PPLN-Based Polarization-Diverse Phase-Sensitive Amplification of 96-Gbaud PDM-PCS-64QAM Signal with Carrier-Phase-Locked Phase-Conjugated Twin Waves

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Abstract: We demonstrated non-degenerate phase-sensitive amplification (PSA) of a 96-Gbaud PDM-PCS-64QAM signal. Phase-conjugated twin waves (PCTWs) with a polarization-independent carrier phase provided low-noise PSA of a 2.5-dB black-box noise figure without polarization tracking of the PCTWs.

1. Introduction

In optical transmission systems using optical amplification, the noise of the optical amplifiers is one of the dominant factors in determining the received signal quality. Phase-insensitive amplification (PIA), e.g., by an erbium-doped fiber amplifier (EDFA), has a lower limit for the noise figure (NF) of 3 dB. Meanwhile, phase-sensitive amplification (PSA) using optical parametric amplification (OPA) can break this limit, theoretically achieving a NF of 0 dB [1]. Highly sensitive signal receiving techniques using PSA have been studied for free-space optics (FSO) systems [2] as well as for fiber-optic transmission systems [3]. Especially, non-degenerate PSA (ND-PSA) has attracted much attention owing to its ability to amplify higher-order QAM and wavelength-division-multiplexing (WDM) signals [2–4]. In transmission systems using ND-PSA, the signal-idler pair, namely phase-conjugated twin waves (PCTWs), generated by optical phase conjugation (OPC) via OPA at the transmitter side are coherently combined by OPA at the receiver side. Recently, a one-photon-per-bit receiver using $\chi^{(3)}$-based PSA was demonstrated for 10-Gbps FSO applications with a single-polarized QPSK signal [2]. Also reported was PSA of a single-polarized 16QAM signal with a 1.0-dB NF by using a periodically poled $LiNbO_3$ (PPLN) waveguide as a $\chi^{(2)}$-medium [5]. However, due to the polarization sensitivity of the OPA process, realization of polarization-independent (PI) PSA of a polarization-division-multiplexed (PDM) signal remains a major challenge.

$\chi^{(3)}$-based vector PSA [6] and polarization-diverse (PD) PSA [7] have been demonstrated for achieving PI-PSA. However, these PSA methods cannot be used when there is a polarization misalignment between the PCTWs, e.g., due to the wavelength-dependent birefringence in long-haul fiber transmission. A theoretical study has shown that PI-PSA of a PDM signal can be accomplished by tracking the state of polarization (SOP) of the idler component, but this requires that the PCTWs have a PI carrier phase [8]. A polarization-dependent carrier phase makes a polarization control of the PCTWs at an input of a PSA stage essential due to SOP rotation in links, even if the PCTWs have a uniform SOP. Recently, we proposed a PPLN-based PD-OPC stage with three optical phase-locking loops (PLLs), which generates PDM-PCTWs with a PI phase-locked carrier component [9]. In this paper, by using this OPC stage, we demonstrate the stable PPLN-based PD-PSA of a 96-Gbaud PDM probabilistically constellation-shaped (PCS) 64QAM signal under the condition of uniform SOP within the PCTWs.

2. Proposed PSA scheme with generation of carrier-phase-locked PDM-PCTWs

Our OPC stage is based on PD-OPA like in a Mach-Zehnder interferometer (MZI). In the MZI configuration, phase drifts occur between each MZI arm and between the pump and signal, resulting in a polarization-dependent carrier phase in the PDM-PCTWs. The proposed OPC stage achieves a PI carrier phase in the generated PDM-PCTWs by compensating for these phase drifts with three PLLs controlled by two pilot lights propagating forward and backward and phase dithering [9]. Figure 1(a) shows the experimental setup of the proposed OPC stage based on PPLN-based OPA. The $\chi^{(2)}$-based OPA requires second-harmonic (SH) light at twice the degenerate frequency as the pump light. We used a two-stage OPA, in which the first stage has a different media as an SH generator (SHG) for pump conversion than that of second one for OPA [5]. For OPA, we used a 4-port PPLN module, in which dichroic mirrors for pump (de-)combining and a PPLN waveguide are integrated [5]. The degenerate frequency of the PPLN waveguide was 194.00 THz. The backward pilot at 194.05 THz was inserted from the output port of the OPC stage with a ~45° linear polarization and then extracted at the input port using optical circulators. At 45° polarization of the extracted pilot, an interference pattern indicating the phase difference between the two arms of the MZI could be observed.

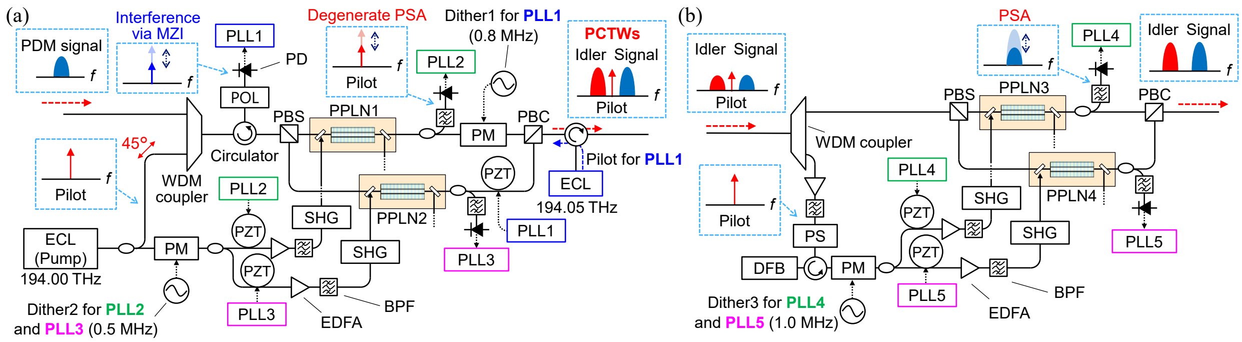

Fig. 1. Experimental setup of (a) proposed PD-OPC stage and (b) PD-PSA stage. ECL: external cavity laser, DFB: distributed feedback laser, BPF: bandpass filter, POL: polarizer, PBS/PBC: polarization-beam splitter/combiner, PM: phase modulator, and PS: polarization stabilizer.

PLL1 controlled the piezoelectric transducer-based phase shifter (PZT) in the MZI to compensate for this phase difference. The forward pilot was generated by splitting the pump light at 194.00 THz (master laser) and combining it with the PDM signal with a WDM coupler. The linewidth of the master laser was ~2 kHz. While the PCTWs were generated in the PPLN, the pilot interfered with its idler generated at the same frequency, resulting in degenerate PSA. The gain of the degenerate PSA depended on the relative phase difference between the pump and pilot. PLL2 and PLL3 controlled the PZTs in the pump lines to maximize the degenerate PSA gain at each arm by utilizing the phase dither modulated into pumps. Since the relative phase between the pilot and pump was fixed, the carrier phase of the PCTWs, which is determined by the relative phase difference between the signal and pump, was also fixed. Since the relative phase difference between the MZI arms was compensated for by PLL1, the PDM-PCTWs with a PI carrier phase were obtained at the output of the PBC. The forward pilot can be used for pump recovery in the PSA stage.

Figure 1(b) shows the setup of the PD-PSA stage [7]. The pilot was first separated from the PCTWs with a WDM coupler and input to a pump recovery section based on optical injection locking (OIL). The pilot was stabilized to the TM polarization by using an automatic polarization stabilizer and input to a slave laser via a circulator for OIL. The PDM-PCTWs were divided into orthogonal polarization components with a PBS and then amplified in PPLN waveguides with phase-locked pumps. The PCTWs were superposed in the OPA process, and thus, phase-sensitively amplified. To achieve maximum PSA gain, the relative phase between the carrier component of the PCTWs and pump must be adjusted. This phase adjustment was accomplished by monitoring the optical power of the amplified signal component and controlling the PZT allocated in each pump line by PLL4 and 5. Here, if the carrier phase of the PDM-PCTWs is polarization dependent, the input SOP of the PCTWs to the PBS must be controlled so that the carrier phase is uniquely determined at each PPLN. Our OPC stage eliminates this process and allows any SOP to be input to the PD-PSA stage. Note that, if the signal and idler SOPs are rotated independently due to long-haul propagation through a birefringent transmission line such as optical fibers, polarization control of one of them is required [8].

3. Demonstration of polarization-diverse PSA with 96-Gbaud PDM-PCS-64QAM signal

Figure 2(a) shows the experimental setup for the proof-of-concept of the proposed PSA scheme. The 96-Gbaud PDM-PCS-64QAM optical signal at 194.15 THz was generated using an I/Q modulator and a polarization-division-multiplexing emulator (PDME) with a 15-m delay between orthogonal polarization components, and its entropy was 10.57 bits. The signal was input to the OPC stage at 1.5 dBm. The optical power at the output of the OPC-stage was 15.7 dBm, including the idler and pilot for OIL. The pilot's contribution to the total power was 0.2 dB. The pump light was input to each SHG at ~1.9 W. The PCTWs passed through the spatial light modulator (SLM), which could control the chromatic dispersion (CD). For achieving broad PSA, the CD of the PCTWs was pre-compensated for on the order of sub-ps/nm, and it was almost zero at the input of the PSA stage [10]. The SLM could also eliminate the phase-conjugated idler component, in which case the PSA stage operated just as an optical parametric amplifier, i.e., PIA operation. The input power to the PD-PSA stage (received power, P_r) was controlled by a variable optical

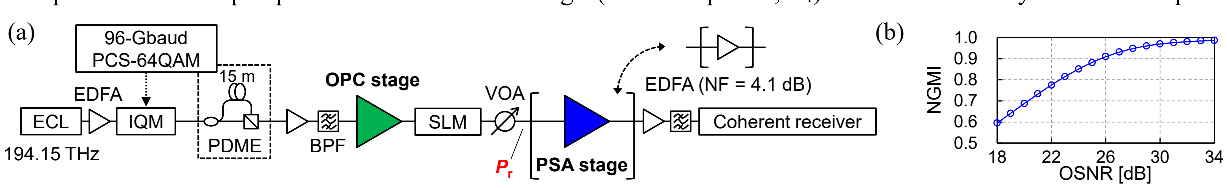

Fig. 2. (a) Experimental setup. ECL: external cavity laser, IQM: I/Q modulator, PDME: polarization-division-multiplexing emulator, SLM: spatial light modulator, and VOA: variable optical attenuator. (b) NGMI characteristics of Tx/Rx for OSNR (noise bandwidth: 0.1 nm).

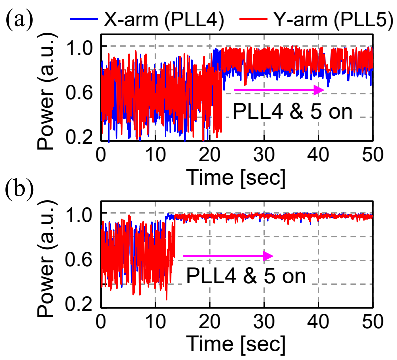

Fig. 3. Monitored power of each polarization arm in PSA stage (a) without carrier-phase locking and (b) with carrier-phase locking.

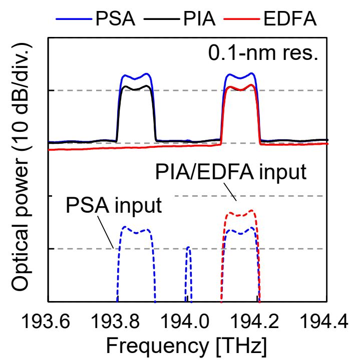

Fig. 4. Optical spectra of 96-Gbaud PDM-PCS-64QAM signal amplified by PSA, PIA, and EDFA at −34-dBm input.

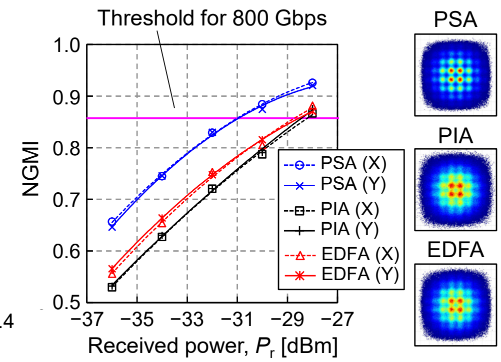

Fig. 5. NGMI as function of received power and constellation diagram in each case at −30 dBm.

attenuator. The SOP of the PCTWs was uncontrolled and free-running. In the PIA case, the split master laser was also used as the pump in the PSA stage. The pump power input to each SHG in the PSA stage was ~3.7 W. The PCTWs output from the PSA stage was amplified by the EDFA, and only the signal component was extracted. Finally, the signal was received and digitized by a coherent receiver with four 70-GHz balanced photodetectors and a 256-GS/s digital oscilloscope. The received signal was recovered by an 8×2 adaptive equalizer [11], and its normalized generalized mutual information (NGMI) was calculated. The net bit rate was 800 Gbps with an NGMI of >0.857 [11]. Figure 2(b) shows the optical signal-to-noise ratio (OSNR, noise bandwidth: 0.1 nm) versus NGMI measured in a back-to-back configuration where the transmitter and receiver are directly connected. For comparison with an EDFA, the same measurement was performed but with the PSA stage replaced with an EDFA (NF: 4.1 dB).

Figure 3 shows the monitored optical power of each polarization arm in the PD-PSA stage which indicates PSA-gain fluctuation. Without carrier-phase locking by PLLs 1–3, the PSA gain fluctuated due to phase drifts in the OPC stage and SOP rotation, even if PLL4 and 5 were operated to stabilize the PSA gain. Note that, in the case without carrier-phase locking, the pump in the OPC stage was split and used as the pump in the PSA stage (i.e., master laser pumping [5]) because the OIL could not be used without operating PLLs 1–3. In contrast, with carrier-phase locking and OIL, the PSA gain was stably locked at the maximum gain when PLL4 and 5 were operated. Figure 4 shows the optical spectra amplified by PSA, PIA, and EDFA at −34-dBm input. The PSA input consisted of the signal, idler, and pilot. The gains of PIA and PSA in the signal component were 23.9 dB and 29.4 dB, respectively. The noise floor of the PIA output was higher than that of the EDFA output by ~0.7 dB. Therefore, the NF of the PIA was estimated to ~4.8 dB, including the loss of the WDM coupler (0.4 dB) and PBS (0.8 dB). The signal and idler powers of the PSA output were higher than those of the PIA output by ~2.3 dB. Thus, from the measured spectra, the black-box NF of the PSA was estimated to be 2.5 dB, including a power penalty of 0.2 dB for the pilot light. Figure 5 shows the NGMI of the received signal as a function of the received power. We can see that the PSA improves the received power required to achieve 800 Gbps by ~2 dB compared with the EDFA case. Since the propagation loss in FSO links is quadratic with reach, the 2-dB improvement in receiver sensitivity can increase the reach by ~1.26 times. The above results demonstrate that the carrier-phase-locked PDM-PCTWs generated with the proposed OPC stage can realize stable and low-noise PSA independent of the input SOP to the PSA stage.

4. Conclusion

We demonstrated PD-PSA of a 96-Gbaud PDM-PCS-64QAM signal with a 2.5-dB black-box NF by using a carrier-phase-locked PCTWs generated by OPC with three PLLs. The proposed scheme provided stable PSA of a PDM signal without controlling the input SOP to the PSA stage under the condition of uniform SOP within the PCTWs.

5. References

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