modes  $\rightarrow \hat{t} = \hat{x}$ :

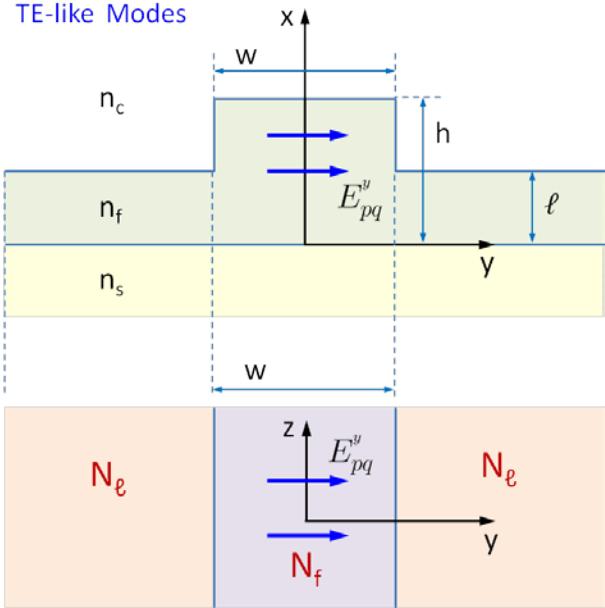
Dominant  $E_x$  and  $H_y$  Fields

For x-waveguide use TM-mode solution  
For y-waveguide use TE-mode solution

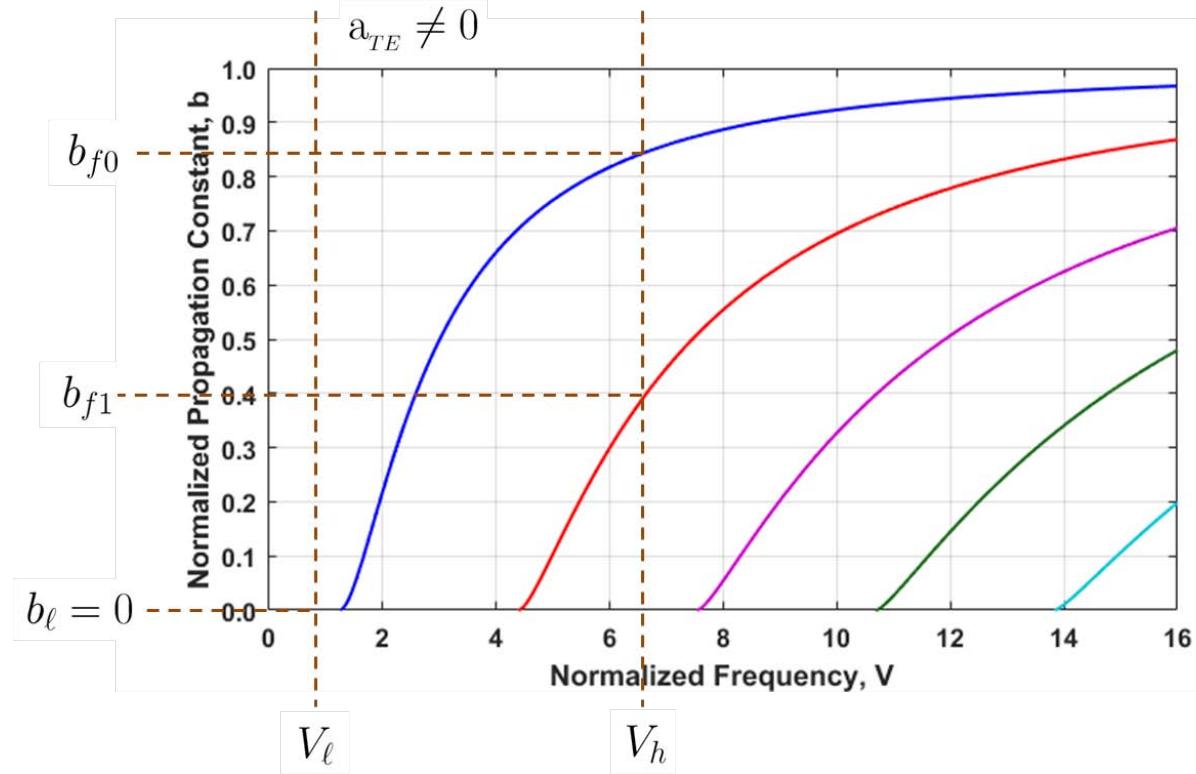
# Rib/Ridge Waveguide

## Effective Index Method

$E_{pq}^y$  - TE-like modes  $\rightarrow \hat{t} = \hat{y}$ :



For x-waveguide use TE-mode solution  
For y-waveguide use TM-mode solution



$$V_f = k_0 h \sqrt{n_f^2 - n_s^2} > \tan^{-1}(a_{TE}) + \pi$$

$$V_\ell = k_0 \ell \sqrt{n_f^2 - n_s^2} < \tan^{-1}(a_{TE})$$

$$N_p^2(y) = \begin{cases} N_{fp}^2 = n_s^2 + b_{fp}(n_f^2 - n_s^2), & p = 0, 1, \quad |y| \leq \frac{w}{2} \\ N_\ell^2 = n_s^2 & |y| > \frac{w}{2} \end{cases}$$

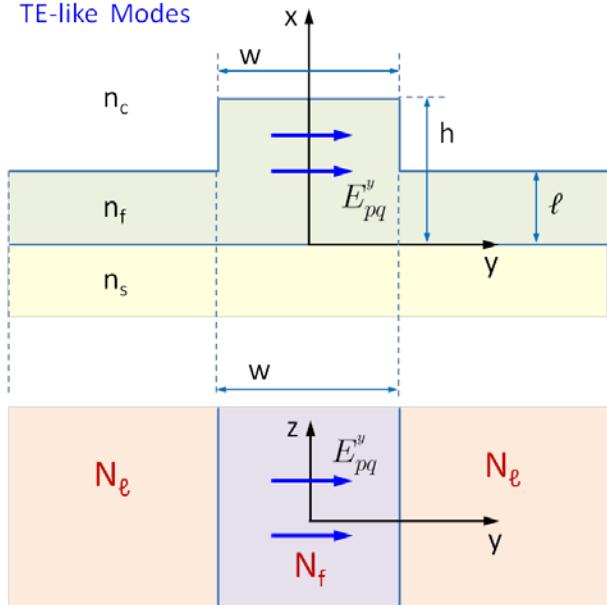
# Rib/Ridge Waveguide

## Effective Index Method

$E_{pq}^y$  - TE-like modes  $\rightarrow \hat{t} = \hat{y}$ :

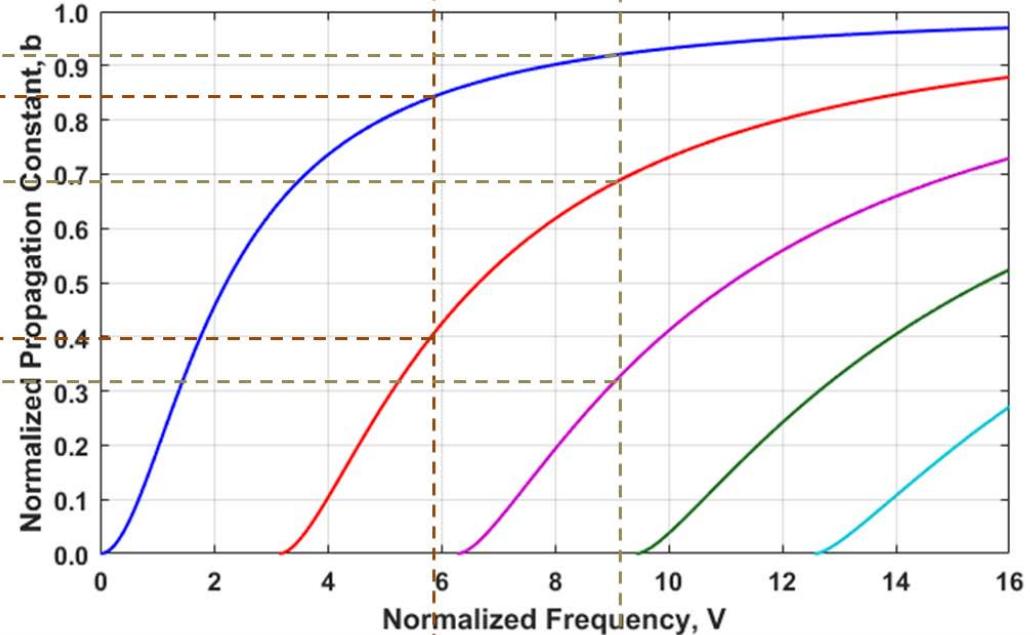
For x-waveguide use TE-mode solution  
 For y-waveguide use TM-mode solution

TE-like Modes



$$a_{TM} = 0$$

Normalized Propagation Constant,  $b$



$$V_{eq,1}$$

$$V_{eq,0}$$

$$V_{eq,0} = k_0 w \sqrt{N_{f0}^2 - N_\ell^2} = k_0 w \sqrt{N_{f0}^2 - n_s^2}$$

$$V_{eq,1} = k_0 w \sqrt{N_{f1}^2 - N_\ell^2} = k_0 w \sqrt{N_{f1}^2 - n_s^2}$$

$$N_{pq}^2 = N_\ell^2 + b_{pq} (N_{fp}^2 - N_\ell^2) = n_s^2 + b_{pq} (N_{fp}^2 - n_s^2)$$

$$\vec{E}_t = \hat{y} \Phi_p(x; y) Y_{pq}(y) \exp[-jk_0 N_{pq} z]$$

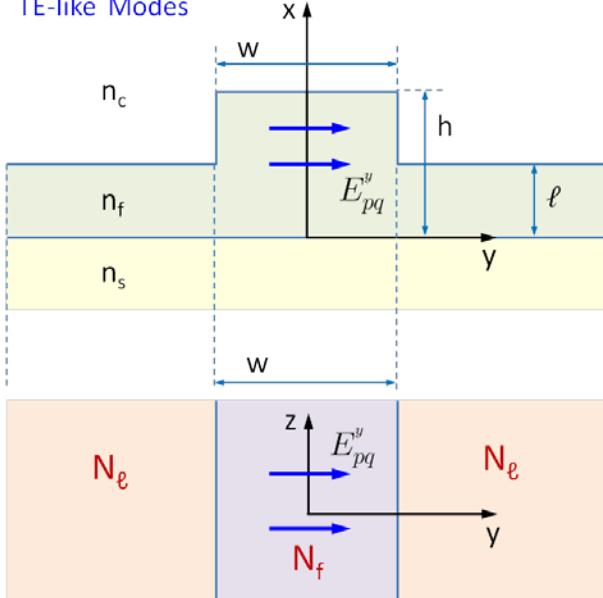
# Rib/Ridge Waveguide

## Effective Index Method

$E_{pq}^y$  - TE-like modes  $\rightarrow \hat{t} = \hat{y}$ :

For x-waveguide use TE-mode solution  
 For y-waveguide use TM-mode solution

TE-like Modes



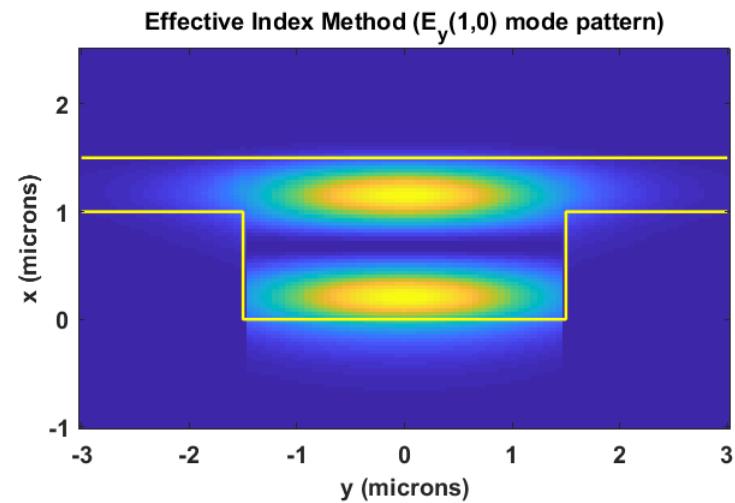
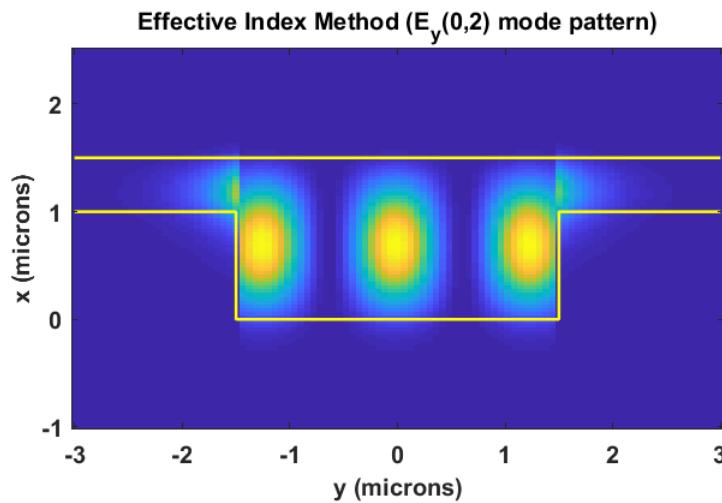
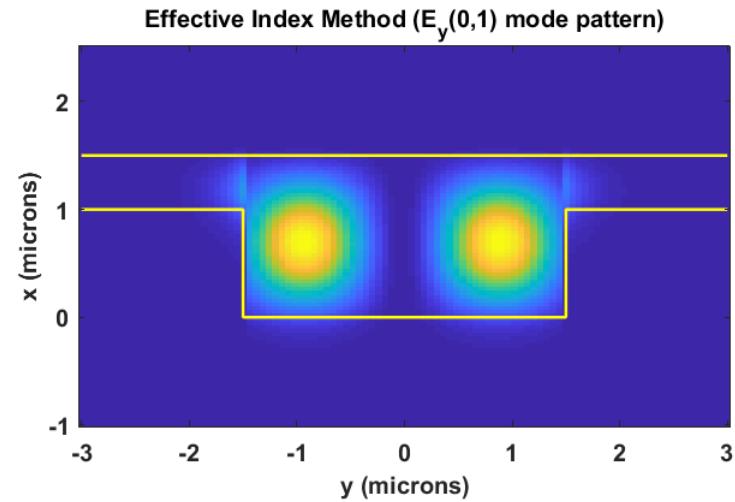
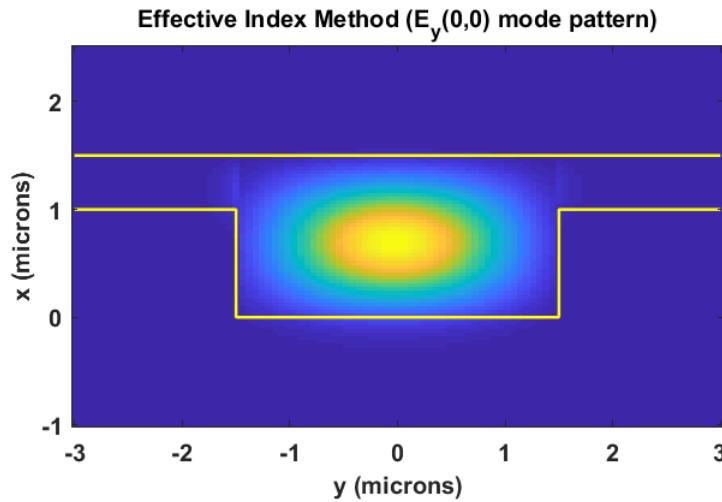
Effective-Index Method Example

$p$	$q$	$b_{pq}$	$N_{pq}$	$E_{pq}^y$
0	0	$b_{00}$	$N_{00}$	$E_{00}^y$
0	1	$b_{01}$	$N_{01}$	$E_{01}^y$
0	2	$b_{02}$	$N_{02}$	$E_{02}^y$
1	0	$b_{10}$	$N_{10}$	$E_{10}^y$
1	1	$b_{11}$	$N_{11}$	$E_{11}^y$

# Inverted Rib Waveguide

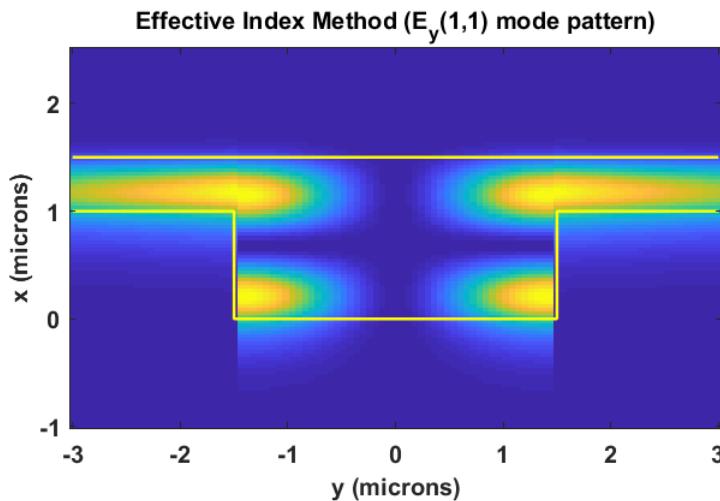
$\lambda_0 = 1.0 \text{ } \mu\text{m}$ ,  $n_{\text{core}} = 1.65$ ,  $n_{\text{clad}} = 1.50$ ,  $n_{\text{cover}} = 1.0$  (air)  
 $t_{\text{rib}} = 1 \text{ } \mu\text{m}$ ,  $t_{\text{core}} = 0.5 \text{ } \mu\text{m}$ ,  $w_{\text{rib}} = 3 \text{ } \mu\text{m}$

$E_{pq}^y$  - TE-like modes  $\longrightarrow \hat{t} = \hat{y}$ :



# Inverted Rib Waveguide

$\lambda_0 = 1.0 \text{ } \mu\text{m}$ ,  $n_{\text{core}} = 1.65$ ,  $n_{\text{clad}} = 1.50$ ,  $n_{\text{cover}} = 1.0$  (air)  
 $t_{\text{rib}} = 1 \text{ } \mu\text{m}$ ,  $t_{\text{core}} = 0.5 \text{ } \mu\text{m}$ ,  $w_{\text{rib}} = 3 \text{ } \mu\text{m}$



Effective-Index Method Example

$p$	$q$	$N_{pq}$	$E_{pq}^y$
0	0	1.6220288	$E_{00}^y$
0	1	1.6046144	$E_{01}^y$
0	2	1.5774486	$E_{02}^y$
1	0	1.5594339	$E_{10}^y$
1	1	1.5527476	$E_{11}^y$

# Finite-Difference Method for Optical Channel Waveguides

## Full-Vectorial Formulation

$$\vec{\nabla}^2 \vec{H}_t + \vec{\nabla}_t (\ln \epsilon) \times \vec{\nabla}_t \times \vec{H}_t + (\omega^2 \mu_0 \epsilon - \beta^2) \vec{H}_t = 0,$$

$$\frac{\partial^2 H_x}{\partial x^2} + \varepsilon \frac{\partial}{\partial y} \left( \frac{1}{\varepsilon} \frac{\partial H_x}{\partial y} \right) + (k_0^2 \varepsilon - \beta^2) H_x + \frac{1}{\varepsilon} \frac{\partial \varepsilon}{\partial y} \frac{\partial H_y}{\partial x} = 0$$

$$\frac{\partial^2 H_y}{\partial y^2} + \varepsilon \frac{\partial}{\partial x} \left( \frac{1}{\varepsilon} \frac{\partial H_y}{\partial x} \right) + (k_0^2 \varepsilon - \beta^2) H_y + \frac{1}{\varepsilon} \frac{\partial \varepsilon}{\partial x} \frac{\partial H_x}{\partial y} = 0$$

## Finite-Difference Formulation

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} \mathbf{H}_x \\ \mathbf{H}_y \end{bmatrix} = N^2 \begin{bmatrix} \mathbf{H}_x \\ \mathbf{H}_y \end{bmatrix}$$

## Finite-Difference Method for Optical Channel Waveguides

$$\frac{\partial^2 H_x}{\partial x^2} + \varepsilon \frac{\partial}{\partial y} \left( \frac{1}{\varepsilon} \frac{\partial H_x}{\partial y} \right) + (k_0^2 \varepsilon - \beta^2) H_x + \frac{1}{\varepsilon} \frac{\partial \varepsilon}{\partial y} \frac{\partial H_y}{\partial x} = 0$$

$$\frac{\partial^2 H_y}{\partial y^2} + \varepsilon \frac{\partial}{\partial x} \left( \frac{1}{\varepsilon} \frac{\partial H_y}{\partial x} \right) + (k_0^2 \varepsilon - \beta^2) H_y + \frac{1}{\varepsilon} \frac{\partial \varepsilon}{\partial x} \frac{\partial H_x}{\partial y} = 0$$

### Semi-Vectorial Formulation

$$\frac{\partial^2 H_x}{\partial x^2} + \varepsilon \frac{\partial}{\partial y} \left( \frac{1}{\varepsilon} \frac{\partial H_x}{\partial y} \right) + (k_0^2 \varepsilon - \beta^2) H_x = 0$$

$$\frac{\partial^2 H_y}{\partial y^2} + \varepsilon \frac{\partial}{\partial x} \left( \frac{1}{\varepsilon} \frac{\partial H_y}{\partial x} \right) + (k_0^2 \varepsilon - \beta^2) H_y = 0$$

Quasi-TE Modes:  $H_x$ ,  $E_y$  the main components

Quasi-TM Modes:  $H_y$ ,  $E_x$  the main components

### Finite-Difference Formulation

$$[\mathbf{A}] [\mathbf{H}_x] = N^2 [\mathbf{H}_x]$$

$$[\mathbf{B}] [\mathbf{H}_y] = N^2 [\mathbf{H}_y]$$

# Finite-Difference Method for Optical Channel Waveguides

## Scalar Formulation

$$\frac{\partial^2 E_x}{\partial x^2} + \frac{\partial^2 E_x}{\partial y^2} + (k_0^2 \varepsilon - \beta^2) E_x = 0$$

$$\frac{\partial^2 E_y}{\partial x^2} + \frac{\partial^2 E_y}{\partial y^2} + (k_0^2 \varepsilon - \beta^2) E_y = 0$$

$$\frac{\partial^2 H_x}{\partial x^2} + \frac{\partial^2 H_x}{\partial y^2} + (k_0^2 \varepsilon - \beta^2) H_x = 0$$

$$\frac{\partial^2 H_y}{\partial x^2} + \frac{\partial^2 H_y}{\partial y^2} + (k_0^2 \varepsilon - \beta^2) H_y = 0$$

Quasi-TE Modes:  $H_x$  or  $E_y$  the main components

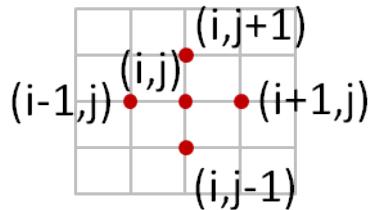
Quasi-TM Modes:  $H_y$  or  $E_x$  the main components

## Finite-Difference Formulation

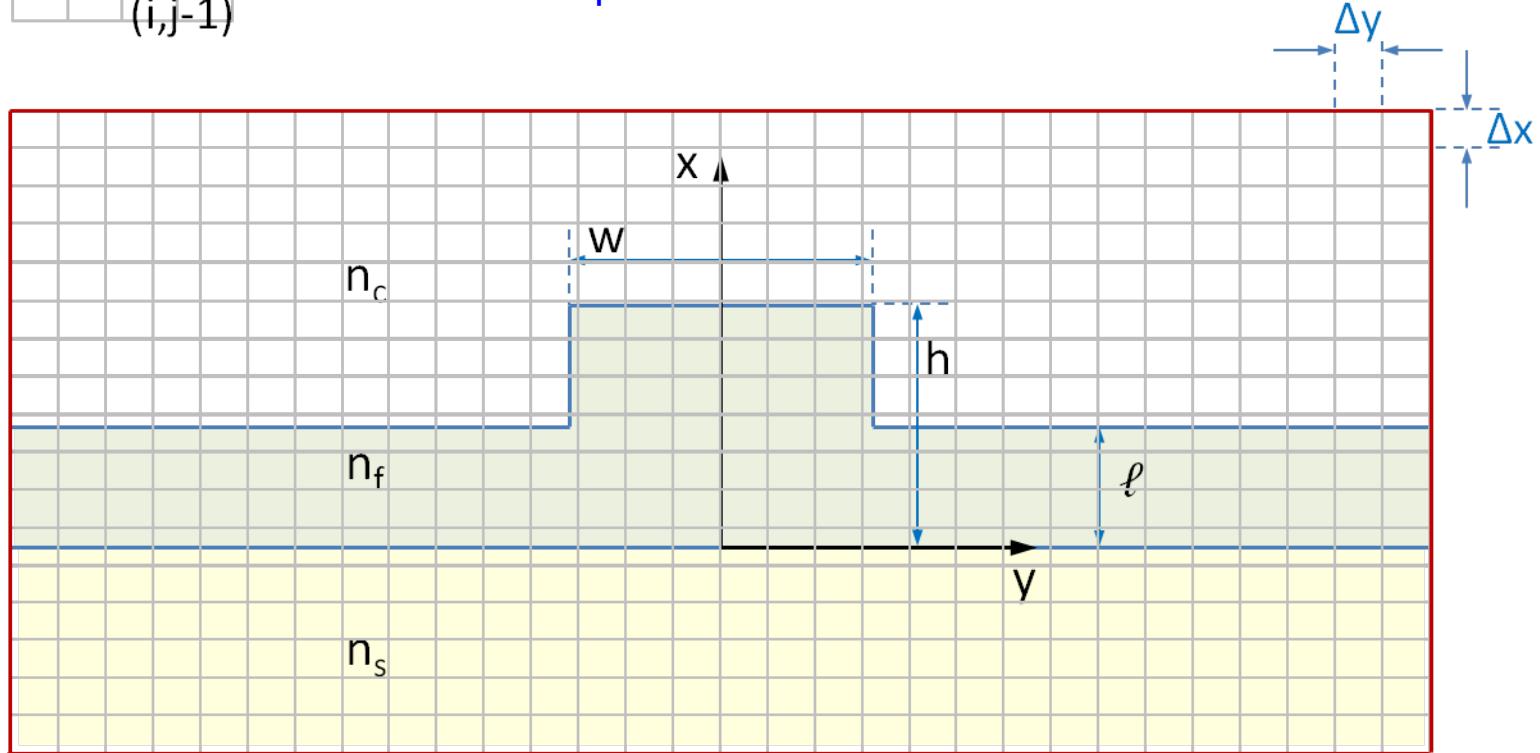
$$[\mathbf{A}] [\mathbf{U}] = N^2 [\mathbf{U}]$$

# Finite-Difference Solution Of The Scalar Wave Equation

## Example of a Rib Waveguide



Computational Window



L. A. Cordren and S. W. Corzine, "Diode Lasers & Photonic Integrated Circuits", J. Wiley & Sons, 1995

# Finite-Difference Solution of the Scalar Wave Equation

Discretized Form of Scalar Helmholtz's Equation

$$\frac{U_j^{i-1}}{\Delta X^2} + \frac{U_{j-1}^i}{\Delta Y^2} - \left( \frac{2}{\Delta X^2} + \frac{2}{\Delta Y^2} - (n_j^i)^2 \right) U_j^i + \frac{U_{j+1}^i}{\Delta Y^2} + \frac{U_j^{i+1}}{\Delta X^2} = \bar{n}^2 U_j^i$$

$$a_j^i = (n_j^i)^2 - \frac{2}{\Delta X^2} - \frac{2}{\Delta Y^2}$$

$$b = \frac{1}{\Delta Y^2}.$$

$$\mathbf{B} = \frac{1}{\Delta X^2} \mathbf{I}$$

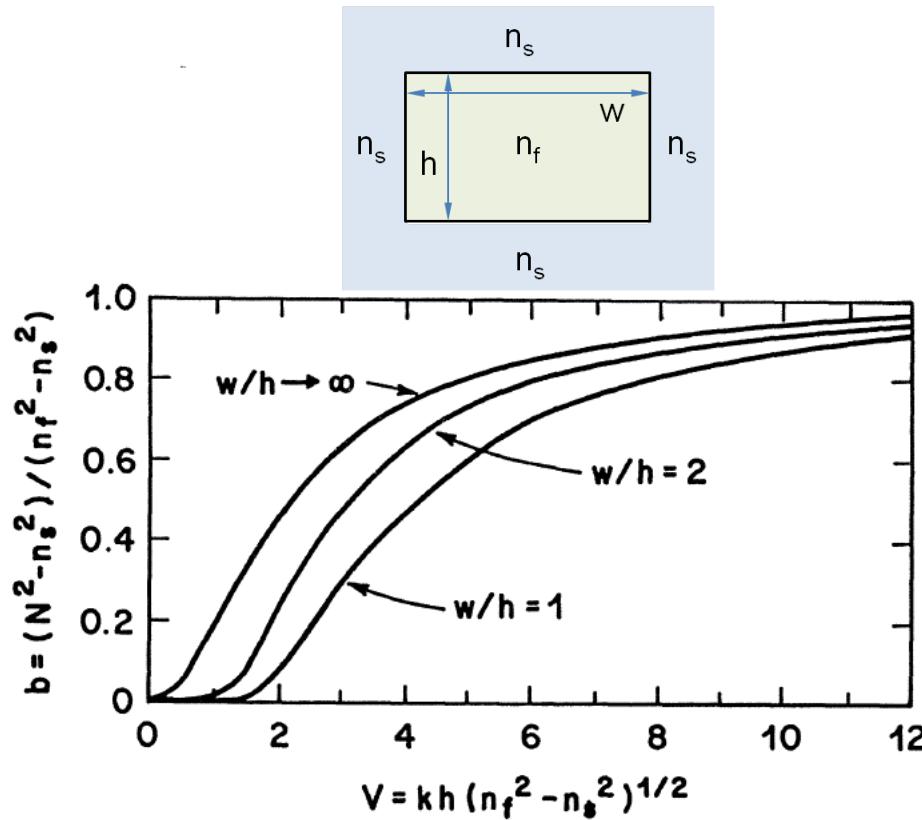
$$\mathbf{A}^i = \begin{bmatrix} a_1^i & b & 0 & \cdots & 0 & 0 \\ b & a_2^i & b & 0 & & 0 \\ 0 & b & a_3^i & b & 0 & \vdots \\ \vdots & 0 & \ddots & 0 & & \\ 0 & 0 & \mathbf{B} & \mathbf{A}^{i-1} & \mathbf{B} & \\ 0 & 0 & \cdots & 0 & \mathbf{B} & \mathbf{A}^i \end{bmatrix}$$

$$\begin{bmatrix} \mathbf{A}^1 & \mathbf{B} & 0 & \cdots & 0 & 0 \\ \mathbf{B} & \mathbf{A}^2 & \mathbf{B} & 0 & & 0 \\ 0 & \mathbf{B} & \mathbf{A}^3 & \mathbf{B} & 0 & \vdots \\ \vdots & 0 & & \ddots & & 0 \\ 0 & 0 & \mathbf{B} & \mathbf{A}^{I-1} & \mathbf{B} & \\ 0 & 0 & \cdots & 0 & \mathbf{B} & \mathbf{A}^I \end{bmatrix} \begin{bmatrix} \mathbf{U}^1 \\ \mathbf{U}^2 \\ \mathbf{U}^3 \\ \vdots \\ \mathbf{U}^{I-1} \\ \mathbf{U}^I \end{bmatrix} = \bar{n}^2 \begin{bmatrix} \mathbf{U}^1 \\ \mathbf{U}^2 \\ \mathbf{U}^3 \\ \vdots \\ \mathbf{U}^{I-1} \\ \mathbf{U}^I \end{bmatrix}$$

L. A. Cordren and S. W. Corzine, "Diode Lasers & Photonic Integrated Circuits", J. Wiley & Sons, 1995

## Buried Waveguide

### Effect of width

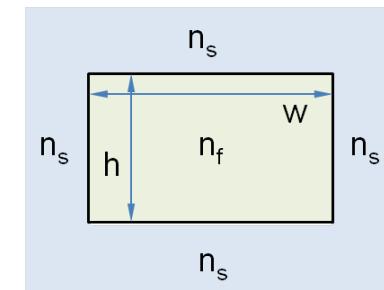
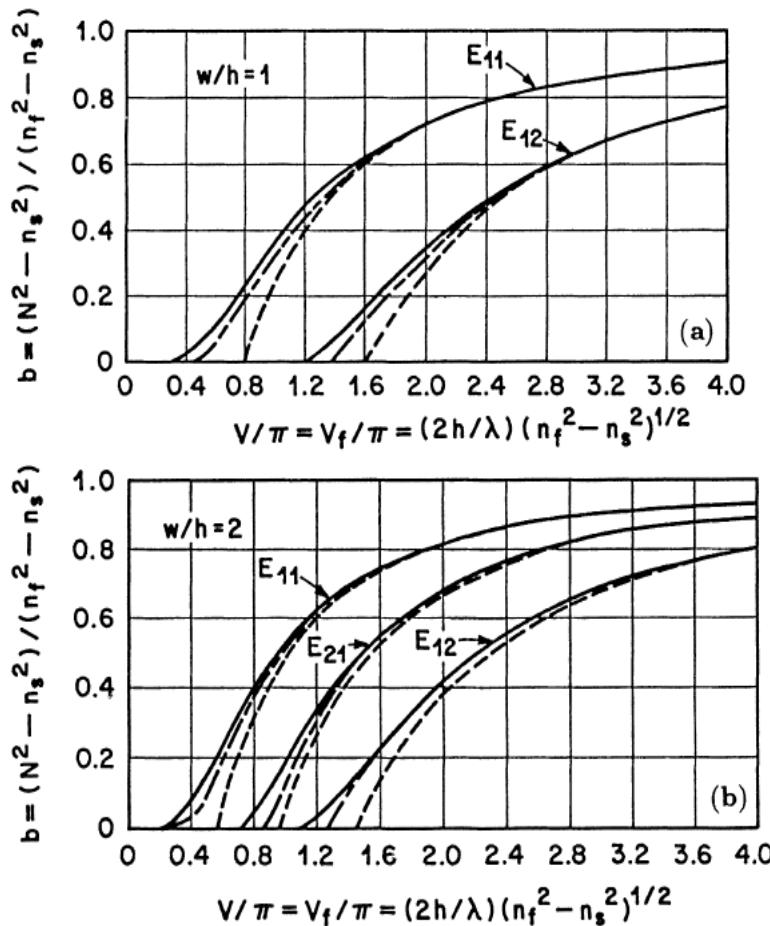


**Fig. 2.25.** Dispersion curves of a buried channel guide of height  $h$  and width  $w$ . The normalized guide index  $b$  is shown as a function of the normalized frequency (or guide thickness)  $V$  for the  $w/h$  ratios of 1, 2, and  $\infty$ , (After [2.58])

T. Tamir, Ed., "Guided-Wave Optoelectronics", Springer-Verlag, 1988

# Buried Waveguide

## Comparison of Effective-Index Method with FDFD Method



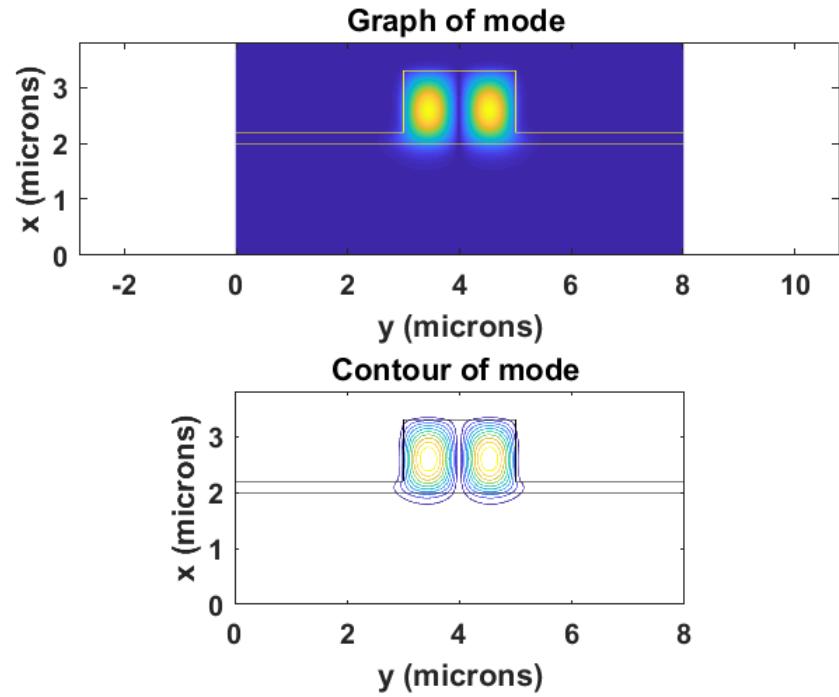
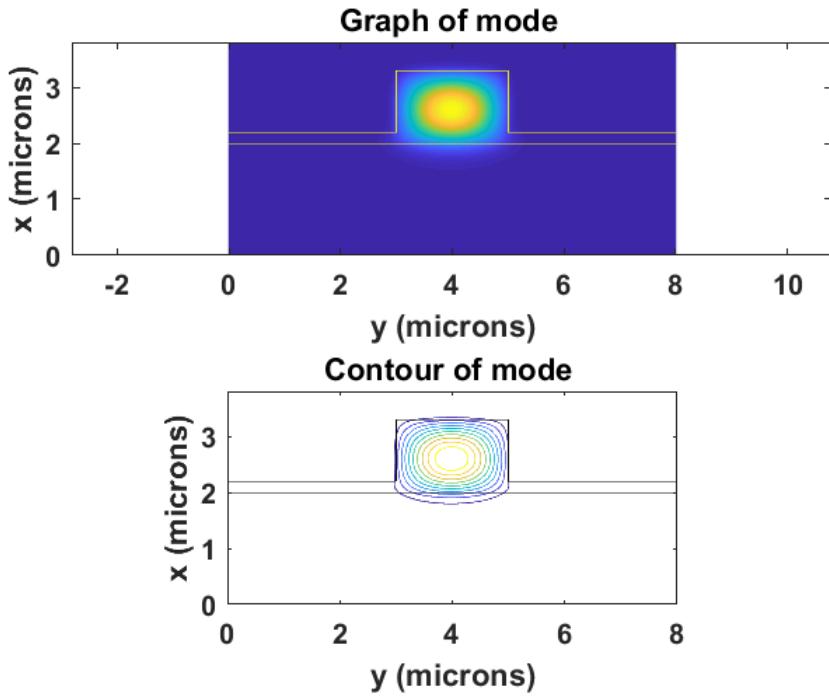
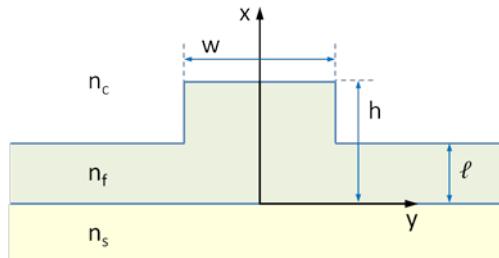
**Fig. 2.29a,b.** Normalized dispersion curves for a buried channel guide comparing the predictions of the numerical calculations (dot-dashed lines), of the effective index method (solid lines), and of the field-shadow method (dashed lines). Comparisons are shown for the aspect ratios of  $w/h = 1$  and  $w/h = 2$ . (After [2.66])

T. Tamir, Ed., "Guided-Wave Optoelectronics", Springer-Verlag, 1988

# Rib Waveguide

## FDFD Method – Scalar Formulation

$n_c = 1.0, n_f = 3.44, n_s = 3.0, t_{\text{rib}} = 1.1 \mu\text{m}, t_{\text{core}} = 0.2 \mu\text{m}, w = 2 \mu\text{m}, \lambda_0 = 1.55 \mu\text{m}$



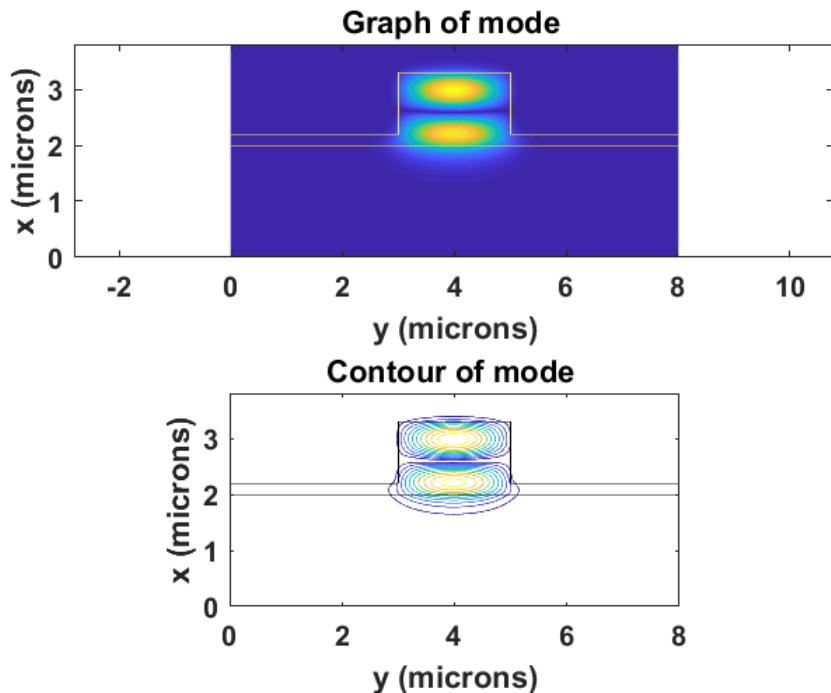
Software by T. Murphy : <http://photonics.umd.edu/software/wgmodes/>

# Rib Waveguide

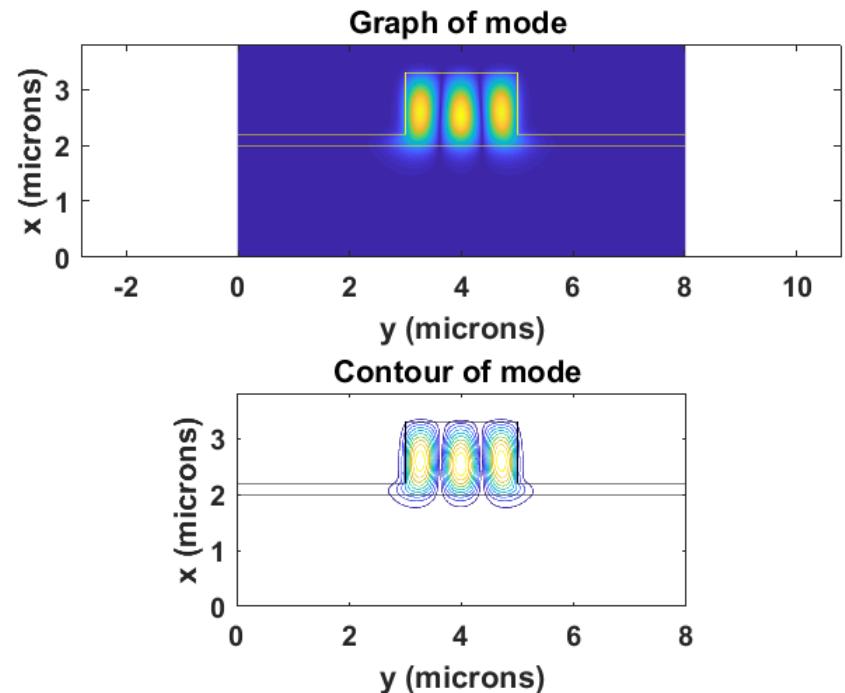
## FDFD Method – Scalar Formulation

$n_c = 1.0, n_f = 3.44, n_s = 3.0, t_{\text{rib}} = 1.1 \mu\text{m}, t_{\text{core}} = 0.2 \mu\text{m}, w = 2 \mu\text{m}, \lambda_0 = 1.55 \mu\text{m}$

$$N_{10} = 3.272121$$



$$N_{02} = 3.232178$$



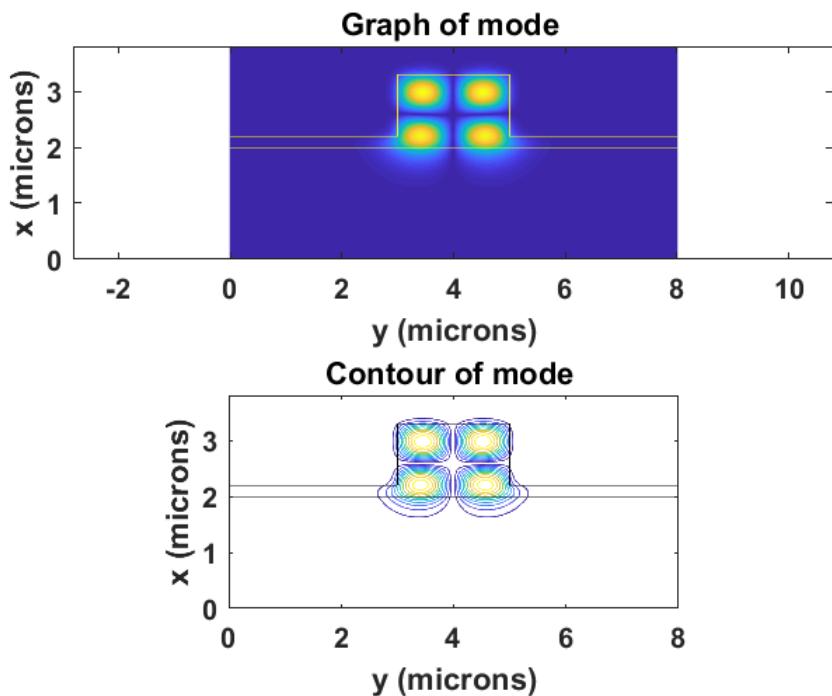
Software by T. Murphy : <http://photonics.umd.edu/software/wgmodes/>

# Rib Waveguide

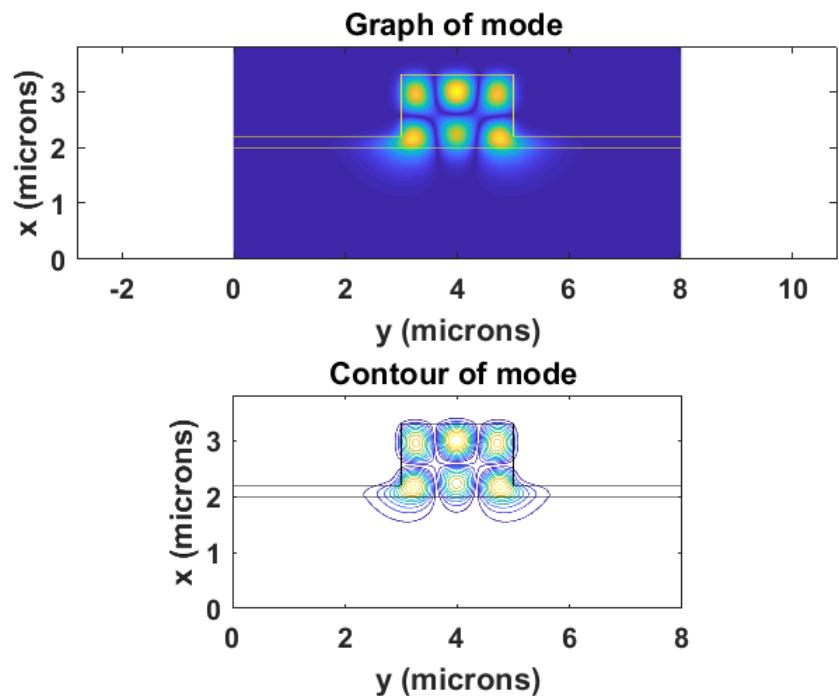
## FDFD Method – Scalar Formulation

$n_c = 1.0, n_f = 3.44, n_s = 3.0, t_{\text{rib}} = 1.1 \mu\text{m}, t_{\text{core}} = 0.2 \mu\text{m}, w = 2 \mu\text{m}, \lambda_0 = 1.55 \mu\text{m}$

$$N_{11} = 3.216175$$



$$N_{12} = 3.124085$$



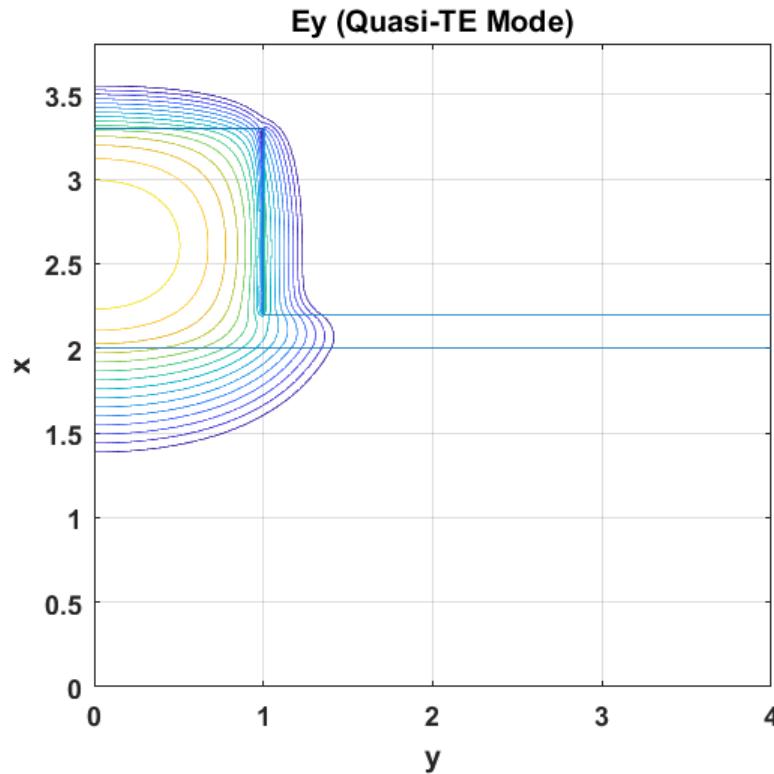
Software by T. Murphy : <http://photonics.umd.edu/software/wgmodes/>

# Rib Waveguide

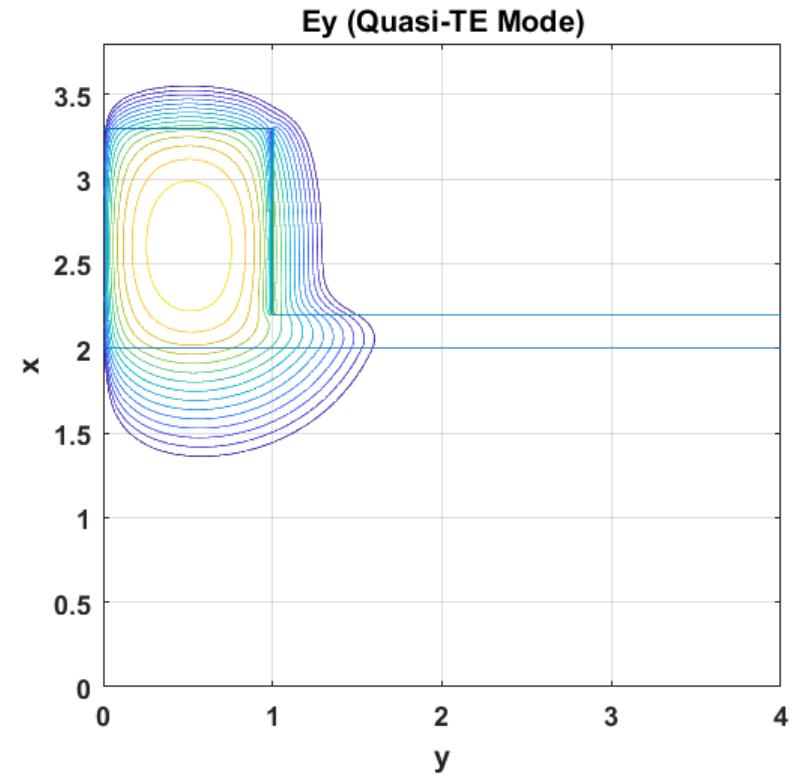
## FDFD Method – Semi-vectorial Formulation

$n_c = 1.0, n_f = 3.44, n_s = 3.0, t_{\text{rib}} = 1.1 \mu\text{m}, t_{\text{core}} = 0.2 \mu\text{m}, w = 2 \mu\text{m}, \lambda_0 = 1.55 \mu\text{m}$

$$N_{00} = 3.380645$$



$$N_{01} = 3.315213$$



Based on the code provided at: <https://www.mathworks.com/matlabcentral/fileexchange/12734-waveguide-mode-solver>

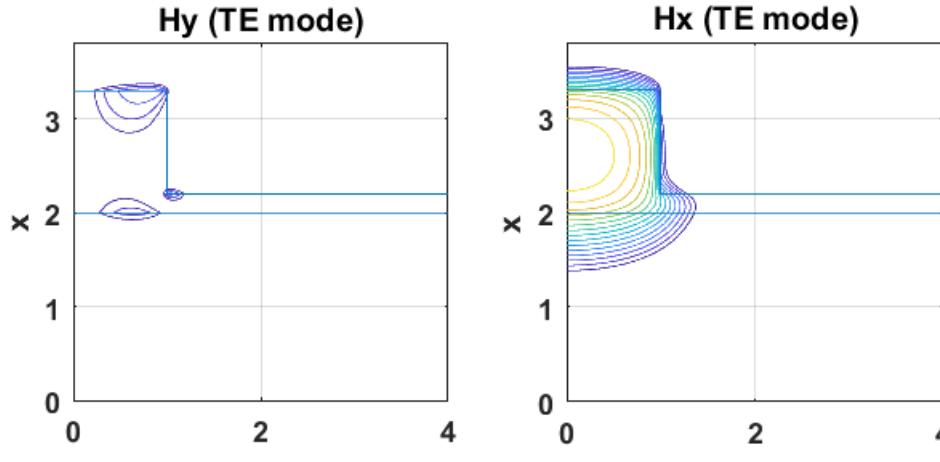
Software by T. Murphy : <http://photronics.umd.edu/software/wgmodes/>

# Rib Waveguide

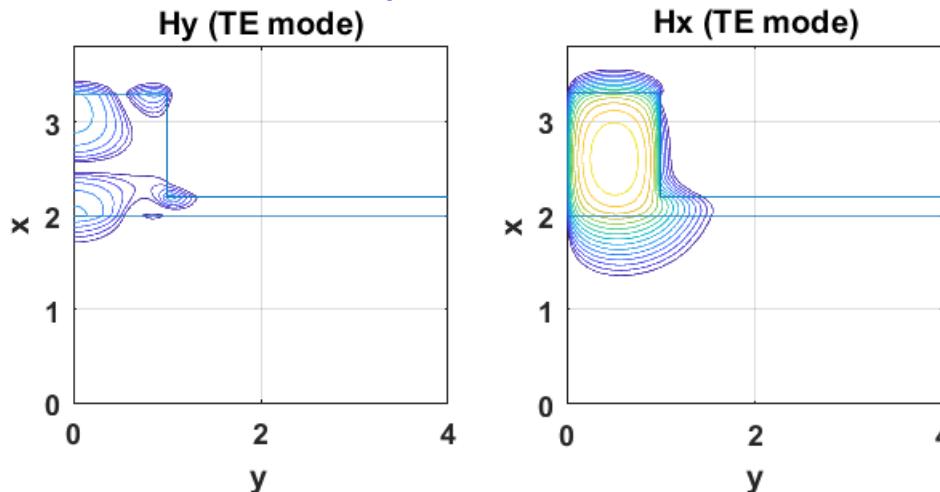
## FDFD Method – Full-vectorial Formulation

$n_c = 1.0, n_f = 3.44, n_s = 3.0, t_{\text{rib}} = 1.1 \mu\text{m}, t_{\text{core}} = 0.2 \mu\text{m}, w = 2 \mu\text{m}, \lambda_0 = 1.55 \mu\text{m}$

$$N_{00} = 3.380640$$



$$N_{01} = 3.315356$$



Based on the code provided at: <https://www.mathworks.com/matlabcentral/fileexchange/12734-waveguide-mode-solver>

Prof. Elias N. Glytsis, School of ECE, NTUA

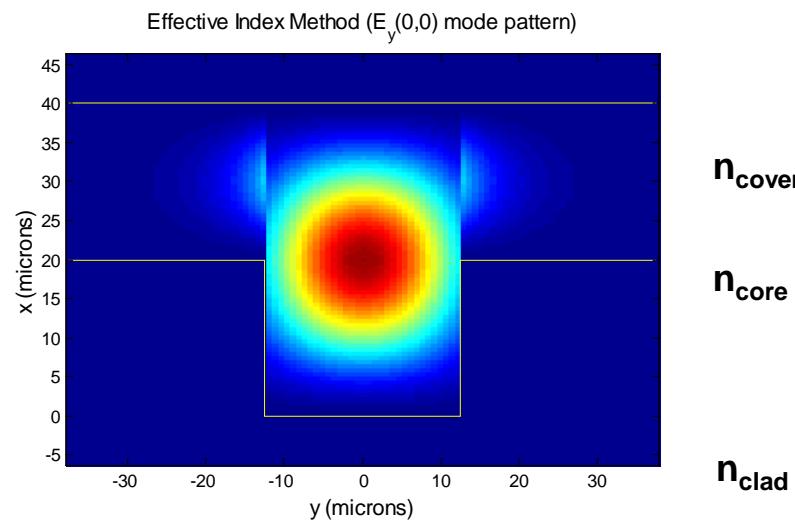
## Inverted Rib Waveguide ( $\lambda_0 = 0.632$ microns)

$n_{\text{core}} = 1.5365$ ,  $n_{\text{clad}} = 1.5085$ ,  $n_{\text{cover}} = 1.50$  ( $\text{SiO}_2$ )  
 $t_{\text{rib}} = 20$  microns,  $t_{\text{core}} = 20$  microns,  $w_{\text{rib}} = 25$  microns

Finite-Difference Method  $N_{\text{eff}} = 1.536449$  ( $E_y(0,0)$  mode)



Effective-Index Method:  $N_{\text{eff}} = 1.536461$



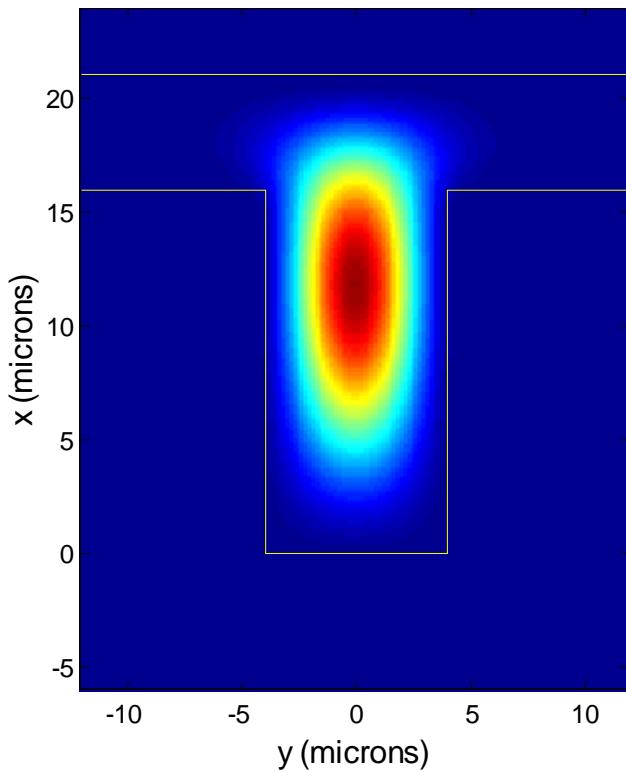
# Inverted Rib Waveguide

$N_{\text{eff}} = 1.537908$  ( $E_y(0,0)$  mode),  $\lambda_0 = 0.83$  microns

$n_{\text{core}} = 1.5387$ ,  $n_{\text{clad}} = 1.5115$ ,  $n_{\text{cover}} = 1.0$

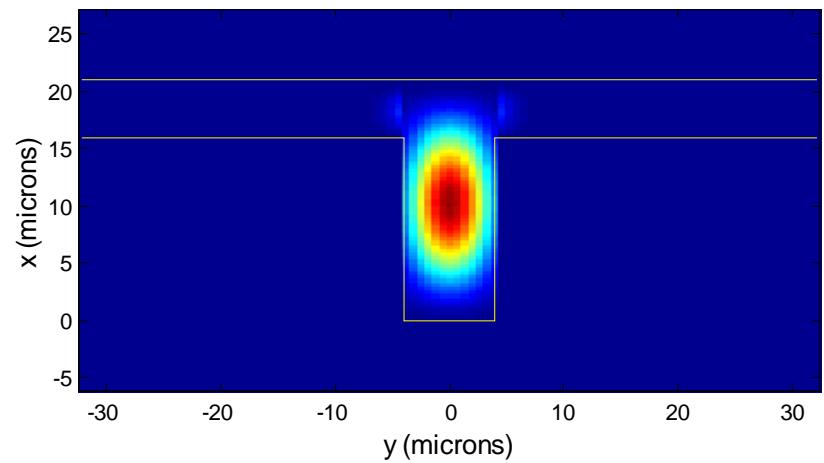
$t_{\text{rib}} = 16$  microns,  $t_{\text{core}} = 5$  microns,  $w_{\text{rib}} = 8$  microns

Semi-vectorial Method  $E_y(0,0)$  mode,  $N_{\text{eff}} = 1.537908$



$N_{\text{eff}} = 1.538180$

Effective Index Method ( $E_y(0,0)$  mode pattern)



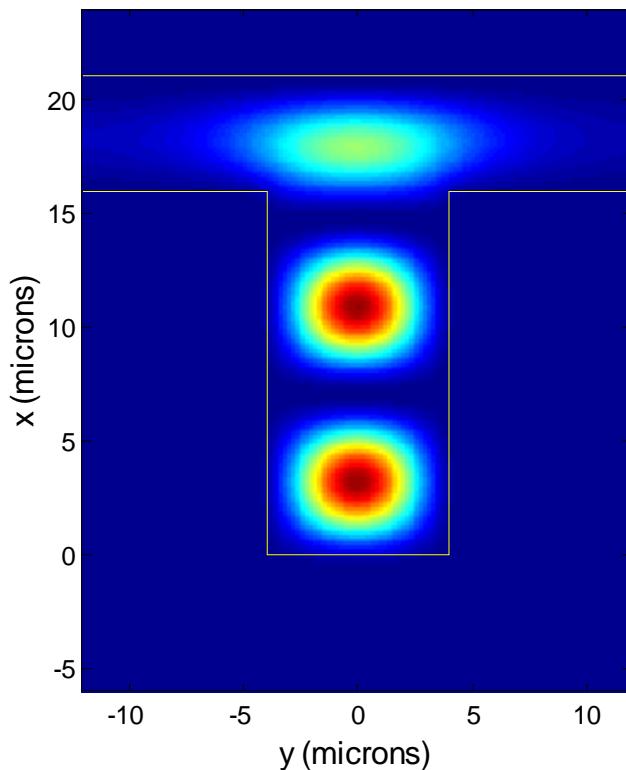
# Inverted Rib Waveguide

$N_{\text{eff}} = 1.537038$  ( $E_y(0,0)$  mode),  $\lambda_0 = 0.83$  microns

$n_{\text{core}} = 1.5387$ ,  $n_{\text{clad}} = 1.5115$ ,  $n_{\text{cover}} = 1.0$

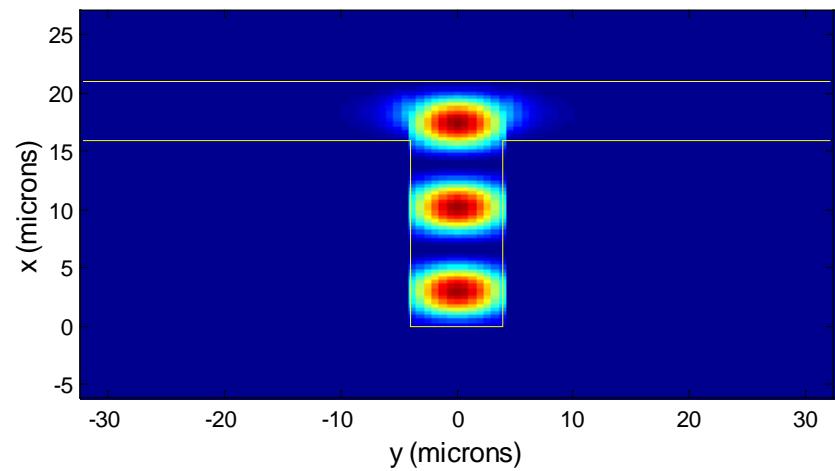
$t_{\text{rib}} = 16$  microns,  $t_{\text{core}} = 5$  microns,  $w_{\text{rib}} = 8$  microns

Semi-vectorial Method  $E_y(2,0)$  mode,  $N_{\text{eff}} = 1.537038$



$N_{\text{eff}} = 1.537335$

Effective Index Method ( $E_y(2,0)$  mode pattern)

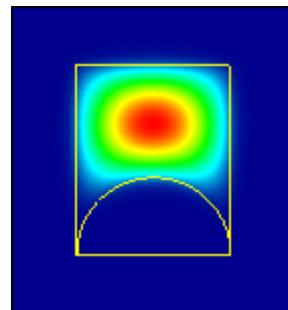


# Modal Fields of Buried BF-Goodrich Waveguide

$\lambda_0 = 0.850 \text{ } \mu\text{m}$ ,  $w = 13 \text{ mm}$ ,  $h = 16 \text{ mm}$ ,  $n_{\text{clad}} = 1.5003$ ,  $n_{\text{core}} = 1.5291$

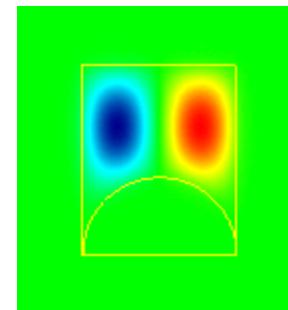
## Finite-Difference Method Results

$E_y(0,0)$



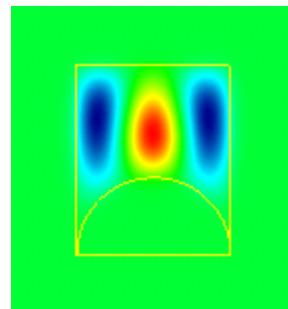
$$N_{00} = 1.528325$$

$E_y(0,1)$



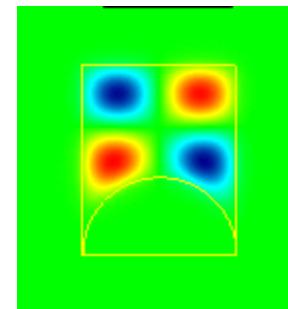
$$N_{01} = 1.528091$$

$E_y(0,2)$



$$N_{02} = 1.526084$$

$E_y(1,1)$



$$N_{11} = 1.526084$$