Quantum Dot SOA Dynamic Range Improvement for Phase Modulated Signals

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Abstract: A 10 dB input power dynamic range advantage is found for amplification of phase-encoded signals with quantum dot SOA compared to low confinement bulk SOA. The effect is attributed to differences in the alpha-factor.

OCIS codes: (250) 5590 Quantum-well, -wire and -dot devices; (060) 5060 Phase modulation.

1. Introduction

SOA have attracted new interest in the last few years due to their ability to amplify signals across the whole spectral range from 1250 nm up to 1600 nm at reasonable costs [1]. A new and interesting question has thereby been the ability of SOA to amplify phase-encoded signals. As a result, it has been shown that the constant envelope of differential phase encoded signals provides higher tolerance towards SOA nonlinear impairments such as cross-gain (XGM) and cross-phase modulation (XPM) compared to on-off keying (OOK) formats [2]. This higher tolerance has its limit once the SOA is operated in saturation where nonlinear impairments reduce the input power dynamics even for phase encoded signals [3-4]. While quantum dots (QD) as an active medium in SOA have been shown to extend the input power dynamic range (IPDR) for OOK formats, their suitability for differential-phase encoded signals has not been studied up to now. QD SOA offer low alpha-factor [5], ultra-fast QD gain response (~ 1ps) [5], greatly expanded gain bandwidth (~ 120 nm) [6], high gain (> 25 dB) [7], large IPDR for OOK signals, and high burst mode tolerance [8].

In this paper, we show for the first time the input power dynamic range improvement for a 28 GBd NRZ-DQPSK signal amplified in a 1.5 µm QD SOA. The IPDR is improved up to 10 dB compared to a low confinement bulk SOA especially designed for amplification. This enhancement found for QD SOA is attributed to the reduced phase error on the differential encoded phase signal, due to the lower alpha-factor. The IPDR of the QD SOA is 20 dB at a bit error ratio of BER = 10^{-9} and exceeds 32 dB for BER = 10^{-3}.

2. QD and bulk SOA characteristics

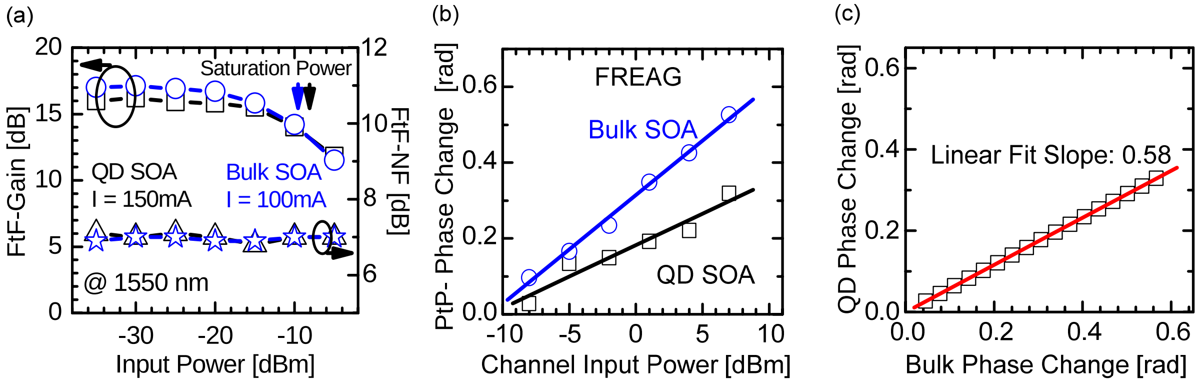

Figure 1: Comparison of QD and bulk SOA characteristics. (a) Fiber-to-fiber (FtF)-gain, FtF-noise figure (NF) and saturation power levels for a 1.5 µm QD SOA and a bulk SOA with low optical confinement of 20%. For equal current densities all characteristics are comparable. (b) Peak-to-peak (PtP)-phase changes of the bulk SOA compared to the QD SOA as a function of the channel input power. The phase changes are measured as XPM of a 33% RZ-OOK 40 Gbit/s 1010 data sequence at a wavelength of 1557 nm on a CW signal at a wavelength of 1554 nm. CW (ch. 1) and average data (ch. 2) input power is always adjusted equally, defining the channel input power. (c) Measured phase changes of the bulk SOA versus the QD SOA from (b). For all input power levels the phase effect of the QD SOA is less than the phase effect of the bulk SOA by a factor of 0.58. The phase results have been obtained using the linear spectrogram technique.

A comparison for phase encoded signals of two SOA with different active media requires similar device performance. Figure 1(a) shows comparable fiber-to-fiber (FtF)-gain, FtF-noise figure and saturation powers of the 1.5 µm QD SOA device (6 layers of InAs/InP quantum dashes) and the bulk SOA operated with the same current density [9]. The low optical confinement (20%) bulk SOA is especially designed for linear applications. The gain peak of both devices is around 1530 nm and the 3 dB bandwidth is 60 nm each. The samples have been provided by Alcatel-Thalés III-V Lab.

Figure 1(b) shows the peak-to-peak (PtP) phase changes of the QD and bulk SOA as a function of channel input power. The phase changes are measured as XPM of a 33% RZ-OOK 40 Gbit/s 1010 data sequence at a wavelength of 1557 nm on a cw signal at a wavelength of 1554 nm. The average input power of the CW (ch. 1) and data (ch. 2) channels is always adjusted equally, defining the channel input power. The phase change is measured using an electro-absorption gating technique based on linear spectrograms [10]. In Figure 1(c) the measured phase changes of the bulk SOA are plotted versus the phase changes of the QD SOA using the results from (b). For all input power levels the phase effect of the QD SOA is less than the phase effect of the bulk SOA. The ratio of the alpha-factors is obtained by linear fit of the data to $\alpha_{\text{QD}}/\alpha_{\text{Bulk}} = 0.58$.

3. Dynamic range improvement for NRZ-DQPSK by quantum dots

The IPDR for amplification of one and two 28 GBd NRZ-DQPSK data signals is studied by evaluating the bit error ratio (BER). The experimental setup comprises two decorrelated data signals at 1554 nm (Ch. 1) and 1557 nm (Ch. 2). The power levels of both channels are adjusted equally before launching them into the device under test (DUT). After amplifying both data signals in the DUT, the 1557 nm channel is blocked by a tuneable filter while the BER of the remaining data channel is analyzed. The DQPSK receiver consists of a delay interferometer (DI) based demodulator followed by a balanced detector and a bit-error ratio tester.

The IPDR is defined as the range of input power levels with less than 2 dB power penalty compared to the back-to-back case at a BER of 10^{-3} (10^{-9}). Figure 2 shows the power penalty as a function of the SOA channel input power for one and two channels at specific BER. Figure 2(a) and (b) show around 6 dB IPRD improvement for the QD SOA compared to the bulk SOA for one and two NRZ-DQPSK channels at a BER of 10^{-9}. Figure 2(c) and (d) show an IPDR improvement of 5 dB for the single channel and >10 dB for the two channel case at a BER of 10^{-3}, respectively. The full symbols correspond to the I-channel whereas the open symbols represent the Q-channel. The QD SOA exhibits a large IPDR of around 20 dB for BER = 10^{-9} and exceeds 30 dB for BER = 10^{-3}.

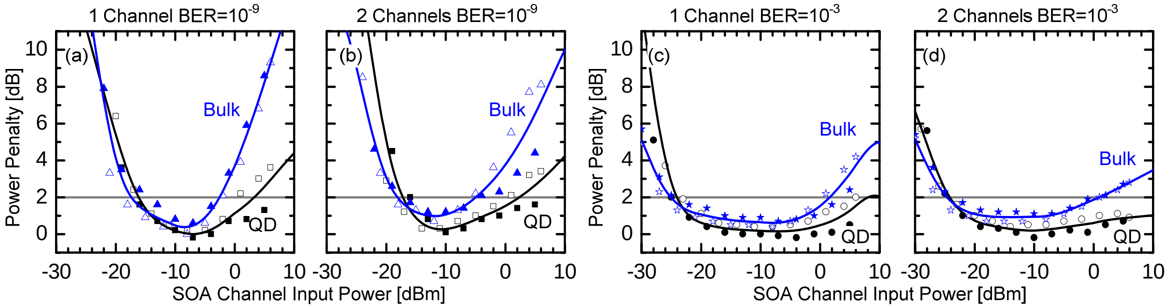

Figure 2: Power penalty for channel input power levels. The IPDR is defined as the range of input power levels with less than 2 dB power penalty compared to the back-to-back case. (a), (b) QD SOA improve the IPDR by 6 dB compared to bulk SOA for one and two 28 GBd NRZ-DQPSK signals at a BER of 10^{-9}. (c), (d) The IPDR is enhanced by 5 dB (1 ch.) and by > 10 dB (2 ch.) in the QD SOA at a BER of 10^{-3}.

4. Low alpha-factor in QD SOA reduces phase error in amplification of DQPSK signals

The unexpected IPDR enhancement found in QD SOA needs explanation. In DQPSK systems with direct detection the signals are received using a delay interferometer (DI) followed by a balanced receiver. One of the main degradation in such systems is the phase error at the DI. For a power penalty less than 2 dB the phase error must be less than 10° [11-12]. Due to the fact that typical NRZ-DQPSK transmitters show fast amplitude transitions if a phase change occurs [13], SOA can induce errors by amplitude and phase fluctuations [14]. Since the gain saturation of both devices is similar (see Figure 1(a)) the observed IPDR difference must be attributed to phase induced errors. Figure 3(a) shows the power penalty of the bulk SOA versus the power penalty of the QD SOA for all channels and BER. In this figure, the power penalties extracted from Figure 2 (a)-(d) are distinguished between the two limitations of the IPDR. For input power levels below -10 dBm the DQPSK signal is limited by noise. For input power levels above -10 dBm saturation of the SOA induces phase errors. The main difference between the samples arises for high input powers. Therefore, the phase limitations on the DQPSK signal performance is studied.

For DQPSK signals a phase error directly translates into a power penalty. In [11] the power penalty is calculated as a function of the phase error. Using this relation, the power penalties of the bulk and QD SOA can be expressed in terms of phase errors. Figure 3(b) compares the calculated phase error of the bulk SOA to the phase error of the

QD SOA. A linear fit of the data shows a slope of 0.5. This slope gives the ratio of the alpha-factors of both devices and is in good agreement with the results extracted from the independently measured PtP-phase changes using the FREAG technique (see Figure 1(c)). The fast amplitude transients in NRZ-DQPSK signals induce amplitude fluctuations in the SOA. These fluctuations induce carrier density fluctuations which cause refractive index variations and therefore phase errors. Due to the fact that the alpha-factor in QD SOA is low, the amplitude to phase conversion is reduced compared to bulk SOA, which improves the resilience to phase errors. This general advantage of QD SOA also applies for other differential phase encoded formats like NRZ/RZ-DPSK or RZ-DQPSK.

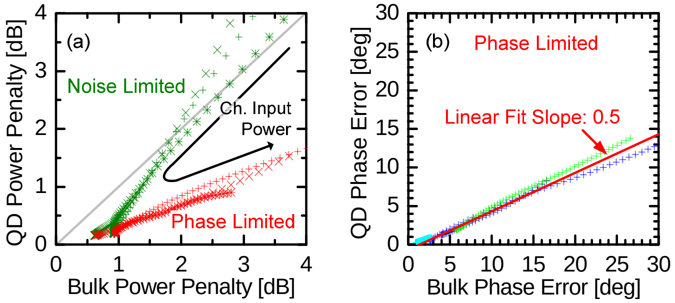

Figure 3: (a) Comparison of QD and bulk power penalty for all channels and BER. The power penalties are distinguished between the two limitations of the IPDR. For low input power levels, the DQPSK is degraded by noise (green). For high input powers, saturation of the SOA induces phase errors (red). (b) The main difference between the samples arises for high input powers. The power penalty for the phase limited case is calculated into phase error by the relation presented in [11]. The slope of a linear fit is 0.5 which corresponds to the ratio of the alpha-factors. The very good agreement between the calculated and measured ratio of the alpha-factors provides the explanation of the advantage of QD SOA in terms of IPDR. The lower alpha-factor compared to the bulk SOA reduces the impairments on the phase.

5. Summary

An input power dynamic range improvement for a 28 GBd NRZ-DQPSK signal amplified in a 1.5 µm QD SOA is demonstrated. The IPDR is improved more than 10 dB compared to a low confinement bulk SOA especially designed for amplification. This enhancement found in QD SOA is attributed to the lower alpha-factor which reduces impairments to the differentially encoded phase signal by phase errors. The IPDR of the QD SOA is 20 dB at a bit error ratio of BER = 10^{-9} and exceeds impressive 32 dB for BER = 10^{-3}.

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