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On-chip high-speed coherent optical signal receiver based on photonic spin-Hall effect

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Abstract

The use of coherent optical signal processing in long-distance optical communication systems has dramatically increased data capacity enabling encoding of multiple-bit information in the amplitude and phase of a light beam. Direct detection of phase information of a high-speed modulated light remains challenging and requires an external, local oscillator for referencing, which is expensive for short-reach optical communications, for example, in datacenters. The availability of less complex integrated photonics devices for coherent signal detection would alleviate this bottleneck. On the other hand, phase information of coherent, orthogonally polarized light beams can be extracted from their polarization states and it is, therefore, possible to achieve phase measurements via fast polarization detection. Here we demonstrate an on-chip, high-speed coherent optical signal receiver enabled by spin-orbit coupling in Si-photonics circuitry. In a coherent communication experiment with up to 16 Gbaud/s rate, the high-speed quadrature phase-shift keying signals detected by a Si nanodisk based polarisation measurements at multiple wavelength in the C-band were recovered with a bit error rate below the forward error correction threshold. The proposed on-chip nanodisk coherent receiver shows promise in high-speed coherent optical communication applications where phase detection is required at low cost and small footprint.

Coherent optical communication technology [1] has the advantage of a high data rate owing to the encoding of information in the amplitude and phase of coherent light signals, and quadrature phase-shift keying (QPSK) signals have dramatically increased the long-haul optical communication capacity [2]. The detection of coherent signals and phase measurements conventionally rely on a complex system of the Mach-Zehnder interferometers and phase shifters with typical coherent signal receivers on a millimeters scale, with expensive local oscillators, which makes their applications in some scenarios, such as datacenters where space is limited and costs must be minimized [3]. The availability of compact and low-cost scheme for coherent signal demodulation would alleviate this bottleneck. Phase detection and phase-signal demodulation relies on a linear mapping between a baseband signal (reference) and an information carrying optical signal. To remove the need for a local oscillator, the so-called self-coherent approach can be used where a reference is transmitted together with the signal in the same fibre [4, 5]. In this case, the coherent interaction between the phase modulated signal and the reference results in the polarisation modulated transmitted light. Phase information can then be recovered from two coherent signal channels with orthogonal polarization states and the signal can be retrieved through the Stokes-vector direct detection.

Traditional polarimeters with separate optical components, such as waveplates and beam splitters, and sometime polarisation maintaining fibres have been used for long-distance coherent optical communication [6, 7]. Polarisation analysis has recently been implemented in integrated nanophotonic devices compatible with a silicon-on-insulator (SOI) technology and complementary metal-oxide-semiconductor processing [8-12]. However, for coherent optical communications, the high-speed polarization state detection is needed, requiring minimal resonant signal delay in the nanophotonic circuit for the polarisation measurements. On-chip nanophotonic devices for polarisation characterisation may be based on plasmonic nanoantennas, metasurfaces, and spin-orbit interactions [13]. Plasmonic nanoantennas typically have relatively low efficiency [14, 15]. The metasurface-based components have been demonstrated for polarization detection in free space applications [16-22]. At sub-wavelength dimensions, on-chip polarimeters have been implemented based on the spin-orbit interaction of light with a single nanostructure coupled to a waveguide [23-26]. In this realization, incident onto a nanoparticle light with different polarisation states is coupled to the waveguide in different directions and Stokes parameters can be recovered comparing intensities of the guided light [25, 26]. This provides an opportunity to achieve the phase demodulation of the self-coherent optical data transmission on a Si-photonic chip.

In this article, we demonstrate integrated on-chip high-speed QPSK coherent signal demodulation using the spin-orbit interactions in Si nanodisks coupled to a network of single-mode Si waveguides on an SOI substrate. Through the photonic spin-orbit effects, a normally incident optical signal selectively couples to Si waveguides depending on its polarisation state. The coupling does not introduce temporal distortion of short pulses but is strong enough to provide efficient energy transfer from an incident beam to Si waveguides. The measurements of the Stokes parameters are demonstrated with accuracy that is competitive with other commercial devices. Stokes vector direct detection is then used to demodulate the phase of the transmitted QPSK signal.

Results.

Design. We consider the self-coherent optical transmission with the QPSK signal encoded in the x-polarised light and the y-polarised light carrying a reference 101010... binary phase-shift keying (BPSK) signal. The phase modulation results in the four varying polarization states which arrive onto the demodulator: linear polarization (LP) states of 45° and 135° orientations and right and left circularly polarized (RCP and LCP) states. If a time dependence of these polarisation states can be measured, the phase relation between the signal and reference beams can be recovered, decoding QPSK signal.

The proposed phase demodulator for QPSK signals consists of a network of four Si single mode fibres coupled to single or double Si nanodisks designed to achieve detection of Stokes parameters of the incoming light through the intensity measurements at the output of the waveguides (Figure 1). In this approach, an arbitrary polarisation state of the incident light can be reconstructed by measuring the intensity of the 90° and 45° LP and RCP and LCP components of the incident signal in an integrated manner. In the developed device, these polarisation components are sorted out and directed in the individual waveguides of the Si integrated circuit and their intensity measured at the waveguide output ports (see Supplementary Materials). From these intensities, the Stokes vectors and then the QPSK phase information encoded in the signals are recovered.

Stoke parameters of the incoming light can be determined if the intensities of the RCP, LCP and linear polarisation components 90° and 45° are known. In order to measure the intensities of the LCP and RCP components, the size of the silicon nanodisks were chosen to support the electric dipole resonances near the operating wavelength, so that the normally incident circularly polarized light excites two out-of-phase electric dipoles forming a circular polarised electric dipole in the nanodisk plane (Figure S2) [25]. Due to the photonic spin-Hall effect, depending on the handedness of the rotating dipole, it radiates in one or another direction in the side-coupled Si waveguide [27]. As a result, the nanodisk separates the RCP and LCP components of the normally incident arbitrary polarized light, which can be measured at the opposite waveguide outputs. The components carrying linear polarisation are coupled equally in both directions (Figure S3f and S4b); their background is then taken into account via the calibration of a retrieval matrix. In order to measure the intensities of the 90° and 45° LP components, we used a double disk system: two nanodisks with the same diameters placed on different sides of the waveguide (Figure S3). By varying the distance between the nanodisks, the interference between the induced dipoles and, therefore, the modes coupled to the waveguide by the nanodisks can be controlled and optimized to detect intensity related to a particular orientation of the linear polarisation with respect to the waveguide axis (see Supplementary Information for details).

Figure 1. Schematic of the on-chip phase demodulator for high-speed coherent optical communications. The normally incident light carries x-polarised QPSK signal and y-polarised BPSK signal, resulting in temporarily varying polarisation. After the interaction with a system of nanodisks and single mode waveguides, different polarisations are coupled to different waveguides and from simple intensity measurements the Stokes parameters can be found and the phase information decoded.

For the experimental implementation, the topology was chosen allowing seamless access to the waveguide output ports (Figure 3a). Each waveguide is coupled to either single or double nanodisks for discriminating linear and circular polarization components, respectively. The basic element consists of a nano-disk next to a 220-nm-thick and 440-nm-wide single-mode Si waveguide, which supports only a fundamental transverse electric (TE) mode (Figure S1). The important operational parameters needed to be considered in the design include the extinction ratio of the polarisations coupled to different waveguides and the coupling efficiency, which will ultimately determine the achievable signal-to-noise ratio.

We define the extinction ratio as the ratio of the output optical power between the desired and undesired channels, i.e., the two ends of the waveguide for the LCP and RCP detection. The extinction ratio was optimized by varying the diameter D of the nanodisk and the distance d from the nanodisk centre to the center of the waveguide separately (Figure S4). For the disk diameter $D = 700$ nm and the optimized distance $d = 500$ nm corresponding to the maximum

extinction ratio approximately 13 dB for the two ends at a wavelength of 1550 nm (Figures S4). The coupling efficiency, defined as the ratio of the power of the incident beam in the given polarization to the power detected at the output is approximately 1.4 % for the same design parameters. The experimentally measured extinction ratio of the RCP and LCP polarisations is larger than 18 dB for output 3 and 15 dB for an output 2, respectively, with an excellent signal-to-noise ratio (Figure 3b). For the double-nanodisks structure, the same size of the nanodisks and disk-waveguide distance was used, and the highest extinction ratio of approximately 8 dB for desired and undesired signals for both 90° and 45° LP states was numerically obtained at the distances between the disks $L_1 = 600$ nm and $L_2 = 750$ nm, respectively (Figure S5). The coupling efficiency is approximately 1% for both polarisations. The intensity extinction ratio for the 90° LP state was measured to be of approximately 10 dB at output 1 and approximately 7 dB at output 4 for the 45° LP state.

For a high-speed operation, it is important that the device does not introduce significant dispersion of the signal. The simulation of the time-response of the device show the pulse broadening up to 40 fs (Figure 2), which negligible for the parameters of modern optical communication systems. The single disk configuration operates in a weakly resonant regime, near the broad electric dipole resonance of the nanodisk (Figure S2c), and the pulse dispersion is minimal. For the double-disk systems, due to the necessity of the resonant interaction between the disks, the pulse broadening is more significant, but the pulse arrival time is not affected. Therefore, high-speed simultaneous measurements of the Stokes parameters can be achieved.

Figure 2. High-speed response of the nanodisk-based device. (a) Time-domain trace of the incident 20-fs pulse. (b-e) Pulse traces at the output of the Si-waveguide for (b) LCP, (c) RCP, (d) 90° LP and (e) 45° LP components. The pulse is measured at points R and L indicated in the inserts at the distance of 1.5 μm from the disks. The diameter of the nanodisk is $D = 700$ nm, the waveguide width is $w = 440$ nm, and the centre-to centre distance between the nanodisk and the waveguide is $d = 500$ nm. The separation between double nanodisks is (d) $L_1=600$ nm and (e) $L_2=750$ nm. The operating wavelength is 1550 nm.

Experimental retrieval of Stokes parameters. In the first step, the performance of the device for the Stokes parameters retrieval (see Supplementary Information and Figure S7 for the details of the experimental set-up). The outcoupled light intensities from the 4 output ports of the device behave according to the simulations when the polarisation of the incident light

changes continuously between linear and circular states and with linear polarisation rotation (Figure 3b, c and S3f).

Figure 3. Optical responses of the on-chip nanodisk polarimeter. (a) SEM images of the 4 elements (numbers corresponds to the waveguide outputs in the schematics Fig. 1). (b, c) Experimentally measured and simulated normalized output intensities from different waveguide ports for (b) single-nanodisk element and (c) two double-nanodisk elements. (d) Stokes parameters retrieved for the test light polarisation obtained by rotating a quarter wave plate (QWP) from 0° to 180° for a half wave plate (HWP) fixed at 5°: (blue) experiment, (red) simulations.

The Stokes parameters of the incident signal need for the subsequent phase retrieval can be recovered from the detected I_{90} , I_{45} , I_{RCP} , and I_{LCP} intensities through [28]

$$\mathbf{S} = \begin{bmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{bmatrix} = \begin{bmatrix} |E_x|^2 + |E_y|^2 \\ |E_x|^2 - |E_y|^2 \\ 2 \operatorname{Re}\{E_x \cdot E_y^*\} \\ 2 \operatorname{Im}\{E_x \cdot E_y^*\} \end{bmatrix} = A \begin{bmatrix} I_{LCP} \\ I_{90} \\ I_{45} \\ I_{RCP} \end{bmatrix}, \quad (1)$$

where the Stokes vector $\mathbf{S} = [S_0 \ S_1 \ S_2 \ S_3]^T$ is related the complex electric fields E_x and E_y , the superscript $*$ denotes a complex conjugate, $\mathbf{I} = [I_{LCP} \ I_{90} \ I_{45} \ I_{RCP}]^T$ corresponds to the intensities of the respective polarisation components, and A represents a

4×4 retrieval matrix, which includes the information on the losses related to the coupling and decoupling efficiencies and propagation in the fibre, waveguides and other optical components. By sending in the input signals with well-defined linearly and circularly polarisations and measuring the intensities at the four output ports, the retrieval matrix A of the device can be determined through the multiple linear regression fitting (see Supplementary Information). The experimentally retrieved Stokes parameters obtained with Eq. 1 and theoretically calculated Stokes parameters for the test data are in a good agreement as shown on the Poincare sphere (Figure 3d). The measurements allow recovering S_1 , S_2 and S_3 Stokes parameters with high precision comparable to the performance of the conventional polarimeters.

Figure 4. QPSK optical communication testing with the integrated receiver. (a, b)

Experimentally retrieved (a) Stokes parameters and (b) constellation diagram for random 4, 8 and 16-GBd/s QPSK signals with 12,280 symbols (input power 17 dBm). (c, d) Measured BER curves of 4, 8 and 16-GBd/s QPSK signals for different (c) input optical powers and (d) wavelengths (input power of 15 dBm).

QPSK decoding. In order to test high-speed coherent optical communication link (for the details of the set-up see Supplementary Materials), light coupling, loss and polarisation rotation effects induced by the signal propagation in the fibre should be included in the retrieval matrix (Eq. 1). We generated 64 different polarization states as training input signals in the fibre link. The measured output data were used to calculate the retrieval matrix A averaged over 16 sets of the training signals. Random 4, 8 and 16-Gbaud/s optical signals with 12,280 symbols were used to test the phase retrieval. The obtained Stokes vectors on the Poincare sphere for different

experimental conditions are shown in Figure 4a. The Jones vector describing the complex electric field of the input signal is obtained from the measured Stokes vector as [29]

$$\mathbf{E} = \begin{bmatrix} E_x \\ E_y \end{bmatrix} = C \begin{bmatrix} \sqrt{1/2(1+S_1/S_0)} \\ \sqrt{1/2(1-S_1/S_0)} \exp[i \arctan(S_3/S_2)] \end{bmatrix}, \quad (2)$$

Where, C is a constant, while S_0 , S_1 , S_2 , and S_3 are the Stokes parameters. Since the QPSK signal is encoded in x-polarisation channel, the intensity and phase of the QPSK signal is obtained from Eq. (2), demonstrating the constellation diagrams with a good likelihood function (Figure 4b). The measured bit error rate (BER) curves of the tested QPSK signals show the BER for a 4-GBd/s decreasing to zero with the input power exceeding 15 dBm. The BER for the 8- and 16-GBd/s QPSK signals satisfies the forward error correction (FEC) threshold of 3.8×10^{-3} for higher powers (Figure 4c), required in modern optical communications [30]. The BER can be further reduced by increasing the input power, which is limited by the erbium-doped fibre amplifier and filter in our experimental setup and relatively low coupling efficiency to the integrated device, realized via a butt-coupler.

For wavelength division multiplexing application, the designed receiver was tested in the spectral range of the optical communication C-band for the wavelengths from 1540 nm to 1560 nm (Figure 4d). Limited by the higher insert loss (approximately 5dB) of the athermal arrayed waveguide grating used at the receiving end for multi-wavelength test (see Supplementary Materials for the details of the experimental setup), the BER at input power of 15 dBm is higher than that in Figure 4c. The demonstrated performance of the integrated coherent optical receiver is competitive with the commercial products in terms of the data rate and BER [31], which could be further improved by optimizing the coupling efficiency and insertion losses present in the used testbed.

Discussion.

We proposed and demonstrated a novel Si-photonics integrated circuit based on spin-orbit interactions of light for ultrafast phase-detection in coherent optical communications. The designed network of single-mode Si waveguides coupled to the system of Si nanodisks is capable to fully determine the Stokes parameters of the incident light in a one-shot intensity measurement. This allowed recovering the phase of the QPSK-modulated signals up to 16 GBd/s with a BER lower than the forward error correction threshold used in modern coherent optical communication systems. The develop device can also be used as a stand-alone integrated polarimeter with performance similar to conventional polarimeters. This on-chip phase-sensitive receiver has the potential for applications in coherent optical communication systems, replacing relatively bulky and expensive receivers (the problem especially pertinent in short distance optical links) with the advantages of a compact size and further microelectronic integration opportunity.

Author contributions

T.L. conceived the idea and designed the device. T.L., C.Z., Z.X., L.D. and A.V.Z. developed the physical concepts. T.L., Z.X. and C.Z. performed the simulations. C.Z. conducted the

optical testing. Y.X. participated in the high-speed optical testing. D.W. and Y.X. participated in the data processing and analysis. B.C. and S.G. fabricated the device. T.L., C.Z. and A.V.Z. wrote the manuscript. T.L., Z.L., A.V.Z. and X.Y. revised the manuscript. T.L., Z.L., A.V.Z. and X.Y. supervised the work. All authors contributed to the discussion of results.

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Figures

Figure 1

Schematic of the on-chip phase demodulator for high-speed coherent optical communications. The normally incident light carries x-polarised QPSK signal and y-polarised BPSK signal, resulting in temporarily varying polarisation. After the interaction with a system of nanodisks and single mode waveguides, different polarisations are coupled to different waveguides and from simple intensity measurements the Stokes parameters can be found and the phase information decoded.

Figure 2

High-speed response of the nanodisk-based device. (a) Time-domain trace of the incident 20-fs pulse. (b-e) Pulse traces at the output of the Si-waveguide for (b) LCP, (c) RCP, (d) 90° LP and (e) 45° LP components. The pulse is measured at points R and L indicated in the inserts at the distance of $1.5 \mu\text{m}$ from the disks. The diameter of the nanodisk is $D = 700$ nm, the waveguide width is $w = 440$ nm, and the

centre-to-centre distance between the nanodisk and the waveguide is $d = 500$ nm. The separation between double nanodisks is (d) $L1=600$ nm and (e) $L2=750$ nm. The operating wavelength is 1550 nm.

Figure 3

Optical responses of the on-chip nanodisk polarimeter. (a) SEM images of the 4 elements (numbers corresponds to the waveguide outputs in the schematics Fig. 1). (b, c) Experimentally measured and simulated normalized output intensities from different waveguide ports for (b) single-nanodisk element and (c) two double-nanodisk elements. (d) Stokes parameters retrieved for the test light polarisation obtained by rotating a quarter wave plate (QWP) from 0° to 180° for a half wave plate (HWP) fixed at 5° : (blue) experiment, (red) simulations.

Figure 4

QPSK optical communication testing with the integrated receiver. (a, b) Experimentally retrieved (a) Stokes parameters and (b) constellation diagram for random 4, 8 and 16-GBd/s QPSK signals with 12,280 symbols (input power 17 dBm). (c, d) Measured BER curves of 4, 8 and 16-GBd/s QPSK signals for different (c) input optical powers and (d) wavelengths (input power of 15 dBm).

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