

Passive silicon nitride on-chip polarimetry: precise polarization detection with imperfect components

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Abstract. Polarization is a fundamental property of light that carries distinct and valuable information. Consequently, its precise measurement is crucial for numerous applications, including biomedical imaging, remote sensing, and optical communication. As polarization cannot be measured directly, it is typically inferred by converting it into intensity signals using dedicated optical elements. Conventional approaches, however, predominantly rely on bulky optical components, leading to considerably high fabrication costs and limited integration density. Here, we introduce a passive photonic integrated circuit capable of precisely determining the polarization state of visible free-space light. A silicon nitride on-chip architecture employing a compact polarization-splitting grating coupler and a set of passive interferometers encodes the polarization information into intensity signals, allowing conventional detectors to accurately reconstruct the polarization state. With increasing compactness of photonic components, however, susceptibility to fabrication tolerances as well as intrinsic design constraints increases, potentially leading to non-ideal behavior. To address this, we introduce a robust calibration procedure that enables precise measurements even in the presence of imperfections. The chip design, combined with the calibration procedure, offers a robust, small-footprint, and high-speed approach to polarimetry, enabling a wide range of applications.

Keywords: integrated photonics; polarimetry; structured light.

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1 Introduction

The massive potential of photonic integrated circuits (PICs), offering unparalleled miniaturization, cost-efficient production, and chip-level integration, has positioned them at the forefront of photonics research. With continuous advancements, PICs have found applications in various fields, such as free-space light metrology.^{1–3} Polarization, as one of the fundamental properties of light,⁴ is of particular interest in this context, and its detection is the main focus of this paper. The precise measurement of polarization has proven great potential in various fields.

In biomedical imaging, for example, it enables non-invasive diagnostics by detecting microscopic tissue changes, aiding in early disease detection.^{5–8} Beyond this, polarization analysis is widely used in remote sensing,⁹ optical communication,¹⁰ quantum communication,¹¹ and other scientific and industrial sectors.

Polarization analysis has a long history, with traditional methods relying on bulky optical elements, such as in the rotating quarter-waveplate method¹² or liquid crystal-based techniques.¹³ Recent advances in meta-surfaces and plasmonics have enabled the development of compact polarimeters, eliminating the need for bulky optical components.^{14–16} Moreover, different waveguide-based on-chip polarimeter designs have been proposed, further enhancing integrability. For instance,

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on-chip polarimetry can be performed using nanometer-scale scatterers^{17,18} or inversely designed structures,^{19,20} demonstrating promising performance while presenting challenges for large-scale fabrication. Another approach involves directing two linearly polarized components of light under investigation into separate waveguides and analyzing them using either passive^{21,22} or reconfigurable^{23,24} on-chip interferometers. Promising measurement results have also been reported for these methods. However, their achievable integration density is constrained by conventional polarization-splitting grating couplers, which require elongated taper regions for efficient coupling, thereby limiting the compactness and scalability of the system. This limitation becomes particularly significant when considering two-dimensional (2D) detector arrays for applications such as imaging polarimetry. Notably, all waveguide-based polarimeters discussed are limited to the near-infrared spectral range. However, recent advancements in reducing waveguide losses have made the development of complex, high-performance PICs for visible light applications possible.^{25,26} Moreover, the compactness of photonic components, such as those used in the polarimeters mentioned above, not only offers advantages but also introduces susceptibility to manufacturing tolerances. Consequently, a calibration procedure following fabrication is often unavoidable^{27,28} and will be an important aspect of this work.

In this paper, we propose and experimentally demonstrate a passive silicon nitride PIC capable of detecting the polarization state of visible free-space light. The design relies on a highly compact polarization-splitting grating coupler, engineered with focusing gratings. The polarization state is analyzed on-chip using a fixed set of passive interferometers, which encode the complete polarization information into the output intensity. The light is processed in a completely passive manner, enabling single-shot measurements. As a result, detection time is constrained only by the response time of the intensity detectors. The compactness of the on-chip elements, combined with unavoidable fabrication tolerances and intrinsic design constraints of the compact polarization-splitting grating coupler, can introduce deviations in the measured polarization signals. Consequently, accurate data evaluation necessitates a precise calibration procedure. To address this, we introduce a flexible calibration technique that enables precise polarization measurements while preserving the advantages of the design's compact footprint.

2 Results

2.1 Compact 2D Grating Coupler Design

We start by introducing the free-space-to-chip interface used in our on-chip polarimeter. One-dimensional (1D) grating couplers are commonly used in PICs to couple light from free-space into waveguides, with their grating patterns typically designed in either rectangular or curved geometries.²⁹ Curved grating couplers offer focusing properties that reduce the need for extended taper regions, enabling a more compact component footprint.³⁰ Although 1D grating couplers exhibit intrinsic polarization sensitivity due to waveguide birefringence, 2D grating couplers offer a more practical and versatile approach for applications resolving polarization.³¹ Ideally, these function as on-chip polarization beam splitters, positioned at the interface between free-space and on-chip circuitry, directing

different polarization states into separate waveguides. Furthermore, 2D grating couplers can also incorporate curved grating grooves to minimize taper regions, thus improving compactness.^{32,33} However, this design may compromise polarization splitting, which will be discussed in further detail below. To demonstrate a size comparison of the different grating couplers, various grating coupler designs are depicted in a schematic illustration in Fig. 1(a).

A scanning electron microscope (SEM) image of the curved 2D grating coupler used in this work is shown in Fig. 1(b). The grating coupler is designed to couple the 45-deg linearly polarized component of the incident light into the fundamental transverse electric (TE) mode of the waveguide at port 1, whereas the 135-deg polarized component is coupled into the fundamental TE mode of the waveguide at port 2. Resulting from the compact design with minimized taper regions, the grating coupler was fabricated with a size of only $30\text{ }\mu\text{m} \times 30\text{ }\mu\text{m}$. Although the curved grating provides significant benefits in terms of component size, it also introduces some technical challenges. Specifically, the overlap of curved grating grooves induces distortions in the grating voids, deviating from their usually rectangular shape, as shown in the inset of Fig. 1(b). Hence, the chosen compactness of this key component of our on-chip polarimeter comes at the cost of imperfect polarization selectivity and extinction ratio, as discussed in more detail below. More detailed information on the grating coupler design, as well as other on-chip components, is provided in Figs. S6–S8 in the [Supplementary Material](#). A detailed comparison of the footprint of reported coupling structures relative to the grating coupler presented in this work is provided in Table S1 in the [Supplementary Material](#).

Figure 1(c) illustrates the normalized transmission for the different ports of the grating coupler, with incident light polarized

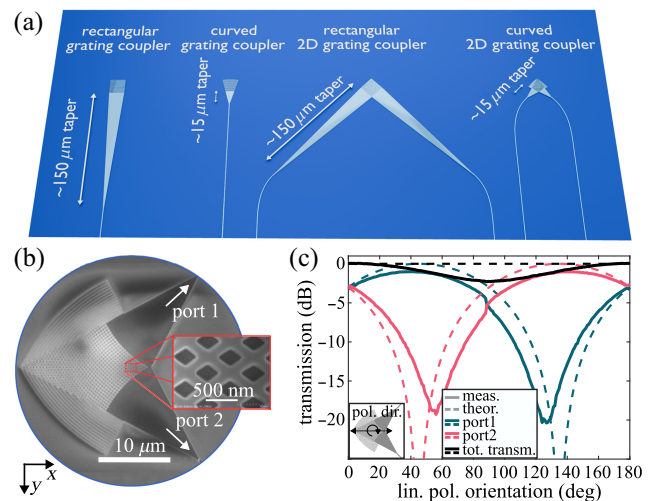


Fig. 1 Design of a compact 2D grating coupler with a focusing grating design. (a) Schematic representation of different types of grating couplers. (b) SEM image of the curved 2D grating coupler. (c) Measured (solid line) and ideal (dashed line) normalized transmission for the different ports of the grating coupler, with incident light linearly polarized at various orientations. The polarization direction was adjusted using the 2D polarization state generator shown in Fig. 3.

at various orientations. The dashed line represents the ideal behavior of a 2D grating coupler, which perfectly splits the two orthogonal polarization components. In contrast, the solid line shows the experimentally measured normalized transmission for the different ports of the compact 2D grating coupler presented in this work. The measurements reveal two significant deviations from the ideal splitter of orthogonal linear polarization states. First, the extinction ratio is substantially worse than in the ideal case. Hence, part of the incoming light is still coupled to port 1 or 2 even though the light is polarized orthogonally to the polarization direction that this port is supposed to be sensitive to. In addition, the measured transmission minima are shifted with respect to the ideal case. This indicates that the light coupled into the two ports is not purely 45 or 135 deg linearly polarized but instead consists of linearly polarized components with slightly different orientations that are not orthogonal to each other. To describe the coupling characteristics of the curved 2D grating coupler, a simple theoretical model has been developed. This model will later enable us to circumvent the issues associated with the non-ideal polarization splitting of curved 2D grating couplers in on-chip polarimeters through a calibration technique that we will discuss in detail below.

We can define a coupling matrix $\hat{\mathbf{C}}$ that relates the Jones vector of the free-space field to the waveguide modes

$$\begin{pmatrix} E_1^{\text{in}} \\ E_2^{\text{in}} \end{pmatrix} = \hat{\mathbf{C}} \begin{pmatrix} E_x \\ E_y \end{pmatrix}, \quad (1)$$

where E_x and E_y represent the complex amplitudes of the x - and y -polarized components of the free-space light, and E_1^{in} and E_2^{in} denote the complex electric field amplitudes of the waveguide modes at the two ports of the grating coupler. The coupling matrix consists of two components: a projection matrix $\hat{\mathbf{P}}$, which accounts for the fact that the coupling does not occur strictly along the 45 or 135 deg polarization directions, and a cross-talk matrix $\hat{\mathbf{X}}$, which accounts for the cross-talk among the different polarization components

$$\hat{\mathbf{C}} = \hat{\mathbf{X}} \hat{\mathbf{P}}, \quad (2)$$

with

$$\hat{\mathbf{P}} = \begin{pmatrix} \cos a & -\sin a \\ \cos a & \sin a \end{pmatrix}, \quad (3)$$

$$\hat{\mathbf{X}} = \begin{pmatrix} \sqrt{1-x_i} & \sqrt{x_i} e^{i\frac{\pi}{2}} \\ \sqrt{x_i} e^{-i\frac{\pi}{2}} & \sqrt{1-x_i} \end{pmatrix}, \quad (4)$$

where a defines the effective polarization directions that the coupler channels into the two ports, and x_i denotes the intensity cross-talk of the different polarization components.

Note that coupling losses are not considered in this model. As a result, only the relative information about the coupled intensity is considered, which is sufficient for our intended application in an on-chip polarimeter.

2.2 Polarimeter Design and Measurement Principle

Having introduced the 2D grating coupler and its properties, we now integrate it into a photonic circuit to develop a fully passive

on-chip polarimeter. The 2D grating coupler directs two linear polarization components of the incident light into separate waveguides, preserving both their relative amplitude and phase information. As a result, the complete polarization information of the free-space light field is contained in the relative amplitude and phase of the waveguide modes. Recently, we introduced a method to retrieve the relative amplitude and phase between two waveguide modes via a single-shot intensity measurement, using a set of all passive on-chip interferometers.³⁴ We can thus integrate the 2D grating coupler with the method described in Ref. 34 to develop a passive photonic chip capable of extracting polarization information from free-space light using only intensity measurements at the outputs.

A schematic of the photonic chip is shown in Fig. 2(a). The free-space-to-chip interface is realized using the 2D grating coupler introduced earlier [indicated in red in the microscope image of the chip in Fig. 2(b)]. A waveguide is connected to each port of the 2D grating coupler. These waveguides are then divided into several channels using a Y-branch splitter.³⁵ Two of these channels are directed to output ports [out₁ and out₂, marked in blue in Fig. 2(b)]. The outputs out₁ and out₂ provide direct information on the amplitude of the linearly polarized component being examined. The remaining channels are paired using a Y-branch combiner. In two of these pairs, the waveguides pass through a passive phase shifter before reaching the combiner. This phase shifter introduces a fixed relative phase shift among the waveguide modes, achieved simply by varying the waveguide width over a certain length.³⁶ Together with the passive phase shifters, the Y-branch combiners form passive on-chip interferometers that enable the effective retrieval of the relative phase in the input waveguides through intensity measurements at the chip's outputs. At the outputs, the light is coupled back into free space using a standard 1D grating coupler, allowing the intensities to be measured via conventional detectors.

To gain a deeper understanding of the phase reconstruction, it is instructive to examine a theoretical model that connects the input fields on the chip (i.e., the fields in the waveguides after the 2D grating coupler) with the output fields³⁴

$$E_1^{\text{out}} = t_{11} E_1^{\text{in}}, \quad (5)$$

$$E_2^{\text{out}} = t_{22} E_2^{\text{in}}, \quad (6)$$

$$\begin{aligned} E_j^{\text{out}} &= t_{1j} E_1^{\text{in}} + t_{2j} E_2^{\text{in}}, \quad \text{for } j = 3, 4, 5. \\ &= A_{1j} e^{i\alpha_{1j}} + A_{2j} e^{i\alpha_{2j}}, \quad \text{for } j = 3, 4, 5, \end{aligned} \quad (7)$$

where E represents the complex-valued electric field amplitude of the waveguide mode, and the complex proportionality coefficients t_{ij} link the field at input i to the field at output j . The amplitudes and relative phases of the coefficients t_{ij} are determined through a calibration procedure, as outlined in a later section. In Eq. (7), we perform a substitution to separate complex-valued variables into real valued amplitude values $A_{ij} = |t_{ij}| |E_i^{\text{in}}|$ and their corresponding phase $\alpha_{ij} = \tau_{ij} + \phi_i^{\text{in}}$, where $\tau_{ij} = \text{angle}(t_{ij})$ and $\phi_i^{\text{in}} = \text{angle}(E_i^{\text{in}})$. Taking the modulus squared of Eq. (7), using the relation $I \propto |E|^2$ and rearranging the equation leads to an expression for the relative phase

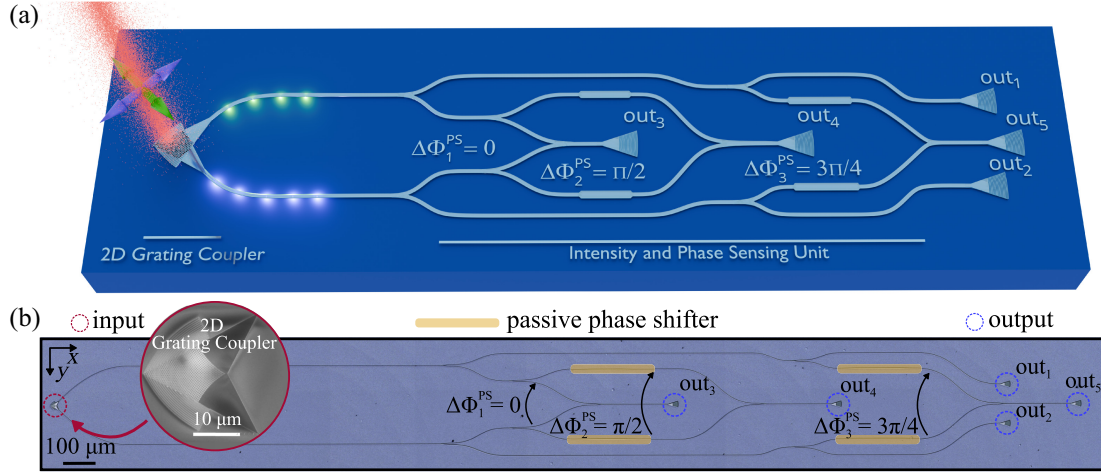


Fig. 2 Artistic illustration of the chip design (a) and optical microscopy image of the fabricated chip (b). A focusing 2D grating coupler serves as the interface that couples free-space light into the waveguides on the chip. This coupler splits the light into two linearly polarized components and directs each into separate waveguides. The two polarization components are then analyzed for their relative phase and amplitude using passive on-chip interferometers, providing complete information about the 2D polarization state of the incident light. Finally, the output signals of the on-chip architecture are coupled back into free space by means of standard grating couplers. To simplify experiments, the chip layout was intentionally designed with certain distances increased, resulting in a total footprint of $3295 \mu\text{m} \times 325 \mu\text{m}$.

$$\alpha_{1j} - \alpha_{2j} = \pm \arccos\left(\frac{I_j^{\text{out}} - (A_{1j}^2 + A_{2j}^2)}{2A_{1j}A_{2j}}\right) + 2\pi n, \quad (8)$$

with $\alpha_{1j} - \alpha_{2j} = \tau_{1j} - \tau_{2j} + \phi_{1j}^{\text{in}} - \phi_{2j}^{\text{in}}$ and n being an integer number. We omit the term $2\pi n$ from our analysis, as it remains unresolved within our system and does not contribute relevant information to the polarization reconstruction. Equation (8) reveals that the relative phase $\alpha_{1j} - \alpha_{2j}$ can be determined, provided the output intensities of the interferometers and the amplitude factors A_{1j} and A_{2j} are known, whereby the values of A_{1j} and A_{2j} can be derived using Eqs. (5) and (6), in conjunction with the intensities measured at the outputs out_1 and out_2 , given the relationship $I \propto |E|^2$. Finally, we need to address the challenge that Eq. (8) provides two possible signs in front of the inverse cosine function. To determine the correct sign for a single interferometer, additional measurements are required that incorporate a known additional relative phase shift. In our case, this is accomplished using three passive interferometers equipped with distinct phase shifters. The phase shifters are designed to introduce a fixed relative phase shift of $\Delta\Phi_1^{PS} = 0$, $\Delta\Phi_2^{PS} = \pi/2$, and $\Delta\Phi_3^{PS} = 3\pi/4$, providing balanced sensitivity of the interferometric phase reconstruction across all possible phase scenarios. However, the phase shifts generated on the chip can deviate considerably from their design values due to minor manufacturing inaccuracies. Consequently, the actual phase shifts are determined through calibration and expressed in terms of the relative phases of the proportionality coefficients t_{ij} .

Once the relative amplitudes and phases of the waveguide modes are determined, the polarization state of the free-space light can be inferred, provided the behavior of the 2D grating coupler is well understood. Mathematically, this corresponds to rearranging Eq. (1) by multiplying it from the left with the complex conjugate of the coupling matrix $\hat{\mathbf{C}}$.

2.3 Experimental Setup

To enable precise calibration and facilitate a comprehensive investigation of the polarimeter's performance, it is crucial to design an experimental setup that offers full control over the polarization state of the light incident on the chip's input section while simultaneously allowing accurate measurement of the chip's output signals. A schematic of the key components of the setup used in this work is shown in Fig. 3(a). The experimental setup employed for investigating the on-chip polarimeter begins with a fiber-coupled laser diode emitting light at a center wavelength of $\lambda = 658 \text{ nm}$. We use a polarization state generator to set the polarization state of the light in a controlled manner. The polarization state generator consists of a horizontally aligned linear polarizer followed by two liquid crystal variable retarders (LCVRs), with their slow axes aligned at $+45$ and 0 deg. This configuration enables the generation of any desired polarization state by applying corresponding voltages to the liquid crystals. The generated polarization states, based on the retardances set at the LCVRs, are shown in Fig. 3(b). After the polarization state is set, the beam impinges onto the input region of the chip. The on-chip architecture encodes relative phase and intensity information from two linear polarization components of the beam into intensity signals. The output signals are monitored by an imaging system consisting of a mirror, an objective, and a camera. The imaging system is designed so that the individual output signals of the chip appear spatially separated on the camera sensor, allowing them to be easily distinguished.

2.4 Calibration Technique

Even minor manufacturing inaccuracies can alter the behavior of on-chip components. For instance, increased sidewall roughness of the waveguides can introduce losses in waveguide modes, whereas deviations in waveguide length or width can lead to

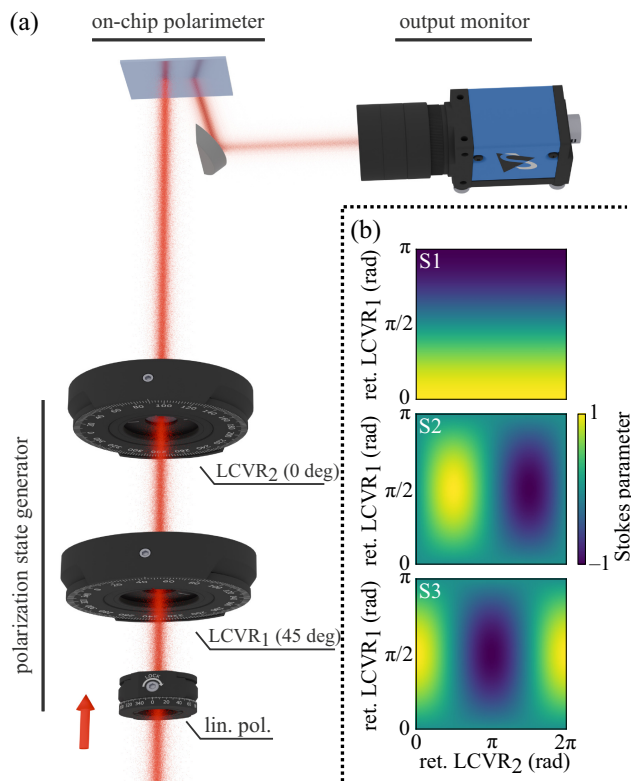


Fig. 3 (a) Illustration of the experimental setup: a collimated Gaussian beam first passes through a polarization state generator, which includes a horizontally aligned linear polarizer and two LCVRs with their slow axes aligned at +45 and 0 deg, respectively. The beam then enters the chip's input region. The chip's output signals are monitored by means of an imaging system, consisting of a D-shaped mirror, an objective, and a camera. (b) Stokes parameters produced by the polarization state generator depending on the retardance set at the two liquid crystal variable retarders. The polarization state generator allows for the controlled creation of any possible polarization state by adjusting the retardance of LCVR₁ between 0 and π and LCVR₂ between 0 and 2π .

unintended phase shifts.³⁷ Furthermore, the design of specialized components can introduce unexpected and undesirable effects that impact their functionality, as seen in the case of the 2D grating couplers with a focusing grating. All these effects impact the chip's response to incident light with different polarizations and, if not accounted for, inevitably lead to increased measurement inaccuracies. To assess the impact of hardware imperfections, a numerical error propagation simulation was conducted, the results of which are discussed in detail in Figs. S1–S5 in the [Supplementary Material](#). Nonetheless, a robust calibration procedure can effectively compensate for these imperfections, allowing for highly accurate measurements even in the presence of significant imperfections in the on-chip components.

The calibration process involves illuminating the chip with light of precisely known parameters while simultaneously measuring the output signals. This allows us to determine the characteristics of the chip components. To achieve this, we require a theoretical model of the chip that takes into account its imperfections. We have already established this for the polarization-splitting grating coupler, which can be characterized by the

coupling matrix $\hat{C}$, as introduced in Eq. (1). We have also developed a theoretical model for the remaining waveguide architecture, described by Eqs. (5)–(7), which accounts for deviations arising from waveguide imperfections. The model uses complex proportionality coefficients t_{ij} , whose amplitudes represent all potential losses experienced by the waveguide mode during propagation from input i to output j . The phases of the coefficients describe any relative phase shifts introduced to the waveguide mode, whether intentionally through passive phase shifters or unintentionally due to manufacturing inaccuracies.

Together with Eqs. (1)–(4), which describe the coupling behavior of the polarization-splitting grating coupler, Eqs. (5)–(7) form a comprehensive theoretical model that accounts for all relevant imperfections in the system, represented by the parameters α , x_i , and t_{ij} .

To determine the parameters, we use the setup shown in Fig. 3(a). The polarization state generator allows us to control the polarization of the reference beam, which we use for calibration. To generate the broadest possible range of input polarization states, we vary the retardance of the liquid crystal LCVR₁ from 0 to π and the retardance of LCVR₂ from 0 to 2π . This allows us to cover the entire surface of the Poincaré sphere, as shown in Fig. 3(b). Simultaneously, we record the output intensities of the chip for each incident polarization state. The experimentally obtained output intensities of the chip are presented in Fig. 4(a). A total of 625 distinct polarization states were generated by applying 25×25 different retardance values to the liquid crystals. As the generated input polarization states are precisely known, we can now extract the chip parameters from the measured output intensities. This is achieved by fitting the previously discussed theoretical model of the chip to the experimental data. The chip parameters α , x_i , and t_{ij} are chosen as free variables in the fitting model, enabling them to be easily extracted once the algorithm converges. Although many fitting algorithms are suitable for this problem, we have chosen a standard least squares method. The output intensities for the various input polarization states, calculated using the fitted theoretical model, are shown in Fig. 4(b). The theoretical results closely match the experimental values. Furthermore, the fitted parameters of the polarization-splitting grating coupler are consistent with the measurements presented in Fig. 1(b) and are further validated by finite-difference time-domain (FDTD) simulations. As previously observed in Ref. 34, owing to minor fabrication inaccuracies, the phase shifts introduced on the chip appear entirely random. However, as they can be accurately determined through the calibration procedure, they do not constitute a fundamental limitation to the proposed measurement method.

It is worth noting that the calibration process can be easily automated, as the reference beam is adjusted via the voltages applied to the liquid crystal retarders. This results in a rapid calibration procedure, enabled by the fast switching time of the liquid crystals, allowing the full calibration of a device to be completed in around 2 min.

2.5 Polarization Measurements

Once it is carefully calibrated, the photonic chip is capable of characterizing the polarization state of incident light with any arbitrary polarization. A single-shot intensity measurement of the chip's output signals is sufficient to deduce the polarization state of the light under investigation. To extract the polarization information from the intensity data, the relative amplitudes and

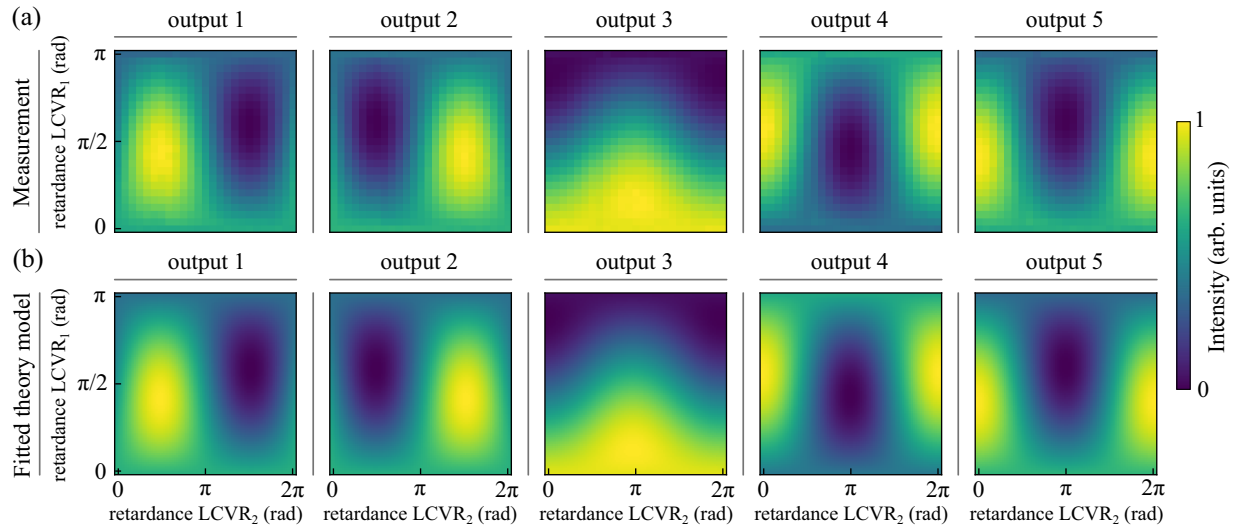


Fig. 4 Results from the calibration procedure, illustrating the output intensities of the chip for various input polarization states. The input polarization states are produced by applying specific retardances to the liquid crystals of the polarization state generator, as depicted in Fig. 3. Consequently, the intensities are presented as a function of the applied retardances. (a) Experimentally measured output intensities. (b) Theoretically calculated values obtained using the fitted theoretical model.

phases of the input waveguide modes are initially retrieved using the on-chip interferometric setup. The obtained amplitude and phase information of the waveguide modes is subsequently translated into the Jones vector of the incident free-space light, using the coupling matrix $\hat{C}$ of the polarization-splitting grating coupler, which is determined during the calibration procedure.

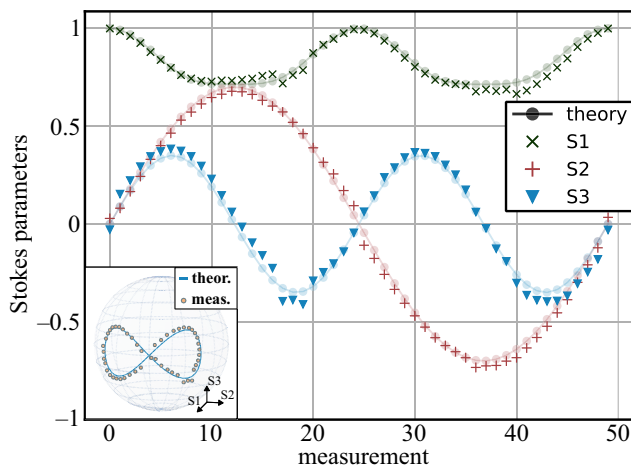


Fig. 5 Measured and theoretically expected Stokes parameters for 50 different polarization states, forming a closed loop on the surface of the Poincaré sphere. The distinct polarization states were probed by the input interface of the chip. The chip's output intensities were used to reconstruct the polarization state of the input light. An alternative representation of the measurement results, with the measurement points depicted as dots on the surface of the Poincaré sphere, is displayed in the inset. The theoretical and experimental values show strong agreement, with a root mean square deviation of $\Delta S_{\text{RMS}} = 0.028$.

To demonstrate polarization measurement using the photonic chip, we once again employ the experimental setup depicted in Fig. 3(a). To evaluate the chip's performance, we illuminate the input interface with light of 50 distinct polarization states, forming a closed loop on the surface of the Poincaré sphere. The retrieved Stokes parameters for the different probed polarization states are shown in Fig. 5. The theoretical values correspond directly to the polarization states set at the polarization state generator. There is strong agreement between the theoretical values and the experimentally determined values, with a root mean square deviation of $\Delta S_{\text{RMS}} = 0.028$ between the measured and theoretical Stokes parameters.

3 Conclusion

A PIC capable of detecting the polarization state of visible free-space light has been proposed and analyzed with respect to its performance. A compact polarization-splitting grating coupler was introduced as the free-space-to-chip interface, employing a focusing grating design that results in a highly compact coupler size. Subsequent to the grating coupler, the light processing on the chip was carried out through an architecture composed of a series of entirely passive interferometers. This chip architecture enables the retrieval of the polarization state of incident free-space light through a single-shot intensity measurement at the outputs.

It was found that the input grating coupler did not exhibit perfect polarization-splitting properties due to inherent characteristics of its design. In addition, the performance of other on-chip components may deviate from their ideal characteristics as a result of manufacturing inaccuracies. To ensure accurate polarization measurements with the chip despite these imperfections, a straightforward, fast, and automatable calibration process was introduced. Finally, we evaluated the calibrated chip's performance by probing 50 distinct polarization states.

Despite the presence of imperfect components, it was possible to achieve highly accurate polarization measurements.

It is important to note that advancements in integrated photonics, such as on-chip detectors³⁸ or inverse-designed components,³⁹ can be seamlessly integrated into our chip design, potentially leading to an even more compact and integrated device. Furthermore, possible extensions could include arranging multiple instances of the presented chip design in an array, enabling the effective measurement of the spatial distribution of the polarization of light fields.

The chip design, together with the methods presented, offers a powerful, cost-effective, and highly compact solution for on-chip polarimetry, which is compatible with CMOS mass production.

Disclosures

The authors declare no conflicts of interest.

Code and Data Availability

The data and MATLAB code supporting the findings of this study are available in Figshare at <https://doi.org/10.6084/m9.figshare.31889203>.

The repository includes calibration data, measurement data, and analysis scripts used to reconstruct polarization states.

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