Experiment and Simulation on the Reduction of the Semiconductor Optical Amplifier Optoelectronic Switching Time

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Abstract-- *A technique to reduce the Semiconductor Optical Amplifier electro-optic switching times is implement. The technique, called PISIC (pre-impulse-step injected current), presented a reduction of the SOA switching times from almost 2ns (simple-step current response) to little more than 200ps (step with pre-pulse response). Forecasts done through simulations, using optimized values of current step and pre-pulse, showed even a faster optical switch response, with switching time reduction to values around 10 ps.*

Index Terms-- *semiconductor optical amplifier, optical switching, pre-pulse current injection*

I. INTRODUCTION

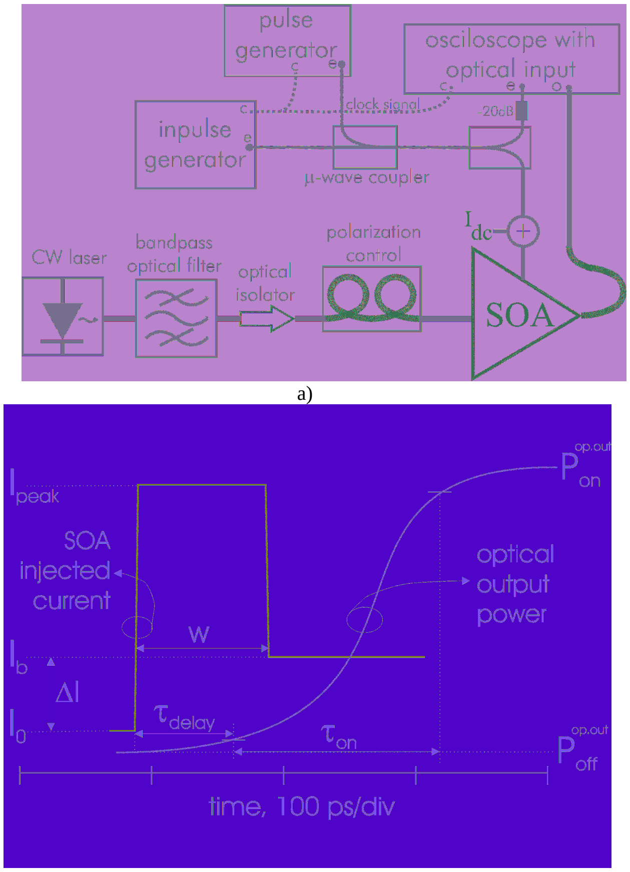
The semiconductor optical amplifier (SOA) is a promising device for add-and-drop links and wavelength conversion in wavelength-division multiplexed (WDM) networks, including applications of space switching [1]. The SOA can also be employed for the regeneration and reshaping (2R) of optical pulsed signals after its degradation by the fiber dispersion effect [2,3]. In addition, once the technology of optoelectronic integrated circuits is mature and less expensive, the semiconductor optical amplifier may be one of the main devices for optical signal processing. This is due to the multifunctional property of SOAs to being able to amplify, detect, modulate or attenuate the optical signal [4]. Finally, the SOA can be employed as an optical switch due to its small size, wide bandwidth and potential to be integrated with other electronic and optical devices [5]. Besides providing signal amplification, where a linear optical gain is desirable, the all other SOA applications are based in the SOA no-linear gain behavior. In fact, the no-linear property is essential to achieve wavelength conversion [6], 2R ([7]) and 3R (reamplification, retiming & reshaping [8]) regenerations, time switching [9], clock recovery [10] and dispersion compensation [11]. For a review of the SOA applications in optical processing, see the work of Saruwatari [12].

In all-optical configurations, the SOA can operate as an all-optical switch with times of hundreds or even tents of pico-seconds [13]. However, for electro-optical applications, the SOA switching time is in the order of nanosecond for good bulk devices. The reduction of this value is important to improve the efficiency of WDM optical space switches and a SOA exponential current injection has been theoretically proposed for those switches [14].

This paper introduces a practical way to implement a technique to reduce the SOA switching time. The technique called PISIC [15] (pre-impulse-step injected current) can reduce the SOA switching time from almost 2ns (simple-step current response) to little more than 200ps (step with pre-pulse response). Simulation predicts switching time reduction to values around 10 ps when using optimized values of PISIC.

II. EXPERIMENT AND SIMULATION

The experimental apparatus used to test the PISIC technique is shown in Fig. 1a. A 250 ps rise time pulse generator (HP8131A) furnishes the voltage step and a faster pulse generator (HP8133A) provides the 150 ps impulse. A clock signal synchronizes the generators in such a way to produce the PISIC signal, illustrated in Fig. 1b.



a)

b)

Fig.1- a) PISIC-technique experimental set-up;
b) PISIC signal and SOA optical response, with parameter definitions

In Fig.1a, the voltage step signal is combined with the pre-impulse signal using a microwave coupler followed by a voltage-to-current converter. The set-up also has a

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tunable semiconductor laser (*Photonetics Nanotunics*, 3645HE15), an optical filter, an optical isolator, a polarization control (*Photonetics Lefevre´s Loop*), a 30 GHz digital communication analyzer (HP83480A) and a semiconductor optical amplifier (*E-TEK*, HSOA 200014333). In order to introduce the PISIC parameters definitions, the Fig.1b is used. The main definitions are: I_0, current initial value; I_b, current base (final) value, ΔI, current step amplitude; I_{peak}, impulse peak value; w, impulse duration; τ_{delay}, *switching delay* time (time from the electronic step action to 10% of the optical output power value variation), τ_{on}, *switching-on* time (time from 10% to 90% of the optical output power value variation), and $P_{off}^{op.out}$ and $P_{on}^{op.out}$, optical output power refereed to the switch off and on cases, respectively, used to calculate the net-gain variation.

The SOA optical response to a step-like current injection is plotted in Fig.2. The electronic signal was obtained just by adding the step signal (HP8131A) to the SOA bias current. In this case, a CW optical input power of 38µW and a bias current of 58mA were applied to the SOA gates. It can be observed in Fig.2 an optical rise time transient of almost 2ns in both SOA gain-switching operations (switch on and off), limiting the switching action to a bit rate of few hundreds of Mbs.

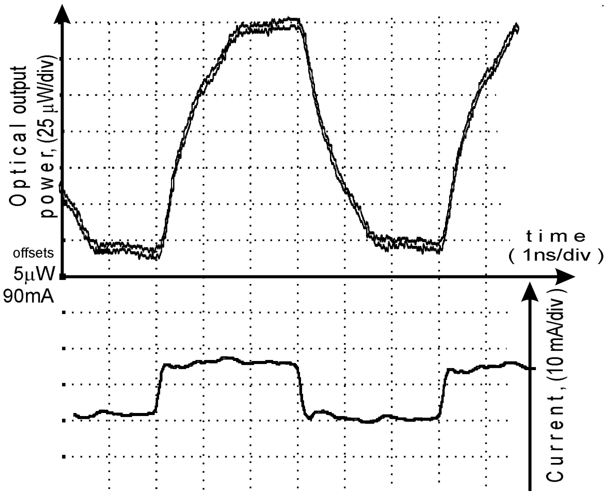


Fig.2: SOA optical response to current step injection.

A computer program based on SOA gain rate equation, as presented in [16, 17], was used to provide the simulated results of the SOA optoelectronic response to a single-step current, as presented in Fig.2. The simulation was used to investigate the speed response and gain limits. It is suitable to emphasize that the model used, in ref. [16,17], just considers two basic SOA non-linearities in its formulation: gain saturation with optical power and dynamic variation of the recombination time in function of carrier density. The parameters (optimized in comparison with experimental data) used in these work are shown in Table I.

The simulated gain step, defined as $\Delta G = 10 \cdot \log\left(\frac{P_{on}^{op.out}}{P_{off}^{op.out}}\right)$, in function of the injected current I_0 and ΔI (see Fig.1b) are presented, in Fig.3, for linear and saturated gain operation cases, i.e., for two input optical powers ($P^{op.in}$= 1 and 100µW). Six values (0, .25, .5, .75, 1 and 1.25) of I_0 normalized by I_{tr} (transparency current, 42.35mA) are used for six (5, 1, 1.25, 1.5, 1.75 and 2), current step amplitudes, equally normalized by I_{tr}.

TABLE I: SIMULATION PARAMETERS

Parameter	Definition	Value
A	trap recombination factor	5.10^7/s
B	spontaneous recomb. fact.	$5.10^{-10}.cm^3/s$
C	Auger recombination factor	$7.5.10^{-29}.cm^6/s$
w	cavity width	1.4 µm
d	cavity height	0.2 um
l	cavity length	350 um
a	transversal section gain	$2\ 10^{-16}.cm^2$
N_{tr}	transparency carrier dens.	$2.10^{18}\ cm^{-3}$
I_{tr}	transparency current	42.35 mA
α	attenuation	2000/m
R	facet reflection	0.0001
β	linewidth enhancem. Factor	5
n_{ef}	effective refractive index	3.4
α_{ins}	total insertion loss	5dB
E_{sat}	saturation energy	0.0449129 pJ
Γ	confinement factor	0.4

The response curves for the linear gain operation (P_{in}=1µW, upper curves), in Fig. 3, clearly show the saturation of the gain step as the I_0 values are increased, with reduction of more than 20dB for the maximum ΔI response. In the saturated gain operation (P_{in}=100µW, lower curves) that gain-step saturation behavior also appears, but with lower intensity because the strongest gain saturation, making the gain step response flatter with the I_0 increasing.

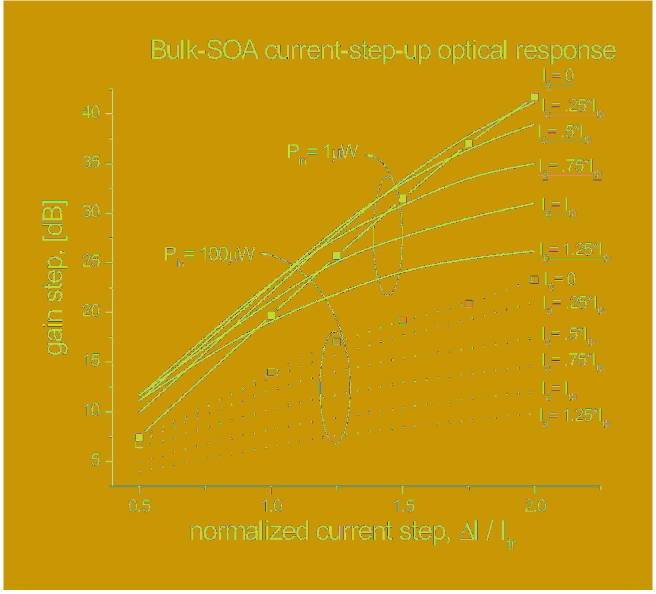


Fig.3: SOA optical response for current step injection: optical gain step x current step.

The simulated values of the *switching-on* time, τ_{on} (see Fig.1b) are presented, in Fig.4, for the same current conditions used in the Fig.3 results.

It is noted, in Fig.4 curves, that the SOA electro-optic switch response is improved as long as the optical input power, the current step and the current initial value are increased. As I_0 increases, the response becomes more flatter until the operation reaches the most saturated condition (P_{in}=100µW and I_0=1.25*I_{tr}), where the response is almost smooth and the fastest switching times appears, with values around hundreds of pico-seconds.

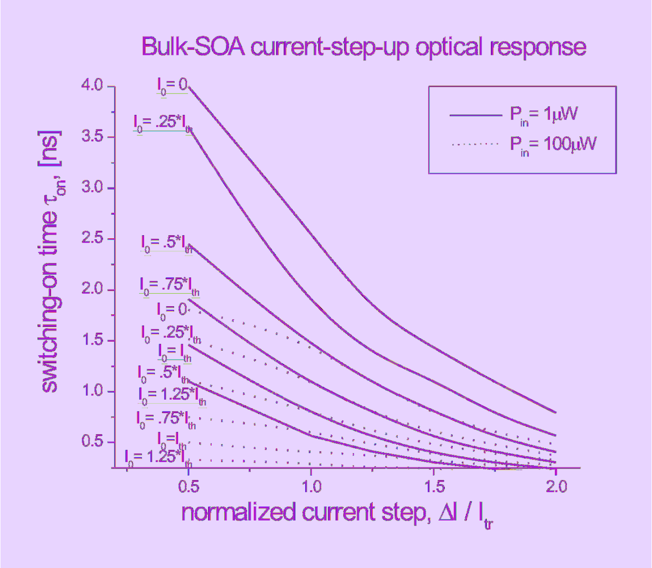
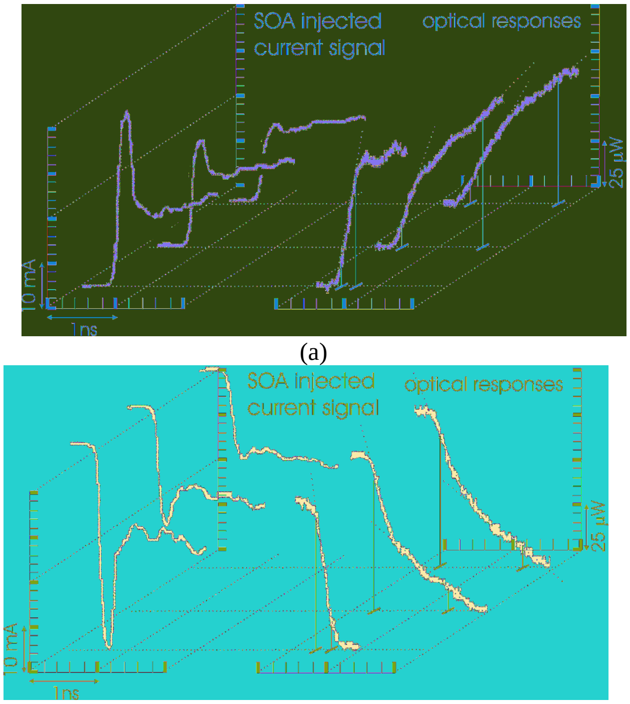


Fig.4: SOA optical response for current step injection: switching time x current step.

In order to improve the SOA electro-optic switching times, the PISIC set-up was implemented. The optoelectronic switching improvement was obtained by adding narrow impulses, with increasing amplitudes, to the step signal and applying the outcome signal to the SOA electronic gate.



(a)

(b)

Fig.5- PISIC-technique *switching-on* (a) and off (b) experimental results: fast switches for higher impulse peaks.

. The *switching-on* and off cases are illustrated, respectively, in Fig.5a and Fig.5b for a 38µW CW input optical power and a SOA bias current of 58mA. Note that the SOA switching speed increases with the pre-pulse amplitude. The best results obtained present switching times less than 200ps, ten times faster than the step-only response obtained with the same device. Oscillations present in the optical response final level are due to imperfections in the electronic pulse. Similar results were obtained for the *switching-off* case by adding a negative impulse in the step-down transition.

In order to validate the simulation model [16] for this kind of operation, simulations were done using current pre-pulse. The theoretical results, joined with experimental curves, are presented in Fig.6, where the simulations were properly shifted (different off-sets and time beginnings) in such a way that the visualization and comparison of the results with the experimental facts are facilitated. It is observed in Fig.6 that the simulation results of that SOA operation mode have good agreement with experiment.

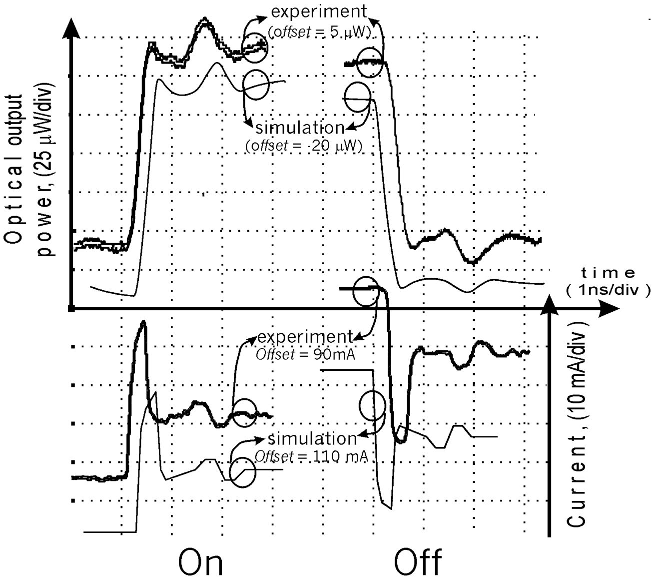


Fig.6: experiment and simulation for switching using pre-pulse.

Due to the experimental limitations (referring to pulse generation) and to the lack of the SOA dynamic impedance variation data, simulations were used to foresee the PISIC limits in increasing the switching speed. In Fig. 7, the cases of optical input power of 1 and 100 µW and initial current I_0 = 0, and step final base current I_b = 2*I_{tr} are presented, for the *switching-on* case, varying the super-gaussian pre-pulse amplitude (I_{peak} from 0 to 20*I_{tr}) and width (w = 100, 150, 200 and 300ps).

It is observed in Fig. 7 the presence of an optimum electronic charge value to be injected in the SOA active region, for each level of optical power and pre-pulse width, so that the switching time decreases from hundreds of pico-seconds (simple step operation) to around 10 ps (optimized PISIC operation). When those optimal values are minimally exceeded, the output optical step begins to be distorted by an overshoot profile. That behavior is signalized in Fig.7 as an increase in the switching time, which in this condition becomes to me measured from 10% of the optical output value to its 110% after the signal peak.

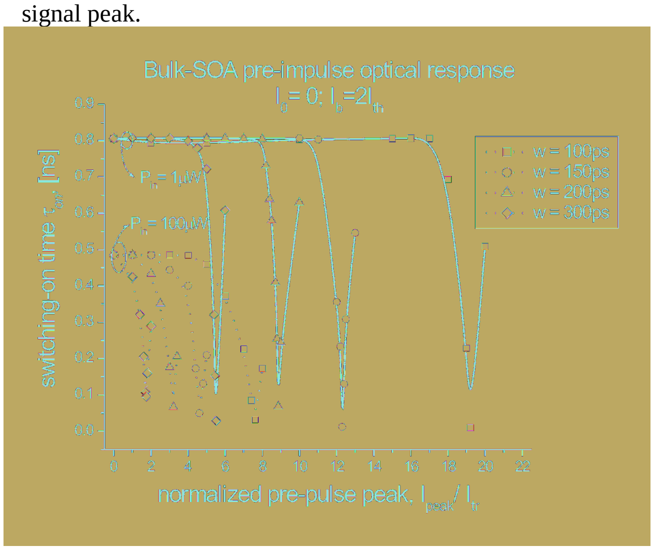


Fig.7: switching times x pre-pulse pick (normalized by I_{tr})

The Fig. 8 presents the simulations data for the operation delaying, τ_{delay} (see Fig.1b), in the same conditions used for the data in Fig.7. In Fig. 8, the curves show their best results closer to their correspondent optimum pre-pulse amplitude, with the best result appearing for the fastest impulse (*w*=100ps). with *switching delay* around 100ps for the linear-gain operation. In the saturated-gain operation, the response is even faster, as occurred in previous results.

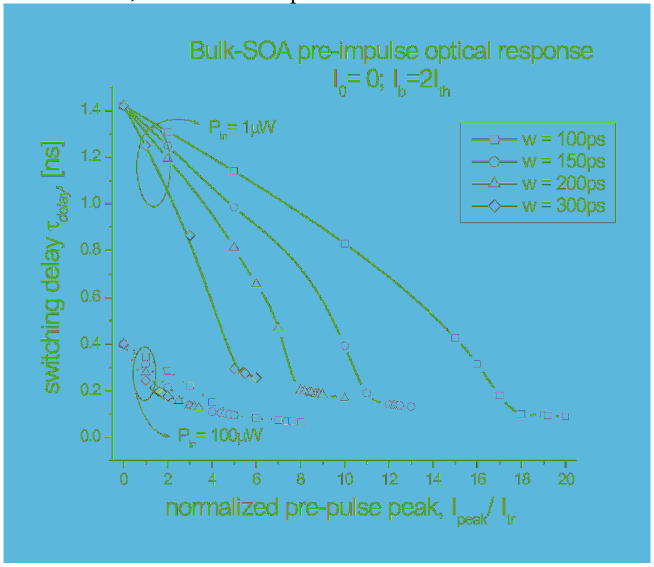


Fig.8: *switching delay* x pre-pulse pick (normalized by I_{tr})

III. CONCLUSION

The PISIC, a technique to reduce the optoelectronic switching times in SOAs, was presented. The experimental results showed switching time reduction from 2 (simple step operation) to 0.2 ns (PISIC operation). Optimized simulation results foresee switching times around tens of pico-seconds. In order to verify the simulation prediction, it is necessary the use of better microwave pulse generators and couplers.

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