Phase sensitive degenerate parametric amplification using directly-bonded PPLN ridge waveguides

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Abstract: We constructed the first CW pumped degenerate parametric amplifier based on periodically poled and ZnO-doped $LiNbO_3$ ridge waveguides. An in-phase gain of + 11 dB was achieved owing to the high conversion efficiency and high damage resistance of the waveguide obtained by employing direct bonding and dry etching techniques. Nearly identical amplification and deamplification were obtained owing to a sufficient spatial and temporal overlap between the pump and signal beams. No secondary wavelength conversion process was observed, and a maximum output of 22 dBm was obtained. We also successfully demonstrated the phase sensitive amplification of a modulated signal light.

OCIS codes: (190.4410) Nonlinear optics, parametric processes; (130.3730) Lithium niobate.

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1. Introduction

Optical amplifiers are key devices in optical communication systems. Erbium-doped-fiber amplifiers (EDFAs) and semiconductor optical amplifiers (SOAs) are most commonly used in current systems. A higher signal-to-noise ratio (SNR) will be required for future large capacity optical links. However, the noise figures (NF) of these amplifiers utilizing stimulated emission cannot be improved much further because they are approaching the 3-dB quantum limit. Phase-insensitive amplifiers (PIAs) such as EDFAs and SOAs amplify not only the quadrature that carries the signal but also the other quadrature. In this case, the SNR is degraded by a factor of two (NF of 3 dB) for high gains. Phase-sensitive amplifiers (PSAs) have unique properties that allow them to break the quantum limit of the optical amplifier’s NF [1]. The reason for breaking the quantum limit is that the PSA amplifies only one of two quadrature phase components in the signal light, while deamplifying the other. Degenerate parametric amplification (DPA) is essential for realizing low-noise signal amplification with a 0-dB quantum-limited NF. In addition to the possibility of achieving low-noise amplification, PSAs have other advantages and the potential for the pulse form reshaping [2], the reduction of modulation instability [3], and amplitude and phase regeneration [4].

$\chi^{(3)}$ and $\chi^{(2)}$ based PSAs have been investigated. As a $\chi^{(3)}$ based PSA, a fiber-optic parametric amplifier (FOPA) utilizing four wave mixing (FWM) has been widely studied. The FOPA can provide a high gain by using a pump laser in the 1.5-μm telecom-band wavelength. The compatibility of fiber with optical communication is also an advantage of FOPA. In a PSA utilizing FWM, the pump and signal are in the same wavelength range. A PSA using a nonlinear optical loop mirror (NOLM) has been investigated to realize degenerate parametric amplification while keeping the signal and pump separate [5]. In a recent PSA demonstration, dual pump wavelengths schemes were used to prevent the noise induced by guided acoustic-wave Brillouin scattering (GAWBS) [6]. Meanwhile, there have been few demonstrations of $\chi^{(2)}$ based PSAs for optical communication. PSAs with a sub-3-dB NF have been realized by using a 1-μm-band pulsed laser using a KTP crystal [7] and a periodically poled $LiNbO_3$ (PPLN) bulk crystal [8]. Recently, phase sensitive amplification was examined using a proton-exchanged type PPLN waveguide, but only a small PSA gain was reported that was limited by the waveguide technology [9]. Moreover, the scheme in Ref [9]. was based on a cascaded SHG/DFG process, and only phase sensitive operation using non-degenerate parametric amplification was demonstrated for a 1.55-μm-band signal, pump and idler. However, a $\chi^{(2)}$ based PSA inherently utilizes the second harmonic of the signal as a pump. Therefore, degenerate parametric amplification, which requires the separation of the signal and pump, should be implemented in a simple configuration using only one pump source. In addition, a PPLN waveguide has several advantages. High non-linear coefficients provide a compact device without additional frequency chirp, and with a high resistance to stimulated Brillouin scattering. The potential exists for integrating multiple functions on one chip.

This letter provides the first report of CW pumped phase sensitive degenerate parametric amplification based on PPLN waveguides. We used a directly-bonded PPLN ridge waveguide, which provided a high conversion efficiency and high power tolerance. We achieved a high in-phase gain of + 11 dB and demonstrated the phase sensitive amplification of a modulated (10 Gb/s NRZ) signal in the telecommunication wavelength range.

2. Fiber-pigtail PPLN modules and experimental setup

A high conversion efficiency and high power tolerance are both desirable if we are to achieve a high parametric gain. We fabricated 5-cm-long PPLN ridge waveguides using the direct bonding method. The Zn-doped $LiNbO_3$ core layer made the waveguides highly resistant to

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photorefractive damage. By using the dry etching technique, we obtained a ridge waveguide with fine uniformity, and it yielded a high SH conversion efficiency of over 2000%/W [10].

We demonstrated phase-sensitive degenerate parametric amplification using two PPLN ridge waveguides. Figure 1 shows the experimental setup. The PPLN waveguides were assembled into fiber-pigtail modules. The module had four input/output ports to allow SH pumping [11]. Polarization-maintaining fibers (PMFs) for 1.55 and 0.78 μm were used in the two signal ports and the two pump ports, respectively. The signal and SH pump were combined with a dichromatic mirror and injected into the waveguide inside the module, and the output signal and SH pump were separated with a dichromatic mirror. The insertion loss was 5.0 dB for the signal. The waveguide temperature was controlled by a Peltier device inside the module.

We used a 1.54-μm-band external cavity laser diode (ECLD) as a pump and signal source. A CW wave at 1537.6 nm was divided by a 3-dB coupler to provide the pump and signal light. The pump light was amplified with an erbium-doped fiber amplifier (EDFA) and injected into PPLN module 1 to generate an SH wave of around 770 nm. To avoid the SNR degradation of the pump, a band pass filter with a 1 nm bandwidth was inserted between the EDFA and PPLN module 1 in some experiments. The generated SH power was injected into PPLN module 2 for the DPA. The dichromatic mirrors in the two modules effectively suppressed the unwanted output of the 1.54-μm-band pump and amplified spontaneous emission (ASE) generated by the EDFA.

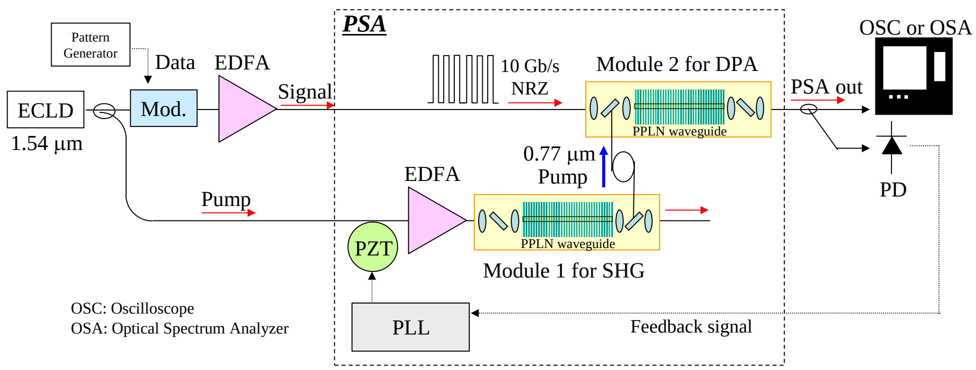

Fig. 1. Experimental setup

The CW signal light was modulated using a $LiNbO_3$ modulator to generate a 10 Gb/s NRZ signal. The modulated signal was amplified by the EDFA and injected into PPLN module 2. To achieve a stable PSA output, a piezoelectric-transducer (PZT) based optical phase-locking loop (PLL) was used to compensate for the slow relative phase drifts between the signal and SH-pump lights induced by temperature variations and acoustic vibrations. Both the in-phase (amplification) and quadrature-phase (deamplification) conditions of the relative phase between the signal and SH-pump lights were individually obtainable by changing the setting of the PLL. The PSA performance was measured by using an oscilloscope (OSC) and/or an optical spectrum analyzer (OSA).

3. PSA operation for CW signal light

First, we confirmed the PSA operation by using a continuous wave (CW) signal light. We amplified the pump light to 31.5 dBm and injected it into PPLN module 1. Then we obtained an SH pump power of 330 mW. The SH pump light and signal without any modulation at a power of 0 dBm were injected into PPLN module 2. Figure 2 shows the in-phase and quadrature-phase PSA output spectra for a CW signal light. An amplification of + 11 dB was obtained with the in-phase signal. While a deamplification of –10 dB was obtained with the quadrature-phase signal. Here, the amplification and deamplification gains are defined as the signal output divided by the signal output without pump injection. These results clearly reveal

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the phase sensitive property. We defined phase sensitive extinction as the difference between amplified and deamplified intensity. We achieved a large phase sensitive extinction of 21 dB, because the highly efficient PPLN ridge waveguide enabled us to provide high gains for both amplification and deamplification with CW pumping.

With DPA, attention must be paid to the leakage power of the pump light. We evaluated the leakage power level with the signal light turned off. The leakage power level of the 1.54 µm-band pump light was attenuated and became 50 dB lower than the signal level. This corresponds to the leakage power being suppressed by a factor of 87 dB compared with the high input pump power of 31.5 dBm even excluding the tap coupler loss. This result reveals that this configuration provides a very high level of pump light extinction, and hence ASE generated by the EDFA can be effectively suppressed.

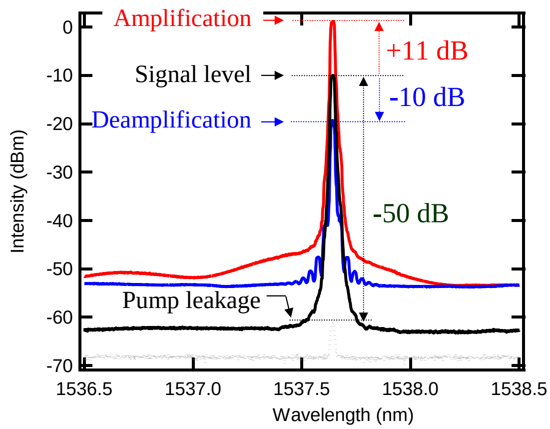

Fig. 2. In-phase and quadrature-phase PSA output spectra for CW signal light

Next, we measured the power dependence of the PSA for the SH pump and signal light. Figure 3 shows the in-phase gain and quadrature-phase gain as a function of the SH pump power obtained. By increasing the SH pump power, the in-phase gain increased, and the quadrature-phase gain decreased symmetrically. In theory, the maximum PSA gain $G=2\gamma-1+2\sqrt{\gamma(\gamma-1)}$ is achieved for an in-phase signal [12]. Here, γ is the parametric gain for the PIA, which increases with pump power approximately as $(1+\eta P_p/2)^2$ [13]. Where, η is the conversion efficiency of the waveguide, and P_p is the SH pump power. The solid line in Fig. 3 is a curve calculated using the equations. Here, we used a conversion efficiency value of 2000%/W and assumed a coupling loss of 5 dB for the SH pump. The experimental result agreed well with the theoretical curve.

Ideally the amplification gain and deamplification gain should be unity. However, a disparity between the amplification and deamplification response has been reported in many DPA experiments using a pulsed pump. In particular, it appears that a large disparity occurs at a high pump power [14]. It is well known that the lack of deamplification is caused by the distortion of the spatial or temporal profile of a laser pulse. In our experiments, the ridge waveguide provides a sufficient spatial mode overlap between the signal and SH pump light. Thanks to CW pumping, temporal mismatching is prevented. These sufficient spatial and temporal overlaps between the pump and signal beams result in nearly identical amplification and deamplification until at least up to a deamplification gain of −10 dB.

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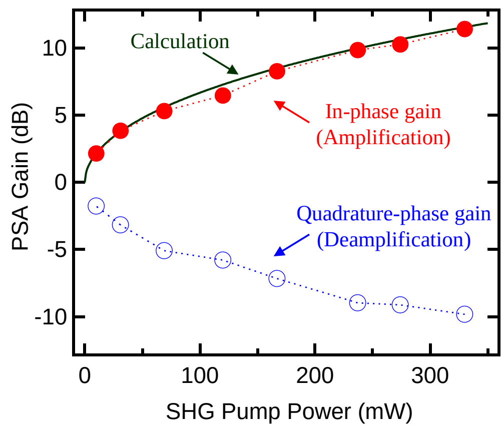

Fig. 3. Power dependence of PSA for SH pump

Figure 4 shows the PSA output signal power as a function of the input signal power. With the fiber based PSA, the dual-pump method has often been used to prevent the noise induced by guided acoustic-wave Brillouin scattering (GAWBS) [6]. In such a configuration, secondary FWM between the signal and pump may induce a comb-like output when the signal is amplified to a high power level [15]. The secondary FWM process might limit the output power of a fiber-based PSA. In contrast, we did not observe any secondary wavelength conversion process even when we increased the signal power in our experiment, and finally we obtained a maximum output power of 22 dBm. In theory, under the small signal approximation, which means that the signal power is sufficiently small to disregard the pump power depression, the PSA gain has no signal power dependence. Therefore, the PSA output power increases linearly with the input signal power. However, if the signal power increases to a level similar to that of the SH pump, pump power depression occurs and this limits the maximum PSA output. Figure 4 shows that the output signal power from the PPLN-based PSA increased linearly with the input signal power for a small power below 10 dBm, this result agrees with the theoretical prediction. While the output power for a high input signal power over 10 dBm deviates from a linear increase. This result is regarded as showing the effect of pump depression because the signal power increases to a level similar to that of the SH pump.

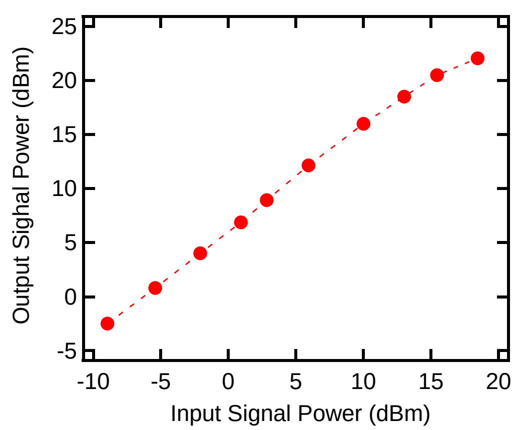

Fig. 4. Power dependence of PSA for signal

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4. PSA operation for modulated signal light

We then examined the PSA with a 10 Gb/s non-return-to-zero (NRZ) signal light. We prepared two different kinds of $LiNbO_3$ Mach-Zehnder (MZ) modulators. One modulator had only a single electrode for an MZ arm, which means that the modulated signal had frequency chirped components. The other modulator performed as a push-pull modulator, which means that modulation could be obtained without frequency chirp.

Figure 5(a) shows an eye diagram for a 10 Gb/s NRZ signal obtained using the single electrode type MZ modulator. First, the signal and SH-pump lights were injected into PPLN module 2 without a PLL. The eye did not open because of the fluctuations in the relative phase, as shown Fig. 5(b). The eye was clearly open when the PLL had an in-phase setting, and a PSA gain of over + 10 dB was obtained, as shown in Fig. 5(d). On the other hand, the eye was closed when the PLL had a quadrature-phase setting, as shown in Fig. 5(c). The center region of the eye diagram was closed, and only the rise-decay region was amplified. These regions are frequency chirped components generated by the modulator with chirp used in this experiment. This result shows that only the frequency chirped components were amplified because of the phase sensitive property. Conversely, as regards amplification, only the frequency chirped components were deamplified. This indicates the possibility of the phase regeneration of degraded signals.

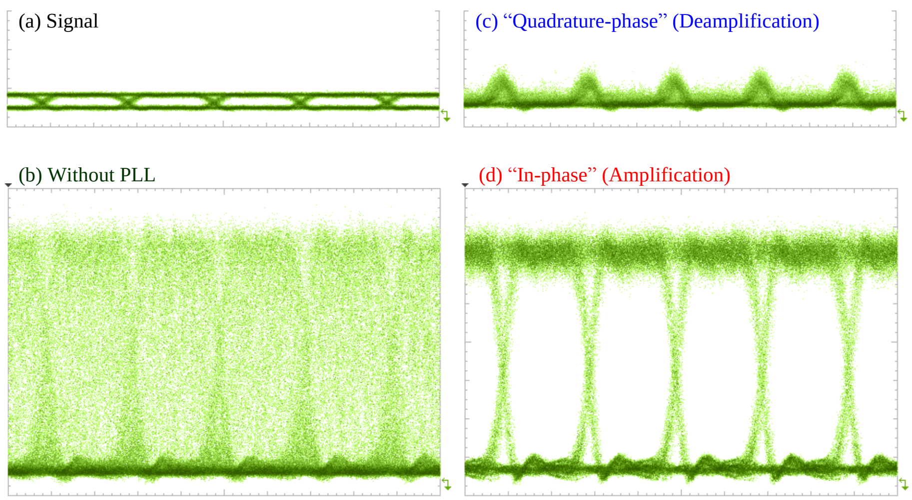

Fig. 5. Eye diagrams: (a) signal using single electrode modulator, (b) PSA without PLL, (c) PSA with quadrature setting of PLL, (d) PSA with in-phase setting of PLL

Figure 6(a) shows the eye diagram for a 10 Gb/s NRZ signal obtained using the push-pull type MZ modulator. Because of the chirpless modulation, a completely closed eye diagram was obtained with the quadrature-phase setting of the PLL, as shown in Fig. 6(b).

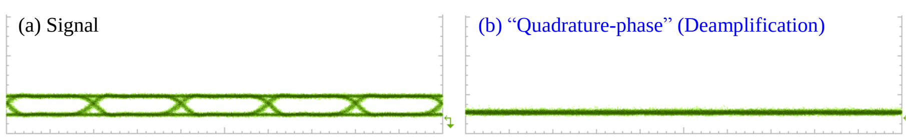

Fig. 6. Eye diagrams: (a) signal using push-pull modulator, (b) PSA with quadrature setting of PLL

The eye diagram in Fig. 5(d) appears to include small noise components. The frequency chirp components from the modulator result in PLL misalignment from the optimum point, and may generate additional noise. If the pump light has a large phase noise, additional noise will be generated by the conversion from phase noise to amplitude noise through the PSA. Therefore, we also change the ECLD from one with a 1 MHz line width to one with a 100

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kHz line width. In addition, if the ASE generated by the EDFA is injected into module 1, the ASE is converted to 0.78 μm band light via the sum-frequency generation process. The beat noise between the SH pump and the sum-frequency light degrades the quality of the amplified signal light. To cut off the injection of the ASE into module 1, we also install a band pass filter (BPF) after the EDFA for the pump light. This will reduce the beat noise in the SH pump. A narrow BPF bandwidth is better to reduce the ASE, but a BPF with a narrower bandwidth has a large insertion loss. To achieve a balance between the effect of reducing the ASE and the insertion loss, we used a BPF with a 1 nm bandwidth in this experiment. Figure 7 shows the PSA eye diagram for a 10 Gb/s NRZ signal obtained by using a push-pull type MZ modulator, a narrow line width ECLD and a BPF. We could reduce the intensity noise of the amplified output by modifying the experimental setting as described.

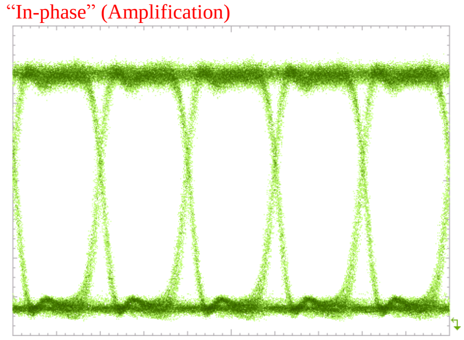

Fig. 7. Eye diagram: PSA with in-phase setting of PLL

5. Conclusion

In conclusion, we demonstrated the first CW-pumped phase-sensitive DPA based on directly-bonded PPLN ridge waveguides. An in-phase gain of + 11 dB and a phase sensitive extinction of 21 dB were achieved by single pass CW SH-pumping. Nearly identical amplification and deamplification were obtained by using CW pumping and realizing a sufficient mode overlap between the signal and SH pump light with a ridge waveguide. No secondary wavelength conversion process was observed, and a maximum output of 22 dBm was obtained. Finally, we successfully demonstrated the phase-sensitive amplification of a modulated (10 Gb/s NRZ) signal light.

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