Inverse-Designed Ultra-Compact Polarization Demultiplexer

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***Abstract*—An ultracompact $(3 \times 3\mu m^2)$ silicon nitride-based 1x2 polarization demultiplexer for near-infrared (1400-1600nm) is designed by the inverse method. It achieves around 90% transmission, efficiently separating TE and TM polarization.**

***Index Terms*—Inverse Design, Polarization Demultiplexer, SiN PICs**

I. INTRODUCTION

Photonic Integrated Circuits (PICs) are vital for applications from optical communication to sensing. Within PICs, Polarization Demultiplexers (PDMs) are essential for separating orthogonal polarization states (TE and TM) into distinct paths, with their performance—low loss, high extinction, broad bandwidth, and compactness—critically impacting system efficiency and density.

The drive for higher integration necessitates ultra-compact components. Traditional PDM designs [1]–[4], while functional, often struggle to achieve optimal performance in minimal footprints and can involve extensive design iterations. Inverse design (ID) methodologies [5]–[10] offer a powerful alternative, algorithmically discovering non-intuitive nanostructures optimized for specific optical functions, often surpassing conventional designs in performance and compactness.

Silicon nitride (SiN) offers a low-loss, CMOS-compatible platform ideal for passive near-infrared (NIR) PICs, especially in the critical 1400-1600 nm telecom window. This work leverages inverse design to realize an ultra-compact SiN-based 1x2 PDM for this NIR range. We demonstrate a device with a minimal footprint that efficiently separates TE and TM polarizations to their respective output ports. This paper details the ID approach, simulation, and performance of the optimized PDM, highlighting the potential of ID for advanced photonic components.

II. DESIGN METHODOLGY

The device is initialized as shown in Fig.1. We have assumed that the device is invariant in the z-direction and the propgation is confined only in the x and y direction. The design region is discretized by rectangular pixels with a size of $\delta x, \delta y$ = 100 nm. Here, each pixel is classified as either SiN or Silica depending on optimization algorithm. The target port for the transmission of TE and TM mode is Port1 and Port 2 respectively.

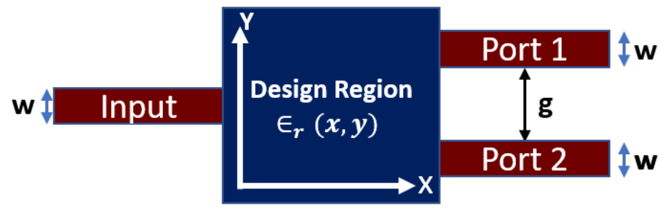

Fig. 1. shows the the block structure of the device. Design Region ϵ_r(x,y) has the size of $3\mu m \times 3\mu m$. Thickness of the device is 350 nm, width(w) of the input and the output waveguide is 550 nm and the gap(g) between the output ports is 1μm.

This 2D approximation reduces computational complexity substantially. The core of the inverse design process is then formulated as an optimization problem. The objective is to maximize a defined Figure of Merit (FOM), which quantifies the device performance, by tailoring the permittivity distribution, $\epsilon(r)$within the specified design region. This optimization problem can be expressed as:

$$\begin{aligned} &\underset{\epsilon}{\text{maximize}} \quad \text{FOM}(\{E_i(\epsilon)\}) \\ &s.t.\nabla \times (\mu_o^{-1} \nabla \times \mathbf{E}_i) - \omega_i^2 \epsilon \mathbf{E}_i = -j\omega_i \mathbf{J}_i \end{aligned} \tag{1}$$

In Equation (1), the subscript 'i' denotes parameters corresponding to different discrete operating wavelengths within the target spectral range. 'E_i'represents the complex electric field phasor at angular frequency 'ω_i'. $\epsilon = \epsilon(r)$ is the spatially varying permittivity distribution within the design region, which is the variable being optimized. 'μ_0' is the permeability of free space. J_i represents the source current density excitation at angular frequency ω_i.

III. RESULTS

The final optimized structure of the polarization demultiplexer, generated by the inverse design algorithm, is presented in Fig. 2. This figure illustrates the distribution of silicon nitride (shown in red) and air cladding (shown in blue) within the design region. The algorithm has converged to a non-intuitive, freeform geometry that is tailored to achieve the desired functionality.

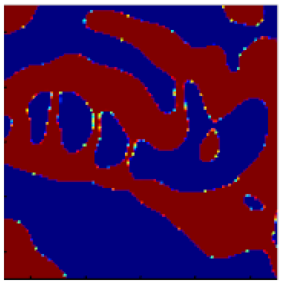

Fig. 2. shows the the final design of the structure. Red color shows the silicon nitride with blue color as the air cladd.

The simulated transmission characteristics of the optimized device for the TM and TE polarizations are shown in Fig. 3 and Fig. 4, respectively, across the near-infrared wavelength range of 1400 nm to 1600 nm.

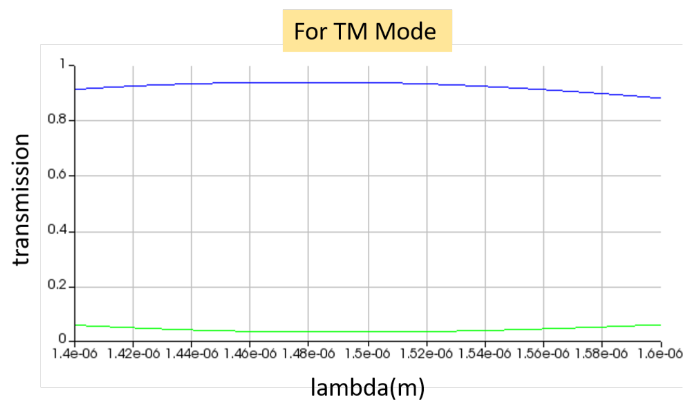

Fig. 3. shows the transmission of TM Mode. Blue color and the Green color shows the transmission at the Port 2 and Port 1 respectively.

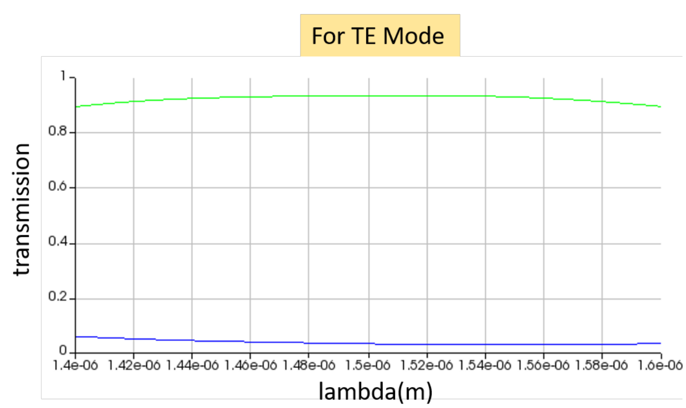

Fig. 4. shows the transmission of TE Mode. Blue color and the Green color shows the transmission at the Port 2 and Port 1 respectively.

As targeted, Fig.3 shows the TM mode predominantly routed to Port 2 (blue curve) with approximately 90% transmission, while crosstalk to Port 1 (green curve) remains minimal (below 4%). Similarly, Fig.4 demonstrates efficient TE mode transmission (around 90%) to Port 1 (green curve), with suppressed crosstalk to Port 2 (blue curve, below 4%). These results collectively validate the successful functionality of the inverse-designed ultra-compact mode demultiplexer, achieving high transmission for both polarizations to their respective target ports over a 200 nm bandwidth within a footprint, underscoring the efficacy of inverse design for miniaturized, high-performance photonic components.

IV. Conclusion

We have successfully demonstrated an ultra-compact silicon nitride-based 1x2 mode demultiplexer for the near-infrared (1400-1600 nm) spectrum using an inverse design methodology. The optimized device exhibits high transmission efficiencies of approximately 90% for both TE and TM polarizations to their respective designated output ports over a 200 nm bandwidth, along with effective polarization separation and low crosstalk. These results validate the capability of inverse design to realize high-performance, miniaturized photonic components with non-intuitive geometries, paving the way for denser integration and enhanced functionalities in advanced photonic integrated circuits.

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