Thin-film lithium niobate slab waveguides

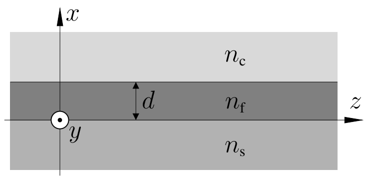
Manfred Hammer*, Henna Farheen, Jens Förstner

Paderborn University
Theoretical Electrical Engineering
Paderborn, Germany

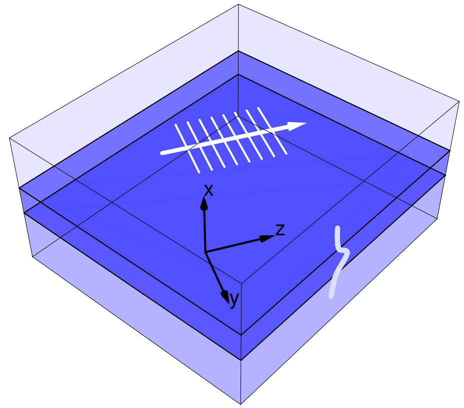
PhoQS Future Meeting, Paderborn University, 07.03.2024

** Paderborn University, Theoretical Electrical Engineering*
Warburger Straße 100, 33098 Paderborn, Germany
Phone: +49(0)5251/60-3560
E-mail: manfred.hammer@uni-paderborn.de

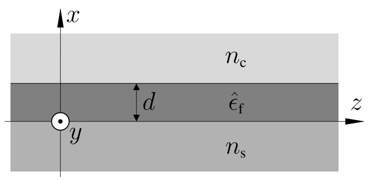
Dielectric slab waveguide



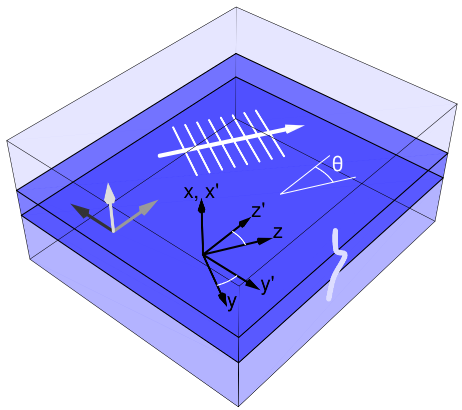
$n_f > n_s, n_c$



Dielectric slab waveguide, anisotropic core



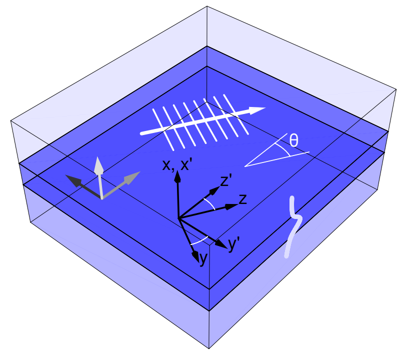
$\hat{\epsilon}_f(\theta)$



Thin-film lithium niobate slab waveguides

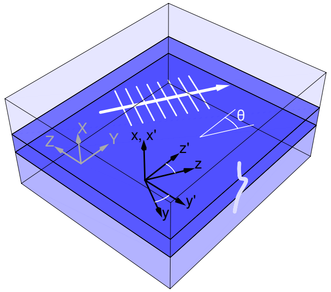
Overview

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

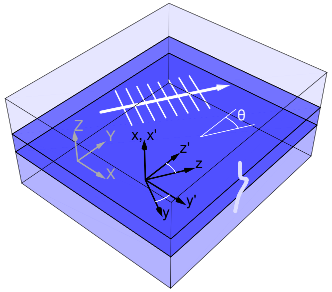


TFLN configurations

X-cut



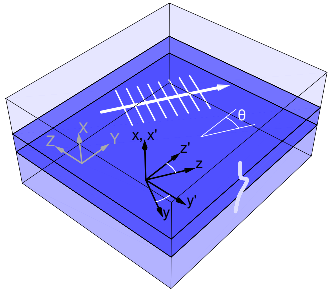
Z-cut



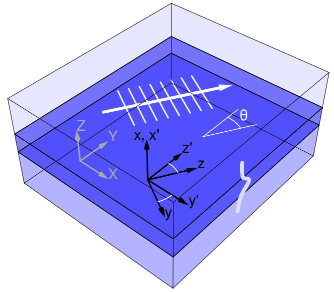
Crystal coordinates $\{X, Y, Z\}$, sample coordinates $\{x', y', z'\}$, wave coordinates $\{x, y, z\}$.

TFLN configurations

X-cut



Z-cut

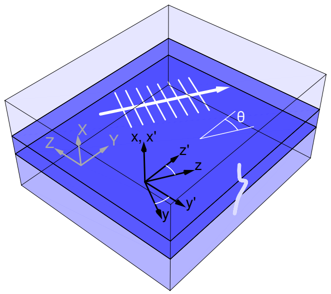


(sample coordinates $\{x', y', z'\}$)

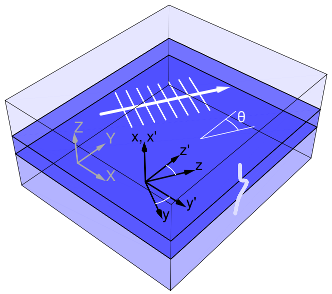
$$\hat{\epsilon}^{\mathrm{x}}_{\mathrm{f},0} = \begin{pmatrix} n_{\mathrm{o}}^2 & 0 & 0 \\ 0 & n_{\mathrm{e}}^2 & 0 \\ 0 & 0 & n_{\mathrm{o}}^2 \end{pmatrix} \qquad \hat{\epsilon}^{\mathrm{z}}_{\mathrm{f},0} = \begin{pmatrix} n_{\mathrm{e}}^2 & 0 & 0 \\ 0 & n_{\mathrm{o}}^2 & 0 \\ 0 & 0 & n_{\mathrm{o}}^2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

TFLN configurations

X-cut



Z-cut

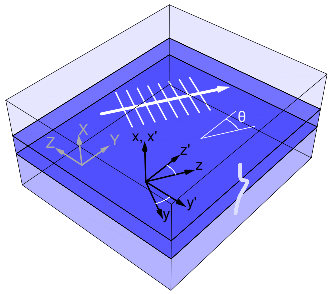


(sample coordinates ′ $\rightarrow$ wave coordinates)

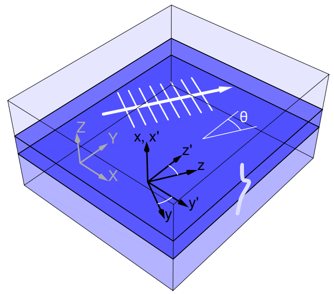
$$\boldsymbol{v} = \mathsf{R}\boldsymbol{v}', \qquad \hat{\epsilon}_{\mathrm{f}} = \mathsf{R}\hat{\epsilon}_{\mathrm{f},0}\mathsf{R}^{\mathsf{T}}, \qquad \mathsf{R} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & -\sin\theta \\ 0 & \sin\theta & \cos\theta \end{pmatrix}.$$

TFLN configurations

X-cut



Z-cut

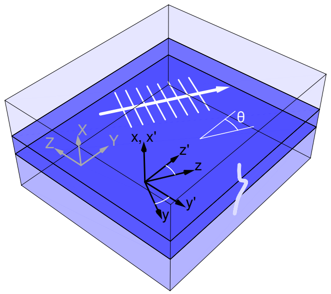


(wave coordinates $\{x, y, z\}(\theta)$)

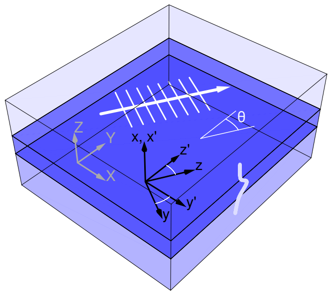
$$\hat{\epsilon}^{\mathrm{x}}_{\mathrm{f}} = \begin{pmatrix} n_{\mathrm{o}}^2 & 0 & 0 \\ 0 & n_{\mathrm{e}}^2\cos^2\theta + n_{\mathrm{o}}^2\sin^2\theta & (n_{\mathrm{e}}^2 - n_{\mathrm{o}}^2)\cos\theta\sin\theta \\ 0 & (n_{\mathrm{e}}^2 - n_{\mathrm{o}}^2)\cos\theta\sin\theta & n_{\mathrm{e}}^2\sin^2\theta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

TFLN configurations

X-cut



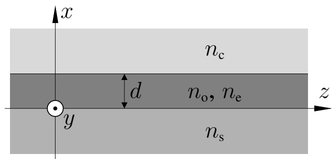
Z-cut



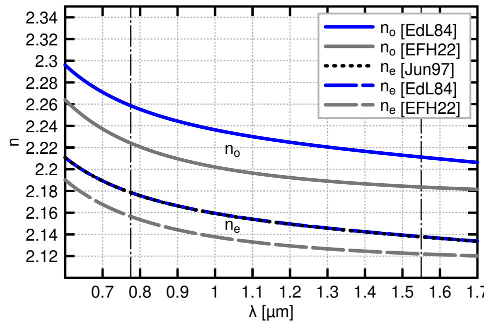
(wave coordinates $\{x, y, z\}(\theta)$)

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

TFLN slabs, material parameters



$\lambda/\,\mu$m	$n_{\rm s}$	$n_{\rm c}$	$n_{\rm o}$	$n_{\rm e}$
1.550	1.4483	1.0 | $n_{\rm s}$	2.1837	2.1220
0.775	1.4589	1.0 | $n_{\rm s}$	2.2242	2.1565

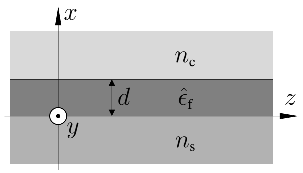


[EdL84] G. J. Edwards, M. Lawrence, *Optical and Quantum Electronics* **16**:373–375, 1984.

[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.

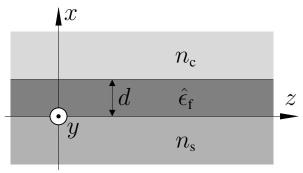
TFLN slabs, modal analysis



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

	ϵ_x	ϵ_y	ϵ_z	δ
(X-cut)	$n_{\rm o}^2$	$n_{\rm e}^2\cos^2\theta + n_{\rm o}^2\sin^2\theta$	$n_{\rm e}^2\sin^2\theta + n_{\rm o}^2\cos^2\theta$	$(n_{\rm e}^2 - n_{\rm o}^2)\cos\theta\sin\theta$
(Z-cut)	$n_{\rm e}^2$	$n_{\rm o}^2$	$n_{\rm o}^2$	0

TFLN slabs, modal analysis

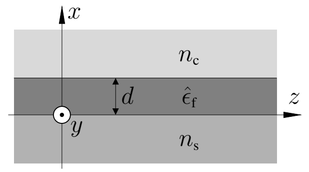


$$\hat{\epsilon}(x) = \begin{cases} n_{\rm c}^2\,\mathbb{1}_3, & \text{if } d < x, \\ \hat{\epsilon}_{\rm f}, & \text{for } 0 < x < d, \\ n_{\rm s}^2\,\mathbb{1}_3, & \text{if } x < 0. \end{cases}$$

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

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

TFLN slabs, modal analysis



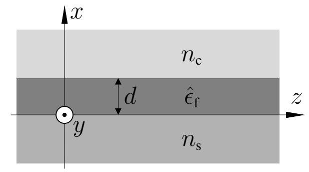
$$\hat{\epsilon}(x) = \begin{cases} n_c^2\,\mathbb{1}_3, & \text{if } d < x, \\ \hat{\epsilon}_f, & \text{for } 0 < x < d, \\ n_s^2\,\mathbb{1}_3, & \text{if } x < 0. \end{cases}$$

(core, $0 < x < d$)

↪

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

TFLN slabs, modal analysis



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

(core, $0 < x < d$)

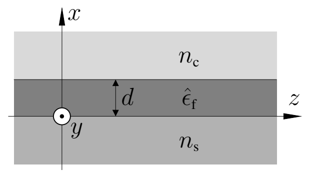
Principal functions $e(x) = \sqrt{\epsilon_0}\,E_y(x), \quad h(x) = \sqrt{\mu_0}\,H_y(x),$

↪

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

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

TFLN slabs, modal analysis



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

(core, $0 < x < d$)

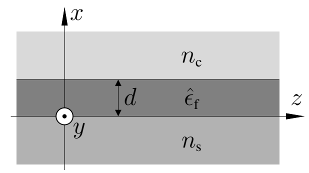
Principal functions $e(x) = \sqrt{\epsilon_0}\,E_y(x), \quad h(x) = \sqrt{\mu_0}\,H_y(x),$

↪

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

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

TFLN slabs, modal analysis



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

(core, $0 < x < d$)

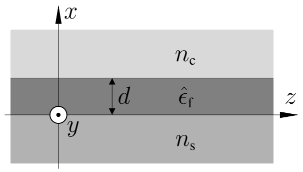
Principal functions $\boldsymbol{p}(x) = \begin{pmatrix} e \\ h \end{pmatrix}(x)$

↪

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

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

TFLN slabs, modal analysis



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

(core, $0 < x < d$)

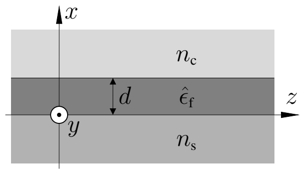
Local solutions, ansatz: $\boldsymbol{p}(x) = \boldsymbol{q}\exp(-\mathrm{i}\kappa x)$

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

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

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

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, $x < 0$)

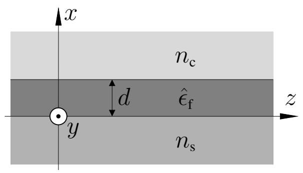
Principal functions $e(x) = \sqrt{\epsilon_0}\,E_y(x)$, $h(x) = \sqrt{\mu_0}\,H_y(x)$,

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

Require normalizable solutions

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

TFLN slabs, modal analysis



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

(cover, $d < x$)

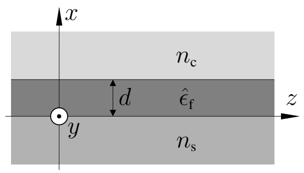
Principal functions $e(x) = \sqrt{\epsilon_0}\,E_y(x)$, $h(x) = \sqrt{\mu_0}\,H_y(x)$,

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

Require normalizable solutions

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

TFLN slabs, modal analysis

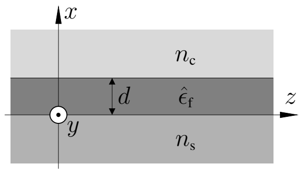


$$\hat\epsilon(x) = \begin{cases} n_c^2\,\mathbb{1}_3, & \text{if } d < x, \\ \hat\epsilon_f, & \text{for } 0 < x < d, \\ n_s^2\,\mathbb{1}_3, & \text{if } x < 0. \end{cases}$$

Mode profile, ansatz: ($A_e^c, A_h^c, A_1^f, A_2^f, A_3^f, A_4^f, A_e^s, A_h^s$: unknowns $\boldsymbol{A}$)

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

TFLN slabs, modal analysis



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

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

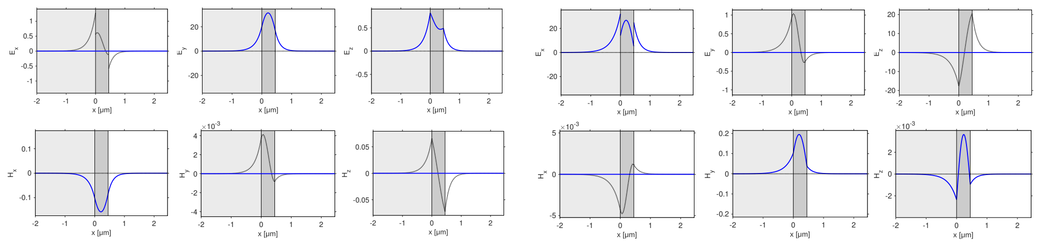
$E_y,\ E_z,\ H_y,\ H_z,\ \epsilon_0(\hat{\epsilon}\boldsymbol{E})_x,\ \mu_0 H_x$ or $e,\ h,\ \partial_x e,\ \frac{1}{\epsilon_z}(\partial_x h - \mathrm{i}k\delta e)$.

↪ $\mathsf{M}(\beta)\boldsymbol{A} = 0.$ (8×8)

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

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

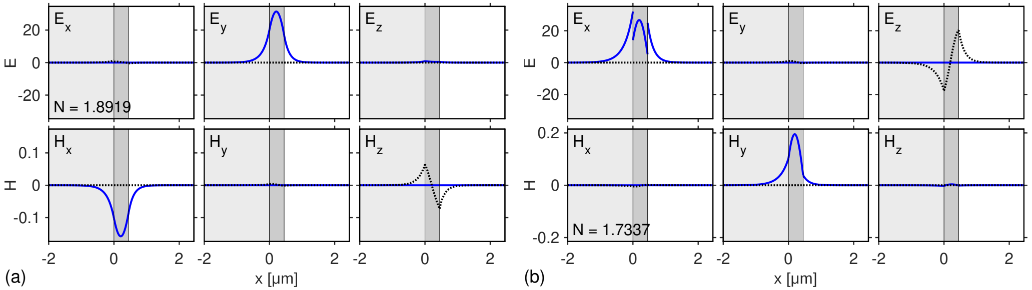
TE_0, $N = 1.8919$, $\Pi > 0.99$ TM_0, $N = 1.7337$, $\Pi < 0.01$



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

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

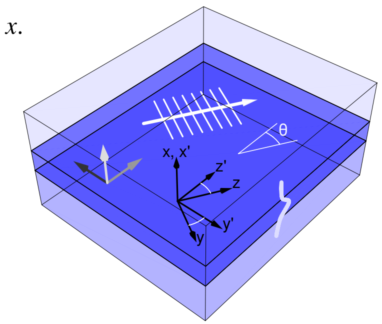
TE_0, $N = 1.8919$, $\Pi > 0.99$ TM_0, $N = 1.7337$, $\Pi < 0.01$



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

TFLN slab modes, general properties

- 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:

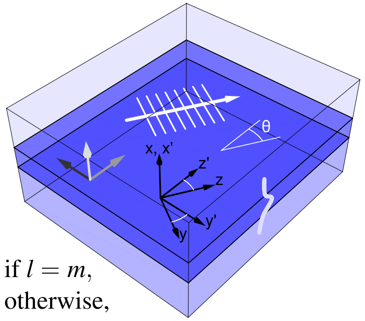


$$N \xrightarrow[d\to\infty]{} \sqrt{\epsilon_y - \delta^2/\epsilon_z} \quad \text{(TE)},$$

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

	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

TFLN slab modes, general properties



- Power orthogonality, normalization:

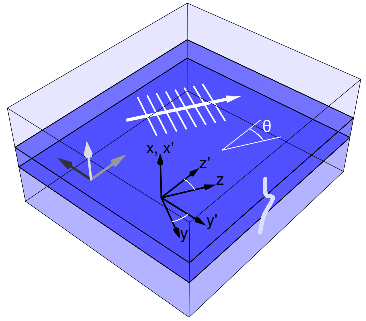
A set of modes $\{N_m, \boldsymbol{E}_m, \boldsymbol{H}_m\}$
supported by the same waveguide $(\lambda, d, \theta, \ldots)$:

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

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

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

TFLN slab modes, general properties

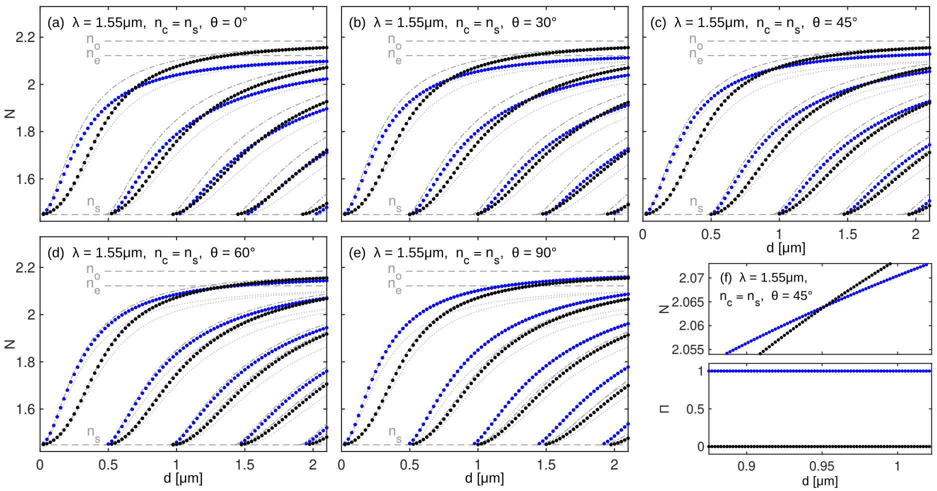


- Polarization ratio
for a mode with profile $\boldsymbol{E}, \boldsymbol{H}$:

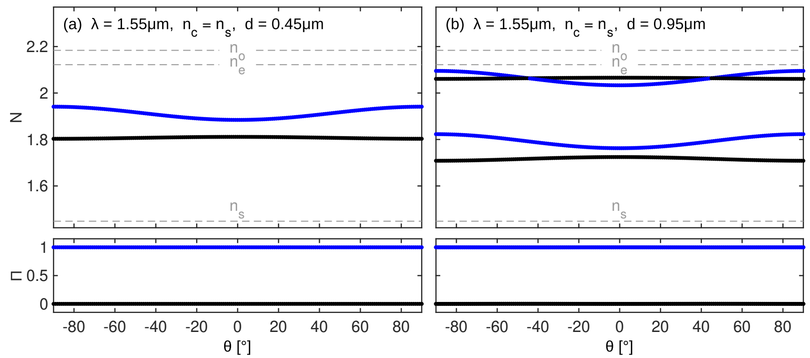
$$\varPi = \frac{-\mathrm{Re}\int E_y^* H_x \,\mathrm{d}x}{\mathrm{Re}\int \left(E_x^* H_y - E_y^* H_x\right)\,\mathrm{d}x},$$

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

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

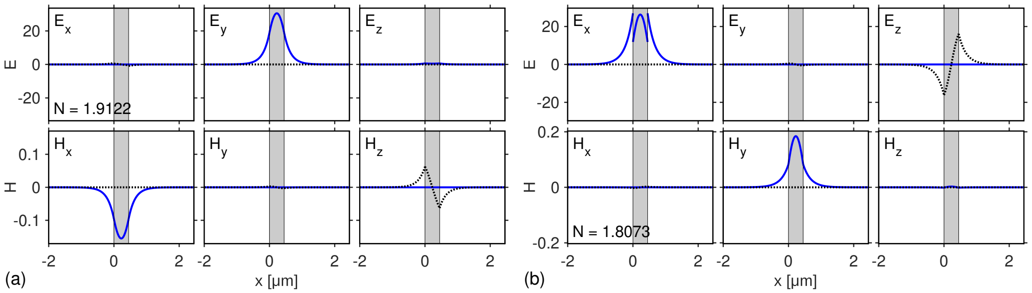


X-cut, angle variation *(SiO_2 : LN : SiO_2)*



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

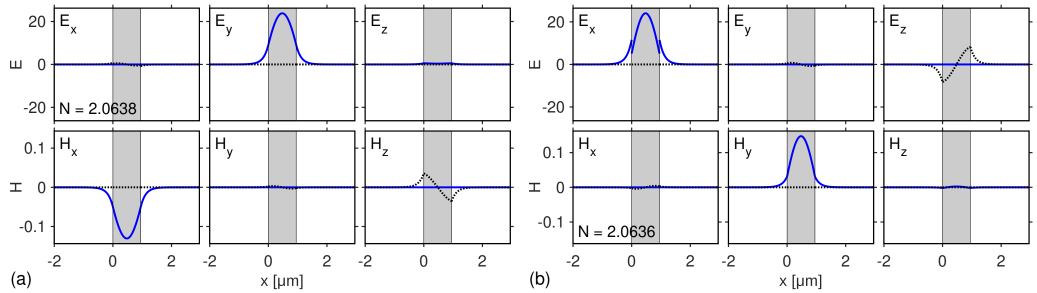
TE_0, $N = 1.9122$, $\Pi > 0.99$ TM_0, $N = 1.8073$, $\Pi < 0.01$



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

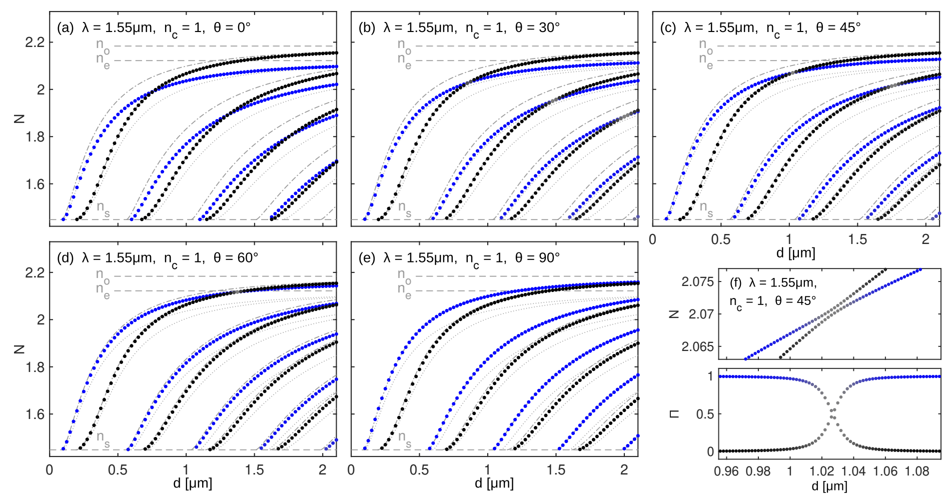
Mode profiles *(X-cut, symmetric, near-degenerate)*

TE_0, $N = 2.0638$, $\Pi > 0.99$ TM_0, $N = 2.0636$, $\Pi < 0.01$

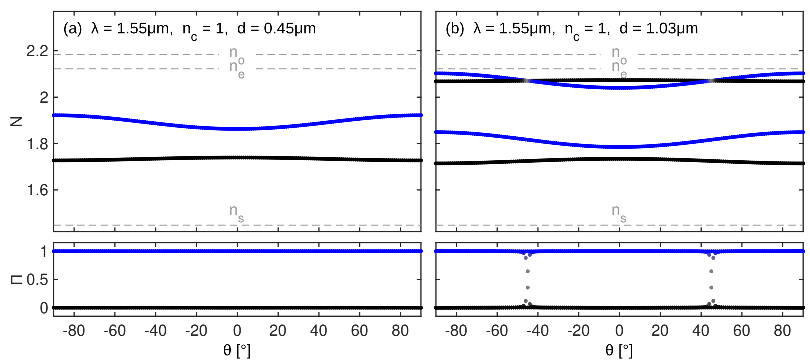


X-cut, $SiO_2 : LN : SiO_2$, $d = 0.95$ µm, $\theta = 45°$

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

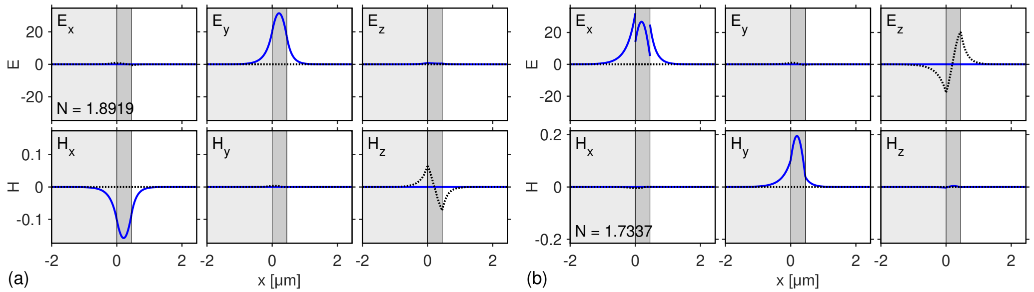


X-cut, angle variation *(SiO_2 : LN : air)*



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

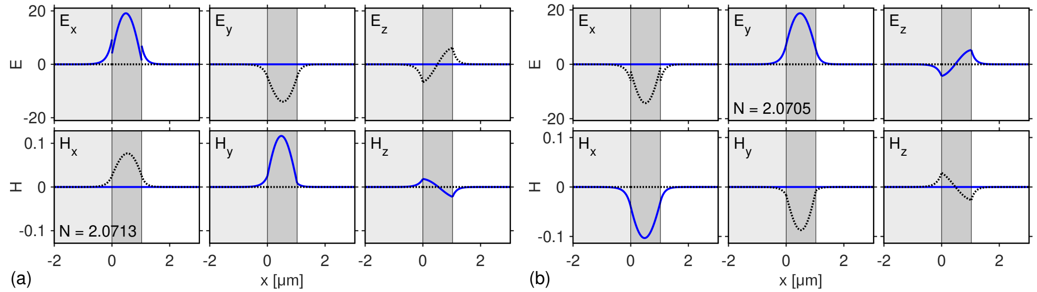
TE$_0$, $N = 1.8919$, $\Pi > 0.99$ TM$_0$, $N = 1.7337$, $\Pi < 0.01$



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

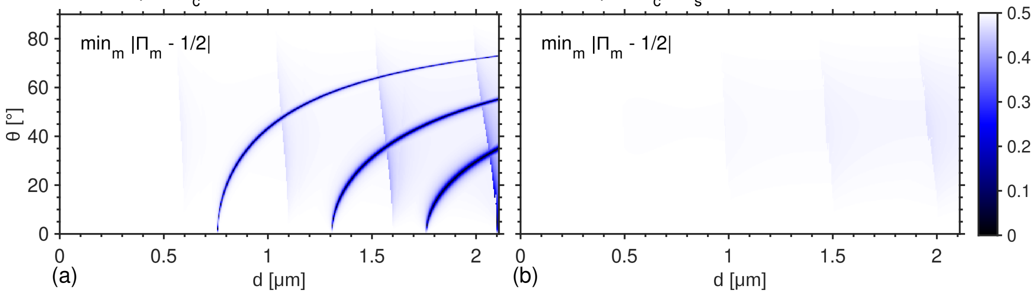
Mode profiles *(X-cut, nonsymmetric, near-degenerate)*

TM$_0$, $N = 2.0713$, $\Pi = 0.36$ TE$_0$, $N = 2.0705$, $\Pi = 0.64$

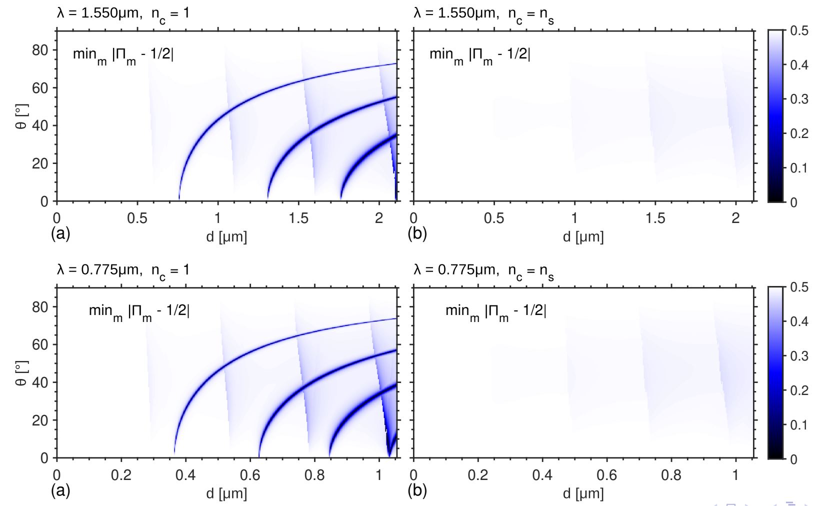


X-cut, $SiO_2 : LN : air$, $d = 1.03$ µm, $\theta = 45°$

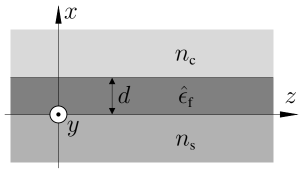
X-cut slabs, hybridization

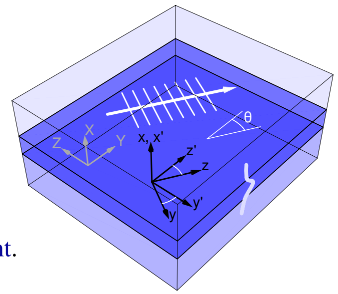


X-cut slabs, hybridization



X-cut slabs, with and without cover

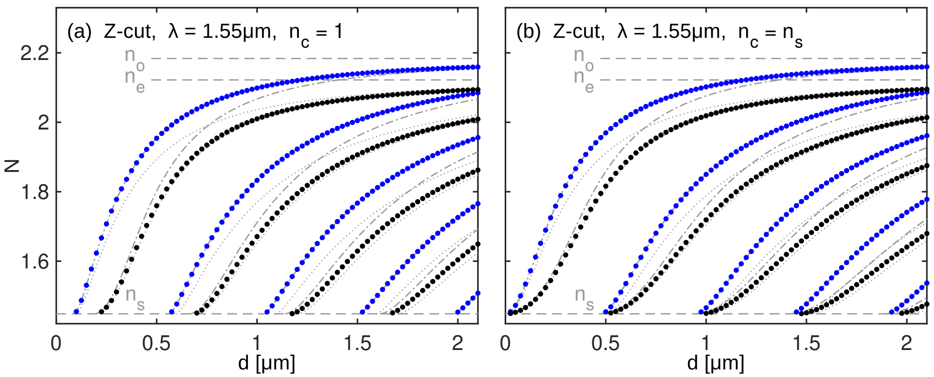




X-cut slabs, oblique propagation, near degeneracies,
SiO_2:LN:air: strong hybridization, SiO_2:LN:SiO_2: absent.

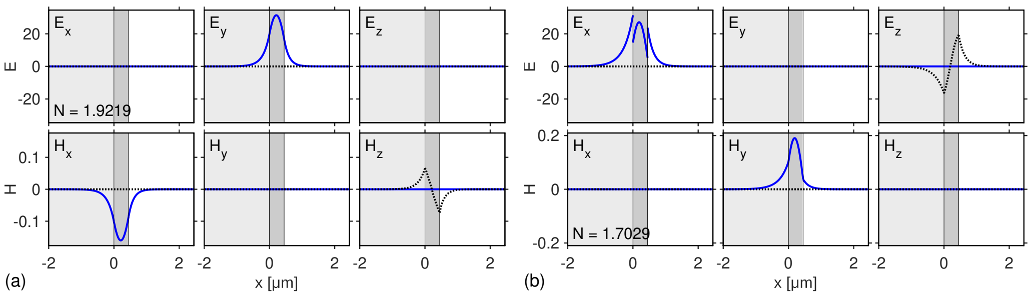
- Result of the theory as discussed.
- Symmetry, $x = d/2$:
  TE_0 and TM_0 modes in the SiO_2:LN:SiO_2-stack belong to different parity classes.
- Coupled mode theory, based on approximate TE and TM modes and perturbation δ:
  Integrals $\sim \int (E_{1y}^* \, \delta \, E_{2z}) \, \mathrm{d}x$ cancel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

Z-cut, thickness variation



Mode profiles *(Z-cut, nonsymmetric)*

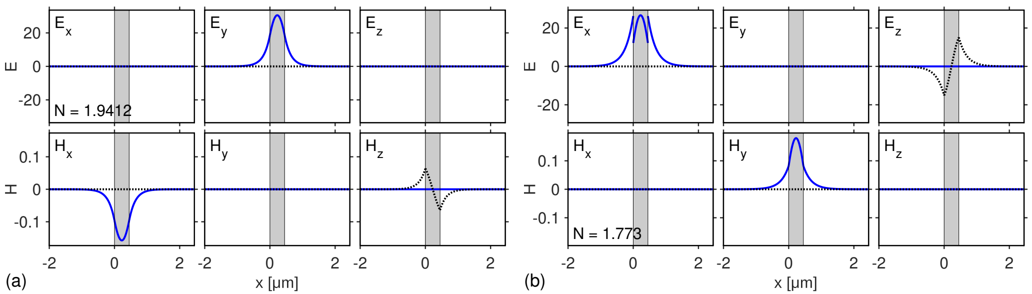
TE_0, $N = 1.9219$ TM_0, $N = 1.7029$



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

Mode profiles *(Z-cut, symmetric)*

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

Funding: Ministry of Culture and Science of the State of North Rhine-Westphalia, project *Photonic Quantum Computing* (PhoQC), Paderborn University.

Ministry of Culture and Science of the State of North Rhine-Westphalia