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# Efficient Simulation of 3D Electro-optical Waveguides Using the Effective Refractive Index Method

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## Abstract


- 3D FEM simulation of millimeter-scale, complex electro-optically induced waveguide based devices demands the use of grids with more than several million nodes. Hence the simulation could take substantial time and require large amounts of available memory.
- We present a computation algorithm based on the conversion of an initial 3D waveguide structure into an analogous 2D structure, where the wave propagation on the 'reduced' dimension is described by an effective refractive index [1].
- It is shown that with the proposed algorithm the computing efficiency could be improved. Moreover the algorithm could be used to simulate large-size passive or electro-optical waveguide structures. For an electro-optical waveguide coupler, we could demonstrate a good agreement between simulated and calculated coupling length.


## Theory

- The wave equation:

$$\nabla \times [\nabla \times \vec{E}(x,y,z)] - k_0^2 n^2(x,y,z)\vec{E}(x,y,z) = 0$$

- For TM modes, the electric field can be approximated by

$$\vec{E}(x,y,z) = E_x(x,y,z)$$

- The wave equation can be re-written as:

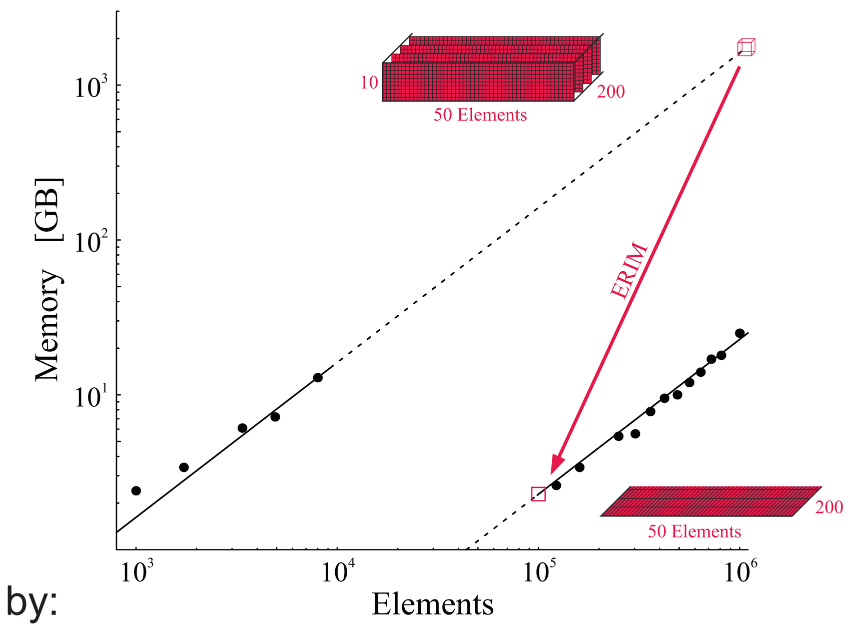
$$-\Delta E_x(x,y,z) - k_0^2 n^2(x,y,z) E_x(x,y,z) = 0$$

- With the following dimension reduction assumption:

$$-\Delta E_x(y,z) - k_0^2 n_{eff}^2(y,z) E_x(y,z) = 0$$

- The effective refractive index $n_{eff}(y,z)$ is extracted for every point $(y_i, z_j)$ by:

$$\mathrm{d}^2 E_x(x,y_i,z_j)/\mathrm{d}x^2 + [k_0^2 n^2(x,y_i,z_j) - k_0^2\, n_{neff}^2(y_i,z_i)]E_x(x,y_i,z_j) = 0$$

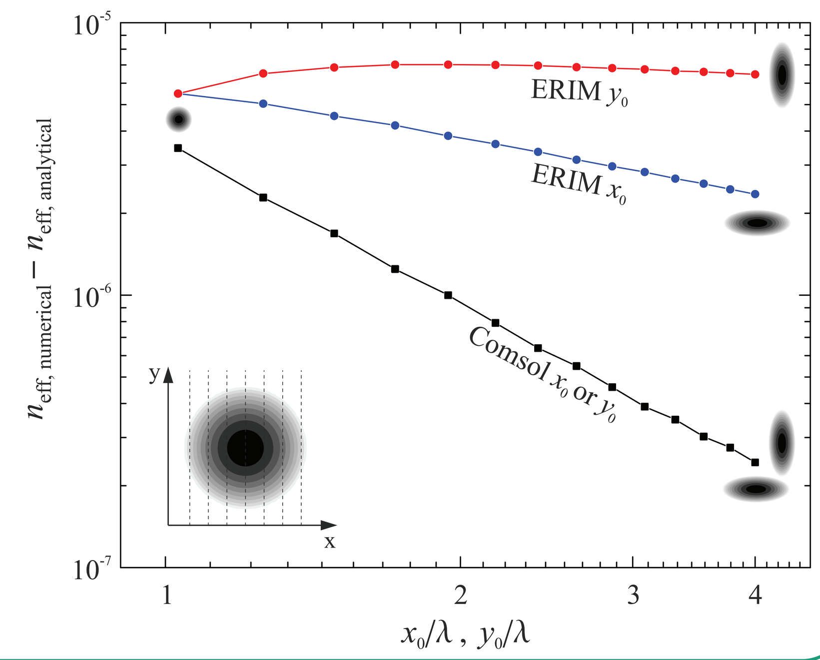



## Proposed algorithm applied on ideal and real structures

### Parabolic refractive index waveguide

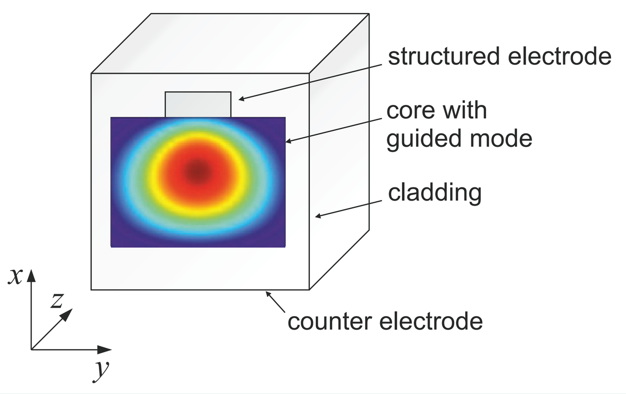
$$n(x,y) = n_0\sqrt{1 - \frac{x^2}{x_0^2} - \frac{y^2}{y_0^2}}$$

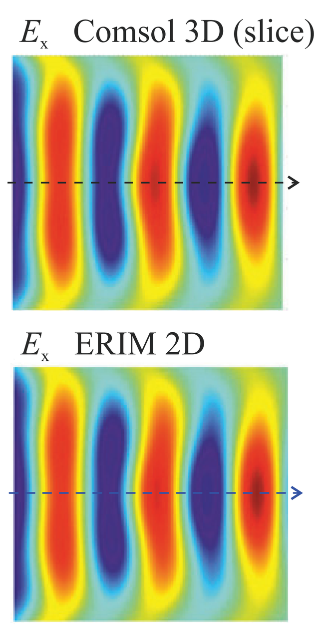
- Model chosen to evaluate the errors of $n_{eff}$ made by the algorithm.
- $n_{eff}$ calculated using a Comsol solver and the reduction algorithm.
- Deviations from the analytical solution found for all simulated results.

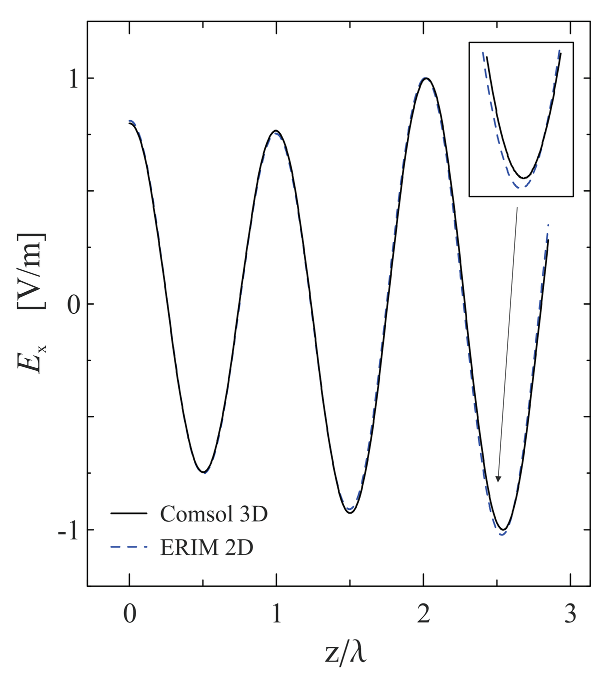



### Electro-optically induced waveguide

- Comparison between Comsol 3D solver and reduction algorithm for a (1x1x1) µm³ structure.
- Only a small difference of less than 1 % for the electric field amplitude is obtained.
- The optical mode is guided in the core material and shaped by the electrical field.

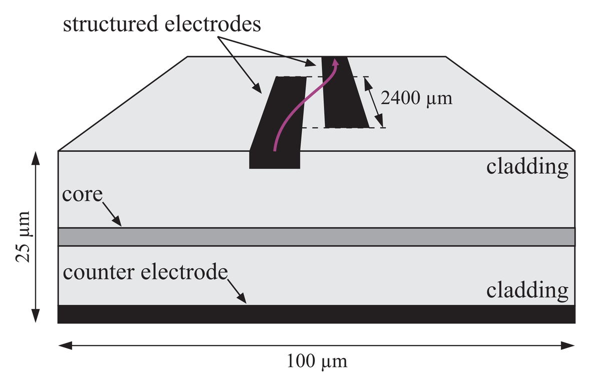


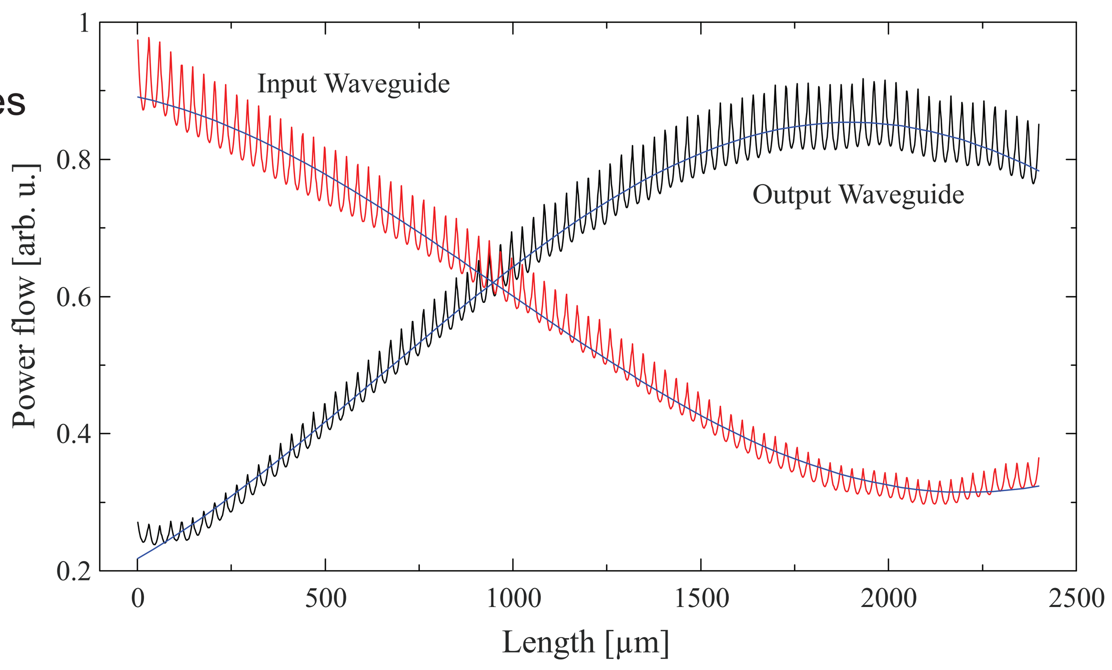




### Directional coupler on the millimeter scale

- 3D Comsol solution not available due to limited resources
- Approximation for power transfer & coupling length [2]: $\frac{I(z)}{I_0} = \sin^2\left(\frac{k_0 \Delta n_{eff}}{2} \cdot z\right)$

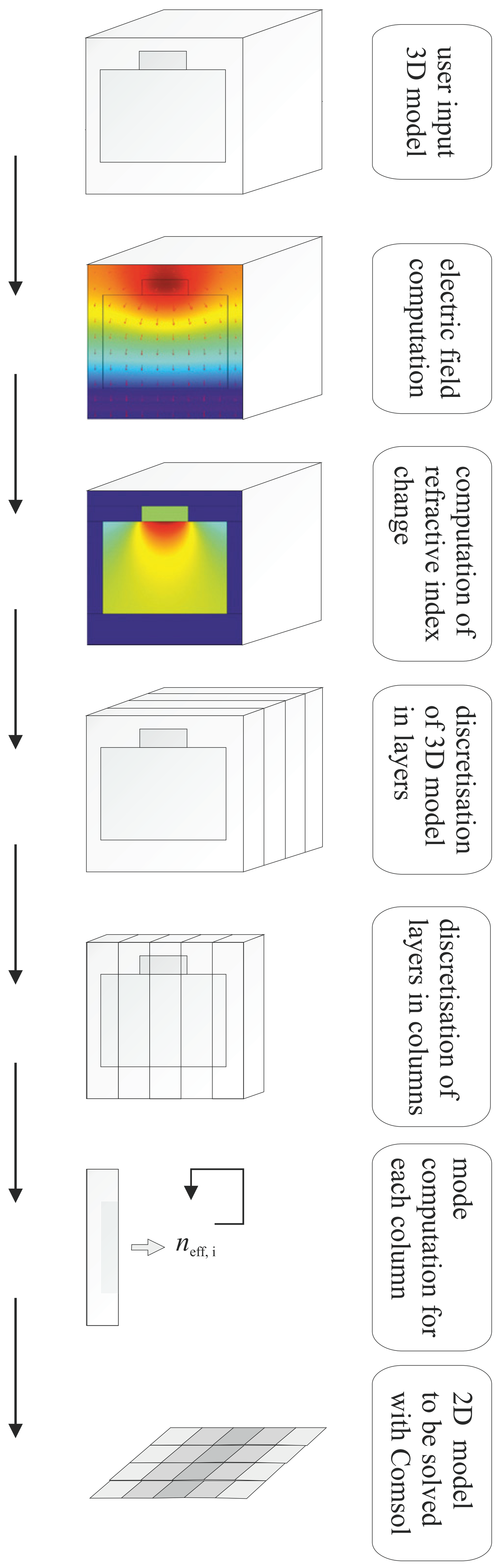



- Input waveguide power decreases with propagation distance, being transferred onto the output waveguide.
- A complete transfer of power is theoretically expected to occur after a coupling length of 2082 µm.
- Simulation took less than a day and the main memory usage was below 10 GB.

### Reduction algorithm flow

- Discretisation done in MatLab
- Calculation of $n_{eff}$ done with Comsol solvers
- Input: Comsol .mph-file with 3D Model
- Output: Comsol .mph-file with 2D approximation




## Conclusions

- A 3D to 2D algorithm based on the effective refractive index method was implemented in Comsol for solving waveguides.
- Algorithm analysis show:
  - The amount of required memory and computation time could be improved.
  - Resulting errors are small.
  - Large-size passive or active (EO) waveguide structures can be simulated.
- For a large scale waveguide coupler structure, a good agreement between the simulated and expected coupling length was demonstrated.

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COMSOL CONFERENCE 2011

References:
[1] K.S. Chiang, Analysis of optical fibers by the effective-index method, *Appl. Opt.*, 25, 348-354 (1986).
[2] Y. Sikorski et al., Analysis of crosstalk between single-mode rectangular optical waveguides, *Opt. Eng.*, 39(8), 2015-2021 (2000)

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