Wave-Matching-Simulations of Integrated Optical Coupler Structures

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Contents

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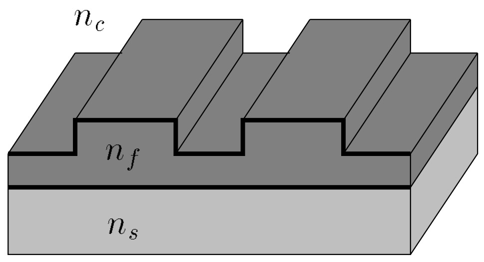
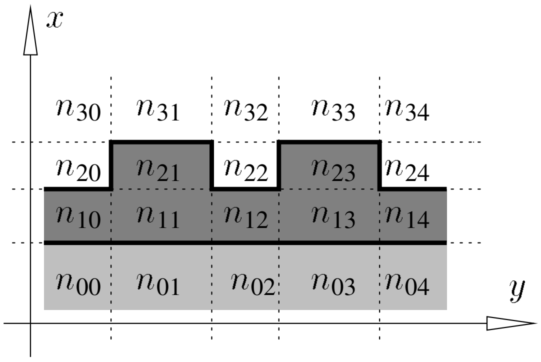
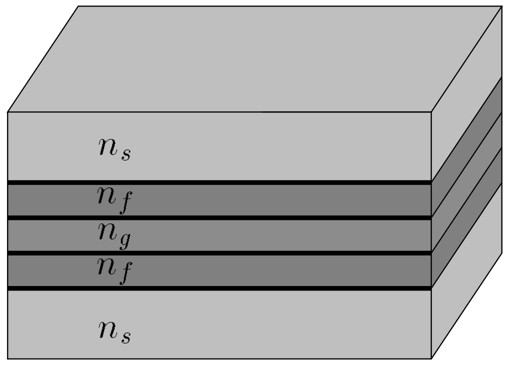
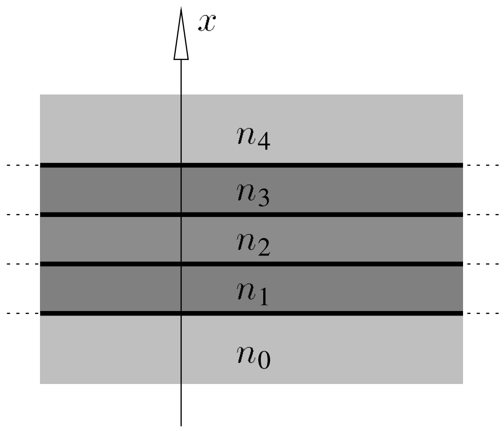
Typical cross section of a central coupler segment:





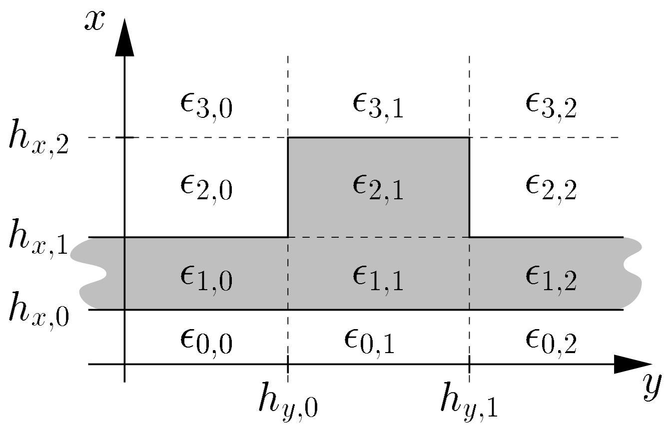
Multilayer slab waveguide analysis:





- Separate ansatz for each layer:
  sum over physically relevant solutions of the wave equation.
- Continuity requirements for the dielectric boundaries combine the unknown coefficients within a system of linear equations.
- This system must be solved for a nonvanishing field.

WMM: Attempt to establish an analogous procedure
for two transverse dimensions . . .



- Guided modes:
  Square integrable fields, all components are of the form

$$F(x,y,z,t) = \Phi(x,y)\,\mathrm{e}^{\mathrm{i}(\omega t - \beta z)}, \quad \omega = kc = 2\pi c/\lambda\,.$$

- Wave equation, valid inside homogeneous rectangles:

$$\partial_x^2\Phi + \partial_y^2\Phi = (\beta^2 - k^2\epsilon)\Phi.$$

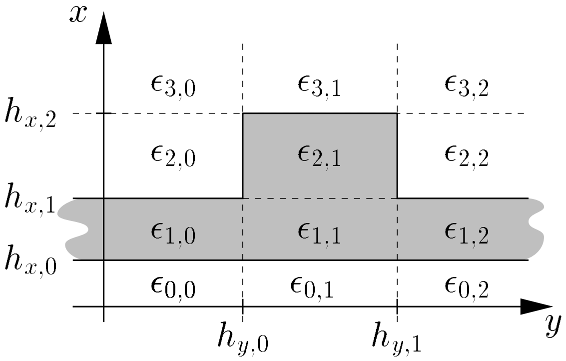
- Ansatz for the mode components Φ:

$$\Phi(x,y) = \sum_j a_j\, F_j(p_j x)\, G_j(q_j y).$$

  F, G $\in \{\sin, \cos, \exp\}$,
  p, q: transverse wave vector components with
  $\pm p^2 \pm q^2 = \beta^2 - k^2\epsilon\,.$

- Spectral discretization:
  For each combination of F, G, separately on each rectangle: Select a number of parameters p, q, such that the corresponding trial fuctions $F(px)\,G(qy)$
  - cover the entire relevant domain for p and q,
  - are numerically linearly independent.

- On unbounded rectangles:
  Consider only exponentially decaying trial functions.



	Quantities continuous on horizontal dielectric boundaries	Quantities continuous on vertical dielectric boundaries
TE	$E_y,\ \partial_x E_y$	$\epsilon E_y,\ \partial_y E_y$
TM	$H_y,\ \epsilon^{-1}\partial_x H_y$	$H_y,\ \partial_y H_y$
VEC	$\epsilon E_x,\ E_y,\ E_z,\ H_x,\ H_y,\ H_z$	$E_x,\ \epsilon E_y,\ E_z,\ H_x,\ H_y,\ H_z$

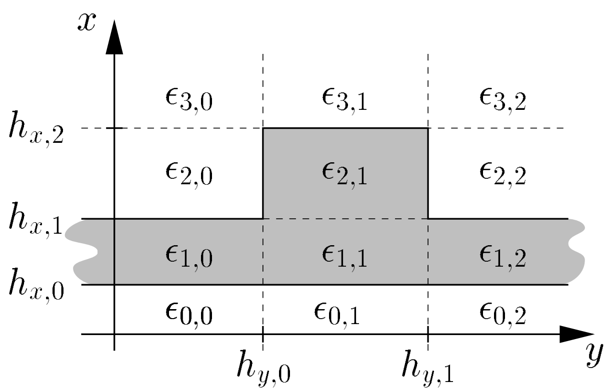
Least squares expression for the field mismatch:

$$D_\beta(\vec{a}) = \sum_{\substack{\text{quantities}\\ \text{required}\\ \text{to be}\\ \text{continuous}}} \ \sum_{\substack{\text{horizontal}\\ \text{/ vertical}\\ \text{boundary}\\ \text{sections}}} \ \int_{\substack{\text{boundary}\\ \text{line}}} \begin{pmatrix}\text{suitable}\\ \text{weighting}\\ \text{factors}\end{pmatrix} \cdot \left| \begin{matrix}\text{difference}\\ \text{in field /}\\ \text{derivative}\end{matrix} \right|^2 \mathrm{d}s$$

Constraint: Normalized fields

$$N_\beta(\vec{a}) = \sum_{\text{rectangles}} \ \iint_{\substack{\text{rectangle}\\ \text{domain}}} \begin{pmatrix}\text{suitable}\\ \text{weighting}\\ \text{factors}\end{pmatrix} \cdot \left| \quad \text{field} \quad \right|^2 \mathrm{d}x\, \mathrm{d}y$$

$$\boxed{\text{Guided Modes: } (\beta, \vec{a}) \text{ with } D_\beta(\vec{a}) = 0 \text{ and } N_\beta(\vec{a}) = 1.}$$



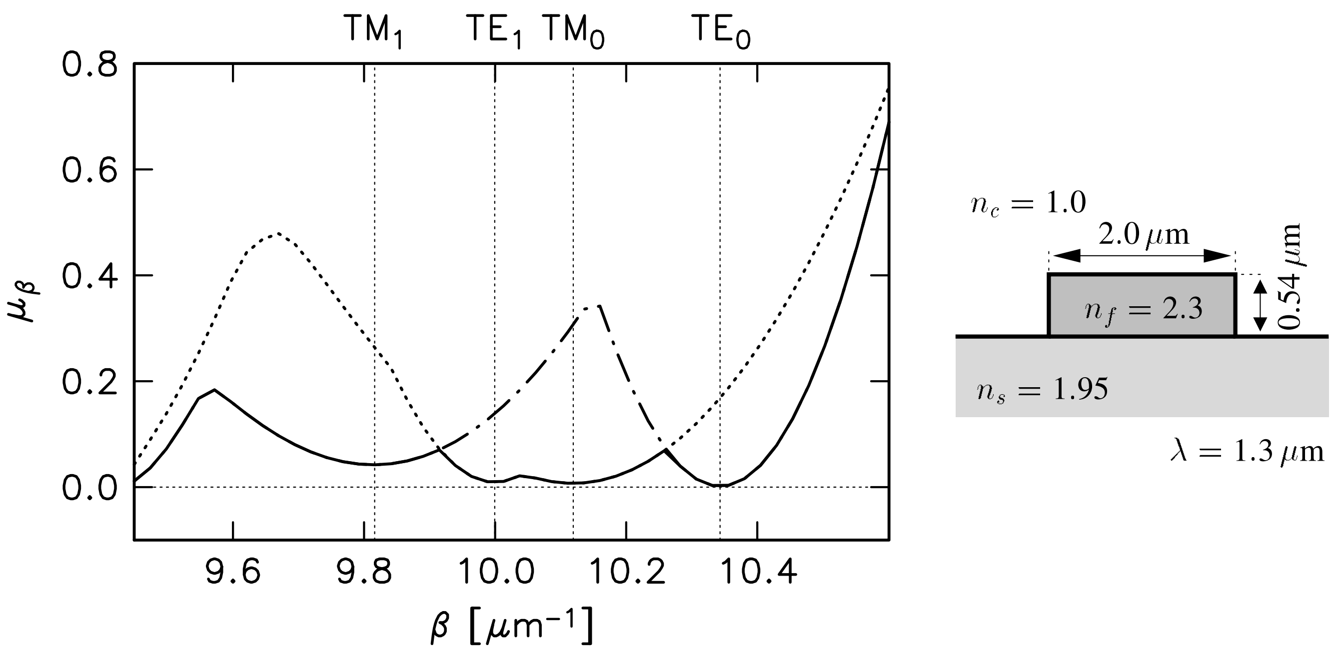
D_β and N_β are quadratic forms:

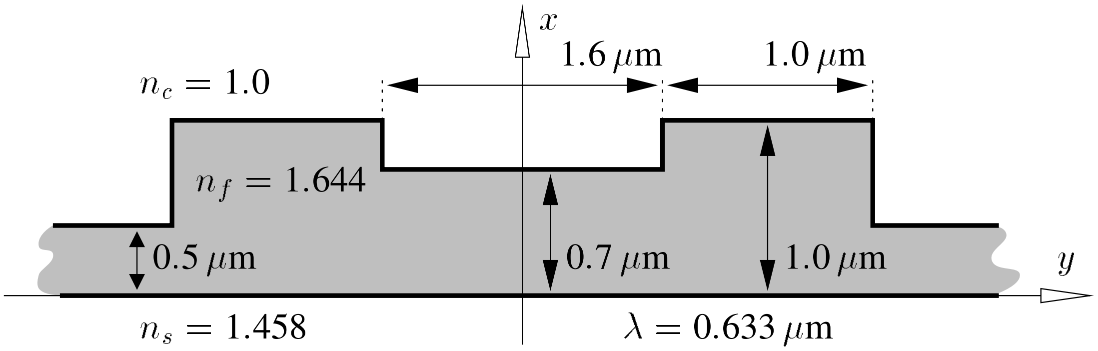
$$D_\beta(\vec{a}) = \vec{a}^{\,\mathsf{T}}\, \mathsf{D}_\beta\, \vec{a}, \qquad N_\beta(\vec{a}) = \vec{a}^{\,\mathsf{T}}\, \mathsf{N}_\beta\, \vec{a}.$$

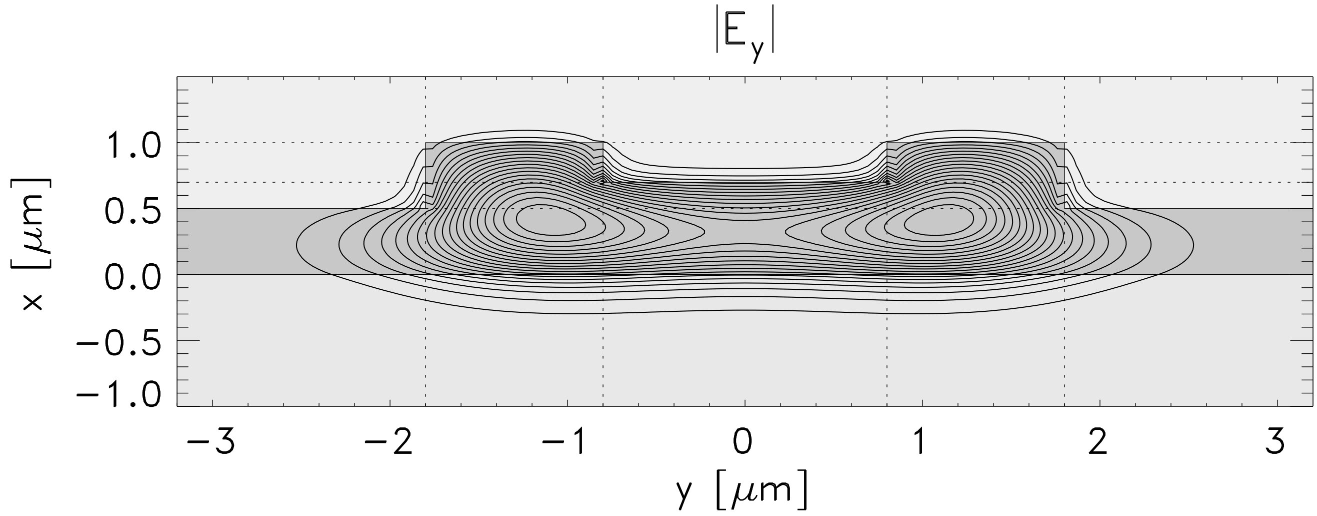
- For given β, find the set of coefficients $\vec{a}$ with minimum error μ_β $\Leftrightarrow$ solve the generalized eigenvalue equation

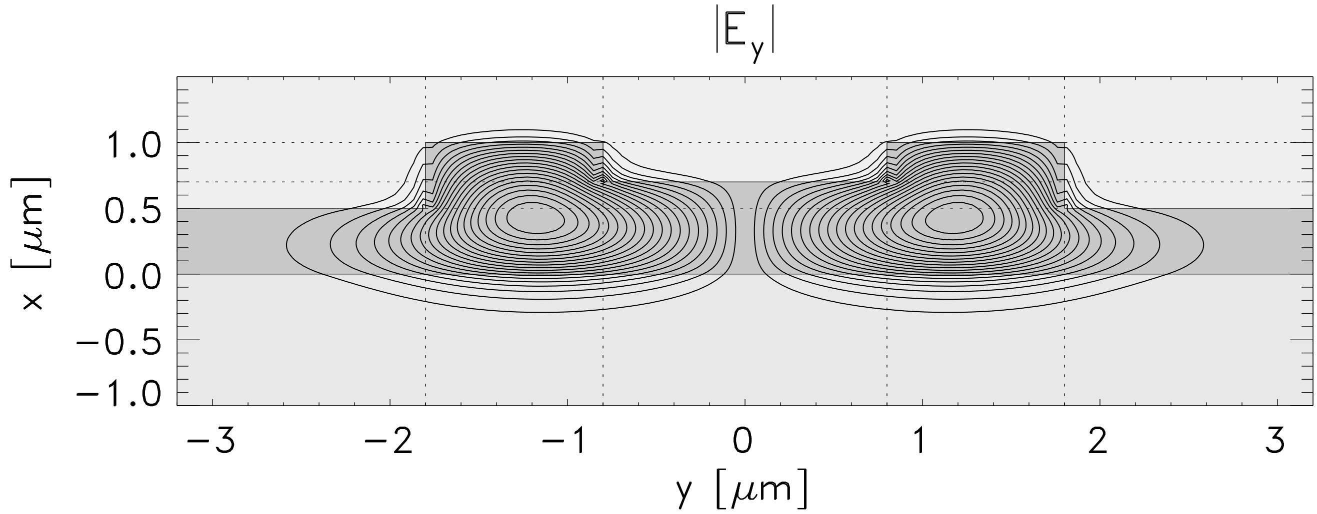
$$\mathsf{D}_\beta\, \vec{a} = \mu_\beta\, \mathsf{N}_\beta \vec{a}\,.$$

- Minimize μ_β with respect to β
$\rightsquigarrow$ estimates for valid propagation constants.



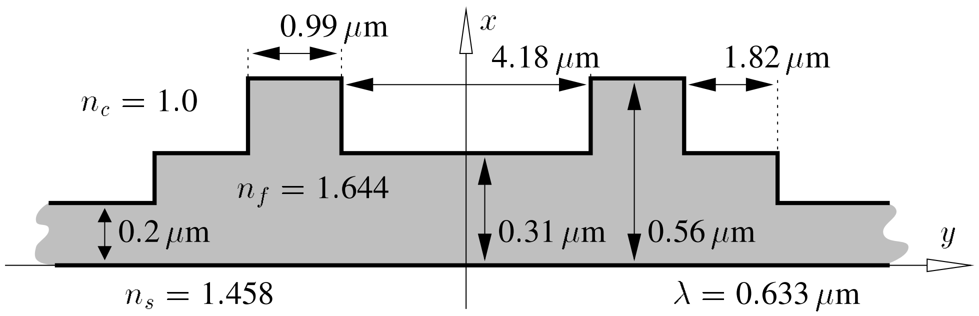


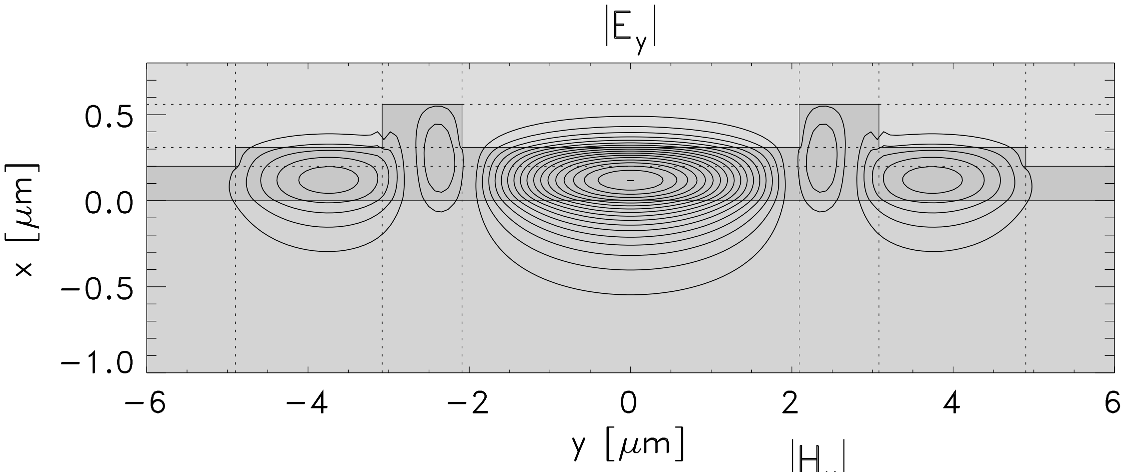


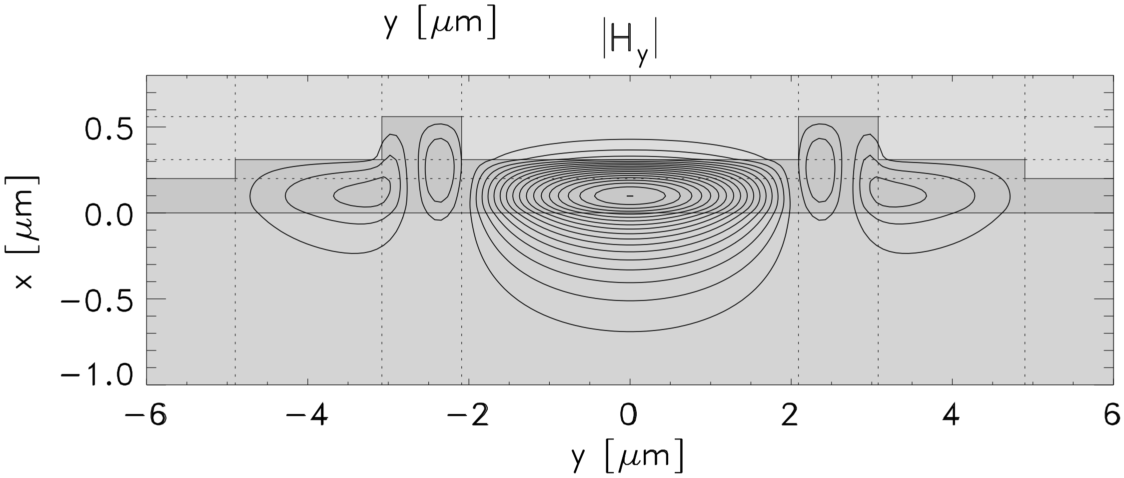


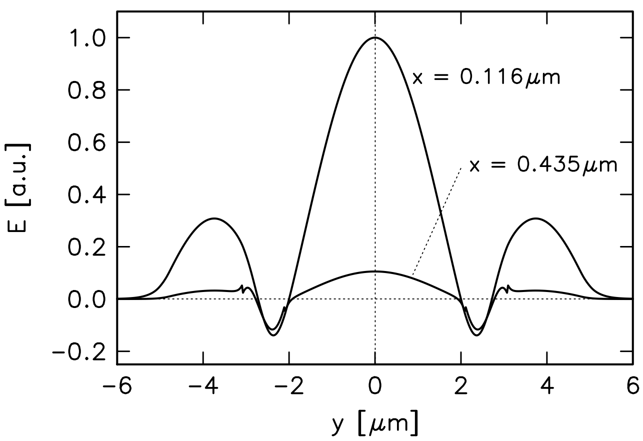
		EIM*	SIM*	FEM*	WMM
β/k	(s)	1.614021	1.611995	1.611412	1.610794
	(a)	1.612877	1.610369	1.609546	1.609100
$L_c = \pi/(\beta_s - \beta_a)$		276 μm	194 μm	170 μm	187 μm

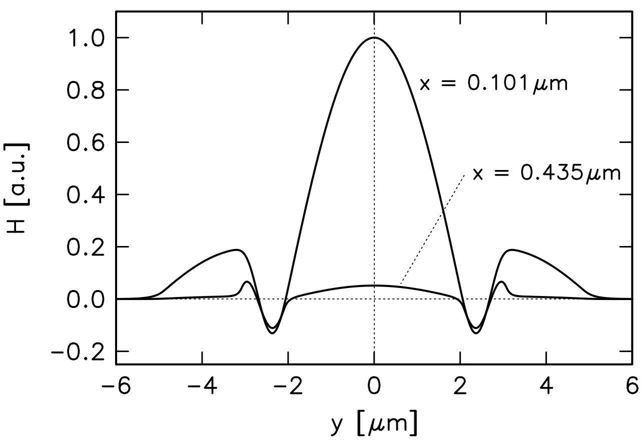
$*$: P. Pola, W. Biehlig, F. Lederer, *JLT* **14**, 1996





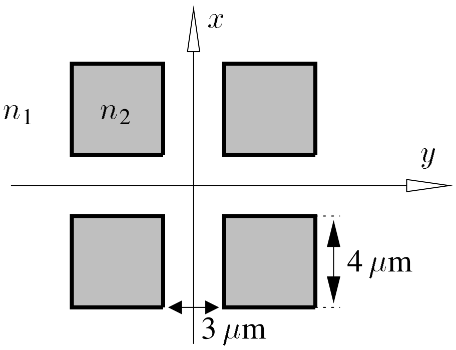




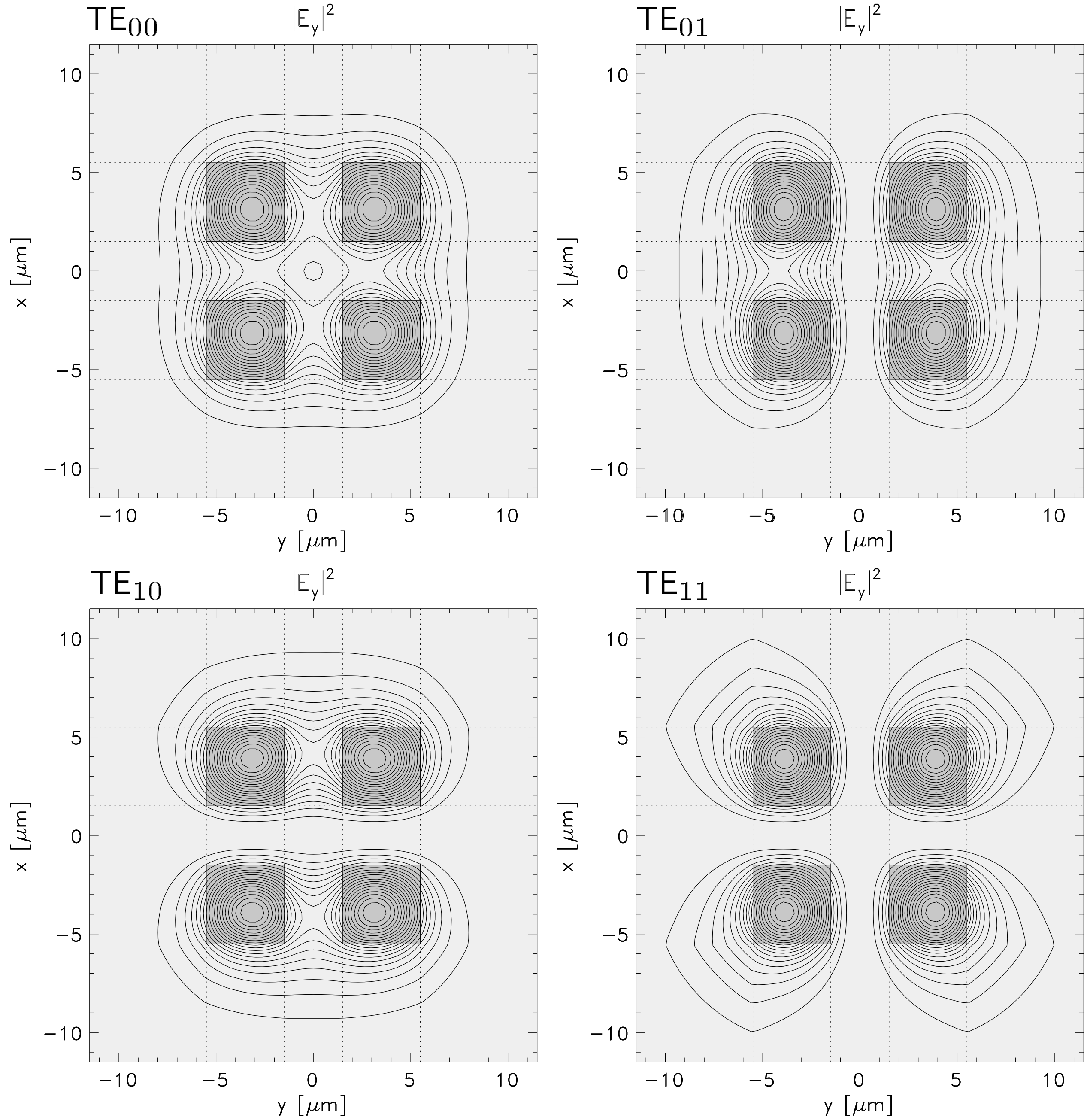


		EIM*	SIM*	FEM*	WMM
β/k	TE	1.534432	1.534115	1.533470	1.534142
	TM	1.507001	1.506904	1.506720	1.506945

$*$: P. Pola, W. Biehlig, F. Lederer, *JLT* **14**, 1996

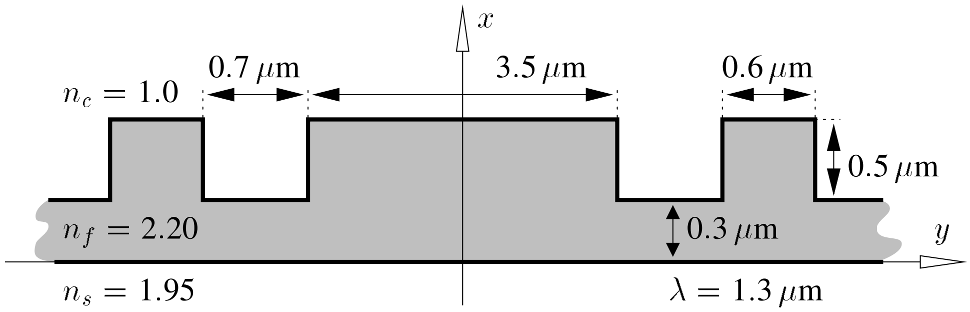


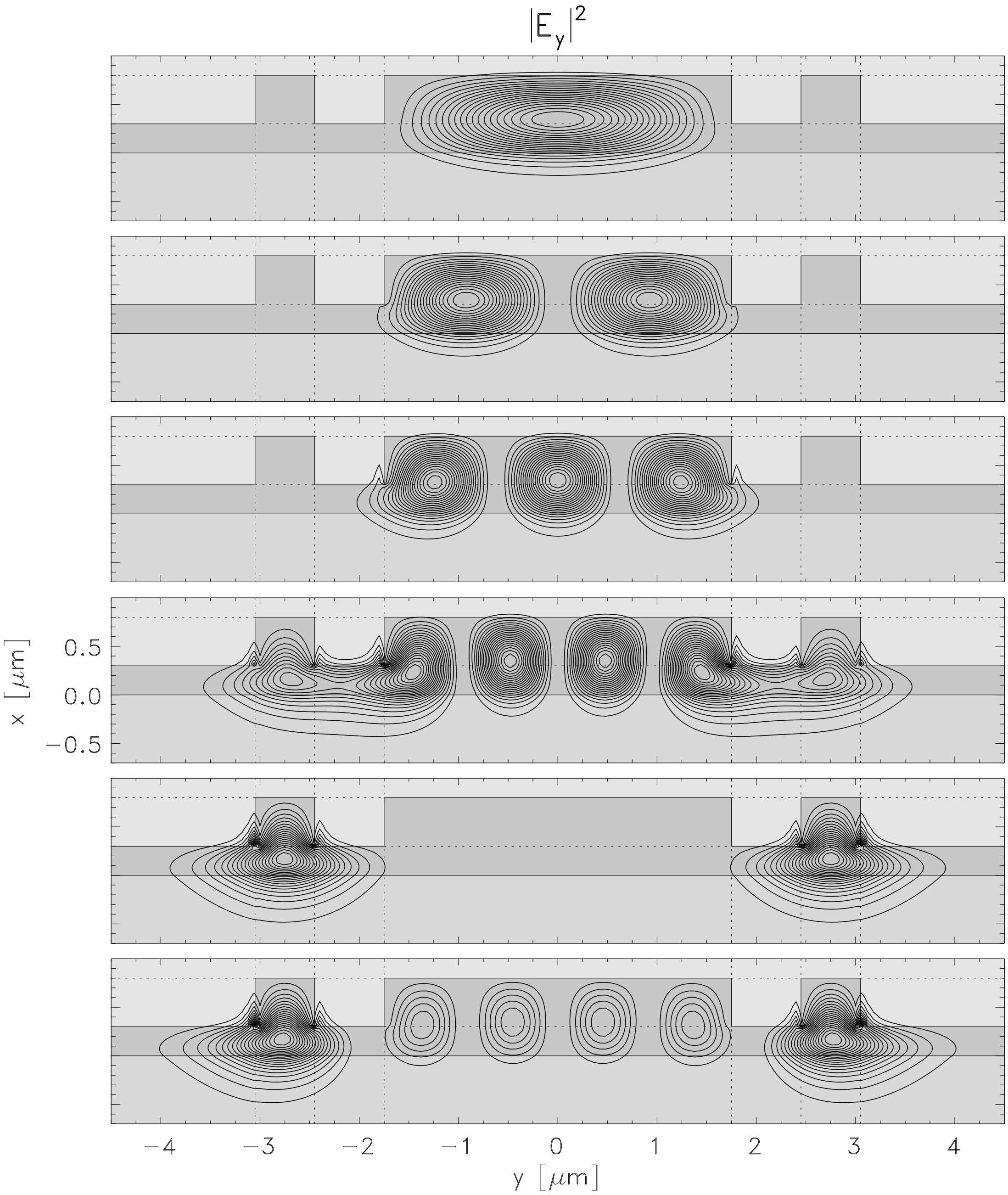
$n_1 = 1.506$
$n_2 = 1.512$
$\lambda = 1.32\,\mu\text{m}$



	β_{00}/k	β_{01}/k	β_{10}/k	β_{11}/k	L_c
VFEM*	1.5075807	1.5067966	1.5067966	1.5060266	850 μm
WMM	1.5078966	1.5071085	1.5071092	1.5064697	925 μm

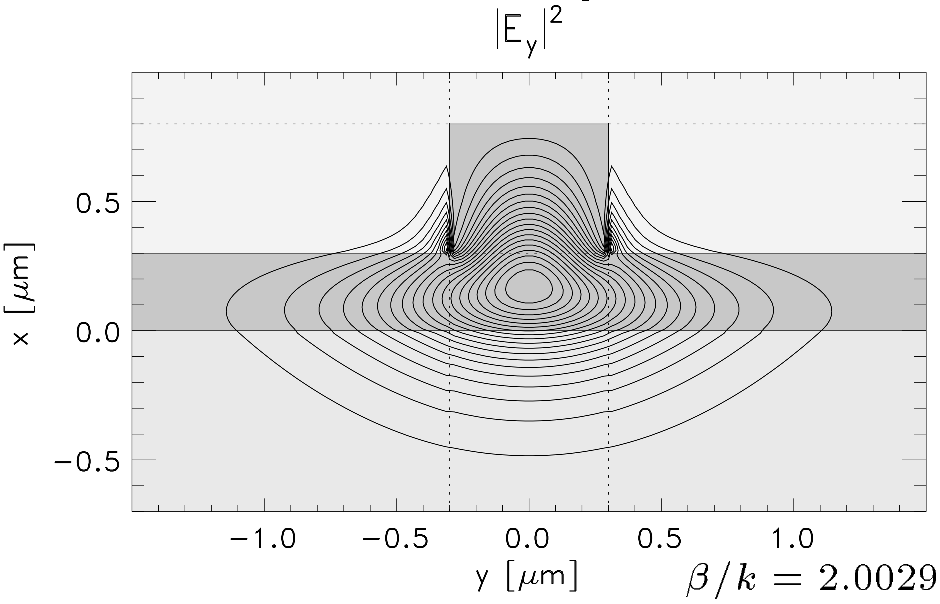
$*$: L. Friedrich, P. Dannberg, C. Wächter, Th. Hennig, A. Bräuer, W. Karthe, *Optics Communications* **137**, 1997



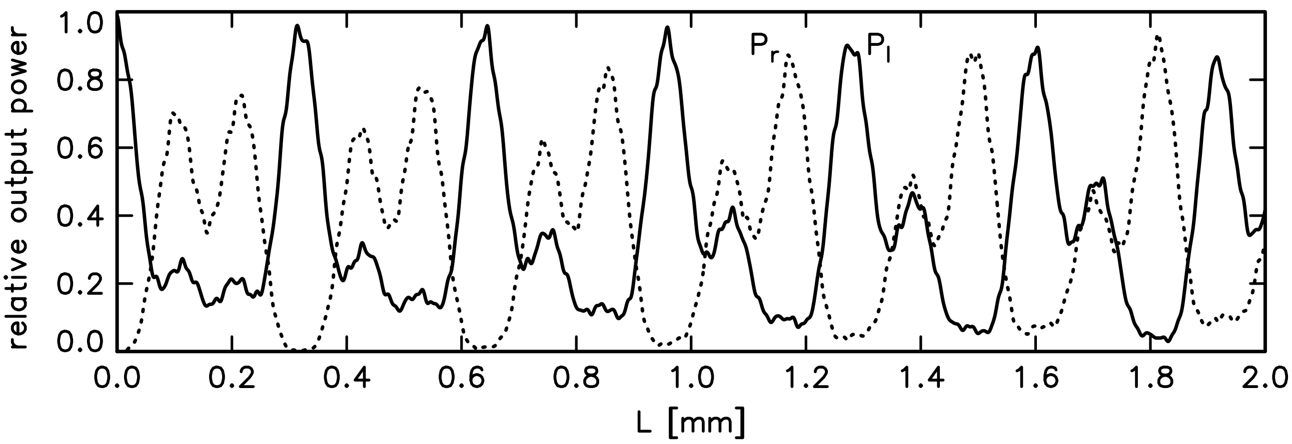


	TE_0	TE_1	TE_2	TE_3	TE_4	TE_5
β/k	2.1152	2.0932	2.0570	2.0108	2.0026	1.9986

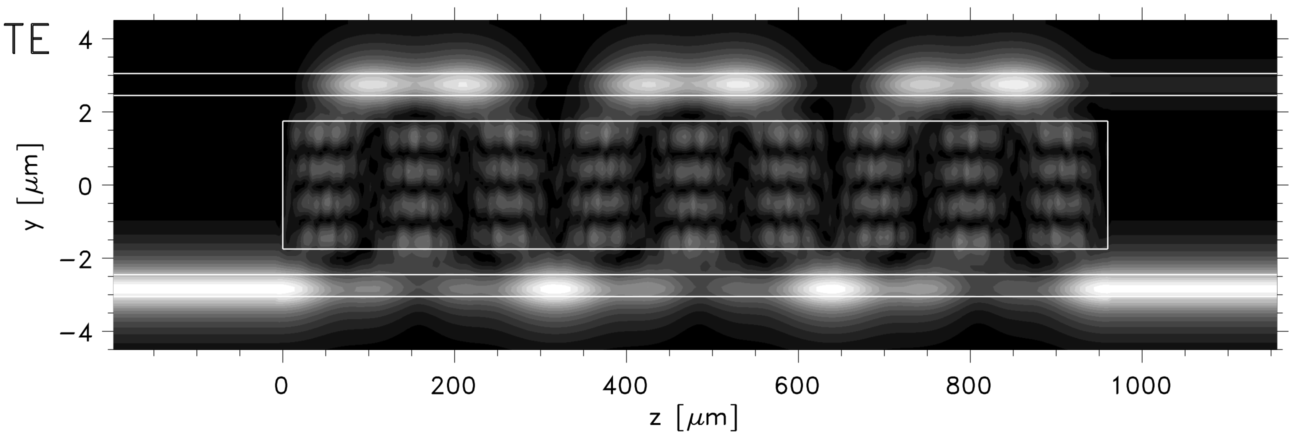
TE mode of the isolated outer waveguides:

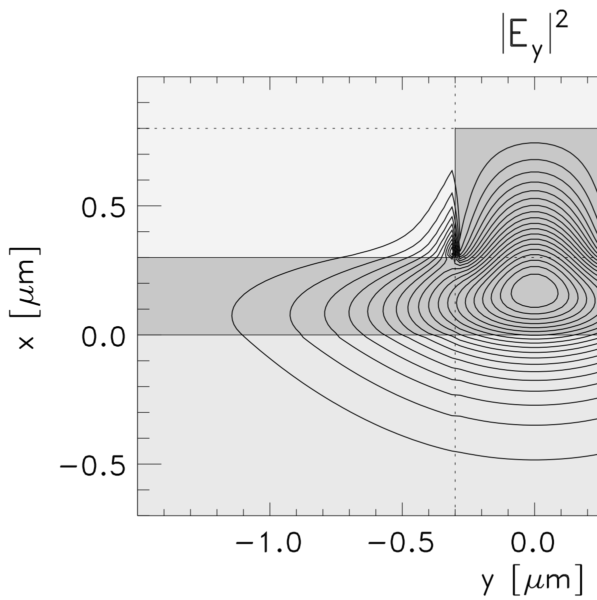


Relative output power for varying coupler length:



Propagating mode analysis, $L = 960\,\mu$m:





Wave-Matching-Method:

- a mode analysis procedure for waveguides with piecewise constant, rectangular refractive index profiles,
- the simple ansatz of superposed factorizing solutions of the Helmholtz wave equation approximates the mode fields well,
- propagation constants are determined by minimizing the field mismatch on the dielectric discontinuity lines,
- there is good agreement with other methods, for semivectorial and fully vectorial analysis of single waveguides as well as for more complex structures,
- moderate memory and time demand,
- yields quasianalytical representations of the mode fields which are not restricted to a finite computational window,
- qualifies well as base for a larger integrated optics design environment.