Linear and Nonlinear Semiconductor Optical Amplifiers

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Abstract: Semiconductor Optical Amplifiers (SOAs) may be designed as linear or nonlinear network elements. We report on recent results that indicate advantageous characteristics for QD SOAs as linear and bulk SOA as nonlinear network elements.

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Introduction

SOAs are in the focus of interest throughout the last years mostly for two different applications: First, they have been identified as reasonably priced amplifiers with typical 10 to 25 dB Gain across a 60 to 120 nm spectral range and a peak-gain anywhere between 1250 nm and 1600 nm, and second, because they hold promise as fast non-linear network element such as needed for all-optical wavelength conversion and signal processing [1]-[6]. Different structures, lengths and active media types are available. The question at stake though is which one best suits the needs.

In this paper we examine the linear and nonlinear characteristics of SOAs and discuss two selected applications. We will show that quantum-dot SOAs have advantageous linear characteristics and therefore might make a good case for amplifiers in access networks. Likewise we discuss the bulk SOAs as nonlinear elements such as regenerative wavelength converters. And while we show here that QD-SOAs are particularly well suited as linear access network elements and that bulk SOA are particularly well suited as nonlinear wavelength converter elements, It needs to be made clear though that the overall parameter choice such as length, confinement factor, doping levels and active media (bulk, QW, QD), pump power and current bias strongly influences the SOA overall performance and ultimately makes an SOA suitable for the respective applications.

Bulk and QD-SOA Characteristics

Fig. 1 shows some typical plots of the static and dynamic Gain of a QD and bulk SOA. Fig. 1(a)-(c) show a highly linear QD SOA. The constant Gain over a huge input power range makes this device particularly suitable for in-line amplification. Conversely, Fig. 1(d)-(f) show the Gain curves of a typical bulk SOA where the Gain strongly

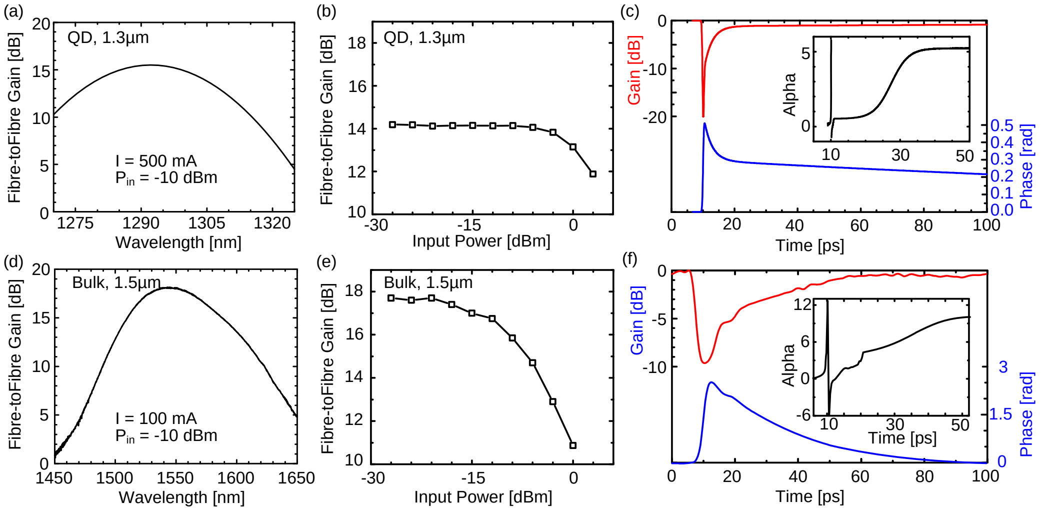

Fig. 1: (a)-(c) Steady state gain and dynamics of a typical QD SOA [7] compared to (d)-(f) a typical bulk SOA [10]. Fig. (b) shows the highly linear Gain of the QD SOA with a constant Gain over a huge input power range. In (c) the Gain and phase response of the QD SOA is plotted. A fast (1 ps) and a slow (200 ps) time constant are visible. The overall phase effects are weak though and dominated by the slow component. The inset shows a low time dependent alpha factor. (e) Typical bulk SOA Gain curve with Gain levels strongly varying with input power levels. The dynamic bulk behavior is depicted in (f). Two time constants (2ps and ~50 ps) can be seen. The phase effects are strong and the time dependent alpha-factor is large.

depends on the input power level. The important nonlinear characteristic here is the input saturation power $P_{\text{sat}}^{\text{in}}$. The QD-SOA depicted here has a large $P_{\text{sat}}^{\text{in}}$ while the $P_{\text{sat}}^{\text{in}}$ of the bulk SOA above is quite small. $P_{\text{sat}}^{\text{in}}$ is given by

$$P_{\text{sat}}^{\text{in}} = \frac{2\cdot\ln 2}{G_0-2}\cdot\frac{A\cdot\hbar\omega}{\tau_c\cdot a\cdot\Gamma}\ , \tag{1}$$

where A is the effective area, Γ the confinement factor, G_0 the unsaturated gain and τ_c the carrier lifetime.

Of particular interest are Fig. 1(c) and (f) that show the dynamic behaviour of the SOAs in a pump-probe experiment. It can be seen that the probe signals respond to the pump by an instantaneous Gain suppression and a nonlinear phase-shift followed by somewhat slower recovery times. Though the general cross-gain and cross-phase modulation effects are similar in the two samples, they still have very distinct characteristic for the bulk and QD materials. In Fig. 1(c), the Gain recovery is dominated by the fast (1 ps) quantum-dot relaxation time. The phase response on the other hand is dominated by the slow component [7]-[9]. The dynamics of the bulk SOA depicted in Fig. 1(e) are different. The bulk SOA Gain recovery time has two dominant time constants. A fairly fast component (2 ps) which has its origin in spectral hole burning and carrier heating effects as well a slower component (~50 ps) that relates to the carrier relaxation time that is due to the carrier refilling. The nonlinear phase effects are strong and mostly dominated by the slower effect [10]. The slower time constant changes with the structure and may lie anywhere between 10 and 100 ps.

The insets in Fig. 1(c) and (d) show how Henry's alpha-factor - defined as the ratio of phase and gain changes - is not constant (as assumed by many SOA simulation programs). Contrarily, it strongly changes under a large signal modulation [10]. The tendency though shows that the QD-SOA has a smaller alpha-factor than it's bulk counterpart. Subsequently, we consider two specific linear and nonlinear applications and show how bulk and quantum-dot SOAs might be instrumental in solving specific network issues.

Linear Application: QD SOA In-Line Amplifier for Reach Extension in Gigabit Passive Optical Networks

In this section we discuss the requirements on amplifiers in access networks and give arguments as well as experimental evidence that QD-SOAs might be most suitable amplifiers for PON networks [11].

Passive Optical access networks such as GPON face particular challenges in the uplink path. First, the wavelength is at 1300 nm, second they passively connect a large number of customers that generate bursty traffic with a huge dynamic input power range. The input power varies considerably, because some customers are more close to the passive combiner than others. As a consequence a potential upstream amplifier will need to cope with a large input power dynamic range (IPDR), needs to be burst resilient and should operate at 1300 nm. On the other hand, the gain not necessarily needs to be high since access networks are short reach networks.

Such burst resilience is inherent to all SOAs and is due to the fast response times of SOAs (in the order of several 10 to 1000 of picoseconds). This is an advantage over fiber based amplifiers such as EDFA, PDFA or Raman amplifiers. Furthermore, SOAs can be fabricated to cover all spectral ranges from 1250 nm to 1650 nm, which by itself is an advantage over competing technologies. So SOAs clearly are reasonable options, yet, the question at stake is which SOA within the bulk, QW and QD SOAs family would be most suitable for PONs.

We have measured the IPDR of three different SOAs for both ASK and PSK modulation formats. The QD-SOA provided an IPDR exceeding 30 dB in all instances. Fig. 2(a) and (b) show the experimental data of (a) the IPDR of

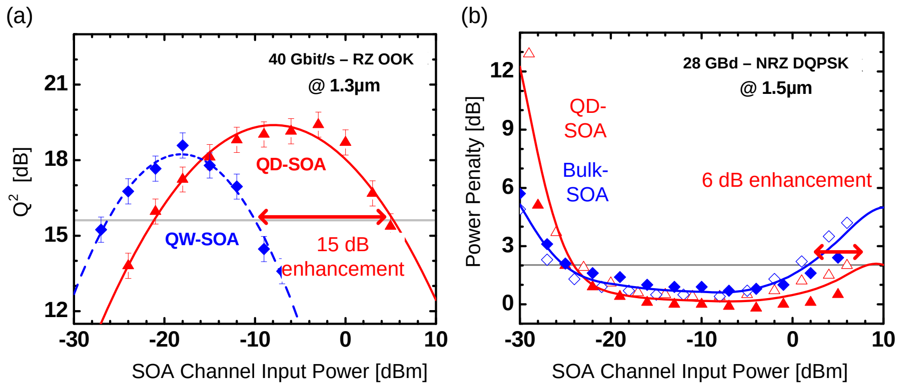

Fig. 2: Input-power dynamic range (IPDR) measurements showing enhanced IPDR range of QD-SOA over other SOAs for ASK as well as PSK encoded signals. (a) Signal quality versus SOA input power for a 40 Gbit/s RZ OOK encoded signal in a 1300 nm QW-SOA (blue diamonds)(and a 1300 nm QD-SOA (red triangles). The IPDR of the QD-SOA is significantly larger than the IPDR of the bulk SOA. (b) Power penalty over the channel input power at BER = 10^{-3} for a 28 GBd NRZ-DQPSK encoded signal. 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. The IPDR is enhanced by as much as 6 dB in the QD-SOA. The plots are taken from Refs. [12][13].

QW and a QD-SOA in a 40 Gb/s RZ on-off keying experiment [12] and (b) the IPDR of a bulk and QD-SOA for a 28 GBd NRZ-DQPSK [13]. In both instances the IPDR of the QD-SOA exceeds the respective IPDR of the QW and bulk SOA. In (a) the IPDR of the QD SOA is 26.7 dB while it is 15.5 dB for the QW SOA. Thus the IPDR of the AD SOA is 11 dB larger than the IPDR of the bulk SOA. For the PSK experiment in (b) the QD-SOA IPDR is 5 dB larger then den IPDR of the respective bulk SOA.

The plots shown here stem from different SOAs at different wavelength ranges and were performed within different experiments. One might therefore argue against the representativeness of the results. Yet, the two plots shown here are taken from larger measurements series published in references [11]-[13]. where also the IPDR of multiple decorrelated input signals was discussed. Also, it should be mentioned that the PSK experiments were actually performed with 1550 nm bulk and QD-SOAs intentionally fabricated by Alcatel-Thalès III-V Lab with identical structures – except for the active layer which was a QD-active layer in one case and a bulk active layer in the other case and operated at similar carrier densities resulting in a similar Gain.

Our interpretation of the findings is as follows. The good performance of the QD-SOA at high input launch power levels may be explained by the large input saturation power of the QD-SOA as per Eq. (1). The input saturation power is large due to the low confinement factor Γ, small differential gain dg/dN, short carrier lifetime τ_c and the moderate gain G_0 over the large effective Area A [14]. It can be shown, that such requirements are most easily met with QD-SOAs. Such optimum performance found here is not automatically granted for any QD-SOA. It is necessary to engineer the SOA accordingly. Otherwise a well-engineered bulk SOA may score better [15].

At low launch powers, the signal performance degrades once the SOAs are operated below the optical signal-to-noise ratio (OSNR) limit. Optimum low launch powers are obtained for SOAs with low noise figures (NF) and high Gain. Among the devices under test the commercial QW SOA had a much higher Gain. Consequently, it scored better for low input-power levels.

The superior IPDR exceeding 30 dB for the QD SOA for the PSK signal is attributed to the small phase error added to the PSK signal. The phase errors are small because the alpha-factor is small in QD SOAs.

Nonlinear Applications: Bulk SOA for Regenerative Wavelength Conversion

Bulk SOA offer advantages compared to QD SOA in designing regenerative wavelength converters. This is due to the fact that the alpha-factor and with this the cross-phase modulation effects are large in bulk SOA which makes the use of a filtering scheme up to highest speeds more efficient.

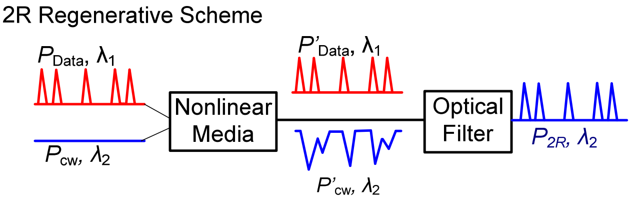

Fig. 3: Generic all-optical regeneration schemes for 2R regeneration and wavelength conversion.

Fig. 3 displays a 2R regenerative wavelength conversion scheme [5]. In this scheme, an incoming data signal P_{Data} at λ_1 is mapped onto a cw signal P_{cw} at λ_2. The regenerative process is as follows. The incoming data signal is launched into a nonlinear media, i.e. a bulk SOA. It thereby changes the refractive index or absorptive characteristics of the nonlinear media. The nonlinear media then passes the information onto a co-propagating cw signal. Unfortunately, the newly encoded signal P'_{cw} typically is distorted. The purpose of the subsequent signal basically is the clean-up of the signal. More precisely, the filter has a threefold purpose. First, the encoding of the data signal onto the cw signal normally leads to a format conversion. This format conversion is undone in the subsequent optical filter. The ideal filter for the conversion can be derived from the complex spectra behind the SOA and the complex spectra of the ideal output signal, see Fig. 4(a)[16]. Various filters have been suggested. For bulk SOA the perfect filter has been identified in the form of a PROF filter [16], which basically is the matched filter to the wavelength converter. Yet more simple implementations exist in the form of Red- or Blue-Shift filtering schemes [17], Delay-Interferometer Schemes [18], etc.. These simper schemes can be understood as approximations to the more general PROF filter. Second, while an instantaneous response of the nonlinear media would be highly desirable, the nonlinear media responses are often slow. This typically is the origin of pattern effects. It has been shown in that pattern effects can be efficiently mitigated by choosing a differential scheme [19] or an optimum optical filter at the output [20]-[22]. Third, the regenerative potential of the scheme depends on the nonlinear transfer function of the nonlinear media and filter. If chosen well, one will be able to successfully mitigate noise in both the spaces and the marks of signals and thereby may improve the OSNR, see Fig. 4(b). If the bandpass characteristics of the filter are chosen properly a good regenerative effect is obtained [23].

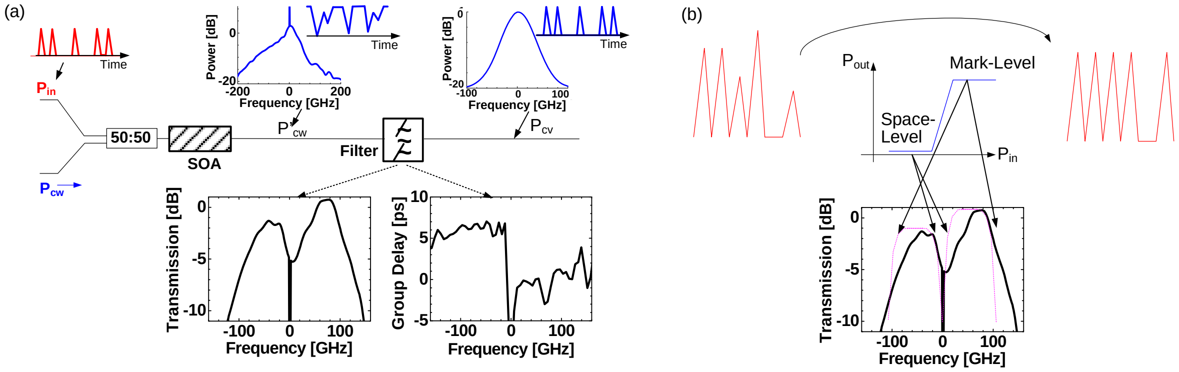

Fig. 4: (a) Schematic of the optimum filtering scheme. The two figures at the bottom show the optimum transmission and group delay for all-optical SOA wavelength conversion. The shapes have been derived from the spectra of P'$_{cw}$ and P_{cv}. (b) In order to optimize the nonlinear transfer function for ideal regeneration, the filter shape needs modification (pink dashed line).

An advantage of bulk SOAs over QW and QD SOAs is the large cross-phase modulation (XPM) effect due to large alpha factors (Fig. 1). A large alpha factor goes along with a large chirping that allows a strong distribution of the red and blue spectral components such that filtering on one or both sides of the spectrum becomes extremely efficient in terms of spectral energy in the filter passband. Another important factor that helps in providing a high SOA nonlinearity is a low saturation power as per Eq. (1). Here the bulk configuration with the inherent high confinement factor of bulk SOAs helps. Other important design factors are a large Gain G_0, lifetime dopings and large current biasing.

At this point it is again worth mentioning that QD SOAs have nonlinear characteristics as well. They have already shown promising all-optical wavelength conversion characteristics [25]. Yet, as the nonlinearity is different, different filters are needed [26] and the application set might be different as well.

Summary

For in-line amplification in future access networks SOAs with large input power dynamic ranges (IPDR) are required. These needs are met with QD SOAs, where a large IPDR can be obtained by means of a large saturation input power and where nonlinear phase noise is low thanks to a low alpha factor. On the other hand, bulk SOA offer advantages as nonlinear network elements such as regenerative wavelength converters. The nonlinear bulk SOA advantages are due to a larger alpha-factor and for bulk SOAs engineered with a low input saturation power.

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