Nanophotonic Computational Design

Jesse Lu* **and Jelena Vučković**
Stanford University, Stanford, California, USA.
jesselu@stanford.edu

Abstract: In contrast to designing nanophotonic devices by tuning a handful of device parameters, we have developed a computational method which utilizes the full parameter space to design linear nanophotonic devices. We show that our method may indeed be capable of designing any linear nanophotonic device by demonstrating designed structures which are fully three-dimensional and multi-modal, exhibit novel functionality, have very compact footprints, exhibit high efficiency, and are manufacturable. In addition, we also demonstrate the ability to produce structures which are strongly robust to wavelength and temperature shift, as well as fabrication error. Critically, we show that our method does not require the user to be a nanophotonic expert or to perform any manual tuning. Instead, we are able to design devices solely based on the user's desired performance specification for the device.

OCIS codes: 230.75370, 130.3990.

References and links

---

1. Introduction

Currently, almost all nanophotonic components are designed by hand-tuning a small number of parameters (e.g. waveguide widths and gaps, hole and ring sizes). However, the realization of increasingly complex, dense, and robust on-chip optical networks will require utilizing increasing numbers of parameters when designing nanophotonic components.

Opening the design space to include many more parameters allows for smaller footprint, higher performance devices by definition; since original designs are still included in this parameter space. Unfortunately, the lack of intuition for what such designs might look like and the inability to manually search such a large parameter space have greatly hindered the ability to employ anything even close to the available parameter space for designing nanophotonic components.

For this reason, we have developed and implemented a computational method which is able to use the full parameter space to design linear nanophotonic components in three dimensions. Critically, our method requires no user intervention or manual tuning. Instead, a *design-by-specification* scheme is used to produce designs based solely on a user's performance specification.

We show that our method can indeed produce designs which are extremely compact, and, at the same time, highly efficient. Furthermore, we demonstrate that devices with novel functionality are easily designed. We also show that our method can be used to produce designs with extreme robustness to wavelength and temperature shift, as well as fabrication error.

Lastly, since all our results are produced by simply specifying the functionality and performance of the desired device, our results suggest that our method may indeed by able to design *all* linear nanophotonic devices.

2. Method

In order to produce designs which utilize the full parameter space, and are based solely on the user's performance specification, we formulate the design problem in the following way:

$$\begin{aligned}
&\text{minimize} \quad && \sum_i^M \|A_i(z)x_i - b_i\|^2 && \text{(1a)}\\
&\text{subject to} \quad && \alpha_{ij} \le |c_{ij}^\dagger x_i| \le \beta_{ij}, \quad \text{for } i = 1,\ldots,M \text{ and } j = 1,\ldots,N_i && \text{(1b)}\\
& && z_{\min} \le z \le z_{\max} && \text{(1c)}
\end{aligned}$$

The explanation for the various terms in (1) follows:

1. $A_i(z)x_i - b_i$ is the *physics residual* for the ith mode. That is to say, $A_i(z)x_i - b_i$ represents the underlying physics of the problem; namely, the electromagnetic wave equation $(\nabla \times \mu_0^{-1} \nabla \times -\omega_i^2 \varepsilon)E_i + i\omega_i J_i$.

   The specific substitutions used in order to transform

   $$(\nabla \times \mu_0^{-1} \nabla \times -\omega_i^2 \varepsilon)E_i + i\omega_i J_i \quad \longrightarrow \quad A_i(z)x_i - b_i$$

   are

   - $E_i \rightarrow x_i$,
   - $\varepsilon \rightarrow z$,
   - $\nabla \times \mu_0^{-1} \nabla \times -\omega_i^2 \varepsilon \rightarrow A_i(z)$, and
   - $-i\omega_i J_i \rightarrow b_i$.

   In contrast to typical schemes for optimizing physical structures, our formulation actually allows for non-zero physics residuals; which can be deduced since $A_i(z)x_i - b_i = 0$ is not a hard constraint. Instead, this formulation is what we call an *objective-first* formulation in that the *design objective* (explained below) is prioritized above satisfying physics.

2. The (field) design objective consist of the constraint $\alpha_{ij} \le |c_{ij}^\dagger x_i| \le \beta_{ij}$. Physically, this constraint describes the performance specification of the device via a series of field overlap integrals at various output ports of the device. Specifically, the $c_{ij}^\dagger x_i$ terms represents an overlap integral between the E-field of the ith mode (x_i) with an E-field of the user's choice (c_{ij}), where the additional subscript j allows the user to include multiple such fields.

   The amplitude of

3. Results

4. Conclusion