Automated Design of Nanophotonic 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 computationally fast, can be extended to multiple dimensions, and requires no trial-and-error.

1 Motivation

1.1 The importance of waveguide mode conversion

Optical mode conversion, the efficient transfer of photons from one guided mode to another, is a fundamental requirement in nanophotonics. Efficient conversion between waveguides modes is critical in the many cases, including:

1. Coupling to and from optical fiber[], to communicate with the outside world.

2. Coupling between various nanophotonic waveguides, since different waveguides are best suited for different applications. For example, ridge waveguides seem ideal for low-loss transport[], but other waveguides, such as photonic crystal waveguides or slot waveguides, may be better suited for slow-light[] or energy-focusing devices[].

3. Coupling between different materials. This is to couple between passive, active[], and non-linear[] materials.

1.2 Common approaches to designing waveguide couplers

Brute-force parameter search is the most popular nanophotonic design strategy to-date because of its sheer simplicity[]. Although it may be suitable for tuning existing designs[], the parameter space for most practical devices is simply too large for such a strategy to be tractable.

Adiabtic mode conversion strategies have been succesful for certain fiber-waveguide[] and waveguide-waveguide[] couplers, although resulting devices are

quite large. However, adiabatic strategy cannot be used in many important cases such as coupling from ridge to some photonic crystal waveguides, coupling in the out-of-plane direction, and coupling between modes of opposite symmetry.

Optimization methods based on local derivatives seem very promising[], in that they are both much faster than brute-force methods and more adaptable than adiabatic strategies. However, these methods still require that every updated design be simulated at least once, and for the user to supply an initial design.

1.3 Advantages of objective-first design

We present an "objective-first" approach to nanophotonic design, and apply it to the problem of high-efficiency waveguide couplers. The resulting algorithm

- does not employ brute-force parameter searches,
- does not require a good initial design,
- is computationally fast (no simulations required),
- generates couplers between seemingly arbitrary waveguide modes, and
- generates these couplers in a very small footprint.

2 Design Method

2.1 Objective-first optimization

The typical approach to designing physical structures can be formulated in the following way, where x is the field variable and p is the structure variable,

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

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 called the *physics residual*.

Such a formulation naturally lends itself to a local derivative strategy where x is a dependent variable and p is an independent variable. The optimization then proceeds by

1. computing x, given p, via $g(x,p) = 0$ (i.e. finding x via simulation),

2. updating p to decrease $f(x)$ (details in appendix).

Not, satisfying the design objective actually has a higher priority than satisfying the underlying physical equation, hence the name "objective-first".

Notice that the design objective is now a constraint (Eq. 2b), and that the quantity to be decreased is now the