Self-Coherent Transmission Using Metasurface-based Stokes-Vector Receiver

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Abstract: Stokes-vector receiver with compact metasurface and two-dimensional photodetector array is developed to demonstrate 15-Gbaud 16QAM self-coherent transmission over 25-km single-mode fiber. Surface-normal configuration enables direct coupling to multicore fibers in the future highly parallelized systems. © 2023 The Author(s)

1. Introduction

Self-coherent transmission systems [1-4] have recently attracted significant attention as a promising approach to achieve beyond-Tb/s transmission in the next-generation short-reach optical links such as inter/intra-datacenter and access networks. In this scheme, a continuous-wave (CW) tone is sent together with a coherent signal from the transmitter side, so that spectrally efficient modulation formats such as 16QAM and 64QAM can be employed without using expensive wavelength-tuned narrow-linewidth lasers as in the conventional coherent systems. The self-coherent systems can therefore bridge the gap between the low-cost but capacity-limited intensity-modulation direct-detection (IM-DD) systems and the high-speed but expensive coherent systems.

Among several variations of self-coherent systems, the polarization-based scheme using a Stokes vector receiver (SVR) is attractive due to the relative simplicity that neither a duplex fiber nor active polarization tracking circuit is necessary. In the previous demonstrations, SVRs were realized using bulky off-the-shelf components [1,5] or waveguide-based devices with several polarization-manipulating components integrated on Si or InP [6-8].

In this work, we demonstrate a simpler and spatially scalable surface-normal SVR with a dielectric-metasurface-based polarization sorting device and a two-dimensional photodetector array (2D-PDA) chip. The demonstrated metasurface implements the functionalities of all the necessary passive components: a 1×3 splitter, three polarization beam splitters (PBSs) with different polarization bases, and six focusing metalenses on a compact chip. The focused

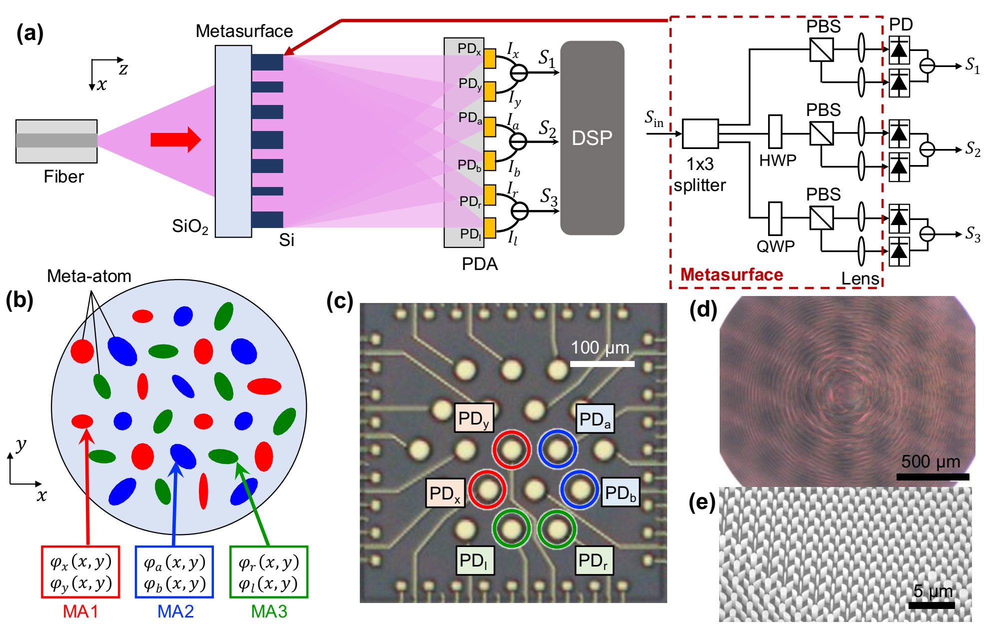

Fig. 1. Metasurface-based Stokes-vector receiver. (a) Schematic of the entire receiver. The right inset represents the schematic of the equivalent receiver. (b) Top view of the metasurface composed of three meta-atom arrays (MA1, MA2, MA3) based on elliptical silicon nanoposts on quartz. (c) 2D-PDA to detect six polarization components. (d) Optical microscope image and (e) SEM image of the fabricated metasurface.

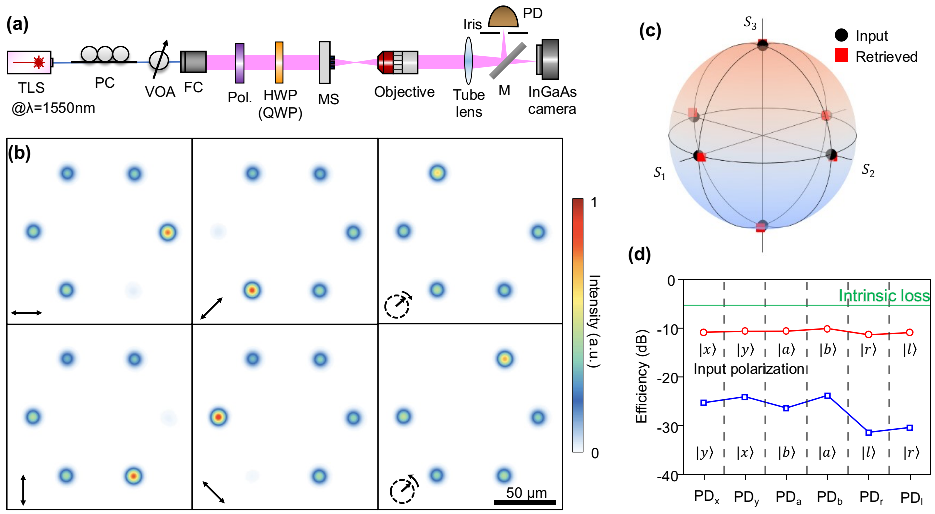

Fig. 2. Measurement results of the fabricated metasurface. (a) Measurement setup. (b) Measured intensity distributions at the focal plane for six different input SOPs. (c) Retrieved Stokes vectors (square) and input Stokes vectors (circle) on the Poincaré sphere. (d) Measured focusing efficiency.

light is incident to six high-speed photodetectors (PDs) integrated on a 2D-PDA chip and converted to electrical signals, from which the Stokes vector is demodulated. Using the fabricated device, we experimentally demonstrate 15-Gbaud 16QAM self-coherent transmission over a 25-km single-mode fiber (SMF). Owing to the surface-normal configuration, the demonstrated 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 [9,10].

2. Metasurface-based Stokes-vector receiver

The schematic of the SVR is illustrated in Fig. 1(a), which is newly designed and fabricated based on our previous work [11]. The input light from a SMF is incident to a metasurface-based device and focused to a high-speed 2D-PDA. As shown in Fig. 1(b), the metasurface is composed of three meta-atom arrays: MA1 (red), MA2 (blue), and MA3 (green). The phase shift $\varphi(x, y)$ induced by MA1 is designed to focus the x-polarized component of light to PD_x and the y-polarized component to PD_y, which are located in different positions at the focal plane as shown in Fig. 1(c). Similarly, MA2 and MA3 function as the PBSs with embedded meta-lenses for the ±45° polarization (a/b) basis and the right/left-handed circular (RHC/LHC) polarization (r/l) basis, respectively, and focus respective components to $PD_{a,b}$ and $PD_{r,l}$ in Fig. 1(c). The Stokes vector $\mathbf{S} \equiv (S_1, S_2, S_3)^T$ can then be derived by taking the difference of the photocurrent signals as $S_1 = I_x - I_y, S_2 = I_a - I_b$, and $S_3 = I_r - I_l$. Finally, the signal is demodulated through digital signal processing (DSP).

As the dielectric metasurface, we employed 1050-nm-high elliptical silicon nanoposts on a quartz substrate. The shape of each nanopost (meta-atom) was designed based on the rigorous coupled-wave analysis (RCWA) simulation results to satisfy the required phase profile $\varphi(x, y)$ [11,12]. Here, the focal length and metasurface diameter were set to 1 cm and 2 mm (corresponding to NA~0.10). The focal points were arranged on regular hexagons with a spacing of 60 µm to match the positions of PDs on the 2D-PDA. The designed metasurface was fabricated by electron-beam lithography and reactive-ion etching using a silicon-on-quartz (SOQ) substrate. An optical microscope image and a scanning electron microscopy (SEM) image of the fabricated metasurface are shown in Fig. 1(d) and 1(e).

We employed a 19-pixel 2D-PDA with InP/InGaAs-based p-i-n structure [13], from which six PDs as shown in Fig. 1(c) were used. Each PD had a diameter of 30 µm and the measured bandwidth above 10 GHz. The 2D-PDA chip was packaged with the radio-frequency (RF) coaxial connectors connected to each PD. Due to the limitation of the current optical setup, the metasurface and the 2D-PDA could not be approached to less than 1 cm, so that a rather large (2 mm) metasurface had to be used in this work. In practice, a fully packaged compact module with the metasurface diameter below 100 µm can be realized by reducing the distance between the metasurface and 2D-PDA.

3. Experimental results

We first characterized the fabricated metasurface by observing the intensity distribution at the focal plane for various input states-of-polarization (SOPs). The experimental setup is shown in Fig. 2(a). The input SOP was modified by rotating the half-wave plate (HWP) and the quarter-wave plate (QWP). The light focused by the metasurface was

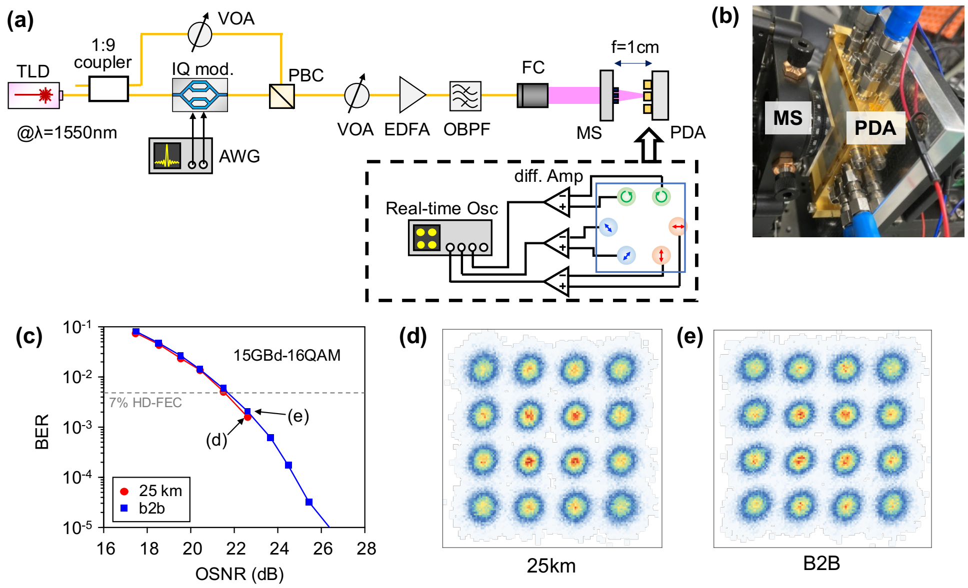

Fig. 3. Self-coherent transmission experiment. (a-b) Experimental setup and photograph. (c)-(e) Measured BER curves and constellations of 15-Gbaud 16QAM signal before (b2b) and after 25-km transmission.

magnified at 50 times by a 4f lens system and captured by an InGaAs camera. From the detected intensities at the six focal positions, the Stokes vector was retrieved as described in Section 2.

Figure 2(b) shows the observed intensity distributions when the input Stokes vector is 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* linear, ±45° linear, and RHC/LHC components of light are focused to the designed positions as expected. Figure 2(c) shows the retrieved Stokes vectors on the Poincaré sphere. We can confirm that the Stokes vectors are retrieved successfully with the average error $\langle|\Delta\mathbf{S}|\rangle$ of 0.028. Figure 2(d) shows the measured focusing efficiency. The excess loss is around 6.1 dB, and the crosstalk to the orthogonal PD position is suppressed by 13-20 dB.

We then conducted self-coherent transmission experiment using the fabricated metasurface and the 2D-PDA. The experimental setup is shown in Fig. 3(a) and 3(b). A 15-Gbaud 16QAM self-coherent signal was generated and sent through a 25-km SMF. At the receiver, the amplified signals from three differential RF amplifiers were captured by a real-time oscilloscope. A 2×3 multi-input-multi-output (MIMO) equalizer was employed at the offline DSP to reconstruct the IQ signal. Finally, the bit-error rates (BERs) were calculated.

Figures 3(c)-(e) show the measured BER curves and the retrieved constellations before and after transmission. We can confirm that BERs well below the 7% HD-FEC threshold are obtained with a negligible optical-signal-to-noise-ratio (OSNR) penalty even after 25-km transmission.

4. Conclusion

We have demonstrated 25-km transmission of 15-Gbaud 16QAM signals using a SVR based on a compact metasurface and 2D-PDA. Owing to the surface-normal configuration and the scalability of 2D-PDA to several hundreds of pixels [14], the demonstrated device can easily be extended to receive multiple spatial channels, enabling ultralow-cost highly parallelized self-coherent systems.

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