Quantum-dot Semiconductor Optical Amplifiers: Novel Technique for Gain Management and Noise Suppression

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Abstract— The saturation behavior of a quantum-dot semiconductor optical amplifier (QD-SOA) is governed by a complex combination of ground state and excited state replenishment in saturation condition. Also, due to inhomogeneously broadened gain of a QD-SOA, various spectral regions are coupled via the common quantum dot (QD) reservoir, i.e., wetting layer, and the barrier layer. Hence, a frequency domain model has been developed to effectively exhibit the saturation properties of a QD-SOA in this article. Based on performed experimental tests, and also, developed model we exploit gain dynamic, gain saturation characteristics and noise suppression capability at different SOA operation conditions. The effect of an external beam on different characteristics of QD-SOAs has been investigated experimentally when the applied beam is in the gain or transparency region of the amplifiers. Also, based on different external beam power levels, the performance of the discussed method is characterized in terms of signal-to-noise ratio at the input of the QD-SOA, and output quality factor, which directly quantifies the level of intensity noise. A comprehensive comparison is performed between the quality factor of noisy input bit stream and the output data which contains the pattern effect at higher bit rates. Finally, noise suppression specification of the device at different bias currents is discussed.

1. INTRODUCTION

The gain recovery process in bulk and QW SOAs (common SOAs) can be enhanced through injection of a light beam into the active region [1]. However, for QD-SOAs the situation is to somewhat different. In QD-SOAs, the wetting layer (WL) and excited state (ES) serve as reservoirs of QD carriers. The intrinsic properties of QDs are usually masked by inhomogeneous broadening due to QD size and composition fluctuations, which make it challenging to reach the ES of QDs to inject an external light for enhancing the ground state (GS) recovery process, as discussed theoretically in [2, 3].

Instead, accelerating the WL recovery process may be considered to decrease the full-recovery time of QD-SOAs. Beside the effect of externally injected light or so-called holding beam (HB) on the gain recovery process (which needs to be applied at the gain transparency wavelength of the amplifier), it would be noteworthy to consider the amplifier characteristics when the HB resides inside the gain region.

On the other hand, it has been shown that noise suppression in gain-saturated SOAs can be achieved completely depending on device operation point and also, the input bit rate [4]. An optimum performance can be achieved by taking into account two factors: The amplifier bias current and the input power [5]. The suppression bandwidth on the other hand depends on the SOA device parameters and the operating point.

2. RESULTS AND DISCUSSION

Figure 1 illustrates the experimental setup utilized for gain characteristics measurement at the presence of the external holding beam (HB). Experiments were performed on a 5-mm-long QD-SOA with active region grown in StranskiKrastanov mode, operating at 12°C and cooled by a thermo-electric cooler element aided by a water cooler.

To inject an external light for recovery acceleration, determination of the gain transparency wavelength (the wavelength where the material gain is zero) is the first step. We determine this wavelength approximately using saturation characteristics of the QD-SOA. The setup presented in Figure 1 was used for this purpose, where a tunable laser source as HB (Agilent 81989A compact tunable laser) and a weak continuous-wave (CW) signal at 1560 nm are applied to the QD-SOA through a Wavelength Division Multiplexing (WDM) coupler. The QD-SOA has a bias current of 1.5A and a 5 nm band-pass filter (BPF) at the output selects the signal wavelength before the optical spectrum analyzer (OSA). First we characterize the gain saturation curve of the amplifier [6].

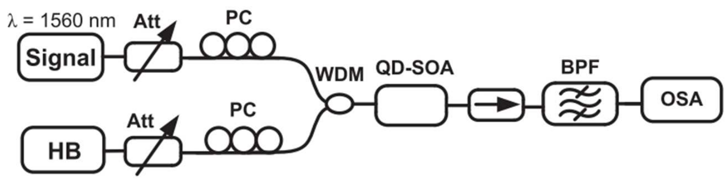

Figure 1: Experimental setup for determination of the gain transparency wavelength.

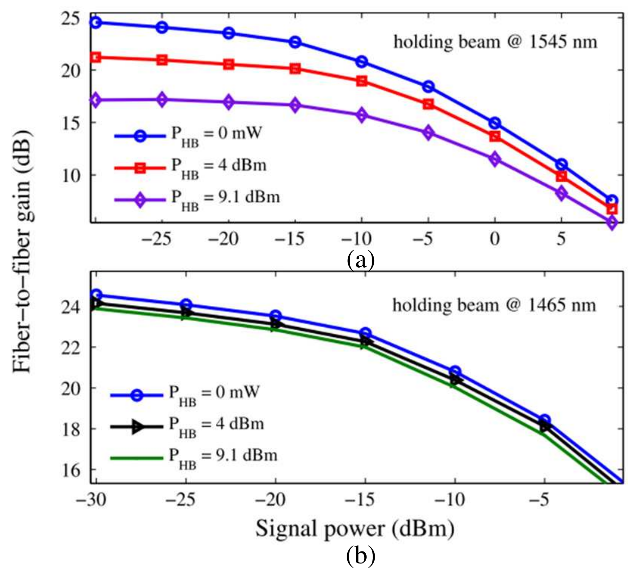

Figure 2: Fiber-to-fiber gain as a function of input signal power for HB powers of 0 mW, 4 dBm, and 9.1 dBm at HB wavelength of (a) 1545 nm and (b) 1465 nm.

Our measurements show 3dB-saturation output powers of −12.5, −9, and −6 dBm for HB powers of 0 mW, 4 dBm, and 9.1 dBm, respectively. Changing the HB frequency toward shorter wavelengths would decrease the saturation effect and also, at the device transparency wavelength, the small signal gain variation becomes negligible (in our case < 1 dB at 1465 nm, as illustrated in Figure 2(b)).

The saturation behavior of a QD-SOA is governed by a complex combination of the GS and the ES replenishment in saturation condition. Hence, a frequency domain model should be developed to effectively exhibit the saturation properties of a QD-SOA. The developed model for analyzing the effect of HB on amplitude noise suppression is similar to the model presented in [7] where coupled carrier and photon rate equations are solved for the position-dependant occupation probabilities in the GS, ES and the WL. A tenfold stack of self-assembled InAs QDs with surface density of $5 \times 10^{10}\,\mathrm{cm}^{-2}$ capped with $In_{0.2}Ga_{0.8}As$ QW layer and GaAs barrier have been considered in the model. Homogeneous and Gaussian inhomogeneous broadenings of 10 meV and 50 meV have been assumed respectively at room temperature based on the four-wave mixing spectroscopy of InGaAs QD amplifier.

Our obtained results denote that deeper saturation level and consequently, higher HB power is required for noise suppression of input stream with SNR of 10 dB compared to initial SNR of 20 dB. It should be noted that, due to higher saturation output power of QD-SOA compared to its bulk and quantum well counterparts (which provides a wide power range for applying the HB), increasing the HB power leads to higher Q-factor at the device output. Hence, depending on the input bit rate and noise figure, the Q-factor of the output can be modified by the HB power. A more complex situation for a noisy data sequence is predicted at higher bit rates when both the amplitude noise and pattern effect participate at the output signal. A Q-factor penalty may be obtained even at relatively low data rates.

To further highlight this condition, Figures 3 and 4 display the effect of input data rate on the output signal characteristics. As it is clear in Figure 3, a small Q-factor enhancement of ~ 1.5 dB is observed at bit rate of 160 Gb/s, while, a Q-factor penalty of ~ 4.5 dB is obtained for bit rate of 640 Gb/s, due to the destructive nature of both the pattern effect and noisy amplitude. Zero-level

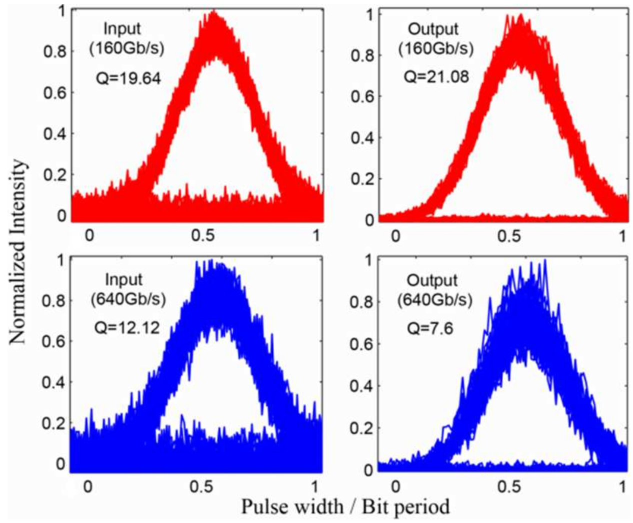

Figure 3: Eye diagrams and corresponding Q-factors for input and output data sequences at 160 Gb/s (upper row) and 640 Gb/s (lower row) bit rates. Input Q-factors have been calculated for SNR = 10 dB, HB power has been set to 0 dBm and the bias current density is 5 kA/cm^2.

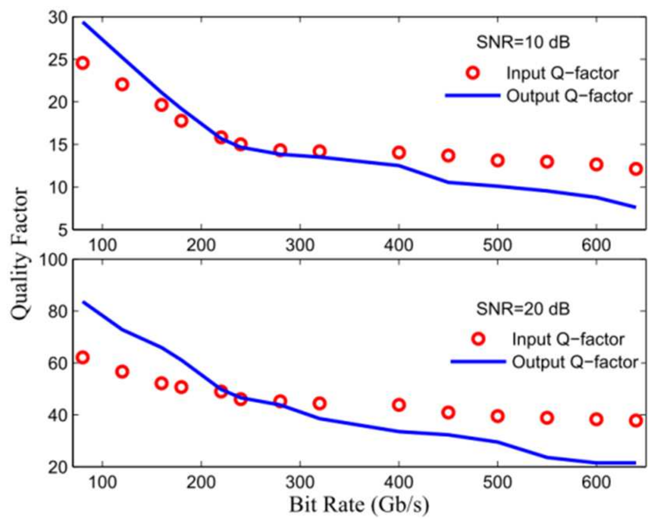

Figure 4: Q-factor versus bit rate analysis of a noisy data stream for initial SNRs of 10 dB (upper panel) and 20 dB (lower panel). HB power is 0 dBm and the bias current density is 5 kA/cm^2.

noise suppression is the main achievement at both data rates which may rely on the fact that high signal state endures the pattern effect at high bit rates whereas for zero-level noise the suppression is realized at SOA saturation regime.

REFERENCES

1. Pleumeekers, J. L., M. Kauer, K. Dreyer, C. Burrus, A. G. Dentai, S. Shunk, J. Leuthold, and C. H. Joyner, "n," *IEEE Photonics Technol. Lett.*, Vol. 14, 12–14, 2002.
2. Rostami, A., H. Baghban, R. Maram, and H. Rasooli, "Tb/s optical logic gates based on quantum-dot semiconductor optical amplifiers," *IEEE J. Quantum Electron*, Vol. 46, 354–360, 2010.
3. Baghban, H., R. Maram, R. Oliaee, R. Yadipour, and A. Rostami, "Quantum dot semiconductor optical amplifiers: Optical pumping versus electrical pumping" *J. Opt.*, Vol. 13, 035406, 2011.
4. Baghban, H. and F. Alimohammadi, "Noise suppression in quantum-dot semiconductor optical amplifiers: A bit rate-SNR analysis," *IEEE Trans. Electron Dev.*, Vol. 62, 909–913, 2015.
5. McCoy, A. D., P. Horak, B. C. Thomsen, M. Ibsen, and D. J. Richardson, "Noise suppression of incoherent light using a gain-saturated SOA: Implications for spectrum-sliced WDM systems," *IEEE J. Lightwave Technol.*, Vol. 23, 2399–2409, 2005.

6. Alavizadeh, S., H. Baghban, and A. Rostami, "Quantum-dot semiconductor optical amplifier performance management under optical injection," *J. Modern Optics*, Vol. 60, 509–514, 2013.
7. Kim, J., et al., "Theoretical and experimental study of high-speed small-signal cross-gain modulation of quantum-dot semiconductor optical amplifiers," *IEEE J. Quantum Electron*, Vol. 45, 240–248, 2009.