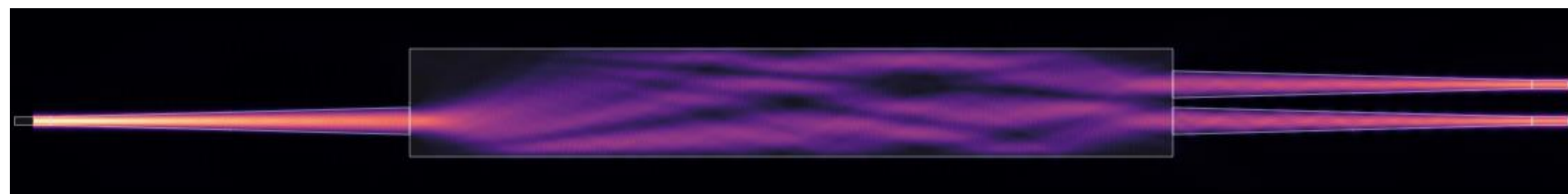


### Abstract

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  $3.2 \mu\text{m} \times 3 \mu\text{m}$  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.

### Conventional MMI-Coupler



Conventional Multi-Mode Interference (MMI)-Coupler, based on self-imaging.

Beat length of the two lowest order modes for a given width  $W_e$ :

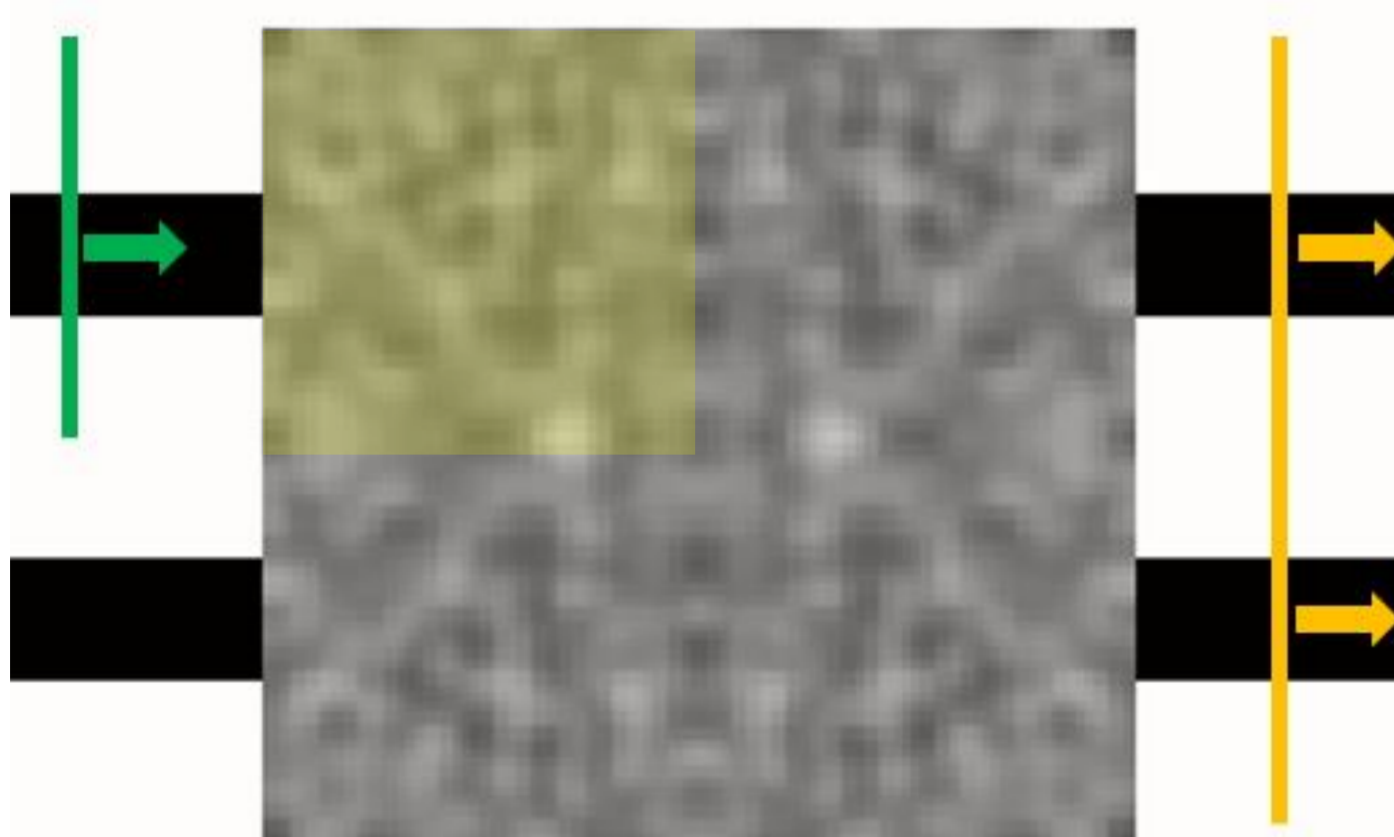
$$L_\pi \approx \frac{4W_e^2}{3\lambda} n_{core}$$

Resulting length for a 2x2 MMI:  $L_{MMI} = \frac{3}{2} L_\pi$

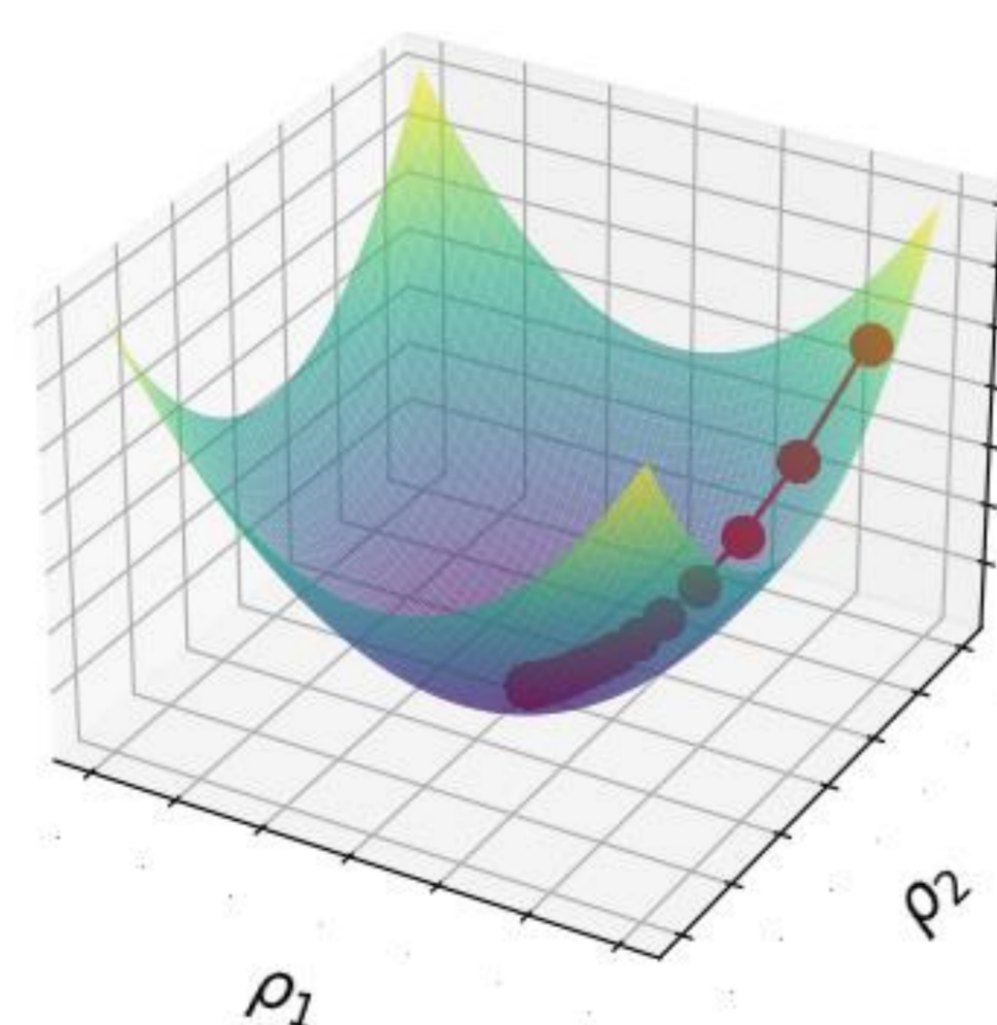
$$\phi_{ij} = -\frac{\pi}{2}(-1)^{i+j+N} + \frac{\pi}{4N} \left[ i + j - i^2 - j^2 + (-1)^{i+j+N} \left( 2ij - i - j + \frac{1}{2} \right) \right]$$

$$S = \frac{1}{\sqrt{N}} \begin{bmatrix} S^I \phi_{11} & \dots & S^I \phi_{1N} \\ \vdots & \ddots & \vdots \\ S^I \phi_{N1} & \dots & S^I \phi_{NN} \end{bmatrix}$$

### Inverse design



Initial design region and waveguides with source and monitor ports and example objective function.



Objective Function  $J(\rho)$

#### The objective function:

Output intensities greater than 0.5 at any output port should not contribute to the FOM:

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

Total contributing power:

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

Output balance at  $\lambda_c = 1550\text{nm}$ :

$$B = 1 - |T_1(\lambda_c) - T_2(\lambda_c)|$$

Optimize on the weighted sum of the overall power and balance:

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

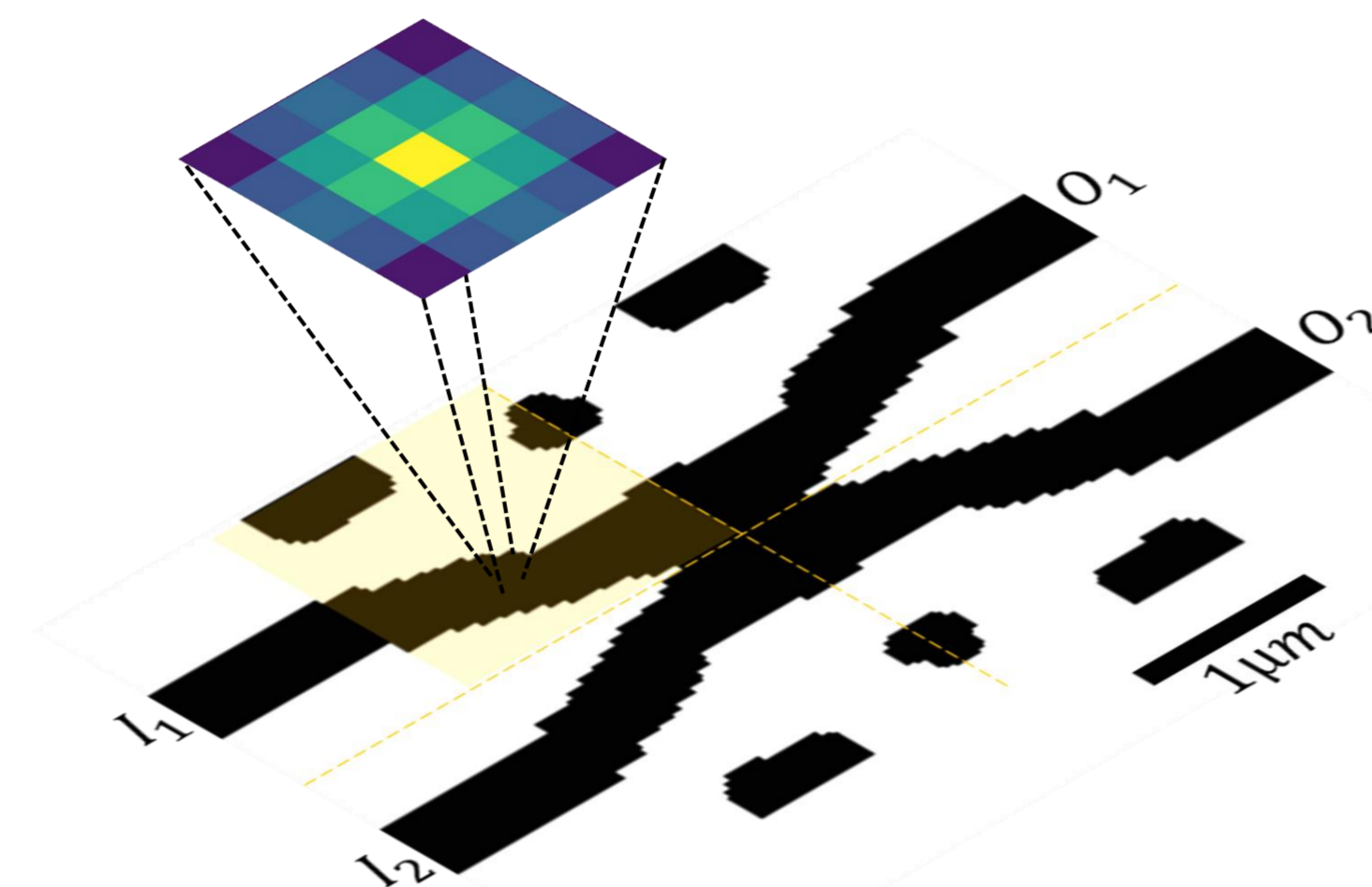
Add a penalty term  $P$  in order to take fabrication intolerances into account:

$$J = FOM - P$$

#### Gradient optimization:

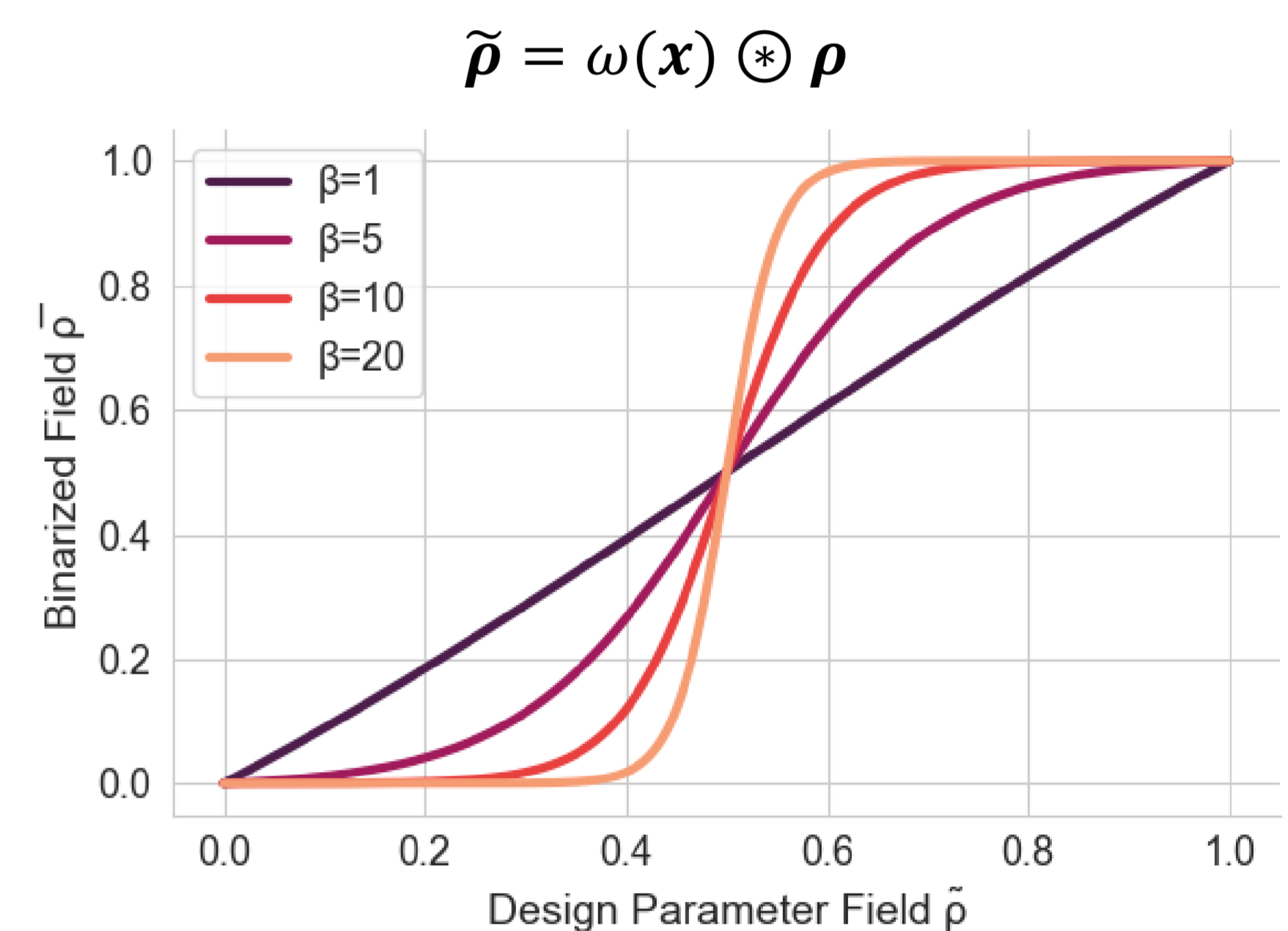
Compute the gradient of the objective function  $\frac{\partial J}{\partial \rho}$  depending on our design parameters  $\rho$  and adjust the parameters in order to maximize  $J$ .

### Binarization



Binarized device and filter kernel. The yellow shaded region was mirrored at both axis of the design region, to create an entirely symmetric design, and ensure equal behavior while injecting light into one of the four ports.

To take the minimum feature size into account, we used a conic filter  $\omega(x)$  with radius  $R = 80 \text{ nm}$ , which exceeds our foundries minimum feature size.



The variables are projected onto a binary value:

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

Calculate the permittivity of the design region:

$$\epsilon_r(\bar{\rho}) = \epsilon_{SiO_2} + \bar{\rho}(\epsilon_{Si} - \epsilon_{SiO_2})$$

### Adjoint Method



Calculate the gradient of  $J$  with respect to the design parameters  $\rho$  by solving the forward

$$Ae = b$$

and adjoint

$$Ae_{adj} = -\frac{\partial J^T}{\partial e}$$

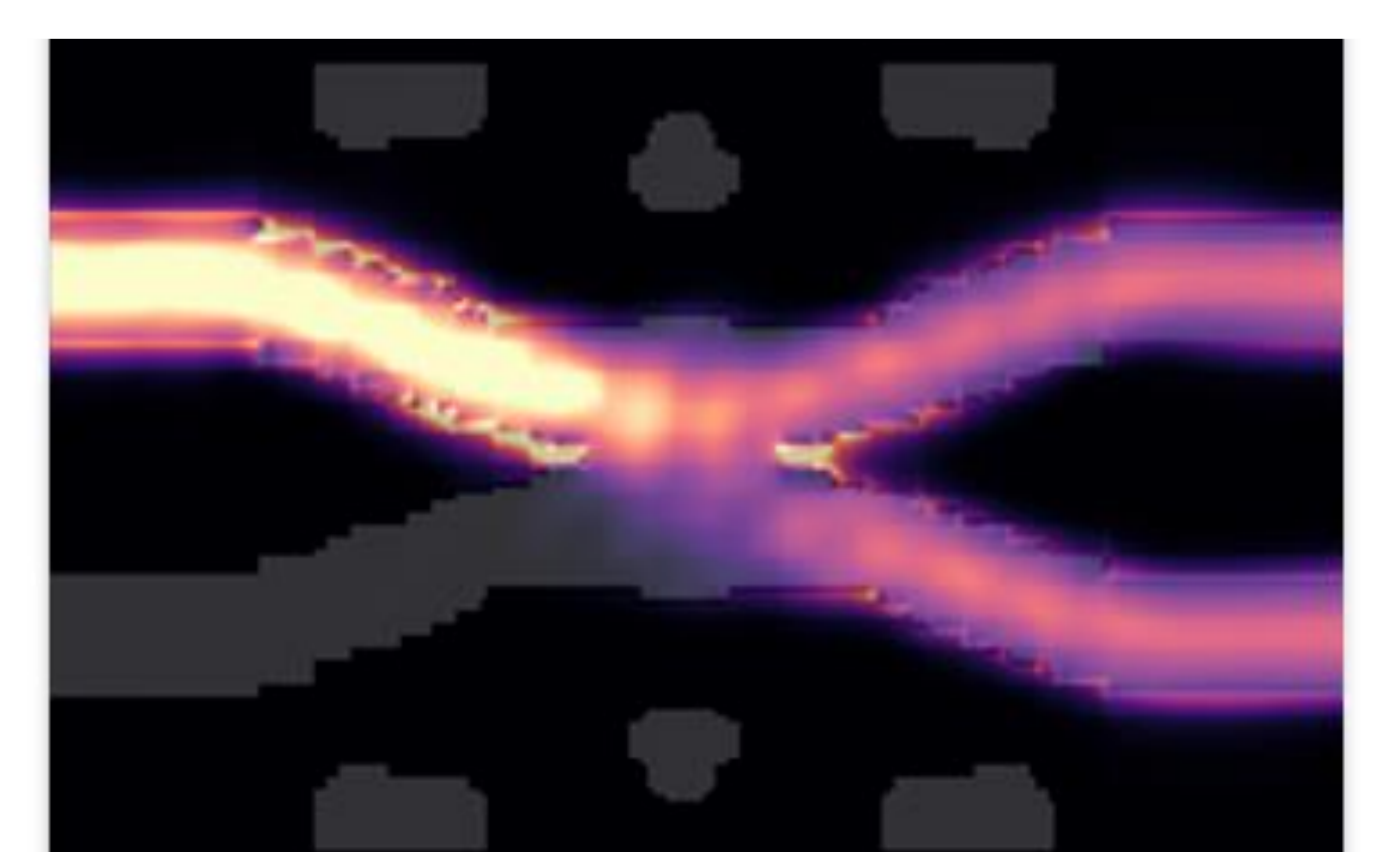
electromagnetic problems and calculate the gradient:

$$\frac{dJ}{d\rho} = -2k_0^2 \sum_{i \in \rho} \mathcal{R}\{e_{adj}^{(i)} e^{(i)}\}$$

[1, 3]

### Results

- $3.2 \mu\text{m} \times 3 \mu\text{m}$  footprint.
- Optimized for  $\lambda_c = 1550 \text{ nm}$ .
- Insertion loss of 0.34 dB.
- Power imbalance of 0.1 dB.



Intensity distribution of the final device.

[1] Hammond, Alec M. "High-Efficiency Topology Optimization for Very Large-Scale Integrated-Photonics Inverse Design." (2022).

[2] Lazarov, Boyan S., Fengwen Wang, and Ole Sigmund. "Length scale and manufacturability in density-based topology optimization." Archive of Applied Mechanics 86 (2016): 189-218.

[3] <https://www.flexcompute.com/tidy3d/solver/>