The non-linear behaviour of laser diodes integrated with semiconductor optical amplifiers.

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ABSTRACT
When injecting an external signal into the optical amplifier of an integrated laser-amplifier photonic circuit, the feedback from the laser may result in a strong non-linearity that can be observed in the output power vs. input power for the signal. We will briefly discuss the nature of this non-linearity. Several applications in optical signal processing (2R regeneration, wavelength conversion, ...) will be discussed in more detail..
Keywords: optical signal processing, regeneration, semiconductor optical amplifiers.

1. INTRODUCTION

There is a general expectation that the future of optical communications lies in all-optical networking in which not only transmission, but also switching is done in the optical domain. Such all-optical networks would then require different new all-optical functionalities, e.g. wavelength conversion, optical signal regeneration, the reading, writing and erasure of optical headers, etc. [1]. Some of these operations will have to occur at very high bitrates (e.g. wavelength conversion, signal regeneration, … must be able at the line rate which can be 40 Gb/s or higher), while others, aimed a processing headers, may only need to fulfil relaxed speed requirements.
Many different solutions have been proposed in the literature for all-optical signal processing and for wavelength conversion and optical signal regeneration in particular. However, despite this fact, there are not yet solutions that are considered mature enough for deployment in real networks. The proposed wavelength converters and regenerators all suffer from serious drawbacks that make it difficult to guarantee stable operation over a long-term and in uncontrolled environments. E.g. regenerators based on different types of interferometers ([2-3], either implemented as photonic integrated circuits or in fibers, require the control of several currents and of temperature and input signal polarisation. Other, non-interferometric regenerators, e.g. based on saturable absorbers or electro-absorption modulators, only provide a rather weak regeneration and then even only for the logical zeroes [4]. Moreover, some of the regenerators and wavelength converters proposed only would operate for a specific signal format (i.e. RZ signals) at a specific bitrate and are therefore hard to include in the sort of evolutionary scenario that is usually taken when increasing capacity or functionality of communication systems.
Recently we have proposed a 2R regenerator that doesn't suffer from these drawbacks: a semiconductor optical amplifier (SOA) integrated with a DFB laser in which the feedback from the laser power to the SOA output can cause flipping of the spatial hole burning in the SOA [5]. In this paper, we review some of the special properties of this configuration. We discuss both numerical and experimental results; with the latter being obtained for a number of special devices. Apart from optical 2R regeneration, we will also briefly touch on potential applications in wavelength conversion and even optical signal monitoring. In particular, we will show that, depending on the wavelength, a good digital characteristic can be obtained both in transmission and reflection. Most of the presented results are for the static behaviour; however we will present some experimental results at 10 Gb/s as well.

2. OPERATION PRINCIPLE AND NUMERICAL SIMULATIONS

The photonic circuit (which is implemented as an integrated circuit) that we use is shown schematically in Figure 1. Also, ideally the laser diode is a perfectly AR-coated DFB laser diode such that the signal light reaching the laser diode is not reflected back into the SOA, but in practical devices there is still some residual reflection. The coupler is characterised by a coupling factor x (i.e. a fraction x of the output of the SOA is coupled into the laser diode).
The regeneration is caused by a switching of the spatial hole burning (longitudinal carrier distribution) in the SOA due to the light from the DFB laser. Indeed, at low input signal power, the laser power is high and saturates the SOA, giving it a low amplification. As the input power increases, more power is injected into the laser diode and this results in less laser power being injected into the SOA from the r.h.s.. As a result of this, the

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amplification of the SOA increases, the power injected into the laser increases and the laser emission decreases even further. At a certain level of input signal power, this feedback mechanism is so strong that it causes the laser diode to switch off or nearly switch off, with then the SOA being saturated by the input signal. The regeneration can be very fast since the SOA is always in a saturated condition with a high power (either from the signal or from the laser). And by properly chosing the laser bias current, one can take care that the laser just switches off but remains close to threshold so that it remains fast.

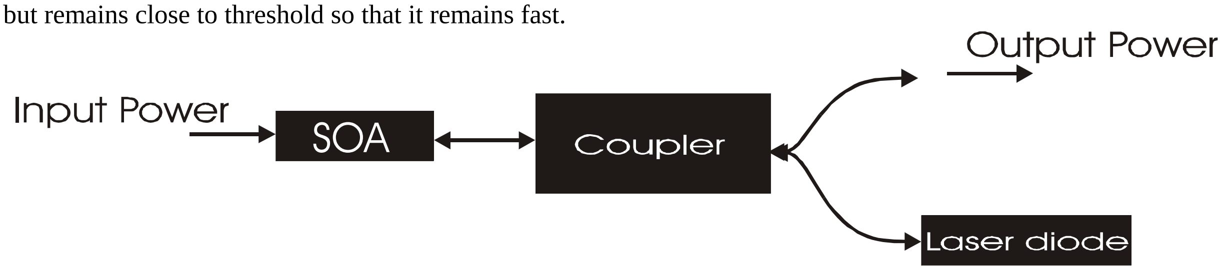

Fig. 1: Schematic of a semiconductor laser integrated with an SOA

Figure 2 shows the calculated output power vs. signal input power for the configuration in Figure 1 for a number of currents injected into the DFB laser. The current injected into the SOA was kept fixed at 120 mA. It can be seen that for the right choice of the DFB and SOA current one can obtain a very steep transition from low to high output power, with a more or less constant output power above the transition. This device can therefore be used as optical regenerator and can give both extinction ratio improvement (especially for small input extinction ratios) and noise and crosstalk reduction for the “1”’s in a signal.

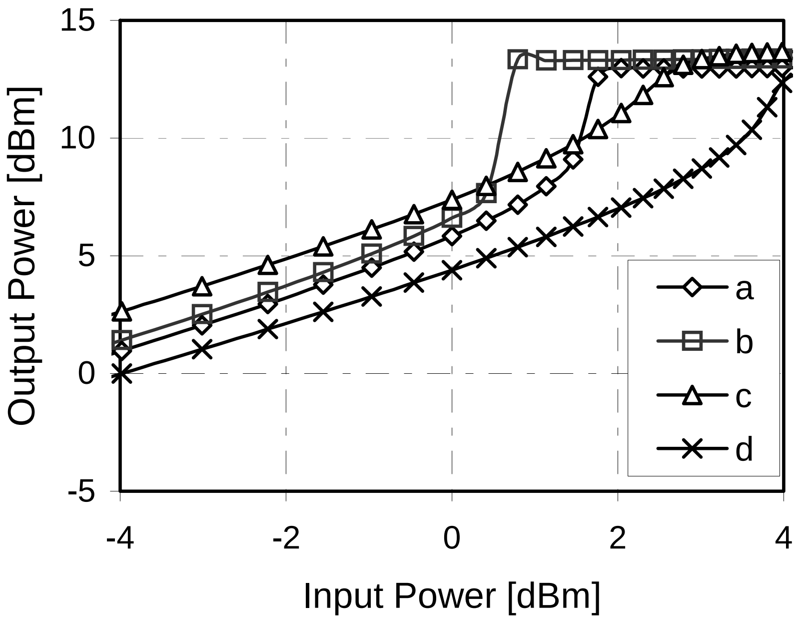

Fig. 2: Calculated static decision characteristics for different coupling factors (x) and drive currents of both SOA and laser diode. (a) x=0.5, I_{laser}=120mA and I I_{SOA}=120mA, (b) x=0.5, I_{laser}=120mA and I_{SOA}=130mA, (c) x=0.6, I_{laser}=120mA and I_{SOA}=120mA, (d) x=0.5, I_{laser}=140mA and I_{SOA} =120mA.

As we will show later, the output power from the laser is nearly constant before the transition in Figure 2 and then drops sharply after this transition. This laser output power can thus be used for wavelength conversion (with inverted operation) and if the DFB laser diode was replaced by a tunable laser diode, one could use the device in Figure 1 for wavelength conversion to any of the wavelengths within the tuning range of the tunable laser diode.

3. EXPERIMENTAL RESULTS AND DISCUSSION

We didn’t have an integrated configuration as shown in Figure 1 available. However, for our first experiments we used a wavelength selectable laser as shown in Figure 3 and described in detail in [8]. It consists of an SOA that is connected to four laser diodes by means of a 1 by 4-coupler. Normally the light is coupled from lasers to SOA.

In our case light is injected into the SOA and coupled out at the back facet of one of the lasers. One can already notice two distinct differences with the originally simulated and measured device. The coupling between laser diode and SOA is smaller which leads to less feedback and the output light has to pass through the laser before being measured.

The experimental results reported hereafter were all obtained for a laser current of 30 mA and an SOA current of 45 mA.

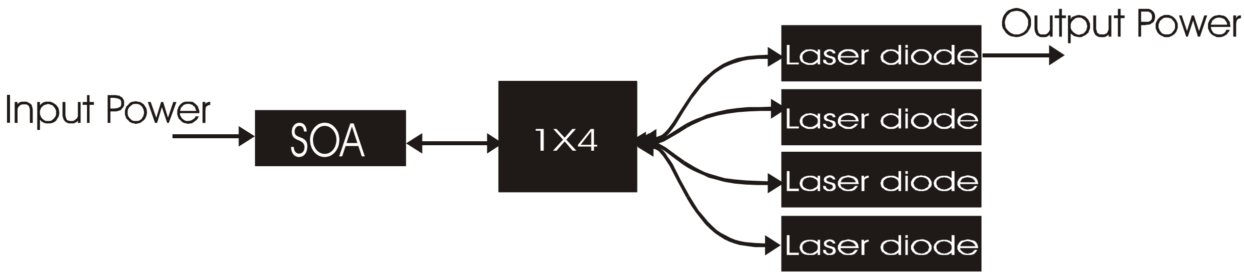

Fig. 3: Schematic of the wavelength-selectable laser used as regenerator

3.1 Optical 2R regeneration

Figure 4 shows the measured static characteristics in transmission for different signal wavelengths. The emission wavelength of the laser diode was around 1540 nm. As can be seen, a good regeneration is obtained for signal wavelengths that are sufficiently far from the lasing or Bragg wavelength and the regeneration curves are in qualitative agreement with the numerical results. The reason is that for signal wavelengths close to the Bragg wavelength, the signal is reflected too much in the laser diode and there will always be a similar amount of signal injection on both sides of the SOA, to such an extent that a flipping of the spatial hole burning is no longer possible. The shift of the decision point towards higher input power for decreasing wavelength is largely due to the wavelength dependence of the amplifier gain, as can be seen from the curves below the decision point.
One can also notice that the output power is extremely flat above the decision point and varies less than 0.5 dB over an input power range of 10 dB.

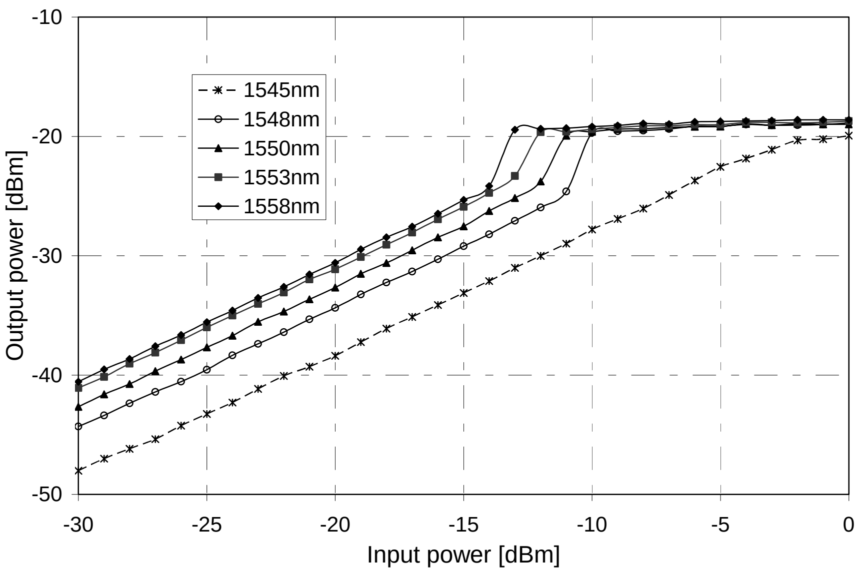

Fig. 4: Measured static decision characteristic in transmission for different signal wavelengths.

Figure 5 shows the regeneration characteristics in reflection. For wavelengths sufficiently far from the Bragg wavelength of the laser, this reflection is due to the residual facet reflectivity. As can be seen, regeneration occurs only far from the Bragg wavelength, when the signal injection into the SOA can be considered asymmetric. For the 1550 nm wavelength, one can observe that an output extinction ratio of around 20 dB can be obtained for an input extinction ratio of less than 5 dB. The power jump at the decision or threshold point varies significantly with signal wavelength though and for a signal wavelength of 1558 nm, the regeneration characteristic is less pronounced. One can also see that the reflected power slowly decreases above the decision point.

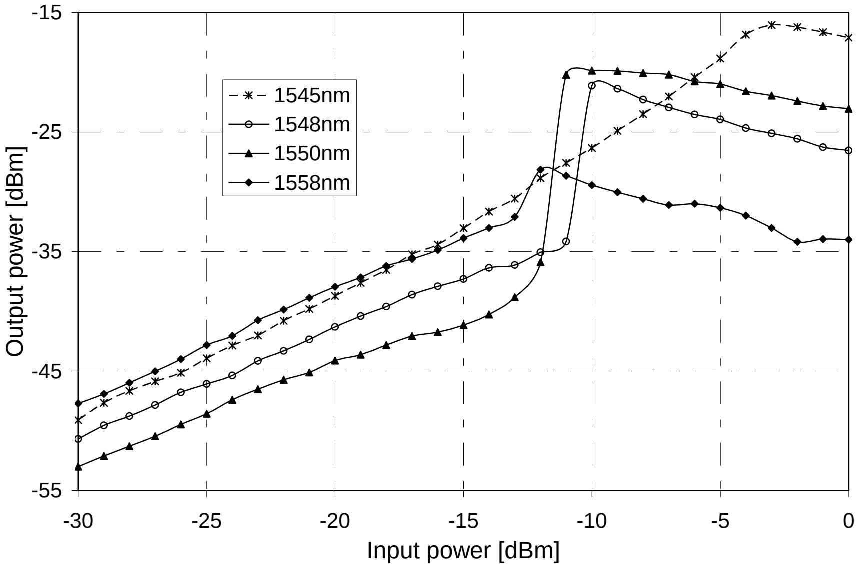

Fig. 5: Measured static decision characteristic in reflection for different signal wavelengths.

3.2 Dynamic operation

We also performed measurements of the signal regeneration at 10 Gb/s using the device both in transmission or reflection. In Fig. 6 input and output eye-diagrams at 10 Gb/s in transmission are shown. It can be seen that an output extinction ratio of 10.3dB was obtained for an input extinction ratio of 3.4dB. The input eye diagram was measured after the 90/10 splitter and with an extra attenuation of 6dB resulting in a total attenuation of 16dB. The output eye diagram was measured with an attenuation of the input power of 14dB. Taking these attenuations into account one can see that the powers in the eye diagrams show good agreement with the difference between input and output power of the decision characteristic shown in Fig. 4 [6].

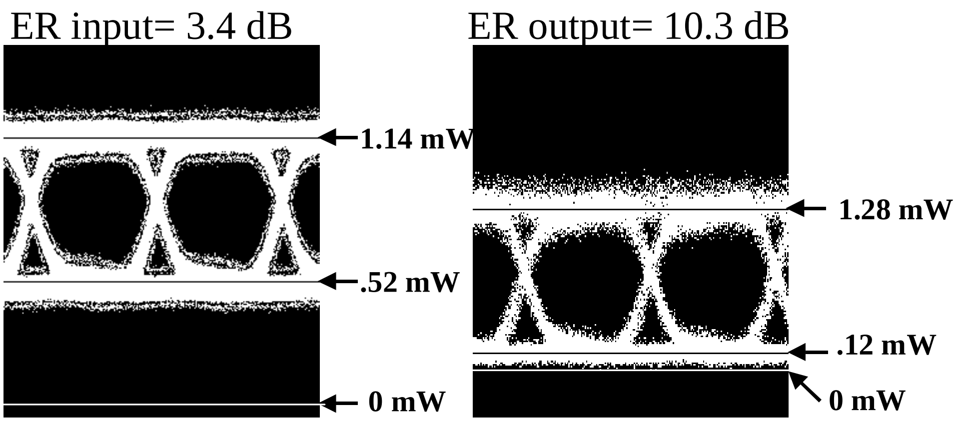

Fig. 6: Input and output eye diagrams at 10 Gb/s in transmission.

In Fig. 7, we show the input and output eye diagrams in reflection mode at 10 Gb/s. An improvement of the extinction ratio with more than 5 dB can be observed and this again, as in the case of transmission, for a rather small input extinction ratio. However, the response in reflection is also seen to be slightly slower than in transmission.

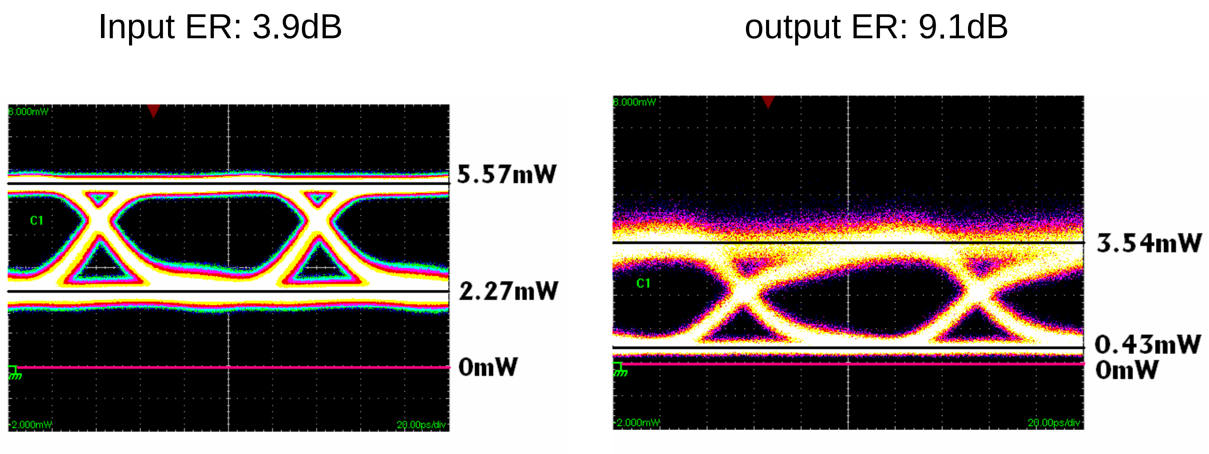

Fig. 7: Input and output eye diagrams at 10 Gb/s in reflection.

Both in transmission and reflection, one can observe a clear noise reduction for the logical zeroes.

3.3 Wavelength conversion and other applications

As has been mentioned above, the output power of the laser diode shows a somewhat opposite variation to the one shown in Figure 4. Figure 8 shows the measured laser power vs. signal input power characteristic under static operation corresponding with one of the regeneration characteristics in Figure 4. One can see a very sharp drop in laser power of about 30 dB for a signal input power of -7 dBm. This drop occurs over 1 dB variation of signal input power. Hence, when using the device of Figure 3 for wavelength conversion, one will also get a large extinction ratio improvement and noise reduction. We didn't yet perform dynamic measurements of the wavelength conversion however.
The difference in threshold level between Figure 8 and Figure 4 is due to different fiber coupling losses.

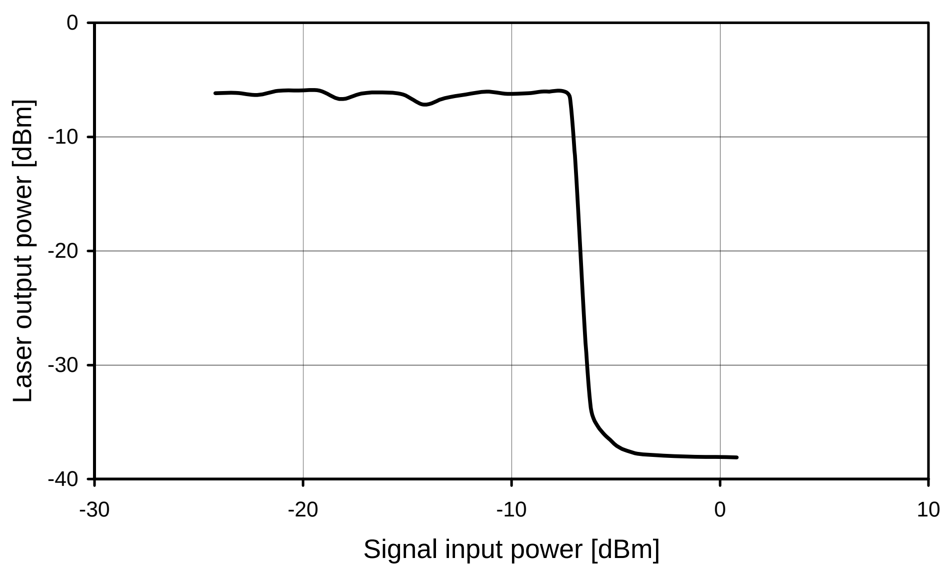

Fig. 8:Output power of the laser diode vs. signal input power.

The very sharp characteristic obtained in Figure 8 is also potentially useful in optical signal monitoring. We have previously demonstrated that a signal histogram can be obtained optically (without the use of high frequency electronics), making use of an optical decision characteristic provided that this decision characteristic is sufficiently sharp [7]. So far we were not capable of experimental demonstration because a stable optical decision circuit that provides a sufficiently sharp characteristic was not available to us. The characteristic given in Figure 5 would however be sufficiently sharp and the device used to obtain it also is a stable, non-interferometric device. Experiments to use the regenerator for optical signal monitoring are therefore planned for the near future.

4. CONCLUSIONS

Applications in optical signal processing and mainly in optical signal regeneration of a DFB laser diode integrated with a SOA has been discussed. 2R optical regeneration at 10 Gb/s has been demonstrated with a large extinction ratio improvement, even for small input extinction ratio, and a noise reduction for logical zeroes. Our results were obtained with non-optimised "off the shelf" devices and thus better results can be expected for optimised devices. In addition to optical signal regeneration, the components could also be used for wavelength conversion and in optical signal monitoring. The laser output power that could be used for such applications exhibits a very sharp drop.

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