Simulation of Directly Modulated RSOA

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***Abstract*-We apply a reduced but efficient model to simulate the operation of a directly modulated reflective semiconductor optical amplifier (RSOA). The numerical results allow us to investigate and assess how the RSOA responds to different data modulation rates and show trends for acceptable performance.**

I. Introduction

Reflective semiconductor amplifiers (RSOAs) have become a key technology for the manipulation of bidirectionally flowing digital information. Specifically, in next generation broadband access applications [1], such as colorless passive optical access networks and radio over fiber, it is necessary to receive and amplify signals in the downstream while remodulate them in the upstream communication link. A single RSOA is an ideal module for performing these tasks simultaneously by exploiting the same device facet for signal input injection and output extraction, thus obviating the need for extra fiber components and multiple optoelectronic devices while exhibiting the attractive advantages of conventional SOAs. Given their significant role, numerical simulation of RSOAs is a helpful means for theoretically describing, predicting and optimizing their behavior. The common approach followed for this purpose is computationally cumbersome, as it involves solving three coupled partial nonlinear differential equations with boundary conditions [2]. In this paper we apply the reduced but accurate model formulated in [3] for the practical case of RSOAs which are directly modulated by an electrical data pattern. In Section II the specific model gives us the lightwave encoded signal at the RSOA output as the solution of a standard differential equation, which greatly simplifies the computational complexity. In Section III it allows us to conveniently assess the RSOA direct modulation capability by investigating the influence of the RSOA finite carrier lifetime, which is primarily responsible for the RSOA limited modulation bandwidth, on appropriately defined performance metrics

II. Modelling

The basic configuration of a directly modulated RSOA is shown in Fig. 1. A continuous wave (CW) signal is inserted in the device having constant power, P_{CW}. Simultaneously, an RF data signal of repetition rate $B_{rep}=1/T$ is superimposed to the RSOA dc bias current and modulates its driving current. Due to the reflective rear edge of the RSOA cavity, the signal makes a double pass inside the active medium of length, L, and exits from the front side. Although a replica of the RF data signal should be reproduced in optical form at the RSOA output, as B_{rep} is increased and exceeds the RSOA modulation bandwidth, B_{mod}, pattern effects occur which result in performance degradation [4].

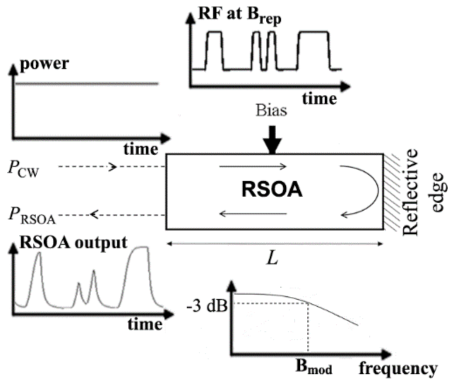

Fig. 1. Configuration of directly modulated RSOA.

The simulation of the RSOA operation requires to know the power at its output, $P_{RSOA}(t)=|E_{RSOA}(t)|^2$, where the signal electric field is [3]

$$E_{RSOA}(t)=\sqrt{P_{CW}}\exp\left[(1-ja)h(t-2Ln_g/c)\right] \quad (1)$$

and a is the RSOA linewidth enhancement factor, n_g is the group refractive index of the semiconductor material and $h(t)$ is the RSOA integrated gain function. $h(t)$ is obtained from the solution of [3]

$$\frac{dh(t)}{dt}=-\frac{h(t)-\Gamma g N_0 L\left[(I(t)/I_0)-1\right]}{T_{car}}-\frac{\exp\left[2h(t)\right]-1}{E_{sat}}P_{CW} \quad (2)$$

where Γ is the RSOA confinement factor, g is the RSOA differential gain, N_0 is the RSOA carrier density at transparency, T_{car} is the RSOA carrier lifetime, E_{sat} is the RSOA saturation energy. The RSOA current required for transparency is $I_0=qALN_0/T_{car}$ [5], where q is the electron charge and A is the area of semiconductor active region. The electrical pulse is modeled as [6]

$$I(t)=I_{dc}-I_m+2I_m\left\{H(t)\left[1-e^{-t^2/t_r^2}\right]-H(t-T)\left[1-e^{-(t-T)^2/t_r^2}\right]\right\} \quad (3)$$

where $H(t)$ is Heaviside step function, $I_{dc}=1.2I_0$ is the RSOA dc bias current, $I_m=0.1I_0$ is the applied modulation current and $t_r=17\%T$ is the pulse rise time.

The 3 dB angular frequency of the RSOA direct modulation response is [5]

$$\Omega_{3\mathrm{dB}} = \frac{\sqrt{3}}{T_{\mathrm{car}}}\left\{1+W\left[\frac{2T_{\mathrm{car}}P_{\mathrm{CW}}}{E_{\mathrm{sat}}}\exp\left(2\bar{g}_0 L+\frac{2T_{\mathrm{car}}P_{\mathrm{CW}}}{E_{\mathrm{sat}}}\right)\right]\right\} \quad (4)$$

where $W[\cdot]$ is Lambert's function available in Matlab and $\bar{g}_0 = \Gamma g N_0\left[\left(I_{\mathrm{dc}}/I_0\right)-1\right]$ is the RSOA steady-state gain.

III. RESULTS

The numerical simulation is performed for the RSOA typical parameters cited in Table I [3], [5]. The capability of the RSOA for direct modulation is explored against the maximum amplitude difference between marks, $AD_{1,\mathrm{max}}$ and between marks and spaces, $AD_{1/0,\mathrm{max}}$, which are defined as in Fig. 3(a)-right column. $AD_{1,\mathrm{max}}$ must be as small as possible, while $AD_{1/0,\mathrm{max}}$ as high as possible. Since, by principle of operation, the RSOA direct modulation is critically affected by T_{car}, these metrics are evaluated against this parameter. Because the RSOA 3 dB bandwidth, $\Omega_{3\mathrm{dB}}/(2\pi)$, is 1.3 GHz, we examine three different modulation rates, i.e. 1 Gb/s, 3 Gb/s and 6 Gb/s. These rates represent RSOA relaxed, medium and tight direct modulation conditions, respectively.

Fig. 2(a) shows that for all rates $AD_{1,\mathrm{max}}$ is increased as T_{car} goes from 100 ps to 400 ps, with the rising slope being more pronounced for the 6 Gb/s curve. At 1 Gb/s $AD_{1,\mathrm{max}}$ is lower than 1 dB and hence acceptable for the entire T_{car} scanned span. At 3 Gb/s this happens when T_{car} is lowered to 210 ps. However at 6 Gb/s this is not possible at all. Also Fig. 2(b) shows that as T_{car} is increased $AD_{1/0,\mathrm{max}}$ is reduced at all rates and deviates from its maximum, which is reached at the left-most extreme of the diagram, to an extent that is higher for 400 ps and 6 Gb/s.

TABLE I
RSOA SIMULATION PARAMETERS

Parameter	Value
P_{CW} (dBm)	-11
L (mm)	0.5
α	5
n_g	3.6
Γ	0.2
g (m^2)	8×10^{-20}
N_0 (m^{-3})	8×10^{23}
E_{sat} (pJ)	1
A (m^2)	1.17×10^{-13}

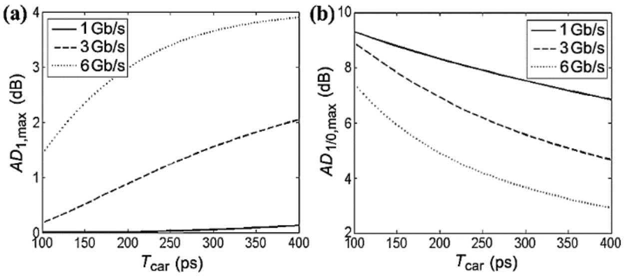

Fig. 2. (a) $AD_{1,\mathrm{max}}$ vs. T_{car} and (b) $AD_{0/1,\mathrm{max}}$ vs. T_{car} for 1 Gb/s (solid line), 3 Gb/s (dashed line) and 6 Gb/s (dotted line).

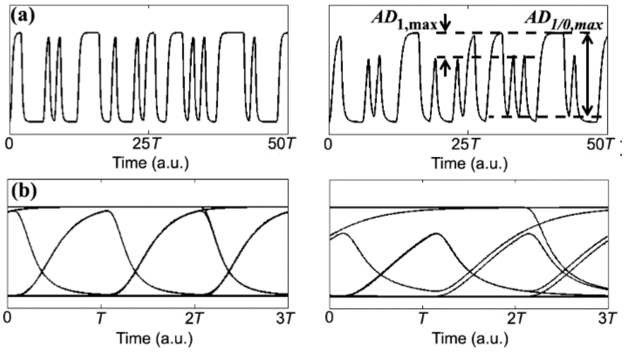

Fig. 3. (a) Pulse waveforms and (b) corresponding pseudo-eye diagrams at RSOA output for T_{car}= 100 ps. Left column: 3 Gb/s. Right column: 6 Gb/s. Arrows show the definitions of $AD_{1,\mathrm{max}}$ and $AD_{1/0,\mathrm{max}}$.

From Fig. 2 a rational choice for improving the quality of the encoded signal is T_{car} = 100 ps. This happens indeed at 3 Gb/s (Fig. 3(a)-left column), where the form of the encoded signal resembles that of the electrical signal modulating the RSOA. This is quantified by $AD_{1,\mathrm{max}}$ = 0.18 dB and $AD_{1/0,\mathrm{max}}$ = 8.9 dB. Moreover, the corresponding pseudo-eye diagram (PED) [6] in Fig. 3(b) is clear and open. At 6 Gb/s, however, the encoded marks and spaces suffer from intense amplitude fluctuations and the signal quality is poor (Fig. 3(a)-right column). Hence $AD_{1,\mathrm{max}}$ and $AD_{1/0,\mathrm{max}}$ are deteriorated to 1.4 dB and 7.4 dB, respectively, while the PED becomes distorted. Dropping $AD_{1,\mathrm{max}}$ below 1 dB would require, according to (4), to reduce the RSOA carrier lifetime by 20% and increase the CW input power by 3 dB. Extending this trend to faster RSOA direct modulation rates would impose tight requirements on the RSOA speed of modulation response and degree of gain saturation. The situation can be relaxed by employing properly tailored optical notch filters [4], which is an option that we intend to investigate for RSOAs.

IV. CONCLUSION

In conclusion, we have conducted a concise simulation of a directly modulated RSOA and identified performance limitations, trends and perspectives.

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