Automated Design of Nanophotonic Waveguide-to-Waveguide Couplers

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Abstract: We demonstrate a design algorithm which automatically generates wavelength-scale coupling devices between arbitrary waveguide modes with high efficiency. Our algorithm is fast (∼20 min.), can be extended to multiple dimensions, and requires no trial-and-error.

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1. Motivation

In order to route and process optical information on-chip, it is absolutely critical to be able to efficiently transfer photons from one waveguide mode to another. However, current strategies either 1) require large device areas and tunable material parameters, 2) are only applicable to effectively 1D systems, or 3) operate on brute force parameter search.

We present an algorithm that quickly (∼20 min.) designs high efficiency (∼95% conversion) nanophotonic waveguide couplers in two dimensions. The resulting devices are extremely compact, on the order of only 1-2 vacuum wavelengths per side, and can couple between seemingly arbitrary waveguide modes. Notably, neither trial-and-error nor the modeling of device subcomponents is needed.

2. Method

The algorithm operates by calculating the boundary electromagnetic fields needed for perfect operation (100% coupling efficiency), and then varying the interior fields and permittivities to reproduce those boundary fields. Numerically, we fix $H(border) = H_{\text{perfect}}$, and then minimize the residual in the electromagnetic wave equation, $\|\nabla \times \varepsilon^{-1} \nabla \times H - \mu\omega^2 H\|^2$, by varying both $H(interior)$ (interior magnetic field) and ε (permittivity).

Note that the algorithm actually places much greater emphasis on achieving perfect device performance than even satisfying physics (the wave equation)! Specifically, it is this "objective-first" approach, coupled with the boundary field formulation, that greatly speeds up the design process by eliminating the need to repeatedly solve the wave equation.

Lastly, we validate our designs in simulation (finite-difference frequency-domain, 2D tranverse electric mode) by exciting the input waveguide mode and then calculating the transmitted power in the desired output waveguide mode.

3. Results

Figs. 1, 2 and 3 show the result of our algorithm, as applied to the design of nanophotonic waveguide couplers in two dimensions. All devices are extremely compact, and yet exhibit high coupling efficiency; even in spite of significant differences in mode size and mode symmetry.

Lastly, for numerical reasons, we allow values of ε to vary continuously between $\varepsilon_{\text{air}} = 1$ and $\varepsilon_{\text{silicon}} = 12.25$, even though discrete values are more amenable to fabrication. Forcing discreteness in ε will be investigated in future work.

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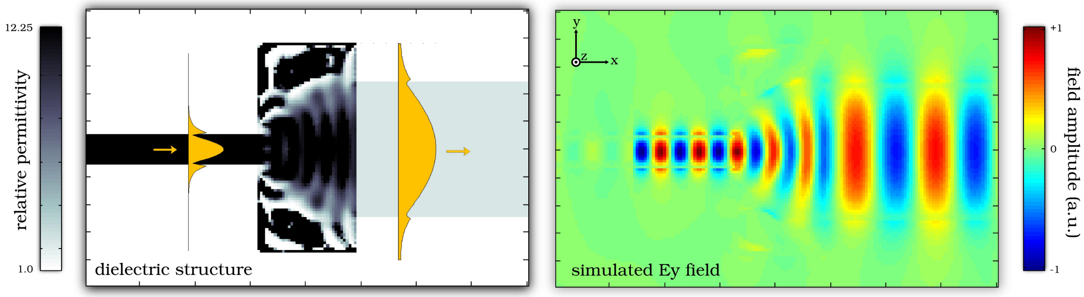

Fig. 1. Waveguide coupler for a wide, low-index waveguide. The dielectric structure of the coupler and surrounding input and output waveguides is shown on the left, while the simulation validating our results is shown on the right. The coupler converts 96.3% of the input power to the designated output mode. The device is extremely compact, convering only 36×66 grid points, where the vacuum wavelength is 42 grid points. Computation time was 20 minutes on a personal computer.

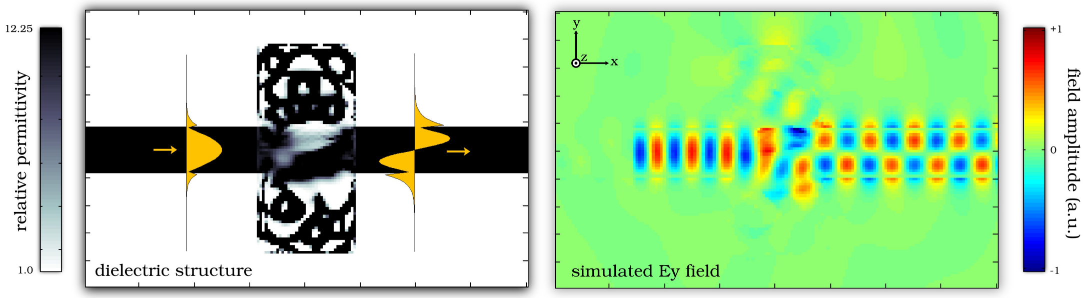

Fig. 2. Coupler that converts the fundamental waveguide mode to the second-order waveguide mode. This problem is quite difficult since the two modes are of opposite symmetry. For example, adiabatic approaches cannot be applied to this case. However, our method produces a device (which has the same dimensions and vacuum wavelength as Fig. 1) which achieves a coupling efficiency of 95.5%. Computation time was extended to 50 minutes to improve efficiency.

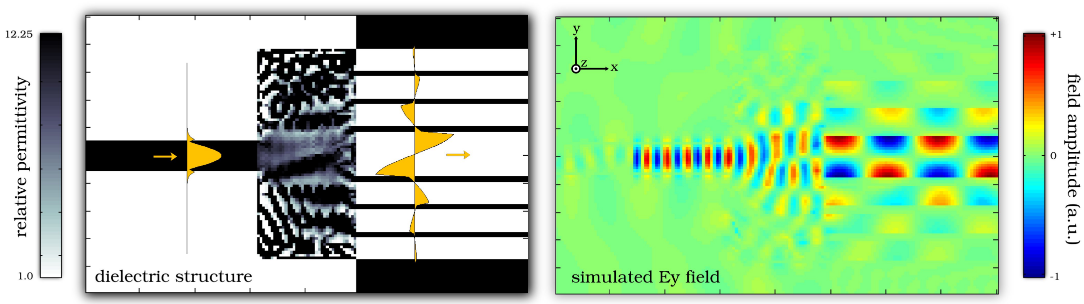

Fig. 3. Coupler to an air-core mode. Here, not only are the modes of opposite symmetry, but the output waveguide operates on a fundamentally different principle (guided by Bragg reflection) than the input waveguide (index guided). The device still achieves an efficiency of 83.3%, demonstrating the versatility of our method. The vacuum wavelength is 25 grid points, while the device footprint is still 36×66 grid points. Computation time was 20 minutes.