Modelling methods for high-index contrast linear and non-linear nanophotonics

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Outline

- Eigenmode expansion for Kerr NL
- Complex Jacobi for Kerr NL
- RCWA for light extraction in OLEDs
Linear mode-expansion

Division of structure in longitudinally invariant sections

- Field in a section described by a superposition of local eigenmodes

- Mode amplitudes calculated using a scattering-matrix approach

\[
\begin{pmatrix} \overline{E(r)} \end{pmatrix}, \begin{pmatrix} \overline{H(r)} \end{pmatrix} \leftrightarrow \begin{pmatrix} \overline{A} \end{pmatrix} = \begin{bmatrix} A_i \end{bmatrix}
\]
Kerr effect

Index depends on local field intensity

\[ n = n_{linear} + n_{Kerr} I \]

Grid + iteration of linear simulations

\[
\begin{align*}
\text{if} \quad n_{old} &\approx n_{new} : \text{solved} \\
\text{else} \quad n_{old} &\leftarrow n_{new}
\end{align*}
\]
Characteristics of method

Flexibility :
- Generic 2D structures: finite AND infinite
- Saturable Kerr, absorption, ...

Rigorous

Bidirectional ↔ standard BPM

Efficiency
- Linear parts need only one calculation
- Small non-linear sections
- CW-solutions
  ↔ FDTD: long pulses
- Adaptive grid straightforward
  ↔ FDTD: boundary difficulties
Resonator next to waveguide

PhC flip flop
Concept of the 2D gap soliton

Frequency in band gap

- Linear:
  Without defects $\rightarrow$ Exponential dampening
  With defects $\rightarrow$ Waveguide

- Kerr nonlinear:
  Field creates its own defect
  $\rightarrow$ Gap soliton
Infinite structures

Iterative eigenmode expansion

\[ n_{\text{new}} = n_{\text{lin}} + n_{\text{Kerr}} |E|^2 \]

Linear Bloch mode

Normalize

\[ |E|^2 \]

E-wall

Bloch boundary

H-wall
Gap soliton
Zoology

On-site

Regular PhC

\( n_{Kerr} < 0 \)

Inter-site

Diatomic PhC

\( n_{Kerr} > 0 \)

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Complex Jacobi Iteration

- promising new numerical method
- proposed by R. Hadley in 2004
- frequency domain solver
- finite differences
- iterative
- good performance, even in 3D
Linear complex Jacobi

Initial field: \( e_{i,j}^0 \)

\[
e_{i,j}^{n+1} = e_{i,j}^n - C_1 \left( \delta_x^2 e + \delta_y^2 e + k_0^2 \varepsilon e \right)
\]

\[
e_{i,j}^{n+2} = e_{i,j}^{n+1} - C_2 \left( \delta_x^2 e + \delta_y^2 e + k_0^2 \varepsilon e \right)
\]

Regular Jacobi iteration

Complex Jacobi iteration, \( C_1 \) and \( C_2 \) complex, \( C_1 = -C_2^* \)

Non linear complex Jacobi

initial field = \( e_{i,j}^0 \)

\[
\begin{align*}
  e_{i,j}^{n+1} &= e_{i,j}^n - C_1 \left( \delta_x^2 e + \delta_y^2 e + k_0^2 \varepsilon e \right) \\
  e_{i,j}^{n+1} &= e_{i,j}^n - C_2 \left( \delta_x^2 e + \delta_y^2 e + k_0^2 \varepsilon e \right) \\
  n_{i,j}^n &= n_{\text{linear}} + n_2 \text{abs}(e_{i,j}^n)^2
\end{align*}
\]
non-linear 1D resonator

Transmission

linear

non-linear

\( \lambda [\mu m] \)

\( n: \) refractive index

Bragg-mirror

Bragg-mirror
Comparison with EME
2D spatial soliton

linear case: diffraction

non-linear case: soliton creation

field injection
Vertical grating coupler

Feedback + non linearity >> optical bistability?
even symmetry breaking: switch?

Collaboration Marc Haelterman (ULB)
Field profiles

\[
n = n_0 + n_2 \text{abs}(E)^2 \quad (n_2 = 10^{-15}-10^{-13}\text{cm}^2/\text{V}^2)
\]

spot of 30 mW on 4 μm x 4 μm:
> 1.2e6 V/m
Transmission spectra

\[ n_2 = 10^{-13} \text{ cm}^2/\text{V}^2 = 10^{-17} \text{ m}^2/\text{V}^2 \]
## Comparison EME and CJ

<table>
<thead>
<tr>
<th>Eigenmode Expansion</th>
<th>Complex Jacobi</th>
</tr>
</thead>
<tbody>
<tr>
<td>+ Fast, requires not many iterations</td>
<td>+ does allow non linearity in entire simulation space, extremely flexible</td>
</tr>
<tr>
<td>+ linear regions are calculated only once.</td>
<td>+ easy algorithm</td>
</tr>
<tr>
<td>- diverges for a smaller non linearity than CJ</td>
<td>- not as fast as EME</td>
</tr>
<tr>
<td>- depends on a grid in the non linear section (calculation of eigenmodes becomes a bottle neck)</td>
<td>- requires a grid in the entire simulation space</td>
</tr>
<tr>
<td></td>
<td>- results are not as intuitive</td>
</tr>
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</table>
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Light extraction from white OLEDs

- $n = 1.7$, 40%
- $n = 1.5$, 40%
- $n = 1.0$, 20%

Emitted Light

Internal reflections (lost).
Model

We want to model:

• spontaneous emission in organic stack

• influence of grating at OLED/glass interface in 3D

• influence of grating at glass/air interface in 3D

lateral structures: wavelength scale
application: white light for lighting
Grating at glass-air interface

perspective view:

side view:
Modelling method

1: calculate field profile emitted by OLED into the substrate
   - expand dipole in plane waves
   - interference in planar stack

2: bounce this field up and down in substrate
   - use RCWA to calculate grating scattering
   - use powers instead of amplitudes!
Influence of period

![Graph showing the influence of period on efficiency and wavelength. The x-axis represents the wavelength, and the y-axis represents the efficiency. Different lines indicate different periods: period = 0.6 µm, period = 1.0 µm, period = 1.4 µm, and planar. The graph compares the efficiency of air and glass under varying x-period and y-period lengths.](image-url)
Influence of depth

![Graph showing the influence of depth on efficiency with different wavelengths (λ = 430 nm, 550 nm, 670 nm). The x-axis represents depth in [μm], and the y-axis represents efficiency. The graph compares air and glass in terms of length and x-period.]
## Summary

<table>
<thead>
<tr>
<th>Grating</th>
<th>Extraction Efficiency</th>
<th>Increase (compared with planar)</th>
</tr>
</thead>
<tbody>
<tr>
<td>![Grating Image]</td>
<td>0.65-0.70</td>
<td>± 50%</td>
</tr>
<tr>
<td>![Grating Image]</td>
<td>± 0.70</td>
<td>± 50%</td>
</tr>
</tbody>
</table>
Experiments

grating attached to 3 mm x 3 mm OLED with an optical contact fluid
Grating at OLED side

- similar in principle to previous case
- but: use amplitudes instead of powers
- average over dipole position

Glass substrate
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Influence of fill factor

Fill factor = length glass/period