High-Efficiency, Small-Footprint Couplers Between Arbitrary Nanophotonic Waveguide Modes

Jesse Lu and Jelena Vučković

Stanford University, Stanford, California, USA.

jesselu@stanford.edu

Abstract: We develop an algorithm for designing high efficiency (∼95%), small-footprint (1-4 square vacuum wavelengths) couplers between arbitrary nanophotonic waveguide modes in two dimensions. Our "objective-first" method is computationally fast (15 minutes on a single-core personal computer), requires no trial-and-error, and does not require guessing a good starting design. We demonstrate designs for various coupling problems which suggest that our method allows for the design of any linear optical device.

OCIS codes: 230.7370, 130.3990.

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1. Motivation

Optical mode conversion, the efficient transfer of photons from one guided mode to another, is a fundamental requirement in nanophotonics. For instance, efficient conversion between waveguides modes is essential for:

- Coupling to and from optical fiber [1], to communicate with the outside world.
- Coupling between various nanophotonic waveguides, since different waveguides are best suited for different applications. For example, ridge waveguides seem ideal for low-loss transport [2], but other waveguides, such as photonic crystal waveguides or slot waveguides, may be better suited for slow-light [3] or nonlinear optical devices based on localized field intensities [4].
- Coupling between different materials systems such as passive, active [5], and metallic [6] devices.

In fact, the problem of converting between nanophotonic modes is essentially the function of all linear nanophotonic devices, since any linear device is completely characterized by its input and output modes.

In this paper, we propose a design algorithm which, we believe, solves this problem. Namely, we outline a method capable of designing nanophotonic devices to efficiently transfer photons between arbitrary input and output modes, and we demonstrate this method by designing various nanophotonic couplers between different waveguides.

Furthermore, we show that our method does not employ brute-force parameter searches; does not require a good initial design; is computationally fast (no simulations required); and can generate high efficiency couplers within a very small footprint.

2. Objective-first formulation

The typical approach to designing physical structures can be formulated in the following way:

$$\begin{aligned} \text{decrease} \quad & f(x) && \text{(1a)} \\ \text{subject to} \quad & g(x,p) = 0, && \text{(1b)} \end{aligned}$$

where x is the field variable and p is the structure variable. Here, $f(x)$, the *design objective*, calculates the performance of the device (e.g. amount of power not coupled to output mode); while $g(x,p)$ is the underlying physical equation for the system (e.g. the electromagnetic wave equation).

In contrast, the objective-first formulation is

$$\begin{aligned} \text{decrease} \quad & \|g(x,p)\|^2 && \text{(2a)} \\ \text{subject to} \quad & f(x) = 0, && \text{(2b)} \end{aligned}$$

where $\|g(x,p)\|^2$ is the *physics residual*. We term this formulation "objective-first" because the design objective is prioritized even above satisfying physics; specifically, we force our design to always exhibit the desired performance ($f(x) = 0$), even at the expense of not perfectly satisfying the underlying physics which governs its operation.

The motivation behind this formulation is two-fold. First, to arrive at a locally-optimal design rapidly by allowing x and p to vary independently, as opposed to Eq. 1 where the value of x is completely dependent on p. Second, to increase the likelihood of arriving at a high efficiency design by forcibly imposing $f(x) = 0$, and thereby circumventing any local optima consisting of low-performance devices.

3. Objective-first design of arbitrary waveguide couplers

We demonstrate the objective-first approach by designing waveguide couplers in two-dimensions. Specifically, we work in the two-dimensional transverse electric mode, and choose H_z as the field variable x, and ε^{-1} (the inverse of the permittivity) as the structure variable p. This results in the following form of the physics residual,

$$\|g(x,p)\|^2 = \|g(H_z, \varepsilon^{-1})\|^2 = \|\nabla \times \varepsilon^{-1} \nabla \times H_z - \mu_0 \omega^2 H_z\|^2, \tag{3}$$

where ω is the angular frequency, and μ_0 is the permeability of free-space.

For the design objective, we choose a boundary-value formulation based on H_z^{perfect}, where H_z^{perfect} is constructed of the exact input and output waveguide modes at the input and output ports of the optimization region (where the coupler will be placed), repectively, and of zero-amplitude fields at the unused ports, as illustrated in Fig. 1.

The mathematical form of the design objective is simply,

$$f(H_z) = \begin{bmatrix} H_z - H_z^{\text{perfect}} \\ \frac{\partial H_z}{\partial n} - \frac{\partial H_z^{\text{perfect}}}{\partial n} \end{bmatrix}_{\text{boundary}} = 0. \tag{4}$$

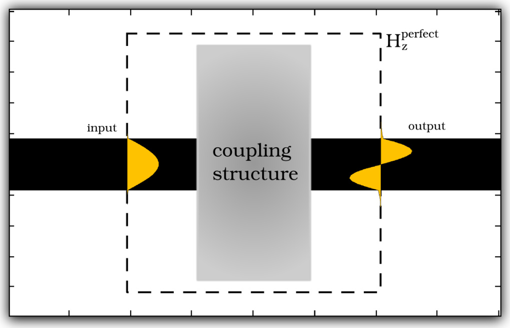

Fig. 1. Boundary-value formulation of the design objective. The values of H_z^{perfect}, defined along the dashed box surrounding the design area (coupling structure), are shown in orange. The values of H_z^{perfect} along the top and bottom edges of the dashed box are set to zero. In this schematic, the fundamental and second-order waveguide modes have been chosen as the input and output modes respectively.

That is to say, the values of H_z and $\partial H_z/\partial n$ (spatial derivative along normal direction) along the device boundary are forced to be those of a device with perfect performance (100% coupling efficiency).

Such a design objective is both extremely simple and widely adaptable to the design of nearly every kind of nanophotonic device. Most importantly, it is trivial to enforce, requiring only that we overwrite boundary field values. Our experience suggests that successful designs are possible for arbitrary choice of relative phase between the input and output fields.

Finally, as in any method based on an objective-first approach, the physics residual is not guaranteed to decrease to zero. Thus, it is entirely possible to never achieve a physically realizable field, H_z. In such cases, which are the norm rather than the exception, we find that a relatively small residual usually leads to fairly good, although imperfect, device performance.

The design problem is now

$$\text{decrease} \quad \|\nabla \times \varepsilon^{-1}\nabla \times H_z - \mu_0\omega^2 H_z\|^2 \tag{5a}$$

$$\text{subject to} \quad \begin{bmatrix} H_z - H_z^{\text{perfect}} \\ \frac{\partial H_z}{\partial n} - \frac{\partial H_z^{\text{perfect}}}{\partial n} \end{bmatrix}_{\text{boundary}} = 0. \tag{5b}$$

This problem contains many local minima (it is non-convex [10]); however, when either the field (H_z) or the structure (ε^{-1}) variable is considered separately, Eq. 5 has only one minimum (it is convex), and can be easily solved using standard methods such as employed in our previous work [11]. We employ such an alternating directions strategy, where both H_z and ε^{-1} are solved independently. This process is extremely inefficient, but is employed because the underlying numerical methods do not need to be tuned by the user. We expect considerable improvements in computational efficiency when more sophisticated algorithms are applied, especially those which can update H_z and ε^{-1} independently.

Lastly, we limit the allowable values of ε to be between the permittivity of vacuum and of silicon,

$$\varepsilon_0 \leq \varepsilon \leq \varepsilon_{\text{silicon}}. \tag{6}$$

A completely binary structure would be preferred, $\varepsilon = \{\varepsilon_0, \varepsilon_{\text{silicon}}\}$, and will be pursued in a future work. That said, the final designs presented here all have significant portions which are already binary.

3.1. Coupler designs

We now present evidence that the method outlined above is indeed able to design coupling structures between essentially any two nanophotonic waveguide modes. To do so, we apply our method to the following five problems:

1. coupling between waveguides of different refractive index and width (Fig. 2);
2. coupling between waveguide modes of different order and symmetry (Fig. 3);
3. coupling between waveguides that confine light using different principles (index guided vs. distributed Bragg reflection guided), i.e., between a slab waveguide and a photonic crystal fiber (Fig. 4)
4. coupling from a dielectric to a plasmonic metal-insulator-metal waveguide (Fig. 5); and
5. coupling from a dielectric waveguide to a (plasmonic) metal wire (Fig. 6).

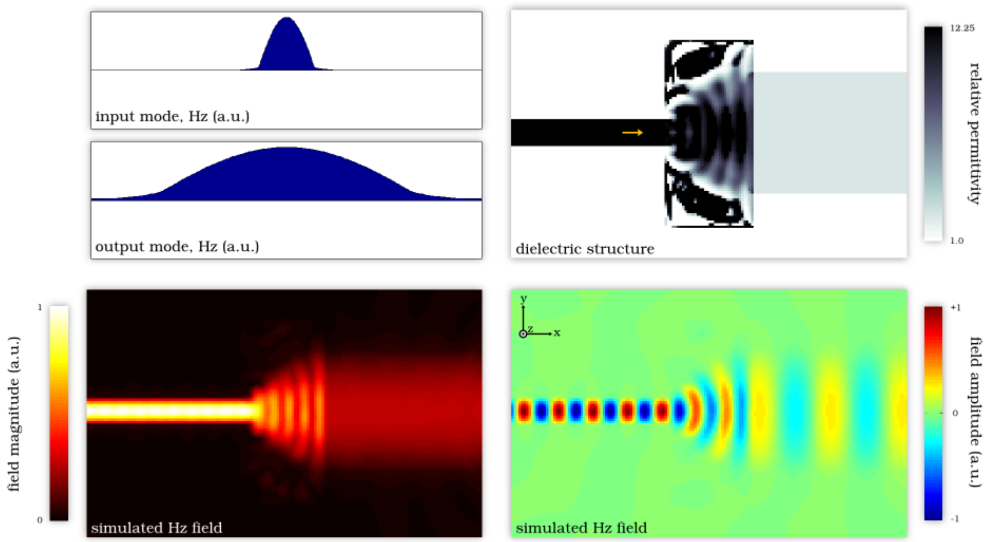

Fig. 2. Coupler from a narrow, high-index ($\varepsilon = 12.25$) waveguide to a wide, low-index ($\varepsilon = 2.25$) waveguide. The H_z^{perfect} boundary values used as the design objective are plotted in the upper-left quadrant, the generated structure is shown in the upper-right quadrant, and the simulated H_z fields of the device are shown in the bottom two plots. The computed efficiency of the coupler is high, 98.2%, and the device is also extremely compact, convering only 36×66 grid points, where the vacuum wavelength is 42 grid points. Computation time was 15 minutes on a personal computer.

These results clearly demonstrate that our method can be applied to arbitrary input and output modes, as seen from the diverse selection of desired output waveguide modes. Moreover, it produces highly efficient devices with typical coupling efficiencies of 95%, which are at the same time compact (with footprints of only 1-4 square vacuum wavelengths). In addition, the method does not require a good initial guess for the design. In our case the initial design was simply $\varepsilon = 9$ everywhere (a somewhat arbitrary guess, other values work as well). Finally, the method is computationally fast, requiring only 15 minutes on a single-core personal computer.

These results form a key advancement in our understanding of nanophotonic design; namely, that it is indeed possible to efficiently design virtually any linear optical device using an objective-first approach.

4. Conclusion

We develop a fundamentally new approach to designing physical structures, which we term “objective-first”, in that we choose to satisfy the design objective even above satisfying the physical equation which governs its operation. We show that such an approach drastically reduces the amount of computation required per iteration, and performs well even with a non-functional initial design.

We then apply an objective-first approach to the design of five practical nanophotonic waveguide couplers which are difficult to solve with existing methods. We show that our method produces high-efficiency designs ($\sim$ 95% efficiency) in small footprints ($\sim$ 1 square vacuum wavelength) between arbitrary waveguide modes. Furthermore, out

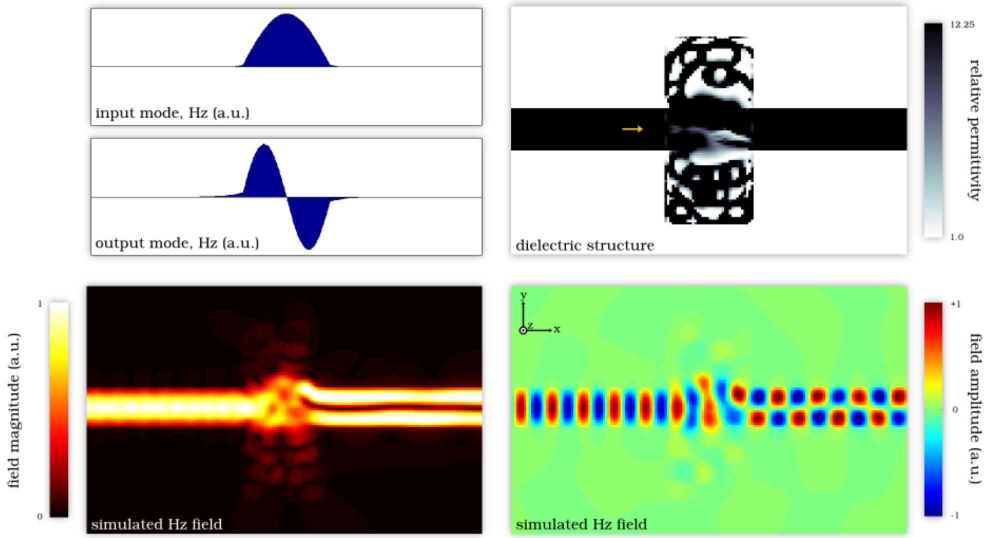

Fig. 3. Coupler that converts the fundamental waveguide mode to the second-order waveguide mode (a movie of the design progress is included as a supplementary material). This problem is quite difficult since the two modes are of opposite symmetry. For example, adiabatic approaches cannot be applied to this case. However, our method produces a device (which has the same dimensions and vacuum wavelength as Fig. 2) with a coupling efficiency of 97.0%. Computation time was 15 minutes on a personal computer.

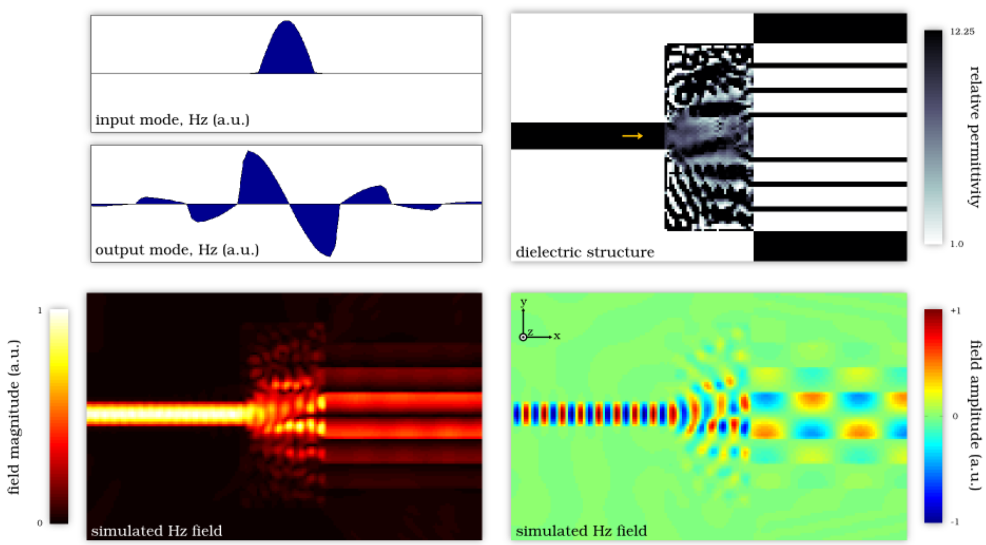

Fig. 4. Coupler between a dielectric slab waveguide to an air-core waveguide. Here, not only are the modes of opposite symmetry, but the output waveguide operates on a fundamentally different principle (distributed reflection) than the input waveguide (index guided). The device still achieves an efficiency of 85.1%, 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 15 minutes on a personal computer.

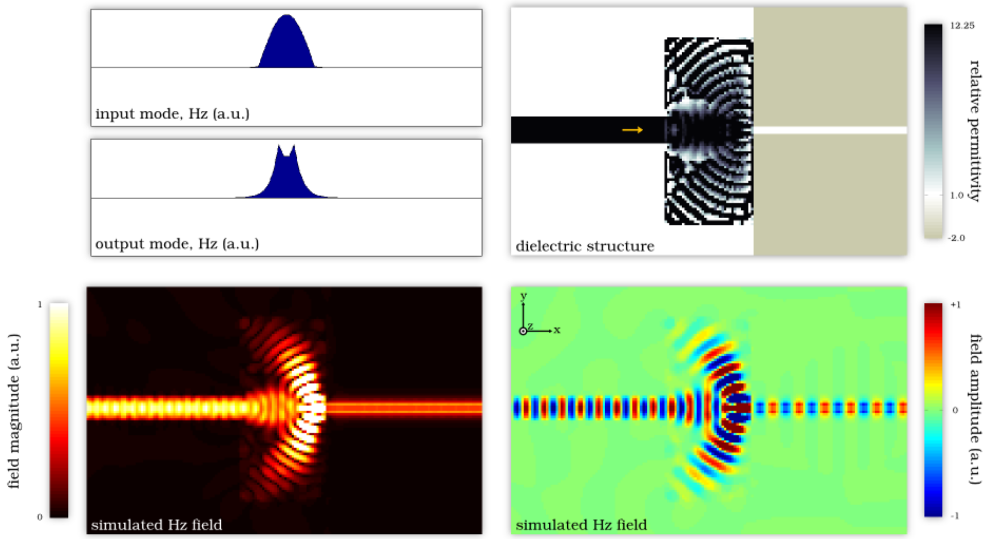

Fig. 5. Coupler between a dielectric slab waveguide to a plasmonic metal-insulator-metal waveguide. The efficiency of the device is 92.9% and has the same wavelength and footprint as the device in Fig. 4. Computation time was 15 minutes on a personal computer.

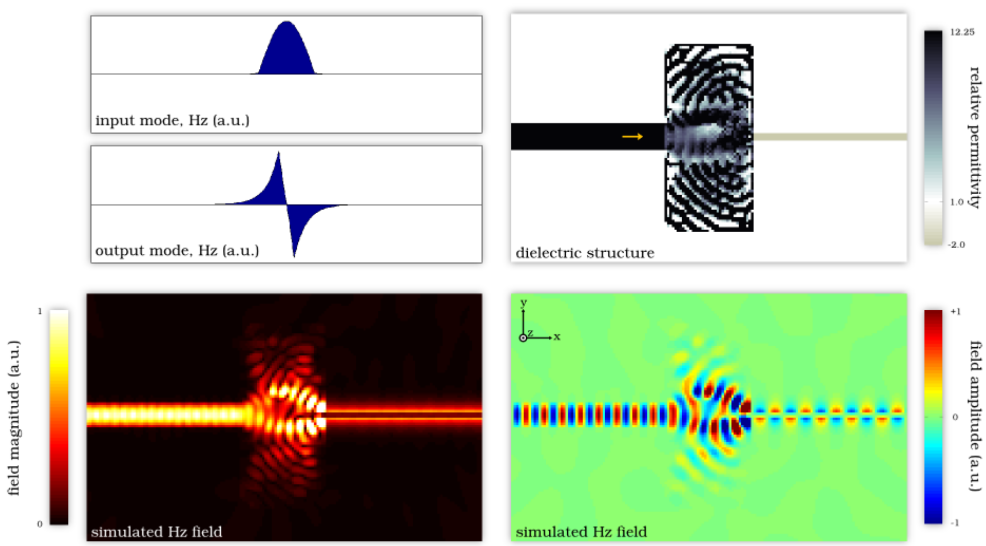

Fig. 6. Coupler between a dielectric slab waveguide to a plasmonic wire waveguide. The efficiency of the device is 93.2% and has the same wavelength and footprint as the device in Fig. 4. Computation time was 15 minutes on a personal computer.

method is computationally fast (15 minutes on a single-core personal computer), and does not require trial-and-error, or even a good starting design.

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