Thin-film lithium niobate slab waveguides

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TET

PhoQC

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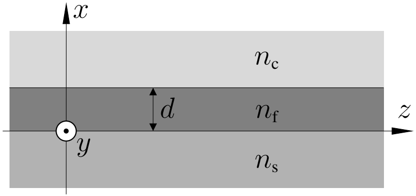
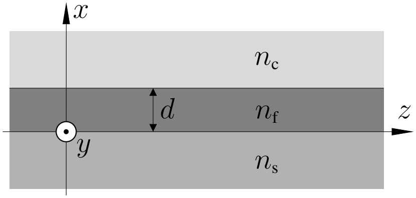
Dielectric slab waveguide



$$n_f > n_s, n_c$$

Dielectric slab waveguide



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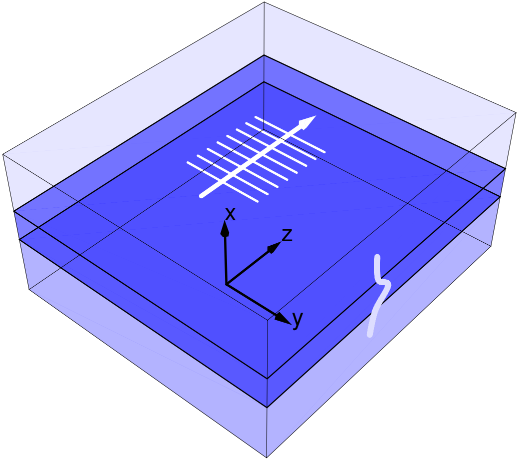
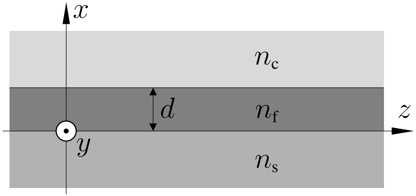


Dielectric slab waveguide



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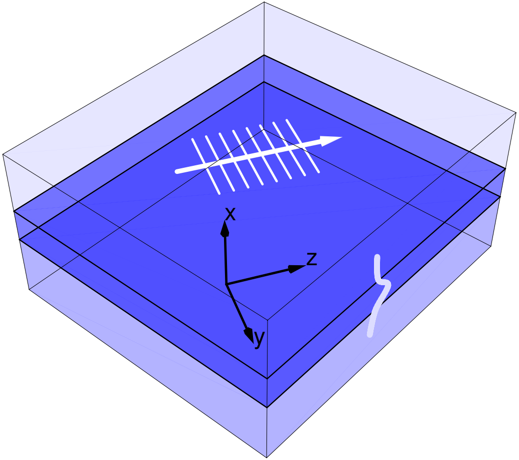
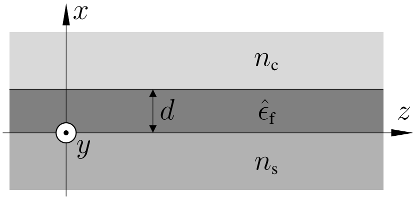


Dielectric slab waveguide, anisotropic core



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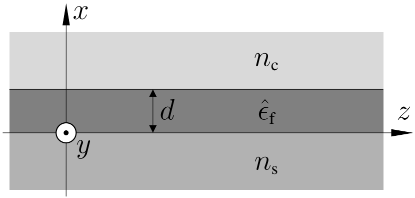
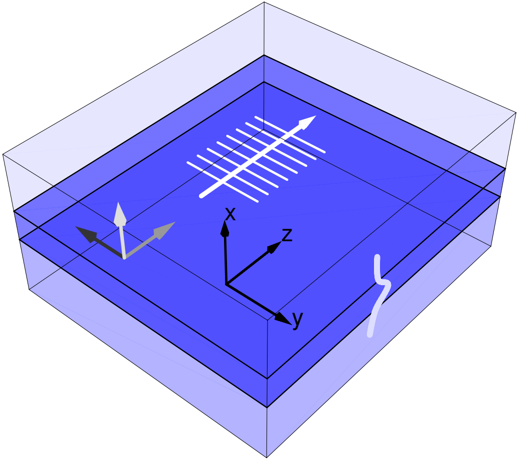
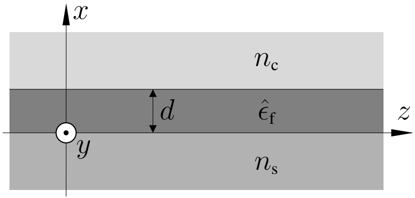
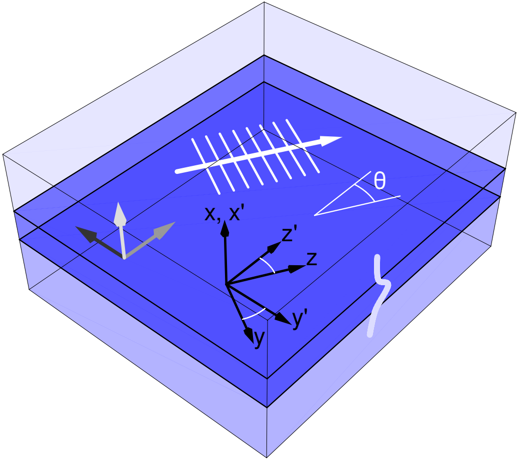




Dielectric slab waveguide, anisotropic core

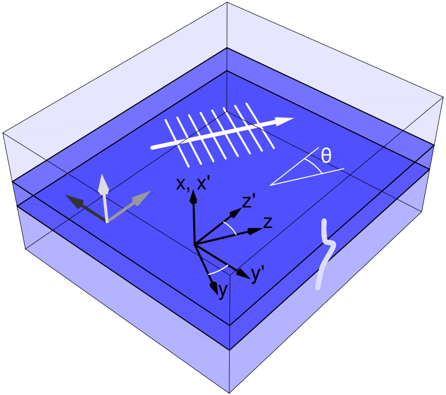


$\hat{\epsilon}_f(\theta)$



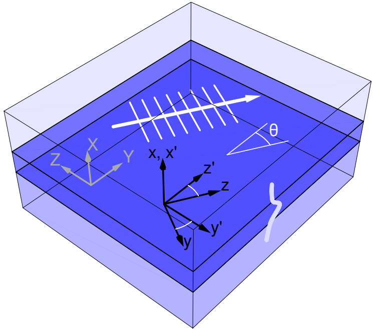
Overview

- TFLN cuts and coordinates
- Parameter values
- Mode analysis procedure
- X-cut TFLN slabs
- Z-cut TFLN slabs

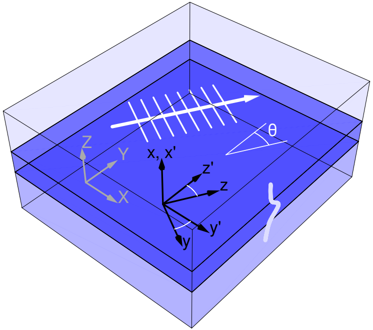


TFLN configurations

X-cut

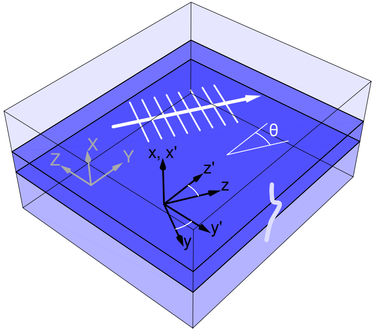


Z-cut

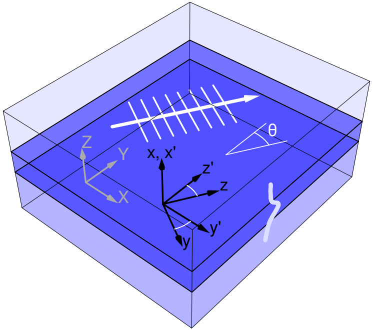


TFLN configurations

X-cut



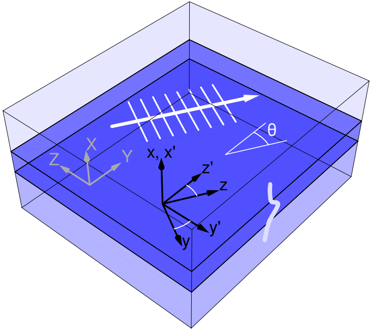
Z-cut



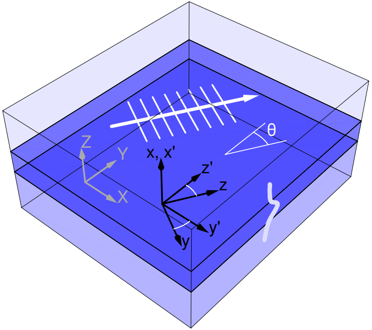
Crystal coordinates $\{X, Y, Z\}$, sample coordinates $\{x', y', z'\}$, wave coordinates $\{x, y, z\}$.

TFLN configurations

X-cut



Z-cut



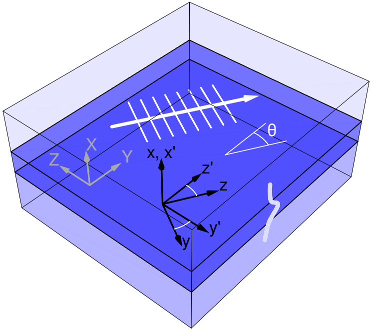
(sample coordinates $\{x', y', z'\}$)

$$\hat{\epsilon}^{\mathrm{x}}_{\mathrm{f},0} = \begin{pmatrix} n_{\mathrm{o}}^2 & 0 & 0 \\ 0 & n_{\mathrm{e}}^2 & 0 \\ 0 & 0 & n_{\mathrm{o}}^2 \end{pmatrix}$$

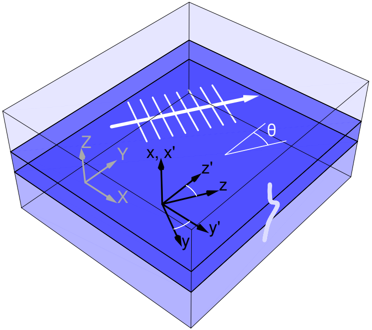
$$\hat{\epsilon}^{\mathrm{z}}_{\mathrm{f},0} = \begin{pmatrix} n_{\mathrm{e}}^2 & 0 & 0 \\ 0 & n_{\mathrm{o}}^2 & 0 \\ 0 & 0 & n_{\mathrm{o}}^2 \end{pmatrix}$$

TFLN configurations

X-cut



Z-cut

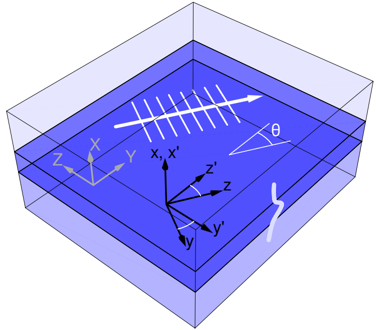


(sample coordinates $'$ $\rightarrow$ wave coordinates)

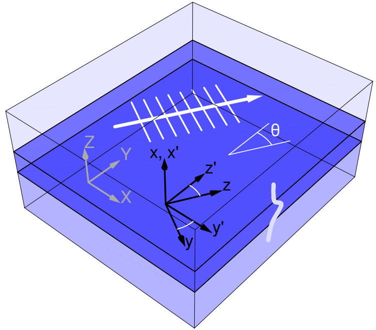
$$\boldsymbol{v} = \mathsf{R}\boldsymbol{v}', \qquad \hat{\epsilon}_{\mathrm{f}} = \mathsf{R}\hat{\epsilon}_{\mathrm{f},0}\mathsf{R}^{\mathsf{T}}, \qquad \mathsf{R} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & -\sin\theta \\ 0 & \sin\theta & \cos\theta \end{pmatrix}.$$

TFLN configurations

X-cut



Z-cut

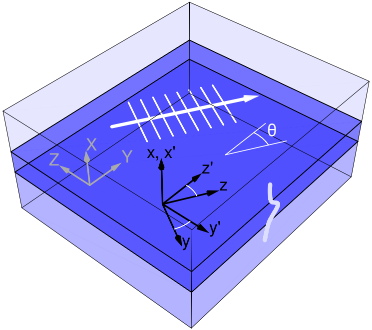


(wave coordinates $\{x, y, z\}(\theta)$)

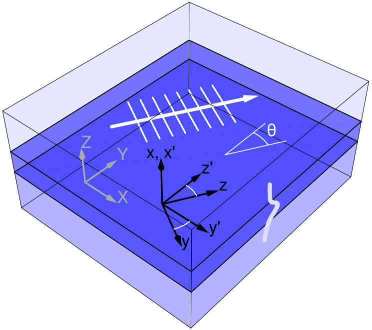
$$\hat{\epsilon}_{\mathrm{f}}^{\mathrm{x}} = \begin{pmatrix} n_{\mathrm{o}}^2 & 0 & 0 \\ 0 & n_{\mathrm{e}}^2 \cos^2\theta + n_{\mathrm{o}}^2 \sin^2\theta & (n_{\mathrm{e}}^2 - n_{\mathrm{o}}^2)\cos\theta\sin\theta \\ 0 & (n_{\mathrm{e}}^2 - n_{\mathrm{o}}^2)\cos\theta\sin\theta & n_{\mathrm{e}}^2 \sin^2\theta + n_{\mathrm{o}}^2 \cos^2\theta \end{pmatrix}$$

TFLN configurations

X-cut

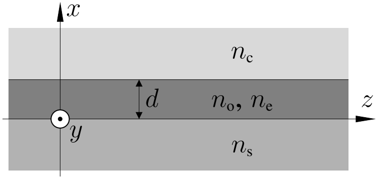


Z-cut

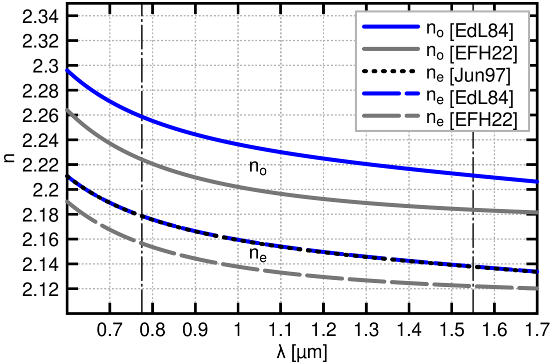


(wave coordinates $\{x, y, z\}(\theta)$)

$$\hat{\epsilon}_{\rm f}^{\rm z} = \begin{pmatrix} n_{\rm e}^2 & 0 & 0 \\ 0 & n_{\rm o}^2 & 0 \\ 0 & 0 & n_{\rm o}^2 \end{pmatrix} \quad \forall\, \theta.$$

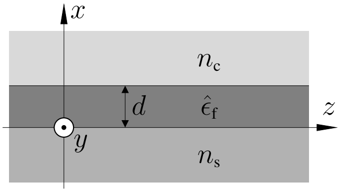


λ/ µm	n_s	n_c	n_o	n_e
1.550	1.4483	1.0 | n_s	2.1837	2.1220
0.775	1.4589	1.0 | n_s	2.2242	2.1565



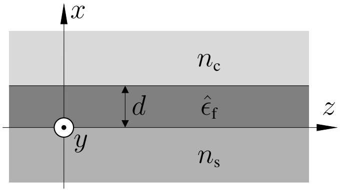
[EdL84] G. J. Edwards, M. Lawrence, *Optical and Quantum Electronics* **16**:373–375, 1984.
[Jun97] D. H. Jundt. *Optics Letters* **22**(20):1553–1555, 1997.
[EFH22] L. Ebers, A. Ferreri, M. Hammer, M. Albert, C. Meier, J. Förstner, P. R. Sharapova, *Journal of Physics: Photonics*, **4**(2):025001, 2022.

TFLN slabs, modal analysis



$$\hat{\epsilon}(x) = \begin{cases} n_c^2\,\mathbb{1}_3, & \text{if } d < x, \\ \hat{\epsilon}_f, & \text{for } 0 < x < d, \\ n_s^2\,\mathbb{1}_3, & \text{if } x < 0. \end{cases} \qquad \hat{\epsilon}_f = \begin{pmatrix} \epsilon_x & 0 & 0 \\ 0 & \epsilon_y & \delta \\ 0 & \delta & \epsilon_z \end{pmatrix}$$

	ϵ_x	ϵ_y	ϵ_z	δ
(X-cut)	n_o^2	$n_e^2 \cos^2\theta + n_o^2 \sin^2\theta$	$n_e^2 \sin^2\theta + n_o^2 \cos^2\theta$	$(n_e^2 - n_o^2)\cos\theta\sin\theta$
(Z-cut)	n_e^2	n_o^2	n_o^2	0

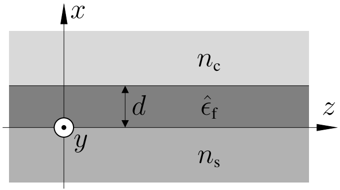


$$\hat{\epsilon}(x) = \begin{cases} n_c^2\, \mathbb{1}_3, & \text{if } d < x, \\ \hat{\epsilon}_f, & \text{for } 0 < x < d, \\ n_s^2\, \mathbb{1}_3, & \text{if } x < 0. \end{cases}$$

$$\sim \exp(\mathrm{i}\omega t), \quad \omega = k\mathrm{c} = 2\pi\mathrm{c}/\lambda, \quad \boldsymbol{\nabla} \times \boldsymbol{\mathcal{E}} = -\mathrm{i}\omega\mu_0\boldsymbol{\mathcal{H}}, \quad \boldsymbol{\nabla} \times \boldsymbol{\mathcal{H}} = \mathrm{i}\omega\epsilon_0\hat{\epsilon}\boldsymbol{\mathcal{E}}.$$

Ansatz: $$\begin{pmatrix} \boldsymbol{\mathcal{E}} \\ \boldsymbol{\mathcal{H}} \end{pmatrix}(x, y, z) = \begin{pmatrix} \boldsymbol{E} \\ \boldsymbol{H} \end{pmatrix}(x)\ \exp(-\mathrm{i}\beta z), \quad \beta = k\,N.$$

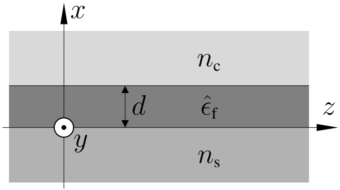
TFLN slabs, modal analysis



$$\hat{\epsilon}(x) = \begin{cases} n_{\mathrm{c}}^2\,\mathbb{1}_3, & \text{if } d < x, \\ \hat{\epsilon}_{\mathrm{f}}, & \text{for } 0 < x < d, \\ n_{\mathrm{s}}^2\,\mathbb{1}_3, & \text{if } x < 0. \end{cases}$$

(core, $0 < x < d$)

$$\begin{pmatrix} \mathrm{i}\,\beta E_y \\ -\mathrm{i}\,\beta E_x - \partial_x E_z \\ \partial_x E_y \end{pmatrix} = -\mathrm{i}\omega\mu_0 \begin{pmatrix} H_x \\ H_y \\ H_z \end{pmatrix}, \quad \begin{pmatrix} \mathrm{i}\,\beta H_y \\ -\mathrm{i}\,\beta H_x - \partial_x H_z \\ \partial_x H_y \end{pmatrix} = \mathrm{i}\omega\epsilon_0 \begin{pmatrix} \epsilon_x & 0 & 0 \\ 0 & \epsilon_y & \delta \\ 0 & \delta & \epsilon_z \end{pmatrix} \begin{pmatrix} E_x \\ E_y \\ E_z \end{pmatrix}.$$



$$\hat{\epsilon}(x) = \begin{cases} n_\mathrm{c}^2\,\mathbb{1}_3, & \text{if } d < x, \\ \hat{\epsilon}_\mathrm{f}, & \text{for } 0 < x < d, \\ n_\mathrm{s}^2\,\mathbb{1}_3, & \text{if } x < 0. \end{cases}$$

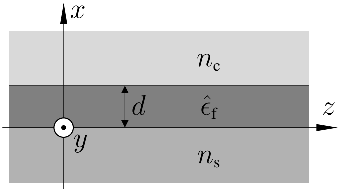
(core, $0 < x < d$)

Principal functions $e(x) = \sqrt{\epsilon_0}\,E_y(x), \quad h(x) = \sqrt{\mu_0}\,H_y(x),$

$$E_x = \frac{\beta}{\omega\epsilon_0\epsilon_x}\frac{1}{\sqrt{\mu_0}}h, \quad E_y = \frac{1}{\sqrt{\epsilon_0}}e, \quad E_z = \frac{-\mathrm{i}}{\omega\epsilon_0\epsilon_z}\frac{1}{\sqrt{\mu_0}}\partial_x h - \frac{\delta}{\epsilon_z}\frac{1}{\sqrt{\epsilon_0}}e,$$

$$H_x = \frac{-\beta}{\omega\mu_0}\frac{1}{\sqrt{\epsilon_0}}e, \quad H_y = \frac{1}{\sqrt{\mu_0}}h, \quad H_z = \frac{\mathrm{i}}{\omega\mu_0}\frac{1}{\sqrt{\epsilon_0}}\partial_x e.$$

TFLN slabs, modal analysis



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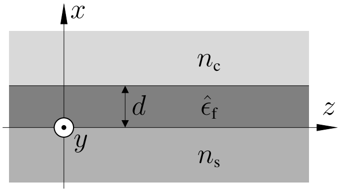
(core, $0 < x < d$)

Principal functions $e(x) = \sqrt{\epsilon_0}\, E_y(x), \quad h(x) = \sqrt{\mu_0}\, H_y(x),$

$$\partial_x^2 e + \left(k^2\left(\epsilon_y - \frac{\delta^2}{\epsilon_z}\right) - \beta^2\right) e - \mathrm{i}k\frac{\delta}{\epsilon_z}\partial_x h = 0,$$

$$\frac{1}{\epsilon_z}\partial_x^2 h + \left(k^2 - \frac{1}{\epsilon_x}\beta^2\right) h - \mathrm{i}k\frac{\delta}{\epsilon_z}\partial_x e = 0.$$



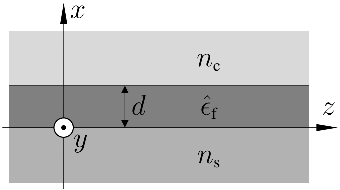
$$\hat\epsilon(x) = \begin{cases} n_c^2\,\mathbb{1}_3, & \text{if } d < x, \\ \hat\epsilon_f, & \text{for } 0 < x < d, \\ n_s^2\,\mathbb{1}_3, & \text{if } x < 0. \end{cases}$$

(core, $0 < x < d$)

Principal functions $\boldsymbol{p}(x) = \begin{pmatrix} e \\ h \end{pmatrix}(x)$

$$\left(\mathbb{1}_2\partial_x^2 - \mathrm{i}\mathsf{B}\partial_x - \mathsf{C}\right)\boldsymbol{p} = 0,$$

$$\mathsf{B} = k\delta\begin{pmatrix} 0 & 1/\epsilon_z \\ 1 & 0 \end{pmatrix}, \quad \mathsf{C} = -\begin{pmatrix} k^2(\epsilon_y - \delta^2/\epsilon_z) - \beta^2 & 0 \\ 0 & k^2\epsilon_z - \epsilon_z\beta^2/\epsilon_x \end{pmatrix}.$$



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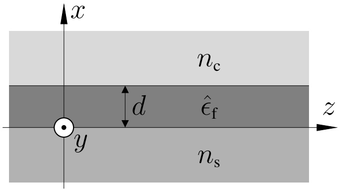
(core, $0 < x < d$)

Local solutions, ansatz: $\boldsymbol{p}(x) = \boldsymbol{q}\exp(-\mathrm{i}\kappa x)$

$\hookrightarrow$ $(\kappa^2\mathbb{1}_2 + \kappa\mathsf{B} + \mathsf{C})\boldsymbol{q} = 0$



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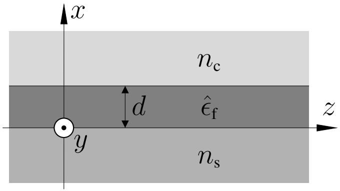
(core, $0 < x < d$)

Local solutions, ansatz: $\boldsymbol{p}(x) = \boldsymbol{q}\exp(-\mathrm{i}\kappa x)$

$$(\kappa^2 \mathbb{1}_2 + \kappa \mathsf{B} + \mathsf{C})\boldsymbol{q} = 0$$

or $$\begin{pmatrix} 0 & \mathbb{1}_2 \\ -\mathsf{C} & -\mathsf{B} \end{pmatrix} \begin{pmatrix} \boldsymbol{q} \\ \boldsymbol{r} \end{pmatrix} = \kappa \begin{pmatrix} \boldsymbol{q} \\ \boldsymbol{r} \end{pmatrix}.$$

TFLN slabs, modal analysis



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(core, $0 < x < d$)

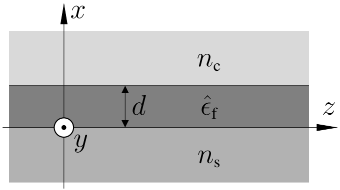
Local solutions, ansatz: $\boldsymbol{p}(x) = \boldsymbol{q}\exp(-\mathrm{i}\kappa x)$

$\hookrightarrow$ $$(\kappa^2 \mathbb{1}_2 + \kappa \mathsf{B} + \mathsf{C})\boldsymbol{q} = 0$$

or $$\begin{pmatrix} 0 & \mathbb{1}_2 \\ -\mathsf{C} & -\mathsf{B} \end{pmatrix} \begin{pmatrix} \boldsymbol{q} \\ \boldsymbol{r} \end{pmatrix} = \kappa \begin{pmatrix} \boldsymbol{q} \\ \boldsymbol{r} \end{pmatrix}.$$

$\hookrightarrow$ $\{\boldsymbol{q}_j, \kappa_j\}$, $j = 1, \ldots, 4$, $(\boldsymbol{r}_j = \kappa_j \boldsymbol{q}_j)$.

TFLN slabs, modal analysis



$$\hat{\epsilon}(x) = \begin{cases} n_c^2\,\mathbb{1}_3, & \text{if } d < x, \\ \hat{\epsilon}_f, & \text{for } 0 < x < d, \\ n_s^2\,\mathbb{1}_3, & \text{if } x < 0. \end{cases}$$

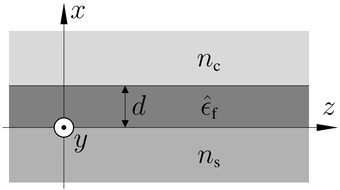
(substrate, $x < 0$)

Principal functions $e(x) = \sqrt{\epsilon_0}\,E_y(x), \quad h(x) = \sqrt{\mu_0}\,H_y(x),$

$$\partial_x^2 e + \left(k^2 n_s^2 - \beta^2\right) e = 0, \quad \partial_x^2 h + \left(k^2 n_s^2 - \beta^2\right) h = 0.$$

Require normalizable solutions

$$e(x) \sim \exp(\kappa_s x), \quad h(x) \sim \exp(\kappa_s x), \quad \kappa_s = \sqrt{\beta^2 - k^2 n_s^2}, \quad N > n_s.$$



$$\hat{\epsilon}(x) = \begin{cases} n_c^2\,\mathbb{1}_3, & \text{if } d < x, \\ \hat{\epsilon}_f, & \text{for } 0 < x < d, \\ n_s^2\,\mathbb{1}_3, & \text{if } x < 0. \end{cases}$$

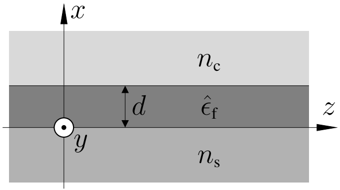
(cover, $d < x$)

Principal functions $e(x) = \sqrt{\epsilon_0}\,E_y(x), \quad h(x) = \sqrt{\mu_0}\,H_y(x),$

$$\partial_x^2 e + \big(k^2 n_c^2 - \beta^2\big) e = 0, \quad \partial_x^2 h + \big(k^2 n_c^2 - \beta^2\big) h = 0.$$

Require normalizable solutions

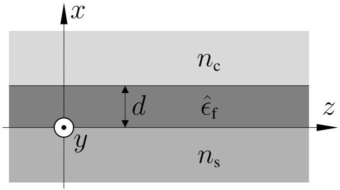
$$e(x) \sim \exp(-\kappa_c x), \quad h(x) \sim \exp(-\kappa_c x), \quad \kappa_c = \sqrt{\beta^2 - k^2 n_c^2}, \quad N > n_c.$$



$$\hat\epsilon(x) = \begin{cases} n_\mathrm{c}^2\,\mathbb{1}_3, & \text{if } d < x, \\ \hat\epsilon_\mathrm{f}, & \text{for } 0 < x < d, \\ n_\mathrm{s}^2\,\mathbb{1}_3, & \text{if } x < 0. \end{cases}$$

Mode profile, ansatz: ($A_\mathrm{e}^\mathrm{c}, A_\mathrm{h}^\mathrm{c}, A_1^\mathrm{f}, A_2^\mathrm{f}, A_3^\mathrm{f}, A_4^\mathrm{f}, A_\mathrm{e}^\mathrm{s}, A_\mathrm{h}^\mathrm{s}$: unknowns $\boldsymbol{A}$)

$$\begin{pmatrix} e \\ h \end{pmatrix}(x) = \begin{cases} A_\mathrm{e}^\mathrm{c}\begin{pmatrix} 1 \\ 0 \end{pmatrix}\exp(-\kappa_\mathrm{c}x) + A_\mathrm{h}^\mathrm{c}\begin{pmatrix} 0 \\ 1 \end{pmatrix}\exp(-\kappa_\mathrm{c}x), & \text{if } d < x, \\ \sum_{j=1}^{4} A_j^\mathrm{f}\begin{pmatrix} e_j \\ h_j \end{pmatrix}\exp(-\mathrm{i}\,\kappa_j x), & \text{for } 0 < x < d, \\ A_\mathrm{e}^\mathrm{s}\begin{pmatrix} 1 \\ 0 \end{pmatrix}\exp(\kappa_\mathrm{s}x) + A_\mathrm{h}^\mathrm{s}\begin{pmatrix} 0 \\ 1 \end{pmatrix}\exp(\kappa_\mathrm{s}x), & \text{if } x < 0. \end{cases}$$



$$\hat{\epsilon}(x) = \begin{cases} n_c^2\,\mathbb{1}_3, & \text{if } d < x, \\ \hat{\epsilon}_f, & \text{for } 0 < x < d, \\ n_s^2\,\mathbb{1}_3, & \text{if } x < 0. \end{cases}$$

Interface conditions: At $x = 0$ and $x = d$, require continuity of

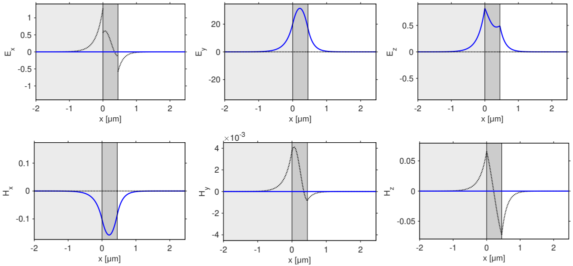
$$E_y,\ E_z,\ H_y,\ H_z,\ \epsilon_0(\hat{\epsilon}\boldsymbol{E})_x,\ \mu_0 H_x \quad \text{or} \quad e,\ h,\ \partial_x e,\ \frac{1}{\epsilon_z}(\partial_x h - \mathrm{i}k\delta e).$$

$$\curvearrowright \quad \mathsf{M}(\beta)\,\boldsymbol{A} = 0. \qquad (8 \times 8)$$

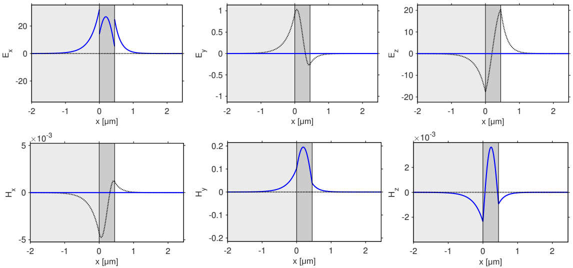
Nontrivial solutions $\{\beta, \boldsymbol{A}\}$ $\rightsquigarrow$ guided modes $\{N, \boldsymbol{E}, \boldsymbol{H}\}$. $(\ldots)$

Mode profiles *(X-cut, nonsymmetric, separate)*

$\mathrm{TE}_0,\ N = 1.8919,\ \Pi > 0.99$

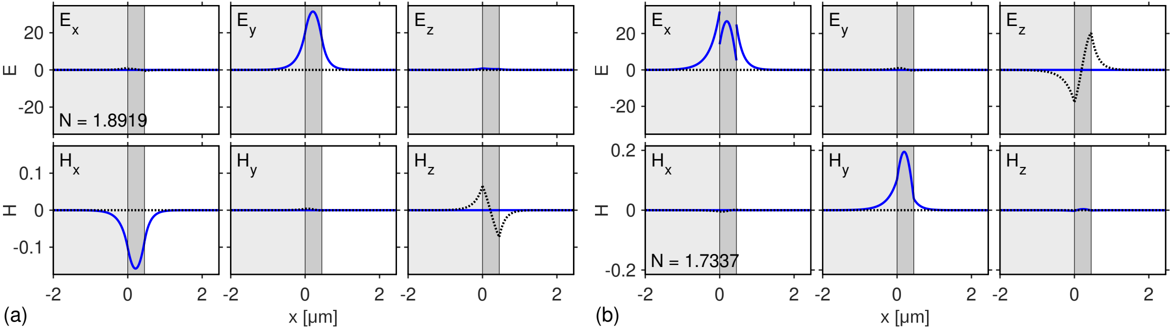


$\mathrm{TM}_0,\ N = 1.7337,\ \Pi < 0.01$



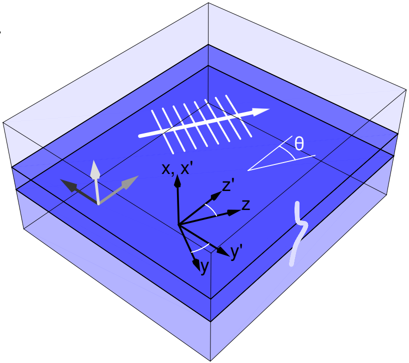
X-cut, $\mathrm{SiO_2:LN:air},\ d = 0.45\ \mu\mathrm{m},\ \theta = 45^\circ$

TE$_0$, $N = 1.8919$, $\Pi > 0.99$ TM$_0$, $N = 1.7337$, $\Pi < 0.01$



X-cut, $SiO_2 : LN : air$, $d = 0.45$ µm, $\theta = 45°$

- Plane waves, "phase" of profiles is constant along x.
- X-cut $\theta = 0, \pm\pi/2, \pi$, Z-cut: strict TE and TM modes.
- $\{N, \boldsymbol{E}, \boldsymbol{H}\}(\theta) \longleftrightarrow \{N, \boldsymbol{E}, \boldsymbol{H}\}(\theta \pm \pi)$.
- $\{N, \boldsymbol{E}, \boldsymbol{H}\}(\theta) \longleftrightarrow \{N, \pm E_j, \pm H_j\}(-\theta)$.

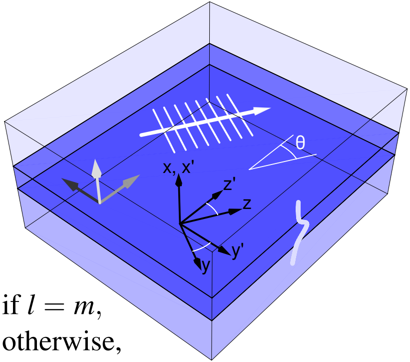


- Limits at large core thickness:

$$N \xrightarrow[d\to\infty]{} \sqrt{\epsilon_y - \delta^2/\epsilon_z} \quad \text{(TE)},$$

$$N \xrightarrow[d\to\infty]{} \sqrt{\epsilon_x} \quad \text{(TM)}.$$

	X-cut, $\theta = 0, \pi$	X-cut, $\theta = \pm\pi/2$	Z-cut
TE	n_e	n_o	n_o
TM	n_o	n_o	n_e



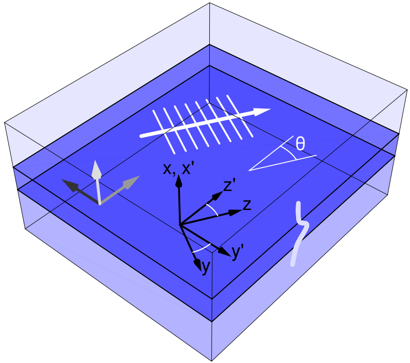
- Power orthogonality, normalization:

A set of modes $\{N_m, \boldsymbol{E}_m, \boldsymbol{H}_m\}$
supported by the same waveguide $(\lambda, d, \theta, \ldots)$:

$$(\boldsymbol{E}_l, \boldsymbol{H}_l; \boldsymbol{E}_m, \boldsymbol{H}_m) = \delta_{lm} P_m, \quad \text{where} \quad \delta_{lm} = \begin{cases} 1, & \text{if } l = m, \\ 0, & \text{otherwise,} \end{cases}$$

$$P_m = \frac{1}{2} \operatorname{Re} \int (\boldsymbol{E}_m^* \times \boldsymbol{H}_m)_z \, \mathrm{d}x = \frac{1}{4} \int (E_{mx}^* H_{my} - E_{my}^* H_{mx} + E_{mx} H_{my}^* - E_{my} H_{mx}^*) \, \mathrm{d}x,$$

$$(\boldsymbol{E}_1, \boldsymbol{H}_1; \boldsymbol{E}_2, \boldsymbol{H}_2) = \frac{1}{4} \int (E_{1x}^* H_{2y} - E_{1y}^* H_{2x} + E_{2x} H_{1y}^* - E_{2y} H_{1x}^*) \, \mathrm{d}x.$$

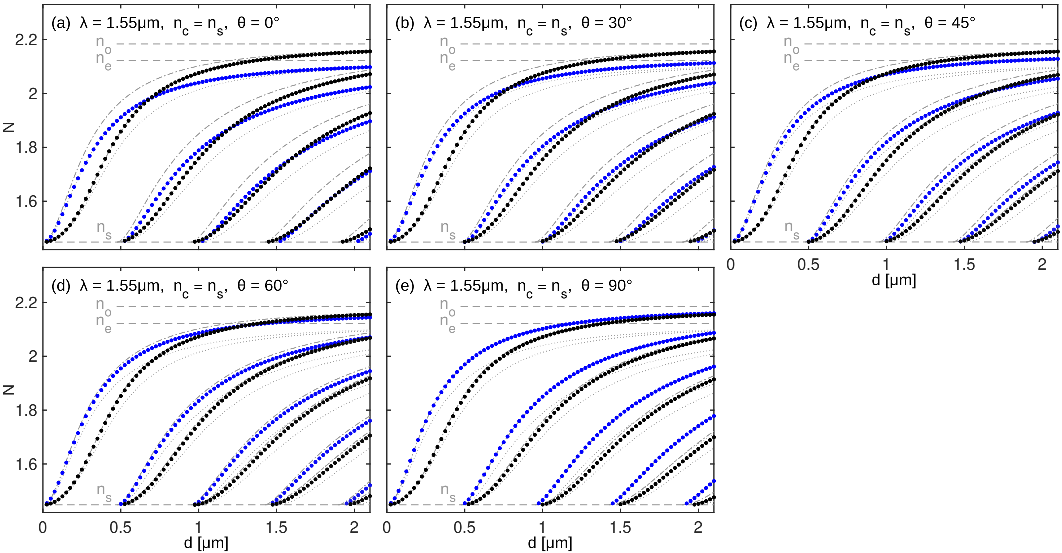


- Polarization ratio
  for a mode with profile $\boldsymbol{E}, \boldsymbol{H}$:

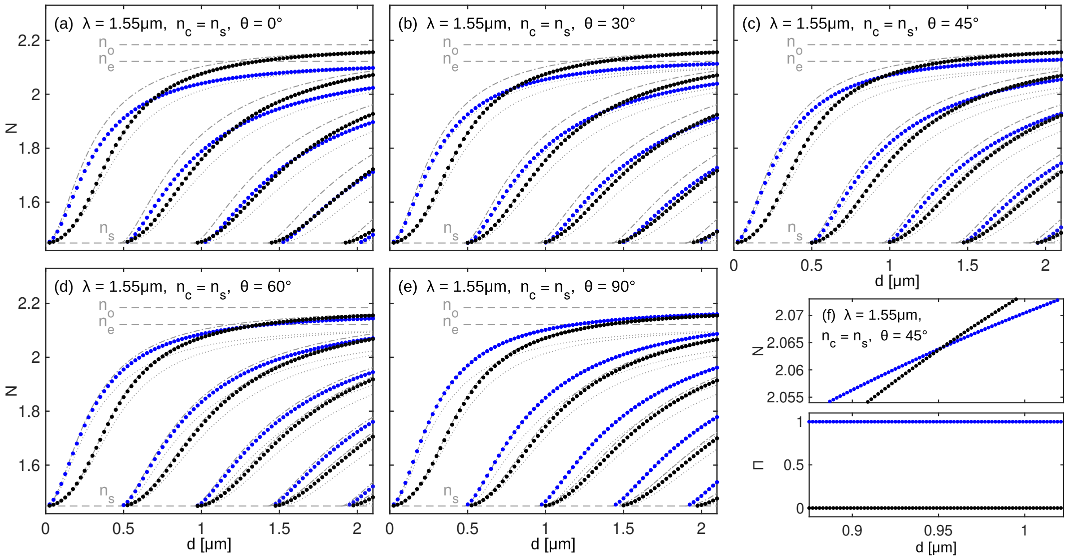
$$\Pi = \frac{-\mathrm{Re} \int E_y^* H_x \, \mathrm{d}x}{\mathrm{Re} \int \left(E_x^* H_y - E_y^* H_x \right) \, \mathrm{d}x},$$

"pure TM": $\Pi = 0$ (black), intermediate: (gray), "pure TE": $\Pi = 1$ (blue).

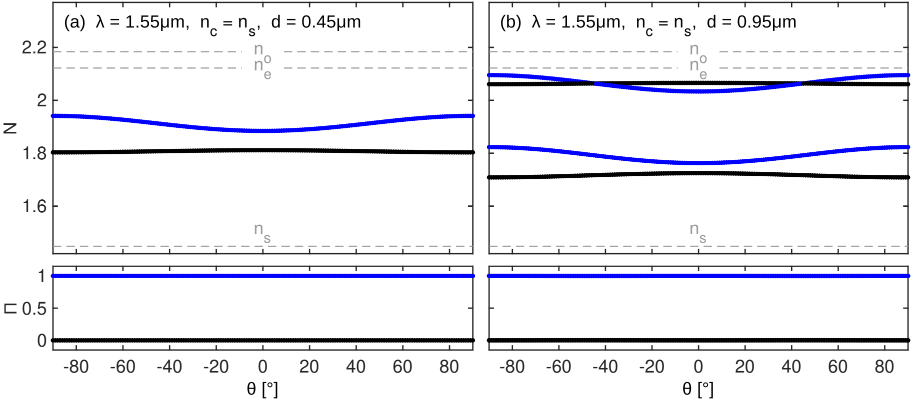
X-cut, thickness variation $(SiO_2 : LN : SiO_2)$



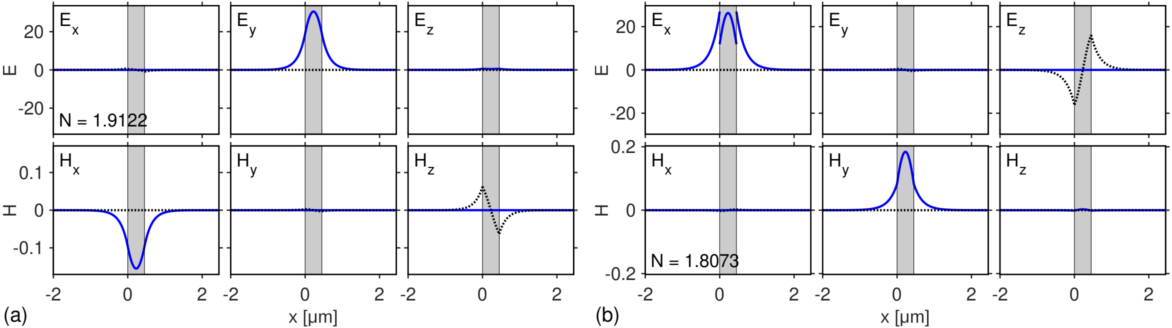
X-cut, thickness variation $(SiO_2 : LN : SiO_2)$



X-cut, angle variation *($SiO_2 : LN : SiO_2$)*

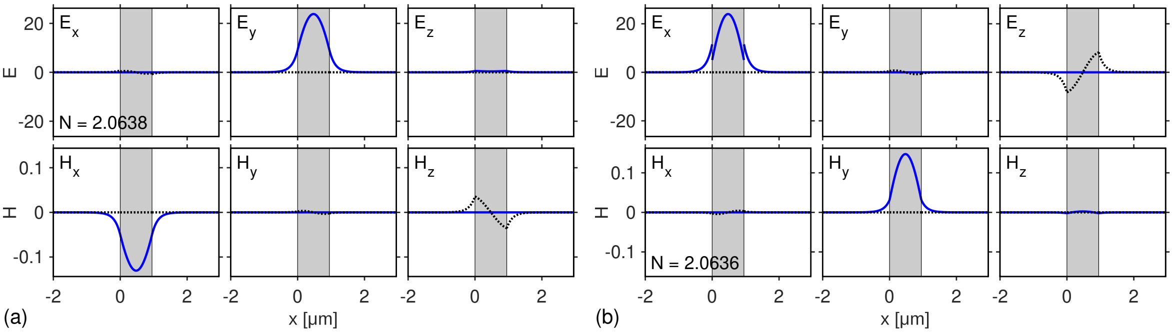


TE$_0$, $N = 1.9122$, $\Pi > 0.99$ TM$_0$, $N = 1.8073$, $\Pi < 0.01$



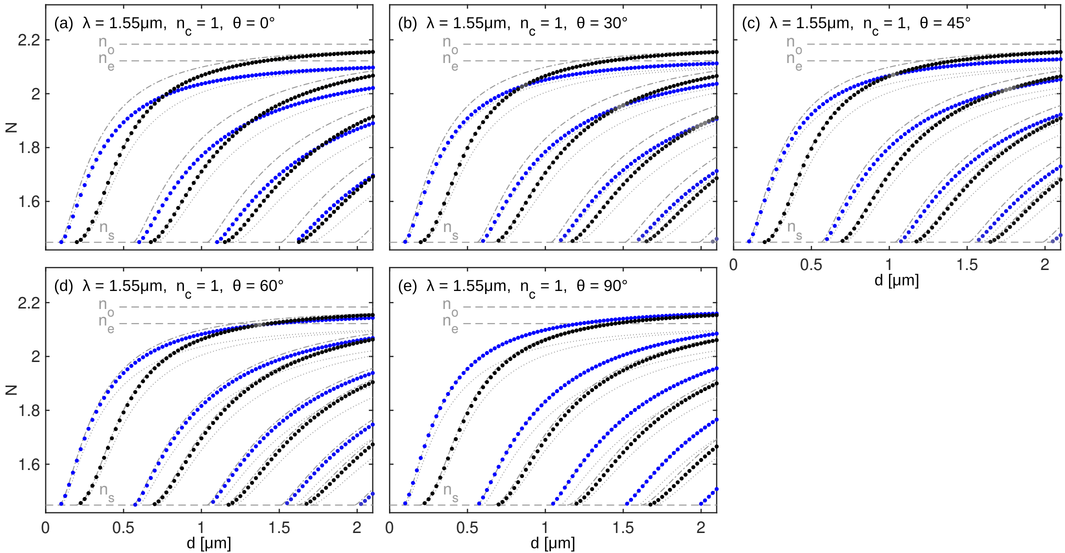
X-cut, $SiO_2 : LN : SiO_2$, $d = 0.45$ µm, $\theta = 45°$

$\mathrm{TE}_0,\ N = 2.0638,\ \Pi > 0.99$ $\mathrm{TM}_0,\ N = 2.0636,\ \Pi < 0.01$

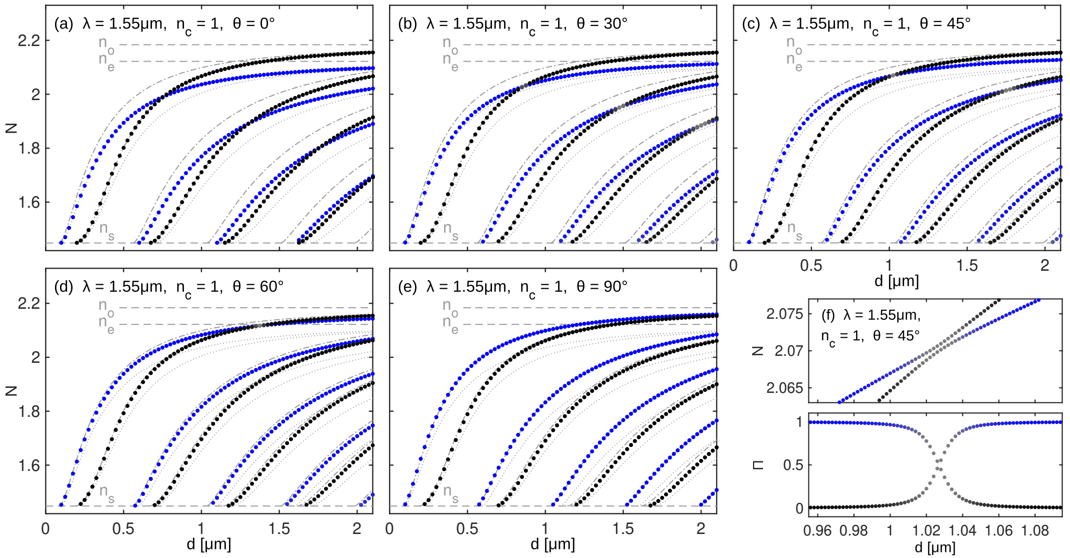


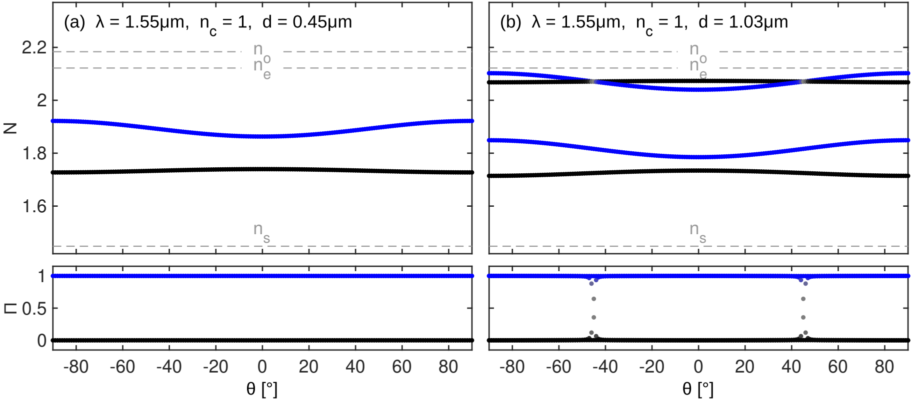
X-cut, $\mathrm{SiO_2 : LN : SiO_2}$, $d = 0.95\ \mu\mathrm{m}$, $\theta = 45^\circ$

X-cut, thickness variation *(SiO_2 : LN : air)*

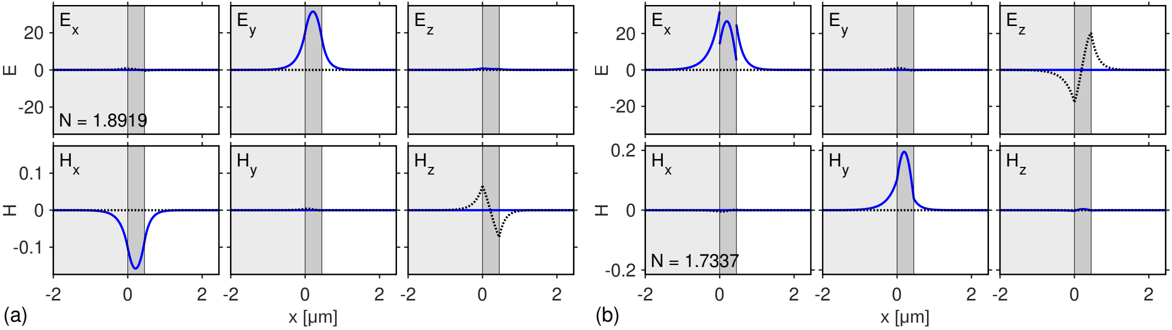


X-cut, thickness variation (SiO$_2$: LN : air)



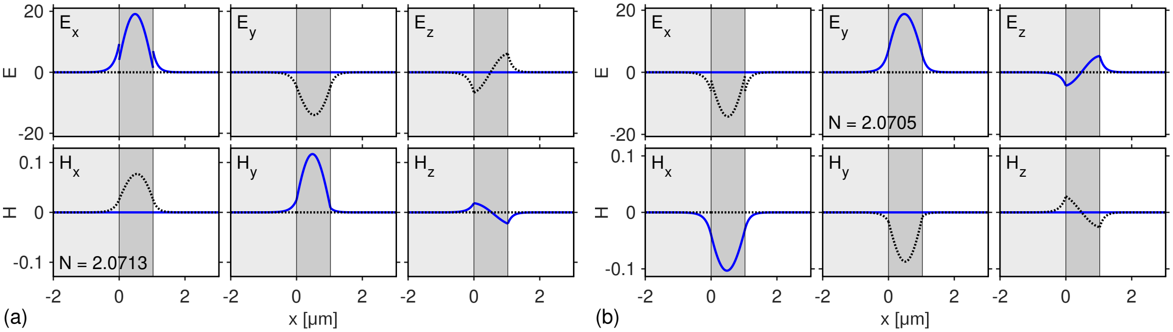

(a) λ = 1.55μm, n_c = 1, d = 0.45μm
(b) λ = 1.55μm, n_c = 1, d = 1.03μm
n_o
n_e
n_s
N
Π
θ [°]
2.2
2
1.8
1.6
1
0.5
0
-80
-60
-40
-20
0
20
40
60
80

TE_0, $N = 1.8919$, $\Pi > 0.99$ TM_0, $N = 1.7337$, $\Pi < 0.01$



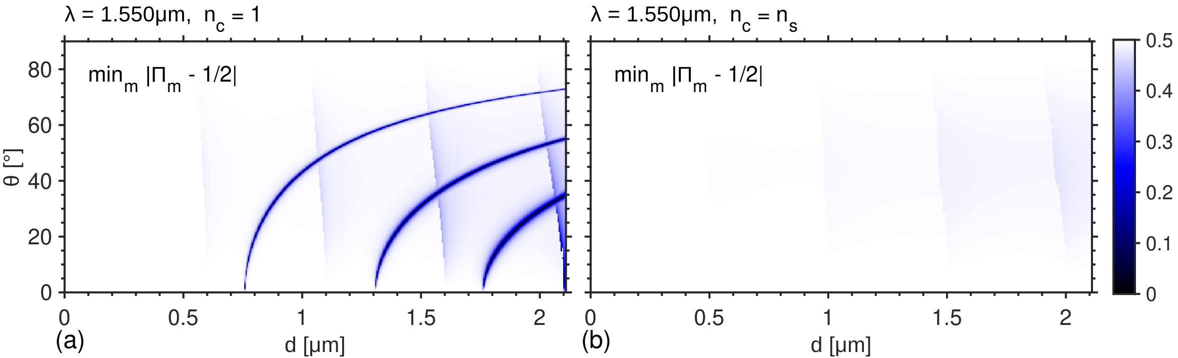
X-cut, $SiO_2 : LN : air$, $d = 0.45$ µm, $\theta = 45°$

TM_0, $N = 2.0713$, $\Pi = 0.36$ TE_0, $N = 2.0705$, $\Pi = 0.64$

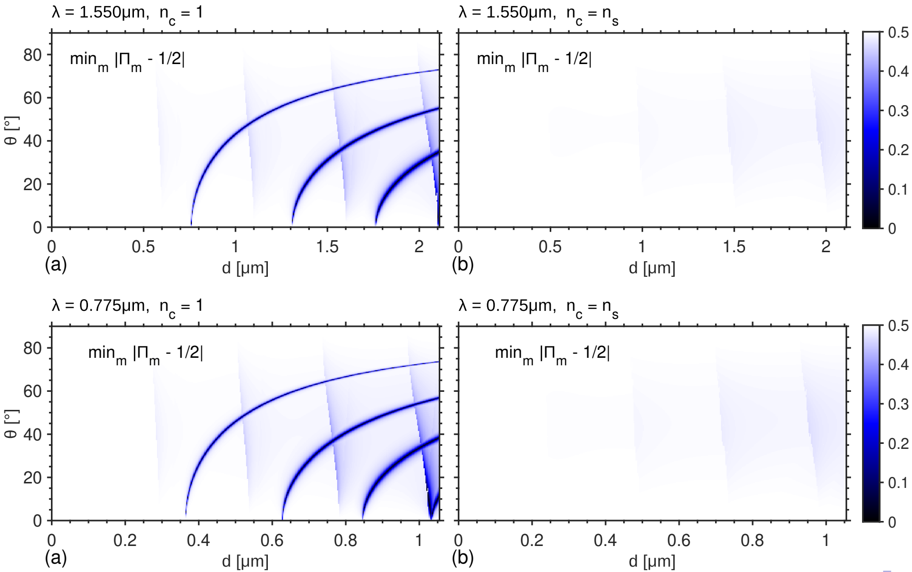


X-cut, $SiO_2 : LN : air$, $d = 1.03$ µm, $\theta = 45°$

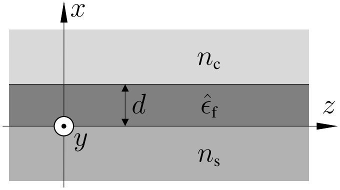
X-cut slabs, hybridization

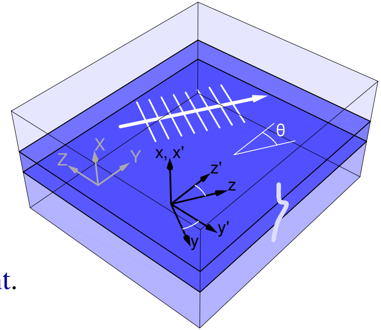


X-cut slabs, hybridization



X-cut slabs, with and without cover

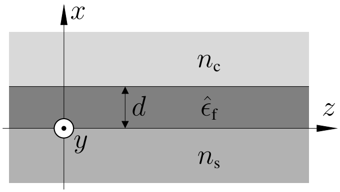


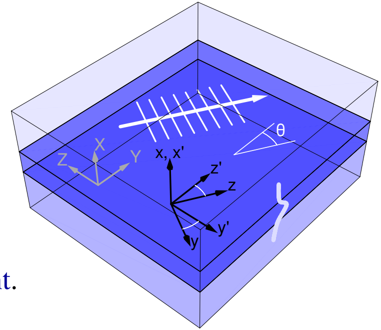


X-cut slabs, oblique propagation, near degeneracies,
SiO_2:LN:air: strong hybridization, SiO_2:LN:SiO_2: absent.

- Result of the theory as discussed.

X-cut slabs, with and without cover

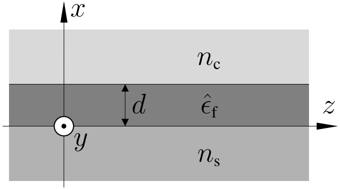


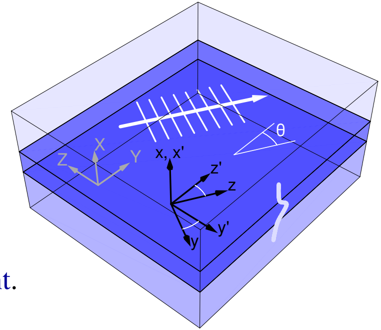


X-cut slabs, oblique propagation, near degeneracies,
SiO_2:LN:air: strong hybridization, SiO_2:LN:SiO_2: absent.

- Result of the theory as discussed.
- Symmetry, $x = d/2$:
  TE_0 and TM_0 modes in the SiO_2:LN:SiO_2-stack belong to different parity classes.

X-cut slabs, with and without cover

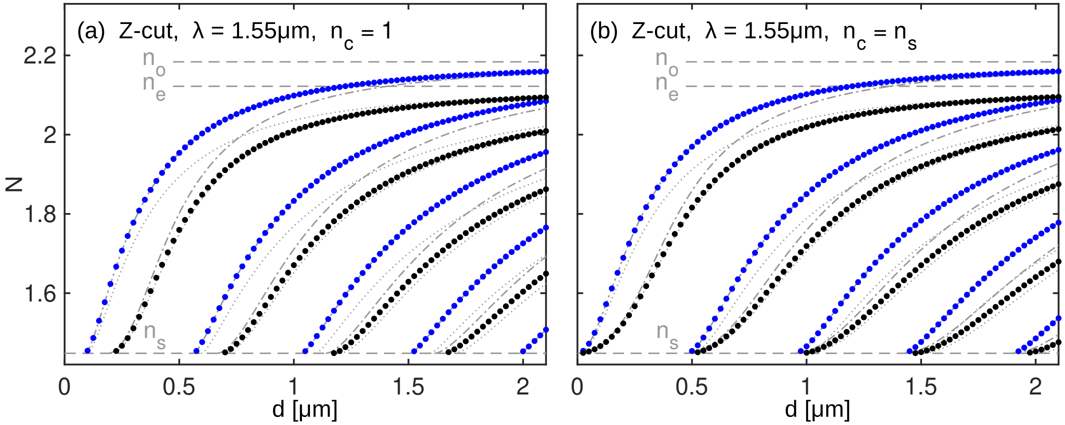




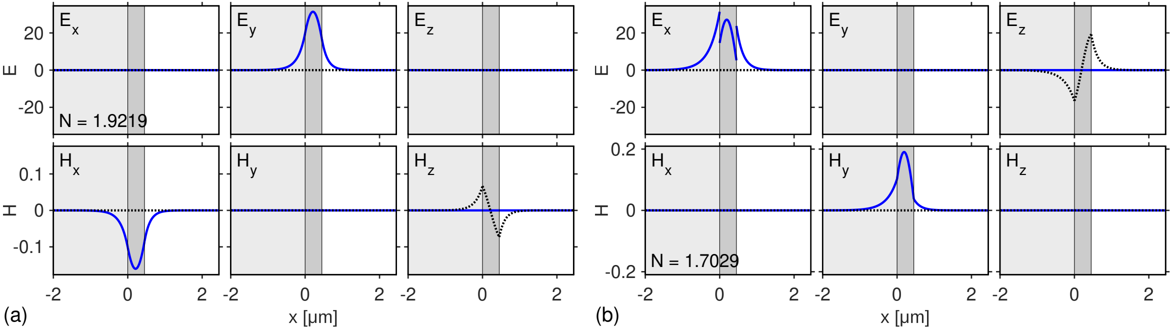
X-cut slabs, oblique propagation, near degeneracies,
SiO_2:LN:air: strong hybridization, SiO_2:LN:SiO_2: absent.

- Result of the theory as discussed.
- Symmetry, $x = d/2$:
  TE_0 and TM_0 modes in the SiO_2:LN:SiO_2-stack belong to different parity classes.
- Coupled mode theory, based on approximate TE and TM modes and perturbation δ :
  Integrals $\sim \int (E^*_{1y}\, \delta\, E_{2z})\, \mathrm{d}x$ cancel due to the symmetry of the components.

Z-cut, thickness variation

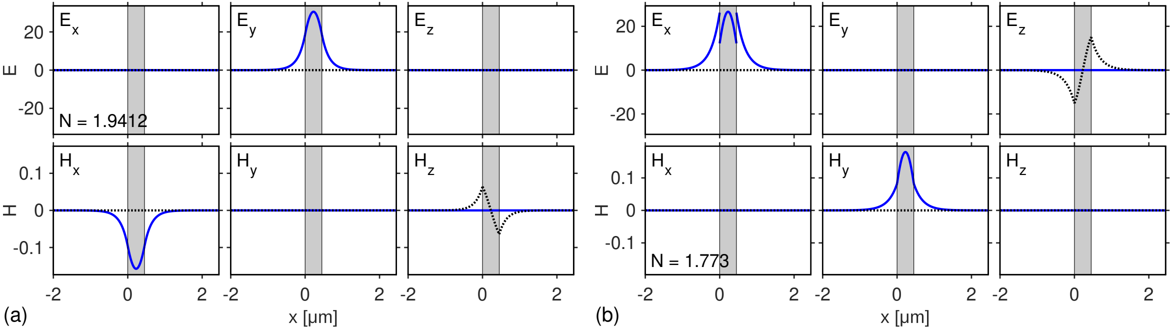


$\mathrm{TE}_0,\ N = 1.9219$ $\mathrm{TM}_0,\ N = 1.7029$



Z-cut, $\mathrm{SiO_2 : LN : air},\ d = 0.45\ \mu\mathrm{m}$

$TE_0, \; N = 1.9412$ $TM_0, \; N = 1.7730$



Z-cut, $SiO_2 : LN : SiO_2$, $d = 0.45$ µm

Concluding remarks

Thin-film lithium niobate slab waveguides

- Quasi-analytical solutions for guided modes: As shown.
- Simulations require precise data for $\hat{\epsilon}$, n_{o}, n_{e}, at the target wavelength.
- X-cut, oblique propagation: Hybridization for nearly degenerate modes.
- The cover matters.
- Transfer of findings to channel waveguides ...

https://www.siio.eu/tflns.html

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