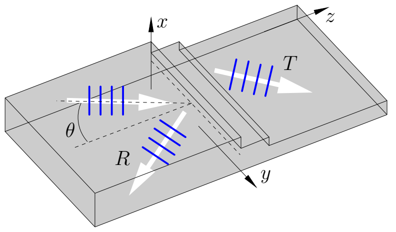
Oblique quasi-lossless excitation of a thin silicon slab waveguide

Manfred Hammer*, Lena Ebers, Jens Förstner

Theoretical Electrical Engineering, Paderborn University, Paderborn, Germany

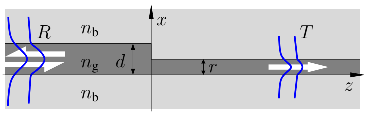
1 A guided-wave-variant of an anti-reflection coating

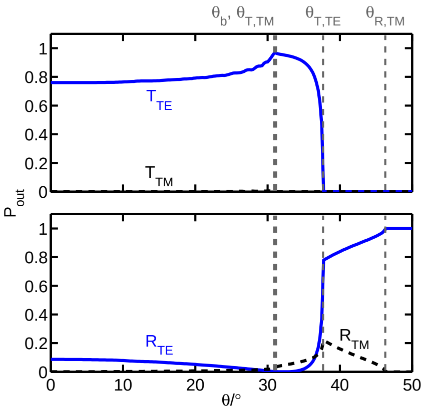
Guided waves traversing an abrupt interface between different slab waveguides typically generate pronounced reflections and scattering losses. The conventional 2-D framework corresponds to normal incidence of the laterally infinite waves on the interface. Applying a semi-analytical vectorial mode expansion solver [1, 2] for the effective 2-D problems, we investigate, for high-contrast silicon slabs, what happens when the waves come in at *oblique* angles. Arguments based on a variant of Snell's law, adapted to the present case of polarized semi-guided waves, predict critical angles of incidence, beyond which all scattering losses are suppressed. In that regime, for our particular parameters with TE-incidence, the transmittance is already raised to about 95%. The waves, however, are still partly reflected, mainly into the backwards TM mode.



Motivated by the traditional technique of reflection suppression, we introduce a short waveguide segment of intermediate thickness at the former interface. Optimization of the transmittance through varying the height and width of that segment leads to a configuration with a guided-wave TE-to-TE transmittance above 99.5%. Rigorous finite-element simulations (COMSOL, [3]) confirm these findings.

2 Abrupt junction, transmittance

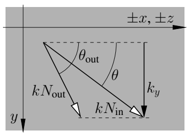




3 Parameters

refractive index, cladding:	$n_b = 1.45$,	critical angles:
refractive index, cores:	$n_g = 3.45$,	$\theta_b = 30.9°$,
larger core thickness:	$d = 0.22\,\mu$m,	$\theta_{T,TM} = 31.2°$,
lower core thickness:	$r = 0.05\,\mu$m,	$\theta_{T,TE} = 37.7°$,
vacuum wavelength:	$\lambda = 1.55\,\mu$m,	$\theta_{R,TM} = 46.3°$.
excitation:	TE_0,	
angle of incidence:	θ,	
thickness, coating segment:	$h = 0.16\,\mu m^*$,	
width, coating segment:	$w = 0.40\,\mu m^*$,	* optimized for $\theta = 33°$.

4 Critical angles



Uniform $k_y = kN_{in}\sin\theta$,
related to incoming mode (N_{in})
& incidence angle θ:

↳ Outgoing modes (N_{out}) leave at angles θ_{out} with $k_y = kN_{out}\sin\theta_{out}$, *different* for every outgoing mode;

generalized Snell's law: $N_{out}\sin\theta_{out} = N_{in}\sin\theta$,

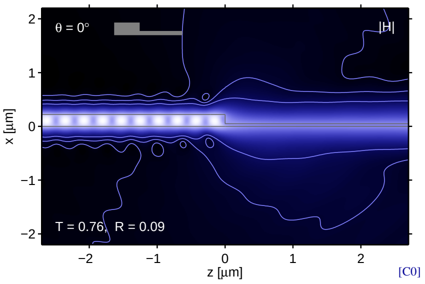
applicable to all (reflected, transmitted, up- or downwards scattered) outgoing *propagating* modes.

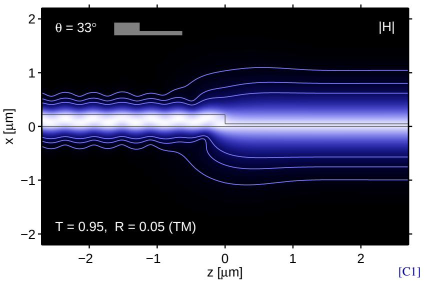
↳ Outgoing modes with $N_{out} \le N_{crit}$ become evanescent for incidence angles $\theta \ge \theta_{crit}$ with $\sin\theta_{crit} = N_{crit}/N_{in}$, i.e. these modes do not carry power away.

Relevant values for the present examples:

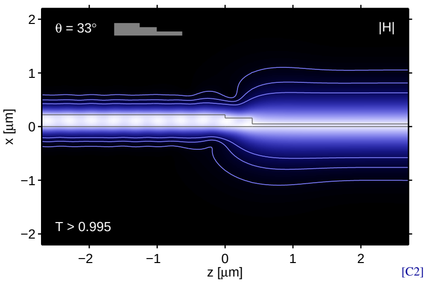
- $\sin\theta_b = n_b/N_{TE0}$, no forward / backward power loss into the cladding for $\theta \ge \theta_b$.
- $\sin\theta_{T,TM} = N_{T,TM0}/N_{TE0}$, no power transmitted to the TM_0 mode for $\theta \ge \theta_{T,TM}$.
- $\sin\theta_{T,TE} = N_{T,TE0}/N_{TE0}$, no power transmitted to the TE_0 mode for $\theta \ge \theta_{T,TE}$.
- $\sin\theta_{R,TM} = N_{R,TM0}/N_{TE0}$, no power reflected into the TM_0 mode for $\theta \ge \theta_{R,TM}$.

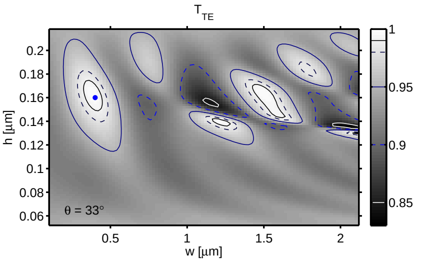
5 Abrupt junction, fields





6 Anti-reflection coating

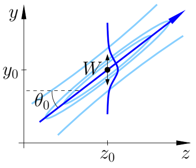


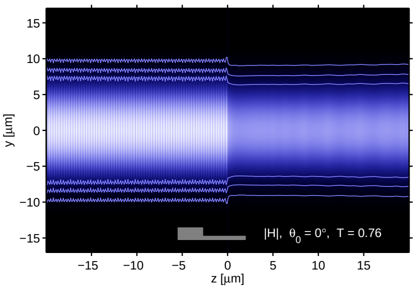


7 Semi-guided wave packets

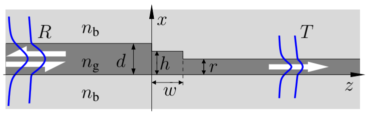
Superimpose the former 2-D solutions for a range of k_y-values / a range of angles θ, such that the input field resembles a vertically (x) guided, laterally (y, z) localized Gaussian beam.

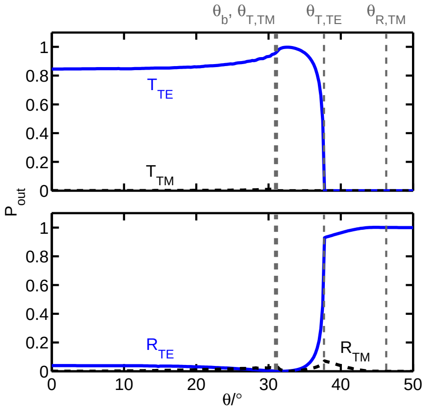
Parameters:
focus (y_0, z_0) at the origin,
primary angle θ_0,
full $1/e$-width along y, at focus:
$W = 10\,\mu$m.



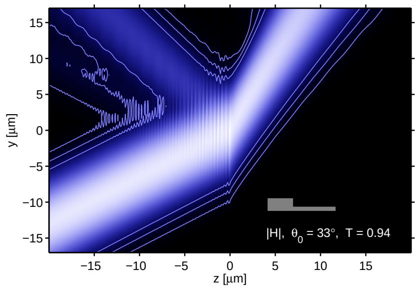


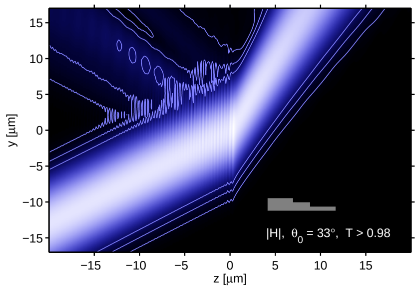
8 Coated junction, transmittance





9 Propagation of semi-guided Gaussian beams





10 Numerical benchmark

	T_{TE}	R_{TE}	T_{TM}	R_{TM}	
[C0] $\theta = 0°$, bare	0.760	0.087	0	0	vQUEP [1]
	0.769	0.084	0	0	COMSOL [3]
[C1] $\theta = 33°$, bare	0.945	0.001	0	0.053	vQUEP [1]
	0.946	0.001	0	0.054	COMSOL [3]
[C2] $\theta = 33°$, coated	0.996	0.003	0	0.001	vQUEP [1]
	0.996	0.003	0	0.001	COMSOL [3]

References

[1] M. Hammer. Oblique incidence of semi-guided waves on rectangular slab waveguide discontinuities: A vectorial QUEP solver. *Optics Communications*, 338:447–456, 2015.

[2] M. Hammer. Quadridirectional eigenmode expansion scheme for 2-D modeling of wave propagation in integrated optics. *Optics Communications*, 235(4–6):285–303, 2004.

[3] Comsol Multiphysics GmbH, Göttingen, Germany; http://www.comsol.com.

[4] L. Ebers, M. Hammer, and J. Förstner. Spiral modes supported by circular dielectric tubes and tube segments. *Optical and Quantum Electronics*, 49(4):176, 2017.

[5] M. Hammer, A. Hildebrandt, and J. Förstner. Full resonant transmission of semi-guided planar waves through slab waveguide steps at oblique incidence. *Journal of Lightwave Technology*, 34(3):997–1005, 2016.

[6] M. Hammer, A. Hildebrandt, and J. Förstner. How planar optical waves can be made to climb dielectric steps. *Optics Letters*, 40(16):3711–3714, 2015.

[7] F. Çivitci, M. Hammer, and H. J. W. M. Hoekstra. Semi-guided plane wave reflection by thin-film transitions for angled incidence. *Optical and Quantum Electronics*, 46(3):477–490, 2014.

Acknowledgements

Support by the Deutsche Forschungsgemeinschaft (DFG, Transregional Collaborative Research Center TRR 142, and project HA7314/1) is gratefully acknowledged.

* Manfred Hammer, Paderborn University, FG Theoretical Electrical Engineering
Warburger Straße 100, 33098 Paderborn, Germany
Phone: ++49(0)5251/60-3560, Fax: ++49(0)5251/60-3524, E-mail: manfred.hammer@uni-paderborn.de

TET

PADERBORN UNIVERSITY
The University for the Information Society