PPLN-based Low-Noise In-Line Phase Sensitive Amplifier with Highly Sensitive Carrier-Recovery System

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***Abstract*— A PPLN-based in-line phase sensitive amplifier with a highly sensitive carrier-recovery system based on two-stage SHG/DFG parametric conversion achieves multi-stage amplification with a low noise figure of 3 dB and a 20-dB gain.**

***Keywords*—phase sensitive amplifier; periodically poled $LiNbO_3$ waveguide;**

I. Introduction

According to Shannon's theory, it is important to improve the signal-to-noise ratio (SNR) to achieve greater transmission capacity [1]. Phase insensitive amplifiers such as the erbium-doped fiber amplifier (EDFA) have a quantum-limited 3-dB noise figure (NF) [2]. A phase sensitive amplifier (PSA) is one of the most promising technologies for improving the SNR because it intrinsically has an extremely low NF [3]. A PSA can be achieved experimentally via a parametric process by using nonlinear susceptibility $\chi^{(2)}$ [4] or via a four-wave mixing process by using nonlinear susceptibility $\chi^{(3)}$ [3, 5-7]. We have reported an NF of below 3 dB with a 6.7-dB gain in a $\chi^{(2)}$-based PSA using directly bonded periodically poled $LiNbO_3$ (PPLN) waveguides (WGs) with high input-power tolerance [8]. However, it is difficult to apply this configuration to in-line amplification because both the pump and signal are generated by a master local oscillator (LO). For the in-line operation of the PSA, the optical carrier must be recovered from the modulated signal itself. Recently, we have demonstrated a PPLN-based in-line PSA with a carrier-recovery and phase-locking system that uses wavelength conversion and injection locking for binary phase shift keying (BPSK) signals [9, 10]. In this carrier-recovery system, the phase of the BPSK signals was doubled to cancel out the phase modulation caused by second harmonic generation (SHG). Using this SHG light, we obtained a recovered carrier by difference frequency generation (DFG) and injection locking.

Meanwhile, when considering practical use, it is realistic that in-line PSAs can be installed as preamplifiers in multistage optical amplifiers with high-gain EDFAs as power-amplifiers, because of their intrinsic low noise. To this end, we need to reduce the NF and increase the gain of the in-line PSA to implement multistage optical amplifiers while balancing a low NF and high gain.

In this paper, we propose an in-line PSA with a new configuration for a highly sensitive carrier-recovery system using two-stage SHG/DFG parametric wave mixing. We confirm both the performance of the optical parametric amplification (OPA) section as the core part of the proposed in-line PSA by evaluating the NF property of the PSA itself and the properties of the proposed carrier-recovery system. We also demonstrate a multistage optical amplifier with a low NF of 3 dB and a 20-dB gain by connecting the proposed in-line PSA and an EDFA in tandem.

II. NF of Multistage Amplification with In-Line PSA and EDFA

With multistage amplification realized by the tandem connection of an in-line PSA and an EDFA, the theoretical equation for the NF is as follows:

$$f_{tandem} = (1 - l_{input})^{-1} \cdot \left\{ f_{PSA} + \frac{(f_{EDFA} - 1)}{g_{PSA}} \right\} \qquad (1)$$

Here, l_{input} is the loss at the input stage of an optical parametric amplifier, f_{tandem}, f_{PSA}, and f_{EDFA} are the NFs of the entire amplifier, the PSA, and the EDFA, respectively, and g_{PSA} is the gain of the in-line PSA. From eq. (1), if the gain of the preamplifier g_{PSA} could be increased, the influence of the noise of the post-stage EDFA could be suppressed. Furthermore, it is important to reduce the loss with a tap coupler for carrier recovery at the input stage and to improve the NF and gain property of the in-line PSA. The development of a highly sensitive carrier-recovery system will lead to a reduction of l_{input} and an improvement in f_{PSA} by the suppression of the amplified spontaneous emission (ASE) in the carrier-recovery system.

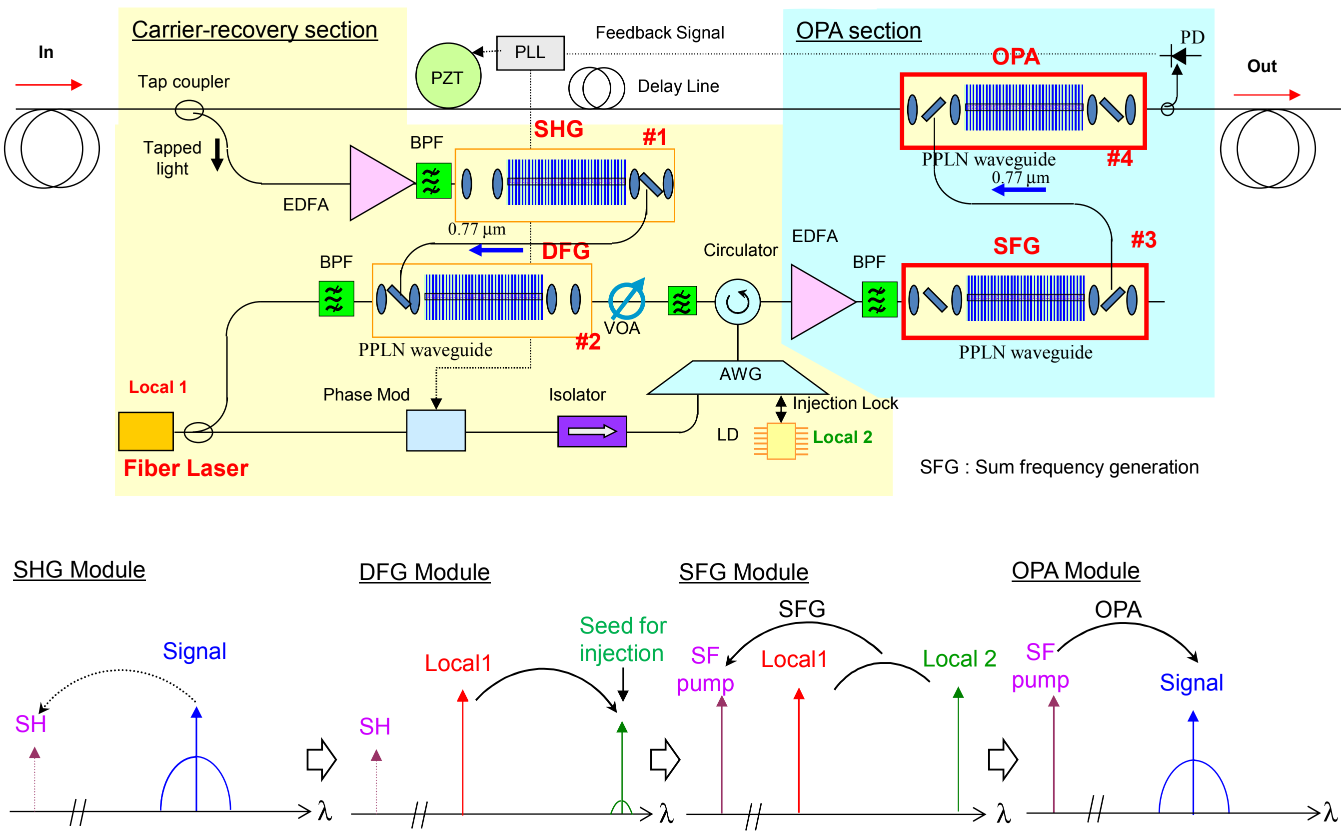

Fig. 1. In-line PSA configuration

III. EXPERIMENTAL CONFIGURATION AND PERFORMANCE OF DIRECTLY BONDED PPLN RIDGE WGS

Figure 1 shows schematics of the proposed in-line PSA based on PPLN WGs. The in-line PSA has an OPA section as the core of the amplifier and is equipped with a carrier-recovery system. The input signal was tapped off by a 1% tap coupler for the carrier-recovery/phase-locking stage. In our previously reported in-line PSA [9, 10], we used a cascaded scheme of SHG/DFG wave mixing in one PPLN WG. Here, for carrier recovery with higher sensitivity, we used a discrete two-stage scheme of SHG and DFG parametric wave mixing in two PPLN WGs. The signal is amplified by a booster EDFA, and the amplified signal generates an SH wave in the PPLN module #1. By doubling the signal phase, the carrier is recovered from a BPSK signal without a carrier component. Then the SH wave and a free-running local CW fiber laser as Local 1 are mixed by the PPLN module #2 to generate an idler wave. The idler wave is filtered using a band-pass filter (BPF) and an arrayed waveguide grating (AWG). Then, the idler wave is injected into a semiconductor slave laser as the second pump (Local 2) for phase locking. Local 1 and Local 2 are combined in the AWG, amplified with the EDFA, and injected into PPLN module #3 to generate a sum frequency (SF) wave of around 770 nm, which corresponds to the SH wave of the signal. The generated SF power and signal are injected into PPLN module #4 for the OPA. To achieve a stable PSA output, a piezoelectric transducer (PZT) based optical phase-locking loop (PLL) is used to compensate for the slow relative phase drifts between the signal and SF-pump lights induced by temperature variations and acoustic vibrations. Owing to the two-stage scheme of SHG/DFG, the conversion efficiency of the seed light for the injection locking can be theoretically quadrupled compared to that of the cascaded one. Therefore, highly sensitive carrier recovery and the reduction of the tapped power are expected, which will lead to the improvement of the NF property of the PSA.

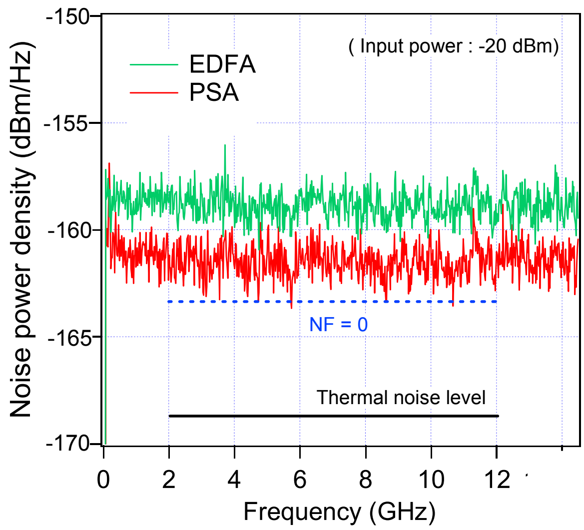

Fig. 2. Electrical noise spectra

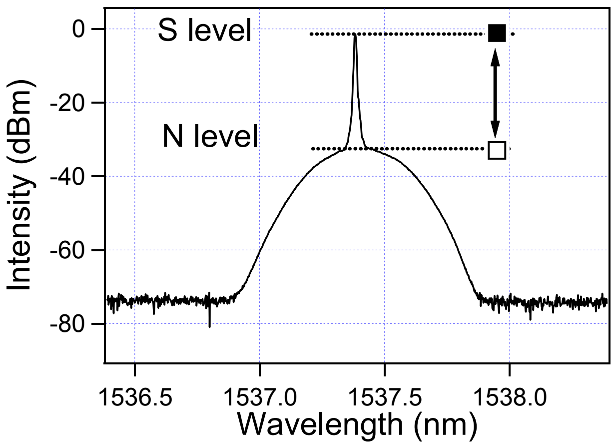

Fig. 3. Spectrum at PPLN #2 output

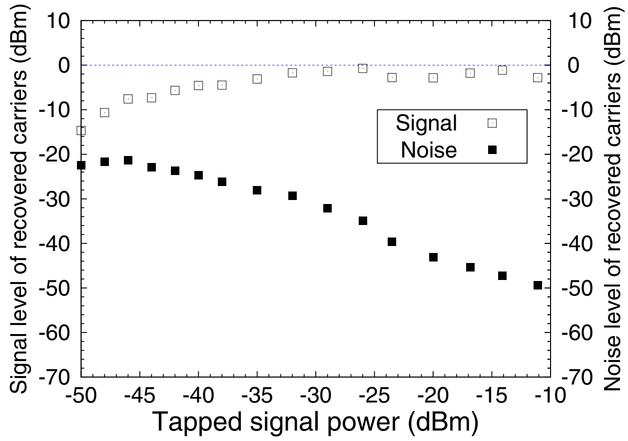

Fig. 4. Tapped power vs. signal and noise levels of recovered carriers

At the PSA, we use directly bonded PPLN [11] ridge WGs fabricated with a dry-etching process [13] for each section. The PPLN ridge WGs were fabricated using ZnO-doped $LiNbO_3$ (LN), which is highly resistant to photorefractive damage, as a core and $LiTaO_3$ as a cladding layer. First, we formed a periodically poled structure on the ZnO-doped LN using the conventional electrical poling method [12]. The two wafers were brought into contact and annealed to achieve complete bonding. The WG layer thickness was reduced by successive lapping and polishing. Then, we fabricated the ridge shape structure using a dry etching technique [13]. Finally, the fabricated WGs were packaged in a fiber-pigtailed module using lens coupling.

Before evaluating the highly sensitive carrier-recovery system, we examined just the OPA section using a CW external-cavity laser as the master LO because the properties of the OPA determine the performance of the in-line PSA. The OPA module gain estimated from the input and output optical spectra was 16 dB. Figure 2 shows the electrical noise spectrum of the PSA when the master LO is used and that of the EDFA measured with an electrical spectrum analyzer (ESA) [8]. We measured them at the same input signal power of -20 dBm and the same external gain of 16 dB. With the master LO, the PSA exhibited a noise power density that was 2.6 dB smaller than that of the EDFA. The NF of the PSA was estimated as follows. The average noise power densities of the PSA and the EDFA ranged from 2 to 12 GHz. Using the NF of the EDFA measured with an optical spectrum analyzer (OSA) as a reference, we calculated the noise power density for NF = 0 dB and then estimated the NF of the PSA. As a result, we obtained a low average NF of around 2 dB.

IV. Characteristics of Highly Sensitive Two-Stage Carrier-Recovery System

Our proposed carrier-recovery system is composed of two PPLN modules: one for SHG and the other for DFG, as shown in Fig. 1. In our previously reported carrier-recovery system with an in-line PSA configuration [9, 10], we used a cascaded scheme in which SHG and DFG occurred in a PPLN WG used for the carrier recovery. In the cascaded scheme, the ASE from the EDFA used to amplify the tapped signal is added throughout the C-band. This ASE degrades the SNR of the light injected into a semiconductor slave laser for phase locking (corresponding to Local 2 in Fig. 1), resulting in the degradation of the SNR of the pump light for the OPA. In contrast, the proposed two-stage carrier-recovery system might prevent this SNR degradation. Since the two modules are coupled through a dichromatic mirror, which splits the 0.77/1.54-μm bands, the ASE noise from the EDFA can be effectively eliminated.

Figure 3 shows a typical output spectrum after PPLN module #2 under a tapped input power condition of -29 dBm. We used the proposed system to obtain a recovered carrier with low noise levels. Figure 4 shows the signal and noise levels of the recovered carrier as a function of the tapped input power. Although we observed an increase in the noise level as the tapped signal power decreased, the signal level remained 7.8 dB higher than the noise level even when the tapped signal power was -50 dBm. Therefore, we confirmed that there was a sufficiently high signal power and SNR for injection locking.

V. NF Measurements and Results

By employing the proposed in-line PSA with the highly sensitive carrier recovery system as a preamplifier, we demonstrated amplification with a high gain and a low NF with

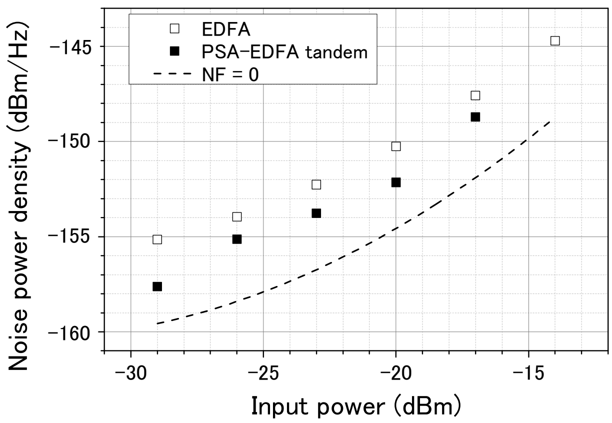

Fig. 5. Input power vs. average noise power density

the multistage amplifier. Thanks to the improvement in the sensitivity in the carrier-recovery system, it became possible to reduce not only the operation power but also the NF in the in-line PSA because the required power from the input signal for carrier recovery can be greatly reduced. Thus, we were able to use a 1% tap coupler in the PSA signal line. We also confirmed that the gain of the in-line PSA was as high as 11 dB. To confirm the potential of the in-line PSA with the proposed carrier-recovery system, we examined multistage amplification with a total gain of 20 dB (11 dB for the PSA and 9 dB for the EDFA). We evaluated the noise levels with the ESA [8]. Figure 5 shows the input power dependence of the output noise power densities from the multistage amplifier and the reference stand-alone EDFA with a 20-dB gain. Using the NF value of the EDFA that we employed as the reference, we confirmed that the average NF of the multistage amplifier is about 3 dB within an input power range of -23 to -17 dBm. The loss improvement at the input stage of the PSA and the high gain and low NF properties of the in-line PSA allow us to achieve a multistage amplifier with both a high gain of 20 dB and a low NF that is almost the same as the quantum noise limit of a phase insensitive amplifier.

VI. SUMMARY

We demonstrated a PPLN-based in-line PSA. The highly sensitive carrier-recovery system achieved a loss reduction in the input stage of the OPA and suppressed unwanted ASE mixing. Our in-line PSA with a high gain of 16 dB obtained using a PPLN-WG-based OPA also contributed to the noise reduction. In addition, we demonstrated a multistage amplifier with a high practical gain of 20 dB and the quantum noise limit of a phase insensitive amplifier.

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