Surface-Normal Stokes Vector Receiver based on Superimposed Metasurface

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Abstract: We demonstrate normal-incident Stokes vector receiver with superimposed metasurfaces to realize sorting and focusing in three different polarization bases. By using the fabricated metasurface with Si nanopost array, we successfully retrieve arbitrary state of polarization. © 2022 The Author(s)

1. Introduction

Stokes vector receiver (SVR), which can directly detect the state of polarization (SOP) of the optical signal, is expected as a potentially low-cost and high-speed receiver in the future metro and datacenter applications [1,2]. Despite being a direct-detection (DD) technique, the SVR enables self-homodyne transmission using the 2D or 3D signal space to increase the spectral efficiency and complete digital compensation of the chromatic and polarization dispersions to extend the transmission reach. To date, SVRs have been demonstrated using off-the-shelf bulky components [1] or waveguide-based devices with a number of polarization-manipulating components integrated on Si or InP [3,4].

In this work, we propose a surface-normal SVR with a compact metasurface-based polarization sorting device. Metasurfaces are generally composed of an array of subwavelength structures that can locally modify the intensity, phase, and polarization of light [5]. Here, by superimposing three-different metasurfaces, we implement the functionalities of all the necessary passive components, namely a 1×3 splitter, three polarization beam splitters (PBSs) with different polarization bases, and six focusing metalenses, inside a compact 500-μm-diameter area on a silicon-on-quartz (SOQ) substrate. By using the fabricated metasurface, we demonstrate successful retrieval of the full Stokes parameters of the incident light. Owing to the surface-normal configuration, our device can easily be extended to a large-scale 2D array to receive spatially multiplexed channels from a multicore fiber (MCF) or a fiber bundle, which are expected in the future >Tb/s highly parallelized optical interconnects [6].

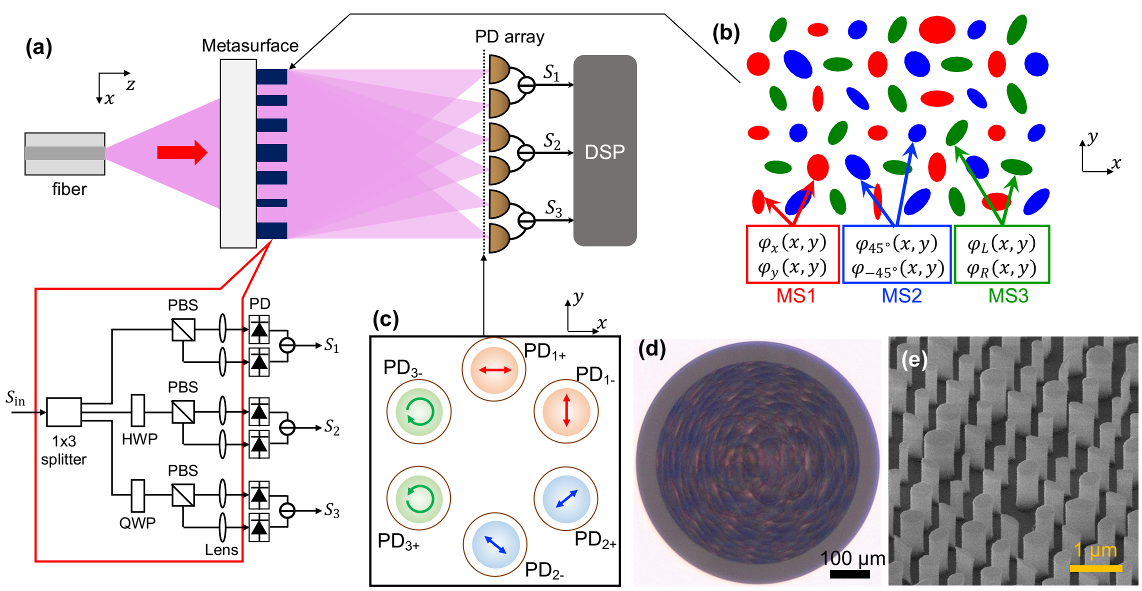

Fig. 1. Stokes vector receiver based on superimposed metasurfaces. (a) Schematic of the entire receiver. The inset below shows the schematic of the equivalent receiver. (b) Superimposed three metasurfaces (MS1, 2, 3), which operate as PBSs and metalenses for *x*/*y*, ±45°, and RHC/LHC polarization bases, respectively. (c) Location of six PDs at the focal plane to detect six polarization components. (d) Photograph and (e) SEM image of the fabricated device.

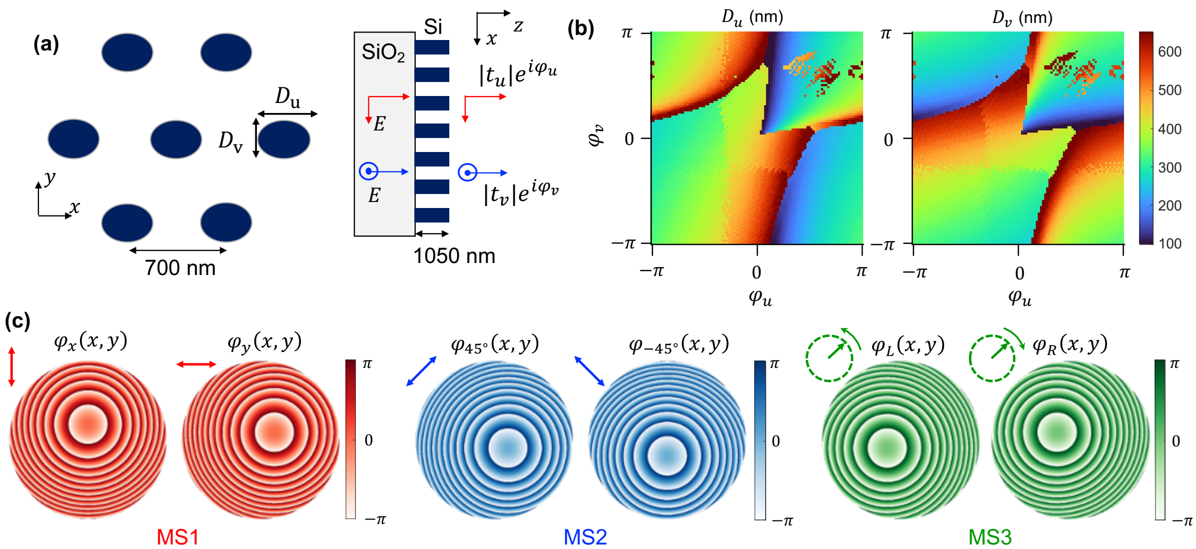

Fig. 2. Metasurface design. (a) Schematic of the Si nanopost array and the definitions of parameters. (b) Required dimensions of the Si nanopost for achieving a transmission phase set (φ_u, φ_v). (c) Required phase profiles for MS1,2, and 3.

2. Stokes vector receiver based on superimposed metasurface

The schematic of the proposed SVR is illustrated in Fig. 1(a). The input light from the fiber is incident to a compact metasurface-based device. As shown in Fig. 1(b), it is composed of superimposed three metasurfaces: MS1 (red), MS2 (blue), and MS3 (green). The phase profile $\varphi(x,y)$ of MS1 is designed to focus the *x*-polarized component of light to PD_{1+} and the *y*-polarized component to PD_{1-}, which are located in different positions at the focal plane as shown in Fig. 1(c). Similarly, MS2 and MS3 function as the polarization-beam splitters (PBSs) with embedded metalenses for the ±45° polarization basis and the right/left-handed circular (RHC/LHC) polarization basis, respectively, which are focused to $PD_{2\pm}$ and $PD_{3\pm}$ in Fig. 1(c). The Stokes vectors $\boldsymbol{S} \equiv (S_1, S_2, S_3)^T$ can then be derived by taking the difference of the photocurrent signals as $S_n = I_{n+} - I_{n-}$ $(n = 1, 2, 3)$, where $I_{n\pm}$ are the photocurrents of $PD_{n\pm}$ $(n = 1, 2, 3)$. Finally, the signal is demodulated through digital signal processing (DSP).

We should note that this scheme with six PDs without polarizers offers the maximum receiver sensitivity among various SVR configurations [2]. In addition, the S_0 parameter can also be retrieved if necessary. Compared with a similar metasurface-based polarimeter demonstrated recently for the imaging application [7], our superimposed device implements the functionality of a 1×3 splitter as well to enable efficient coupling from a single-mode fiber (SMF). Owing to the compact surface-normal configuration, it could easily be scaled to a 2D array to detect highly parallelized signals from a MCF or a fiber bundle.

3. Metasurface design and fabrication

In this work, we use a dielectric elliptical nanopost array fabricated on SOQ with a 1050-nm-thick Si layer. The desired transmission phase can be acquired by changing the geometrical parameters (dimensions D_u, D_v defined in Fig. 2(a) and the rotation angle θ) of each Si nanopost. First, we simulate the transmission characteristics of a single nanopost for the *x*- and *y*-polarized light at a wavelength (λ) of 1550 nm by the rigorous coupled-wave analysis [8]. Here, we adopt the hexagonal lattice with a lattice constant of 700 nm and fix the rotation angle to 0, as shown in Fig. 2(a). From these results, we can acquire the required $D_u(\varphi_u, \varphi_v)$ and $D_v(\varphi_u, \varphi_v)$ to achieve a transmission phase set (φ_u, φ_v), as shown in Fig. 2(b). We can confirm that by setting the dimensions appropriately, arbitrary phase shifts for *x*- and *y*-polarized lightwaves can be independently achieved. Furthermore, by tuning the rotation angle of the elliptical post, arbitrary phase shifts can be given to any orthogonal polarization pair [5,9].

In order to realize the function of a metalens, the metasurface must impart a spatially-dependent phase profile given as $\varphi(x,y) = -2\pi/\lambda(\sqrt{(x-x_0)^2+(y-y_0)^2+f^2}-f)$, where (x_0, y_0) is the focal point position, and f is the focal length. Here, the focal length is set to 2500 μm (NA~0.10), and focal points are arranged on regular hexagons with a spacing of 50 μm, as shown in Fig. 1(c). Under these conditions, the phase profiles required for MS1, 2, and 3 are depicted in Fig. 2(c). Then, we design the geometrical parameters of each nanopost to satisfy these phase profiles.

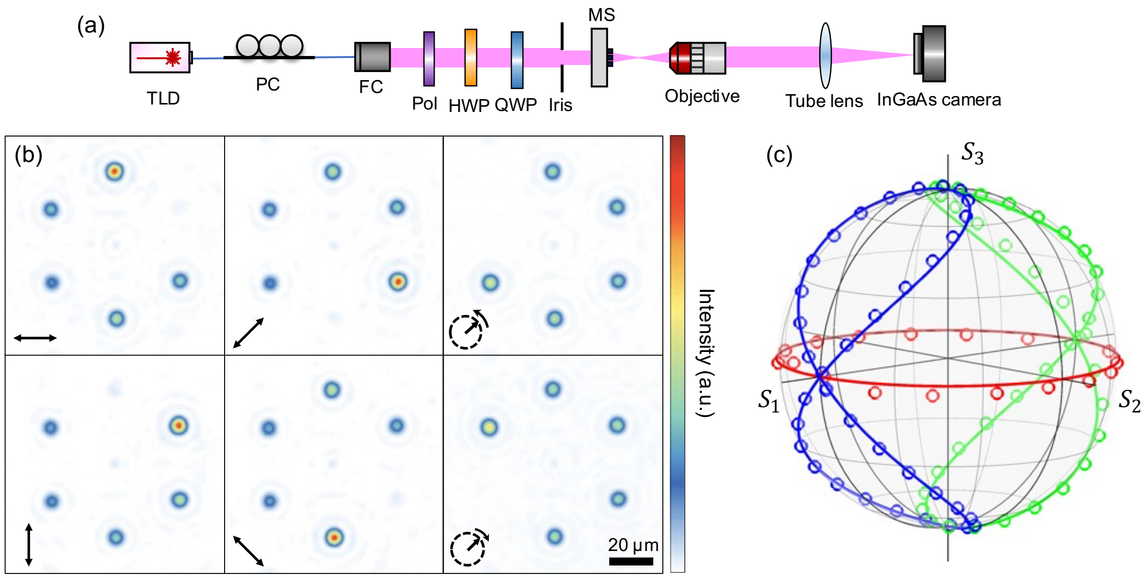

Fig. 3. Measurement results of the fabricated metasurface. (a) Measurement setup. (b) Measured intensity profiles at the focal plane with six different SOPs. (c) Retrieved Stokes vectors (circles) and input Stokes vectors (lines).

The designed metasurface was fabricated on a SOQ substrate. Following the electron-beam lithography using ZEP520A resist, inductively coupled plasma reactive ion etching (ICP-RIE) process and O_2 ashing process were employed to form the subwavelength pillars. Fig. 1(d) and Fig. 1(e) show the photograph and the scanning electron microscope (SEM) image of the fabricated metasurface. The diameter of the device was 500 μm.

4. Evaluation of the fabricated metasurface

To characterize the fabricated metasurface, we observed the intensity distribution at the focal plane for various input SOPs. The experimental setup is shown in Fig. 3(a). A continuous wave from a tunable laser diode (TLD) with a wavelength of 1550 nm is emitted from a fiber collimator (FC) and incident to the metasurface. The SOP is modified by rotating a half-wave plate (HWP) and a quarter-wave plate (QWP) (θ_{HWP} and θ_{QWP}). The light focused by the metasurface is magnified at 50 times by a 4-f system with an objective lens and observed by an InGaAs camera. From the detected intensities $I_{n\pm}$ at the six focal positions, the Stokes vector is retrieved as described in Section 2.

Fig. 3(b) shows the measured intensity distributions when the input Stokes vectors are set to (±1, 0, 0), (0, ±1, 0) and (0, 0, ±1). We can confirm that the incident light is focused to the six well-defined points by transmitting through the metasurface. Moreover, its intensity distribution changes with the SOP; *x*/*y*, ±45°, and RHC/LHC components of light are focused to the designed positions as expected. Then, Fig. 3(c) shows the retrieved Stokes vectors, calculated from the measured intensities at the six focal positions. The red plot shows a case where θ_{HWP} and θ_{QWP} are both varied as $\theta_{\mathrm{QWP}} = 2\theta_{\mathrm{HWP}}$. Similarly, the blue (green) plot shows a case where θ_{HWP} is fixed at 0° (45°) and θ_{QWP} is varied. We can see that the measured results (circles) agree well with the actual SOPs (line) in all cases. Finally, the Stokes vectors are retrieved over the entire Poincaré sphere by varying θ_{HWP} from 0° to 90° in 5° increments and θ_{QWP} from 0° to 180° in 5° increments. The average value of the deviation $\langle|\Delta\mathbf{S}|\rangle$ is 0.052.

5. Conclusion

We have proposed a surface-normal SVR with superimposed metasurfaces and successfully retrieved arbitrary SOPs using the fabricated metasurface. By scaling this metasurface to multiple channels and combining with a high-speed PD array [10], the proposed SVR can be used to realize low-cost, highly parallelized self-coherent systems.

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