Experimental Investigation of Phase-Sensitive Amplification in Quantum-Dot Semiconductor Optical Amplifier

Guo-Wei Lu,[1, 2] Tianwai Bo,[3] Takahide Sakamoto,[1] Kouichi Akahane,[1] Benjamin J. Puttnam, [1]
Calvin Chun-Kit Chan,[3] and Naokatsu Yamamoto[1]
[1] National Institute of Information and Communications Technology (NICT), Japan
[2]Institute of Innovative Science and Technology, Tokai University, Japan
[3] Department of Information Engineering, The Chinese University of Hong Kong, Hong Kong
gordon.guoweilu@gmail.com

Abstract: We experimentally investigate the phase-sensitive amplification characteristics in quantum-dot semiconductor optical amplifier. Phase-sensitive dynamic ranges (PSDRs) of ~3dB and ~11dB are obtained for degenerate and non-degenerate components, respectively, with 5-dBm total launch power.

OCIS codes: (190.4410) Nonlinear optics, parametric processes; (190.4380) Nonlinear optics, four-wave mixing; (250.5980) Semiconductor optical amplifiers; (060.5060) Phase modulation.

1. Introduction

Optical phase-sensitive amplifiers (PSAs) have been extensively studied for various applications including noiseless amplification, optical phase regeneration, dispersion compensation, and quadrature decomposition. They have been experimentally demonstrated through third-order or cascaded second-order nonlinearities in various nonlinear platforms such as highly-nonlinear fiber (HNLF) [1], semiconductor optical amplifier (SOA) [2], silicon and chalcogenide waveguides, and periodically poled lithium niobate (PPLN) [3]. Among them, the SOA-based PSA shows potential for on-chip integration and modest optical power requirement, eliminating the need for additional optical amplification. Recently, quantum-dot SOAs (QD-SOAs) have attracted considerable interest for their unique properties like large unsaturated gain, remarkable ultrafast response, lower noise figure and broader gain bandwidth compared with the traditional bulk or quantum-well SOAs. Therefore, it is potentially useful to explore the phase squeezing performance of PSA based on QD-SOA. We have successfully fabricated a QD-SOA which contains highly-stacked Stranski-Krastanow QDs and has a 2-mm-long device length [4]. In this paper, for the first time to our knowledge, we experimentally characterize the phase-sensitive amplification and de-amplification performance of both degenerate and non-degenerate components in such dual-pump QD-SOA-PSAs. Phase-sensitive dynamic ranges (PSDRs) of ~3dB and ~11dB are obtained for degenerate and non-degenerate components, respectively, with a total launch power of ~5dBm.

2. Experiments and results

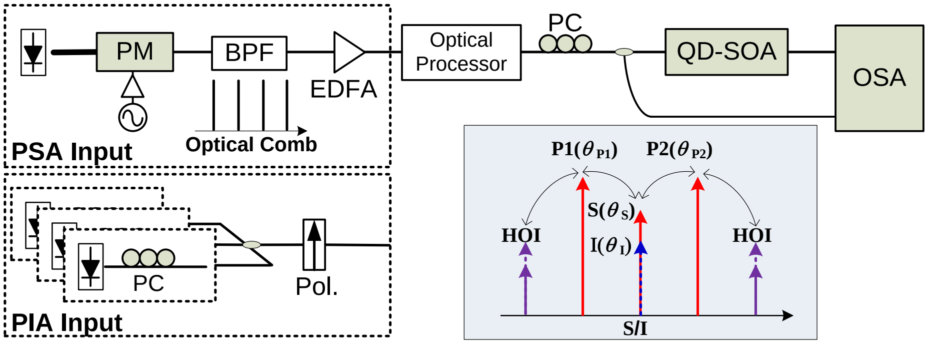

Fig. 1. Experimental setup of QD-SOA-based PSA and PIA. Inset: optical spectra (a) before and (b) after SOA.

A PSA based on dual-pump four-wave mixing (FWM) is illustrated in the inset of Fig. 1. After degenerate FWM, the phase of the generated idler (I) fulfils the relation: $\theta_I=\theta_{P1}+\theta_{P2}-\theta_S$, where $\theta_{P1,\ P2,\ S,\ \text{or}\ I}$ denotes the phase of pumps (P1 and P2), signal (S) and idler (I). If the input signal and two pumps are phase correlated, after the interference interaction between S and I, the phase-sensitive amplification and de-amplification are achieved under the relative phase difference $\theta_{Rel}= \theta_{P1}+\theta_{P2}-2\theta_S=\pi/2$ and $\theta_{Rel}=-\pi/2$, respectively. Meanwhile, at non-degenerate components, i.e. high-order idlers (HOIs), the amplification also follows this relationship to the relative phase difference. The experimental setup for characterizing the phase-sensitive gain in dual-pump QD-SOA-PSA is also depicted in Fig. 1.

Three coherent tones generated from an optical comb served as signal and pumps in the experiment. For simplicity, no data modulation was applied to signal. To generate coherent tones, a continuous wave (CW) light centered at 1547.08 nm was modulated by a phase modulator (PM), which was driven by a 30-GHz RF clock with ~20-dBm power. The three tones at the comb center were selected as the pumps and signal for the subsequent PSA process via an optical bandpass filter (BPF). After power amplification, an LCoS optical processor was used to apply attenuation and static phase shift to the signal, thus adjusting the pump-signal ratio and relative phase difference correspondingly. A polarization controller (PC) was used to control the polarization of three tones before entering the QD-SOA, which has a maximum 25-dB gain around C-band. The QD-SOA was biased at 500 mA and stabilized at 25^{o}C in the experiment. The optical spectra before and after QD-SOA were measured using an optical spectrum analyzer. As shown in Figs. 2(a) and 2(b), degenerate and non-degenerate FWM components, denoted as S/I and HOI, were obtained after QD-SOA with input pump-signal ratio of around 7 dB. For comparison, phase-insensitive amplification (PIA) was also performed by launching three co-polarized free-running CWs with a 30-GHz spacing. To avoid optical damage to the device, the total launch power to QD-SOA was kept at 5dBm in the experiment.

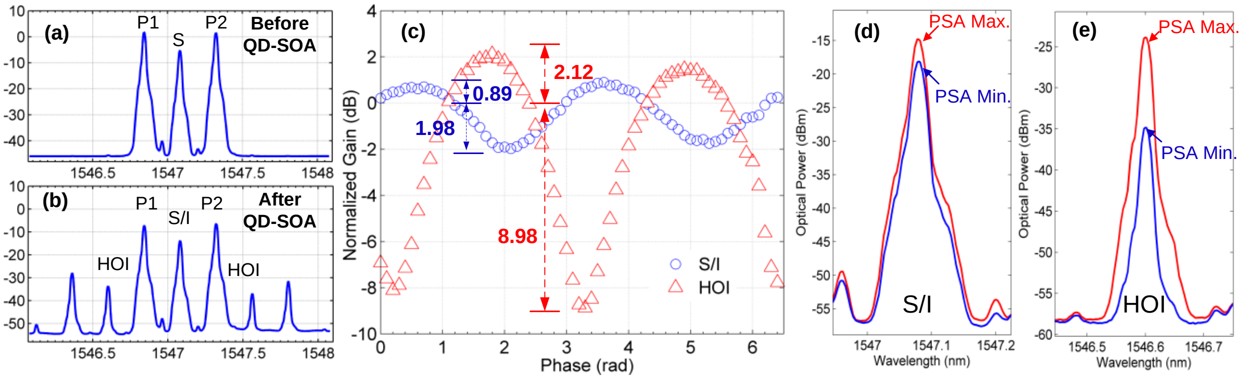

Fig. 2. Measured optical spectra (a) before and (b) after QD-SOA, phase-sensitive gain response of degenerate (S/I) and non-degenerate (HOI) components in QD-SOA-PSA, and measured PS amplification and de-amplification of (d) degenerate (S/I) and (e) non-degenerate (HOI) components.

Figure 2(c) shows the characterization of the phase-sensitive gain response of degenerate (S/I) and non-degenerate (HOI) components in QD-SOA-PSA as a function of a static phase shift applied to the input signal (S). The phase-sensitive gain was normalized by measurement of PIA power with the same signal and pump power. At the degenerate PSA component (S/I), around 0.89-dB PS amplification and 1.98-dB PS de-amplification, corresponding to 2.87-dB PSDR, was observed. On the other hand, 2.12-dB PS amplification and 8.98-dB PS de-amplification, i.e. 11.02-dB PSDR, was obtained at the non-degenerate PSA component (HOI). Here, the PSDR is defined as the difference between the maximum and minimum PSA gains. It is obvious that, compared with the degenerate component, the non-degenerate component exhibits larger PSDR, providing more efficient phase squeezing capacity. This is mainly because of the competing parametric and non-parametric gain of the degenerate component in PSA, whereas the non-degenerate components are not degraded by this competing gain process [2]. This phenomenon is different from that in PSA based on passive media like HNLF. The observed maximum and minimum gain of S/I and HOI are plotted in Figs. 2(d) and 2(e), respectively.

3. Conclusions

We have experimentally characterized the phase-sensitive amplification of dual-pump PSA based on QD-SOA. The experimental results show that, with just 5-dBm total launch power, around 11-dB PSDR was obtained for the non-degenerate PSA component, showing potential applications in the all-optical phase processing.

4. References

[1] R. Slavik, F. Parmigiani, et al., "All-optical phase and amplitude regenerator for next-generation telecommunications systems," Nature Photonics 4, 690-695 (2010).

[2] S. Sygletos, M. J. Power, F. C. G. Gunning, R. P. Webb, R. J. Manning, A. D. Ellis, "Simultaneous dual channel phase regeneration in SOAs," in Proc. ECOC, paper Tu.1.A.2 (2012).

[3] B. J. Puttnam, D. Mazroa, S. Shinada, N. Wada, "Phase-squeezing properties of non-degenrate PSAs using PPLN waveguides," Opt. Express **19** (26), B131-B139 (2011).

[4] K. Akahane, N. Yamamoto, T. Umezawa, A. Kanno, and T. Kawanishi, "A semiconductor optical amplifier comprising highly stacked InAs quantum dots fabricated using the strain-compensation technique," Jpn. J. Appl. Phys. **53**(04EG02) (2014).