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

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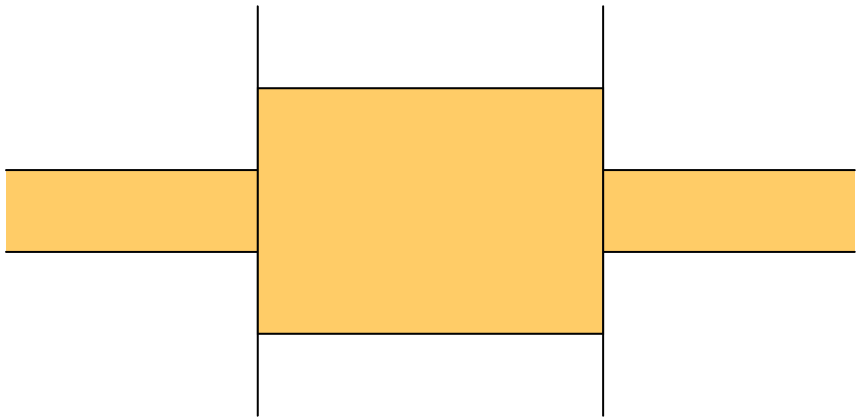
Outline

- 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

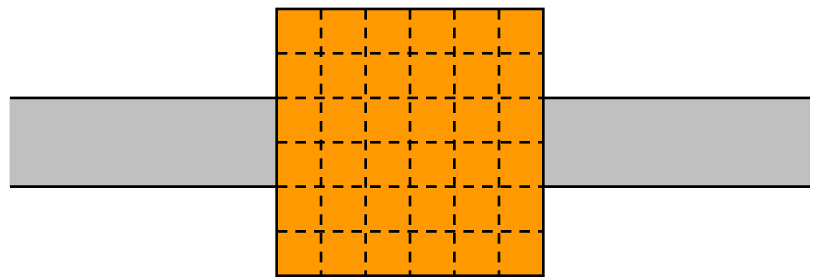
$$\left(\overline{E}(\overline{r}), \overline{H}(\overline{r})\right) \leftrightarrow \overline{A} = \left[A_i\right]$$

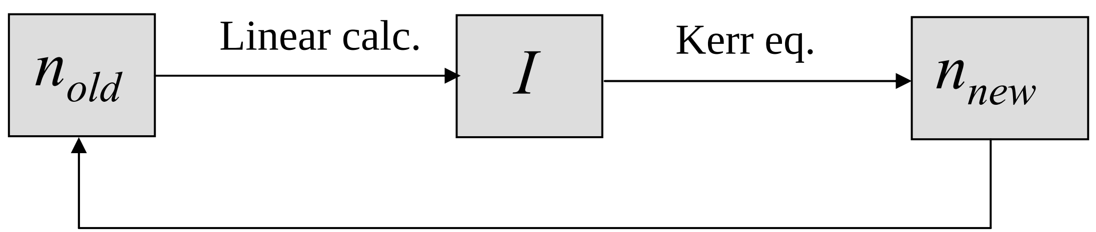
Kerr effect

Index depends on local field intensity

$$n = n_{linear} + n_{Kerr} I$$

Grid + iteration of linear simulations





if $\quad n_{old} \approx n_{new}$: solved

else $\quad n_{old} \leftarrow n_{new}$

Characteristics of method

Flexibility :

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

Rigorous

Bidirectional ↔ standard BPM

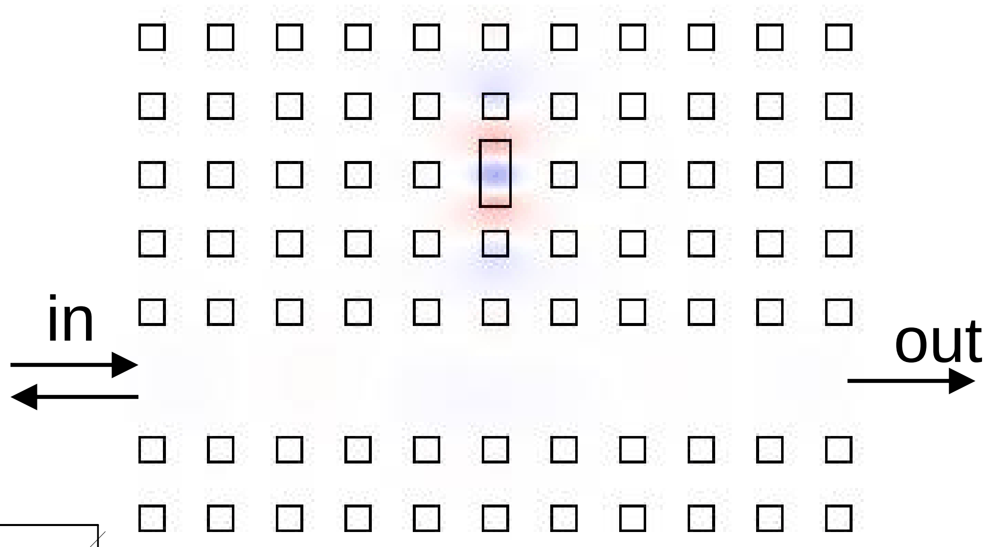
Efficiency

- Linear parts need only one calculation
- Small non-linear sections
- CW-solutions

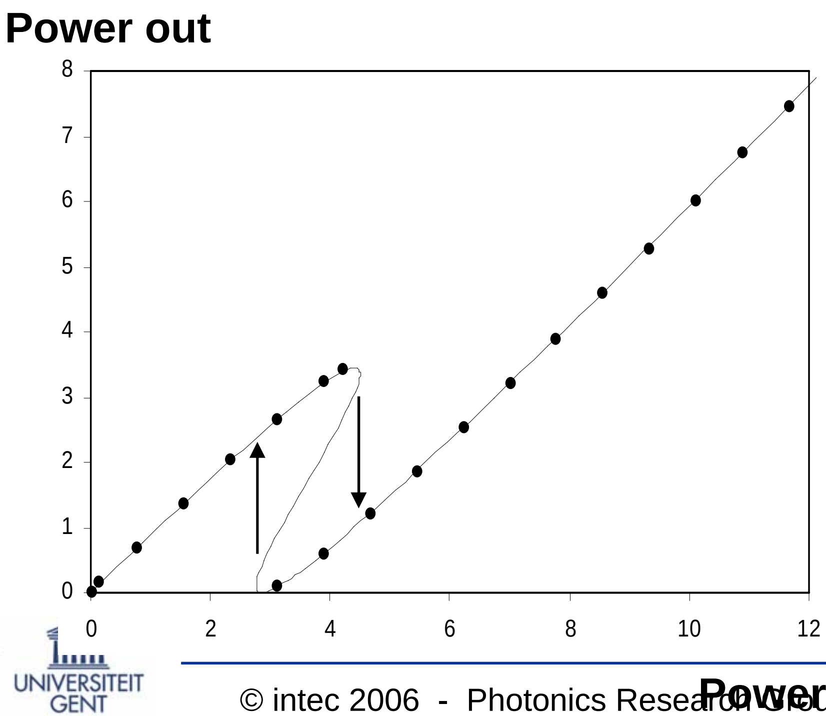
  ↔ FDTD: long pulses
- Adaptive grid straightforward

  ↔ FDTD: boundary difficulties

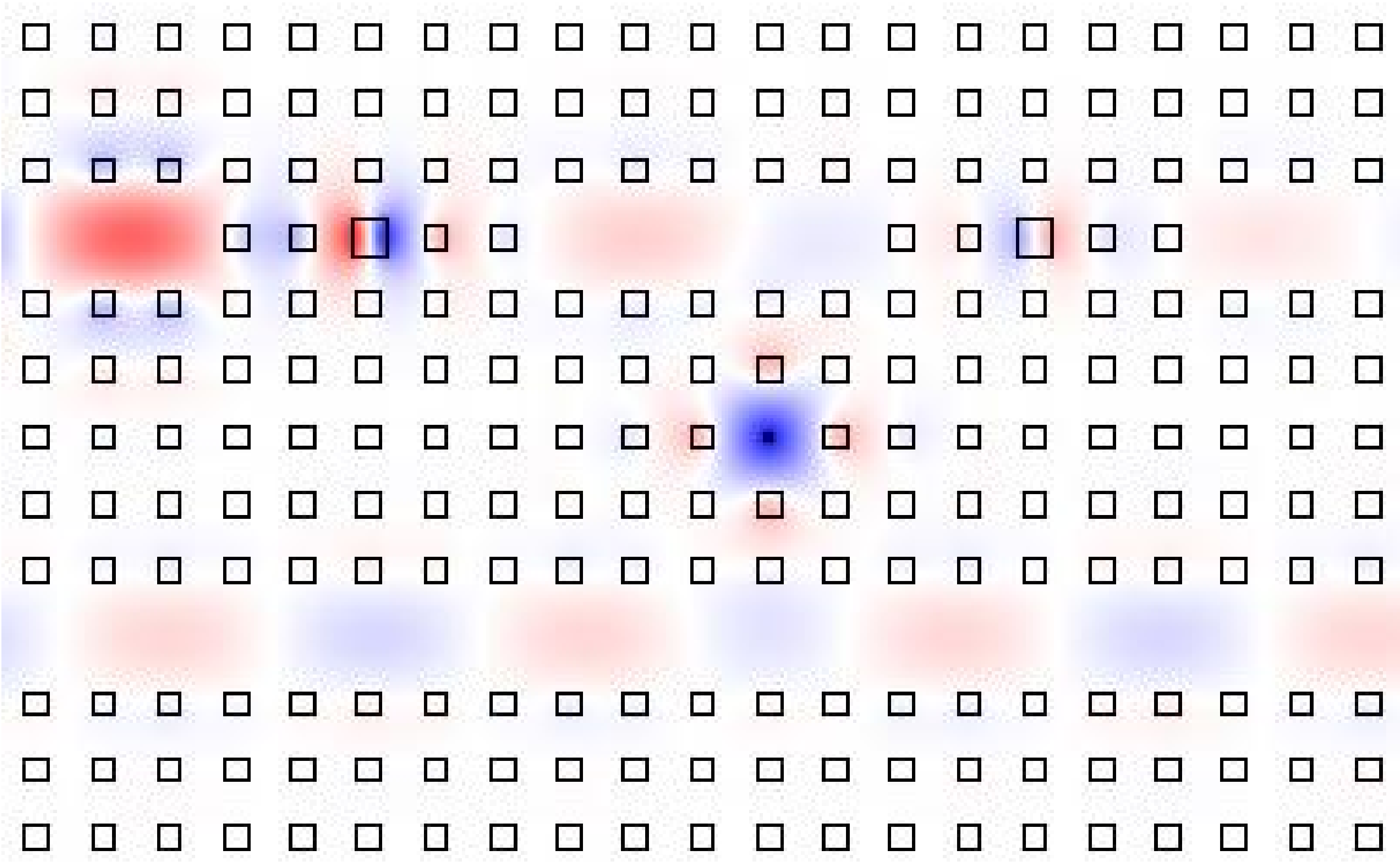
Resonator next to waveguide



Yanik et al, APL, 2003.



PhC flip flop



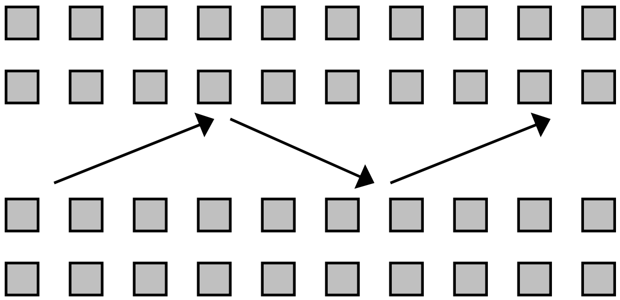
Concept of the 2D gap soliton

Frequency in band gap

- **Linear:**

  Without defects → Exponential dampening

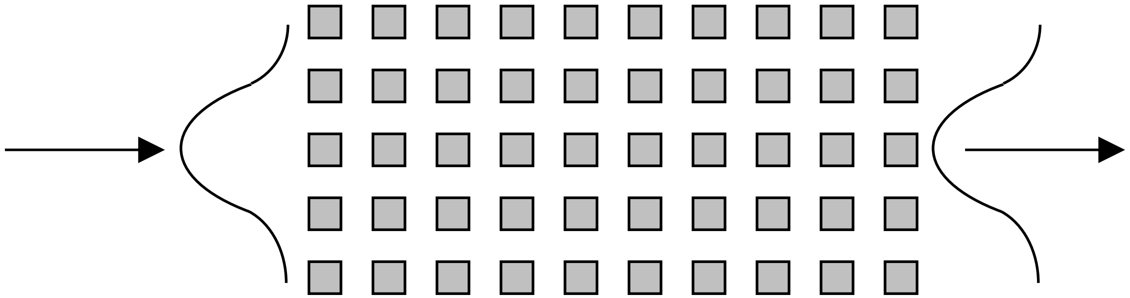
  With defects → Waveguide



- **Kerr nonlinear:**

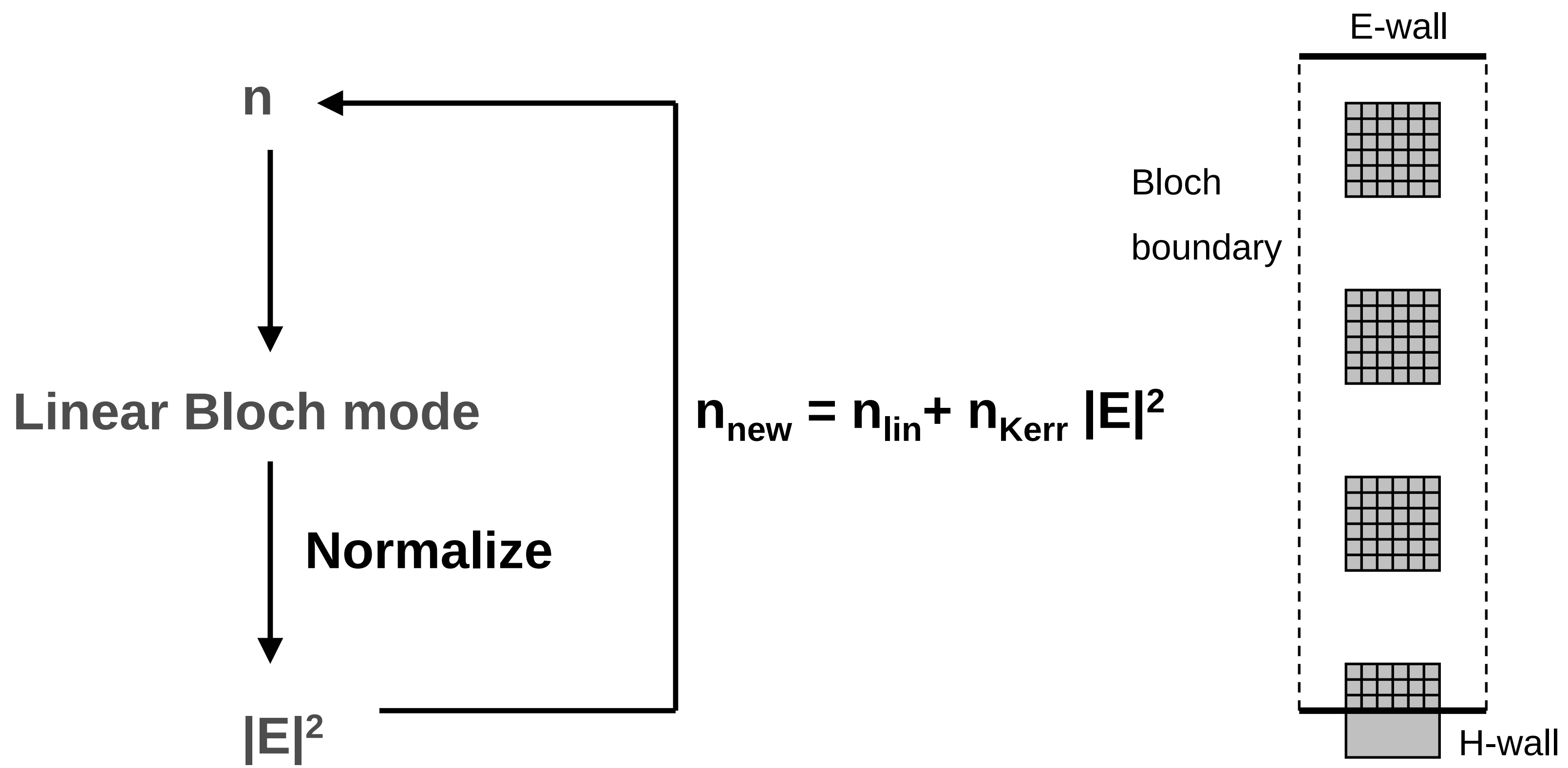
  Field creates its own defect

  → Gap soliton

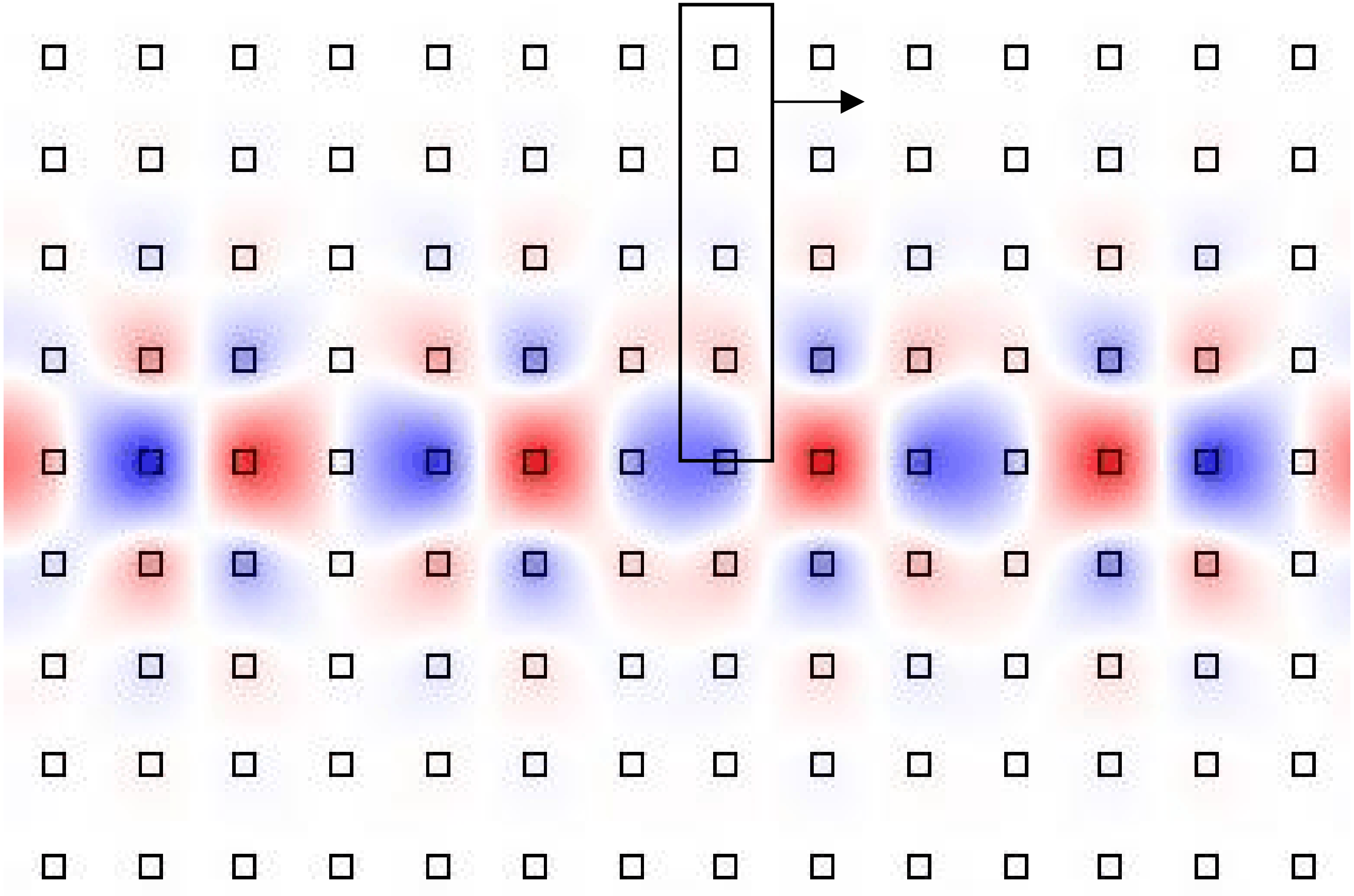


Infinite structures

Iterative eigenmode expansion



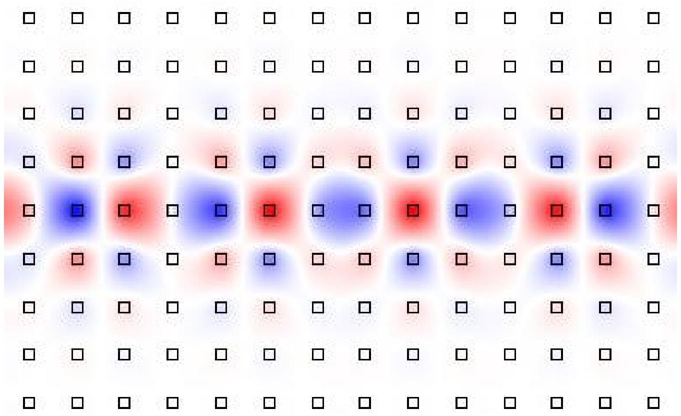
Gap soliton

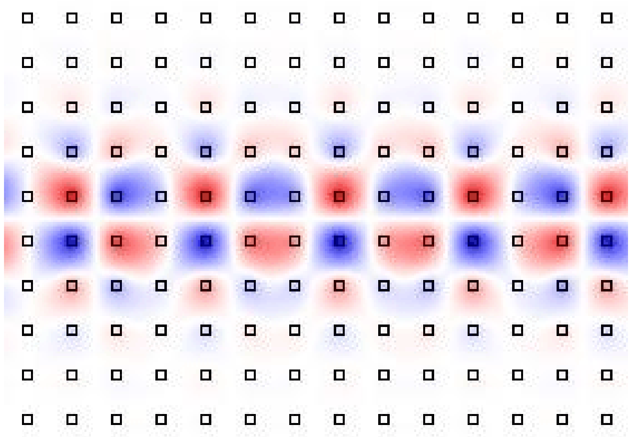


Zoology

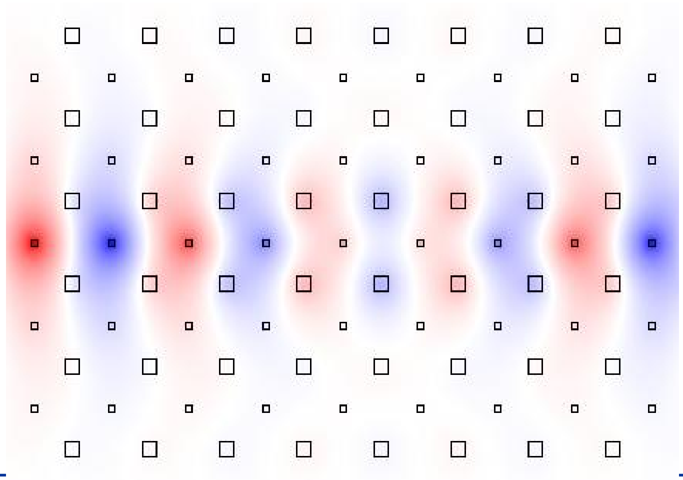
On-site | **Inter-site**

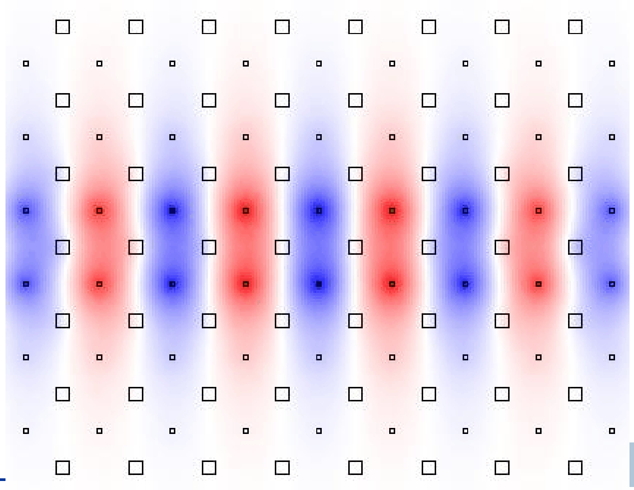
Regular PhC $n_{Kerr}<0$





Diatomic PhC $n_{Kerr}>0$





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imec

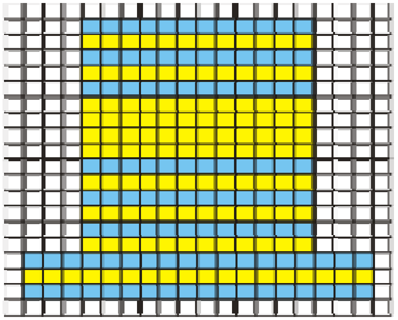
Outline

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

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



$$\text{initial field} = e^{0}_{i,j}$$

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

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

regular Jacobi iteration

complex Jacobi iteration, C_1 and C_2 complex, $C_1 = -C_2^*$

G. Ronald Hadley, "A complex Jacobi iterative method for the indefinite Helmholtz equation“, *Journal of Computational Physics*, 203 pp.358-370 (2005) .

Non linear complex Jacobi

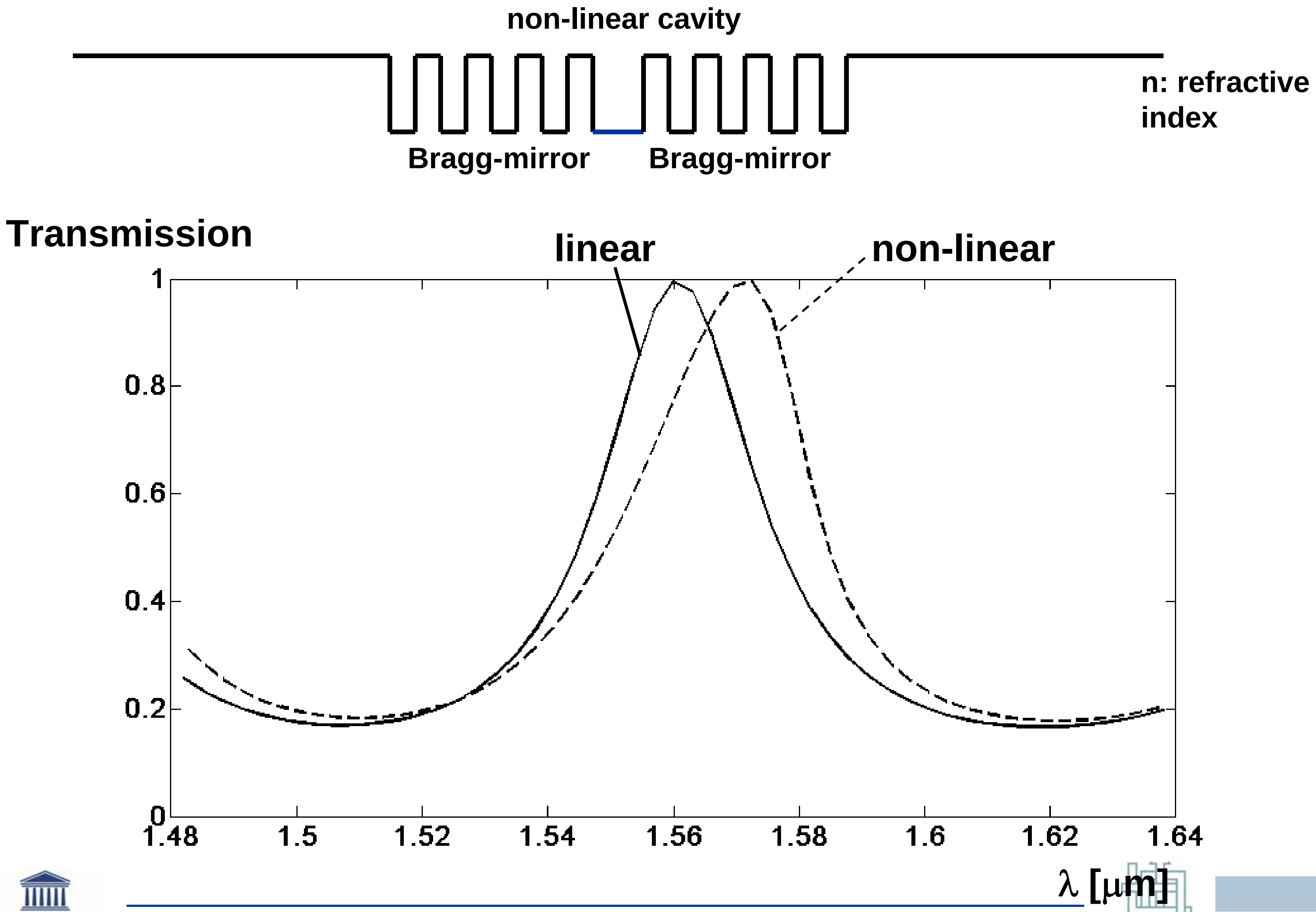
$$\text{initial field} = e_{i,j}^{0}$$

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

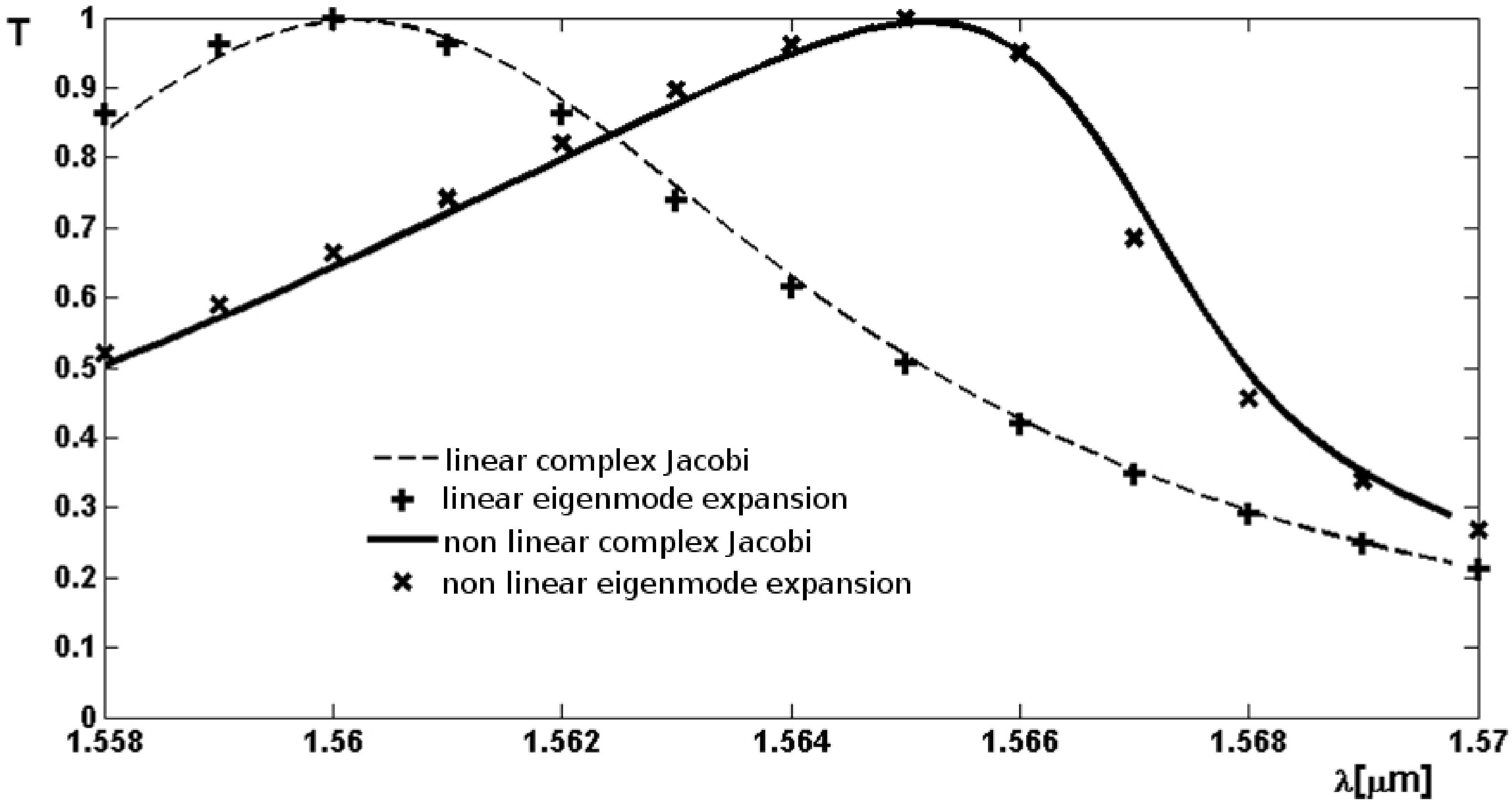
$$e_{i,j}^{n+1} = e_{i,j}^{n} - C_2\left(\delta_x^2 e + \delta_y^2 e + k_0^2 \varepsilon e\right)$$

$$n_{i,j}^{n} = n_{\text{linear}} + n_2 \text{abs}(e_{i,j}^{n})^2$$

non-linear 1D resonator



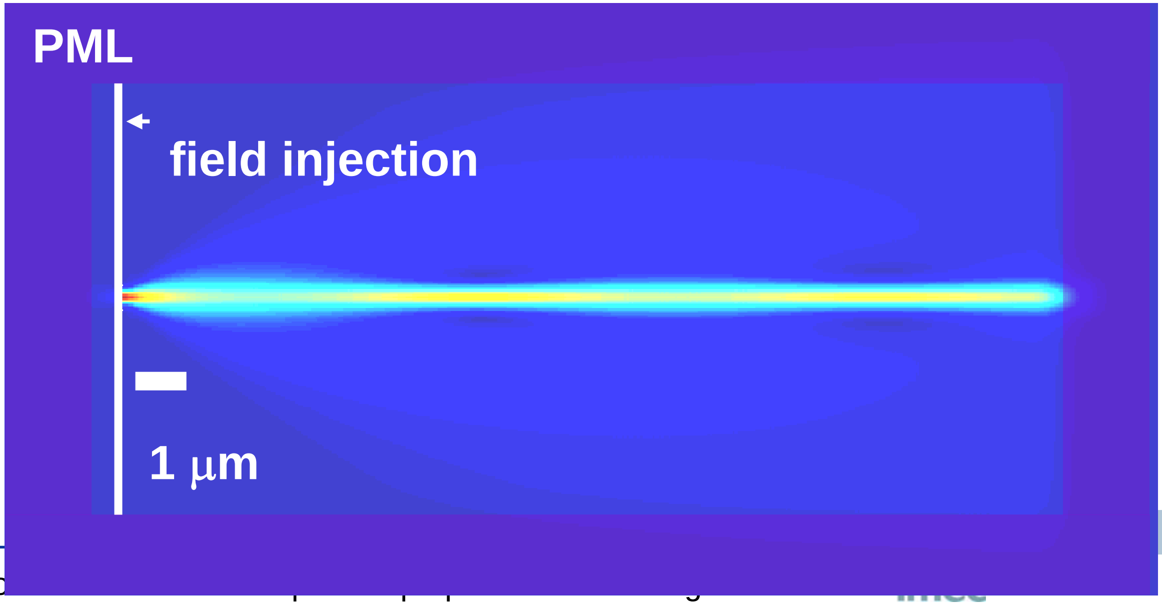
Comparison with EME



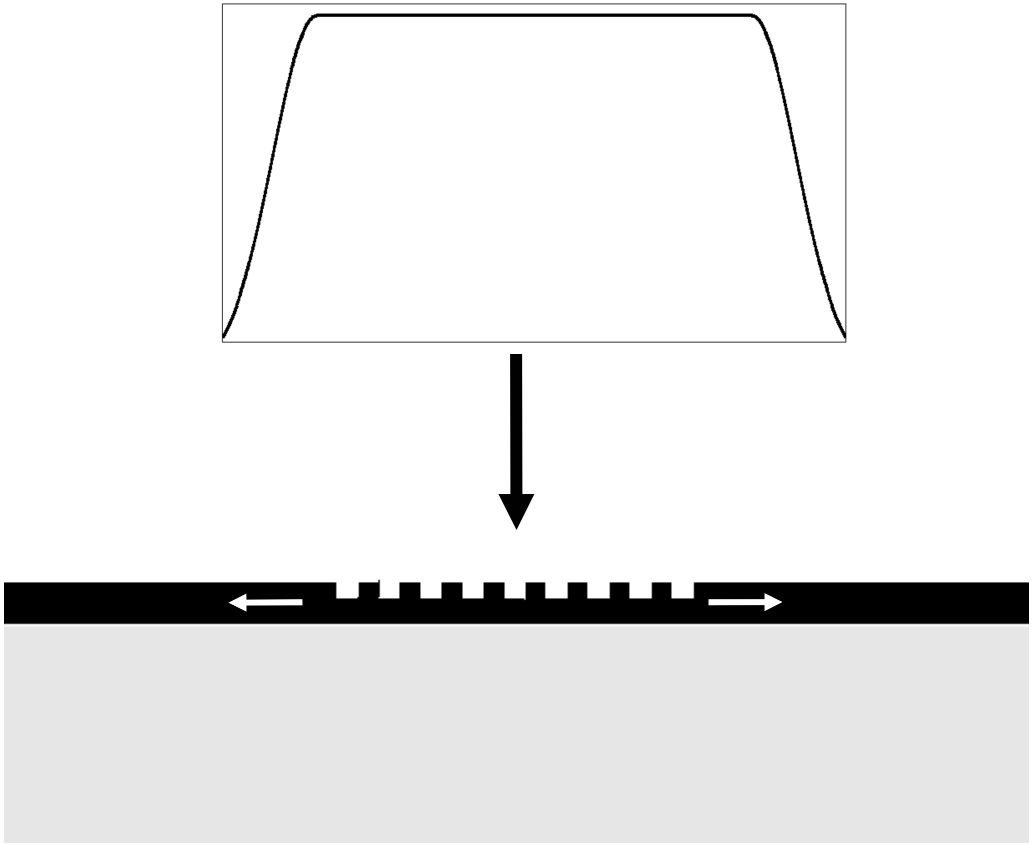
2D spatial soliton

linear case:
diffraction

non-linear case:
soliton creation



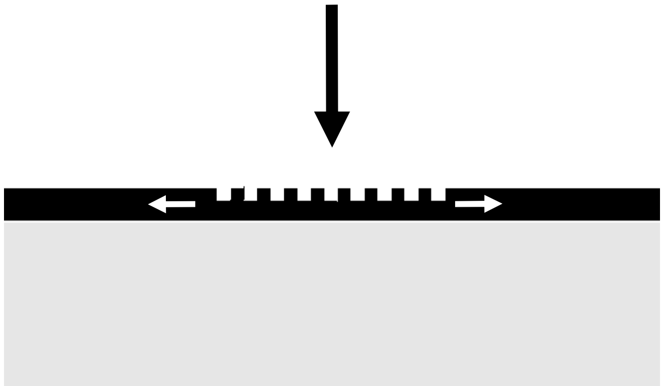
Vertical grating coupler

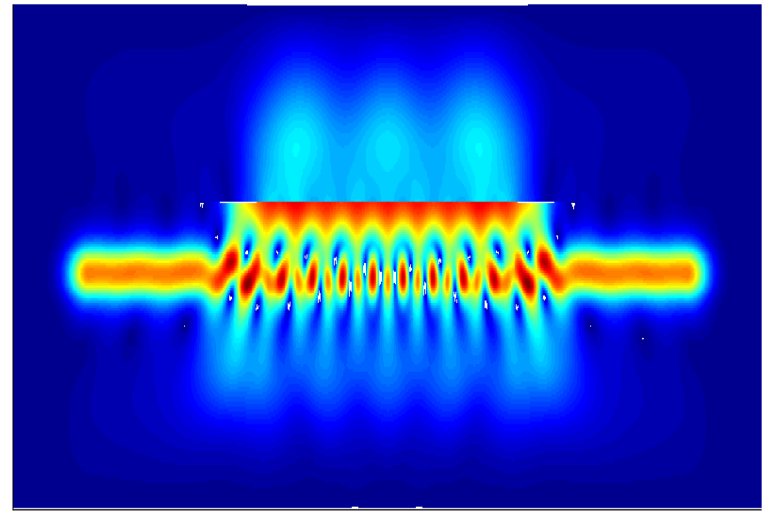


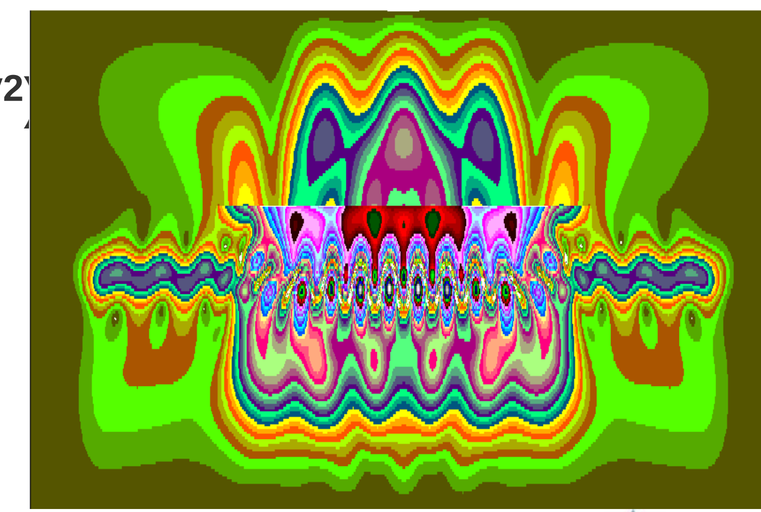
Feedback + non linearity >> optical bistability?
even symmetry breaking: switch ?

Collaboration Marc Haelterman (ULB)

Field profiles





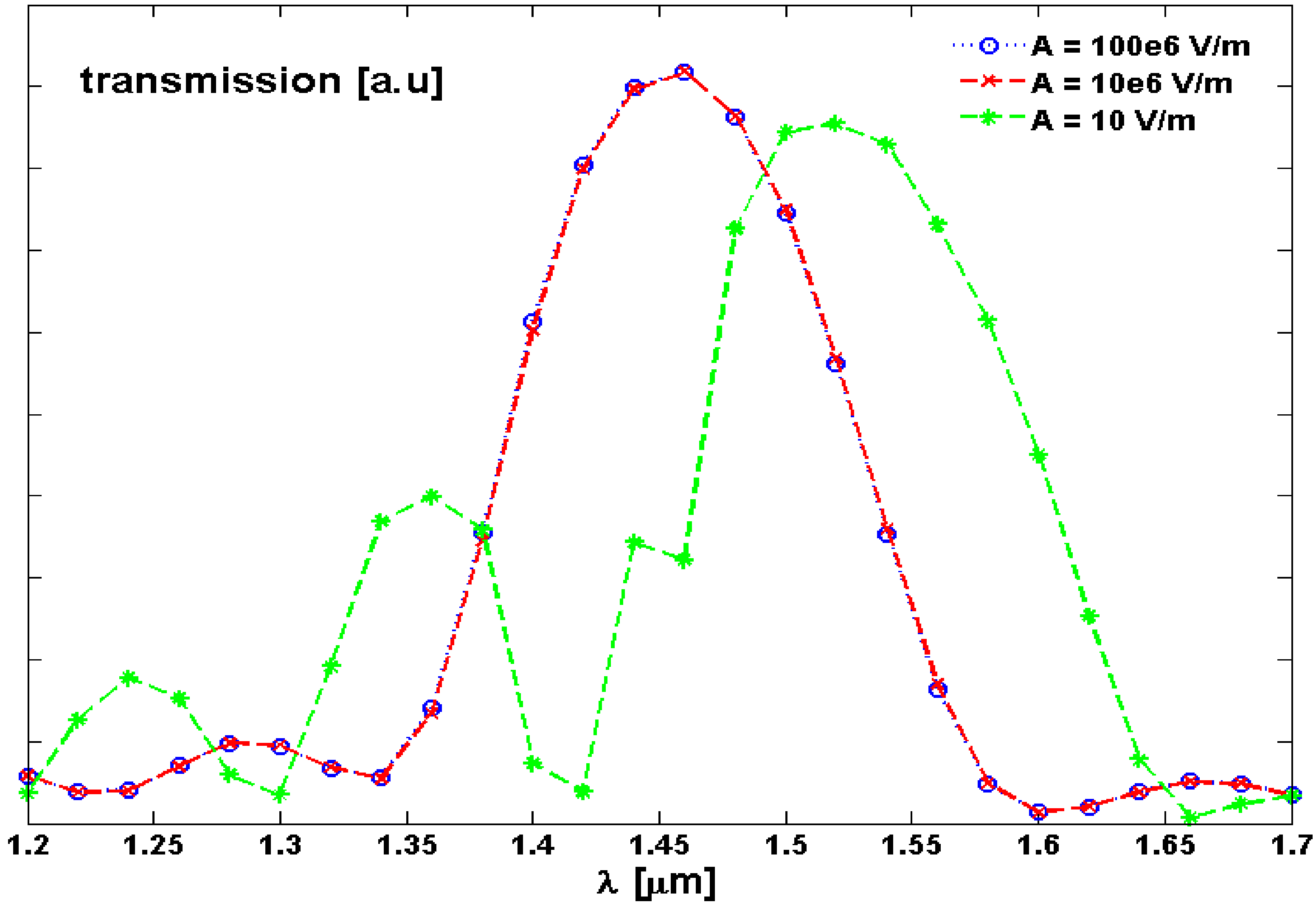


$n = n_0 + n_2 abs(E)^2$ ($n_2 = 10^{-15}$-$10^{-13} cm^2/V^2$)

spot of 30 mW on 4 μm x 4 μm:

> 1.2e6 V/m

Transmission spectra



$n_2 = 10^{-13}\ cm^2/V^2 = 10^{-17}\ m^2/V^2$

Comparison EME and CJ

Eigenmode Expansion	Complex Jacobi
+ Fast, requires not many iterations + linear regions are calculated only once.	+ does allow non linearity in entire simulation space, extremely flexible + easy algorithm
- diverges for a smaller non linearity than CJ -depends on a grid in the non linear section (calculation of eigenmodes becomes a bottle neck)	- not as fast as EME - requires a grid in the entire simulation space - results are not as intuitive

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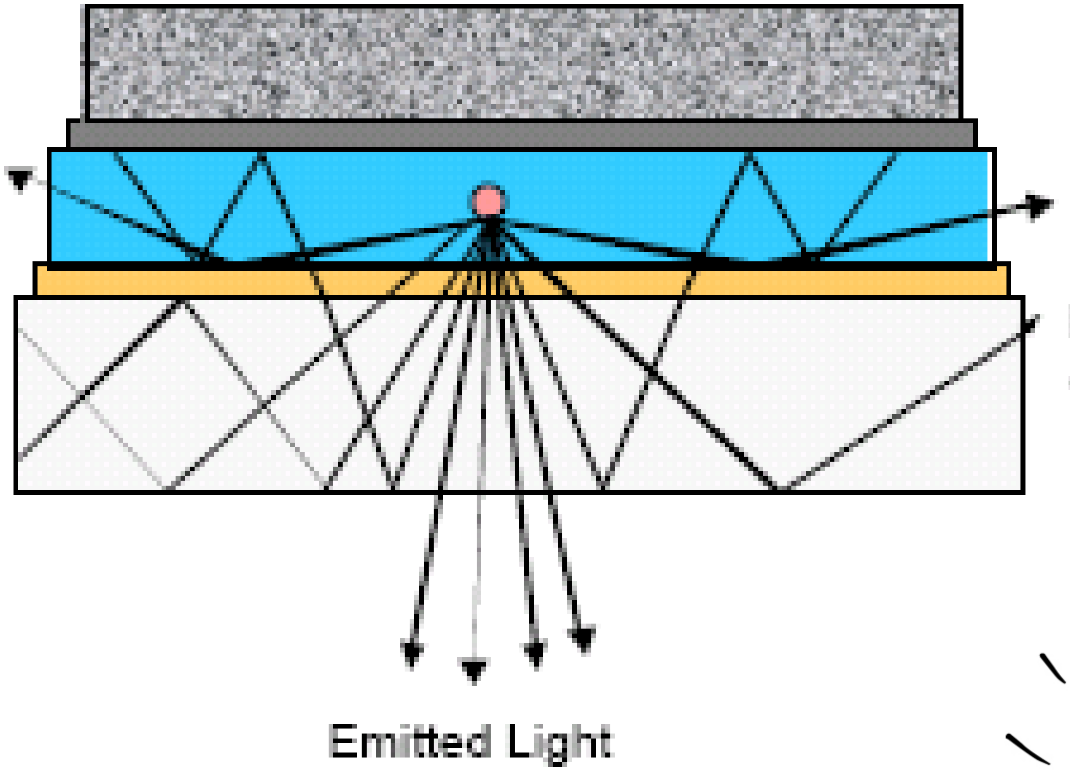
Light extraction from white OLEDs

n = 1.7, 40%

n = 1.5, 40%

n = 1.0, 20%



Model

We want to model:

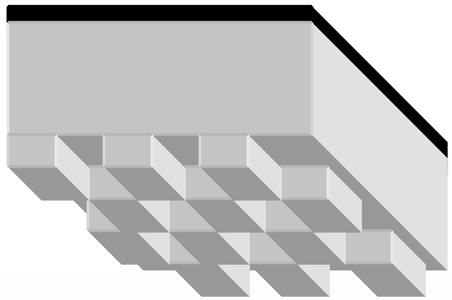
- **spontaneous emission in organic stack**
- **influence of grating at OLED/glass interface in 3D**
- **influence of grating at glass/air interface in 3D**

lateral structures: wavelength scale

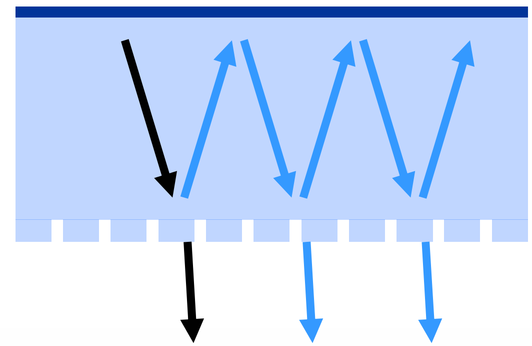
application: white light for lighting

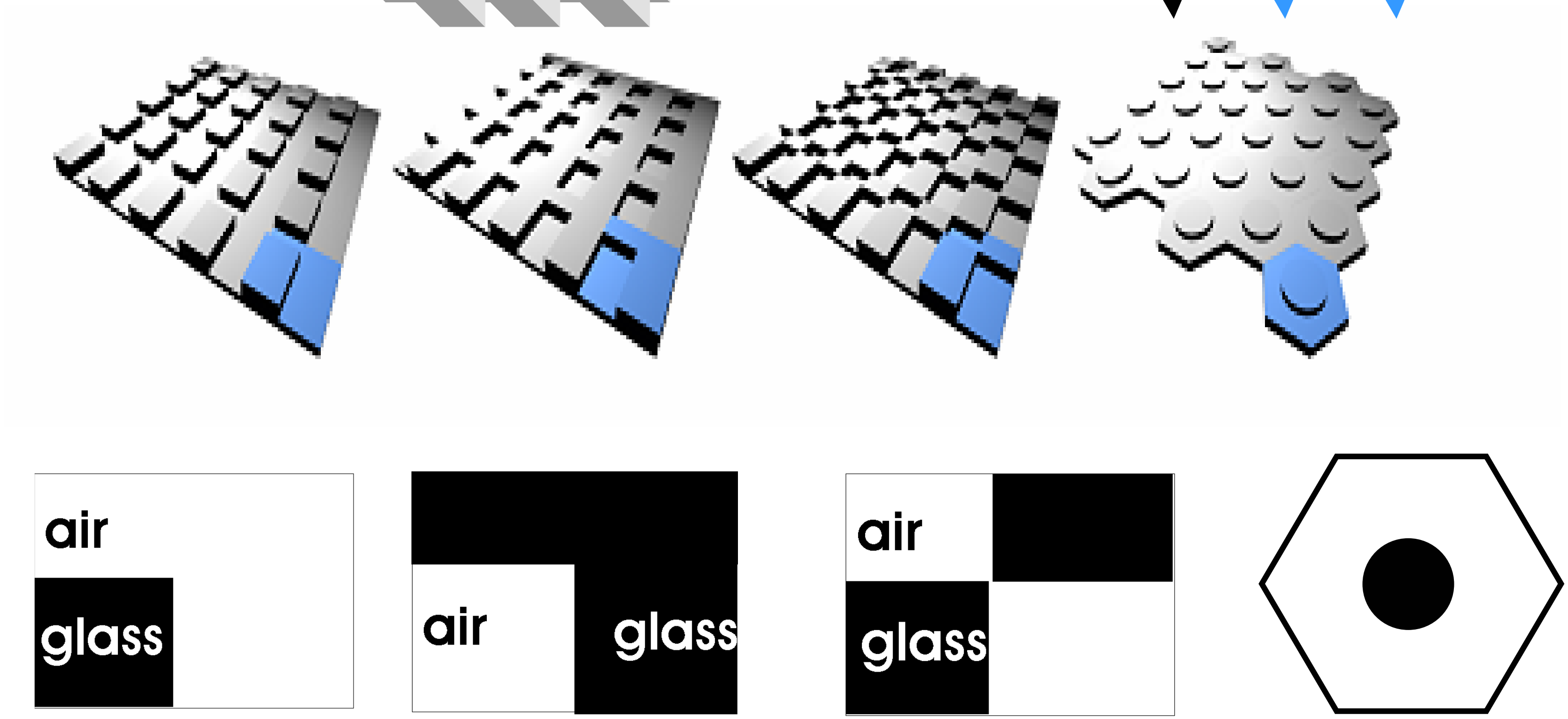
Grating at glass-air interface

perspective view:



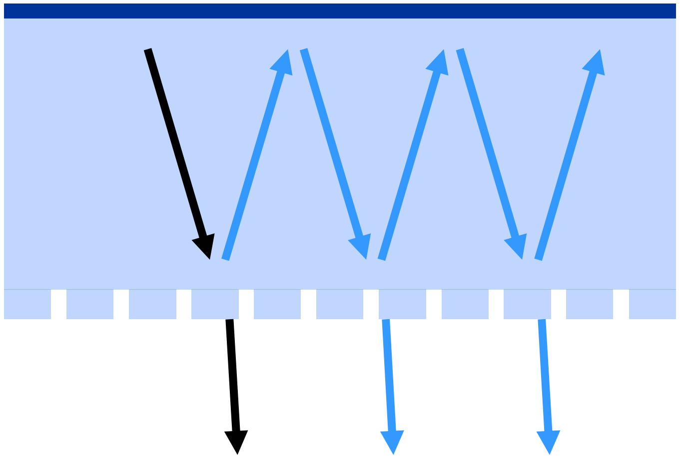
side view:





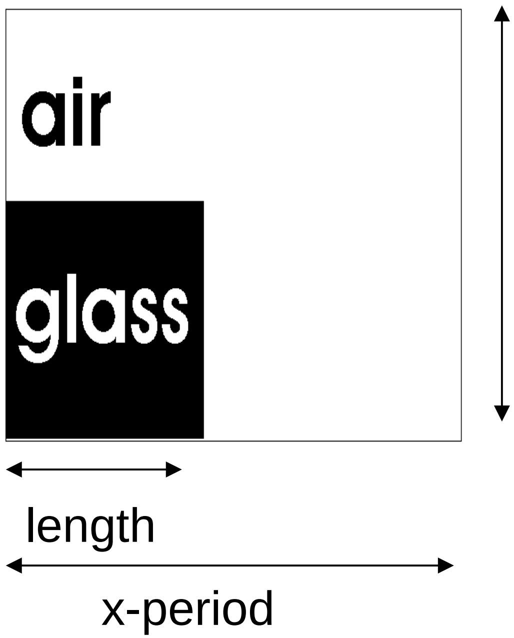
Modelling method

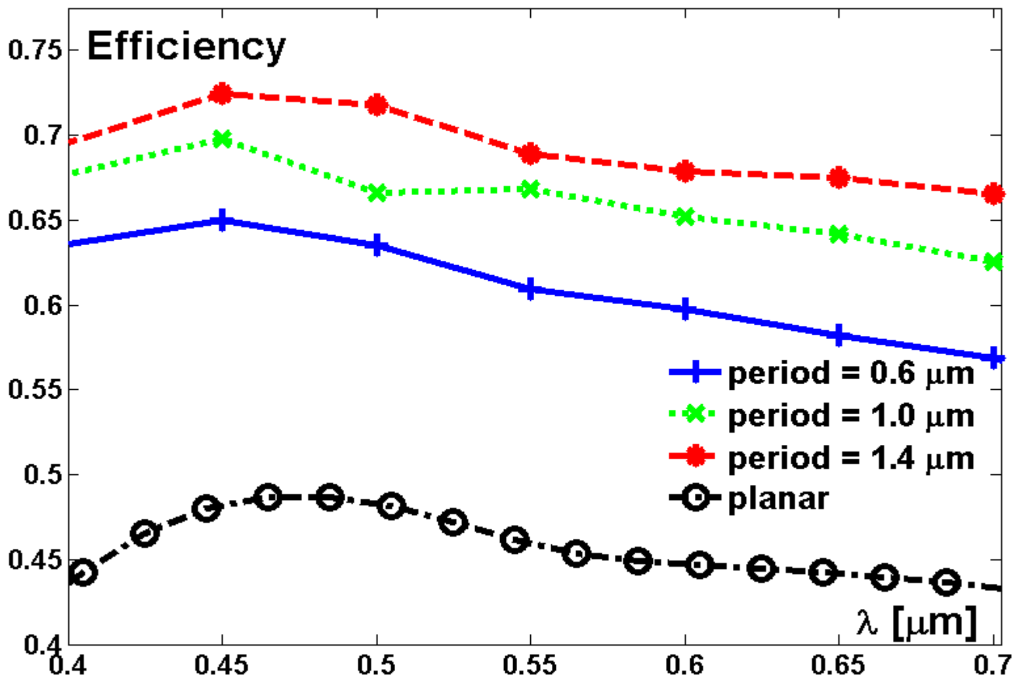
- 1: calculate field profile emitted by OLED into the substrate
  - expand dipole in plane waves
  - interference in planar stack



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

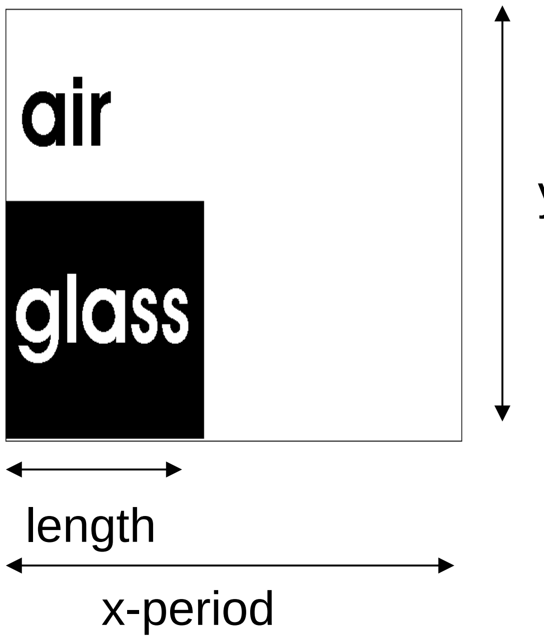
Influence of period

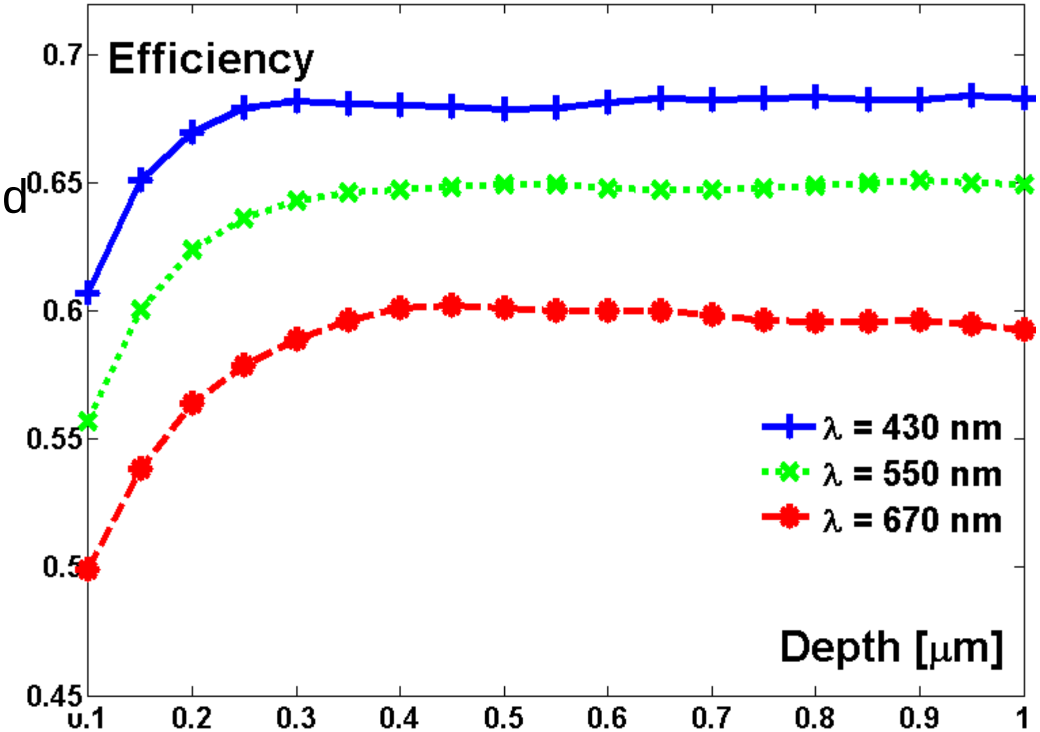




wavelength

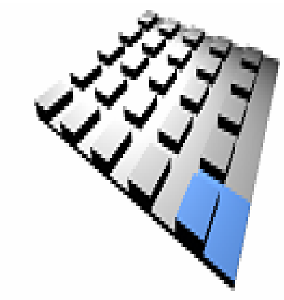
Influence of depth





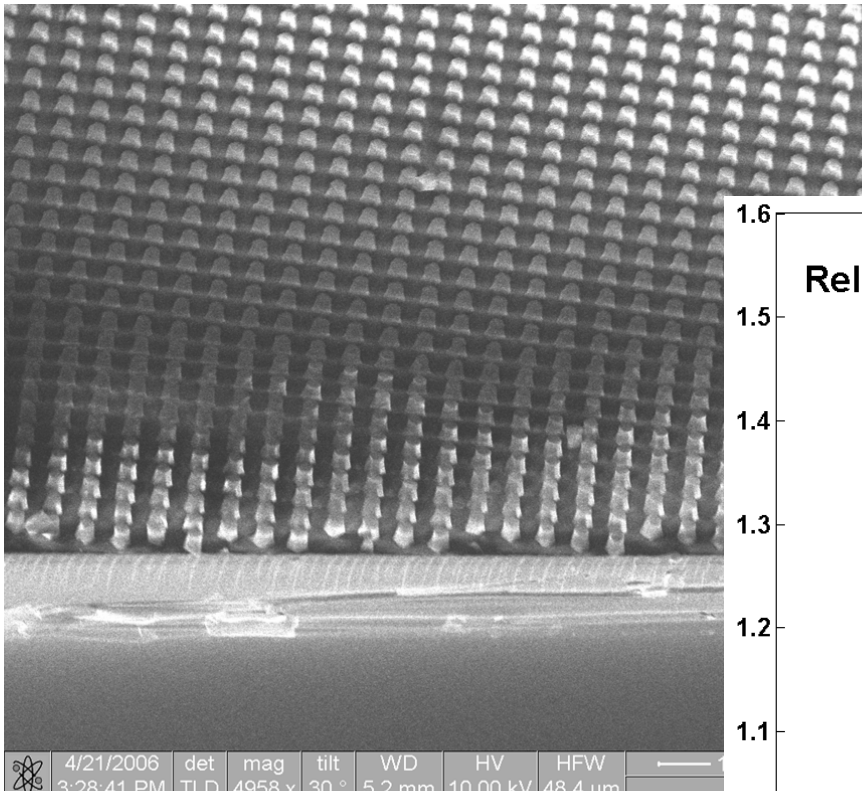
depth

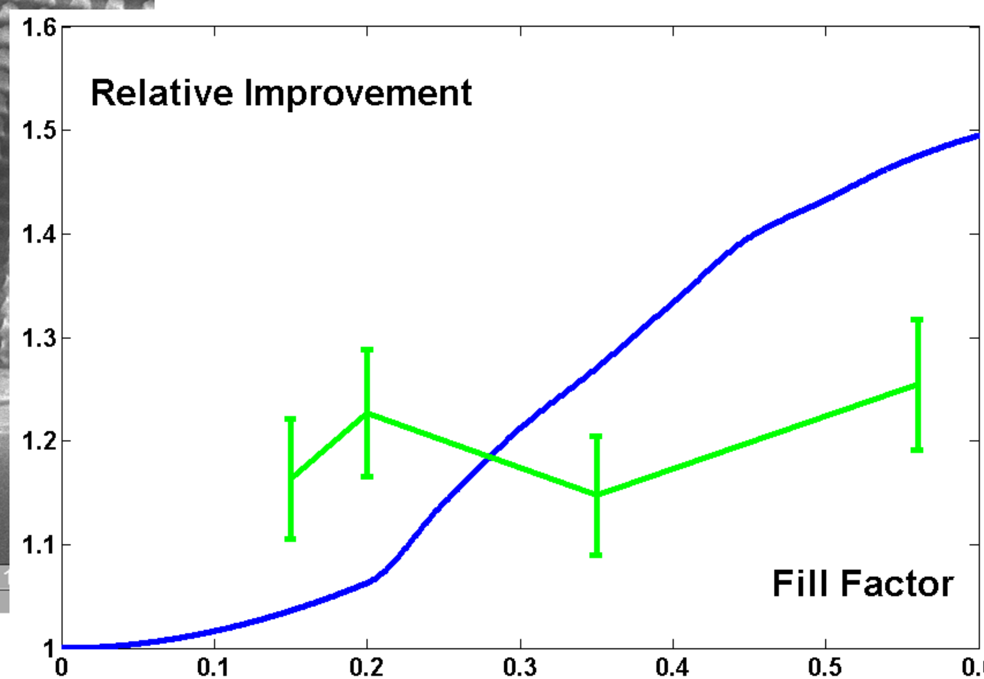
Summary

grating	Extraction efficiency	Increase (compared with planar)
	0.65-0.70	± 50%
	± 0.70	± 50%

Experiments

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



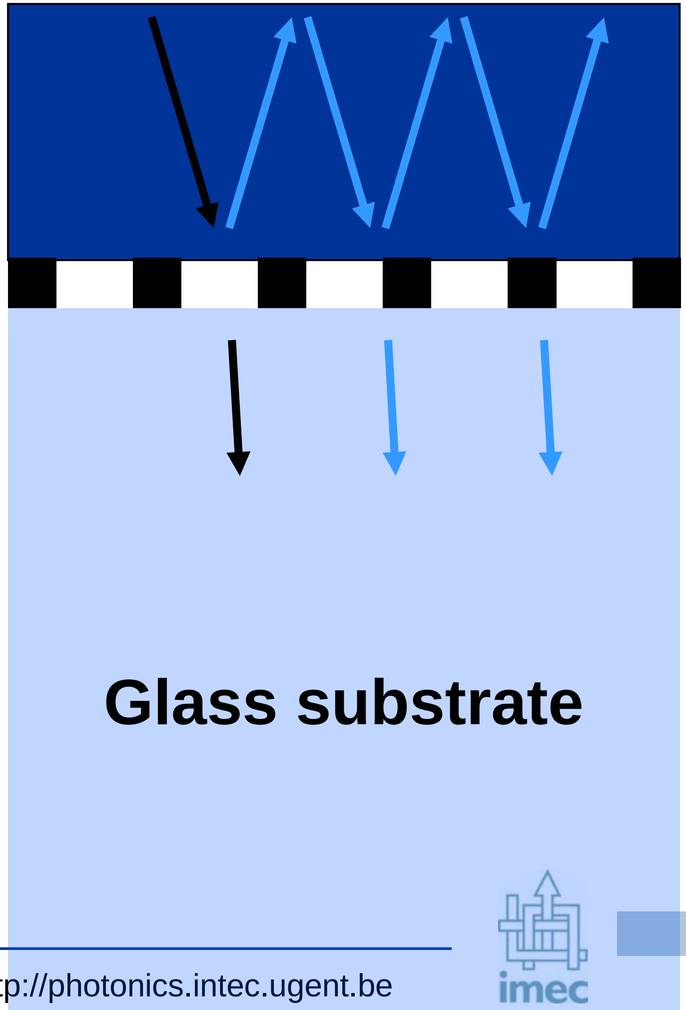


Grating at OLED side

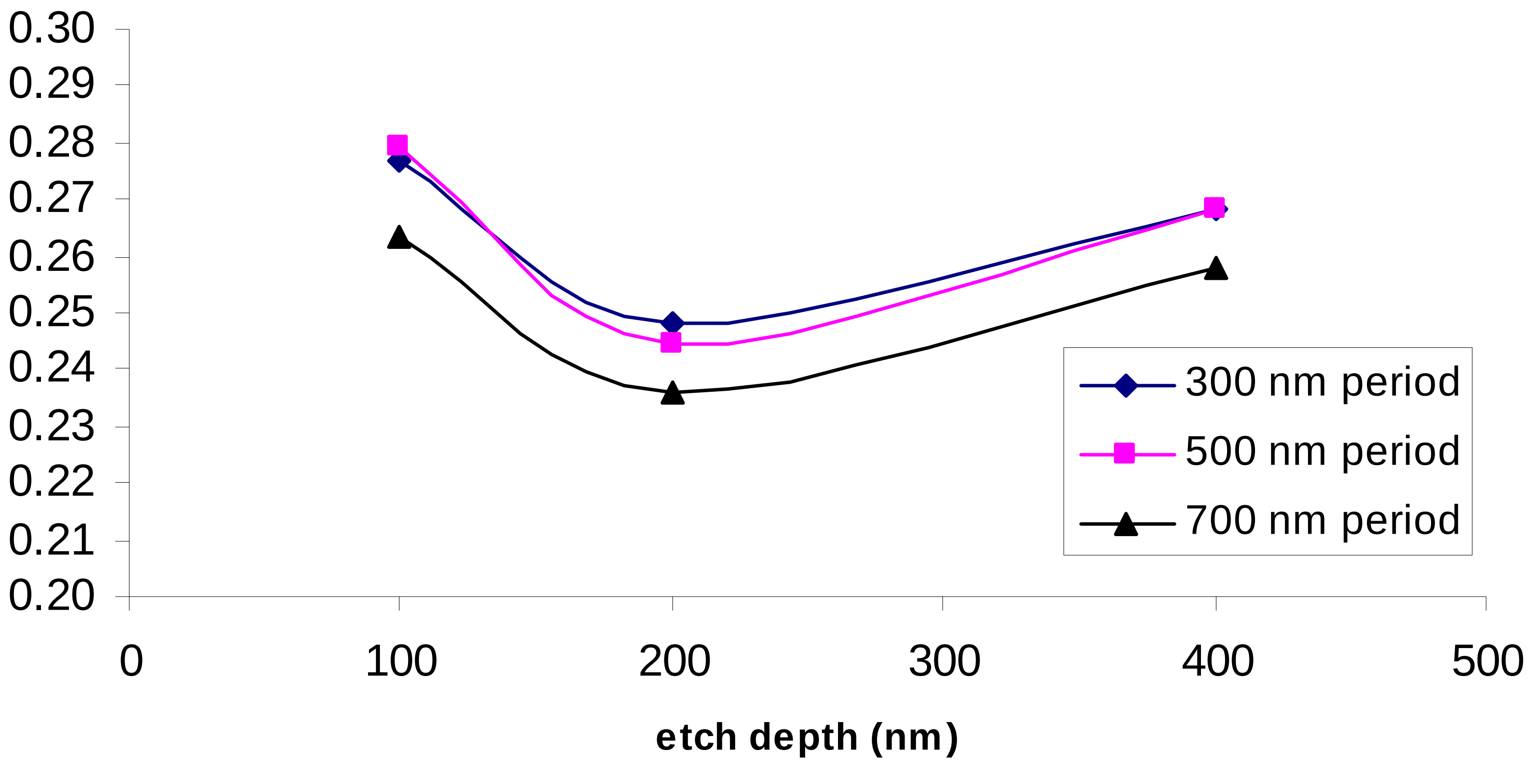
• similar in principle to previous case

• but: use amplitudes instead of powers

• average over dipole position



Extraction to air (at 565 nm)



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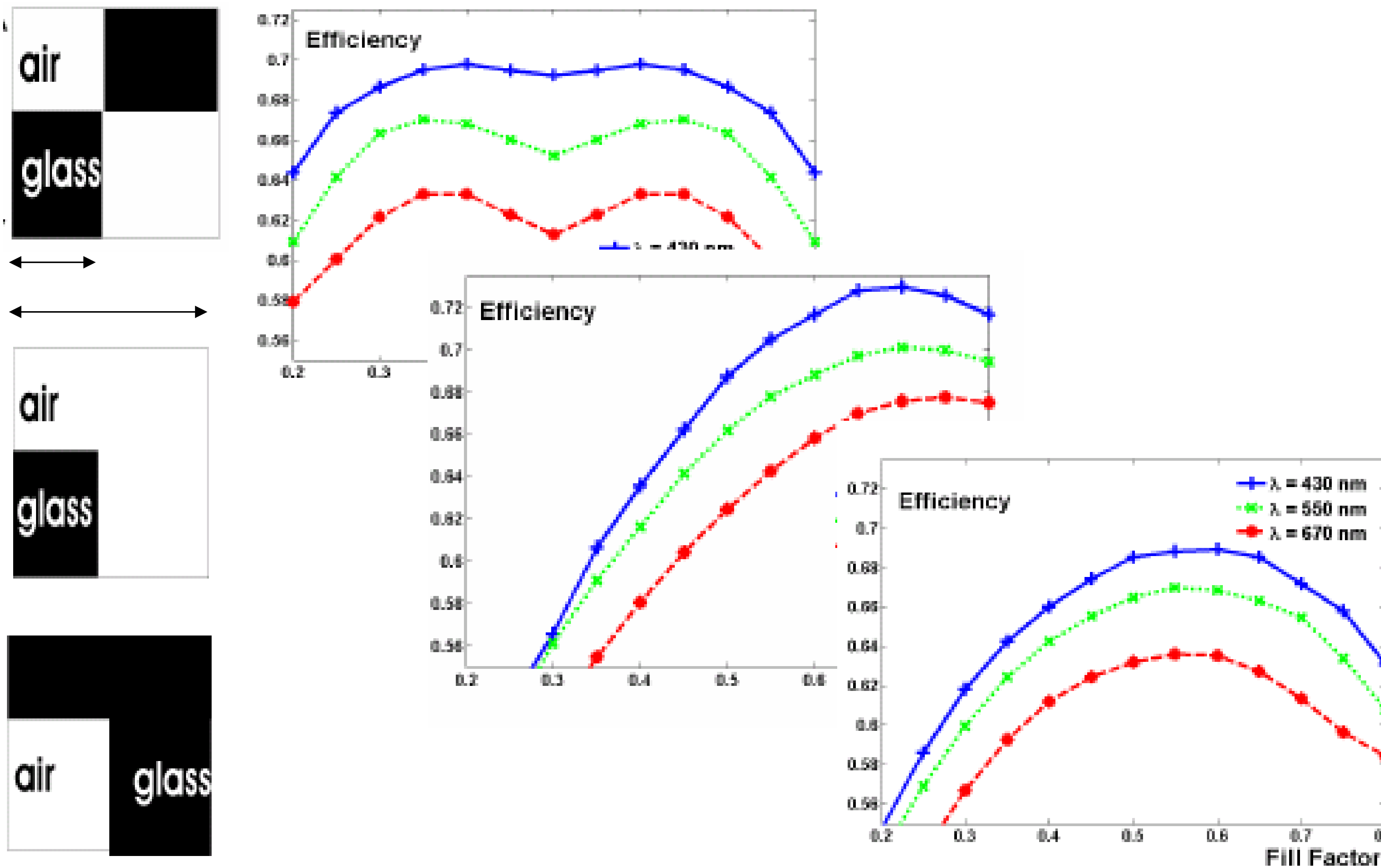
Influence of fill factor



Fill factor = length glass/period