Investigation of Polarization-Insensitive Phase Regeneration Using Polarization-Diversity Phase-Sensitive Amplifier

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Abstract *We investigate a polarization-diversity PSA for polarization-insensitive phase regeneration of single- and dual-polarization phase modulation formats. We show effective reduction on phase noise insensitive to signal's polarization by simulations and preliminarily verify this PSA by experiments.*

Introduction

To meet growing demands on network capacity and reach, advanced modulation formats with high spectral efficiency become increasingly important. Phase modulation formats, such as binary and quadrature phase-shift keying (BPSK and QPSK), have been shown to provide better robustness to fiber nonlinearities and transmission performance as compared to other formats. Coherent detection based dual-polarization (DP) QPSK has been adopted in 100G systems. Phase modulation format may be a preferred candidate for next-generation 400G and 1T systems. However, deleterious phase noise still imposes strict requirements on the system designs for further extending the maximal reach of phase modulation formats[1].

To suppress phase noise, several methods have been reported using digital signal processing (DSP) or optical signal processing[2-10]. DSP's complexity greatly increases with data rate and interactions between phase noise and other impairments. As compared to DSP-assisted OEO regenerator placed in the receiver side, optical regenerator that can be placed either in the mid-link or in the receiver side becomes beneficial. Most recently phase-sensitive amplifier (PSA) has been shown to provide high gain with low noise figure, and broadband phase and amplitude regeneration function[3-10]. PSA may become an effective solution to suppressing phase noise. Single- and dual-pump non-degenerate PSA and dual-pump degenerate PSA have been successfully demonstrated for single-polarization (SP) BPSK and QPSK. However, PSA's performance is highly sensitive to signal's state of polarization.

Here we investigate a polarization-diversity PSA structure employing bi-directional four-wave mixing (FWM) on orthogonal polarizations separately. We show that phase noise can be effectively squeezed using this PSA, which is less sensitive to signal's state of polarization. This polarization-diversity PSA can support both of SP- and DP- phase-modulated signals.

Concept and Operation Principle

Conventional dual-pump degenerate PSA, as shown in Fig. 1(a), uses a straight HNLF to perform FMW and thus phase regeneration. Pump1 and pump2 need be phase-locked to the signal using one wavelength-conversion stage and one injection-locked laser before the PSA stage[6]. Polarization alignment between signal and two pumps needs to be matched to achieve maximal phase regeneration. Regeneration effect may vanish greatly as large misalignments occur. Signal's polarization can drift slowly due

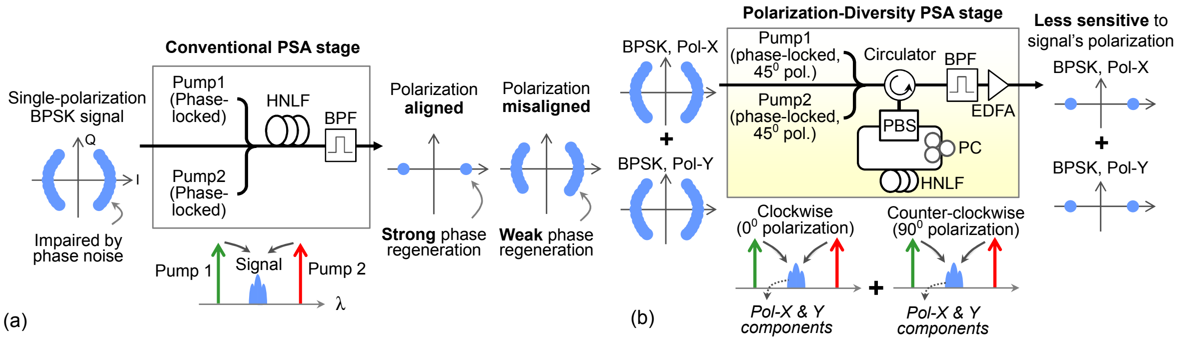

Fig. 1: (a) Conventional dual-pump degenerate PSA using a straight HNLF: phase regeneration effect varies with polarization alignment between BPSK signal and two phase-locked pumps. (b) Polarization-diversity PSA for regenerating SP- or DP-BPSK signal: phase regeneration effect can be less sensitive to signal's state of polarization since signal is split into orthogonal polarizations and regenerated separately.

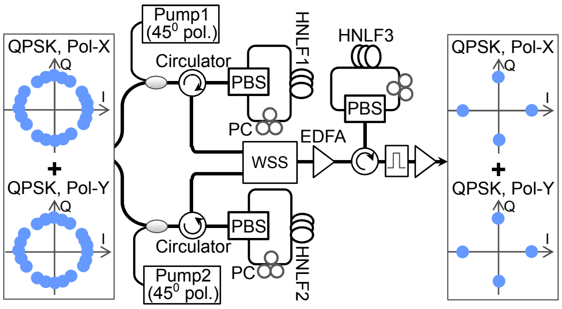

Fig. 2: Polarization-diversity PSA for regeneration of SP- or DP-QPSK, consisting of two polarization-diversity wavelength-conversion stages (HNLF1 and HNLF2) for generating two conjugate pumps and one polarization-diversity PSA stage (HNLF3).

to environmental conditions (e.g., fluctuation or temperature) or change rapidly due to the polarization scrambling applied to mitigate fiber nonlinearities in fiber. As a result, conventional PSA may have limited applicability to any polarization-varying signal.

To overcome such issue, a polarization-diversity HNLF loop is used in PSA stage, as shown in Fig 1(b). Note that the polarization-diversity structure has been demonstrated for polarization-insensitive wavelength conversion, amplification and so forth[11]. The polarization of Pump1 and Pump2 is fixed to 45^0 into a polarization beam splitter (PBS) that has fixed 0^0 and 90^0 orthogonal axes. Regardless of BPSK

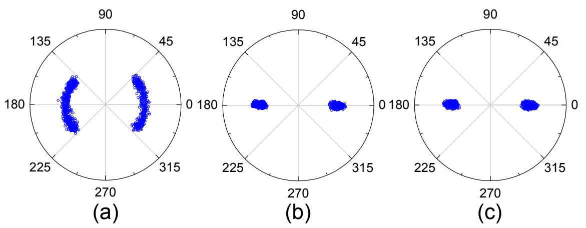

Fig. 3: Simulated constellation: (a) SP-BPSK without PSA; (b) regenerated SP-BPSK with 0^0-polarization into PSA; (c) regenerated SP-BPSK with 45^0-polarization into PSA.

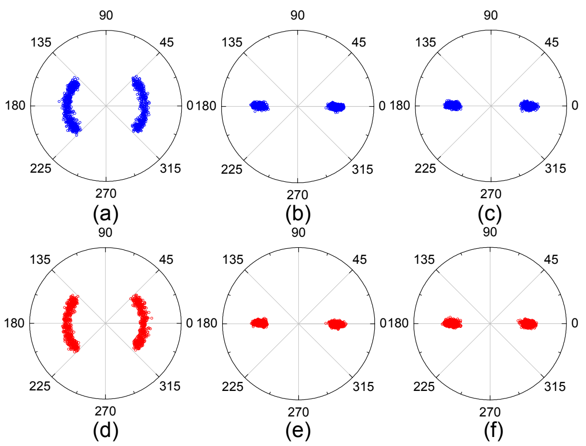

Fig. 4: Simulated constellation of DP-BPSK: (a) Pol-X without PSA; (b)(c) regenerated Pol-X with 0^0-pol. and 45^0-pol. into PSA; (d) Pol-Y without PSA; (e)(f) regenerated Pol-X with 0^0-pol.and 45^0-pol. into PSA.

signal's polarization, the signal can be split into orthogonal polarizations, mixed with two pumps in HNFL bi-directionally, regenerated separately, and then recombined. Owing to such unique operation, this polarization-diversity PSA may be also applicable to DP-BPSK. As shown in Fig. 2, it can be used in our proposed PSA structure[10] to enable polarization-insensitive regeneration of SP- and DP-QPSK. The first two diversities are used to generate two locked conjugate pumps and the third diversity is used for regeneration in a polarization-insensitive fashion.

Results and Discussions

First we investigated this polarization-diversity PSA (Fig. 1(b)) for SP-BPSK by simulation using VPI. 25Gbaud SP-BPSK signal was set to 193.54THz frequency, 100KHz linewidth, 35dB OSNR, -2.5dBm power, and phase noise of ~90^0 distribution. Each pump was set to 100KHz linewidth, 45^0 polarization with respect to PBS, power of 26dBm, and spacing of 700GHz symmetrically adjacent to signal. HNLF was set to 600m length, 3dB loss, nonlinear coefficient of $9.2W^{-1}\cdot km^{-1}$, zero dispersion wavelength (ZDW) around 1550 nm and dispersion slope of $0.018ps/km/nm^2$. Note that stimulated Brillouin scattering (SBS) effect in HNLF is not included in simulation. At PSA's output, SP-BPSK signal was filtered, amplified to a fixed power of 3dBm, and sent to a coherent receiver for signal performance evaluation. To determine phase regeneration effect solely enabled by PSA, no phase correction algorithm was used.

Fig. 3(a) shows the non-regenerated SP-BPSK signal (before PSA), whereas the phase noise was distributed ~90^0. In contrast, Fig. 3(b) and 3(c) show regenerated SP-BPSK with 0^0-polarization (i.e., best case) and 45^0-polarization (i.e., worst case) into PSA, indicating effective phase regeneration insensitive to SP-BPSK's polarization. The amplitude noise on the regenerated signal increases slightly due to

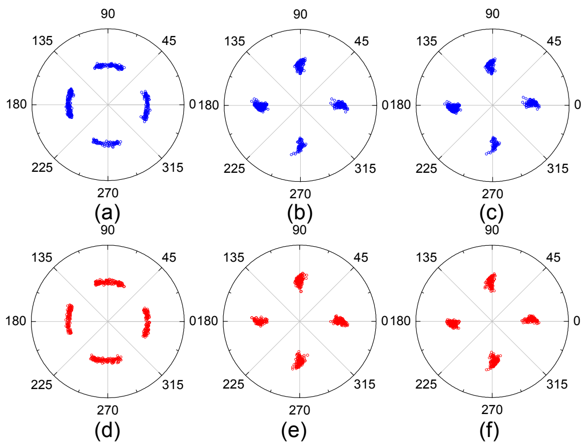

Fig. 5: Simulated constellation of DP-QPSK: (a) Pol-X without PSA; (b)(c) regenerated Pol-X with 0^0-pol. and 45^0-pol.into PSA; (d) Pol-Y without PSA; (e)(f) regenerated Pol-X with 0^0-pol. and 45^0-pol. Into PSA.

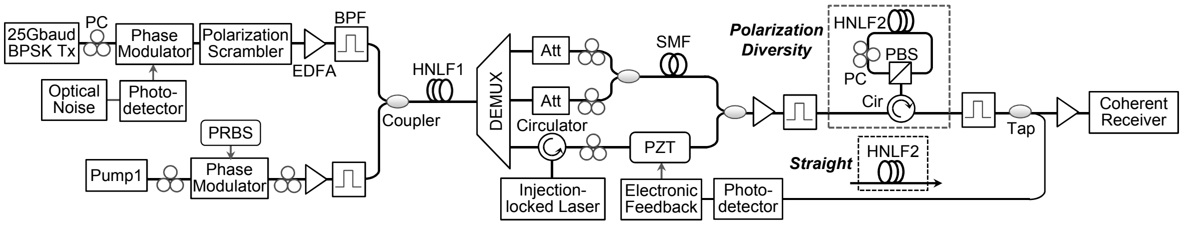

Fig. 6: Experimental setup for phase regeneration of SP-BPSK signal: both of a polarization-diversity PSA and a conventional PSA (i.e., straight HNLF) were demonstrated for comparisons.

inherent phase-to-amplitude conversion in PSA. Fig. 4 further shows this polarization-diversity PSA is applicable to DP-BPSK. To further investigate its applicability to DP-QPSK, the PSA structure shown in Fig. 2 was utilized. The length of HNLF1 and HNLF2 is 200m while the length of HNLF3 is 520m. The other parameters are the same as the HNLF used in SP/DP-BPSK case. Fig. 5 shows this polarization-diversity PSA can be applicable to DP-QPSK.

Fig. 6 illustrates the preliminary experimental setup used for verifying PSA performance. 25-Gbaud/s SP-BPSK was operated at 1557.44nm. A phase modulator driven by noise source added phase noise on the signal. A polarization scrambler operated at 20GHz rotated signal's polarization. Pump1 at 1559nm was phase modulated by a low-rate random data to suppress SBS effect. Signal and Pump1 were amplified and then sent through HNLF1 (100m length, nonlinear coefficient of $11.5W^{-1}\cdot km^{-1}$, dispersion slope of $0.016ps/km/nm^2$ at 1550nm, and ZDW around 1558nm) to generate an idler. One AWG was used to demux signal, Pump1 and idler. The idler generated at 1555.88nm was recovered by an injection-lock laser (i.e., phase-locked Pump2), and a PZT was used to mitigate the slow phase variation. Consequently, signal, Pump1, and Pump2 were amplified and then sent through HNLF2 (300m length, nonlinear coefficient of $11.5W^{-1}\cdot km^{-1}$, dispersion slope of $0.016ps/km/nm^2$ at 1550nm, and ZDW around 1560nm), which was operated in straight and polarization-diversity configurations. Finally, the output signal was sent to a coherent receiver for signal performance evaluation.

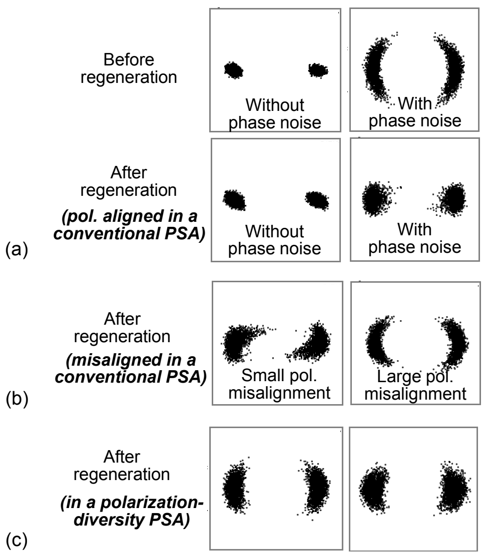

Fig. 7: Measured constellations: (a) w/o & w/ phase noise before & after regeneration; (b) regeneration using conventional PSA is sensitive to polarization alignment; (c) regeneration at two polarizations using polarization-diversity PSA is less sensitive to signal's polarization, in which improved squeezing effect can be expected by increasing the PSA gain.

Fig. 7(a) and 7(b) show the measured constellations using a conventional PSA. Effective regeneration can be achieved only if the polarization alignment between the signal and two pumps is maintained. As polarization was changed, phase regeneration became very sensitive to signal's polarization. In contrast, Fig. 7(c) shows the preliminary results of a polarization-diversity PSA. The sensitivity to signal's polarization was reduced as compared to a conventional PSA (Fig. 7(b)). The resultant phase squeezing effect is not high enough due to the limitation on maximal gain of EDFA in use and the insertion loss of polarization diversity. We may expect the improvement by further optimizing this system.

Conclusions

A polarization-diversity PSA was investigated by simulation and preliminary experiment to verify polarization-insensitive phase regeneration. We showed that phase noise can be effectively squeezed less sensitive to signal's polarization. This PSA is applicable to both single- and dual-polarization phase modulation formats.

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