Small-scale online simulations in guided-wave photonics

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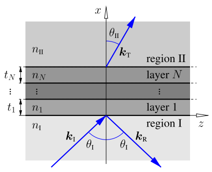
1 Online dissemination of academic simulation tools

Current mobile devices provide a computing power that is comparable to the supercomputers of two decades ago. Hence, it should be possible to harness those facilities for highly advanced physical simulations, by the standards of 2000, even if things appear merely small-scale today. With HTML5 and JavaScript, recent years have seen some standardization in the encoding of web-pages and of active content, such that it now seems worthwhile to devote effort to the realization of projects for specialized scientific audiences. We illustrate this approach with a series of quasi-analytical solvers for typical problems in guided wave photonics. The solvers are embedded in HTML-pages, with a user-interface encoded in JavaScript, including graphics facilities (inline SVG). For the actual core computations, reasonably mature C++-sources exist. With a respective tool (Emscripten) these are *compiled* to JavaScript/WebAssembly, and thus become directly available for the online computations. When comparing simulations carried out in a web-browser running the JavaScript code with a native program, where the respective C++-sources where compiled (gcc) and executed on the same desktop machine, we observed penalty factors of about 2 in computational time.

On the one hand, in a context of scientific simulations, this environment has certain shortcomings, mostly related to the particularities of the program language, and to security restrictions required for external web pages. On the other hand, all the burdens (compatibility, installation, distribution) that otherwise might prevent the use of an academic simulation tool by "others" are entirely absent. Our solvers have proven to be particularly useful for purposes of demonstration and teaching, but just as well also for other, more "serious" tasks in integrated photonics design. All programs are free to use, available online at `https://www.siio.eu`.

2 MuLS

Oblique incidence of plane waves on dielectric multilayer stacks

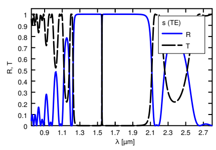


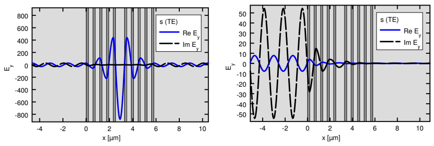
$\sim \exp(\mathrm{i}\omega t)$,
$\partial_y = 0$, 2-D TE/TM,
$\begin{pmatrix}\boldsymbol{E}\\ \boldsymbol{H}\end{pmatrix}(x,z) = \boldsymbol{\phi}(x)\,\exp(-\mathrm{i}k_{\mathrm{I},z}z)$, $k_{\mathrm{I},z} = kn_\mathrm{I}\sin\theta_\mathrm{I}$,
$\partial_x^2\phi + (k^2n^2 - k_{\mathrm{I},z}^2)\phi = 0$

scattering problem ⇝ ϕ.

A Bragg-resonator,
19 interior layers, normal incidence $\theta_\mathrm{I} = 0°$,
target wavelength $\lambda = 1.55\,\mu$m,
refractive indices $n = 1, 2, 1, 2, \ldots, 2, 1$,
quarter-wave thicknesses $t_i = \lambda/(4n_i)$,
central cavity layer $t_{10} = \lambda/(2n_{10})$.

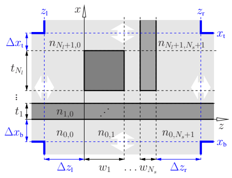
Plots: transmittance T and reflectance R versus wavelength λ, field profiles E_y at $\lambda = 1.55\,\mu$m, at resonance, and at $\lambda = 1.7\,\mu$m, off-resonance, in the reflectance bandgap.





3 QuEPS

2-D frequency domain solver for rectangular optical guided-wave scattering problems



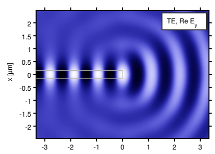
$\sim \exp(\mathrm{i}\omega t)$,
$\partial_y = 0$, 2-D TE/TM,
$\partial_x^2\phi + \partial_z^2\phi + k^2n^2\phi = 0$

scattering problem ⇝ ϕ.

Facet of a slab waveguide,
a Si_3N_4-core ($n = 1.99$) of thickness $t_1 = 0.3\,\mu$m surrounded by SiO_2 ($n = 1.45$). Incidence of the guided TE_0-wave at vacuum wavelength $\lambda = 1.55\,\mu$m leads to about 2% reflectance.

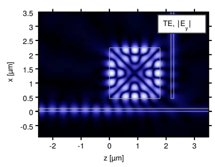
QUEP-computation with 124×133 spectral terms, $(x_\mathrm{t} - x_\mathrm{b}) \times (z_\mathrm{r} - z_\mathrm{l}) = 9.6 \times 10.3\,\mu\mathrm{m}^2$.

Plot: snapshot of the principal TE component E_y.



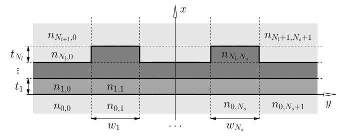
A square 2-D microresonator
with perpendicular port waveguides, cores of thickness $t_1 = w_3 = 0.1\,\mu$m, separated by gaps $t_2 = 0.355\,\mu$m, $w_2 = 0.385\,\mu$m from the cavity of dimension $w_1 \times t_3 = 1.786\,\mu\mathrm{m}^2$, index contrast $3.4 : 1.0$; TE_0-excitation from the left at $\lambda = 1.55\,\mu$m, guided output power 22% (left), 46% (top), 22% (right).

133×133 spectral terms,
$(x_\mathrm{t} - x_\mathrm{b}) \times (z_\mathrm{r} - z_\mathrm{l}) = 10.2 \times 10.3\,\mu\mathrm{m}^2$.
Plot: principal TE component E_y, absolute value.



4 EIMS

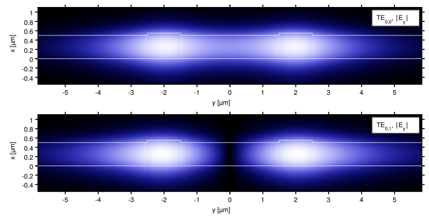
2-D multilayer waveguide mode solver, variational effective index approximation



$\sim \exp(\mathrm{i}\omega t)$, $\partial_z n = 0$, $(\boldsymbol{E},\boldsymbol{H})(x,y,z) = \boldsymbol{\phi}(x,y)\,\exp(-\mathrm{i}\beta z)$, $\beta = kN_\mathrm{eff}$,
variational effective index approximation, semivectorial, separable components

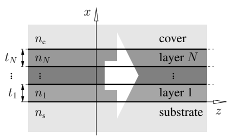
eigenvalue problem ⇝ $\approx\beta, \approx\boldsymbol{\phi}$.

Coupler of two rib waveguides,
shallow ribs with thicknesses $t_1 = 0.5\,\mu$m, $t_2 = 0.05\,\mu$m, of widths $w_1 = w_3 = 1\,\mu$m, at a distance of $w_2 = 3\,\mu$m, refractive index contrast $1.45 : 1.99 : 1.0$. At wavelength $\lambda = 1.55\,\mu$m, the VEIMS solver identifies two quasi-TE-modes with effective indices $N_\mathrm{eff} = 1.77202$ ($TE_{0,0}$) and $N_\mathrm{eff} = 1.76965$ ($TE_{0,1}$), and thus predicts a coupling length $L_\mathrm{c} = 328\,\mu$m.



5 OMS

1-D mode solver for dielectric multilayer slab waveguides

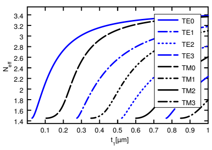


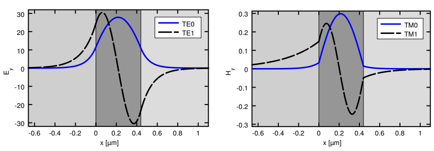
$\sim \exp(\mathrm{i}\omega t)$,
$\partial_y = 0$, 2-D TE/TM,
$\begin{pmatrix}\boldsymbol{E}\\ \boldsymbol{H}\end{pmatrix}(x,z) = \boldsymbol{\phi}(x)\,\exp(-\mathrm{i}\beta z)$, $\beta = kN_\mathrm{eff}$,
$\partial_x^2\phi + (k^2n^2 - \beta^2)\phi = 0$

eigenvalue problem ⇝ β, ϕ.

A standard Si/SiO_2 slab waveguide,
air cladding, vacuum wavelength $\lambda = 1.55\,\mu$m,
refractive indices $n = 1.45, 3.45, 1.0$.

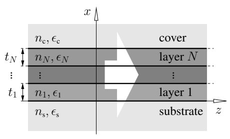
Plots: effective indices N_eff of guided modes versus the thickness t_1 of the core layer, fundamental and first order modes for a layer of thickness $t_1 = 0.44\,\mu$m, principal components E_y and H_y of TE- and TM-modes, respectively.





6 PlasS

1-D mode solver for attenuating, amplifying, or leaky optical multilayer step-index slab waveguides



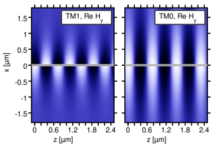
$\sim \exp(\mathrm{i}\omega t)$,
$\partial_y = 0$, 2-D TE/TM,
$\begin{pmatrix}\boldsymbol{E}\\ \boldsymbol{H}\end{pmatrix}(x,z) = \boldsymbol{\phi}(x)\,\exp(-\mathrm{i}\gamma z)$, $\gamma = kN_\mathrm{eff} = \beta - \mathrm{i}\alpha \in \mathbb{C}$,
$\partial_x^2\phi + (k^2\epsilon - \gamma^2)\phi = 0$

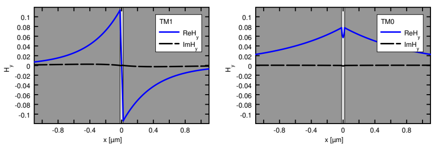
eigenvalue problem ⇝ γ, ϕ.

A thin gold layer in air,
thickness 40 nm, at wavelength $\lambda = 0.775\,\mu$m,
permittivity $\epsilon = 1.0 : -23.6 - \mathrm{i}1.69 : 1.0$.

"Short-range" (TM_1, SR) and "long-range" (TM_0, LR) surface-plasmon-polariton (SPP) modes are supported, with effective indices N_eff of $1.04805 - \mathrm{i}5.69\cdot10^{-3}$ (SR), $1.00976 - \mathrm{i}2.77\cdot10^{-4}$ (LR), and propagation lengths $L_\mathrm{p} = 1/(2\alpha)$ of $10.8\,\mu$m (SR), $222.3\,\mu$m (LR).

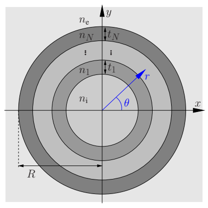
Plots: propagation snapshots and profiles of the principal magnetic field component H_y.





7 FiMS

Modes of circular multi-step index optical fibers



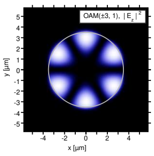
$\sim \exp(\mathrm{i}\omega t)$,
$x, y, z \to r, \theta, z$, $\partial_\theta n = \partial_z n = 0$,
$l \in \mathbb{Z}$,
$\begin{pmatrix}\boldsymbol{E}\\ \boldsymbol{H}\end{pmatrix}(r,\theta,z) = \boldsymbol{\phi}(r)\,\exp(-\mathrm{i}l\theta - \mathrm{i}\beta z)$, $\beta = kN_\mathrm{eff}$,
$\partial_r^2\phi + r^{-1}\partial_r\phi + (k^2n^2 - r^{-2}l^2 - \beta^2)\phi = 0$

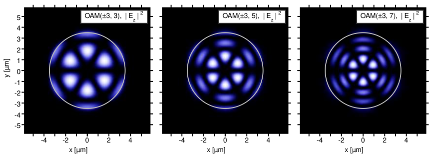
eigenvalue problem ⇝ β, ϕ.

A multimode step-index fiber,
refractive index $1.45 : 1.0$, core radius $R = 3.5\,\mu$m,
vacuum wavelength $\lambda = 1.55\,\mu$m.

The fiber supports (among several others) orbital-angular-momentum modes OAM$(\pm3, m)$ of angular order ±3 with effective indices N_eff of 1.4082 ($m = 1$), 1.3349 ($m = 3$), 1.2232 ($m = 5$), and 1.0705 ($m = 7$).

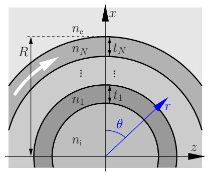
Plots: axial electric field $|E_z|^2$ for superpositions of OAM$(-3, m)$ and OAM$(3, m)$ (degenerate), unit amplitudes.





8 BendS

1-D mode solver for slab waveguide bends

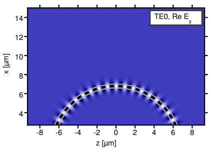


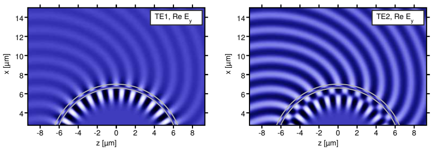
$\sim \exp(\mathrm{i}\omega t)$,
$\partial_y = 0$, 2-D TE/TM,
$x, y, z \to r, \theta, y$, $\partial_\theta n = 0$,
$\begin{pmatrix}\boldsymbol{E}\\ \boldsymbol{H}\end{pmatrix}(r,\theta) = \boldsymbol{\phi}(r)\,\exp(-\mathrm{i}\gamma R\theta)$, $\gamma = kN_\mathrm{eff} \in \mathbb{C}$,
$\partial_r^2\phi + r^{-1}\partial_r\phi + (k^2n^2 - r^{-2}\gamma^2R^2)\phi = 0$

eigenvalue problem ⇝ γ, ϕ.

A bent slab waveguide,
SiO_2/Si_3N_4 layers with air cladding, index contrast $1.45 : 1.99 : 1.0$, core thickness $t_1 = 0.4\,\mu$m, bend radius $R = 7\,\mu$m (outer rim), TE waves at vacuum wavelength $\lambda = 1.55\,\mu$m.

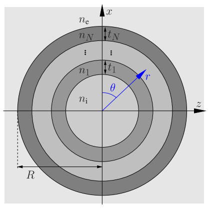
Plots: modes of lowest radial order with effective indices $N_\mathrm{eff} = 1.65 - \mathrm{i}\,1.4\cdot10^{-13}$ (TE_0), $1.17 - \mathrm{i}\,2.9\cdot10^{-4}$ (TE_1), $1.02 - \mathrm{i}\,6.4\cdot10^{-3}$ (TE_2); principal electric component E_y, time snapshots.





9 WGMs

Whispering gallery modes of circular 2-D dielectric optical cavities

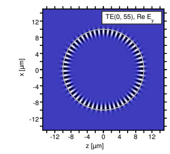


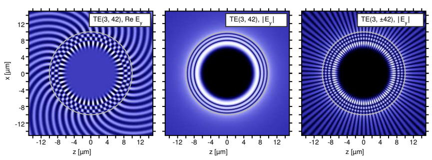
$\partial_y = 0$, 2-D TE/TM,
$x, y, z \to r, \theta, y$, $\partial_\theta n = 0$,
$m \in \mathbb{Z}$,
$\begin{pmatrix}\boldsymbol{E}\\ \boldsymbol{H}\end{pmatrix}(r,\theta,t) = \boldsymbol{\phi}(r)\,\exp(\mathrm{i}\omega_\mathrm{c}t - \mathrm{i}m\theta)$, $\omega_\mathrm{c} \in \mathbb{C}$,
$\partial_r^2\phi + r^{-1}\partial_r\phi + (c^{-2}\omega_\mathrm{c}^2n^2 - r^{-2}m^2)\phi = 0$

eigenvalue problem ⇝ ω_c, ϕ.

A dielectric disk,
refractive index contrast $1.5 : 1.0$, radius $R = 10\,\mu$m,
TE waves at target vacuum wavelength $\lambda = 1.55\,\mu$m.

Plots: whispering gallery modes of specific radial and angular order, with resonance wavelength $\lambda_\mathrm{r} = 1.548\,\mu$m and quality factor $Q = 2.3\cdot10^8$ ($TE_{0,55}$), $\lambda_\mathrm{r} = 1.538\,\mu$m and $Q = 1.6\cdot10^2$ ($TE_{3,42}$); time snapshots of the principal E_y field and absolute value $|E_y|$, for single WGMs and for a superposition of degenerate modes $TE_{3,42}$ and $TE_{3,-42}$.





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