Leakage suppression for TM modes in optical waveguides with shallow etching

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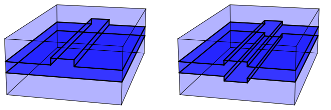
1 Rib and plus waveguides

Dielectric optical rib waveguides are among the most popular types of channels in integrated photonic circuits. While generally these waveguides support a guided fundamental TE mode, the lowest order TM mode is affected by lateral leakage, if the etching depth is below a certain limit [1–5]. Exceptions are singular, rather critical "magical widths" [6], at which also guided TM modes exist. This feature can be of advantage in certain contexts. In other situations, however, one might wish to reliably operate waveguides with shallow etching for guided light of both polarizations. Examples could be found in the field of quantum photonics [7,8], where low losses are of the utmost importance for the processing of (single, entangled) photons associated with orthogonal polarization states.

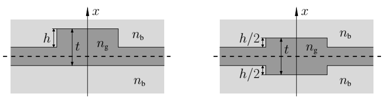
As a way out, in this contribution we discuss a slightly modified waveguide geometry, where a downwards and an upwards protruding rib, each of half the former etching depth, together with the lateral film, form a waveguide core with a "plus" shaped cross section [9]. It turns out that the plus structure supports strictly guided TM modes for *any* core width, regardless of the etching depth.



The effect can be explained in terms of local slab modes. Vertical symmetry of the overall waveguide with respect to the central horizontal plane is required. Symmetry properties then prohibit a coupling between TM slab modes in the central rib segment and outwards propagating TE slab modes in the lateral segments. The TM mode of the channel becomes symmetry protected [10]. We illustrate the properties of the plus waveguides by a series of numerical examples (Comsol [11], JCMwave [12]), and evaluate tolerances regarding typical fabrication errors.

2 Waveguides with shallow etching

- Channels with equal substrate and cover refractive indices:

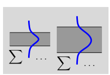


- Frequency domain description: time variation $\sim \exp(\mathrm{i}\omega t)$, $\omega = k\mathrm{c} = 2\pi\mathrm{c}/\lambda$.
- Potentially leaky modes, propagation along z, optical electromagnetic fields

$$\begin{pmatrix}\boldsymbol{\mathcal{E}}\\ \boldsymbol{\mathcal{H}}\end{pmatrix}(x,y,z) = \begin{pmatrix}\boldsymbol{E}\\ \boldsymbol{H}\end{pmatrix}(x,y)\ \mathrm{e}^{-\mathrm{i}(\beta - \mathrm{i}\alpha)z},$$

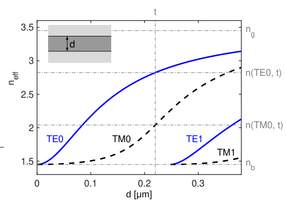
  phase constant $\beta = kN_{\mathrm{eff}}$, effective index N_{eff}, attenuation constant α.
- Power decay $\sim\exp(-2\alpha z)$, power loss $\mathrm{LO}/z = 20\,\alpha/\ln(10)$ [dB/distance].
- Parameters, Si photonics: $\lambda = 1.55\,\mu$m, $n_g = 3.45$, $n_b = 1.45$, $t = 220\,$nm.

- Piecewise expansion into local TE & TM slab eigenmodes:



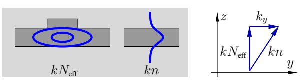
$n(\mathrm{TE0}, t) = 2.823$,
$n(\mathrm{TM0}, t) = 2.040$,

h	$n(\mathrm{TM0}, t-h)$
25 nm	1.851
50 nm	1.702
100 nm	1.537



3 Lateral leakage

Oblique propagation of exterior slab modes:



$$k^2n^2 = k^2N_{\mathrm{eff}}^2 + k_y^2,\qquad k_y = k\sqrt{n^2 - N_{\mathrm{eff}}^2}.$$

$n < N_{\mathrm{eff}},\ k_y \notin \mathbb{R}$: evanescent slab mode, no power transport along $\pm y$.
$n > N_{\mathrm{eff}},\ k_y \in \mathbb{R}$: propagating slab mode ⟿ lateral leakage possible.

TE: guided modes with $N_{\mathrm{eff}} \in [n(\mathrm{TE0}, t-h), n(\mathrm{TE0}, t)]$.
TM: $n(\mathrm{TM0}, t-h) < N_{\mathrm{eff}} < n(\mathrm{TM0}, t) < n(\mathrm{TE0}, t-h)$,
leakage attributed to the TE0 slab mode.

Leakage suppression:

- Deep etching, such that $n(\mathrm{TE0}, t-h) < n(\mathrm{TM0}, t)$.
- External destructive interference of lateral TE waves originating from the rib flanks, at specific "magical widths" [6, 5].
- Symmetry protection of TM modes ⟿ plus configuration:

Slab modes, symmetry:

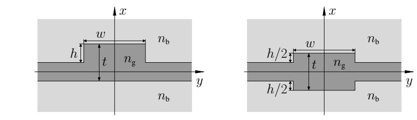
	E_x	E_y	E_z	H_x	H_y	H_z	
$\mathrm{PMC}_{x=0}$	−	+	+	+	−	−	TE0, TM1, …
$\mathrm{PEC}_{x=0}$	+	−	−	−	+	+	TM0, TE1, …

- Symmetry of the full plus structure ⟿ symmetry of the channel modes. Channel, TM_{00}: $\mathrm{PEC}_{x=0}$; slab, TE0: $\mathrm{PMC}_{x=0}$, no contribution to TM_{00}.
- Coupling between slab modes in the central and lateral segments ⟿ overlaps between slab modes $(\boldsymbol{E}_1, \boldsymbol{H}_1)$ and $(\boldsymbol{E}_2, \boldsymbol{H}_2)$:

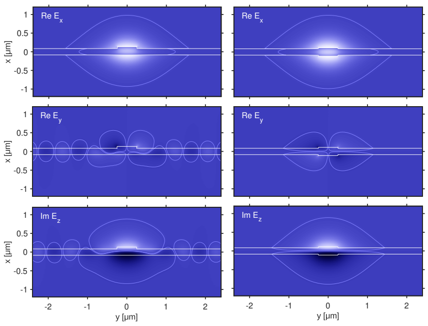
$$\langle \boldsymbol{E}_1, \boldsymbol{H}_1; \boldsymbol{E}_2, \boldsymbol{H}_2\rangle = \frac{1}{4}\int (E_{1z}^* H_{2x} - E_{1x}^* H_{2z} + E_{2z}H_{1x}^* - E_{2x}H_{1z}^*)\,\mathrm{d}x\,.$$

  Symmetry: Overlaps of TE0 and TM0 slab modes vanish.

4 Mode profiles



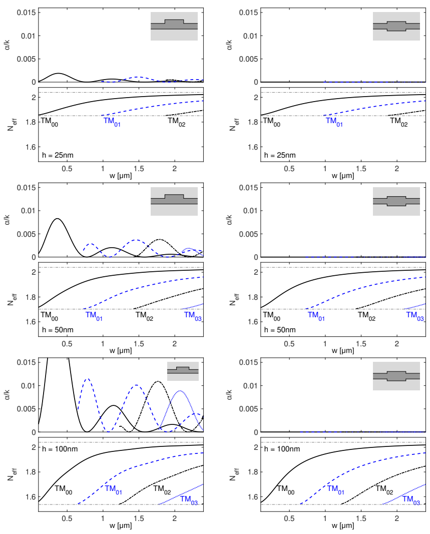
$\lambda = 1.55\,\mu$m, $n_g = 3.45$, $n_b = 1.45$, $t = 220\,$nm, $h = 50\,$nm, $w = 0.5\,\mu$m.



Rib, TM_{00}:
$N_{\mathrm{eff}} = 1.8604$, $\alpha/k = 0.0056$.

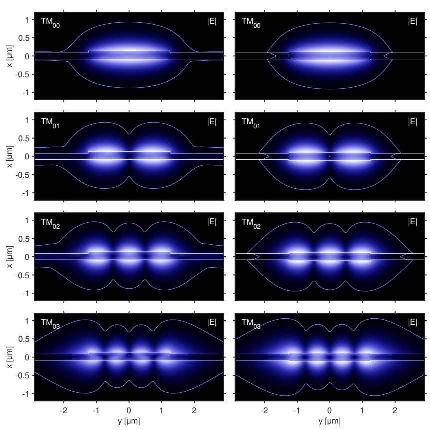
Plus, TM_{00}:
$N_{\mathrm{eff}} = 1.8616$, $\alpha = 0$.

5 Dispersion curves: rib width and height



6 Multimode channels

$\lambda = 1.55\,\mu$m, $n_g = 3.45$, $n_b = 1.45$, $t = 220\,$nm, $h = 50\,$nm, $w = 2.5\,\mu$m.

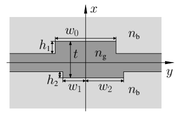


Rib	N_{eff}	α/k
TM_{00}	2.02175	0.00007
TM_{01}	1.96687	0.00066
TM_{02}	1.87942	0.00200
TM_{03}	1.76269	0.00002

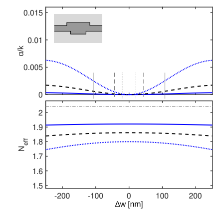
Plus	N_{eff}	α/k
TM_{00}	2.02155	0
TM_{01}	1.96719	0
TM_{02}	1.87792	0
TM_{03}	1.76190	0

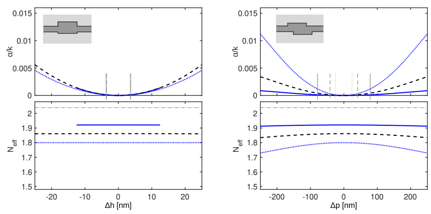
7 Channels with partly vertical symmetry

Errors in feature width: Δw,
etching depth: Δh,
mask alignment: Δp.



$w_0 = w + \Delta w$,
$w_{1,2} = w/2 - \Delta w/2 \mp \Delta p$,
$h_1 = h/2 + \Delta h$, $h_2 = h/2 - \Delta h$.





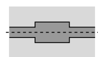
TM_{00}, $w = 0.5\,\mu$m, $h = 25\,$nm (solid), $h = 50\,$nm (dashed), $h = 100\,$nm (dotted).

Tolerances: $\alpha/k < 2.84\cdot 10^{-5}$ or $\mathrm{LO} < 1\,$dB/mm, if (separately)
$|\Delta w| < 108\,$nm, $|\Delta h| < 4\,$nm, $|\Delta p| < 79\,$nm ($h = 25\,$nm),
$|\Delta w| < 44\,$nm, $|\Delta h| < 4\,$nm, $|\Delta p| < 41\,$nm ($h = 50\,$nm),
$|\Delta w| < 21\,$nm, $|\Delta h| < 4\,$nm, $|\Delta p| < 25\,$nm ($h = 100\,$nm).

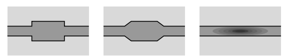
8 Remarks

… on the plus-concept, in comparison to rib waveguides at "magical widths":

- Symmetry protection of TM modes ⟿ vertically symmetric layer stack.

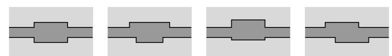


- Applicable to waveguides with other shapes of cross sections (slanted sidewalls, index gradients), and independently of refractive index contrast.

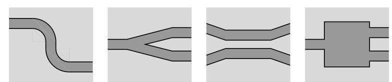


- Broadband: The symmetry protection works entirely wavelength independent.

- Fabrication tolerances: Manageable, for the configurations as discussed.



- Applies automatically to multimode configurations and to channels with longitudinally varying cross sections.



References

[1] S.-T. Peng and A. Oliner. Guidance and leakage properties of a class of open dielectric waveguides: Part I — mathematical formulations. *IEEE Transactions on Microwave Theory and Techniques*, MTT-29(9):843–854, 1981.
[2] A. Oliner, S.-T. Peng, T.-I. Hsu, and A. Sanchez. Guidance and leakage properties of a class of open dielectric waveguides: Part II — new physical effects. *IEEE Transactions on Microwave Theory and Techniques*, MTT-29(9):855–869, 1981.
[3] M. A. Webster, R. M. Pafchek, A. Mitchell, and T. L. Koch. Width dependence of inherent TM-mode lateral leakage loss in silicon-on-insulator ridge waveguides. *IEEE Photonics Technology Letters*, 19(6):429–431, 2007.
[4] X. Xu, S. Chen, J. Yu, and X. Tu. An investigation of the mode characteristics of SOI submicron rib waveguides using the film mode matching method. *Journal of Optics A: Pure and Applied Optics*, 11(1):015508, 2008.
[5] T. G. Nguyen, A. Boes, and A. Mitchell. Lateral leakage in silicon photonics: Theory, applications, and future directions. *IEEE Journal of Selected Topics in Quantum Electronics*, 26(2):1–13, 2020.
[6] T. G. Nguyen, R. S. Tummidi, T. L. Koch, and A. Mitchell. Rigorous modeling of lateral leakage loss in SOI thin-ridge waveguides and couplers. *IEEE Photonics Technology Letters*, 21(7):486–488, 2009.
[7] H. Herrmann, X. Yang, A. Thomas, A. Poppe, W. Sohler, and C. Silberhorn. Post-selection free, integrated optical source of non-degenerate, polarization entangled photon pairs. *Optics Express*, 21(23):27981–27991, 2013.
[8] P. R. Sharapova, K. H. Luo, H. Herrmann, M. Reichelt, T. Meier, and C. Silberhorn. Generation and active manipulation of qubits in $LiNbO_3$-based integrated circuits, 2017. arXiv:1704.03769 [quant-ph].
[9] N. Üstün, H. Farheen, M. Hammer, and J. Förstner. Symmetry-protected TM modes in optical rib-like waveguides with shallow etching, 2024. (manuscript in preparation).
[10] M. Hammer, L. Ebers, and J. Förstner. Configurable lossless broadband beam splitters for semi-guided waves in integrated silicon photonics. *OSA Continuum*, 4(12):3081–3095, 2021.
[11] Comsol Multiphysics GmbH, Göttingen, Germany; https://www.comsol.com.
[12] JCMwave GmbH, Berlin, Germany; https://www.jcmwave.com.

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