Numerical simulation of loosely coupled circular waveguide arrays

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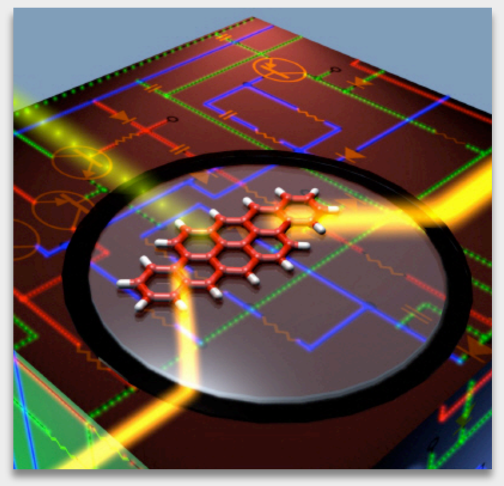
Photonic Circuits

Simply put, a photonic circuit is analogous to an electric circuit, with one important difference – it is photons that are being manipulated, not electrons.

The chief advantages are speed and size; photonic circuit components can (theoretically) be made orders of magnitude faster and smaller than their electronic counterparts.

The difficulties are in manufacturing these components, and moreover generating and guiding the light where it is needed. Photons do not follow wires like electrons do.

This is where waveguides come in. The design and study of waveguides will make photonic circuits more practical, more cost-efficient, and more functional.

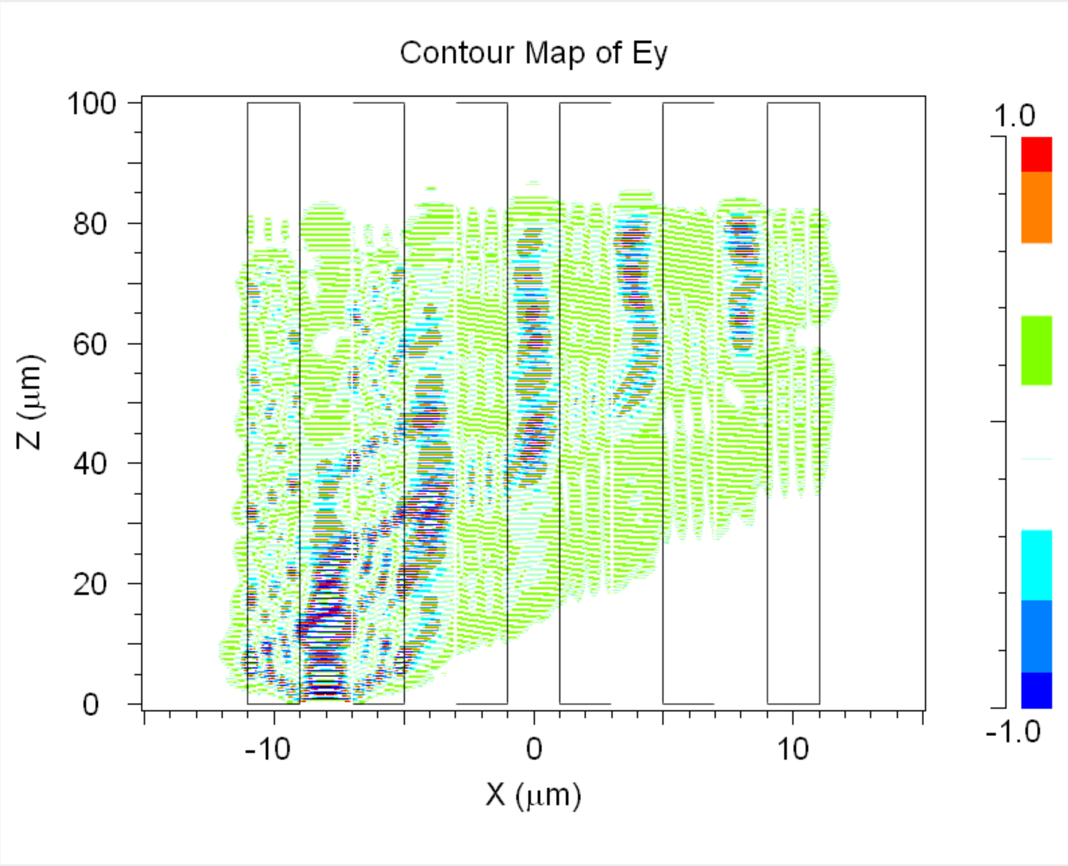


Artist's view of a photonic circuit.

Coupled Optical Waveguides

Coupled optical waveguides are very useful devices in optical signal processing. They can be used as power splitters and optical switches. They also have many potential applications including amplifiers, power filters and logic gates, etc.
Coupled optical waveguides can be analyzed by finding the coupling coefficient using superposition. However, due to numerical difficulties and the size of the problem, different software are often used for numerical simulation.

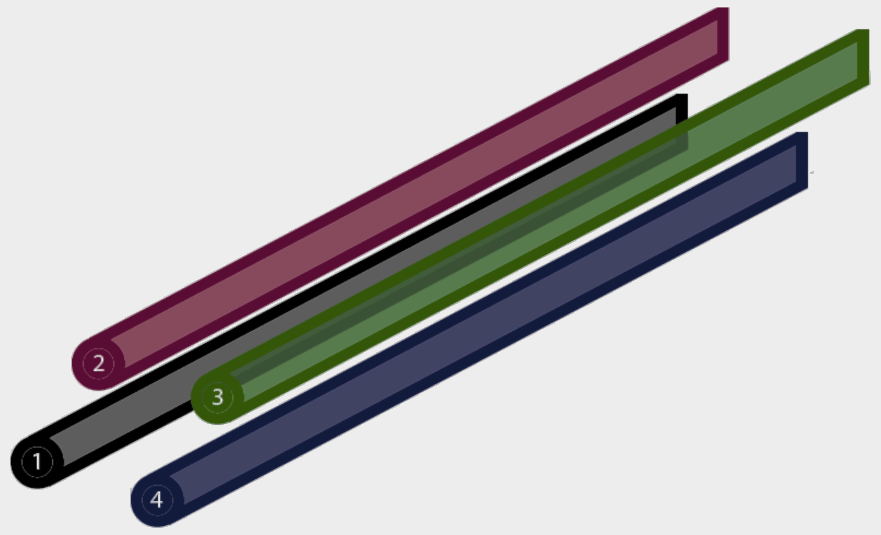
One configuration of coupled optical waveguide was simulated using the Fullwave software and the result is shown below. The simulation starts with electromagnetic waves propagating only in the leftmost waveguide. As shown in the picture, the simulation ends with waves propagating in all of the waveguides and energy is actually exchanges among different waveguides when waves are propagating.



Implementation

The simulations were originally implemented in Matlab (not by us), but ported to use C with Numerical Recipes because of the overwhelming performance advantage. The architecture, broadly, is a template that implements the general kind of simulation we are performing, and separate programs for each combination of parameters (e.g. number of waveguides). Because all of the math and the common program structure is in the template, the source files for these individual programs can be very small and reflect only the salient aspects of that particular simulation.

Theory Overview



When waveguides are placed in close proximity, there is an evanescent electromagnetic field outside each guide that has light going through it. By adjusting the coupling (i.e. spacing), adjacent guides can be excited to varying degrees.

With a circular array, interesting effects can be achieved, such as splitting the power of one guide over the entire array, or transferring power from one guide to another. In all the cases we are studying, only one guide is excited before the array (although, in principle, our results are reversible).

We use coupled-mode theory, explained in the paper by L. Molter and J. Makin, to model the behavior of a waveguide array.

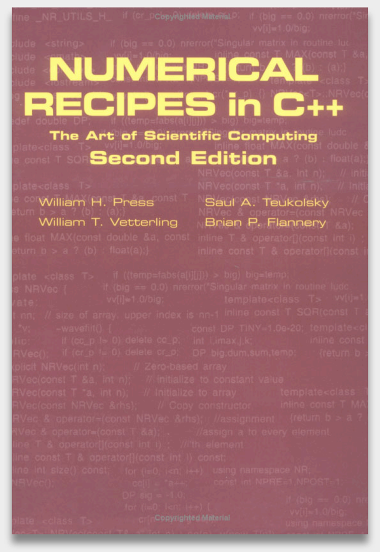
The equations can be solved by hand for symmetric cases and small numbers of guides, but the matrices quickly become intractable for humans. Hence, we use the computer to get an approximate numerical solution.

In addition to adjusting the spacing between each pair of waveguides, each waveguide can be "detuned." Detuning can affect the output much like coupling but can be changed in real time in a device, so it allows (for example) optical toggle switches.

Numerical Recipes

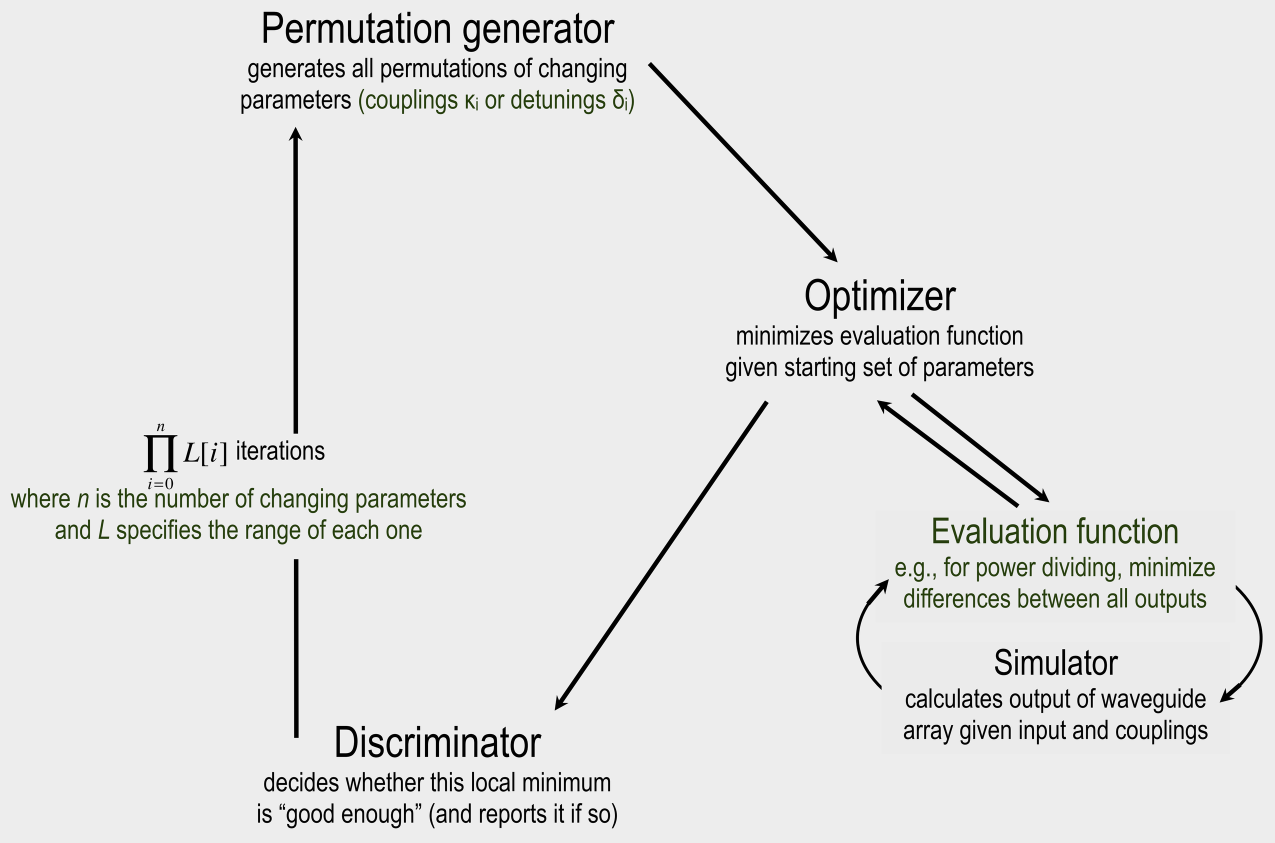
Programming in Matlab allows for convenient access to advanced numerical routines, but it is an interpreted language and as such runs very slowly when scaled to advanced simulations. It is common practice to start with Matlab for its ease of development, and then re-implement in C for performance.

The Numerical Recipes series provides sample implementations of a host of numerical algorithms. Our simulations make use of Powell's method for multivariable function minimization and several matrix manipulation routines.



Computation Details

The program iterates through every combination of starting parameters, and optimizes to a local minimum from each. Green text denotes components that change for each individual simulation; the rest is general.



The Math Behind the Simulator

System matrix M
- Used to calculate waveguide output given input
- Detuning parameters (normally zero) on diagonal
- Coupling parameters on off-diagonals
- Circulant matrix
- To find output field strengths, take the matrix product of:
- matrix of eigenvectors of M
- matrix with *e* raised to the eigenvalues of M on the diagonal
- inverse of the matrix of eigenvectors of M
- column vector of waveguide input field strengths

$$M = \begin{pmatrix} \delta_1 & \kappa_1 & & & \kappa_n \\ \kappa_1 & & \ddots & & \\ & \ddots & \ddots & \ddots & \\ & & \ddots & & \\ \kappa_n & & & \kappa_{n-1} & \delta_n \end{pmatrix}$$

$$[\phi, d] = eig(M)$$

$$a(z) = \phi * diag(e^{d}) * \phi^{-1} * input$$

Porting to Windows

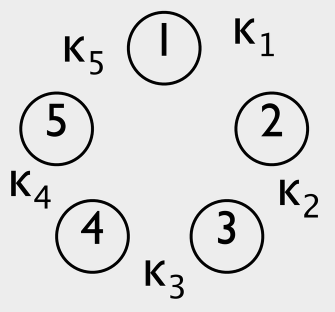
- Ported from Solaris 5 to Windows XP using Cygwin
- In the process, many memory leaks/inefficiencies discovered and eliminated
- On faster machines and with fewer leaks, programs run faster and over a larger range of inputs
- Mac OS X also used for development, but results not used due to floating-point library differences

Version Control

- Subversion used to manage development
- Repository hosted on-site by the Swarthmore College Computer Society
- Ensured a central repository of our latest work, even though we used separate computers
- Provides comprehensive view of project history
- Extremely useful for isolating and rolling back breaking changes

Results

- Solutions for switching to the nearest neighbor were examined.
- The principle focus was on determining a solution to a 5 guide circular array.



- Expected symmetry for a switching solution from guide 1 to guide 2 would be:

$$\kappa_1 = A_1$$
$$\kappa_2 = \kappa_5 = A_2$$
$$\kappa_3 = \kappa_4 = A_3$$

- This general pattern for κ symmetry is consistent with the solutions for the even ordered guides and the 3 guide arrays.
- We determined a solution for the 5 guide circular array for nearest neighbor switching, which can be seen below:

$$\kappa_1 = 16\pi$$
$$\kappa_2 = \kappa_5 = 15\pi$$
$$\kappa_3 = \kappa_4 = \pi\sqrt{45.5}$$

Conclusions and Future Work

- A program to simulate loosely coupled circular arrays of waveguides was improved.
- An adjacent switching solution was discovered for the five waveguide array conforming to:

$$\kappa_1 = 16\pi$$
$$\kappa_2 = \kappa_5 = 15\pi$$
$$\kappa_3 = \kappa_4 = \pi\sqrt{45.5}$$

- It is likely that there exists adjacent switching in odd ordered arrays with more than 5 waveguides. This needs to be verified with future work.
- Further investigation of possible detuning parameters for the different switching configurations should be undertaken.

Acknowledgements and Sources

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- Joe Makin for his previous work on this project
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- Swarthmore College

Papers

- Design and modeling of passive optical switches and power dividers using non-planar coupled fiber arrays
  Hudgings, J.; Molter, L.; Dutta, M.
  Quantum Electronics, IEEE Journal of, Volume 36, Issue 12, Dec 2000 Page(s):1438 - 1444
- Generalized switching, splitting, and multiplexing operations using circular arrays of coupled waveguides
  Makin, J. Molter, L.
  Optical Fiber Communications Conference, 2003. OFC 2003.