High performance integrated silicon polarization beam splitter based on all-dielectric metamaterial cladding

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A polarization beam splitter is an essential building block in integrated silicon photonics. We propose a polarization beam splitter design based on all-dielectric metamaterial cladding structures. Exceptionally high extinction ratio and low insertion loss were achieved in an ultra-wide bandwidth for both polarizations.

Keywords: *Silicon photonics, polarization beam splitter, all-dielectric metamaterials*

INTRODUCTION

In photonic integrated circuits (PICs) based on silicon (Si) material platform polarization handling components are crucial due to a strong waveguide (WG) birefringence. The high refractive index contrast between Si and SiO_2 combined with asymmetry in WG width and height result in a large difference in effective refractive index of the transversal electric (TE) and magnetic (TM) mode in single mode WGs. This means that the performance of silicon photonics devices is typically polarization dependent. To tackle this, a so called polarization diversity approach can be employed requiring polarization management components [1]. A polarization beam splitter (PBS) splits a signal at the input, which can include both, TE and TM mode, into TE mode at one output and TM mode at another output. A PBS is an essential building block in polarization diversity circuits. Low insertion loss (IL), high extinction ratio (ER) and wide bandwidth (BW) for both polarizations as well as small footprint are required in the design of a PBS in PICs. Meeting all these requirements at the same time is a challenge. Various approaches have been used to achieve polarization splitting, including devices based on directional couplers (DCs), multimode interferometers (MMIs), Bragg gratings and many more [2]. Over the last few years all-dielectric metamaterials have been researched to achieve high performance polarization splitting [3]. An all-dielectric metamaterial consists of two or more periodically exchanging materials with the period well below the wavelength of light. Such a structure acts as an anisotropic material exhibiting different refractive indexes in the direction parallel to the layers and perpendicular to the layers. By etching subwavelength Si ridges parallel to a strip Si WG core, a so called WG with metamaterial cladding can be formed. Due to the anisotropic nature of the cladding structure, the evanescent field is modified, altering the coupling between adjacent WGs. All-dielectric metamaterial cladding can, if properly designed, drastically suppress the coupling of TE modes, whereas the coupling of TM modes is increased [4]. This can be utilized in the design of a PBS based on a DC with metamaterial cladding. [5]. Such devices can achieve exceptionally large extinction ratios (ER), however, their bandwidth (BW) is limited due to inherent properties of the DC. In this contribution we present a novel PBS design based on two compact MZIs with metamaterial cladding along with a metamaterial TE polarizer to simultaneously achieve wide BW, high ER and low insertion loss (IL).

DESIGN AND METHODS

Our proposed design (Fig. 1a and 1b) is based on two WGs with metamaterial cladding structure in between the two WG cores. By changing the geometry of the metamaterial structure the coupling length (defined as the length at which all the light couples to the adjacent WG) for the TE and TM mode is affected. In the first step we design the geometry of the metamaterial cladding to achieve exceptionally long coupling length for TE mode (> 1 cm) and short coupling length for TM mode (12.6 µm). To achieve broadband coupling of the TM mode to the adjacent WG, leading to a high transmission of the TM mode at the Cross port of the device, we propose a structure including two metamaterial compact MZIs. By cascading two MZIs in a point symmetrical configuration, we can achieve broadband coupling of the TM mode, which could not be achieved by a single DC structure [6]. The structure consists of three straight sections of two WGs with metamaterial cladding, acting as DCs and two bends where the WGs remain in parallel. This leads to a small difference in path length between the two WGs in the bends, since the there is a slight difference in bend radii of the two WGs. This way we can achieve the required phase delay in MZI operation. Due to relatively short bent sections the coupling that occurs there is very small. The structure can be therefore described discretely by interchanging DCs and phase delays as is schematically shown in Fig. 1b. Our proposed concept results in a significantly more compact device, compared to conventional cascaded MZI configuration. The metamaterial cladding structure is employed in between WG cores along the whole structure to suppress the coupling of TE mode, ensuring high transmission of the TE mode at the Thru_{int} port. To reduce the remaining TM polarization at the Thru port of the device and further increase the ER, we employ a bend TE polarizer with metamaterial cladding. The design concept was adopted from [7]. The metamaterial cladding with variable fill factor (ratio between the rib width and the period) ensures that the TM mode is diffracted into free space without significantly affecting the transmission of the TE mode which passes thru the polarizer with low loss. The designed PBS has a footprint of 82 µm and a minimal feature size of 70 nm.

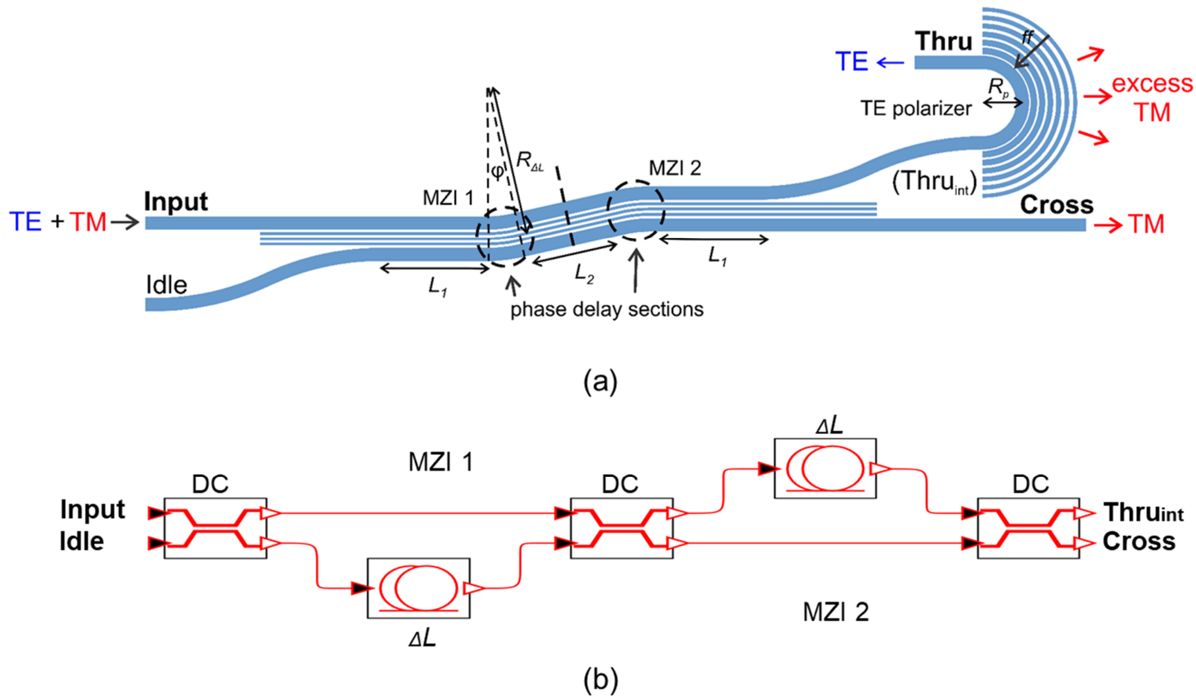

Figure 1: (a) The geometry of our proposed PBS device. Main geometrical parameters as well as input and output ports are depicted in the figure. (b) A network level schematic of the metamaterial compact dual MZI part of the device (without the TE polarizer).

To design and optimize the geometry of the PBS we employed different simulation methods. To design the metamaterial cladding structure FEM mode analysis using COMSOL program package was used. The coupling length was calculated using coupled mode theory from the symmetric and antisymmetric modes of WG systems. To define selected geometry parameters of the dual MZI structure (L_1, L_2, φ) we employed transfer matrix method (TMM) coupled with a simulated annealing optimization algorithm with the purpose of maximizing the bandwidth of the device. In these calculations we assumed the circuit topology shown in Fig. 1b. The TE polarizer was designed following the concepts described in [7]. Its performance was numerically evaluated by FDTD simulations using Lumerical program package. For final designs we also employed full 3-D FDTD simulations of the entire device as shown in Fig. 1a, to accurately evaluate and predict its performance.

The device was fabricated using 100 keV electron beam lithography (EBL) at Applied Nanotools, Inc. [8] with a silicon on insulator (SOI) wafer (2 µm thick buried oxide, 220nm thick Si layer) was used as the substrate. The fabrication process allows for fabrication of devices with minimal feature sizes down to 70 nm. Characterization of fabricated devices was performed using a tunable laser source and a power meter. We used a fiber polarization controller to tune the input polarization. Grating couplers were employed to couple the light from the optical fiber to the chip.

RESULTS

3-D FDTD results for the optimized PBS structure (including the TE polarizer) are shown in Fig. 2. The results for TE mode show a high transmission at the Cross port (above -0.2 dB) of the device in the whole simulated wavelength range from 1300 nm to 1700 nm. The simulated TE mode transmission at the Cross port of the device is below -32 dB in the whole simulated wavelength range. The simulated TM transmission at the Cross port is above -1 dB in a wide wavelength range of 300 nm. At the Thru port the simulated TM transmission remains below -33 dB in the wavelength range of over 300 nm. The simulation results indicate noticeable polarization splitting performance of the device with *ER* > 33 dB, *IL* < 1 dB in the *BW* of 273 nm.

Measurement results for the fabricated device are shown in Fig.2. Measurements were performed in a wavelength range from 1450 nm to 1590 nm due to a limited tuning range of the laser. We fabricated two sets of devices: one was connected to TE mode grating couplers and the other to TM mode grating couplers. This enabled us to separately measure the TE and TM mode transmission at all ports of the device. It can be observed that the measurement results follows predictions from simulations. Note that in certain cases transmission exceeds 0 dB.

This is a measurement artefact that occurred due to the variability of grating couplers. For that reason, the *IL* cannot be accurately determined, however, we can make a conservative assessment that it remains below 2 dB in a *BW* of at least 140 nm. The measured *ER* of the device is above 30 dB in a *BW* of at least 140 nm. As it was indicated by simulations, the bandwidth of the device is possibly significantly wider.

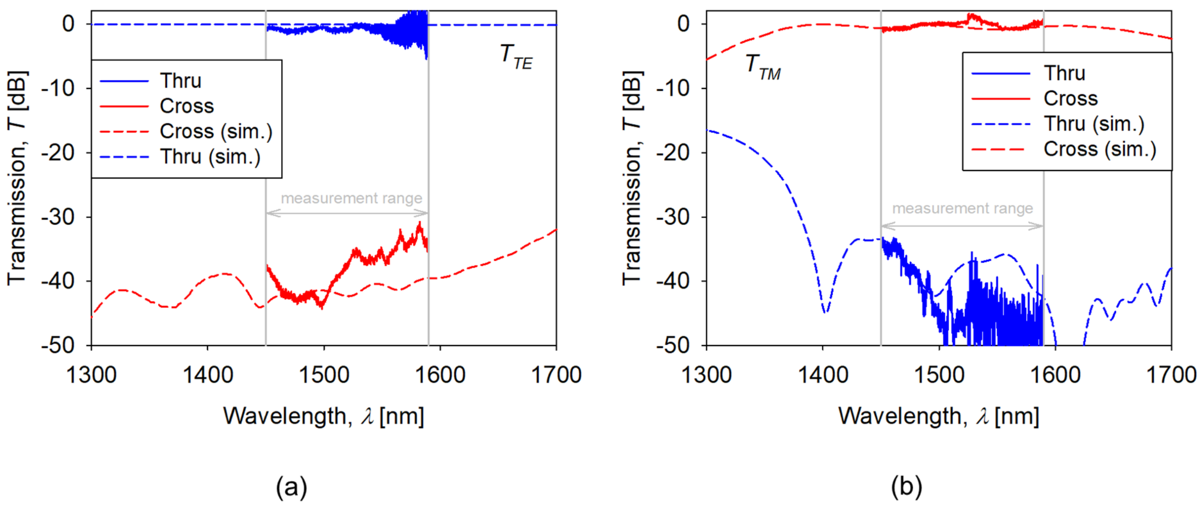

Figure 2: FDTD simulation results and experimental results for TE mode (a) and TM mode (b) transmission at the Thru and Cross ports of the PBS device.

CONCLUSION

We theoretically and experimentally demonstrated a novel polarization beam splitter device in integrated silicon photonics utilizing all-dielectric metamaterial structures. Exceptionally high *ER*, low *IL* and ultra-wide *BW* were predicted by simulations. Measurements of fabricated device confirmed high performance polarization splitting of the proposed PBS.

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