Computational photonics
— scattering problems in guided wave optics

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TW colloquium, University of Twente, 22.03.2007

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Photonics

"Photonics is the science and technology of generating, controlling, and detecting photons, particularly in the visible light and near infra-red spectrum.

. . . quantum optics, . . . optoelectronics . . .

. . . the overlap between all these fields and optics is unclear, and different definitions are used in different parts of the world and in different industries.

. . . goal of establishing an electronics of photons instead of electrons.

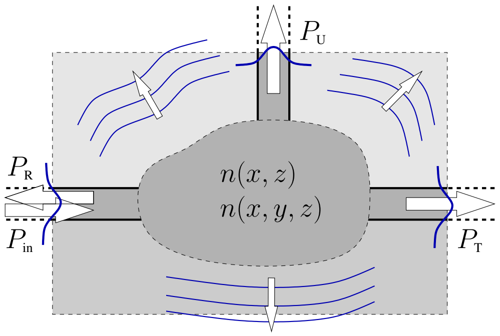
. . . strong interest in optical communication . . . usually based on laser light."

http://www.wikipedia.org

Outline

- Simulations in guided wave optics
  - Macroscopic Maxwell equations
  - Stationary and time-domain problems
  - 2-D problems
  - Modes of dielectric waveguides
- Quadridirectional eigenmode propagation
  - Problem setting
  - Eigenmode expansion
  - Algebraic procedure
- 2-D PSTM model
  - Probing evanescent fields
  - Hole defect in a slab waveguide
  - Waveguide Bragg grating: experiment & 2-D model
  - Resonant defect cavity
- Optical switching by NEMS-actuated resonator arrays

Abstract scattering problem



Typical parameters:

- vacuum wavelength
  $\lambda \in [400, 700]$ nm (visible light),
  $\lambda \approx 1.3\,\mu$m, $1.55\,\mu$m
  (optical fibers, attenuation min.),
- refractive indices $n \in [1, 3.4]$,
  small attenuation
  (transparent dielectrica).

- Interesting domain: $(10\,\lambda — 100\,\lambda)^d$, $d = 2, 3$ (2-D, 3-D).
- Details: $\approx \lambda/10$, $\approx \lambda/100$.
- Influx and outflux: guided & nonguided waves ↔ boundary conditions.

- Emphasis: device concepts, design.

Macroscopic Maxwell equations

... for the electromagnetic fields

$$\boldsymbol{\mathcal{E}}(x,y,z,t) = \frac{1}{2}\Big(\boldsymbol{E}(x,y,z)\,\mathrm{e}^{\mathrm{i}\omega t} + \boldsymbol{E}^*(x,y,z)\,\mathrm{e}^{-\mathrm{i}\omega t}\Big)\,,$$

$\hat{=}\ \boldsymbol{\mathcal{B}}, \boldsymbol{B},\ \boldsymbol{\mathcal{D}}, \boldsymbol{D},\ \boldsymbol{\mathcal{H}}, \boldsymbol{H},\ \boldsymbol{\mathcal{P}}, \boldsymbol{P},\ \boldsymbol{\mathcal{M}}, \boldsymbol{M},\ \omega = k\mathrm{c} = 2\pi\mathrm{c}/\lambda$,

in frequency domain form, SI (source-free):

$$\mathrm{curl}\,\boldsymbol{E} = -\mathrm{i}\omega\boldsymbol{B}, \quad \mathrm{curl}\,\boldsymbol{H} = \mathrm{i}\omega\boldsymbol{D}, \quad \mathrm{div}\,\boldsymbol{D} = 0, \quad \mathrm{div}\,\boldsymbol{B} = 0,$$

$$\boldsymbol{B} = \mu_0(\boldsymbol{H}+\boldsymbol{M}), \quad \boldsymbol{D} = \epsilon_0\boldsymbol{E}+\boldsymbol{P}.$$

Typical media:

- uncharged, no free currents and charges,
- nonmagnetic at optical frequencies, $\boldsymbol{M} = 0$,
- dielectrica, susceptibilities $\hat{\chi}^{(j)}(x,y,z;\omega)$:

$$P_j = \epsilon_0\Big(\sum_k \chi^{(1)}_{j,k}E_k + \sum_{k,l}\chi^{(2)}_{j,k,l}E_kE_l + \sum_{k,l,m}\chi^{(3)}_{j,k,l,m}E_kE_lE_m \ldots\Big).$$

Convention: eliminate $\boldsymbol{D}$ and $\boldsymbol{B}$ $\rightsquigarrow$ formulation in $\boldsymbol{E}$ and $\boldsymbol{H}$.

Linear problems

$$\boldsymbol{P} = \epsilon_0\hat{\chi}^{(1)}\boldsymbol{E}, \quad \boldsymbol{D} = \epsilon_0(1+\hat{\chi}^{(1)})\boldsymbol{E} = \epsilon_0\hat{\epsilon}\boldsymbol{E}\,;$$

$\hat{\epsilon} = 1 + \hat{\chi}^{(1)}$: relative permittivity.

Simplest case: isotropic, lossless dielectrica; refractive index n :

$$\hat{\epsilon} = \epsilon 1, \quad \epsilon = n^2, \quad n(x,y,z;\omega) \in \mathbb{R}.$$

Frequently n is piecewise constant $\leftrightsquigarrow$ interface conditions for $\boldsymbol{E}$, $\boldsymbol{H}$.

Complications:

- anisotropic media, $\hat{\epsilon} \not\sim 1$ (crystals, ordered materials),
- attenuation, $\hat{\epsilon}^\dagger \neq \hat{\epsilon}$, $n \notin \mathbb{R}$,
- nonlinear problems, $\hat{\chi}^{(2)}$, $\hat{\chi}^{(3)}$ ...

Stationary problems

Continuous wave excitation, ω a given parameter:

$$\mathrm{curl}\,\boldsymbol{E} = -\mathrm{i}\omega\mu_0\boldsymbol{H}, \quad \mathrm{curl}\,\boldsymbol{H} = \mathrm{i}\omega\epsilon_0\hat{\epsilon}\boldsymbol{E}, \quad \mathrm{div}\,\hat{\epsilon}\boldsymbol{E} = 0, \quad \mathrm{div}\,\boldsymbol{H} = 0,$$

or

$$\mathrm{curl}\,\mathrm{curl}\,\boldsymbol{E} = k^2\hat{\epsilon}\boldsymbol{E}, \quad \mathrm{curl}\,\hat{\epsilon}^{-1}\mathrm{curl}\,\boldsymbol{H} = k^2\boldsymbol{H},$$

$\boldsymbol{E}(x,y,z) \in \mathbb{C}^3$, $\boldsymbol{H}(x,y,z) \in \mathbb{C}^3$.

Helmholtz solver:

Given $\hat{\epsilon}$ and an optical “influx”, find $\boldsymbol{E}$, $\boldsymbol{H}$ on a computational domain, subject to suitable boundary conditions.

Scans over ω $\rightsquigarrow$ Spectral data.

Time dependent modeling

Propagation of time dependent signals, pulsed excitation:

$$\mathrm{curl}\,\boldsymbol{\mathcal{E}} = -\mu_0\partial_t\boldsymbol{\mathcal{H}}, \quad \mathrm{curl}\,\boldsymbol{\mathcal{H}} = \epsilon_0\hat{\epsilon}\partial_t\boldsymbol{\mathcal{E}}, \quad \mathrm{div}\,\hat{\epsilon}\boldsymbol{\mathcal{E}} = 0, \quad \mathrm{div}\,\boldsymbol{\mathcal{H}} = 0,$$

or

$$\mathrm{curl}\,\mathrm{curl}\,\boldsymbol{\mathcal{E}} = -\frac{1}{c^2}\hat{\epsilon}\partial_t^2\boldsymbol{\mathcal{E}}, \quad \mathrm{curl}\,\hat{\epsilon}^{-1}\mathrm{curl}\,\boldsymbol{\mathcal{H}} = -\frac{1}{c^2}\partial_t^2\boldsymbol{\mathcal{H}},$$

$\boldsymbol{\mathcal{E}}(x,y,z,t) \in \mathbb{R}^3$, $\boldsymbol{\mathcal{H}}(x,y,z,t) \in \mathbb{R}^3$.

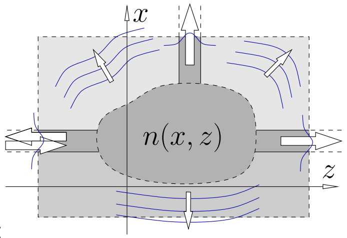
Time domain solver:

Given $\hat{\epsilon}$ and an optical “influx” signal, find $\boldsymbol{\mathcal{E}}$, $\boldsymbol{\mathcal{H}}$ on a computational domain within a certain time interval, subject to suitable boundary conditions.

Fourier transform with respect to time $\rightsquigarrow$ spectral data.

2-D problems

$\partial_y \epsilon = 0,\ \epsilon(x,z) = n^2(x,z),$
$\partial_y \boldsymbol{E} = 0,\ \partial_y \boldsymbol{H} = 0;$
equations split into two subsets:



TE, E_y, H_x, and H_z, principal component E_y:

$$\mathrm{i}\omega\mu_0 H_x = \partial_z E_y, \quad \mathrm{i}\omega\mu_0 H_z = -\partial_x E_y, \quad \mathrm{i}\omega\epsilon_0\epsilon E_y = \partial_z H_x - \partial_x H_z,$$

or

$$\partial_x^2 E_y, + \partial_z^2 E_y + k^2 \epsilon E_y = 0.$$

TM, H_y, E_x, and E_z, principal component H_y:

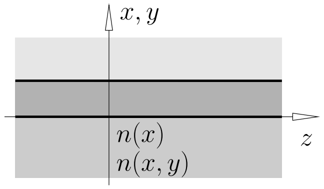
$$\mathrm{i}\omega\epsilon_0\epsilon E_x = -\partial_z H_y, \quad \mathrm{i}\omega\epsilon_0\epsilon E_z = \partial_x H_y, \quad -\mathrm{i}\omega\mu_0 H_y = \partial_z E_x - \partial_x E_z,$$

or

$$\partial_x \frac{1}{\epsilon} \partial_x H_y, + \partial_z \frac{1}{\epsilon} \partial_z H_y + k^2 H_y = 0.$$

Dielectric waveguides

$\partial_z \epsilon = 0,\ \partial_z n = 0,$ modal solutions with
profile $\tilde{\boldsymbol{E}},\ \tilde{\boldsymbol{H}},$ and propagation constant β;
$\boldsymbol{E}(x,y,z) = \tilde{\boldsymbol{E}}(x,y)\,\mathrm{e}^{-\mathrm{i}\beta z},$
$\boldsymbol{H}(x,y,z) = \tilde{\boldsymbol{H}}(x,y)\,\mathrm{e}^{-\mathrm{i}\beta z}:$



$$\boldsymbol{\mathcal{E}}(x,y,z,t) = \mathrm{Re}\,\tilde{\boldsymbol{E}}(x,y)\,\mathrm{e}^{\mathrm{i}\omega t - \mathrm{i}\beta z}, \quad \boldsymbol{\mathcal{H}}(x,y,z,t) = \mathrm{Re}\,\tilde{\boldsymbol{H}}(x,y)\,\mathrm{e}^{\mathrm{i}\omega t - \mathrm{i}\beta z}.$$

Guided modes: $\iint |\tilde{\boldsymbol{E}}|^2 \mathrm{d}x\,\mathrm{d}y < \infty, \quad \iint |\tilde{\boldsymbol{H}}|^2 \mathrm{d}x\,\mathrm{d}y < \infty.$

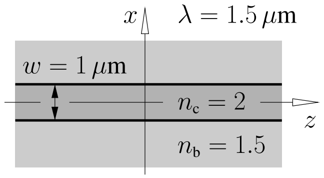
Mode solver: Eigenvalue problem for $\tilde{\boldsymbol{E}},\ \tilde{\boldsymbol{H}},$ and β.

- Basis for all kinds of design considerations,
- basis fields for various types of perturbational simulations,
- input / output fields for Helmholtz & time domain solvers.

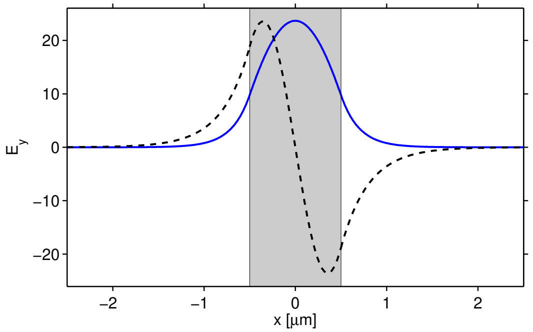
Guided modes, 2-D, TE

$$\left(\partial_x^2 + k^2 n^2(x)\right) \tilde{E}_y = \beta^2 \tilde{E}_y\,, \quad \int |\tilde{E}_y|^2 \mathrm{d}x < \infty\,, \quad \tilde{H}_x = \frac{-\beta}{\omega\mu_0} \tilde{E}_y\,, \quad \tilde{H}_z = \frac{\mathrm{i}}{\omega\mu_0} \partial_x \tilde{E}_y\,,$$

$$\boldsymbol{\mathcal{E}}(x,z,t) = \mathrm{Re}\begin{pmatrix} 0 \\ \tilde{E}_y \\ 0 \end{pmatrix}(x)\,\mathrm{e}^{\mathrm{i}\omega t - \mathrm{i}\beta z}, \qquad \boldsymbol{\mathcal{H}}(x,z,t) = \mathrm{Re}\begin{pmatrix} \tilde{H}_x \\ 0 \\ \tilde{H}_z \end{pmatrix}(x)\,\mathrm{e}^{\mathrm{i}\omega t - \mathrm{i}\beta z},$$

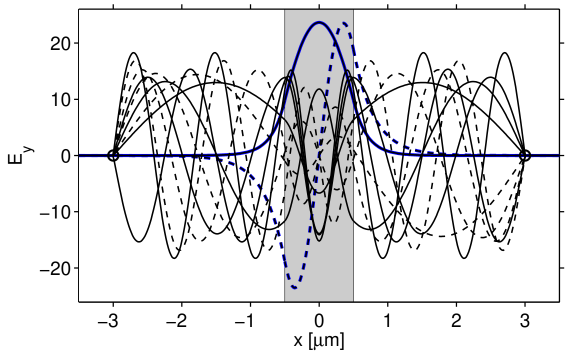


$\beta_0/k = 1.923,\ \beta_1/k = 1.697.$



- Mode propagation
- "Coupling" of modes

Modal basis sets



$$\left(\partial_x^2 + k^2 n^2(x)\right) \tilde{E}_y = \beta^2 \tilde{E}_y\,, \quad \int_{x_0}^{x_1} |\tilde{E}_y|^2 \mathrm{d}x = 1\,, \quad \tilde{E}_y(x_0) = \tilde{E}_y(x_1) = 0\,.$$

$\{\beta_j, E_{y,j}\}$: complete discrete set of eigenmodes, expansion basis.

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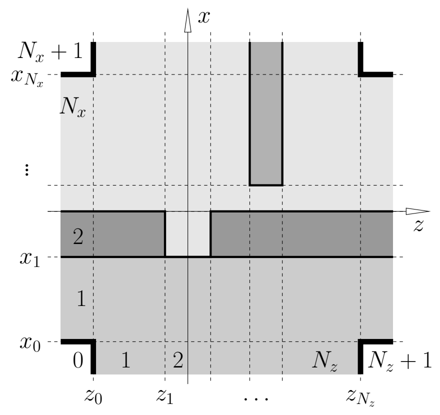
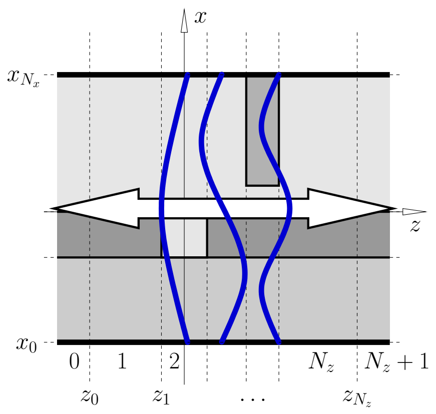
QUEP simulations, problem setting



- 2-D TE/TM Helmholtz problem, vacuum wavelength $\lambda = 2\pi/k$.
- Piecewise constant, rectangular refractive index distribution; linear, lossless materials.
- Rectangular interior computational domain, influx & outflux across all four boundaries, outwards homogeneous external regions.
- Assumption $E_y = 0$, $H_y = 0$ on the corner points and on the external border lines is reasonable for the problems under investigation.

Ingredients: "horizontal" modes

Basis fields,
defined by Dirichlet boundary conditions $E_y = 0$ (TE) or $H_y = 0$ (TM):



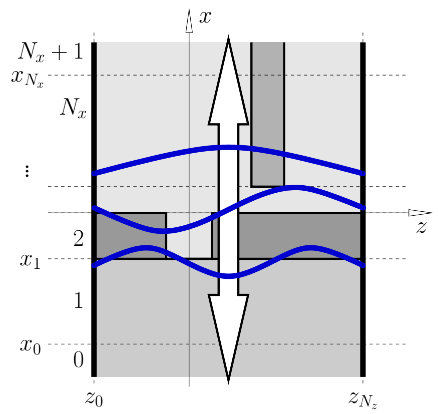
Horizontally traveling eigenmodes:

M_x profiles	$\psi^d_{s,m}(x)$
and propagation constants	$\pm\beta_{s,m}$

of order m, on slice s,
for propagation directions $d =$ f, b,

Ingredients: "vertical" modes

Basis fields,
defined by Dirichlet boundary conditions $E_y = 0$ (TE) or $H_y = 0$ (TM):

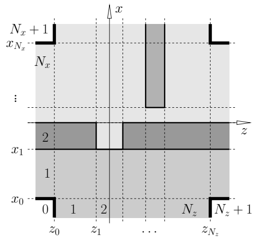


. . . *and* vertically traveling fields:

M_z profiles	$\hat\psi^d_{l,m}(z)$
and propagation constants	$\pm\hat\beta_{l,m}$

of order m, on layer l,
for propagation directions $d =$ u, d.

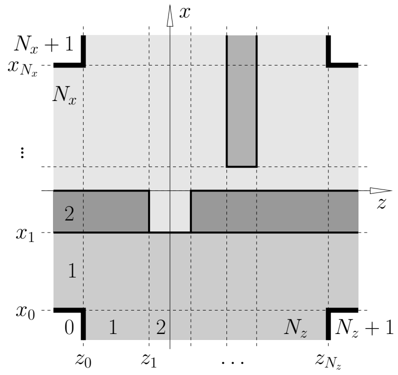
Eigenmode expansion



Ansatz for the optical field,
for $z_{s-1} \le z \le z_s,\ s = 1,\dots,N_z$,
and $x_{l-1} \le x \le x_l,\ l = 1,\dots,N_x$:

$$\begin{pmatrix} \boldsymbol{\mathcal{E}} \\ \boldsymbol{\mathcal{H}} \end{pmatrix}(x,z,t) = \mathrm{Re}\left\{ \sum_{m=0}^{M_x-1} F_{s,m}\boldsymbol{\psi}^{\mathrm{f}}_{s,m}(x)\,\mathrm{e}^{-\mathrm{i}\beta_{s,m}(z-z_{s-1})} + \sum_{m=0}^{M_x-1} B_{s,m}\boldsymbol{\psi}^{\mathrm{b}}_{s,m}(x)\,\mathrm{e}^{+\mathrm{i}\beta_{s,m}(z-z_s)} + \sum_{m=0}^{M_z-1} U_{l,m}\hat{\boldsymbol{\psi}}^{\mathrm{u}}_{l,m}(z)\,\mathrm{e}^{-\mathrm{i}\hat\beta_{l,m}(x-x_{l-1})} + \sum_{m=0}^{M_z-1} D_{l,m}\hat{\boldsymbol{\psi}}^{\mathrm{d}}_{l,m}(z)\,\mathrm{e}^{+\mathrm{i}\hat\beta_{l,m}(x-x_l)} \right\} \mathrm{e}^{\mathrm{i}\omega t}.$$

Eigenmode expansion

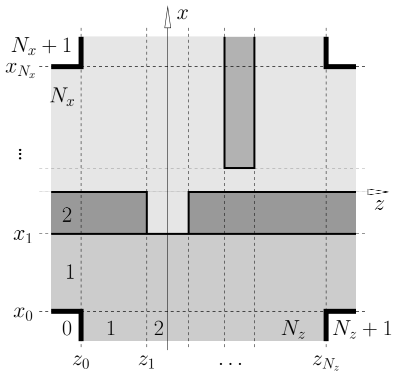


Mode products ↔ normalization, projection:

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

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

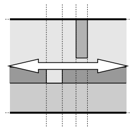
Algebraic procedure



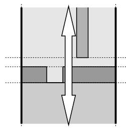
- Consistent bidirectional projection at all interfaces
  $\longrightarrow$ linear system of equations in $\{F_{s,m}, B_{s,m}, U_{l,m}, D_{l,m}\}$.
- Influx: $\boldsymbol{F}_0,\ \boldsymbol{B}_{N_x+1},\ \boldsymbol{U}_0,\ \boldsymbol{D}_{N_z+1}$ $\longrightarrow$ RHS, given.
- Outflux: $\boldsymbol{B}_0,\ \boldsymbol{F}_{N_x+1},\ \boldsymbol{D}_0,\ \boldsymbol{U}_{N_z+1}$ $\longrightarrow$ primary unknowns.

Algebraic procedure

- "Exact" mode profiles $\longrightarrow$ interior problems decouple:

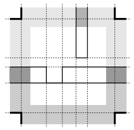


Solve for $\boldsymbol{F}_2,\dots,\boldsymbol{F}_{N_z}$ and $\boldsymbol{B}_1,\dots,\boldsymbol{B}_{N_z-1}$
in terms of $\boldsymbol{F}_1$ and $\boldsymbol{B}_{N_z}$ $\longrightarrow$ BEP I.



Solve for $\boldsymbol{U}_2,\dots,\boldsymbol{U}_{N_x}$ and $\boldsymbol{D}_1,\dots,\boldsymbol{D}_{N_x-1}$
in terms of $\boldsymbol{U}_1$ and $\boldsymbol{D}_{N_x}$ $\longrightarrow$ BEP II.

- Continuity of E and H on outer interfaces:



Interior BEP solutions
$+$ equations at $z = z_0, z_{N_z},\ x = x_0, x_{N_x}$
$\longrightarrow \boldsymbol{B}_0,\ \boldsymbol{F}_{N_x+1},\ \boldsymbol{D}_0,\ \boldsymbol{U}_{N_z+1}$.

"QUadridirectional Eigenmode Propagation method" (QUEP).

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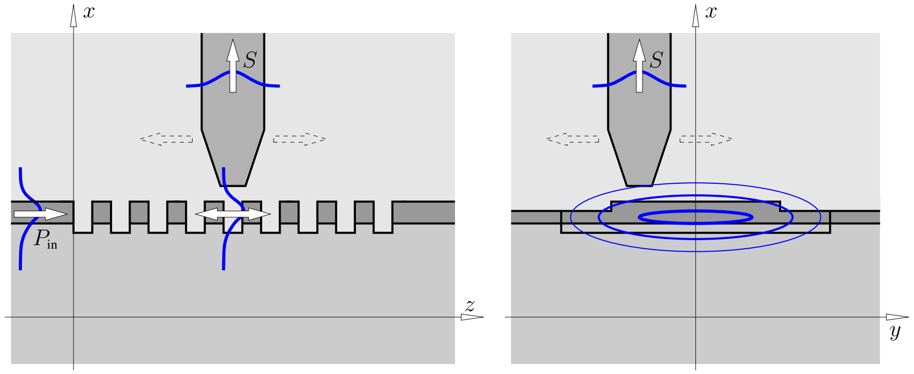
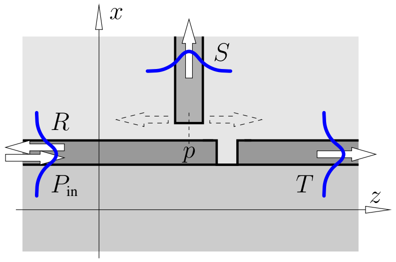
Photon scanning tunneling microscopy (PSTM) of photonic devices



Simplified 2-D model



$P_{\rm in} = 1. \quad S(p) = ?$

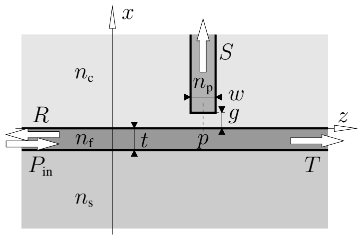
$R(p), T(p) = ?$

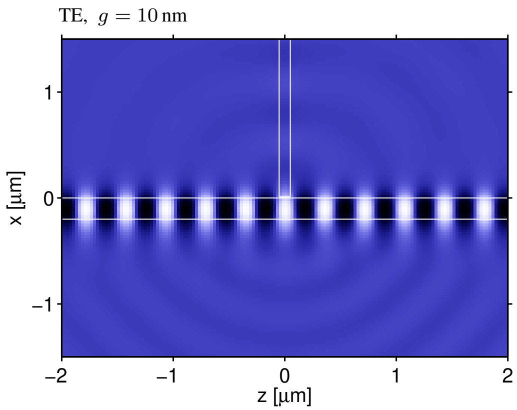
$S(p) \overset{?}{\longleftrightarrow} (\text{optical field})|_p$

Fixed optical frequency, rectangular piecewise constant refractive index, horizontal & vertical guided wave in- and outflux

$\longrightarrow$ *QUEP simulations*

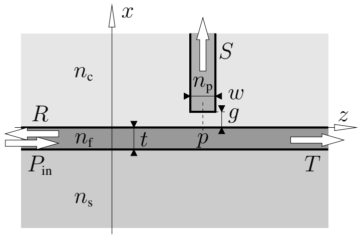
Probing evanescent fields

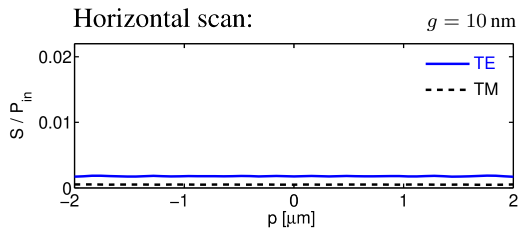




$n_{\rm s} = 1.45$, $n_{\rm f} = 2.0$, $n_{\rm c} = 1.0$, $t = 0.2\,\mu$m, $w = 100\,$nm, $n_{\rm p} = 1.5$, $\lambda = 0.633\,\mu$m, $(x, z) \in [-3.0, 3.0] \times [-3.0, 3.0]\,\mu\text{m}^2$, $M_x = M_z = 80$.

Probing evanescent fields





$n_s = 1.45$, $n_f = 2.0$, $n_c = 1.0$, $t = 0.2\,\mu$m, $w = 100\,$nm, $n_p = 1.5$,
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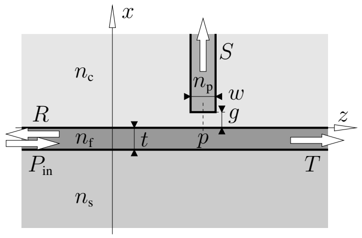
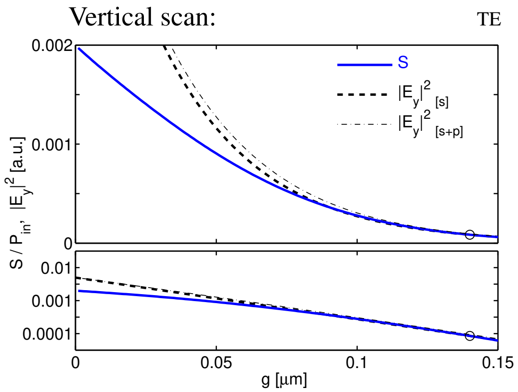
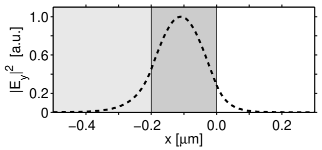
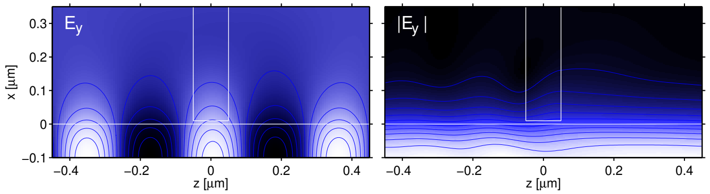
Probing evanescent fields

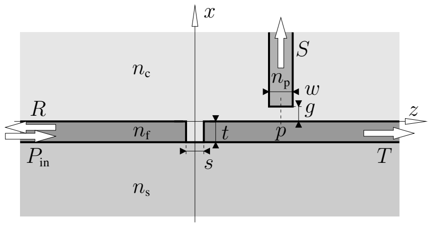


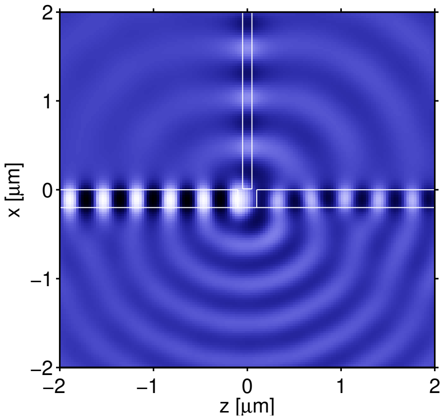






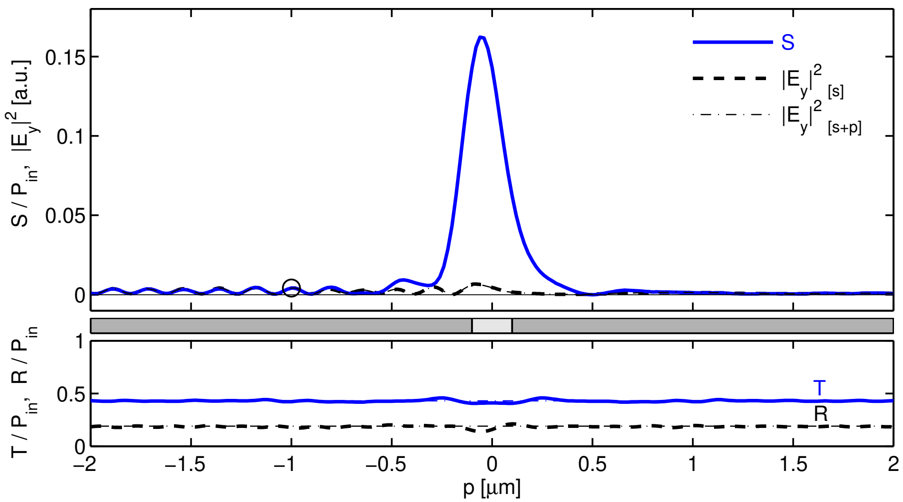
Hole defect in a slab waveguide



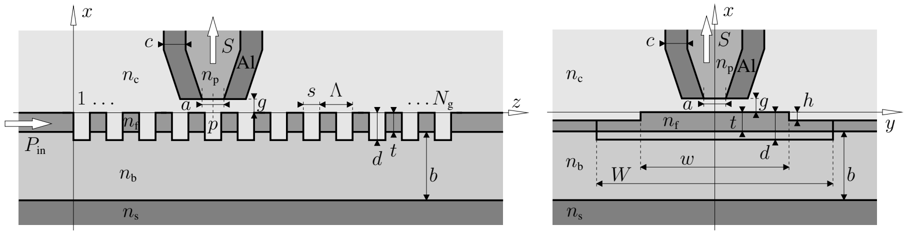


$n_s = 1.45$, $n_f = 2.0$, $n_c = 1.0$, $t = 0.2\,\mu$m, $s = 0.2\,\mu$m, $g = 10\,$nm, $w = 100\,$nm, $n_p = 1.5$,
TE, $\lambda = 0.633\,\mu$m, $(x, z) \in [-3.0, 3.0] \times [-3.1, 3.1]\,\mu\mathrm{m}^2$, $M_x = M_z = 80$.

Hole defect in a slab waveguide



Bragg grating: PSTM experiment *

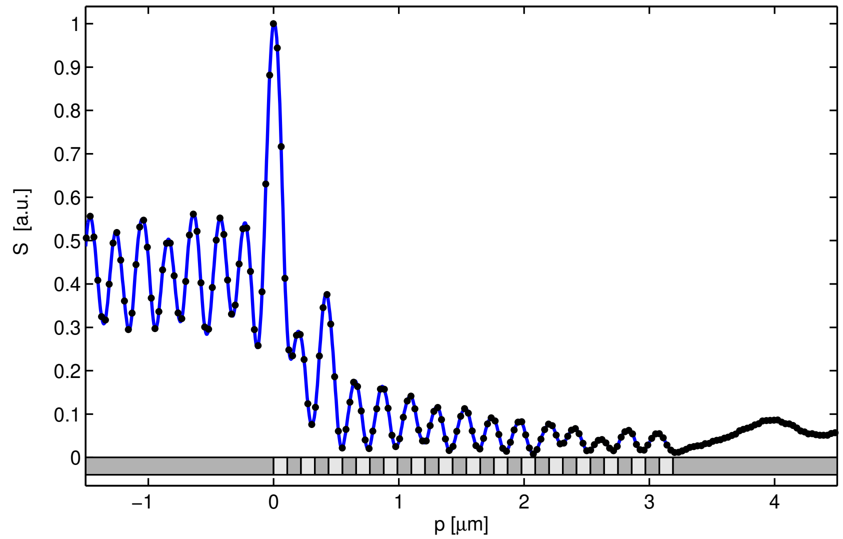


Sample: Rib waveguide with a series of deep, rectangular slits, $n_s = 3.4$, $n_b = 1.45$, $n_f = 2.01$, $n_c = 1.0$, $t = 55$ nm, $h = 11$ nm, $w = 1.5\,\mu$m, $W = 2.5\,\mu$m, $b = 3.2\,\mu$m, $\Lambda = 220$ nm, $s = 110$ nm, $d = 70$ nm, $N_g = 15$.

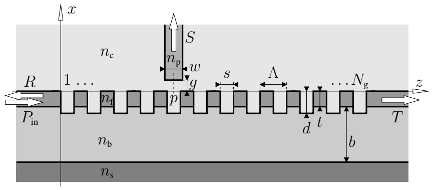
Probe: Tapered cylindrical fiber tip with aluminium coating, $a \approx 80$ nm, $c \approx 100$ nm, $g = 10$ nm, $n_p = 1.5$; TE polarized light, vacuum wavelength $\lambda = 0.6328\,\mu$m.

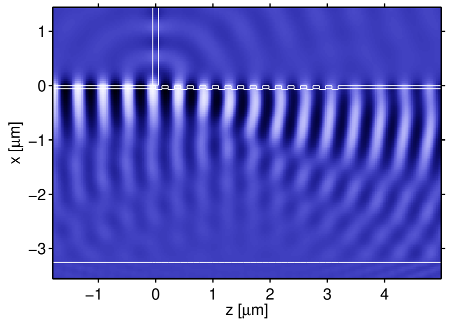
* E. Flück, M. Hammer, A. M. Otter, J. P. Korterijk, L. Kuipers, N. F. van Hulst, *Amplitude and phase evolution of optical fields inside periodic photonic structures*, Journal of Lightwave Technology **21**(5), 1384-1393 (2003)

Bragg grating: PSTM experiment



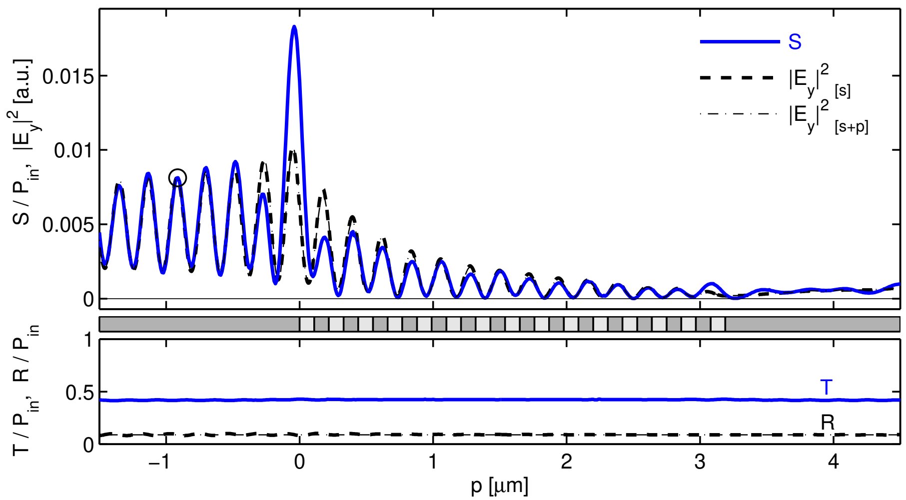
Waveguide Bragg grating



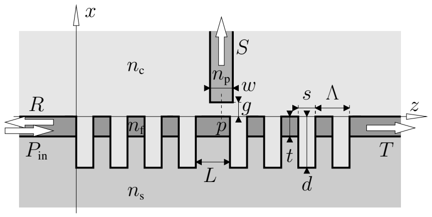


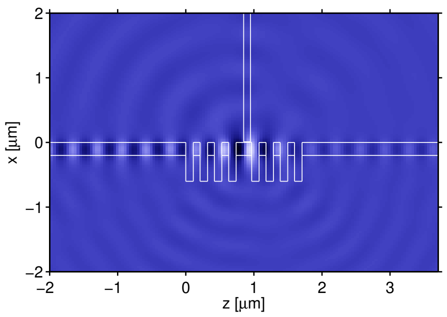
$n_s = 3.4$, $n_b = 1.45$, $n_f = 2.01$, $n_c = 1.0$, $t = 55$ nm, $b = 3.2\,\mu$m, $d = 70$ nm, $\Lambda = 220$ nm, $s = 110$ nm, $N_g = 15$, $g = 10$ nm, $w = 100$ nm, $n_p = 1.5$, TE, $\lambda = 0.6328\,\mu$m, $(x, z) \in [-3.5, 1.5] \times [-2.0, 5.2]\,\mu\text{m}^2$, $M_x = 80$, $M_z = 100$.

Waveguide Bragg grating



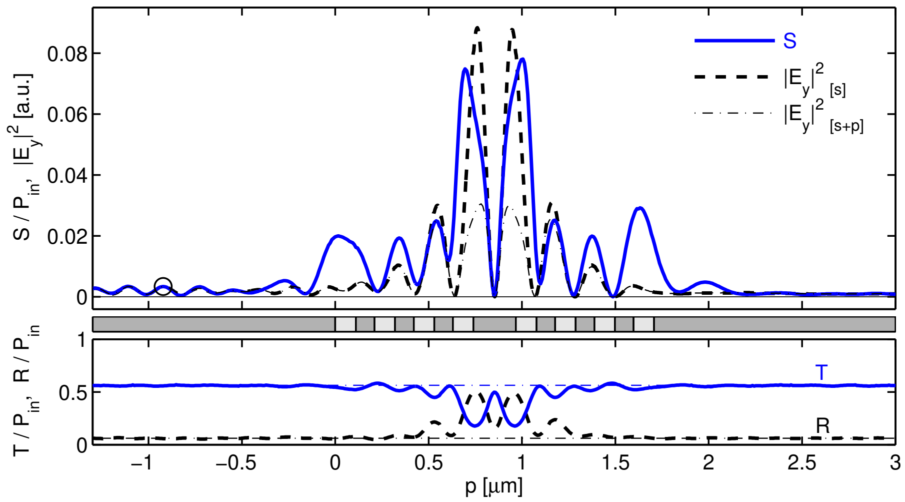
Resonant defect cavity





$n_s = 1.45$, $n_f = 2.0$, $n_c = 1.0$, $t = 0.2\,\mu$m, $d = 0.6\,\mu$m,
$\Lambda = 0.21\,\mu$m, $s = 0.11\,\mu$m, $L = 0.2275\,\mu$m, $g = 10\,$nm, $w = 100\,$nm, $n_p = 1.5$,
TE, $\lambda = 0.633\,\mu$m, $(x, z) \in [-3.0, 3.0] \times [-3.0, 4.7075]\,\mu\text{m}^2$, $M_x = 100$, $M_z = 120$.

Resonant defect cavity

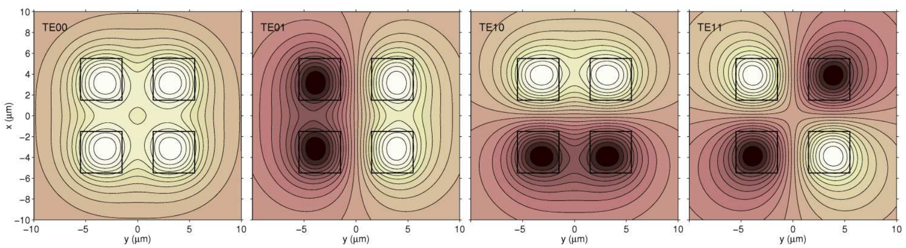


$T(p)$, $R(p)$: the probe switches the transmission.

Outline

- Simulations in guided wave optics
  - Macroscopic Maxwell equations
  - Stationary and time-domain problems
  - 2-D problems
  - Modes of dielectric waveguides
- Quadridirectional eigenmode propagation
  - Problem setting
  - Eigenmode expansion
  - Algebraic procedure
- 2-D PSTM model
  - Probing evanescent fields
  - Hole defect in a slab waveguide
  - Waveguide Bragg grating: experiment & 2-D model
  - Resonant defect cavity
- Optical switching by NEMS-actuated resonator arrays

Ongoing: TOE.7143



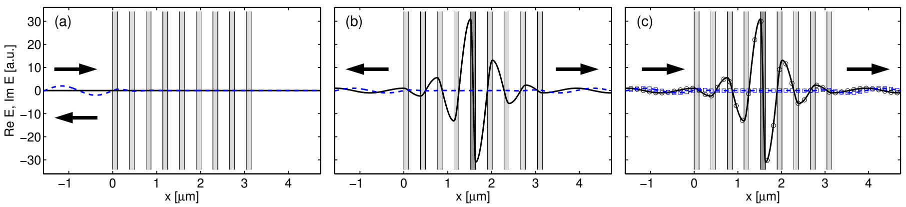
Olena Ivanova

Projection techniques for dimensionality reduction 3-D → 2-D

nano ned

NanoPhotonics Flagship, project TOE.7143
Optical switching by NEMS actuated resonator arrays — modeling & simulation tools

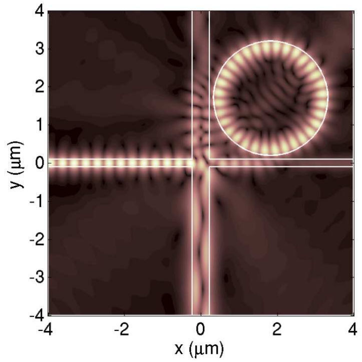
Ongoing: TOE.7143



Milan Maksimovic

Time domain characterization of resonances & perturbations

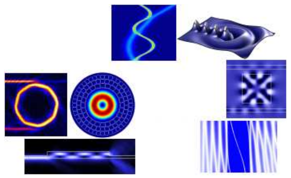
Ongoing: TOE.7143



Remco Stoffer

Numerical simulation tools
& interaction with projects
TOE.7144, NEMS, group TST (EEMCS, EL),
TOE.7145, Optics, group IOMS (EEMCS, EL).

Photonics @ AAMP



http://www.math.utwente.nl/aamp/

http://www.math.utwente.nl/aamp/research.html#MATHOPT