Compact 2x2 Inverse-Designed Beam Splitter for Integrated Silicon Photonics

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***Abstract*—This work presents the inverse design and topology optimization of a compact 2x2 beam splitter for 220 nm silicon-on-insulator (SOI) integrated photonics. We were able to achieve a significant reduction in the device footprint to 3.2 µm x 3 µm with a simulated insertion loss of 0.34 dB and power imbalance of 0.1 dB at 1550 nm. The device geometry is mirrored along the horizontal and vertical axis in order to reduce the parameter space and the number of simulations required for the optimization.**

***Index Terms*—integrated photonics, simulation, inverse design, topology optimization, beam splitter**

I. Introduction

With the increasing complexity and number of components on photonic integrated circuits (PICs), the demand for compact and efficient devices with tailored abilities, such as mode conversion [1] and wavelength devision multiplexing [2], grows.

However, traditional designs often face challenges in terms of size and performance, or need to be combined to fulfill a specific task.

Inverse design offers a powerful solution to this problem by enabling the engineer to create a device tailored to the demands of the circuits task. By optimising the geometry of the device, this method can significantly reduce the size of photonic devices while maintaining or even improving their performance.

Among various devices, beam splitters are key elements of PICs and widely used in applications such as photonic neural networks [3], photonic quantum circuits [4], non-blocking switches [5] and many more, often as a fundamental building block for Mach-Zehnder Interferometers (MZIs).

In this paper, we present an inverse-designed 2x2 beam splitter, optimized using the adjoint method and a state-of-the-art FDTD solver [6]. The resulting design is well suited for integration into dense photonic circuits, addressing the growing need for miniaturisation. The design process, simulation results, and potential improvements of the presented device are discussed in the following sections.

II. Simulation

We used density-based topology optimization [7], where each pixel in our design region can take an arbitrary value between n_{SiO_2} and n_{Si}. The device gets binarised during optimization. At the first step, the pixels in our design region are described by the design parameters $\boldsymbol{\rho}$, where each element can take a value between 0 and 1. To take the minimum feature size into account, we use a conic filter $\omega(\boldsymbol{x})$ with radius $R = 80$ nm, which exceeds our foundries minimum feature size. First, we smooth the design region by applying a 2D convolution twice on the design parameters:

$$\tilde{\boldsymbol{\rho}} = \omega(\boldsymbol{x}) \circledast \boldsymbol{\rho} \tag{1}$$

Subsequently, the variables are projected onto a binary value using:

$$\bar{\boldsymbol{\rho}} = \frac{\tanh(\beta\eta) + \tanh(\beta(\tilde{\boldsymbol{\rho}} - \eta))}{\tanh(\beta\eta) + \tanh(\beta(1 - \eta))} \tag{2}$$

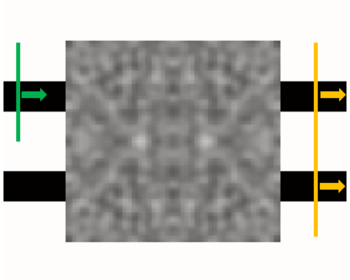
The parameter β controls the steepness of the projection and is continuously increasing over the optimization steps, while η denotes the offset and is chosen to be 0.5.

The permittivity of the design region is given by:

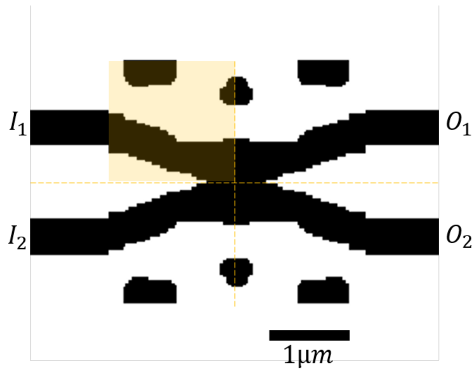
$$\varepsilon_r(\bar{\boldsymbol{\rho}}) = \varepsilon_{SiO_2} + \bar{\boldsymbol{\rho}}(\varepsilon_{Si} - \varepsilon_{SiO2}) \tag{3}$$

In order to attain the desired objective and enhance the performance of our device, a figure of merit (FOM) is defined and optimized by the algorithm. Our design goal is maximum transmission and equal splitting, thus the FOM consists of the total transmission $\bar{T}$ and the output balance B. The definitions are in the following way: $T_i(\lambda_c)$ represents the transmission at output O_i (Figure 1(a)) and wavelength $\lambda_c = 1550$ nm.

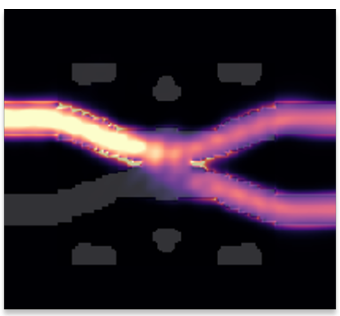
To avoid that the optimization converges to $T_i \rightarrow 1$, T_i has to be clipped at 0.5.



(a)



(b)



(c)

Fig. 1. Simulated 2x2 beam splitter. a) Initial design region with source and monitor ports. b) Binarised device. The yellow shaded region was mirrored at both axis of the design region, to create an entirely symmetric design, and ensure equal behaviour while injecting light into one of the four ports. Therefore, the number of simulations needed to design the device reduced from eight to only two simulations required for the adjoint optimization, while only one fourth of the design parameters are necessary to represent the whole area. c) Intensity distribution of the final device.

$$\tilde{T}_i = \min\left(T_i(\lambda_c), 0.5\right) \quad \text{for } i \in \{1,2\} \tag{4}$$

The total power contributing to the FOM is then given as:

$$\bar{T} = \sum_{i \in \{1,2\}} \tilde{T}_i \tag{5}$$

In order to take the equal output balance into account we define:

$$B = 1 - |T_1(\lambda_c) - T_2(\lambda_c)| \tag{6}$$

For equal splitting, i.e. $T1 = T2$, B has its maximum at $B = 1$.

Finally, the FOM is given by the weighted sum of 5 and 6:

$$FOM = \alpha \cdot \bar{T} + \gamma \cdot B \tag{7}$$

The values of the constants α and γ, which represent the weights, have been set to 0.6 and 0.4, respectively.

The overall objective function J is given as:

$$J = FOM - P \tag{8}$$

P represents a penalty, calculated based on the variations of the design parameters after applying erosion and dilation. The whole process is described in detail in [8] and well implemented in the simulations software adjoint plugin. We can now compute the gradient of the objective function $\partial J / \partial \boldsymbol{\rho}$ depending on our design parameters $\boldsymbol{\rho}$ with only two FDTD simulations using the adjoint method and adjust our parameters in order to maximise J. We continuously increased the β parameter during the optimization, forcing the material in the design region to be closer to the physical values of n_{Si} and n_{SiO_2}. We found the best performing device after 55 iterations with a beta value of only 22. For the final simulation however, we forced the material to be either Silicon or Silicon dioxide, leading to a slightly worse performance especially in terms of power imbalance.

III. Conclusion

In this work, we demonstrated a fast and straightforward design and optimization of a compact 2x2 beam splitter using inverse design. The resulting device exhibits a minimized footprint, making it suitable for integration into dense photonic circuits. Further improvements could be achieved by increasing the radius of the conic filter to take fabrication constraints stronger into account, and eliminate the sharp edges in the device layout. Additionally, further optimization iterations and hyperparameter tuning could enhance the device performance or even reduce the device footprint.

Acknowledgment

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