64-QAM Self-Coherent Transmission Using Symmetric Silicon Photonic Stokes-Vector Receiver

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Abstract: We propose a robust silicon photonic Stokes-vector receiver based on fully symmetric waveguides without a mode-selective directional coupler. By using a fabricated receiver, we experimentally demonstrate 30-Gb/s 64-QAM self-coherent transmission over a 25-km single-mode fiber. © 2022 The Author(s)

1. Introduction

As a cost-effective alternative to the current coherent systems, self-coherent (or self-homodyne) transmission systems have recently attracted a great deal of attention for use in short/medium-reach applications such as intra/inter-data center networks. Since the signal and local oscillator (LO) components share the same laser source, the self-coherent system eliminates the need for precise wavelength control and enables uncooled operation of the laser. Therefore, it has the potential to drastically reduce the system cost compared to the conventional coherent systems. Thus far, numerous self-coherent transmission experiments have been reported [1]. For example, [1] demonstrated a bi-directional self-coherent system using a fiber pair. However, since the signal and LO components are transmitted over physically different fiber channels, it is technically challenging to exactly adjust the path mismatch between the two paths. Recent studies have shown that such a path mismatch induces larger phase noise and thus deteriorates the system performance [2,3].

On the other hand, this path mismatch issue can be solved by polarization-multiplexing the LO and transmitting it together with the signal component over the same fiber channel. Then, a Stokes-vector receiver (SVR) is used to detect this polarization-multiplexed signal and reconstruct the original IQ components through a 2×3 multi-input-multi-output (MIMO) process [4]. While such SVRs have been implemented using off-the-shelf bulky components in many demonstrations [5], fully integrated silicon photonic SVR has also been reported to enable drastic reductions in size and cost [6]. To split the dual-polarization components inside a silicon chip, the conventional SVR employed a mode-selective directional coupler (DC). However, such mode-selective DC generally suffers from a strict fabrication tolerance and a strong wavelength dependence. In addition, the inherent asymmetric structures of the DC itself and the entire circuit inevitably break the balance among different paths inside the chip that is necessary to minimize the penalty.

In this paper, we propose and experimentally demonstrate a silicon photonic SVR based on fully symmetric waveguides. Unlike the conventional SVR, the DC is replaced with a symmetric mode-independent splitter to extract the linear superpositions of the X and Y polarization components of the input signal. As a result, the entire device functions as an SVR with its basis rotated on the Poincaré sphere. Since such unitary transformation of the polarization basis is automatically removed by the MIMO, it has no impact on the system performance. On the other hand, owing to the symmetric layout without DC, it is inherently fabrication-tolerant and assures automatic balances of the optical power and the path lengths inside the chip. We fabricate the proposed SVR on a silicon-on-insulator (SOI) platform and successfully demonstrate 30-Gbps 64-QAM self-coherent transmission over a 25-km single-mode fiber (SMF).

2. Device concept and design

Figure 1(a) illustrates the schematic of the conventional SVR. A and B represent the X and Y polarization components of the input signal, which excite the TE0 and TM0 modes (denoted as A_{TE0} and B_{TM0}) at the input of the chip, respectively. Inside the adiabatic mode converter, the width of a silicon rib waveguide is tapered gradually so that it maintains TE0 unchanged while converting TM0 to TE1 (denoted as B_{TM1}) [7]. Then, the TE1 mode is selectively coupled to the TE0 mode (B_{TE0}) and extracted by a mode-selective DC. By mixing A_{TE0} and B_{TE0} inside the TE-mode 90° hybrid, S_2 and S_3 Stokes components are retrieved [6].

In contrast, Fig. 1(b) shows the concept of the symmetric SVR proposed in this work. The mode-selective DC is replaced with a symmetric mode-independent splitter. As a result, A_{TE0} is split equally with the same polarities, while B_{TE1} is split with the opposite polarities due to the odd symmetry of the TE1 mode profile. Therefore, the optical fields at the two output ports can be written as $E_1 \propto A + Be^{i\theta}$ and $E_2 \propto A - Be^{i\theta}$, where the factor $e^{i\theta}$

accounts for any phase retardance between the two modes inside the chip. When $\theta = m\pi$ (m: integer), E_1 and E_2 are represented as $A \pm B$, which corresponds to the $\pm 45°$ linear polarization components of the input signal. More generally, for an arbitrary θ, the input signal is split with respect to an orthonormal basis, defined by two orthogonal states of polarization (SOPs) on the S_2-S_3 plane of the Poincaré sphere. Then, the full Stokes components are retrieved with respect to this basis. It should be emphasized that this unitary transformation of the polarization basis merely rotates the reference axes in the Stokes space and has no impact on the system performance. Unlike the conventional SVR in Fig. 1(a), the proposed symmetric SVR has an intrinsic advantage that the optical powers at the balanced photodetectors (PDs) and the path length matching before the 90° hybrid are automatically satisfied.

Figure 2 describes the mode-independent splitter designed in this work. The optimal design (Fig. 2(a)) is obtained using the particle swarm optimization (PSO) algorithm so that both TE0 and TE1 modes are split equally with minimal losses. Figures 2(b) and (c) show the simulated electric field distributions for both modes. Figure 2(d) shows a scanning electron microscope (SEM) image of the actual fabricated device. The entire dimension of the splitting section is 1.5 μm × 2 μm, which is more compact compared with a mode-selective DC.

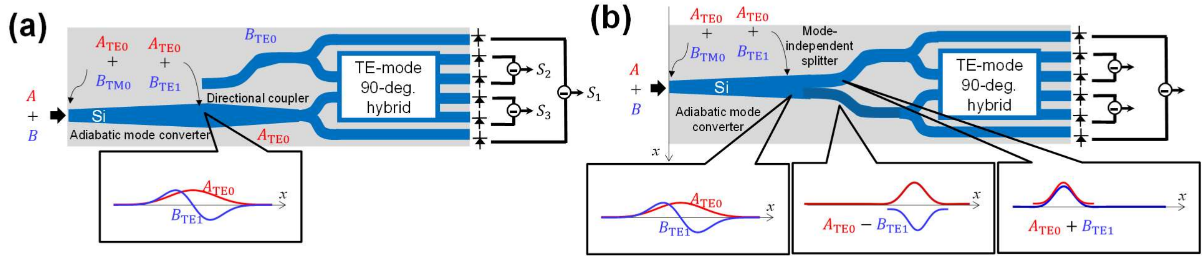

Fig. 1: Schematics of (a) the conventional SVR and (b) the proposed SVR. (For convenience of explanation, a special case where θ=0 is assumed in the insets.)

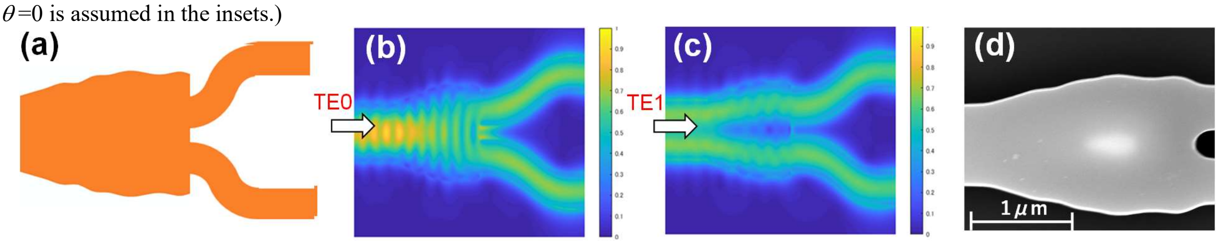

Fig. 2: Mode-independent splitter: (a) Schematic, (b, c) simulated field distributions, and (d) the SEM image of the actual fabricated device.

3. Experiments

3.1 Si photonic SVR

The designed SVR was fabricated by an 8-inch SOI multi-project wafer foundry service. Figure 3(a) shows the top photograph of the silicon photonic SVR. The two outputs from the mode-independent splitter are divided by 1x2 multimode interference (MMI) couplers. One of them is guided to a 2×4 MMI (90° optical hybrid) and mixed with the other input. Then, all six paths are guided to Ge PDs.

3.2 Static characterization

We first characterized the static performance of the device. The experimental setup is shown in Fig. 3 (b). (The setup used for this static characterization is enclosed in the parentheses.) A continuous-wave (CW) light at 1550 nm from a laser diode (LD) is launched to the device after controlling its SOP by a combination of a polarizer (POL), a half-wave plate (HWP), and a quarter-wave plate (QWP). Then, the Stokes parameters were calculated by subtracting the photocurrents of each PD pair. Figure 4(b) shows the measured Stokes vectors by our SVR when we rotate the input Stokes vector on the S_2-S_3 plane (the red ring shown in Fig. 4(a)) and on the S_1-S_3 plane (the blue ring shown in Fig. 4(a)). We can confirm that the two orthogonal rings in the Stokes space are detected as expected. The fixed rotation of these rings, which is due to the polarization change at the input fiber pigtail and the nonzero phase retardance (θ) inside the chip as explained in Section 2, can be compensated for by the digital signal processing (DSP).

3.3 30-Gb/s 64-QAM signal transmission experiments

Next, we conducted transmission experiments. On the transmitter side, we split the optical signal into two paths: one was for the signal path and the other was for the LO path. At the signal path, a 30-Gb/s (5-Gbaud) 64-QAM optical signal was generated and polarization-multiplexed with the unmodulated signal from the LO path. We should note that the baudrate in these experiments was limited by the electrical bandwidth of the 6-channel real-time oscilloscope (Keysight MXR608A) and not by the SVR. Then, the optical signal was transmitted over a 25-km single-mode fiber (SMF) with a launched power of +10 dBm. On the receiver side, the received optical power was controlled using a variable optical attenuator (VOA) and amplified using an erbium-doped fiber amplifier (EDFA) before input to the silicon chip. The six electrical outputs from the PDs were simultaneously captured using the 6-channel real-time digital oscilloscope and processed by offline DSP. It should be noted that balanced-detection circuits would halve the number of ADC ports but we directly captured all outputs from the six single-ended PDs due to experimental restrictions. To equalize and reconstruct the IQ signals, we employed a 2×6 MIMO equalizer at the offline DSP. Finally, we measured the BER performance.

Figure 4(c) shows the results with an inset showing a 64-QAM constellation. We also plot a BER curve in a back-to-back (B2B) state (the blue curve) for comparison. The 64-QAM signal was successfully transmitted over 25 km and retrieved using the SVR with a negligible power penalty from the B2B state. A BER below the threshold of a 7% HD-FEC code was achieved.

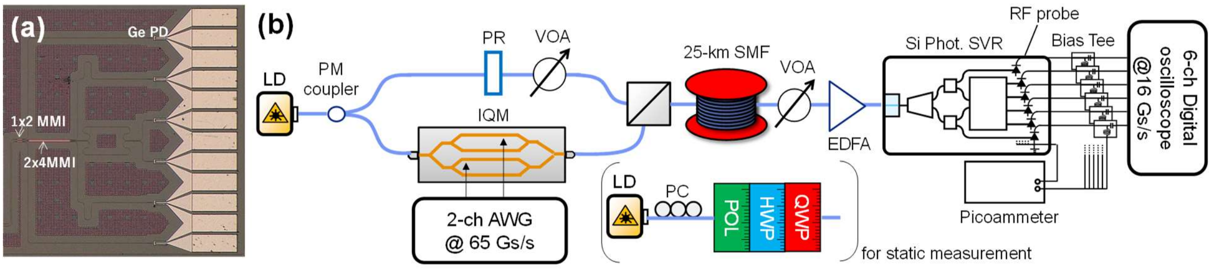

Fig. 3: (a) Image of the silicon SVR and (b) the experimental setups.

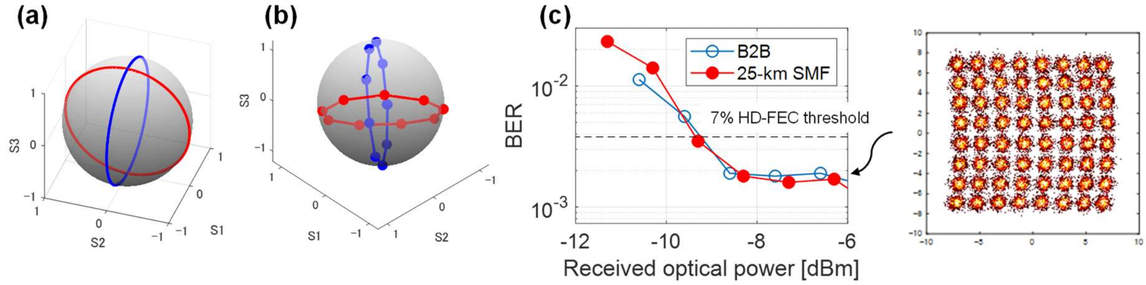

Fig. 4: (a) Transmitted Stokes vectors, (b) measured Stokes vectors, and (c) the results of the transmission experiment.

4. Conclusions

We have proposed and demonstrated a novel silicon photonic SVR based on fully symmetric waveguides. Unlike the conventional SVR that requires a complicated asymmetric mode-selective DC, it has inherent advantages to minimize the path imbalance and to reduce the fabrication and wavelength sensitivities. A compact SVR was fabricated on an SOI platform to demonstrate 30-Gbps 64-QAM self-coherent transmission over a 25-km SMF, where the baudrate was merely limited by the electrical bandwidth of the available 6-channel oscilloscope.

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5. References

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