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Phase Sensitive Amplifier Using Periodically Poled $LiNbO_3$ Waveguides and Their Applications*

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SUMMARY Recent advances in phase-sensitive amplifiers (PSAs) using periodically poled $LiNbO_3$ are reviewed. Their principles of operation and distinct features are described. Applications in optical communication are studied in terms of the inline operation and amplification of a sophisticated modulation format. Challenges for the future are also discussed.

key words: *optical amplifier, lithium niobate, quasi-phase marching, optical communication*

1. Introduction

The capacity of optical communication has continued to grow in recent years, which has enabled various communication services. This growth has been enabled by several innovative technologies, such as laser diodes, optical fibers, and optical amplifiers. According to Shannon's theory, the maximum spectral efficiency is given as $\log_2(1+SNR)$ [1]. A high signal-to-noise ratio (SNR) is required to realize high spectral efficiency. In principle, the SNR in optical communication is proportional to the optical power. In real systems, however, the SNR is limited and could be degraded as the input power to the transmission fiber is increased. This is due to the interaction between the nonlinearity of the optical fiber and the optical noise generated in optical amplifiers. This phenomenon is called the nonlinear Shannon limit, and it potentially limits the capacity in optical communications [2]. Therefore, it is desirable to improve the SNR by either reducing the noise without increasing the input power or reducing nonlinear noise.

The phase-sensitive amplifier (PSA) is of particular interest because it has the potential to mitigate the noise in optical communication systems. It is known that the noise figure of conventional phase-insensitive amplifiers (PIAs), such as the erbium-doped fiber amplifier (EDFA), cannot be improved to below the 3-dB quantum limit [3]. On the other hand, the quantum-limited noise figure (NF) of the PSA is 0 dB, thus making it capable of reducing the intensity of noise [4]. In addition, utilizing the phase dependent gain, PSAs are capable of squeezing the phase noise of an input signal [5].

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In this paper, we review recent advances in PSA using periodically poled $LiNbO_3$ (PPLN) waveguide and their applications.

2. Principle of Operation

A PSA is defined as an amplifier that exhibits phase-dependent gain. The principle of the PSA is analogous to the coherent detection of electrical signals, or a phase-sensitive detector (PSD) using the heterodyne technique. Figure 1 illustrates the conceptual diagram of PSDs and PSAs. In the PSD, the signal, modulated at frequency ω, and a local oscillator (LO) with frequency ω are input to a frequency mixer based on the nonlinear circuit, as shown in Fig. 1 (a). The mixer generates the sum frequency 2ω and a DC signal. The DC signal is extracted using a low-pass filter (LPF). Using this configuration, the signal amplitude is converted into a DC frequency and can be detected with high sensitivity. In the PSA based on second-order nonlinearity $\chi^{(2)}$, the LO is converted into the second harmonic (SH) 2ω using the first frequency mixer. The SH pump and signal with frequency ω are input to the second mixer in a degenerate PSA, as shown in Fig. 1 (b). In the mixer, the sum frequency (SF) 3ω and difference frequency (DF) ω are generated. Utilizing the quasi-phase matching (QPM) technique, which will be explained later, only the DF can be efficiently generated [6]. The frequency of the DF wave is the same as that of the input signal, such that the DF wave is coherently added to the signal. As a consequence, the signal is amplified or de-amplified depending on the relative phase between the pump and signal. Figure 1 (c) illustrates a non-degenerate PSA

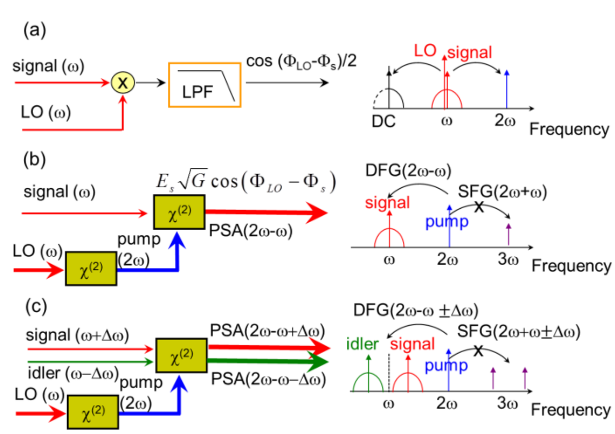

Fig. 1 Comparison between (a) PSD and (b), (c) $\chi(2)$-based PSAs

Table 1 Typical optical amplifiers

PIA (Stimulated Radiation)	PSA (Parametric frequency mixing)
EDFA SOA FRA	PPLN waveguide ($\chi^{(2)}$ media) HNLF ($\chi^{(3)}$ media)

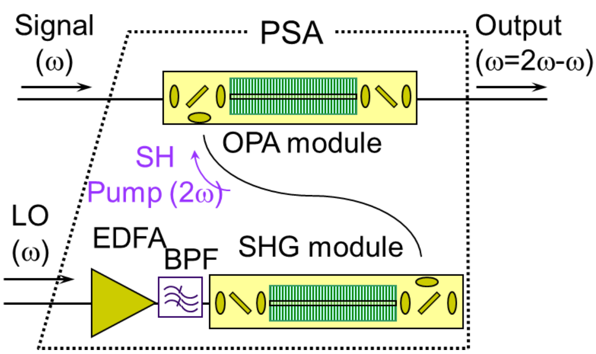

Fig. 2 Configuration of PPLN-based PSA

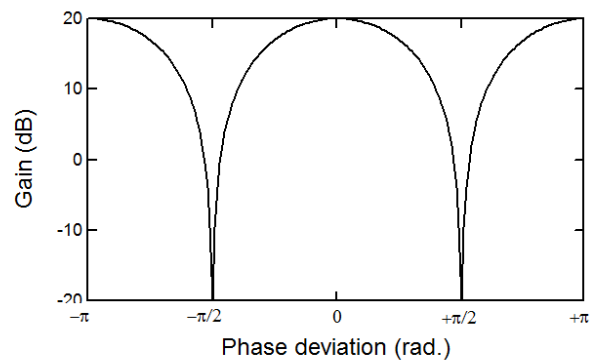

Fig. 3 Gain as a function of phase deviation

based on $\chi^{(2)}$ media. In this case, a signal with frequency $\omega + \Delta\omega$, an idler with frequency $\omega - \Delta\omega$, and an SH with frequency 2ω are input to the second mixer in a non-degenerate PSA. If the signal and idler have phase correlation, the DF between the idler and SH is coherently added to the signal, and the DF between the signal and SH is also coherently added to the idler. As a consequence, the signal and the idler are amplified by a parametric gain, which depends on the relative phase between the three interacting waves. In the real implementation of a PSA based on $\chi^{(2)}$ media, the SH wave can be also generated through the generation of the sum frequency of two phase-correlated LOs, as discussed in Sects. 4 and 5.

Table 1 summarizes currently available optical amplifiers. Conventional optical amplifiers based on stimulated radiation, such as the EDFA, semiconductor optical amplifier (SOA), and fiber Raman amplifier (FRA), are categorized as PIAs. On the other hand, a PSA can be constructed by using parametric frequency mixing using $\chi^{(2)}$ or $\chi^{(3)}$ media. PPLN waveguides and highly nonlinear fibers (HNLF) are used as typical $\chi^{(2)}$ and $\chi^{(3)}$ media, respectively.

Figure 2 shows the principle part of the PSA based on a PPLN waveguide [7]. To obtain phase-sensitive gain, we prepare an LO whose phase is locked to the carrier of the signal. To obtain sufficient power of SH, the LO is amplified using an EDFA. The LO is converted to the SH using the first PPLN waveguide. The SH and the signal are input to a second PPLN waveguide. Utilizing optical parametric amplification with the SH as a pump, the signal is amplified.

The key component in the PSA is efficient nonlinear optical media. We have been studying the fabrication of PPLN waveguides as efficient frequency mixers. PPLN have been developed to obtain an efficient laser wavelength converter. When two individual frequencies are input to a $\chi^{(2)}$ material, the SF and DF are generated. In general, the input frequency and the new frequency component propagate with different phase velocities, such that the phase of each component is not matched and the conversion efficiency is not high. However, the phase of the new component can be reversed by changing the direction of the spontaneous polarization of LiNbO$_3$. By using a periodically poled structure with a proper poling period, it is possible to compensate for the phase mismatch between the three interacting waves. A high conversion efficiency can be selectively obtained for a desired combination of three waves. This technique is called quasi-phase matching (QPM) [6]. The combination of a periodically poled structure and a waveguide enables us to obtain a high conversion efficiency. Many studies have been reported to achieve efficient wavelength conversion in the telecom wavelength range [8]–[11].

Many papers have reported PSAs using highly nonlinear fiber (HNLF) [4], [5], [12]. The advantages of a PPLN waveguide in comparison with HNLF are as follows. (1) Typically, 100-m–1-km long HNLF are used for PSAs [4], [5], [12]. In contrast, owing to its high second-order nonlinearity, sufficient gain can be expected using a relatively short PPLN waveguide, which is typically a few cm long [7]–[11]. (2) Owing to a lower third-order nonlinearity, the signal is not degraded by nonlinear phase modulation. (3) We can expect a potential for the integration of several functions on a chip. Several issues to be addressed are as follows. (1) Coupling loss between the optical fiber and PPLN waveguide should be minimized. (2) The SH pump wavelength is not compatible with standard telecom components. (3) Photorefractive damage to the PPLN waveguide may degrade amplification performance [13]. Because of these difficulties, PPLN-based PSAs have only been adopted in fundamental studies, such as the generation of squeezed light using a pulsed-laser light source [14]. To cope with these issues, we have developed a highly efficient PPLN waveguide module. We have employed direct-bonding and dry-etching techniques to fabricate a PPLN waveguide with high efficiency and high resistance to photorefractive damage [15]. We assembled the waveguide in a fiber pigtail module, which enables the coupling of the signal and SH pump individually [7]. Such advances on PPLN waveguides and their module packaging technology have allowed us to obtain a large parametric gain, even with CW operation, and enables us to explore PPLN-based PSAs for optical communications.

Figure 3 shows the gain of a degenerate PSA as a function of the relative phase difference between the signal and pump. The PSA amplifies only the in-phase component, and deamplifies the quadrature component. Using this characteristic, PSAs are capable of squeezing the phase noise of an input signal. Owing to the phase sensitive gain, the PSA generates a lower spontaneous emission than conventional phase insensitive amplifiers (PIAs). This characteristic allows us to implement low-noise amplification.

3. Low-Noise Characteristics

The noise characteristics of a PSA using degenerate parametric interactions were studied thoroughly in the 1990s, considering the use of HNLF [4]. The average photon number $\langle n_{out} \rangle$ in the output of ideal PSAs and PIAs are given by following equations.

$$\text{PSA:} \quad \langle n_{out} \rangle = G\langle n_{in} \rangle + \frac{1}{4}\left\{(G-1) + \left(\frac{1}{G} - 1\right)\right\} \tag{1}$$

$$\text{PIA:} \quad \langle n_{out} \rangle = G\langle n_{in} \rangle + (G-1)n_{sp}m, \tag{2}$$

where G is the gain, $\langle n_{in} \rangle$ is the input photon number, n_{sp} is the spontaneous emission coefficient, and m is number of polarization modes. The first term denotes the amplified signal, and the second term denotes the amplified spontaneous emission (ASE).

Figure 4 shows a schematic diagram of complex electrical fields in the output of PIA and PSA. In PIA, SNR at the output is degraded by the interference between the amplified signal and excessive spontaneous emission, as shown in Fig. 4 (a). In a PSA, the power of the in-phase spontaneous emission is half that of a PIA, and the quadrature component is negligible, as shown in Fig. 4 (b). As a consequence, the interference between the amplified signal and the excessive spontaneous emission is suppressed. This means that the PSA generates minimal spontaneous emission noise, but the SNR at the input is preserved at the output. If we compare PSAs and EDFAs, a PSA amplifies only one polarization mode, whereas an EDFA amplifies the two polarization modes. This comparison indicates that the total ASE power of the PSA is 9 dB less than that of the EDFA.

Figure 5 shows the optical spectra of a PPLN-based PSA and EDFA with identical gain [7]. The ASE power generated by the PSA was much lower than that of the EDFA.

From the measured ASE power and the ASE power calculated theoretically using the measured gain, we obtained an NF value of 1.8 dB for the PSA. To the best of our knowledge, this was the first demonstration of an NF below the 3-dB limit in a CW-pumped PSA using a PPLN waveguide. The low-noise characteristics were also confirmed by the electrical spectrum method and by the improvement in the receiver sensitivity when a PSA was used as a preamplifier.

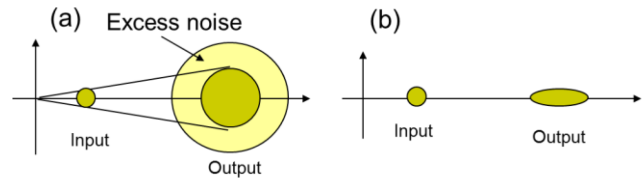

Fig. 4 Complex electrical fields in the output of (a) PIA and (b) PSA

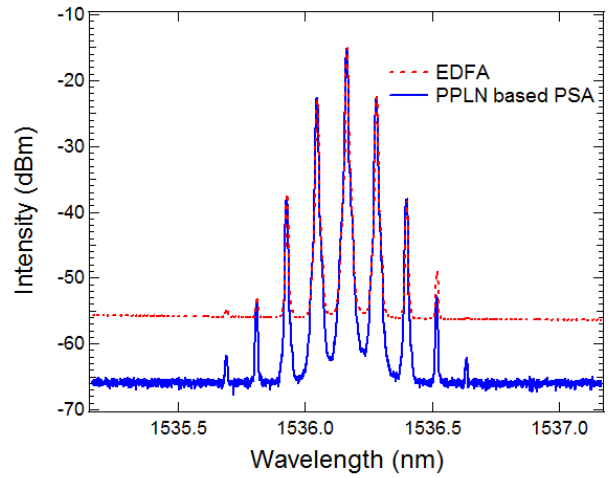

Fig. 5 Output spectra of PSA and EDFA

The residual NF is mainly caused by the coupling loss between the optical fiber and the PPLN waveguide, and would be improved by reducing the coupling loss.

4. In-Line Amplification

In the early stages of the study, we demonstrated the PPLN-based PSA by using a pump and a signal generated from a single laser [7]. However, to adapt a PSA for optical transmission, we should generate a phase-locked SH pump from the transmitted signal. To achieve in-line operation of the PSA, we have developed a carrier phase-recovery and phase-locking technique [16]. Figure 6 (a) shows the experimental setup of the in-line PSA for a binary PSK. In this configuration, the transmitted PSK and local oscillator 1 (LO1) are combined, amplified with an EDFA, and injected into a PPLN waveguide module. The PSK signal is converted to SH in the PPLN. By doubling the signal phase, the PSK modulation is canceled out, as shown in Fig. 6 (b). This allows us to recover the carrier phase. The difference frequency generation (DFG) between the SH wave and LO1 in the PPLN was employed to copy the carrier phase to a 1.5-μm band idler, as shown in Fig. 6 (b). The idler was used as a seed light for injection locking of the laser diode (LD). The injection-locked LD acts as local oscillator 2 (LO2); thus, we obtain two phase-locked LOs. LO1 and LO2 are amplified with an EDFA and injected into PPLN module 2 to generate a pump light through the sum frequency generation (SFG), as shown in Fig. 6 (c). The pump and signal are injected into PPLN module 3 for parametric amplifica-

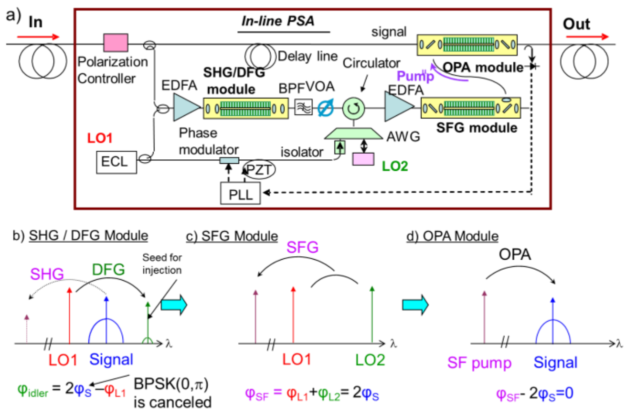

Fig. 6 Configuration of in-line PSA for PSK signal

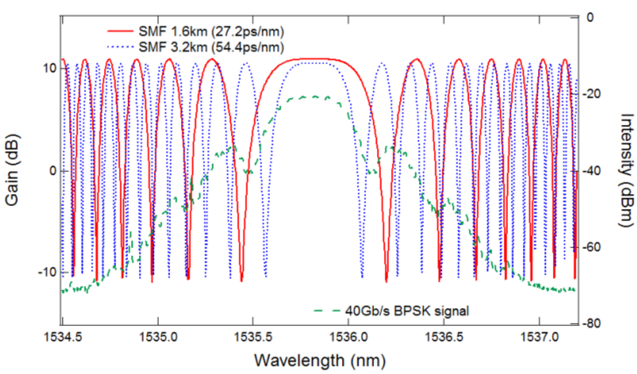

Fig. 7 Gain spectra assuming parabolic phase variations

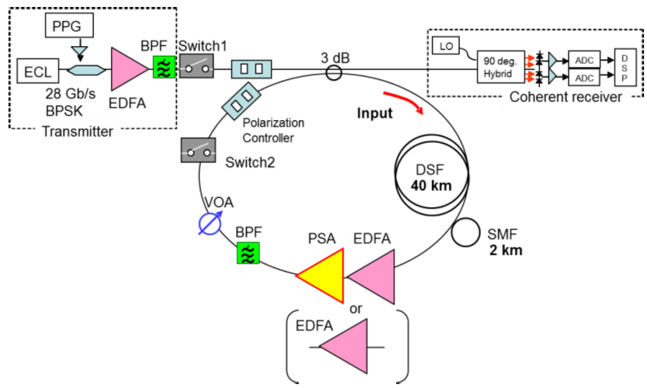

Fig. 8 Experimental setup of the recirculating transmission experiment

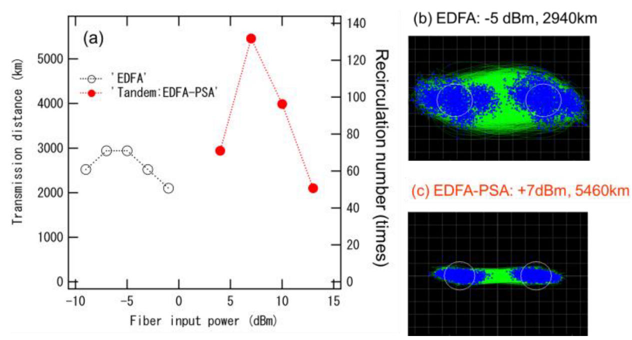

Fig. 9 Experimental results of the recirculating transmission experiment. (a) Transmission distance, constellation diagram with (b) EDFA and (c) PSA

tion, as shown in Fig. 6 (d). The in-line PSA is equipped with a phase-locked loop (PLL) based on an electro-optic (EO) phase modulator. This enables us to achieve high-speed phase synchronization. A high external gain of 12 dB was achieved for the in-line PSA as a black box.

To evaluate the regeneration of the degraded signal due to the group velocity dispersion in transmission fiber, the dispersion tolerance of the in-line PSA was examined. We found that the parabolic phase variation due to second-order dispersion and phase-dependent gain in the PSA caused wavelength-dependent gain [17].

Figure 7 shows the calculated gain spectra, assuming a standard single-mode fiber of 1.6 km and 3.2 km, as well as the optical spectrum of the 40-Gb/s BPSK signal. As shown in Fig. 7, as dispersion is increased, the gain bandwidth decreases. We confirmed that the signal quality can be regenerated via phase squeezing, provided that the phase variation within the signal bandwidth is less than $\pi/2$ [17].

Recent signal distortions due to group velocity dispersion can be compensated by using a digital coherent receiver. However, it is difficult to compensate for signal distortions due to nonlinear optical effects in the transmission fiber, even with the digital coherent receiver. We examined the signal regeneration capability of the in-line PSA in long-haul transmission by conducting a recirculating transmission experiment [18]. Figure 8 shows the experimental setup.

The transmission line consisted of a 40-km dispersion-shifted fiber, whose dispersion was compensated using a standard single-mode fiber. To utilize gain saturation for amplitude regeneration, we used the EDFA as a pre-amplifier and the PSA as a post-amplifier in this experiment. For comparison, we also conducted an experiment using EDFA repeaters. In the parametric amplifier, the gain is saturated due to pump depletion as the input signal is increased. The gain responds almost instantaneously to the variation of the input intensity, and the intensity variation can be reduced by utilizing the gain saturation [19].

Figure 9 (a) shows the maximum distance at a bit error rate of 2×10^{-3}, which corresponds to the forward error correction (FEC) limit with a 7% overhead, as a function of fiber input power. The maximum transmission distance of 2940 km was obtained at a fiber input power of −5 dBm for the EDFA link. Figure 9 (b) shows the constellation map for the longest transmission distance. The distance was limited by the non-linear noise in the fiber. In contrast, when we used an EDFA and a PSA as a repeater, we could obtain a longer transmission distance (5460 km) using a much higher fiber input power (+7 dBm). Figure 9 (c) shows the constellation map at the longest transmission distance with the PSA. It is clear that the nonlinear phase noise is largely suppressed, even when using a higher fiber input power than that of the EDFA link. These results suggest the PSA technology has the potential to overcome the nonlinear Shannon limit.

5. Amplification of Multi-Level and Polarization-Multiplexed Signals

A PSA using the degenerate parametric interaction can amplify only the in-phase component of the signal, so that it is applicable to BPSK or ASK signals. On the other hand, high-capacity communications will require the use of spectrally efficient multilevel modulation or polarization-multiplexed signals. To utilize PSA for high-capacity transmission, the operation for such a modulation format is preferred. We have demonstrated in-line amplification of QPSK utilizing carrier recovery with multiple-quasi-phase matched (M-QPM) devices and non-degenerate parametric amplification [20]. Figure 10 illustrates the configuration of the in-line PSA for QPSK signals.

We used three PPLN waveguides, one for carrier recovery, one for pump generation, and one for parametric amplification. A QPSK signal and LO1 are amplified and input to PPLN1, which is a multiple-QPM device. Figure 11 shows the output spectrum of PPLN1. Using multi-stage frequency mixing, it generates a series of idler waves. The phase of the input is multiplied four times in idler 3, so that the QPSK modulation is canceled. Idler 3 exhibits a line spectrum as a consequence of the carrier phase recovery.

Idler 3 is extracted with a wavelength-selectable switch based on a liquid crystal on silicon (LCOS) device and injected to the LO to obtain phase-locked LO2. LO1 and LO2 are combined, amplified, and injected into PPLN2. A 0.78-μm band pump is generated through SFG and injected to PPLN3. The signal and idler 2 outputs from PPLN1 are filtered and injected into PPLN3 for non-degenerate parametric amplification. The phase of the input is tripled in idler 2, resulting in the complex conjugate of the QPSK signal. Figure 12 shows an example of the calculated gain and output phase of the PSA.

The maximum gain can be obtained at a multiple of $\pi/2$ phase variation, and the output phase is regenerated to give a $\pi/2$ step variation in idler 3 [21]. Utilizing the phase-sensitive gain, we attempted to regenerate the QPSK signal. Artificial phase noise was added to the QPSK signal by using an EO phase modulator driven with a 4.2-GHz sinusoidal signal. Figure 13 shows constellation diagrams of the input and amplified signals with several levels of superimposed phase noise. Owing to phase squeezing of the PSA, we could observe a reduction of the phase noise after the phase regeneration of the in-line PSA. We also observed a slight degradation in the amplitude noise. This is due to the conversion loss of the idler and ASE noise added by the EDFA. Further improvement of the efficiency of the idler generation should remedy the amplitude noise degradation.

We have also demonstrated the amplification of 16-

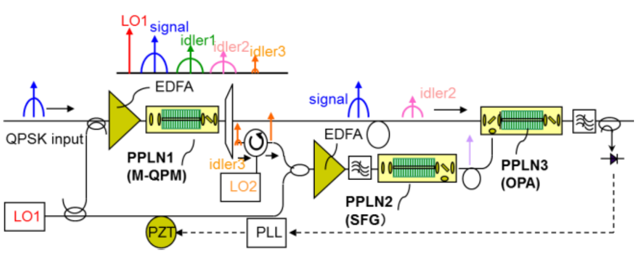

Fig. 10 Configuration of in-line PSA for QPSK signals

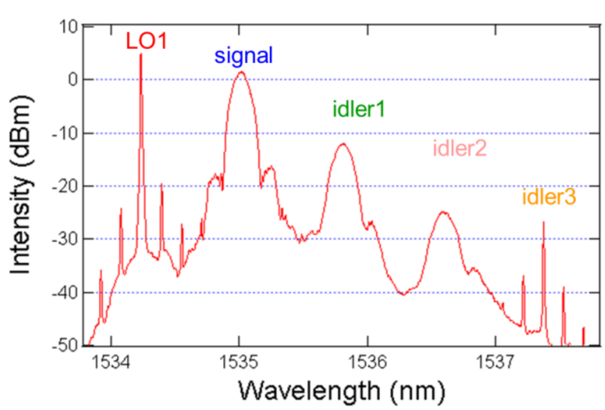

Fig. 11 Output spectra of multiple QPM devices

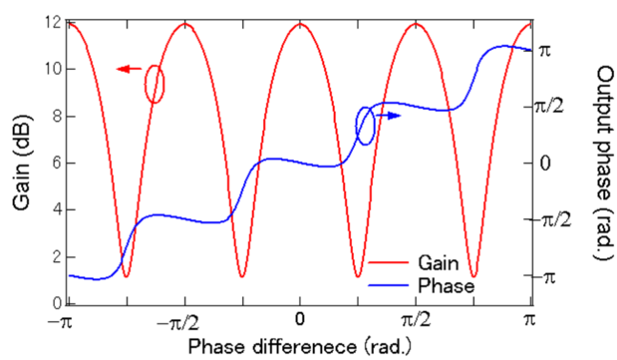

Fig. 12 Gain and output phase of the PSA for QPSK signal

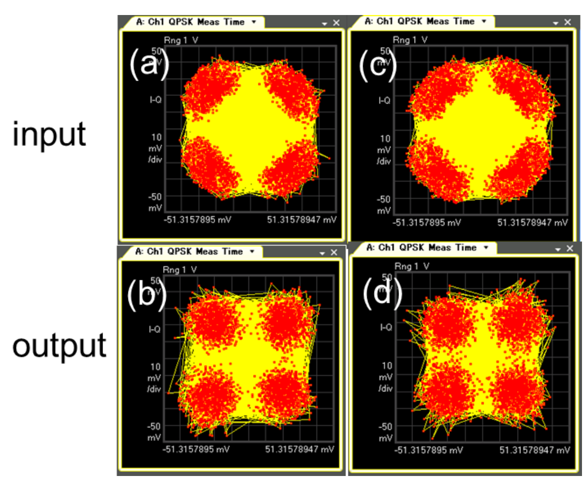

Fig. 13 Constellation diagram of (a), (c) input and (b), (d) output

QAM signals using a non-degenerate PSA [22]. Figure 14 shows the experimental setup. In this case, the phase-conjugate idler is generated by DFG using a local pump, then amplified in an OPA module, which is pumped by an identical pump light for the DFG. Figure 15 shows the constellation diagrams of the input and amplified signals. The error vector magnitudes (EVM) of the input signal and the PSA output were 9.7% and 9.6%, respectively. The 16-QAM signals were amplified without distortion because of the high-gain linearity of the PPLN-based PSA.

To accommodate the PDM signal, we adapt polarization diversity. In principle, this can be achieved using bi-directional amplification of orthogonal polarization in a PPLN waveguide with a polarization diversity loop. In reality, the residual reflection from the facet of the PPLN waveguide causes operational instability. To solve the instability issue, a polarization-diversity loop with two individual PPLN waveguides was proposed [23]. Figure 16 shows the experimental setup. Using this configuration, stable amplification of PDM signal was successfully demonstrated.

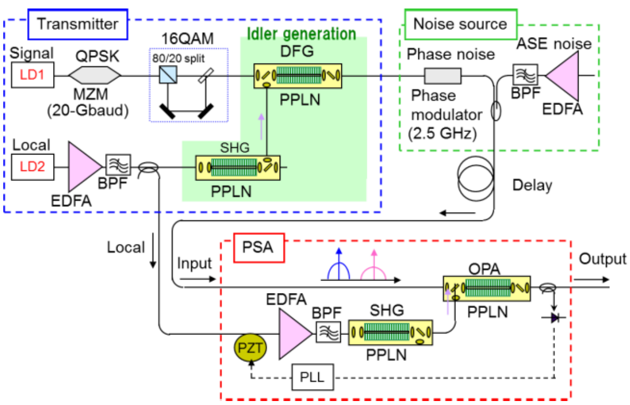

Fig. 14 Experimental setup of PSA for QAM signal

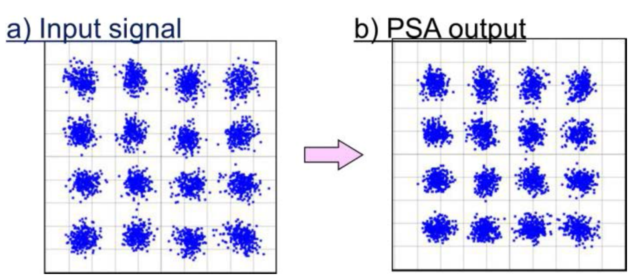

Fig. 15 Constellation diagram of (a) input QAM signal, and (b) PSA output

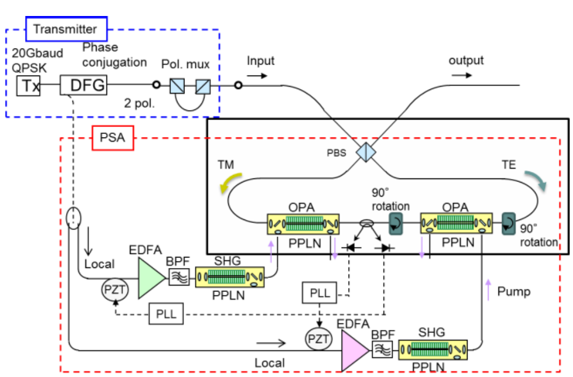

Fig. 16 Experimental setup of PSA for PDM signal

6. Future Prospects

So far, recent advances on the PPLN based PSA have been reviewed. In this section, we address several challenges we must overcome before the PPLN-based PSA can be implemented in a real system. In most experimental demonstrations, several PPLN waveguides are connected using optical fiber to construct the PSA. To deal with multilevel phase-coded and polarization-multiplexed signals, the integration of several PPLN waveguides will be preferred.

Figure 17 shows an example of an integrated device, which has two PPLN waveguides for SHG and DFG/OPA and two MMI couplers for signal/pump multiplexing [24]. PSA using the integrated device was successfully demonstrated [25]. The integrated device is promising for adaptation to a complexed modulation format.

In most experimental demonstrations, a Ti-diffused $LiNbO_3$ waveguide phase modulator was used for optical PLL. In that case, the modulator should be inserted in front of the EDFA to avoid photorefractive damage to the modulator. However, the insertion loss of the modulator degrades the pump SNR. To address this issue, a PPLN waveguide integrated with an EO modulator was fabricated using the direct bonding process [26]. Figure 18 shows the experimental setup of a PSA using a PPLN waveguide integrated with an EO phase modulator. Owing to the high resistance to photorefractive damage to the directly bonded waveguide, we can insert the modulator at the output of an EDFA, and

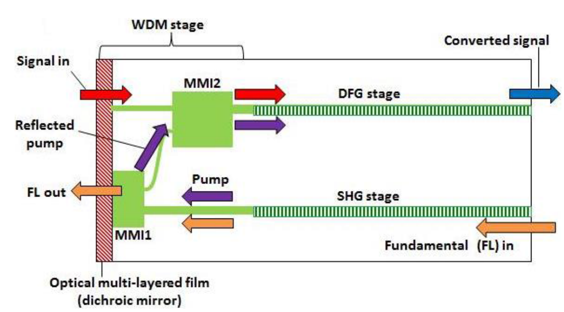

Fig. 17 PPLN waveguides integrated with MMI couplers

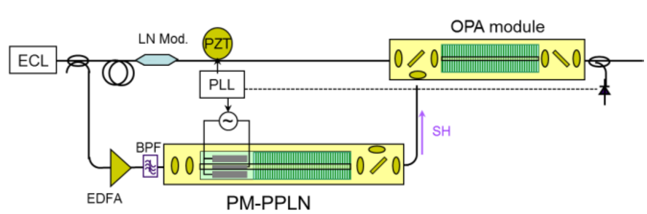

Fig. 18 PSA using PPLN integrated with a phase modululator

an improved SNR at the output of PSA was demonstrated using the integrated device.

Although phase recovery has been demonstrated for BPSK and QPSK signals, carrier recovery from more complicated signals remains an issue. Finally, the coupling loss between PPLN waveguides and fiber should be minimized to take advantage of the low-noise characteristics of the PSA.

7. Conclusion

Recent advances in PPLN waveguide technology have enabled us to explore PPLN-based PSAs for optical communication. Low-noise characteristics and phase squeezing properties are now well-known. In-line operation and amplification of multi-level and PDM signals have been demonstrated. However, because basic concepts are still being confirmed, there are several challenges to overcome before considering real applications. As further deployment can be expected by undertaking further studies on such topics as integration, the improvement of PPLN waveguide gain, and phase-locking technology, we can expect this technology to develop in the future.

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