Gain Ripple and Passband Narrowing due to Residual Chromatic Dispersion in Non-Degenerate Phase-Sensitive Amplifiers

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Abstract: We theoretically show dispersion dependence of gain spectrum in non-degenerate PSA under phase locking, and experimentally demonstrate WDM amplification of PS-64QAM signal using PPLN-based PSA with gain-flattened spectrum by estimation and compensation of chromatic dispersion.

1. Introduction

Amplified spontaneous emission (ASE) noise from optical amplifiers and nonlinear distortion are dominant factors limiting the transmission capacity and distance in optical fiber communication. Toward further high-capacity optical networks, phase-sensitive amplifiers (PSAs) have attracted much attention because of their potential for low-noise amplification and nonlinear phase noise mitigation [1–5]. In particular, the frequency non-degenerate (signal and idler have separate frequencies) PSAs (ND-PSAs) can be applied for high speed transmission link because it can provide compatibility with multichannel signals and arbitrary modulation formats, unlike the frequency degenerate (identical signal and idler frequencies) configuration. Recently, WDM amplification and an SNR advantage of around 5 dB compared with EDFAs have been demonstrated using periodically poled $LiNbO_3$ (PPLN) or highly nonlinear fiber as an amplification medium in ND-PSAs [2–5]. However, one of the most important problems we face in an actual ND-PSA is the effect of chromatic dispersion (CD) on the signal and idler in the link. As well as the relative time delay, the phases of the signals and idlers must be adjusted before the PSA. Therefore, fine adjustment of the phase using a spatial light modulator (SLM), such as a wavelength selective switch, or a variable delay line is generally performed [4,5]. As mentioned above, residual CD is an important factor in designing a transmission system using PSAs. Only CD tolerance for degenerate PSA was investigated [6], but there have been no detailed reports on amplification characteristics of ND-PSAs under residual CD.

In this work, we theoretically and experimentally investigated the effect of residual CD on ND-PSAs by using PPLN-based modules. First, we present the theoretical gain ripple of an ND-PSA with phase locking under residual CD conditions and compare it with experimental results. Then, we describe the effect of passband narrowing due to the ripple for a single channel using an advanced modulation format, probabilistic-shaped 64QAM (PS-64QAM), with two symbol rates of 5 Gbaud and 20 Gbaud. Finally, we compare WDM-amplification characteristics under sub-ps/nm order residual CD conditions with and without CD compensation.

2. Gain Spectrum of ND-PSA with Phase Locking and Effectiveness of CD Compensation

The dispersion dependence of the gain spectrum, $G(f)$, in a degenerate PSA has been reported [6]. The gain spectrum for an input electrical field, $E(f)$, is expressed as

$$G(f) = G_{\mathrm{in}}\cos^2\big(\Delta\phi(f)\big) + \frac{1}{G_{\mathrm{in}}}\sin^2\big(\Delta\phi(f)\big), \qquad \Delta\phi(f) = \frac{\pi D c}{{f_0}^2}(f_0 - f)^2, \tag{1}$$

where, G_{in} is the PSA gain of the in-phase component, f_0 is the degenerate frequency, D is the residual CD, c is the velocity of light, and $\Delta\phi$ is the phase difference between $E(f)$ and $E(f_0)$. The residual CD is assumed to be the second-order dispersion. This equation is based on the assumption that the relative phase between the signal and pump is optimized so that the gain at f_0 is maximized by a phase-locked loop (PLL). It cannot simply be applied for ND-PSA. This is because the relative phase between the signal-idler pairs and the pump is locked so that the gain at a signal channel used for PLL, not at f_0, is maximized in ND-PSA schemes. Consequently, if the signal channel is assumed to be always amplified independently of the residual CD, the gain spectrum is modified as

$$G(f) = G_{\mathrm{in}}\cos^2(\Delta\phi(f) + \phi_{\mathrm{offset}}) + \frac{1}{G_{\mathrm{in}}}\sin^2(\Delta\phi(f) + \phi_{\mathrm{offset}}), \qquad \phi_{\mathrm{offset}} = -\frac{\pi D c}{{f_0}^2}\Delta f^2, \tag{2}$$

where, Δf is the difference between f_0 and f_{PLL} as the frequency of the signal channel used for PLL, and ϕ_{offset} is the phase difference between each component at f_{PLL} and f_0.

To validate Eq. (2), we measured the gain spectrum of a PSA in two cases that continuous wave at f_1 (193.0 THz) or f_2 (194.0 THz) was used for PLL. f_0 was set to 193.0 THz (= f_1), and hence, amplification of f_1 was performed as degenerate phase-sensitive amplification. Figure 1 shows experimental setup. PPLN waveguides were used as nonlinear mediums. The detailed operation of each module is described elsewhere [4]. The optical phase conjugation (OPC) stage generated the idler and ASE in PPLN1 by using a second harmonics (SH) pump from PPLN2. The ASE had symmetric phase correlation centered on f_0, like a signal-idler pair. The light then passed through PMFs, which acted as dispersion mediums, and was amplified by the PSA with an SH pump from PPLN4. The carrier recovery and frequency locking of LO2 was performed by a sum-frequency-generation-assisted optical PLL (OPLL) [7]. We used a piezoelectric-transducer- (PZT-) based PLL to compensate for the relative phase drifts between the signal and the SH pump. The PZT-based PLL monitored the power of the tapped output signal extracted by bandpass filter (BPF) with 60-GHz bandwidth and controlled the relative phase so that the measured power was maximized. The gain of the PSA was 23 dB. Figure 2 shows the spectrum of the PSA output. The amplified ASE spectrum corresponded to the PSA-gain spectrum because the ASE also had symmetric phase correlation. The gain ripple caused by residual CD was confirmed. We need to get an accurate estimation of the residual CD, which affects PSA gain, in order to compare the experimental and theoretical spectra. However, it is difficult to accurately estimate the residual CD because CD only from immediately after idler generation to amplification medium contributes the gain ripple. Therefore, we evaluated the residual CD from the gain spectrum locked using f_1 amplified by the degenerate PSA configuration [Fig. 2(a)]. According to Eq. (1), residual CD is calculated as

$$D = \frac{4{f_0}^2}{c{B_n}^2}n \quad (n = 1,2,\ldots), \tag{3}$$

where, B_n is the bandwidth between the n^{th} right and left peaks when the peak at f_0 is the 0^{th} peak, i.e., the bandwidth with a phase difference of $2n\pi$. We obtained residual CD of 0.68 ps/nm and demonstrated that the experimental spectrum agreed well with the theoretical spectrum. Moreover, the gain spectrum in the case of phase locking for f_2 was in good agreement with the theoretical spectrum evaluated from Eq. (2) and CD of 0.68 ps/nm [Fig. 2(b)]. These results validate Eq. (2). For amplification of WDM signals, the bandwidth of the 0^{th} peak in the gain spectrum is important for the flat gain profile. To extend the 0^{th} peak, we compensated for the residual CD by using an LCoS-SLM-based optical programmable filter. The amount of phase modulation fed back to the SLM at each frequency was calculated from the CD estimated using the method above. Figure 2(c) shows the spectrum with and without CD compensation of 0.92 ps/nm ($f_{\text{PLL}} = f_2$). The 0^{th} peak was extended, and a flat gain spectrum within 1 dB was observed over 3.5 THz. From this spectrum and Eq. (2), the compensation reduced the residual CD to less than 0.015 ps/nm. This result suggests that broad WDM amplification can be attained by estimating the residual CD, which affects PSA gain, and then compensating for it on the order of sub-ps/nm.

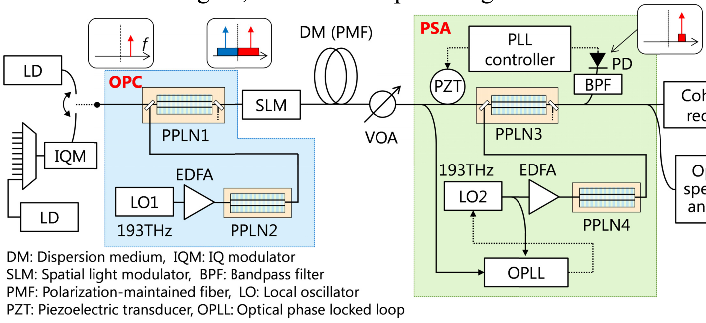

Fig. 1. Experimental setup.

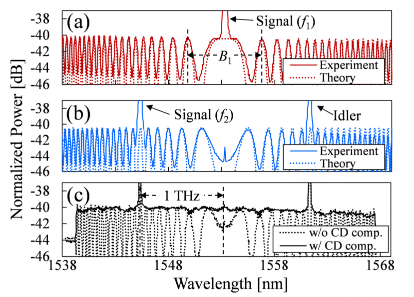

Fig. 2. Gain spectrum under CD conditions of 0.68 ps/nm with locking for (a) f_1 (193 THz) and (b) f_2 (194 THz). (c) w/ and w/o CD compensation of 0.92 ps/nm.

3. Single Channel and Simultaneous WDM Amplification Experiments Using PS-64QAM

As described above, the channel used for PLL is always amplified regardless of residual CD. However, the signal undergoes passband narrowing if the bandwidth of the gain spectrum at the frequency of that channel is narrower than the signal bandwidth. The signal bandwidth and the gain bandwidth depend on the symbol rate and Δf, respectively. We experimentally determined that the CD tolerance in an ND-PSA for a single channel depends on the symbol rate and Δf. The modulation format was single-polarized PS-64QAM with entropy of 5.0 bit. The symbol rates were set to 20 Gbaud and 5 Gbaud. The channels used were 194.0 THz and 193.1 THz, and Δf were 1 THz and 100 GHz, respectively. The residual CDs were generated by cascaded PMFs with various lengths; the CD of each PMF was estimated using the method described in Sec. 2. The OSNR at the output of the PSA was adjusted to about 23 dB regardless of PMF length and symbol rate. The received signals were demodulated offline using data-aided algorithm, and signal quality was evaluated using normalized generalized mutual information (NGMI). In addition, we also performed numerical simulations for each experimental condition. Figure 3 shows NGMI dependence on symbol rates and Δf. In 194.0-THz channel, the 20-Gbaud signal rapidly degraded from about 2 ps/nm. Figure 4 shows the spectra for 194.0-THz channel amplified by PSA under residual CD conditions. The signal was shaped in the form of a gain ripple and suffered from passband narrowing shown in results of 2.81 ps/nm and 9.31 ps/nm. The tolerance with an NGMI penalty of 0.1 was enhanced to about 9 ps/nm for the 5-Gbaud signal because of its narrower bandwidth. These results were worse than the simulation results because the PLL was unstable due to passband narrowing. Moreover, 193.1-THz channel had high CD tolerance because its frequency was in a region with a relatively wide gain spectrum. These results suggest that, for a high symbol-rate signal, more accurate CD compensation is required and the channel frequency should be close to f_0.

We also performed 10-WDM amplification using Ch. 1–10, which were 100-GHz grid in 193.1–194.0 THz and 20-Gbaud PS-64QAM signals, with the CD compensation described in Sec. 2. The input power was set to −35 dBm per channel, resulting in OSNR of 23 dB. Ch. 1 was extracted by BPF and used for PLL. In an ideal situation without residual CD, phase locking could be performed by monitoring one arbitrary channel because signal-idler pairs were simultaneous generated by one SH pump. The residual CD was 0.92 ps/nm. Figure 5 shows the PSA-output spectra with and without CD compensation. Although a gain difference of over 10 dB was observed in the spectrum without CD compensation, the spectrum variation was suppressed to within 2 dB by compensating for the CD. Figure 6 shows the channel dependence of the NGMI. Several channels maintained good quality while gain ripple degraded other channels in the case of without CD compensation. Although Ch. 8 (1546.9 nm) appeared to be strongly amplified, its NGMI was degraded due to passband narrowing. Meanwhile, the flat NGMI characteristic was achieved across all channels by compensating for the residual CD of 0.92 ps/nm.

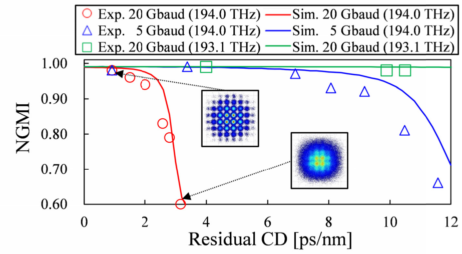

Fig. 3. NGMI as a function of residual CD for each symbol rate and Δf.

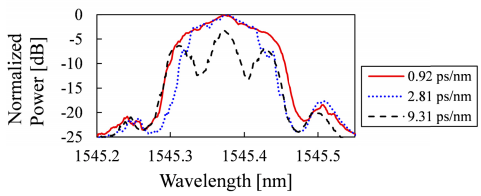

Fig. 4. Spectra of 194.0-THz channel (Δf = 1THz) amplified by PSA under residual CD conditions.

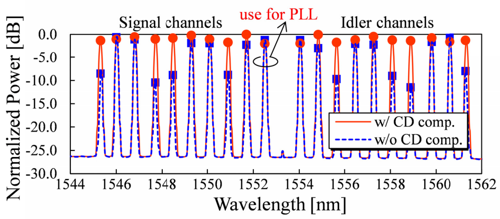

Fig. 5. WDM spectrum output for PSA.(Plot shows peak of each channel.)

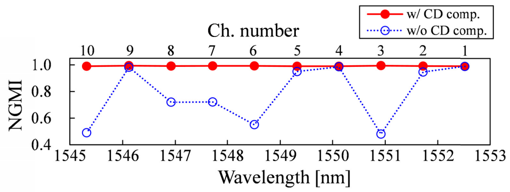

Fig. 6. NGMI characteristics for each channel.

4. Conclusion

We have theoretically and experimentally investigated the impact of residual CD on ND-PSA using PPLN modules for designing transmission system using PSA. We verified theoretical gain ripple caused by CD and confirmed that 3.5-THz broad amplification without the ripple can be realized by compensating for the CD to less than 0.015 ps/nm. We also characterized the effect of residual CD on signal quality for a single channel and WDM channels. It was shown that, the higher the symbol rate of the signal, the greater the compensation accuracy needed to prevent passband narrowing. The signal close to degenerate frequency had high CD tolerance. Moreover, WDM amplification was achieved by accurately estimating and compensating for the residual CD.

5. References

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