Ultra-broadband polarization beam splitter with a gradual anisotropy engineered subwavelength metamaterial

(Student paper)

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Polarization management is a key requirement in highly birefringence photonic platforms such as silicon-on-insulator. Many on-chip solutions to handle polarization leverage subwavelength grating metamaterials, as they provide control over material birefringence. Here we show the design of a polarization beam splitter based on an advanced SWG topology which controls the propagation of multiple TE and TM modes at the same time. The proposed device achieves a simulated insertion loss <1 dB and extinction ratio >20 dB over a 400 nm bandwidth.

Keywords: *Photonic integrated devices, polarization management, subwavelength gratings.*

INTRODUCTION

Silicon photonics is leading the landscape of integrated photonics, with the Silicon-On-Insulator (SOI) having important commercial applications specially on the data/telecom industry [1]. The huge success of SOI principally comes from its high integration density and the compatibility with CMOS fabrication processes of SOI chips with the CMOS fabrication process. However, the CMOS compatibility comes with the drawback of restricting the available materials to those compatible with the fabrication process, hindering the design of high-performance devices. Moreover, the high index contrast between silicon in the waveguide core (n_{Si}=3.476) the silicon dioxide cladding (n_{SiO2}=1.444), combined with the usually rectangular waveguide geometries lead to an extremely a high polarization birefringence. However, polarization independent operation is often desired to handle the random changes in the polarization state that usually occurs in optical fibers. A usual method to achieve polarization transparency is by using polarization diversity schemes which require polarization beam splitters (PBS), polarization rotators (PR) and polarizations filters (PF). Many state-of-the-art polarization management devices in SOI are designed by using SWG metamaterials because they provide lithographic control over optical material properties, including modal birefringence [2,3]. In this work, a polarization beam splitter based on a gradual index (GRIN) lens is proposed. We use an SWG topology with a variable duty cycle [4] and with gradual shifting [5], as shown in Fig. 1, enabling the control of both polarizations almost independently. In a gradual SWG (see Fig. 1a), the duty cycle of the periodic structure is gradually modulated along the transversal direction, DC(x), enabling the synthesis of a gradual material. In a bricked-modulated SWG (see Fig. 1b), a conventional SWG periodic structure is transversely divided in periodic segments, alternatively shifting the resulting blocks a length, Δz(x), providing control over the TE modes. The combination of both topologies (See Fig. 1c) provides control over both polarization by first setting the TM modes with the gradual index profile and then adjusting the TE modes with the shifting. By using this strategy, a GRIN lens-based PBS has been designed, obtaining IL<1 dB with an ER>20 dB in a bandwidth over 400 nm. To the best of our knowledge this is one of the polarization splitters with broadest bandwidth reported to date.

WORKING PRINCIPLE OF A GRIN LENS BASED POLARIZATION BEAM SPLITTER

In a conventional isotropic GRIN lens, the refractive index profile follows a parabolic distribution (see Fig. 2a):

$$n_{\mathrm{GRIN}}(x) = n_{max}\sqrt{1-\alpha^2 x^2}, \quad \text{with} \quad \alpha = \frac{1}{w_{\mathrm{GRIN}}/2}\sqrt{1-\left(\frac{n_{\min}}{n_{\max}}\right)^2}, \tag{1}$$

where $n_{\max}$ and $n_{\min}$ are the refractive indices at the center and the edge of the lens and w_{GRIN} is the width of the lens. A paraxial ray at the input of GRIN lens with the profile given by Eq. (1) is collimated at a distance equal to the

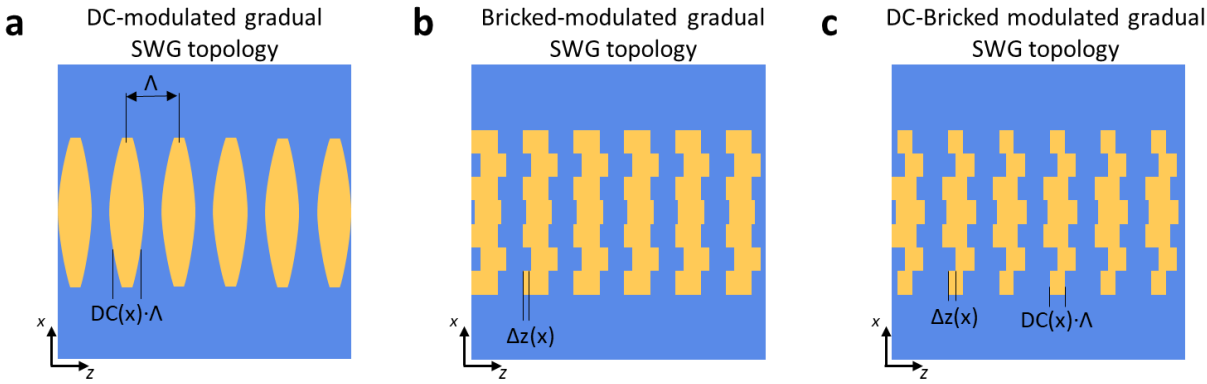

Figure 1. Schematic representation of SWG topologies allowing to implement a GRIN profile, including a) a DC-modulated gradual SWG topology, b) a bricked-modulated gradual SWG topology and c) a combination of the SWG topologies shown in (a) and (b), the DC-bricked modulated gradual SWG topology.

focal length, $f = \pi/(2\alpha)$, and then it is focused again at a distance $2f$ on the symmetrical point [See Fig. 2b, red line]. This behavior can be used to design a polarization beam splitter by achieving that the focus length for both polarizations, f_{TE} and f_{TM}, verify the condition:

$$L/2 = mf_{\mathrm{TE}} = nf_{\mathrm{TM}}, \tag{2}$$

where L is the device length and m and n are integers, with $|m - n|$ being an odd number, typically $m = 2$ and $n = 1$. By doing so, the input polarization will be split as schematically shown in Fig. 2b, where the blue line represents the TE polarization and the red line the TM polarization.

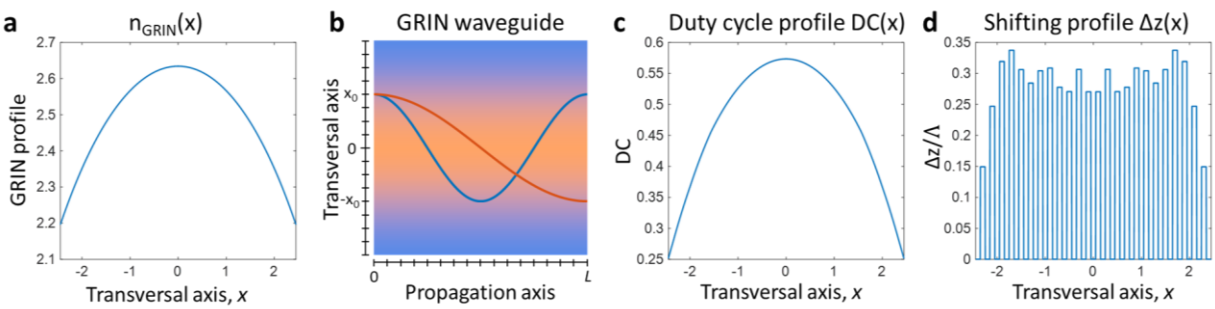

Figure 2. a) Parabolic index profile required to implement a GRIN lens. b) Schematic of the trajectory of an input TE/TM ray (blue/red line) in a GRIN waveguide. c) Duty cycle profile to implement the desired GRIN profile by using a duty cycle modulated gradual SWG metamaterial. d) Shifting profile to correct the focal length of the TE polarization ensuring the polarization splitting condition [Eq. (2))].

DESIGN OF THE GRIN LENS WITH SWG METAMATERIAL

A 5 µm wide SWG metamaterial waveguide is used to implement the GRIN lens PBS. By using the design process described in [4], the required duty cycle DC(x) to implement the index profile given in Eq. (1) is obtained (see Fig. 2c). This GRIN profile has a simulated focal length $f_{\mathrm{TM}} = 8.22$ µm for the TM polarization and $f_{\mathrm{TE}} = 5.45$ µm for TE polarization. This focus lengths are calculated with the Floquet mode simulations as $f = \lambda_0/[4(n_{\mathrm{eff1}} - n_{\mathrm{eff2}})]$, where n_{eff1} and n_{eff2} are the effective indices of the first and second mode of the GRIN metamaterial waveguide. To satisfy the splitting condition given by Eq. (2), the focal length of the TE polarization has to be decreased to ~ 4.11 µm. For this purpose, the SWG metamaterial is bricked to engineer the TE polarization while virtually unaffecting the TM modes. By using a perturbational method [6], the shifting profile, Δz(x), which set the desired focus length is obtained (see Fig. 2d).

DEVICE PERFORMANCE

The resulting DC-bricked SWG structure is shown in Fig 3a, including the input transitions tapers. To calculate the device performance, a 3D-FDTD simulator is used, calculating the insertion loss and the polarization extinction ratio as:

$$\mathrm{IL}^{\mathrm{TE}} = \frac{\mathrm{P}_{\mathrm{bar}}^{\mathrm{TE}}}{\mathrm{P}_{\mathrm{in}}^{\mathrm{TE}}}; \quad \mathrm{IL}^{\mathrm{TM}} = \frac{\mathrm{P}_{\mathrm{cross}}^{\mathrm{TM}}}{\mathrm{P}_{\mathrm{in}}^{\mathrm{TM}}}; \quad \text{and} \quad \mathrm{ER}^{\mathrm{TE}} = \frac{\mathrm{P}_{\mathrm{cross}}^{\mathrm{TE}}}{\mathrm{P}_{\mathrm{bar}}^{\mathrm{TE}}}; \quad \mathrm{ER}^{\mathrm{TM}} = \frac{\mathrm{P}_{\mathrm{bar}}^{\mathrm{TM}}}{\mathrm{P}_{\mathrm{cross}}^{\mathrm{TM}}}; \tag{3}$$

where $\mathrm{P}_{\mathrm{bar}}^{\mathrm{TE/TM}}$ and $\mathrm{P}_{\mathrm{cross}}^{\mathrm{TE/TM}}$ is the power in the fundamental TE/TM mode in the bar and cross ports, and $\mathrm{P}_{\mathrm{in}}^{\mathrm{TE/TM}}$ is the power of the fundamental TE/TM mode the input port [See Fig. 3b and 3c]. The proposed device has a simulated insertion loss lower than 1 dB and extinction ratio larger than 20 dB over a 400 nm bandwidth.

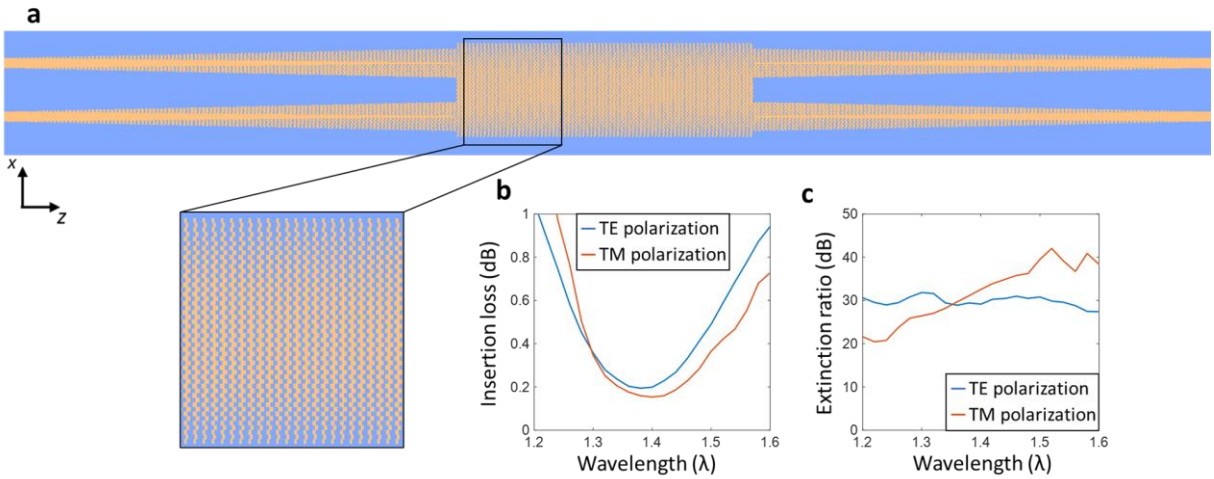

Figure 3. a) Schematic representation of the designed GRIN lens polarization beam splitter. b) Simulated insertion loss and c) extinction ratio of the TE and TM polarization.

CONCLUSION

In this talk, a new polarization beam splitter which uses the combination of two SWG topologies to control light propagation is presented. The proposed device not only exhibits an impressive performance but also shows the potential of this advanced SWG topology, enabling the precise manipulation of multiple modes of both polarizations at the same time. This capability opens new venues for the control of the light propagation on integrated chips.

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