Electromagnetic Inverse Design of a Compact Wavelength Demultiplexer

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Introduction

Photonics, the study and application of the microscopic properties of light, is a rapidly expanding field with an impact in technologies ranging from telecommunications to medical imaging. Yet despite their importance, photonic devices are still largely designed "by hand," with researchers relying on simulations and simple intuition to vary a few parameters.

However, recent years have seen the rise of a new strategy *Inverse design* utilizes algorithms whose computational costs does not depend strongly on the number of possible configurations, allowing one to explore a larger set of fabricable devices than in the past.

We applied algorithms from the open-source software Spins-B to determine the optimal design of various two-dimensional wavelength demultiplexers. Our results suggest that gradient-descent and adjoint methods allow for the creation of optimal photonics devices whose designs are unintuitive and impractical to design by other means.

Wavelength Demultiplexers

We decided to optimize a wavelength demultiplexer, a device that guides signals of different wavelengths from a single incoming channel into separate outgoing channels. Such devices have applications in areas like fiber-optics, where they are used to combine or split multiple optical carrier signals from a single optical fiber.

How do we determine if a given device is optimal? Since the purpose of a demultiplexer is to split different wavelengths of light into different channels, a quantitative measure for determining a given device's performance is provided by the transmission coefficients for each wavelength of light in that device. These transmission coefficients, or a properly weighted combination of them, defines what is known as our *objective function*. This function depends on the transmission coefficients corresponding to a given design, which in turn depends on the electric field and permittivity specified by the geometry of the design configuration.

Representing this device geometry by a parameterization vector *p* in the set *S* of fabricable devices means we can formulate our question above as the general optimization problem shown in Figure 1. This problem can then be approached and solved by the method of inverse design, as described below.

Figure 1

$$\min_{p} \quad f_{obj}(E(\epsilon(p))) \quad \text{subject to} \quad p \in S_{fab}$$

Inverse Design

The core technique of inverse design is gradient-descent iteration, where a system's quality of interest is evaluated by minimising a corresponding multivariate objective function. From vector calculus, the gradient of this function points in the direction of greatest increase, meaning that for enough steps and sufficiently small step size, moving along the negative gradient of *f* brings one closer to its minimum and the corresponding optimal design.

Within the device's design space, there are varying permittivities which manipulate light and split it into individual wavelengths. Dividing the design space into 0.1 x 0.1 µm "pixels" – each with a permittivity of 0 or 1 based on whether it will be vacuum space or silicon – makes use of all possibilities. The parameterization vector that categorizes the permittivity of each "pixel" in the space serves as the objective function's input. This vector represents a single possible design configuration whose elements consist of any relevant parameters, with each element allowed to vary to some degree.

As shown in Figure 2, the E field distribution depends on the permittivity distribution, which in turn depends on the parameterization vector *p*. If N wavelengths are being transmitted, the objective function will comprise of N terms.

We used the open source SPINS-B software and Python. Our code had four primary methods. First, the simulation space is created – like most optimizations, this requires a foreground and a background. Next, SPINS creates the objective function by measuring the wavelengths at both ends of the demultiplexer. Then, transformations are set based on discrete values, with the silicon is represented by 1 and empty space is represented by 0. Finally, the actual optimization is run using the previous methods, returning a GDS file that can be visualized.

Figure 2

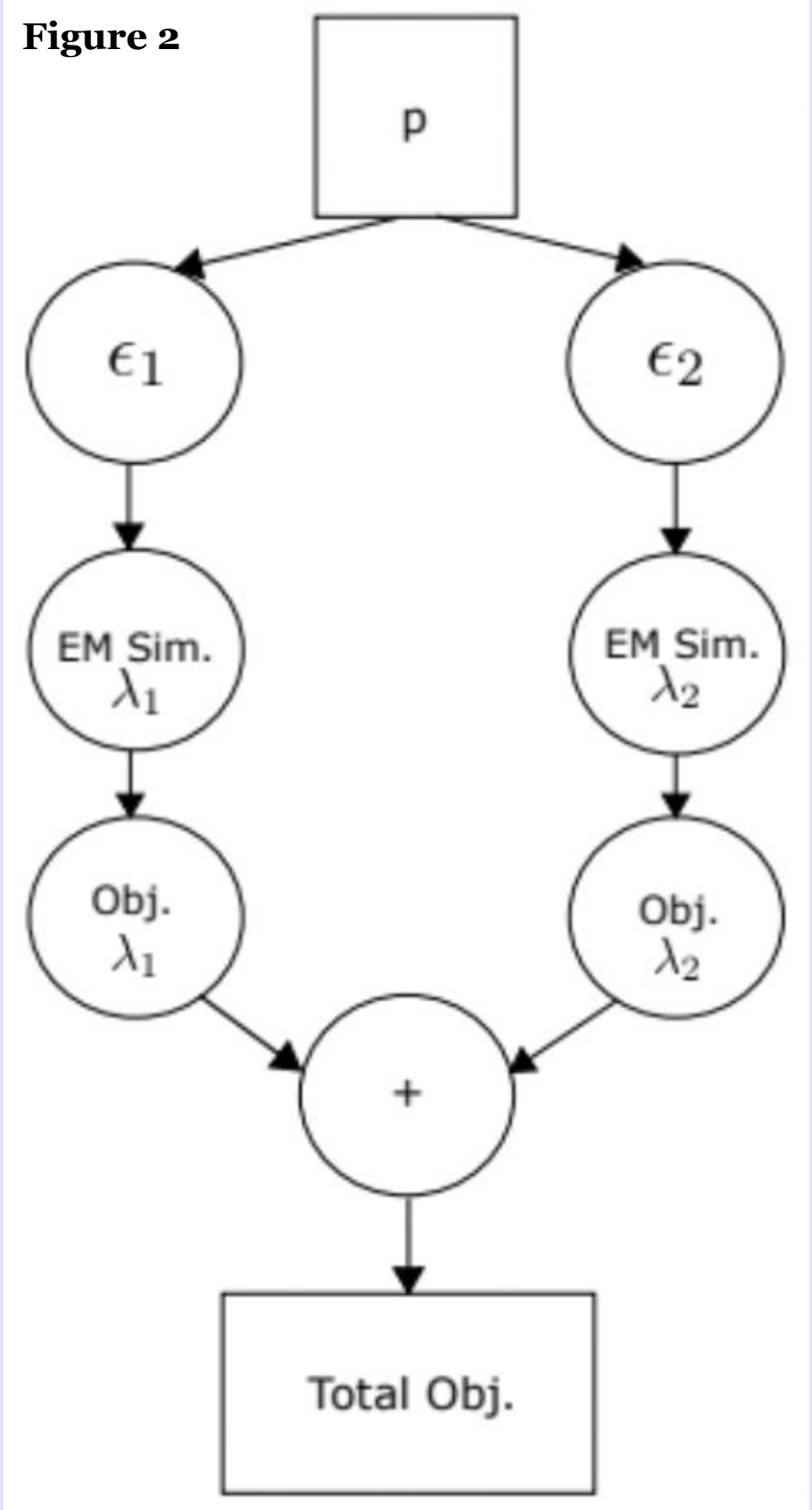


Figure 3

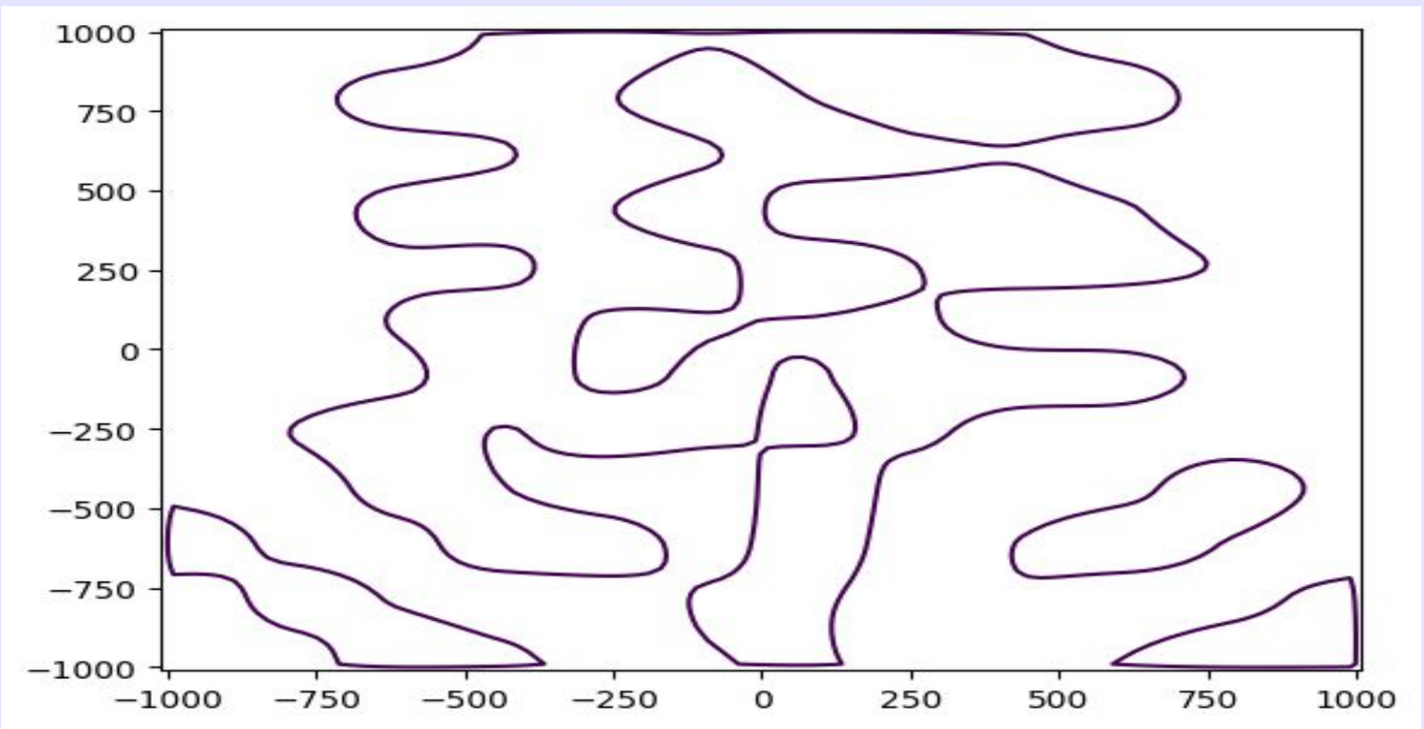


Figure 4

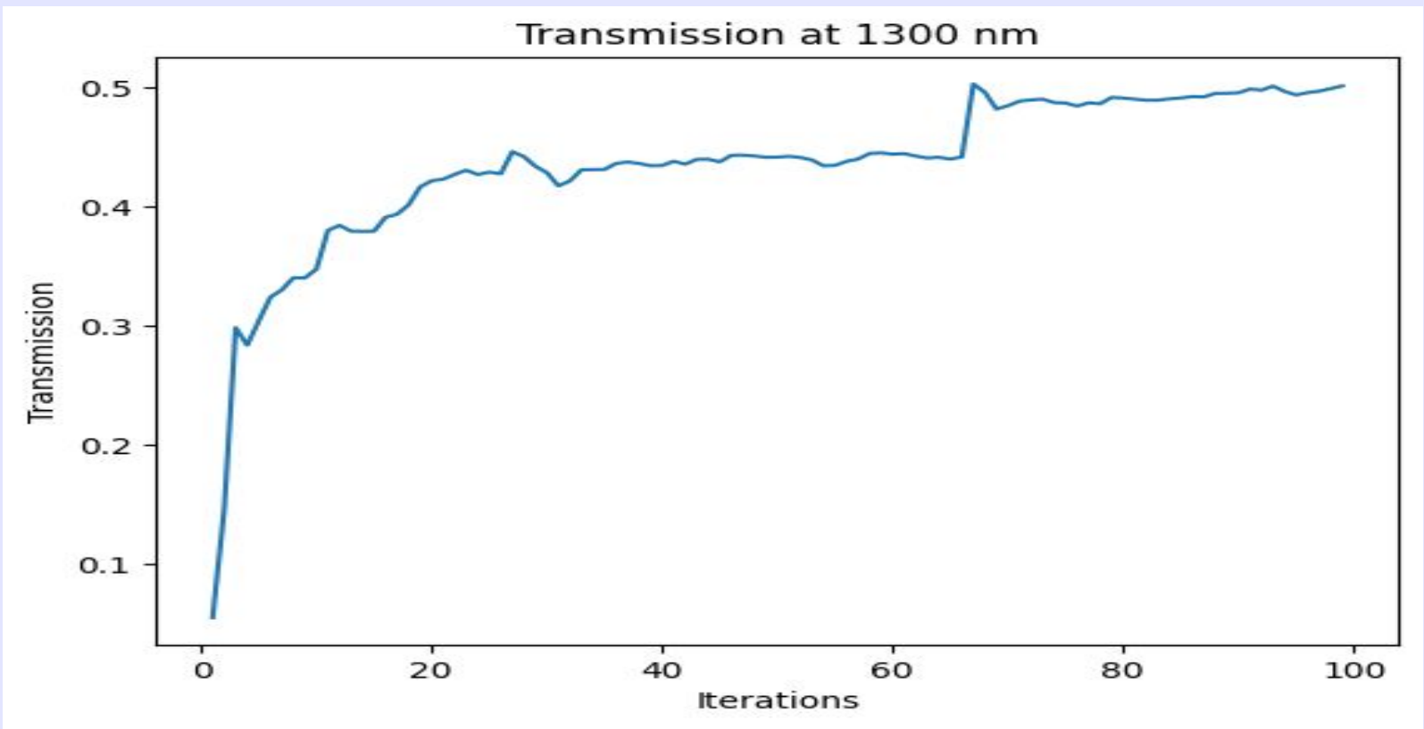


Figure 5

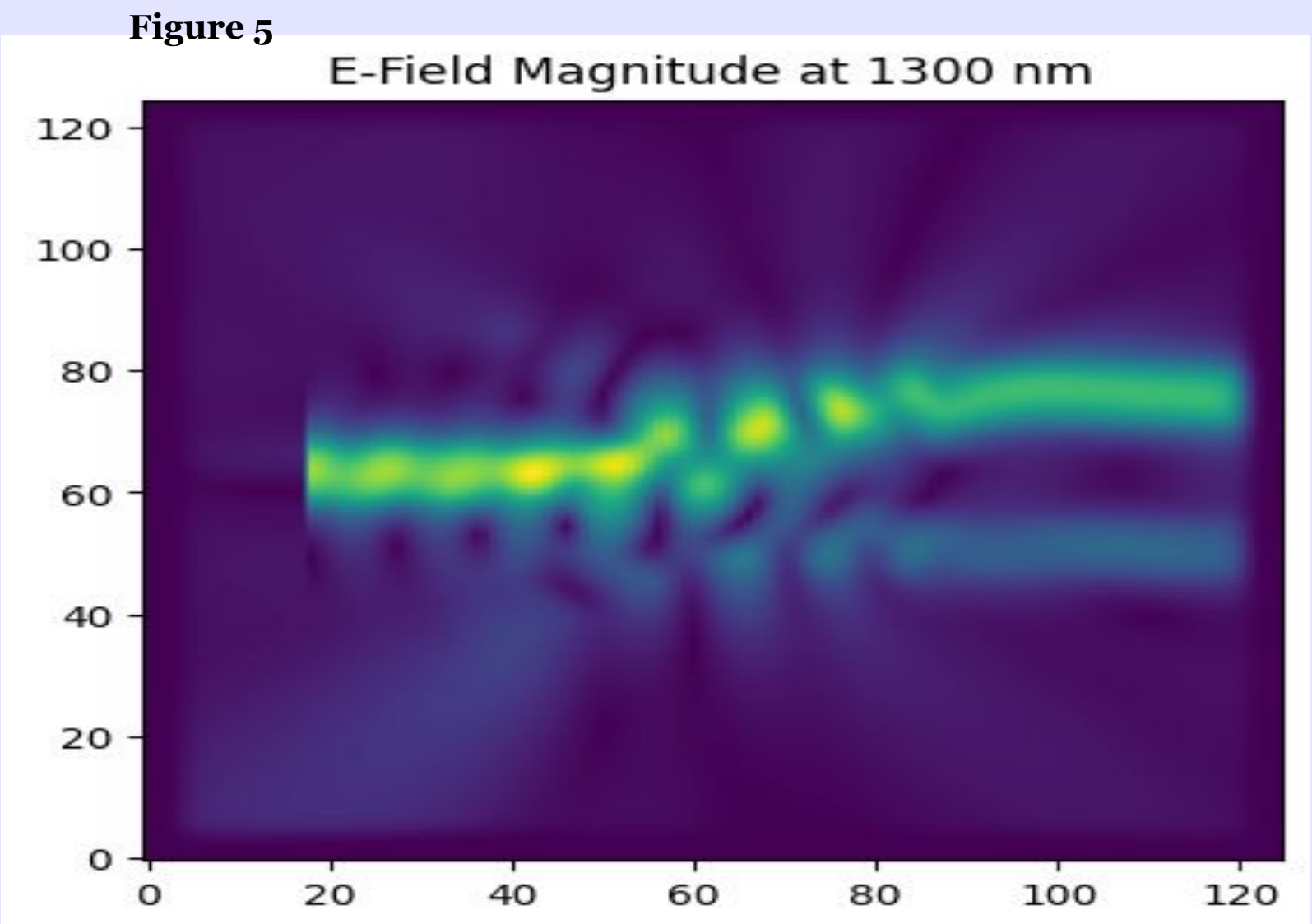


Figure 6

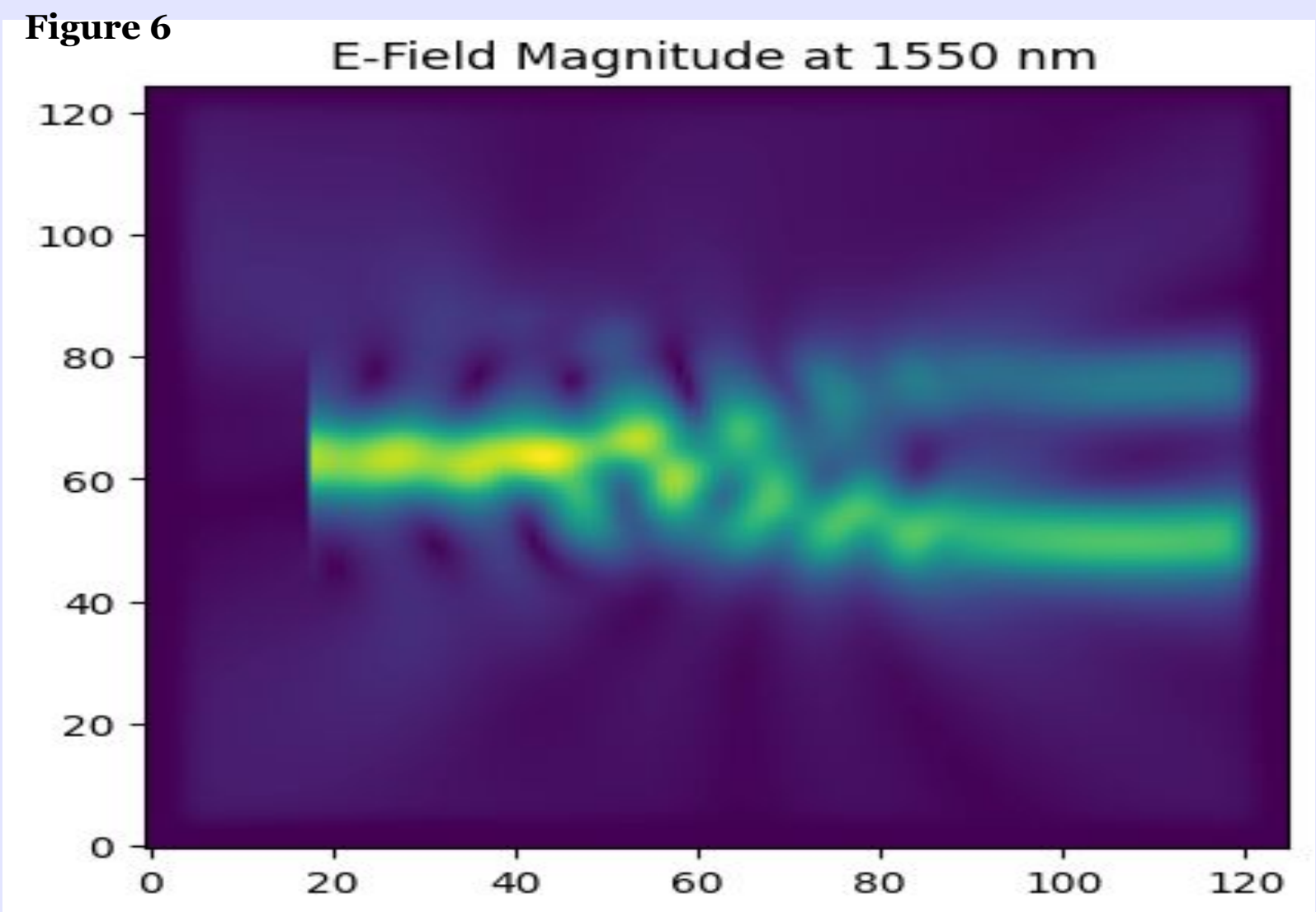


Figure 7

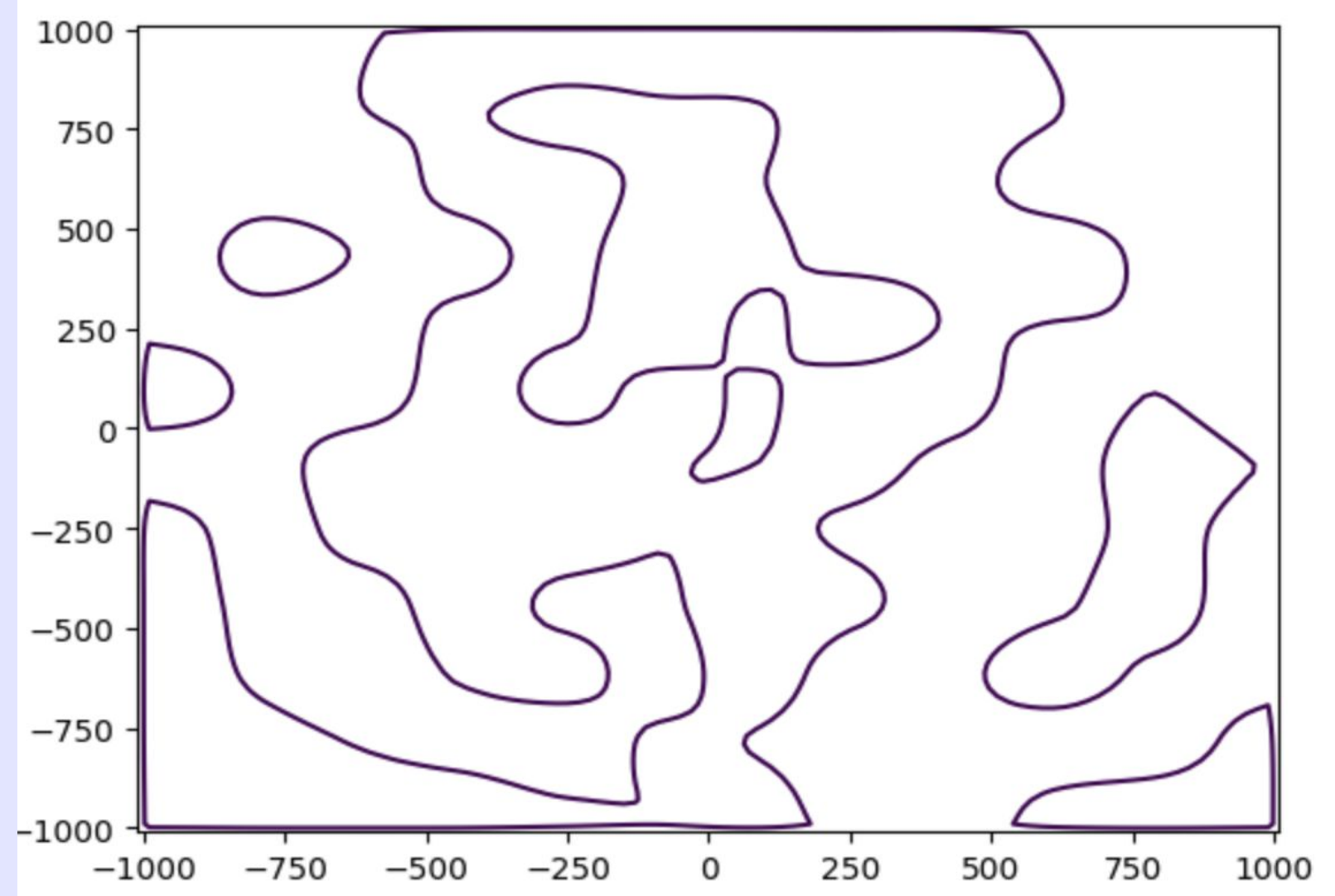


Figure 8

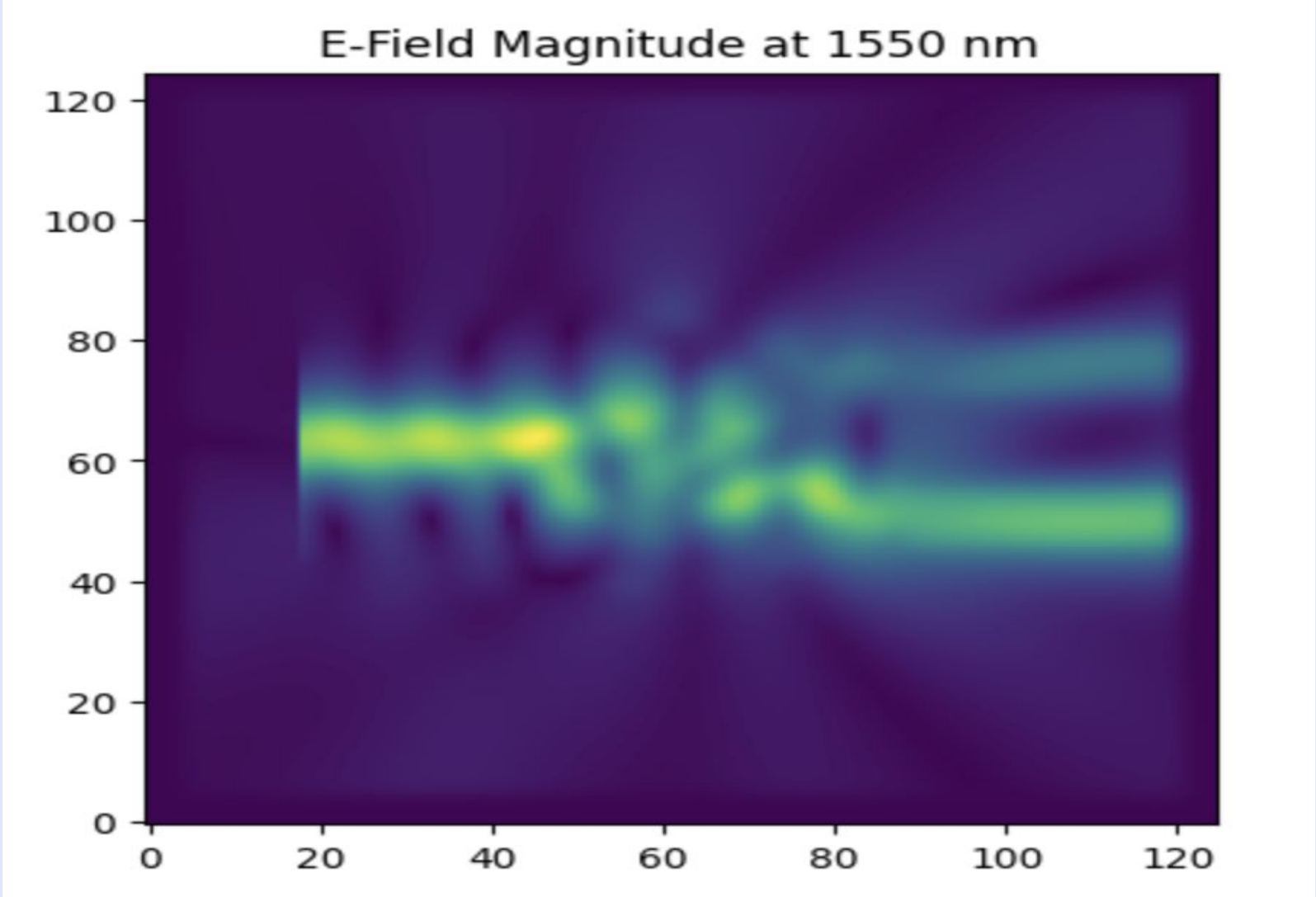


Figure 9

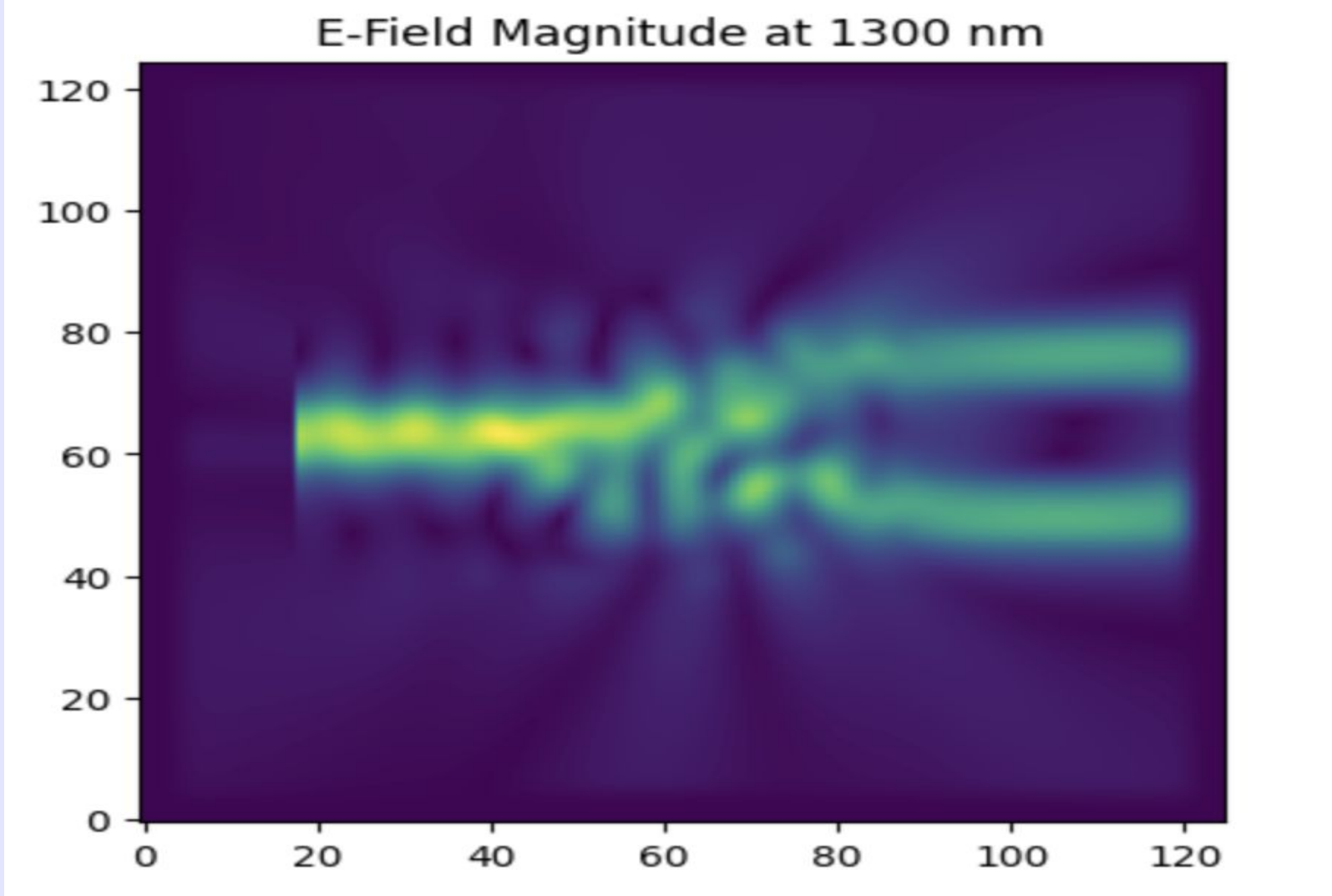
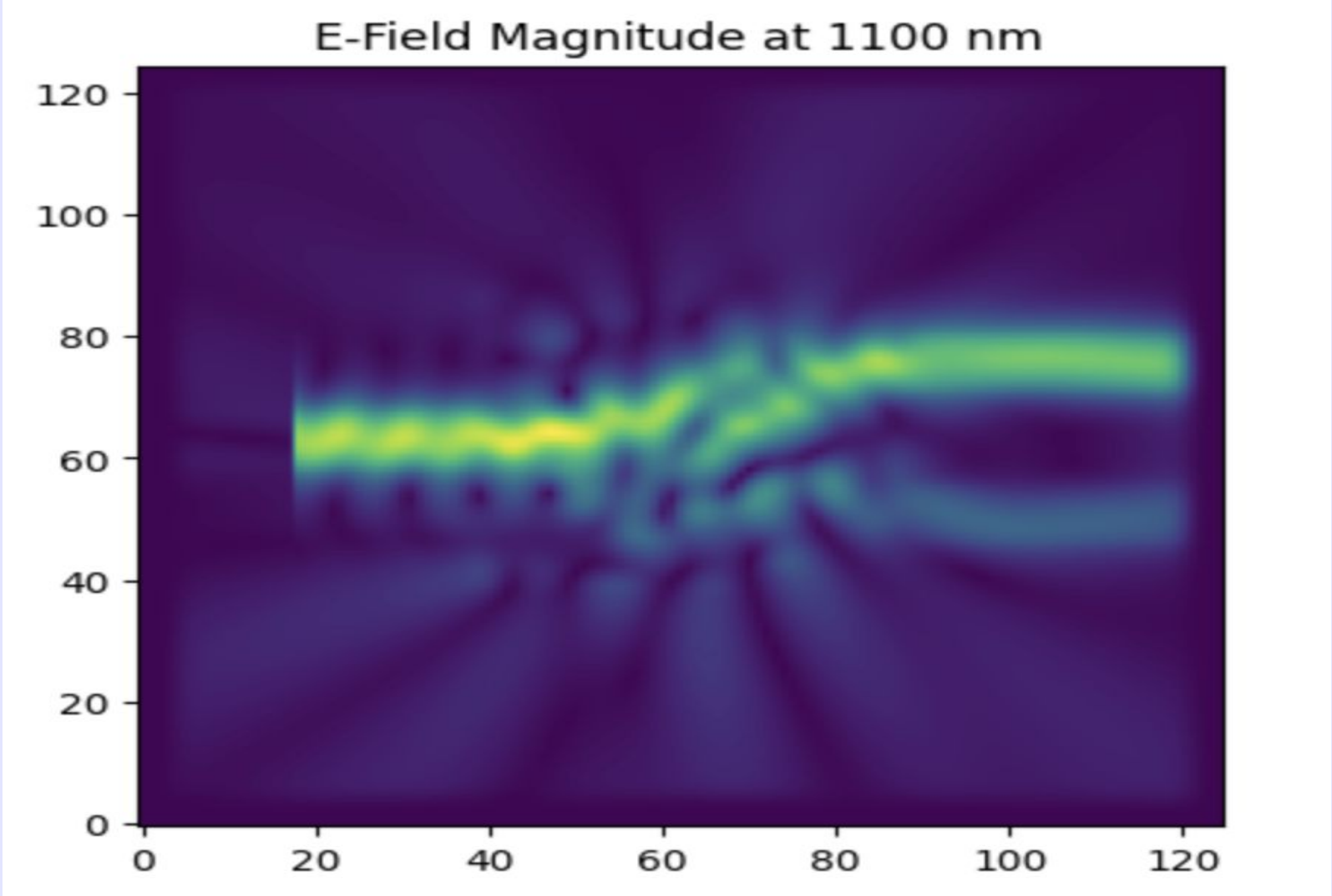


Figure 10



Results

During our research period, we began by designing simple wavelength demultiplexers with two output nodes, as seen in Figure 4. A channel of 1300 and 1550 nm was input. Transmission was as high as 0.5 for 1300 nm and 0.47 for 1550 nm. It should be noted that the optimized design was found after only 72 iterations, illustrating the time efficiency of inverse design. This transmission data can be seen in Figure 4.

Further, we used inverse design to create wavelength demultiplexers with three output nodes, as seen in Figure 8. Wavelengths of 1100 nm, 1300 nm, and 1550 nm were input. Transmission for each wavelength around 0.7. This shows that is it possible to use inverse design for multiple output nodes, which is extremely useful for industry applications in which devices have numerous wavelengths input.

There are also practical constraints on designs created. If a 2D design were to be manufactured, all silicon "pixels" would need to be connected so the demultiplexer would be one piece, i.e. every silicon pixel would need to touch at least one other pixel. One benefit of inverse design is that all 2D designs followed this principle.

For both of the demultiplexers above, the designs created by inverse design are unintuitive compared to the designs created in industry today. As seen in Figure 3 and Figure 7, the silicon areas are non-geometric and unable to be designed through trial and error. Additionally, with their unintuitive shape, inverse designed wavelength demultiplexers have more ideal transmission coefficients than traditional designs. Our research successfully acts as a proof-of-concept for engineering applications of gradient descent algorithms.

Material Properties

One of the most practically significant parameters that we varied was the choice of material to serve as the substrate for the demux. *(Specifically, the refractive index of the substrate was the relevant factor.)*

Analyzing the performance of 5 different designs, we found that substrates of lower refractive indices *(closer to the surrounding vacuum)* consistently produced both fewer discernible features and weaker transmission to the output channels.

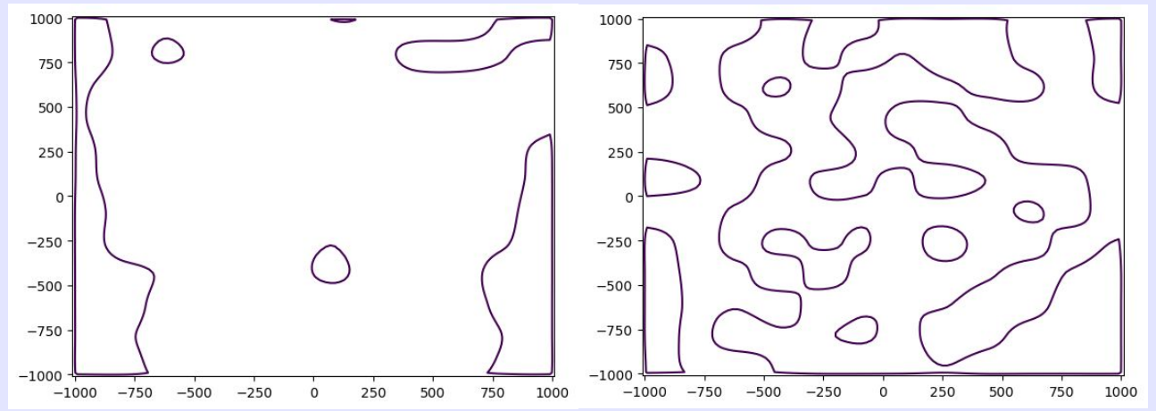


Figure X_1: Designs for RI of 1.0 *(left)* and of 2.65 *(right)*

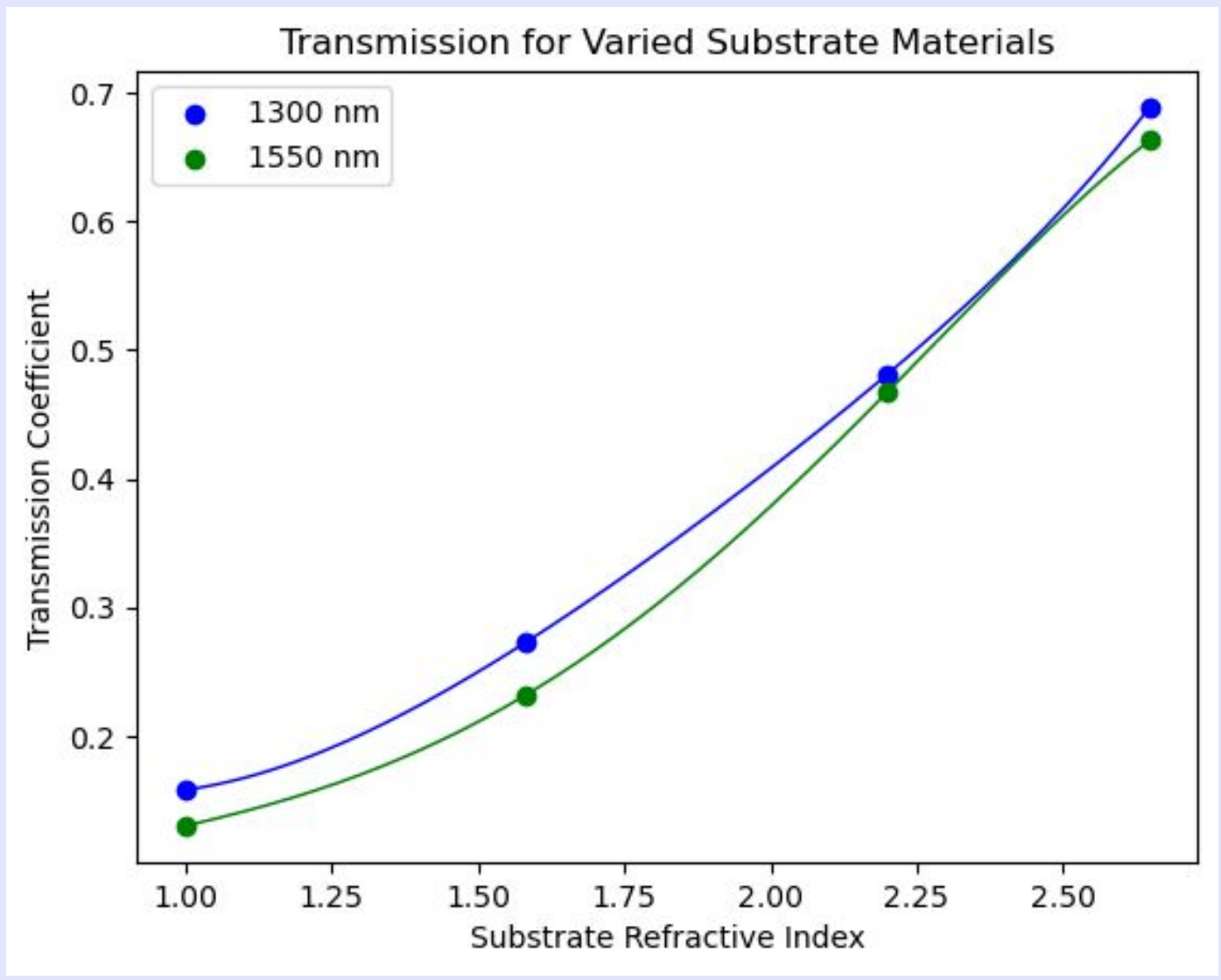


Figure X_2:
Plot of transmission coefficients for designs of diff. RI's

Final Remarks

Having produced a number of designs with generally acceptable transmission coefficients, we have been able to demonstrate the effectiveness of the inverse design method. For their given constraints *(size, available materials)* these designs provide excellent performance with geometries that are unintuitive except in the simplest cases.

Furthermore, we have demonstrated that the method is robust to many different possible configurations or use-cases that might be required. Given the general nature of the technique, we believe that the application of this method should be widely applicable in quickly generating effective solutions that can accommodate a quite large range of specifications.

Further Topics

Possible topics for future study include the optimization of a 3D wavelength demultiplexer. Asides from needing greater computational power, this project would also call for more careful consideration of boundary conditions to ensure that the designs explored are reasonably practical. Examples of this include requiring all material pixels to be connected to the device boundary and for the device to be structurally stable, reasonable constraints if one aims to apply inverse design to technology and engineering.

Additionally, we could optimize a larger dataset of refractive materials, in 2D or 3D. Doing so would allow us to develop a better fit for the relationship between refractive index and transmission coefficient, which we could then compare to theoretical predictions.

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