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Impact of alfa-factor on SOA Dynamic Range for 20 GBd BPSK, QPSK and 16-QAM Signals

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Abstract: Impact of SOA α-factor on dynamic range limitation decreases for higher-order modulation formats leading to undistinguishable performances of bulk and QD SOAs. Results are supported by experiments at 20 GBd BPSK, QPSK and 16-QAM.

OCIS codes: (250) 5590 Quantum-well, -wire and -dot devices; (060) 1660 Coherent communications

1. Introduction

Semiconductor optical amplifiers (SOA) have attracted considerable interest in the last years due to their ability to amplify data signals of different modulation formats across a large wavelength range [1,2]. Promising applications include SOA as reach extender in access networks, or as amplifier in photonic integrated circuits of metro network switches. In such networks one hot candidate for next generation modulation formats after quadrature phase-shift keying (QPSK) is the *M*-ary quadrature amplitude modulation (QAM). As a consequence, it is of interest to learn about the ability of SOA to amplify *M*-ary QAM data – and whether bulk or quantum dot (QD) SOA provide better results. In the past, it has been shown that QD SOA (due to their lower α-factor) provide an extended input power dynamic range (IPDR) for differential quadrature phase-encoded signals (DQPSK) [3]. Therefore, one might expect that QD SOA would outperform their bulk counterparts for *M*-ary QAM formats as well.

In this paper, the influence of SOA α-factors on the amplification of 20 GBd binary phase-shift keying (BPSK), QPSK and 16-QAM signals at 1.55 µm is investigated for bulk and QD SOA. It is found that the IPDR advantage of QD SOA with a low α-factor reduces from 7 dB at BPSK to 4 dB at QPSK, and vanishes for 16-QAM. This significant change is due to the smaller probability of large amplitude transitions, which in turn leads to reduced phase errors by amplitude-phase coupling via the α-factor. The resulting IPDR of the QD SOA is around 40 dB for BPSK, 33 dB at QPSK and 12 dB at 16-QAM. This governs the optimal amplifier choice for future networks: the mature bulk SOA technology will be used for *M*-ary QAM formats and non-saturating input power levels; the relatively new QD SOA technology will be used for purely phase-encoded signals and saturating input powers.

2. QD and bulk SOA characteristics

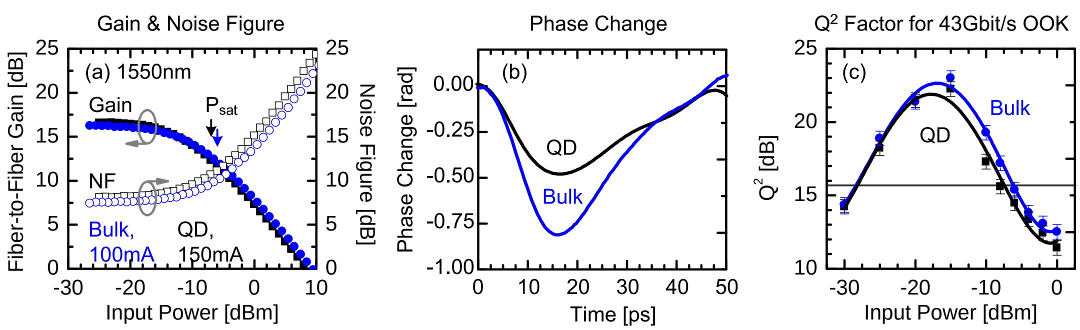

Fig. 1: Comparison of QD and bulk SOA characteristics. (a) Fiber-to-fiber gain, noise figure and saturation power levels for a 1.5 µm QD SOA (black) and bulk SOA (blue). For equal current densities all characteristics are comparable. (b) Phase response in relation to an 8 ps wide impulse. The bulk SOA shows 1.7 times the peak-to-peak phase change of the QD SOA. (c) Q^2 factor for amplification of a 43 GBit/s RZ-OOK data signal for different device input powers. Since the dynamic range (grey-line; $Q^2 = 15.6$ dB) of both SOA is almost identical, the device performance differs only in the α-factor.

For a study of the impact of the SOA α-factor on the amplification of signals with advanced modulation formats we require devices with similar characteristics. We investigated a 1.5 µm QD SOA (6 layers of InAs/InP quantum dashes) and a low optical confinement (20%) bulk SOA [4] operated with the same current density. Fig. 1(a) shows that fiber-to-fiber (FtF)-gain, FtF-noise figure and saturation input powers are indeed comparable. The gain peak of both devices is around 1530 nm, and the –3 dB bandwidth is 60 nm each. Fig. 1(b) shows the phase response of the QD and bulk SOA to an 8 ps wide impulse with an average input power of +7 dBm. The phase change is measured by means of cross-phase modulation onto a cw signal with –15 dBm. The bulk SOA shows 1.7 times higher phase changes than the QD SOA. Therefore, the ratio of the α-factors is $\alpha_{bulk} / \alpha_{QD} = 1.7$. In Fig. 1(c) the signal quality (Q^2) of a 43 GBit/s RZ-on-off keying data signal with varying input power is shown after amplification with a QD and bulk SOA. The input power dynamic range—defined as the range of input power levels for which an error-free amplification of the data signal ($Q^2 = 15.6$dB) is possible—is around 22 dB for both amplifiers. Therefore, the device performances only differ in their phase response, a fact that enables a comparison for BPSK, QPSK and 16-QAM signals in terms of the α-factor.

3. Multi-format transmitter and coherent receiver

The IPDR for amplification of 20 GBd BPSK, QPSK and 16-QAM data signals is studied by evaluating the error-vector magnitude (EVM). The experimental setup (Fig. 2(a)) comprises a software-defined multi-format transmitter [5] encoding the data onto the optical carrier at 1550 nm, the devices under test (DUT) and a coherent receiver (Agilent N4391A Optical Modulation Analyzer (OMA)). The symbol rate is 20 GBd resulting in 20 Gbit/s BPSK, 40 Gbit/s QPSK and 80 Gbit/s 16-QAM signals. The signal power level is adjusted before launching it into the DUT. After amplification, we analyze EVM as well as magnitude and phase errors (Fig. 2(b)). The OMA receives, post-processes, and analyzes the constellations. Instead of pure phase modulation, the practical implementation generates amplitude transitions which are shown in the constellations (Fig. 2(c)). In Fig. 2(d) the corresponding transition probabilities for all occurring transition lengths are depicted. The transition probability of the largest transition reduces from 50% for BPSK to 25% at QPSK down to below 5% for 16-QAM.

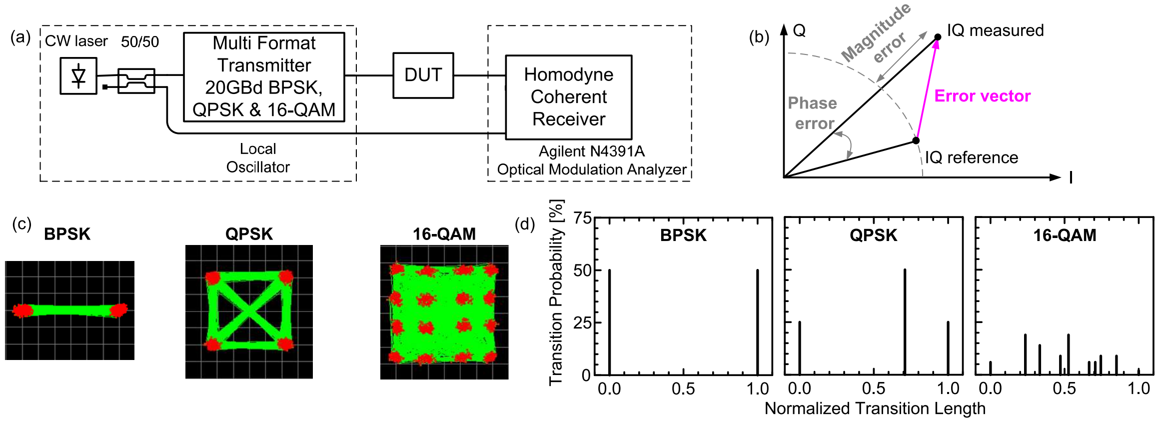

Fig. 2: Experimental setup and constellations. (a) The setup consists of a software-defined multi-format transmitter encoding 20 GBd BPSK, QPSK, and 16 QAM signals onto an optical carrier. The signal power level is adjusted before launching it to the QD or bulk SOA (DUT). The optical modulation analyzer receives, post-processes, and analyzes the data. (b) Definition of error-vector magnitude, magnitude error and phase error. (c) Complex constellation diagrams with amplitude and phase transitions. (d) Transition probability of large transitions decreases for higher order modulation formats.

4. Low QD SOA alfa-factor advantage for modulation formats with high probability of large transition

The IPDR is defined as the range of input power levels for error-free signal amplification. The EVM limits are 23.4% (bit error ratio BER = 10^{-9}) for BPSK, 16.4% for QPSK, and 10.6% (BER = 10^{-3}) for 16-QAM [6]. In Fig. 3(a)-(c) the EVM for the different modulation formats as a function of SOA input power are depicted. For low input power levels the EVM is limited by a low optical-signal-to-noise-ratio (OSNR), whereas for high input power levels SOA nonlinearities limit the performance. Fig. 3(a) shows an IPDR exceeding 40 dB with around 7 dB enhancement for the QD SOA compared to the bulk SOA and for BPSK modulation. Fig. 3(b) shows an IPDR of 33 dB with an improvement of 4 dB for the QD SOA and for QPSK modulation. The IPDR for 16-QAM (12 dB) shows no difference between both amplifier types, see Fig. 3(c).

To study the IPDR limitations for low and high input power levels, the magnitude and phase errors (Fig. 2(b)) relative to the back-to-back (BtB) values are evaluated. The IPDR for low input power is limited due to optical-signal-to-noise-ratio (OSNR) degradations. Fig. 4(a)-(c) show the monotonous increase in magnitude and phase error corresponding to the noisy constellation points. As expected, for low input power levels no difference between both samples is found. The main difference between the samples shows at large input powers. For BPSK and QPSK encoded signals the amplitude is virtually error-free, whereas the phase error significantly increases with increasing input power. The fast transients induce gain changes in the SOA. These changes induce carrier density fluctuations

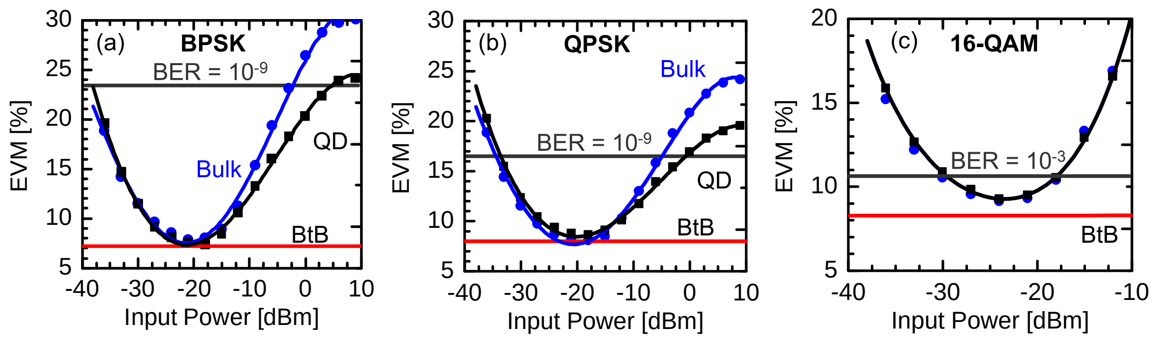

Fig. 3: EVM for different modulation formats and SOAs versus input power. (a) Low alfa-factor QD SOA shows an IPDR enhancement of 7 dB compared to bulk SOA for BPSK modulation. The IPDR is exceeding 40 dB. (b) IPDR enhancement at QPSK is reduced, but still 4 dB. An IPDR of 33 dB is found. (c) No difference is found at 16-QAM. The IPDR for both devices is 12 dB.

which in turn cause refractive index variations and therefore phase errors. Because the α-factor for the QD SOA is lower compared to bulk SOA, the amplitude-to-phase conversion is lower as well increasing the resilience to phase errors. The phase error for QPSK is smaller compared to BPSK due to a lower probability of large amplitude transitions, Fig. 2(d). This results in a reduced influence of the α-factor, and therefore decreases the IPDR advantage of a QD SOA against a bulk SOA. For the 16-QAM signal, magnitude and phase errors contribute to the EVM. Since the probability for a large transition is low (Fig. 2d), the cumulative phase error from the high number of short transitions dominates, so that the advantage of the low QD SOA α-factor vanishes. The EVM degradation for 16-QAM caused by phase errors is accompanied by amplitude errors. The gain for the three different amplitude levels is different leading to magnitude errors due to gain saturation, which can be seen from the constellation in Fig. 4(c).

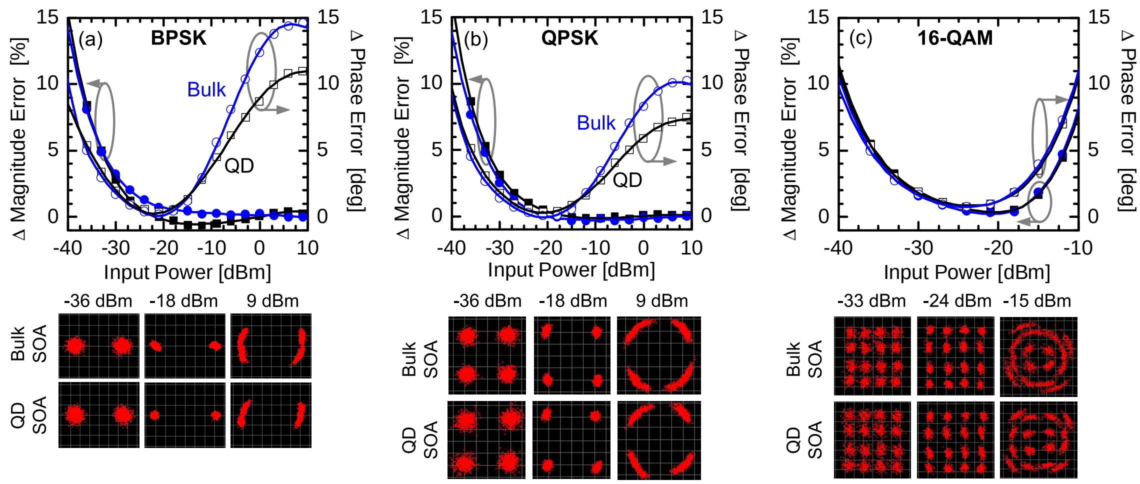

Fig. 4: Relative IPDR limits resolved for magnitude and phase error with respect to the BtB symbol. The degradation for low input powers is due to OSNR limitations. The upper limit is due to phase errors for (a) BPSK and (b) QPSK. A magnitude error hardly occurs. (c) At 16-QAM the phase error is accompanied by gain saturation inducing magnitude errors. The alfa-factor impact decreases due to a lower probability for large transitions. The constellation diagrams support these findings.

5. Summary

The impact of the α-factor on the amplification of 20 GBd BPSK, QPSK and 16-QAM has been studied for a QD and a bulk SOA. The impact of the α-factor decreases with increasing modulation-format complexity, due to a lower probability for large amplitude transitions which in turn reduces the influence of gain changes and the associated phase errors. Therefore, SOAs for *M*-ary QAM may as well rely on the more mature bulk technology operated at non-saturating input power levels. In contrast, the relatively new QD technology is preferentially used for purely phase-encoded signals (BPSK, QPSK) under gain saturation.

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