Photonic Crystal Polarization Beam Splitter in Silicon-On-Insulator Platform

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Abstract:
In this work we report an ultracompact (8.7 μm x 10.6 μm) integrated planar photonic crystal polarization beam splitter in silicon-on-insulator platform with 18.6 dB and 11.1 dB extinction ratio at a wavelength of 1520 nm at the outputs for transverse-magnetic and transverse-electric polarization, respectively. The physical separation of both polarization states is achieved by negative and positive refraction through a compact (2.7 μm x 9.6 μm) hexagonal type photonic crystal in silicon substrate with silica filled holes. The simulation and measurements show the polarization splitting effect in a wide wavelength range.

I. Introduction:
Polarization beam splitters (PBS) are important devices in integrated photonic circuits. Their functionality is to separate transverse-electric (TE) and transverse-magnetic (TM) polarization states. The need for this kind of devices arises from the polarization-sensitive behavior of nanophotonic components, which can suffer from structural birefringence, especially on silicon-on-insulator (SOI) chips. Hence, PBS would decrease the polarization-dependent loss if integrated in polarization diversity schemes [1]. Another important functionality of PBS is the use of both polarization states in advanced optical modulation formats like dual polarization quadrature phase shift keying (DP-QPSK), which improves the spectral and power efficiency [2].

Many PBS structures such as directional couplers [3, 4], metal-loaded embedded waveguides [5] and Mach-Zehnder interferometers [6] have been proposed. However, these devices have a typical length of several hundreds of micrometers, making them not promising for high density integration. Other candidates for PBS are photonic crystals (PC). PCs are composite structures with a spatially periodic variation of the refractive index and can exhibit complicated photonic band systems, behaving differently for the orthogonal polarization states TE and TM. These structures have as consequence a variety of attractive effects to split polarizations such as the bandgap-effect [7 - 9], prohibiting the light to propagate inside the PC for one state and allowing the other to go through. The second effect is known as negative refraction [10], which makes the light not follow the conventional refraction direction. Making use of the last effect, a spatial separation of TE and TM polarizations can be achieved by adjusting the PC parameters in such a way that one state follows a negative and the other state a positive refraction. Besides excellent performance and low costs of the SOI technology, the high refractive index contrast can be very attractive for PC realization in this platform, which can pave the way to achieve very compact photonic integrated circuits.

II. Layout and simulation results:
Fig. 1 shows the schematic illustration of the proposed PC PBS structure. The 220 nm thick silicon (Si) layer is sandwiched between two silicon dioxide (SiO2) layers with a thickness of 2 μm and 500 nm. The input and output waveguides for the PC have a width of 400 nm and thus are single mode for TE and TM at wavelengths around 1550 nm. The grating couplers shown in Fig. 1 are used to couple the light to and from the waveguides. As these structures are polarization sensitive, the PC PBS is designed twice with the corresponding grating coupler. For TM the period of the grating is \( \Lambda = 1080 \) nm, whereas \( \Lambda = 630 \) nm for TE. The gratings have in addition a fill factor \( F = 0.5 \) and are etched 70 nm in the Si layer.

The two-dimensional PC is composed of 5 rows of SiO2 holes arranged in a triangular lattice with a lattice constant \( a = 660 \) nm and a hole radius \( R = 200 \) nm. The normal of the PC lies along the ΓM direction and is tilted by 20° from the input and output waveguides, which are connected to the couplers by linear tapers.
Fig. 1. Schematic illustration of the PC and the tapered input / output waveguides with the grating couplers in SOI platform. The angle \( \alpha \) corresponds to the optical fiber tilt from the normal.

The working principle of the PC is investigated in a first step by the plane wave expansion method using the software BandSOLVE [11] and then by the three-dimensional (3D) finite-difference-time-domain (FDTD) method using FullWAVE [11] to visualize the polarization splitting effect. Fig. 2a shows the band diagram of the designed PC and the normalized frequency 0.426, corresponding to the target wavelength 1550 nm. At this operating point the TE (electric field in plane of PC) and TM (magnetic field in plane of PC) exhibit different behaviors, which make them follow different paths. It can be seen that the band curves of the 4\(^{th}\) and 2\(^{nd}\) modes of the TE and TM, respectively, have opposite slopes, and hence opposite refractive index signs [12]. The equi-frequency contours (EFC) in Fig. 2b illustrates this fact: The incident wave vector \( \mathbf{k}_i \) at 20° from \( \Gamma M \) direction generates a refracted wave vector \( \mathbf{k}_r \) in the PC with the requirement that the tangential component of the wave vector has to be conserved, as shown in the figure through the dotted line. The group velocity vector \( v_g \) is perpendicular to the EFC at the intersection between the construction line and the EFC, pointing towards higher frequencies. Since the energy propagation direction is determined by the group velocity vector, the designed structure is able to refract the TM negatively and TE positively, and hence working as a polarization splitter.

Fig. 3 shows the electric field distribution of the PC PBS structure at both polarization states using the 3D FDTD method. Perfectly matched layers are used as absorbing boundaries. The refractive indices of Si and SiO\(_2\) for simulation are \( n_{Si} = 3.474 \) and \( n_{SiO2} = 1.444 \), respectively. As can be seen from the figure, the PC exhibits a negative effective refractive index for TM waves making this polarization of the input light propagate to output 1, whereas the TE waves follow a positive refraction and propagate to output 2. In addition to the negatively refracted main beam in the left figure, a secondary positively refracted beam is observed. This beam arises in fact from the 2\(^{nd}\) TM mode but does not affect output 2, so that the polarization splitting effect is still preserved. Since the PC has only 5 rows and a length of only 2.7 \( \mu m \), it is considered as an ultracompact structure.

![Fig. 1](image1.png)

![Fig. 2](image2.png)

Fig. 2. a) Band diagram of the designed PC structure for both polarizations. Dotted line indicates operating frequency \( a/\lambda = 0.426 \). b) Wave vector diagrams at operating frequency. The effective refractive index of the single mode incident wave from the SOI slab is calculated by the beam propagation method using BeamPROP [11].
III. Measurement results:
The designed structure is realized cost-effectively by ePIXfab at IMEC [13] and is illustrated in Fig. 4a. As mentioned above, coupling light into the integrated waveguides is ensured by grating couplers that offer the manageability of aligning optical fibers in comparison to butt coupling [14]. For normalization purposes, two S-bend waveguides representing both outputs are also designed to calibrate the losses existing outside the PC PBS. Fig. 4b shows the setup for measuring the transmission spectra of both polarizations. A tunable laser working in the wavelength range 1460 nm – 1580 nm serves as a source and is connected to a polarization controller that adjusts the desired polarization state. Piezoelectric elements are used to align the single mode fibers on the grating couplers and an optical power meter to measure the transmitted optical power.

The polarization beam splitting effect of the designed structure is evaluated by investigating the measured and simulated transmission spectra of both polarizations at each output, as shown in Fig. 5, and determining the extinction ratio (ER). The ER is given by the expression $ER_i = 10 \log_{10} (T_1/T_2)$, where $T_1$ is the transmission value of the desired polarization state in the corresponding output $i$ and $T_2$ is the transmission value of the cross polarization in this output.

As can be seen from Fig. 5, the fabricated PC works in effect as PBS, driving TM to output 1 and TE to output 2 for a wide range of wavelengths. While the simulation results show $ER_1 = 19.5$ dB and $ER_2 = 8.2$ dB at 1550 nm, a wavelength shift of around 30 nm is observed in the measurement results and the polarization splitting behavior is present at lower wavelengths than 1550 nm. This wavelength shift could be due to a lower than 220 nm Si layer thickness and some manufacturing errors in the...
technology process. Nevertheless, the measured data show $ER_1 = 18.6$ dB and $ER_2 = 11.1$ dB at 1520 nm that are comparable to the simulation results.

In addition, $ER_1$ is greater than 15 dB in a wide wavelength range of 55 nm (from 1504 nm to 1559 nm), whereas $ER_2$ is greater than 5 dB in a wavelength range of 24 nm (from 1505 nm to 1529 nm). The best measured ER values are $ER_1 = 26.6$ dB at 1525 nm and $ER_2 = 13.1$ dB at 1517 nm.

![Fig. 5. Measured and simulated transmission spectra at output 1 and 2 of the PC PBS.](image)

IV. Conclusion:

In conclusion, a polarization beam splitter based on photonic crystal fabricated in SOI technology is demonstrated experimentally. The designed structure is combined with grating couplers that serve as coupling elements for the incoming light on the surface of the wafer without need for polishing the facets, and hence allowing wafer-scale testing of the photonic integrated circuits. Despite the offset between simulation and measurements, the realized polarization splitter exhibits a good functionality with extinction ratios as high as 18.6 dB and 11.1 dB at 1520 nm for the TM and TE outputs, respectively. The transmission behavior can be further improved by tapering the structure adequately and decreasing the side losses of the photonic crystal. Since SOI technology offers a good refractive index contrast, the band gap effect of photonic crystals can be utilized to design more effective polarization splitters with enhanced transmission and extinction ratios.

With a size of only 8.7 µm x 10.6 µm and only 2.7 µm long photonic crystal, this structure is considered as one of the most compact fabricated polarization beam splitters.

References: