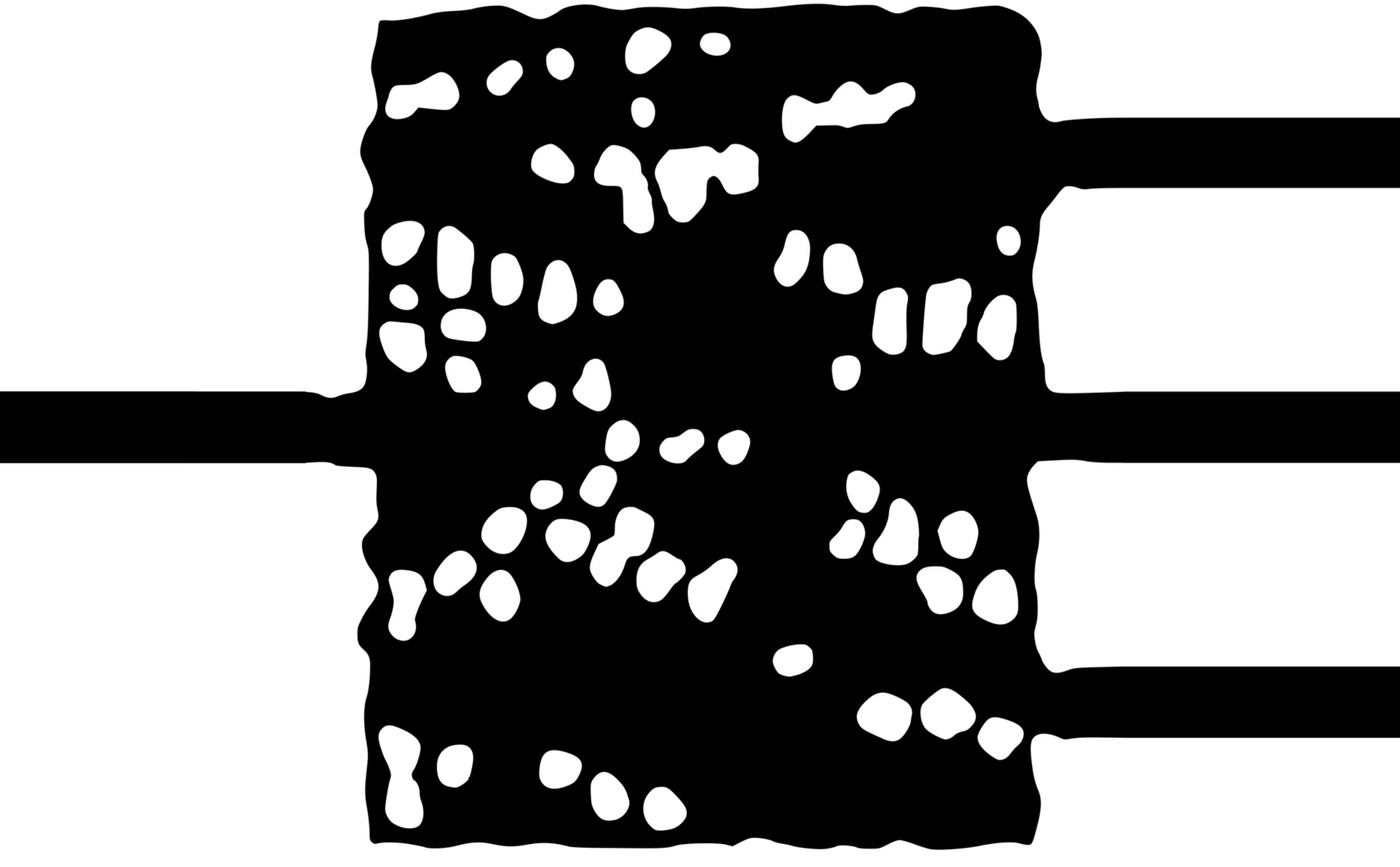
Stanford Photonics Inverse Design Software

(Spins)



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I. Introduction

A. Executive Summary

Photonics is poised to play a key role in a wide variety of applications, ranging from short-range optical interconnects and compact optical sensors to transparent displays for augmented reality systems. However, the design of photonic devices and systems remains extremely labor-intensive and requires engineers with detailed knowledge and extensive experience.

To improve upon traditional photonics design methods, the Vuckovic group at Stanford University has developed **Spins**, an automated photonics design suite that can:

- Automatically design photonic devices with no human guidance
- Design any passive, linear photonic element
- Efficiently search the full space of fabricable devices using gradient-based optimization
- Produce designs that are significantly more compact, have higher performance, and potentially realize novel functionalities
- Incorporate fabrication constraints to ensure devices are readily fabricable
- Streamline the design process for planar waveguide devices and grating couplers through the use of provided device *design kits* which only require the user to input high-

level parameters.

This software is now being licensed to any interested parties through Stanford's Office of Technology Licensing (OTL).

B. Optimization Approach

Traditionally, photonic devices have been designed by hand. A designer selects an initial geometry based on analytical results and intuition and fine tunes the design using brute-force parameter sweeps. Due to the inefficient nature of the parameter sweeps, only a few degrees of freedom (typically less than 10) are available to the designer.

The simplest approaches that improve upon these brute force parameter sweeps are *derivative-free* optimization methods, such as particle swarm optimization, genetic search algorithms, and iterated random search. These approaches directly sample the parameter space of devices and do not make use of any additional information that may be available from the physics. Consequently, derivative-free methods are computationally inefficient and only work well for small numbers of degrees of freedom.

In contrast, Spins makes use of *gradient-based* optimization, which can efficiently optimize over many of degrees of freedom. These methods work by computing the gradient of a figure of merit and moving in the direction opposite of the gradient to arrive at a local minimum. Using a variety of gradient-based methods, it is possible to quickly optimize over thousands or even millions of degrees of freedom.

The main challenge to gradient-based optimization is calculating the gradient, which can be computationally expensive for large numbers of degrees of freedom. Fortunately for electromagnetic design, we can exploit the physics of the system using *adjoint sensitivity analysis* to efficiently compute gradients [1]. Typically, only two electromagnetic simulations are required to compute the gradient, a "forward" simulation and an "adjoint" simulation, *irrespective of the number of degrees of freedom* in the design. Using this approach, one can efficiently explore extremely large design spaces, which in turns, enables the design of devices with significantly improved capabilities.

C. Capabilities and Demonstrations

Spins is an extremely flexible and adaptable photonics design software and can be used to design any linear, passive photonic element. To use Spins, the designer simply specifies a design region and desired functionality for a device. The software will then automatically design a device that satisfies these specifications. In contrast with traditional design, Spins searches the full space of fabricable devices, which produces designs which are significantly more compact, have higher performance, and can have novel functionalities.

Using Spins, we have designed and experimentally demonstrated a variety of waveguide-based silicon photonics devices [2-5]. In particular, this includes a 1300 nm / 1550 nm wavelength splitter with a footprint of only 2.8×2.8 μm (Fig. 1(a)), which was the smallest dielectric wavelength splitter at the time [3].

More recently, we have introduced fabrication constraints, which allow the user to specify a minimum feature size in the device to ensure fabricability. Applying these constraints, we demonstrated an improved 3-channel wavelength demultiplexer operating in the C-band shown in Fig. 1(b) [4] and a compact 3-way power splitter shown in Fig. 1(c) [5].

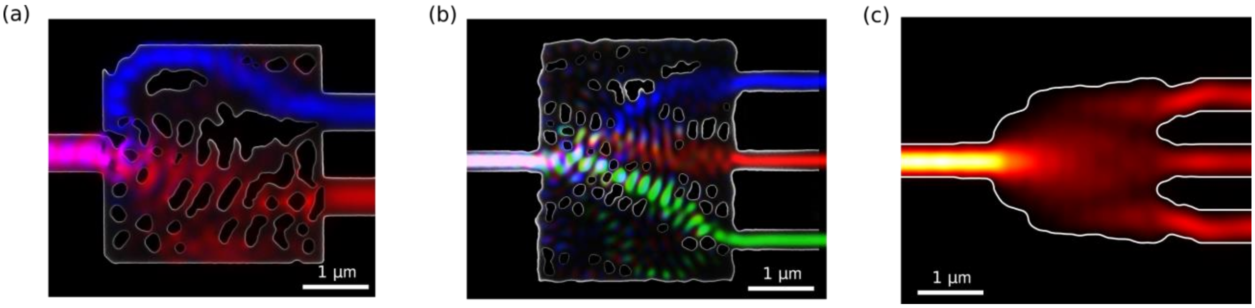

Figure 1: Three dimensional designs produced using Spins (a) 2-channel wavelength demultiplexer separating 1300 nm and 1550 nm (b) 3-channel wavelength demultiplexer separating 1500 nm, 1540 nm and 1580 nm and (c) 3-way power splitter.

Finally, we have shown that Spins can also be used to quickly and efficiently design a wide variety of grating couplers (Fig. 2), providing state-of-the-art performance and novel functionalities [6].

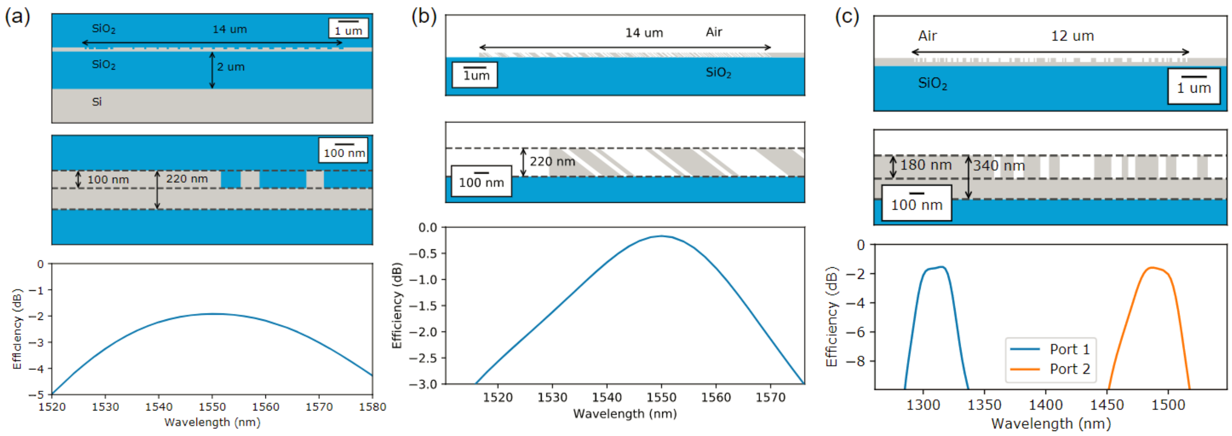

Figure 2: Designs produced using Spins (a) Partially etched grating coupler achieving insertion loss of 1.94 dB at 1550 nm, (b) Blazed grating with under 0.2 dB loss at 1550 nm (c) Wavelength demultiplexing grating coupler separating 1310 nm and 1490 nm into two different waveguide modes.

II. Design Paradigm

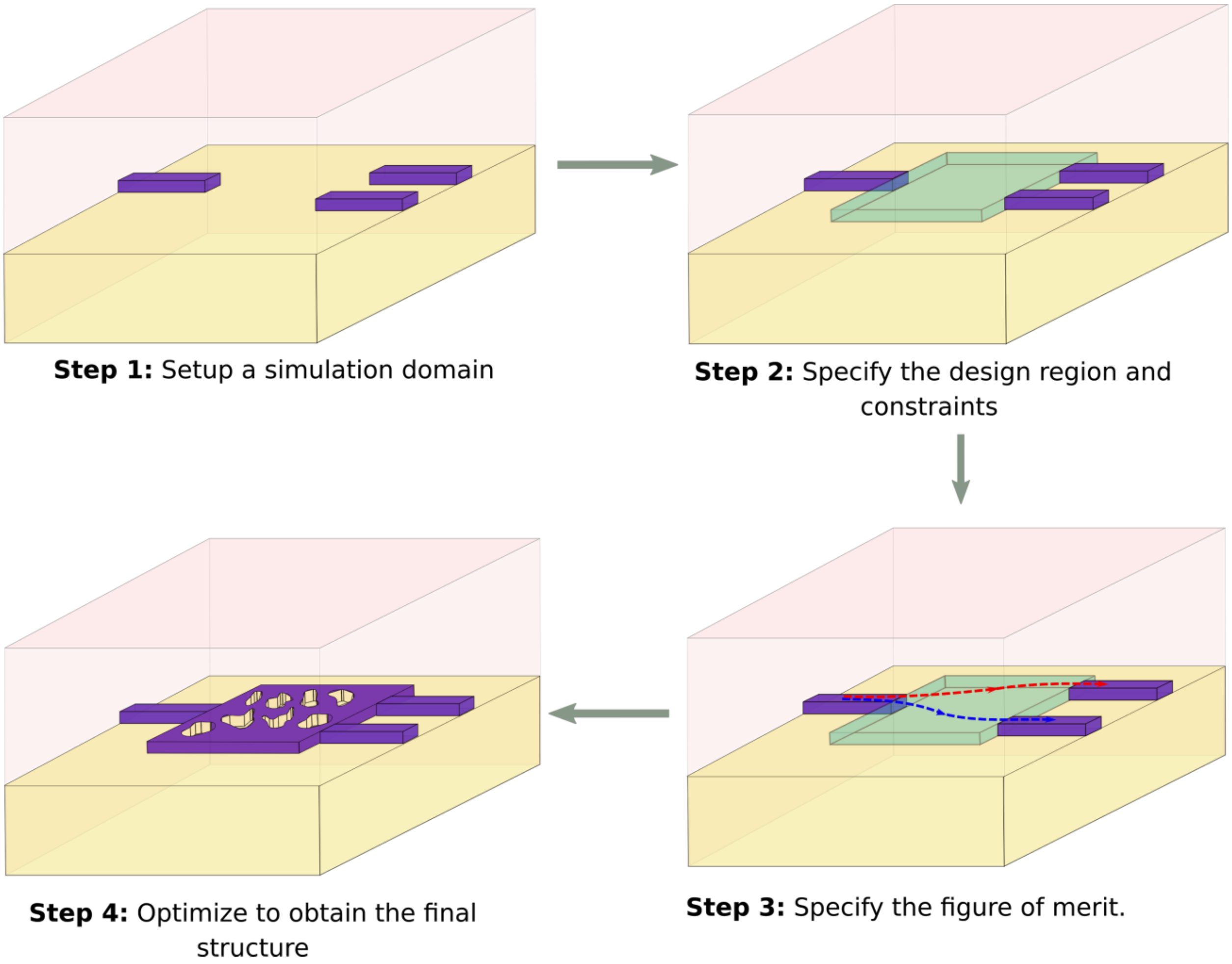

Figure 3: Flow chart depicting the basic steps involved in designing a photonic device with Spins

Optimizing a photonic device in Spins consists of the four steps outlined in Fig. 3.

1. *Setup a simulation domain*
The first step is to create simulation domain that will contain the device to be optimized. Spins provides a library containing the building blocks required for setting up an electromagnetic simulation: creating current sources (e.g. Gaussian beam, waveguide modes), handling boundary conditions, and drawing supporting structures (e.g. waveguides, photonic crystals).

2. *Specify the design region and constraints*
Next, the user selects a design region. Although a simple rectangular slab suffices for most devices, this design region can be arbitrarily complicated and can consist of multiple disconnected sub-regions. The optimized device will obey specified feature size constraints, but advanced users can choose to control precisely how the permittivity distribution may vary.

3. *Specify a figure of merit*
The figure of merit must be encapsulated by an objective function. Spins already implements basic figures of merit, such as power (field overlap) and far-field directivity, but adding custom, user-defined, figures of merit is straightforward.

4. *Optimize to obtain the final structure*
At this point, the objective function (figure of merit) can be passed to a gradient-based optimizer, which will iteratively find better devices. For the most common devices, the default optimizer in Spins will suffice, but advanced users can choose to use other optimizers for even better results.

III. Overview of Software

Spins is provided as Python package that consists of three different components:

1. **Design and Optimization Library**
   The core of our software consists of a design and optimization library. Using this library, the user specifies a physical structure, the desired functionality, and any fabrication constraints. The specifications are then fed into the provided design and optimization routines. This library is flexible and can be adapted to design essentially any linear photonic element.

2. **Device Design Kits**
   To streamline the design process, we have developed device design kits for the design and optimization of specific classes of devices. To use these design kits, the user only needs to provide high-level specifications for the devices, and does not need to directly interact with the design and optimization library. Currently, we have design kits available for waveguide-based silicon photonics devices and one-dimensional grating couplers.

3. **Open-source GPU accelerated EM solver**
   The majority of the computational effort required to design photonic devices is spent in electromagnetic simulations. To speed up the design process, we developed a GPU-accelerated finite-difference frequency-domain (FDFD) electromagnetic simulator.
   For typical photonic devices, our FDFD solver is significantly faster than time-domain methods.

A. Design and Optimization Library

1. Structure and Simulation Setup

The simulation module allows the user to define an electromagnetic simulation with arbitrary permittivity and permeability distributions. This can be accomplished by setting the values manually or by using the provided drawing functions. The module supports non-uniform meshing to resolve small, high-contrast features. The simulation domain is terminated through the choice of various boundary conditions including: periodic, perfectly matched layer (PML), and Bloch boundary conditions.

Once the system geometry and the optimization regions are constructed, sources can be introduced in the form of free-space beam inputs, waveguide mode inputs, or arbitrary user-defined current sources.

Finally, the user specifies the design regions, the regions which are allowed to change during the optimization.

2. Objective Function

The objective function encapsulates the desired functionalities of the device. Spins minimizes this objective function to design an optimal device.

Spins provides some objective function which describe common optical design problems, such as optimizing coupling into a specified waveguide mode and tailoring far-field emission profiles. In addition, the user can define custom objectives that are a function of the device permittivity and fields from electromagnetic simulation. Finally, Spins provides an easy way to combine multiple figures of merit into one function.

3. Fabrication Constraints

Optical devices fabricated by lithographic processes have to adhere to strict design rules. The library provides a level set representation to describe lithographic devices, and constraints to assure fabricability.

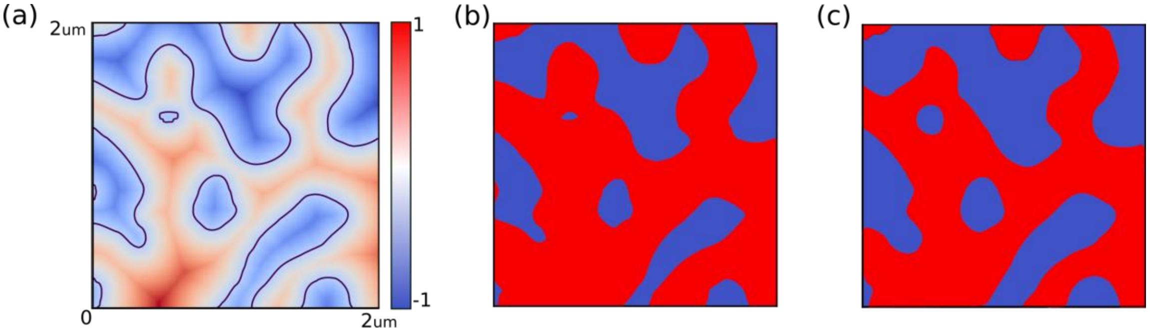

Figure 4: (a) An example of a level set function, (b) structure corresponding to the level set function shown in (a) and (c) structure after imposing fabrication constraints.

The level set representation uses a continuous function to describe regions in the design space that are either etched or not-etched. Etched regions are regions where the level set function is negative, as illustrated in Figs. 4(a) and (b). The level set representation is very convenient for describing structures with smooth, curved boundaries and arbitrary topologies. In particular, level sets naturally handle the creation and merging of holes in a structure.

Functions that characterize the feature/gap-size and curvature are available in the library. These functions can be implemented as a constraint in the optimization so as to enforce fabricability. Figs. 4(a) and (b) show a structure before and after applying fabrication constraints respectively.

4. Optimization

The optimization library contains optimizers used for minimizing objective functions. In most cases, the default optimizer (L-BFGS-B) in Spins will be sufficient. However, since the most effective optimization method varies depending on the objective function, the optimization library also implements an assortment of common gradient-based optimization methods, including gradient descent and Nesterov’s accelerated gradient (momentum). Constrained optimization is supported through penalty functions and the augmented Lagrangian method. In addition, the optimization library has interfaces to open-source gradient-based optimizers and can be easily extended to use custom optimization methods.

5. Output

After optimization, the final structure and the simulated fields of the final iteration are available to the user for further analysis. The level set parametrization of the structure can also be exported as a set of polygons or as a GDS file.

B. Device Design Kits

1. Planar Waveguide Devices

The planar waveguide design kit can design any single-layer planar device with input and output rib waveguides, intended primarily for silicon photonics applications. The user defines the footprint of the device, the input and output waveguides, and the desired coupling between the waveguide modes. Examples of devices that can be designed with this kit include polarization splitters and rotators, power splitters, and wavelength and spatial mode multiplexers [3-5,7]. These devices represent the state-of-the-art in footprint and functionality.

Features:

- **Robust fabrication and temperature insensitivity:** With the built-in fabrication constraints and ability to design broadband devices, structures produced are ensured to be fabricable as well as insensitive to spectral drift due to temperature fluctuations.
- **Compact footprint:** The devices designed by Spins typically have a footprint of a few square wavelengths.

2. Grating Devices

The grating coupler design kit provides software specifically for the design of non-uniform 1D gratings optimized to the specific material stack, fabrication capabilities, and desired functionalities. This kit has been used to design a wide class of fiber-to-chip grating couplers, including polarization-insensitive couplers, wavelength-demultiplexing couplers, multi-layer gratings, and highly efficient single-wavelength couplers [6].

Features:

- **Automated design process**: Whereas other grating methods may require a suitable choice of starting structure, the gradient coupler design kit uses a completely random initial condition. This capability is particularly useful when designing multi-functional gratings.
- **Efficient optimized gratings**: The gratings produced by the design kit have been shown to match or exceed the performance of conventional gratings.
- **Fast design time**: By using gradient-based optimization over particle swarm and genetic algorithms, grating design is quicker, enabling faster iteration time.

- **Broadband design**: Gratings can be designed to have large frequency bandwidth and angular bandwidth.
- **Flexible geometry:** The grating geometry can be fully-etched, partially-etched, etched at an angle, or even multi-layered.

C. GPU Accelerated EM Solver

An optimization often takes a few hundred objective function and gradient evaluations. This can result in very long optimization times, particularly for 3D design problems. The library therefore relies on an open source GPU-accelerated FDFD-solver that was also developed by the Vuckovic group. The CUDA-based code solves Maxwell's equations using iterative algorithms, such as CG, BiCGSTAB or GMRES. For large simulations, the solver can distribute the problem over multiple GPUs in order to further reduce the solution time.

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