The polarization of light conveys unique information that can be exploited by crucial applications. The bulky and costly discrete optical components used in conventional polarimeters limit their broad adoption. A compact, low-cost polarimeter would bring this functionality into a myriad of new scenarios and revolutionize its exploitation. Here we present a high-performance, full-Stokes polarimeter on a silicon chip. A surface polarization splitter and on-chip optical interferometer circuit produce the analysis matrix of an optimally conditioned polarimeter. This solid-state polarimeter is a system-on-a-chip with exceptional compactness, stability, and speed that could be used singly or in integrated arrays. Large arrays can increase the speed and resolution of full-Stokes imaging; therefore, our design provides a scalable polarimeter solution.

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Characterization of the state of polarization (SoP) of light is crucial for many important applications. In the field of astronomy, polarimetry can characterize the rotation of stars [1] and their stellar magnetic fields [2], which cannot be accurately measured using other properties of light. Polariometry is also a powerful tool to characterize aerosol particles, a subject of increasing importance to both human health and our natural environment [3]. Although the earliest polarimeter dates back to the 1850s [4], state-of-the-art commercial polarimeters remain bulky, or unable to provide all four elements of the Stokes tensor, i.e., full-Stokes functionality. Recently, some miniaturized full-Stokes polarimeters have been proposed [5–8]. Capasso and co-workers designed an ultra-compact in-line polarimeter using polarization-dependent scattered fields of plasmonic metasurface [6]. Their polarimeter requires an off-chip camera to collect the scattered light, and their use of metallic nanoantennas creates parasitic absorption losses.

Fig. 1. A schematic of the proposed polarimeter. Incident light is decomposed into two orthogonal linear-polarization components (indicated by the blue and red arrows) that are split and coupled to four waveguides. The orange arrows point to the propagation direction of light. The outputs of the six ports are connected to photodetectors for intensity readouts: $I_0, I_L, I_{45}, I_{135}, I_R,$ and $I_90$. Four directional couplers compose an optical interferometer circuit to calculate the third and fourth Stokes parameters.

Silicon photonics brings to the manipulation light the economies of scale and advantages of tremendous integration long enjoyed by VLSI in electronics. Silicon photonics can integrate a vast number of optical components on a single chip in proximity with microelectronics. The manipulation of light is therefore enhanced with digital signal processing to create complete systems-on-a-chip. While silicon photonics initially targeted optical interconnects, a broader range of applications is now under development, such as sensors, light detection and ranging (LiDAR), and imaging [9]. Large-scale silicon photonic integrated circuits have been demonstrated [10–15], and are being turned to the polarimetry application. Martínez, et al., used the spin-orbit interaction of light to demonstrate the use of sub-wavelength scattering on silicon for local observation of SoP [7]. They used the careful manipulation of a metallic nanoparticle or supplemental polarization filtering for their SoP characterization, however, the accuracy of their polarimeter has yet to be established with either method. A silicon photonic Stokes vector receiver has been demonstrated for high-speed optical communications [16]. It uses a nanotaper on the edge of a chip to collect light from a fiber; on-chip components such as beam splitters, polarization rotators, and optical hybrids are used for polarization decomposition and phase readouts. This structure,
A two-dimensional dielectric grating structure [17] is used to provide intensity measurements with information on the linear polarization of incident light at specific directional rotations. Since most photo-detectors (PDs) are only sensitive to intensity, an optical interferometer circuit is designed to convert phase information into intensity. The interferometer is realized via four directional couplers (DCs). As shown in Fig. 1, the device has six outputs. Four outputs provide intensity measurements with information on the linear polarization of incident light at specific directional rotations: linear horizontal ($l_0$), linear $45^\circ$ ($l_{45}$), linear vertical ($l_{90}$), and linear $135^\circ$ ($l_{135}$). Two outputs provide intensity measurements with information on the circular polarization: right-handed circular ($l_R$), and left-handed circular ($l_L$) polarization.

Straight paths without directional couplers provide

$$I_0 \propto \frac{1}{2} |E_x|^2$$

$$I_{90} \propto \frac{1}{2} |E_y|^2$$

The interferometric structure provides

$$I_L \propto \frac{1}{8} |E_x e^{-i\frac{\pi}{4}} + E_y|^2$$

$$I_{45} \propto \frac{1}{8} |E_x + E_y|^2$$

The interferometric structure provides

$$I_0 \propto \frac{1}{8} |E_x - E_y|^2$$

$$I_R \propto \frac{1}{8} |E_x + E_y e^{-i\frac{\pi}{4}}|^2$$

Equation 8 is only valid under ideal conditions. Imperfections such as imbalanced splitting ratios of the SPS and DCs, waveguides losses, and phase errors should be taken into consideration. For a general expression, we rewrite the E-fields in the form $S \propto M_S \cdot I$.

We present a novel chip-scale, full-Stokes polarimeter in silicon photonics with proven SoP accuracy, compatibility with imaging polarimetry, and scalability to large arrays to enhance speed and resolution. Our polarimeter consists of a surface polarization splitter (SPS) and on-chip optical interferometers that convert the SoP directly to intensity readouts. In addition to the fiber-optic application of sensor and communication, our compact polarimeter element can be arrayed for free-space applications such as polarimetric LiDAR and imaging polarimetry.

The schematic of the proposed device is shown in Fig. 1. A two-dimensional dielectric grating structure [17] is used as a SPS to decompose incoming light with an arbitrary SoP, $(S_0, S_1, S_2, S_3)$, into two orthogonal linearly polarized E-field components, $E_x$ and $E_y$. The E-field components are separated; each has it power split (ideally a 50:50 split) and coupled into two single-mode waveguides that exit the structure in opposite directions. Note that the excited optical waves propagating in the four waveguides, $\frac{\sqrt{2}}{2} E_x, \frac{\sqrt{2}}{2} E_y, \frac{\sqrt{2}}{2} E_x + \frac{\sqrt{2}}{2} E_y$, carry full SoP information on the incoming light. The SoP can be retrieved using their intensities and the relative phase between the two orthogonal E-field components. Since most photo-detectors (PDs) are only sensitive to intensity, an optical interferometer circuit is designed to convert phase information into intensity. The interferometer is realized via four directional couplers (DCs).

As shown in Fig. 1, the device has six outputs. Four outputs provide intensity measurements with information on the linear polarization of incident light at specific directional rotations: linear horizontal ($l_0$), linear $45^\circ$ ($l_{45}$), linear vertical ($l_{90}$), linear $135^\circ$ ($l_{135}$). Two outputs provide intensity measurements with information on the circular polarization: right-handed circular ($l_R$), and left-handed circular ($l_L$) polarization.

Performance of the SPS. For input of $x$-polarized light at normal incidence, a) measured (solid) and simulated (dotted) coupling efficiency of light propagating in vertical waveguide (red), i.e., $y$-direction ($\eta_y$), and horizontal waveguide (blue), i.e., $x$-direction ($\eta_x$); b) The simulated intensity distributions within the SPS under the $x$-polarized light at 1550 nm wavelength.

We write the full-Stokes vector as $S = (S_0, S_1, S_2, S_3)^T$ and the intensity vector as $I = (I_0/2, I_1, I_{45}, I_{90}, I_{135}, I_R/2)^T$. The full-Stokes vector can be recovered from the six outputs via

$$S \propto M_S \cdot I$$

where $M_S$ is the synthesis matrix of the polarimeter, given by

$$M_S = 4 \cdot \begin{pmatrix}
1 & 0 & 0 & 0 & 0 & 1 \\
1 & 0 & 0 & 0 & -1 & 0 \\
0 & 1 & -1 & 0 & 0 & 0 \\
0 & 1 & 0 & -1 & 0 & 0
\end{pmatrix}$$

Fig. 2. SEM images of the fabricated device. The green, blue, and red areas are the surface polarization splitter (SPS), waveguides, and directional couplers, respectively. The inset shows an enlarged image of the SPS.

Fig. 3. Performance of the SPS. For input of $x$-polarized light at normal incidence, a) measured (solid) and simulated (dotted) coupling efficiency of light propagating in vertical waveguide (red), i.e., $y$-direction ($\eta_y$), and horizontal waveguide (blue), i.e., $x$-direction ($\eta_x$); b) The simulated intensity distributions within the SPS under the $x$-polarized light at 1550 nm wavelength.
where light coupled into x-directional and y-directional waveguides, mal incidence) simulation results are shown in Fig. 3 when inputting (via nor-
of the SPS are given in Supplementary 2. The experimental and
length band around 1550 nm, but could be directed to the band
Fig. 2). This design focused on the telecommunications wave-
holes fully etched through silicon with a period of
in Fig. 2. The SPS is formed using a 20
D and a hole diameter of
596 nm
Four known independent SoPs were used to calibrate the de-
and to calculate the system polarimetric matrix $M'_S$ (Eq. 9).
Then the performance of the polarimeter was experimentally
tested using a series of SoPs spread widely over the surface of
the Poincaré sphere, as illustrated in Fig. 4a and b. For each point
in this series of randomly generated SoPs, we simultaneously
measured the SoP with our device and a commercial in-line
polarimeter (details about the experiment are given in Supple-
mentary 3). At each measurement we normalized the SoP to a
unitary first component, and plotted the remaining three compo-
ents, i.e., $S' = (S_0, S_1, S_2, S_3)/S_0$. The measured SoP results
are summarized in Fig. 4c. Excellent agreement is observed
between the SoP measurements using our device and a commer-
cial bench-top polarimeter. The root-mean-square error between
measurements with the integrated and the bench-top instrument
is 0.07. This error is dominated by intensity measurement er-
ors due to the set-up variations and PD noise (Supplementary
5).[18] This error can be significantly reduced by PDs integrated
on the same chip. Notice that high-responsivity, high-speed
Ge-on-Si PDs have already been demonstrated [19, 20] and are
now widely available in silicon photonics foundry processes.

The condition number of the analysis matrix indicates how
sensitive the reconstructed SOP is to systematic errors such as
calibration. The signal-to-noise ratio (SNR) of a polarimeter
is determined by the condition number, with SNR maximized
when the condition number is minimized. The ideal polar-
imeter has a condition number of $\sqrt{3}$, the minimum value for

\[
\begin{pmatrix}
\frac{2}{\xi_{p1}} & 0 & 0 & 0 & 0 & \frac{2}{\xi_{p1}} \\
\frac{2}{\xi_{i1}} & 0 & 0 & 0 & 0 & -\frac{2}{\xi_{i1}} \\
0 & a & b & -b & a & 2a^2e_{x}^2 \\
0 & b & a & -a & -b & 2b^2e_{y}^2
\end{pmatrix}
\]
full-Stokes analysis.[18] In addition to imperfections captured in (Eq. 9), $\kappa^{AB}$ and its condition number is a function of wavelength due to the wavelength dependencies of the DCs and the SPS. To mitigate this effect, we used a broadband DC design with an asymmetric-waveguide-assisted section leading to a near 200 nm 1 dB bandwidth of splitting ratio (Supplementary Fig. S8).[14] The condition number as a function of wavelength is numerically simulated and is shown in Fig. 5. We can observe that the curve shows a flat bottom very close to the optimal value $\sqrt{3}$ across a wide spectral range from 1.5 to 1.6 $\mu$m. The condition number is also calculated using the parameters (the coupling coefficients of the DC and the extinction ratio of the SPS) extracted from measurement (Supplementary 4), and agrees well with the numerical simulation (Fig. 5).

![Fig. 5. The experimental and simulated condition number of the device. The red and blue line are the experimental and numerical condition number $\kappa$ of the matrix $M^s$ as a function of the wavelength.](image)

The demonstration of a silicon full-Stokes polarimeter paves the way to polarimetry sensor systems on a chip for a vast number of applications. Avoiding the use of free-space optical and mechanical components, this solid-state solution enables significant improvement in system robustness, size and cost. A polarimeter array can also be fabricated on a single chip with minimum increase in footprint and cost, proving a scalable solution for applications such as imaging polarimetry and polarimetric LiDAR. For large-scale arrays (e.g., in 2D polarization imaging), we can spatially separate the SPS and the optical interferometer circuit, which allows us to group the SPS elements in a compact footprint to achieve a large fill factor. Furthermore, a number of the SPS elements can share one set of optical interferometer circuit and integrated PDs through on-chip optical switches [21, 22] so that the SOP received by each SPS can be analyzed in a time series. Our device can also be used as a polarization analyzer for polarimetric fiber-optic sensors whose application is limited by the high cost of currently available polarimeters. The proposed structure can be applied to other CMOS-compatible materials such as silicon nitride and germanium for a broad spectrum from visible to mid-infrared.[23, 24] Furthermore, it can be readily integrated with other silicon photonics functions such as spectrometers [25] for a multi-dimensional optical measurement system on a chip.

REFERENCES

1. D. V. Cotton, J. Bailey, I. D. Howarth, K. Bott, L. Kedziora-Chudczer, P. Lucas, and J. Hough, Nat. Astron. 1, 690 (2017).
2. A. Chrysostomou, P. W. Lucas, and J. H. Hough, Nature. 450, 71 (2007).