

Sound Of Lasers (SOL) – An audiovisual approach to semiconductor laser dynamics

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Abstract — We present an educational software addressed to the students of optical communication courses, for a simple visualization of the basic dynamic processes of semiconductor lasers. The graphic interface allows the user to choose the laser and the modulation parameters and it plots the laser power output and instantaneous frequency versus time. Additionally, the optical frequency variations are numerically shifted into the audible frequency range in order to produce a sound wave from the computer loudspeakers. Using the proposed software, the student can simultaneously see and hear how the laser intensity and frequency change, depending on the modulation and device parameters.

Keywords: educational software, optical communications, semiconductor lasers, laser rate equations model, frequency chirp, direct modulation.

I. INTRODUCTION

Optical communications have become more and more relevant in the last decades in speeding up and increasing the bandwidth of worldwide communication channels. It is then understood why photonics courses are usually offered to the students of electronics and communication engineering. Understanding of photonics components by a student audience is then a relevant issue, and demands intuitive educational tools.

A fiber optic channel has its key component in the optical transmitter, the semiconductor laser (SL), which is usually externally or directly modulated by an electrical current source to generate the data stream. In Directly Modulated (DM) lasers the transmitter is controlled with an electrical signal which carries the bit information sequence. Usually DM SLs are the preferred choice in short distance connections, due to their reduced cost. However they present a highly “chirped” output due to the coupling between amplitude and phase, i.e. the amplitude modulation is associated to an optical frequency modulation. This limits the achievable transmission distance and bit rate in dispersive media, such as optical fibers.

A simple simulation tool for DM SL is a useful resource for optical communications courses. We have developed such an instrument, by implementing in Matlab® [1] a simple SL model, based on the Rate Equations (RE) approach [2, 3]. By the use of a Graphic User Interface (GUI), the student can vary

the modulation parameters and the device parameters and see how they affect the laser output power and instantaneous frequency. The frequency “chirp”, which occurs in the THz region with variations in the order of GHz is numerically shifted to the audible frequency range and sent to the computer loudspeakers. In this way, an intuitive and immediate image of the chirped nature of DM SLs is given to the student.

This work is organized as follows. In Section II, the proposed simulation tool is described, giving details of the mathematical model in use, its numerical implementation and the user control interface. In Section III, some examples of use are presented, in which the program is run in different conditions, changing the laser internal parameters and the modulation parameters. Finally, in Section IV, the main conclusions of the proposed work are summarized.

II. SOFTWARE DESCRIPTION

A. The Rate Equations Model

The light-matter interactions occurring in a SL can be modeled in a simple way by using the RE model [2, 3]. The RE model considers the interplay between carriers and photons in the laser cavity in terms of conservation equations. The number of electrons and holes is assumed to be the same, thus only one equation for carriers is considered in the model. The main assumption of the model is that carriers and photons are considered to be uniformly distributed in the longitudinal and transversal directions.

Taking into account these considerations and assuming a single mode laser, the relationship between the carrier density, $N(t)$, the photon density, $S(t)$, and the optical phase, $\phi(t)$, can be expressed by the following differential equations:

$$\frac{dN(t)}{dt} = \frac{I(t)}{qV_{act}} - \frac{N(t)}{\tau_N} - v_G \frac{dG(N(t) - N_0)}{dN} \frac{S(t)}{1 + \epsilon S(t)} \quad (1)$$

$$\frac{dS(t)}{dt} = v_G \Gamma \frac{dG(N(t) - N_0)}{dN} \frac{S(t)}{1 + \epsilon S(t)} - \frac{S(t)}{\tau_P} + \beta \Gamma \frac{N(t)}{\tau_N} \quad (2)$$

$$\frac{d\phi(t)}{dt} = \frac{\alpha}{2} \left(v_G \Gamma \frac{dG}{dN} (N(t) - N_0) - \frac{1}{\tau_P} \right) \quad (3)$$

where the descriptions of the symbols and their values are given in Tab. 1. Typical values for a 1550 nm Distributed Feed Back (DFB) laser [4] are used by default.

B. The Graphic User Interface

The Graphic User Interface (GUI) is shown in Fig. 1. It is composite of five panels and two graphs.

From the *Modulation Parameters* panel the user can choose the current waveform, the bias point, the peak-to-peak amplitude and the frequency of the modulating current. Current waveform can be selected from a drop-down menu, among sinusoidal, rectangular or step-alike.

TABLE I. MODEL PARAMETERS

1550 nm DFB Laser [4]			
Symbol	Description	Value	Units
V_{act}	Active volume	$2 \cdot 10^{-11}$	cm^3
Γ	Confinement factor	0.25	-
dG/dN	Differential gain	$1.7 \cdot 10^{-15}$	cm^2
v_G	Group velocity	$9.4 \cdot 10^9$	cm/s
N_0	Transparency carrier density	$1.6 \cdot 10^{18}$	cm^{-3}
τ_N	Carrier lifetime	0.75	ns
τ_P	Photon lifetime	0.8	ps
ϵ	Nonlinear gain compression factor	$1.7 \cdot 10^{-17}$	cm^3
β	Spontaneous emission coefficient	$1 \cdot 10^{-4}$	-
α	Linewidth enhancement factor	3.5	-

The laser parameters can be introduced by the user in the *Laser Parameters* panel, placed on the right side of the GUI.

By pressing the *Run* button, the program solves Eqs. 1-3, and returns the values of carrier density, photon density and optical phase at each temporal instant. By default, the temporal range considered is of 10 ns duration, with a temporal resolution of 1 ps. The instantaneous frequency, $\nu(t)$, is calculated from the temporal derivative of the phase, as $\nu(t) = (2\pi)^{-1} d/dt(\phi(t))$. Two graph panels on the left side of the GUI show the results of the simulation. On the lower panel, the output power (red line, left axis) and the instantaneous frequency (blue line, right axis) are shown. On the upper panel, the current (black line, left axis) and the carrier density (blue, right axis) are plotted, as a function of their threshold values, I_{TH} and N_{TH} , respectively. The expected correspondence between carrier density and instantaneous frequency profiles is clearly seen in the example shown in Fig. 1. The *Graphics Control* panel allows the user to explore the two graph panels, by zooming in and out along the vertical and horizontal axes.

From the laser intensity and chirp, the software builds an amplitude- and frequency-modulated signal of the form $A(t) \cdot \cos(2\pi f(t))$, where $A(t)$ is proportional to $S(t)$ and $f(t)$ is the frequency $\nu(t)$ shifted into the audible frequency range. This conversion is obtained with a constant factor of 10^9 , changing nanoseconds into seconds and GHz into Hz. The central frequency of the audible chirp, can be introduced by the user into the *Audio Conversion* panel. The button *Play* in the same panel sends the audio waveform to the computer loudspeakers. Finally, the *Save Data* button allows the user to export the simulation results to a text file, where the time, current, number of carriers, output power and instantaneous frequency vectors are stored in a tab separated format.

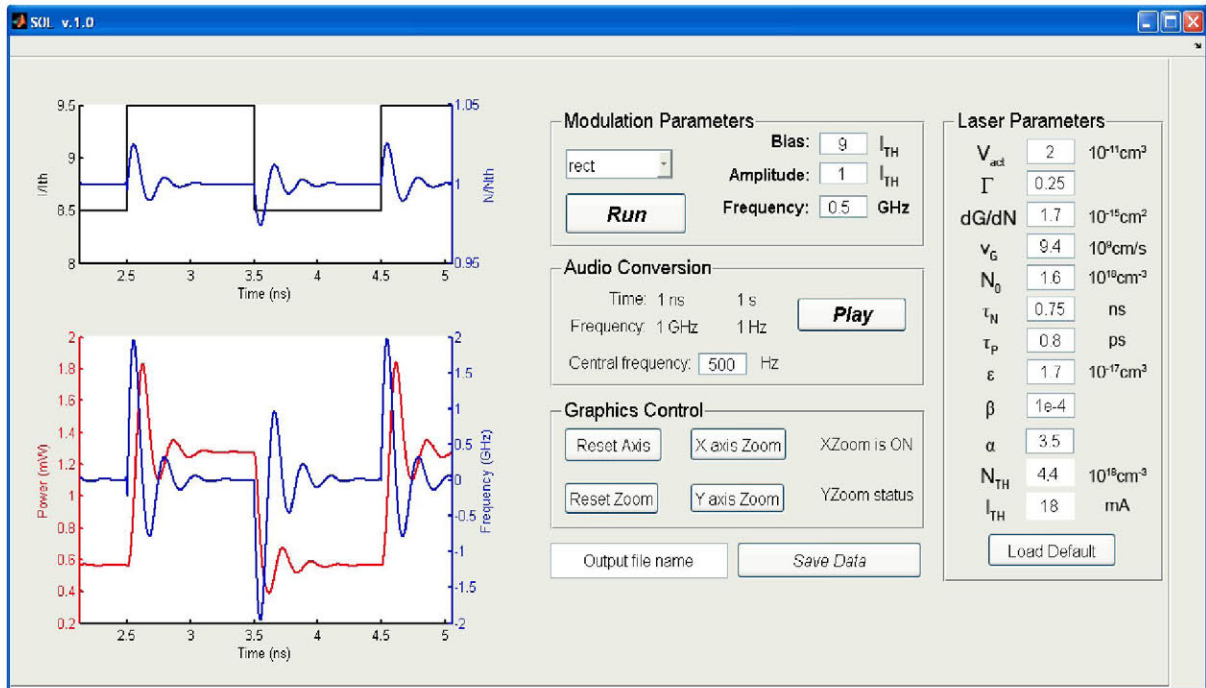


Figure 1. The Graphic Unit Interface.

III. EXAMPLES.

In this Section, we present some simulation results that can be useful for the understanding of the dynamics of a DM SL. We show the dependence of the laser output, in terms of intensity and instantaneous frequency, on its internal parameters and on the modulation conditions, i. e. current waveform, current amplitude and bias point. In the proposed examples, attention is given both to the graphical representation of the results and on the impact of the audible output on the user understanding of the simulated phenomenon.

These examples are directed to a student audience with previous basic notions on the theory of laser dynamics. Here we explain how to use the proposed simulation tool and its potential for a better learning experience, giving a brief theoretical description of the simulated phenomena. Results are exported with the *Save Data* button and presented in figures.

A. Laser Switch On

We first consider the simple case in which the SL is switched on with a step like current function. In order to have this, in the *Modulation Parameters* panel, the *step* current waveform is selected, I_{BIAS} is set to 0, the amplitude is set to $3 I_{\text{TH}}$ and the frequency field is left blank as it is ignored in case the *step* function is selected.

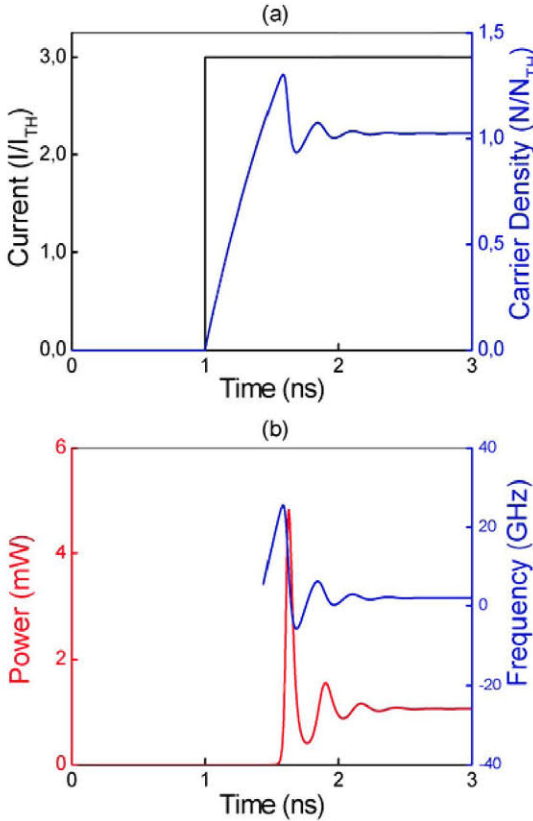


Figure 2. Results obtained with the *step* current waveform selected, bias set to 0 and amplitude $3 I_{\text{TH}}$. (a) current and carrier density, black line left axis and blue line right axis, respectively and (b) output power and chirp, red line left axis and blue line right axis, respectively.

This corresponds to inject the laser with a current step function with low level equal to 0 and a high level current of $3 I_{\text{TH}}$. The laser parameters are set to the default values.

After the *Run* button is pressed, the program takes some seconds to complete the simulation and the results are finally shown in the current/carriers and in the power/chirp graphs. Results are shown in Fig. 2 (a) and (b).

When the step current is applied, the carrier density grows as $1 - \exp(-t/\tau_N)$ from the low level steady state to N_{TH} , as expected from laser theory [2, 3]. $N(t)$ undergoes damped oscillations around the threshold density value before reaching the steady state value clamped at N_{TH} . This corresponds to the relaxation oscillations of the output power, due to carrier induced gain modulation, and of the instantaneous frequency, due to the carrier induced index modulation.

The user can appreciate in an intuitive manner, the coupled amplitude/frequency modulation, by pressing the *Play* button in the *Audio Conversion* panel. As expected, when the laser is off, for $I(t) = 0$, no sound is produced, then a chirped sound is emitted, when power and instantaneous frequency oscillate, and finally a single frequency tone is produced, corresponding to the optical carrier of the laser shifted into the audible band (arbitrary selected by the user in the field *Central Frequency* in the *Audio Conversion* panel, e. g. 500 Hz).

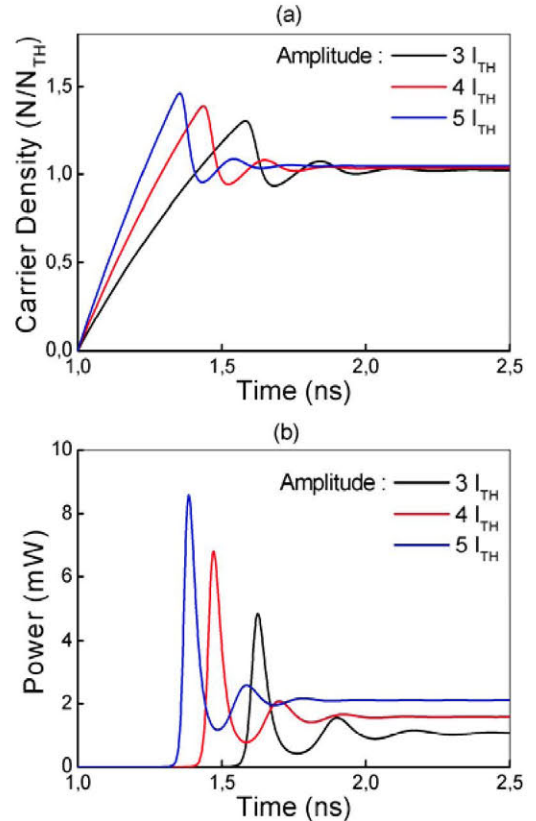


Figure 3. Carrier density (a) and output power (b) obtained with the *step* current waveform selected, bias set to 0 and three values of amplitude: 3, 4 and $5 I_{\text{TH}}$, black, red and blue lines, respectively.

We now consider the case in which one of the modulation parameter is changed with respect to the previous case and we observe its effect on the laser output.

We set the *Amplitude* field of the *Modulation Parameters* panel to $3, 4, 5 I_{TH}$ and results are compared in Fig. 3 (a) and (b). The turn-on time of the laser, defined as the time interval between the current step and the laser output, is reduced and the frequency chirp excursion is larger, due to a deeper carrier induced index modulation, see Fig. 3 (a). The power oscillations are more pronounced and the oscillation period is reduced. The large degree of freedom in setting different modulation parameters given to the user should allow a better understanding of the laser dynamics, once the results are promptly visualized into the graphs and can be heard with the help of the *Audio Conversion* panel buttons.

B. Direct Modulation

In this example, we consider the DM of the laser with a periodic rectangular current waveform, with the low and high current level both above the threshold current value I_{TH} . In the *Modulation Parameters* panel, the *rect* current waveform is selected, I_{BIAS} is set to $4 I_{TH}$, the amplitude is set to $2 I_{TH}$ and the frequency field is set to 0.5 GHz.

After pressing the *Run* button, the results are plotted in the current/carriers and power/chirp graphs. The user can appreciate the amplitude-frequency modulation in the audible band by pressing the *Play* button in the *Audio Conversion* panel. In this case, the well known phenomenon of *transient* and *adiabatic* chirp in DM SLs is clearly appreciated after listening to the audible output. The transient chirp is usually referred to the instantaneous frequency variation associated to the transition between the two levels of the injected current, i. e. the damped oscillations of $v(t)$ which follows from low to high and from high to low current level transitions. The adiabatic chirp is the frequency difference between the frequency produced during the high level and the frequency produced during the low level of injected current. The adiabatic chirp is directly related to the gain compression factor ϵ . As shown in Fig. 4 (a) and (b), the carrier density is not clamped to the threshold value N_{TH} as in the ideal case ($\epsilon = 0$).

In the proposed simulation, the audio output is composite of a single higher tone during the high level state, a lower single tone during the low level state (corresponding to the adiabatic chirp) and a chirped sound when the current switches from low to high level and viceversa (corresponding to the transient chirp). This is also appreciated from the power/chirp plot, where the frequency difference between low and high level of the injected current due to the adiabatic chirp, is clearly shown in Fig. 4 (a) and (b). If the gain compression factor ϵ is set to zero, the adiabatic chirp signature disappears from the audio output and the graphs, as expected from theory.

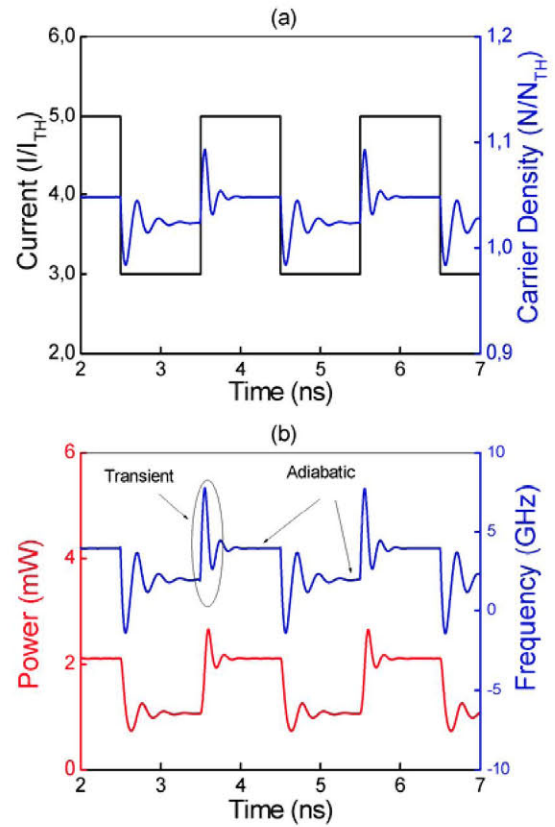


Figure 4. Results obtained with the *step* current waveform selected, bias set to $4 I_{TH}$, amplitude $2 I_{TH}$ and frequency 0.5 GHz: (a) current and carrier density, black line left axis and blue line right axis, respectively and (b) output power and chirp, red line left axis and blue line right axis, respectively.

An example of how the laser output changes as a function of its internal parameters is given by the results obtained with different values of the linewidth enhancement factor α . In this case, we use the modulation parameters as previously set, bias $4 I_{TH}$, amplitude $2 I_{TH}$ and frequency 0.5 GHz, the value of ϵ is restored to the default value and three simulations are run for $\alpha = 1.5, 3.5$ and 5.5 . The output power is the same for the three values of α , plotted in Fig. 4 (b).

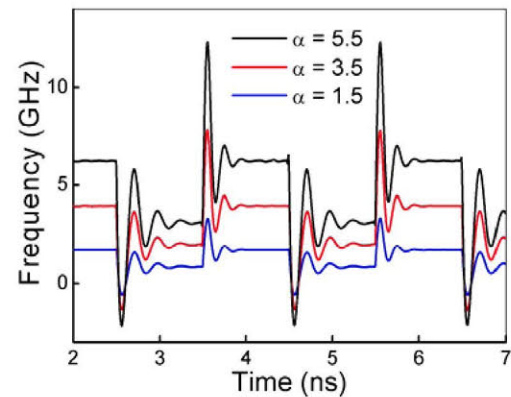


Figure 5. Temporal profiles of the instantaneous frequency obtained with the *step* current waveform selected, bias set to $4 I_{TH}$, amplitude $2 I_{TH}$ and frequency 0.5 GHz, for three different values of α 1.5, 3.5 and 5.5, blue, red and black lines, respectively.

The obtained frequency chirp temporal profiles are shown in Fig. 5. The linewidth enhancement factor gives the coupling strength between amplitude and phase of the laser output, consequently a low value of α , with unchanged modulation condition corresponds to a small frequency variation of the chirp. The adiabatic chirp is also affected from the different values of α , resulting in a larger frequency excursion between the low and high level, at greater values of the linewidth enhancement factor. This can be appreciated from the chirp profile in Fig. 5 and from the audio output.

C. Gain Switching

In this example we consider the generation of a periodic pulse train from a SL using the gain switching technique [5]. Pulses are generated from Gain Switched (GS) SLs by injecting the laser with a periodic current waveform with low and high current levels below and above the threshold current value. By proper choice of the amplitude, bias and waveform period, the SL is switched on and off at each period and only the first spike of the relaxation oscillations is generated, producing a pulse train at a repetition rate equal to the current waveform period. In Fig. 6, the results obtained with the *rect* current waveform selected, amplitude of $6 I_{TH}$, bias of $3 I_{TH}$ and frequency of 2 GHz. This corresponds to a current excursion from 0 to $6 I_{TH}$, with a periodic rectangular electrical pulse with a duration of 0.25 ns and a repetition rate of 0.5 ns.

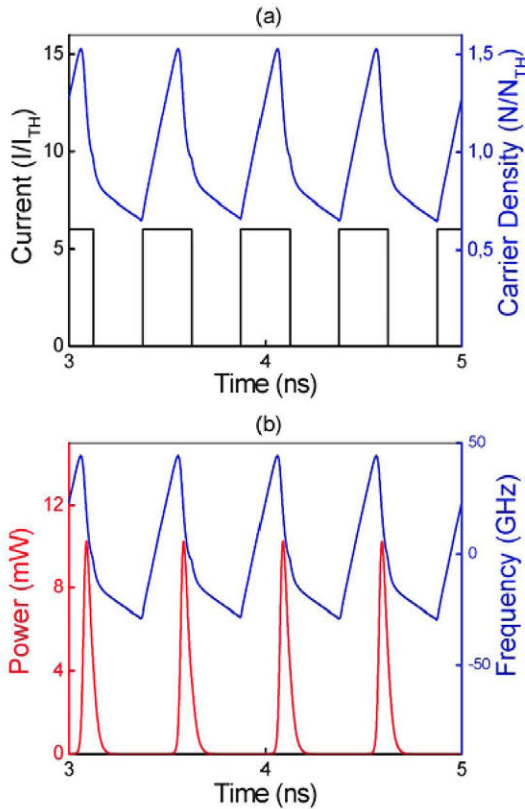


Figure 6. Gain switching operation obtained with the *step* current waveform selected, bias set to $3 I_{TH}$, amplitude $6 I_{TH}$ and frequency 2 GHz: (a) current and carrier density, black line left axis and blue line right axis, respectively and (b) output power and chirp, red line left axis and blue line right axis, respectively.

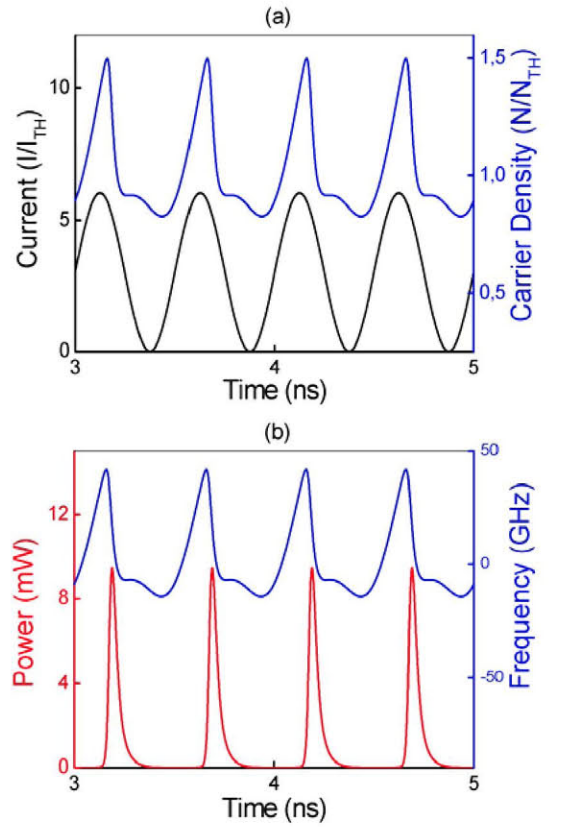


Figure 7. Gain switching operation obtained with the *sin* current waveform selected, bias set to $3 I_{TH}$, amplitude $6 I_{TH}$ and frequency 2 GHz: (a) current and carrier density, black line left axis and blue line right axis, respectively and (b) output power and chirp, red line left axis and blue line right axis, respectively.

The obtained optical pulses have Full Width Half Maximum (FWHM) duration of 45 ps and peak intensity of about 10 mW at 2 GHz. Due to the turn on time delay, the optical pulses have a shorter duration than the electrical rectangular pulse at each period. Pulses are strongly chirped, as expected from the large excursion of carrier density around threshold, typical in GS SLs. This is also appreciated from the audible output obtained from the *Audio Conversion* panel

Results obtained with a sinusoidal current waveform at 2 GHz and same bias and amplitude parameters as in the rectangular current waveform case, are shown in Fig. 7. Similar pulse duration and peak amplitude are obtained and the chirp and carrier density profile is smoother with respect to the rectangular current waveform excitation.

The shorter pulse duration obtainable from GS SLs depends on the laser parameters and the modulation conditions. Here an example is given on how the bias current influences the pulse duration and peak amplitude. Simulations are performed for three different values of the bias current: $1.5 I_{TH}$, $3 I_{TH}$ and $3.5 I_{TH}$, with the sinusoidal current waveform, the current amplitude equal to $6 I_{TH}$ and frequency 2 GHz. The results are shown in Fig. 8.

The bias parameter affects several aspects of the obtained pulse as expected in GS SLs, i. e. the peak power, the FWHM duration, the shape and the turn on time delay. The higher peak intensity (~ 10 mW) and shortest duration (45 ps)

are obtained for a bias parameter value of $3 I_{TH}$. The smaller bias of $1.5 I_{TH}$ produces weaker pulses (~ 4 mW) with longer duration (52 ps). Finally, the greatest value of the bias parameter considered, gives a pulse shape in which the second relaxation oscillation starts to appear, resulting in longer pulse duration of 58 ps. All these results are in agreement with the expected typical behavior of GS SLs [5].

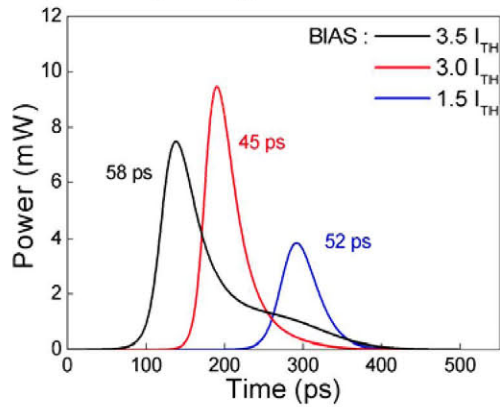


Figure 8. Pulses obtained with the sinusoidal waveform current, amplitude equal to $6 I_{TH}$, frequency 2 GHz for three values of the bias parameter: 1.5, 3 and $3.5 I_{TH}$, with blue, red and black line, respectively. The FWHM duration of each pulse is shown with the respective color.

IV. CONCLUSIONS

We have presented a novel educational software for the simulation of current injected semiconductor lasers. The

proposed tool is directed to undergraduate students of photonics and optical communications courses.

The software is based on the well known RE model for SLs, and it is numerically implemented on a Matlab® platform. The GUI allows the student to choose the laser internal parameters and the modulating conditions. The simulation results are plotted and the amplitude/frequency modulation typical of current injected SLs is shifted to the audible frequency range for an intuitive understanding of the phenomenon. Several examples are given, i. e. the laser turn on, laser direct modulation and gain switching pulse generation, and results are discussed for different laser and modulation parameters.

The proposed software allows the user to explore and test his knowledge on SL dynamics with an interactive tool by changing the operating conditions of the simulated device and see and listen to the consequent results in the laser output.

REFERENCES

- [1] www.mathworks.com
- [2] G. P. Agrawal, Fiber-Optic Communication Systems, John Wiley & Sons, Inc., 2002.
- [3] L. A. Coldren and S. W. Corzine, Diode Lasers and Photonic Integrated Circuits, John Wiley & Sons, Inc., 1995.
- [4] John C. Cartledge and R. C. Srinivasan, "Extraction of DFB Laser Rate Equation Parameters for System Simulation Purposes", J. Lightwave Technol., vol. 15, iss. 5, pp. 852-860, 1997.
- [5] K. Y. Lau, "Gain switching of semiconductor injection lasers," Appl. Phys. Lett. vol 52, iss. 4, pp. 257-259, 1988.