Simulink™ blocks for simulation of light sources

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Abstract — **In this work is shown how to construct blocks to simulate and analyze optical sources using Simulink. The versatility of this software is used to form analisys blocks in the time and frequency domains. Results for LED (FD), Quantum Well (TD.) and Fabry Perot (FD) LASERs are shown, and it is possible to change various parameters to obtain new results according to the necessity.**

Index Terms — **LED, Fabry-Perot LASER, Quantum Well LASER, Rate Equations, Simulink™.**

I – INTRODUCTION

The use of educational softwares is widely recommended in present days as a complementary tool in eletrical engineering and associated disciplines. This results primarily from the fact that these softwares offer convenient means for mathematical manipulations and for the visualization of the physical phenomena associated with these disciplines. In addition, the high cost of modern laboratories in this area enhances the interest of a more diversified use of these softwares [1], [2].

The Matlab, Mathcad, Maple and Mathematica softwares, for example, are widely used in engineering, not only as a teaching but also as a professional tool. Besides, these softwares provide a friendly computational environment in which the facilities of numerical and/or classical algebraic equations solutions combine with the facilities of visualization and document integration. As a result, the difficulty, quite often encountered by undergraduate and graduate students, is partially overcome from the moment that these students are faced with a didactic computational tool and of easy comprehension, implemented in an environment familiar to the students [2]-[3].

The objective of this work is show how to construct Simulink™ blocks to observe the behavior of three kinds of light sources, the LED diode, Quantum Well and Fabry Perot LASERs. Another feature is that the simulation parameters can be changed, and the influence of a certain varible can be investigated.

II – SOURCES

In the FD the Fourier Transform (FT) of the optical power, $P_e(f)$ (watts) can be expressed as:

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$$P_e(f) = H_T(f).I_d(f), \tag{1}$$

Where $H_T(f)$ is the transfer function of the source and $I_d(f)$ is the FT of the injected current (A)

The transfer function can be decomposed in two parts:

$$H_T(f) = H_T(0).H_T^*(f) . \tag{2}$$

In the previous equation, $H_T(0)$ is the quantum efficiency of the light source (W/A), $H_T^*(f)$ is the normalized frequency response of the light source.

A) *LED*

For the LEDs the transfer function can be expressed as [5].

$$H_T(0) = \left(\frac{h.c}{\lambda.q}\right)\eta_{\text{int}}\eta_{inj}\eta_{ext} \tag{3}$$

where

$$\eta_{\text{int}} = \frac{\tau_{nr}}{\tau_{nr+}\tau_r} , \tag{4}$$

$$\eta_{ext} = \left[1-\left(\frac{n_s - n_m}{n_s + n_m}\right)^2\right]\left[1-\cos\left(\frac{n_m}{n_s}\right)\right] \tag{5}$$

The term $H_T^*(f)$ in (2) is expressed by

$$H_T^*(f) = \frac{1}{1 + jf/f_c} , \tag{6}$$

where

$$f_c = \frac{1}{2\pi\tau_r} \tag{7}$$

The meaning of parameters in (3)-(7) are given at TABLE I.

B. *Multimode Fabry-Perot:*

For the Fabry-Perot laser the transfer function can be expressed as [4].

$$H_T(0) = \left(\frac{h.c}{\lambda.q}\right)\eta_{\text{int}}\eta_{ext}\left[\frac{I_d - I_{th}}{I_d}\right] \tag{8}$$

TABLE I

PARAMETERS OF (3),(7)

η_{ext}	External Quantum efficiency
η_{int}	Internal Quantum efficiency
η_{inj}	Injection current efficiency
h	Planck's constant $(6.62\times10^{-34} J.s)$
c	Light velocity in the vacuum $(2.99793\times10^{8} m/s)$
λ	Emission wavelength (m)
q	Electron charge $(1.60218\times10^{-19} C)$
τ_{nr}	Nonradiative recombination lifetime
τ_r	Radiative recombination lifetime
n_s	Semiconductor refraction index
n_m	Refraction index (air =1)
f_c	Optical cutoff frequency (3 dB)

where

$$\eta_{ext} = \frac{\ln\left(\frac{1}{R_1}\right)}{\gamma.l + \ln\left(\frac{1}{R_1}\right)} \quad (9)$$

and η_{int} is the same as in (4).

$$H_T^*(f) = \frac{f_0^2}{f_0^2 - 4\pi^2 f^2 + j\beta 2\pi f} \quad (10)$$

where

$$f_0^2 = \frac{(I_0 - I_{th})}{\tau_{sp}\tau_{ph}I_{th}} \quad (11)$$

$$\beta = \frac{I_0}{\tau_{sp}I_{th}} \quad (12)$$

The description of new parameters at (8)-(12) are given in TABLE II.

TABLE II

PARAMETERS OF (8)-(12)

I_d	Injected current
I_{th}	the threshold current (A).
R_1	Mirror reflectancy (m)
γ	loss coeficient
l	Cavity longitudinal dimension (m)
I_0	Polarization current (A)
τ_{sp}	Carrier recombination lifetime (s)
β	Dumping frequency (Hz)
f_0	Resonant frequency (Hz).

Obs : the former expressions are valid only for $I_d > I_{th}$, i.e., in the stimulated emission region

C. Quantum-Well (QW) LASER.

To obtain the response of the quantum-well (QW) LASER was not used a FD model, but a implementation in the time domain through a block diagram using SIMULINK, according to the following rate equations [5]:

$$\frac{dN}{dt} = \frac{I}{qV_{act}} - g_0(N - N_0)(1 - \varepsilon S)S - \frac{N}{\tau_n} + \frac{N_e}{\tau_n} \quad (13)$$

$$\frac{dS}{dt} = \Gamma g_0(N - N_0)(1 - \varepsilon S)S + \frac{\Gamma\beta N}{\tau_n} - \frac{S}{\tau_p} \quad (14)$$

$$\frac{S}{P_f} = \frac{\Gamma\tau_p\lambda_0}{V_{act}\eta hc} = \upsilon \quad (15)$$

The terms of the above equation are described in TABLE III

TABLE III

PARAMETERS OF (13)-(15)

N	Active region carrier density
S	Photon density
P_f	LASER output power
I	Injection current
V_{act}	Active region volume
g_0	Gain coefficient.
N_0	Optical transparency density.
ε	Fenomenological gain-saturation term
τ_n	Carrier lifetime
N_e	Equilibrium carrier density
Γ	Optical confinement factor
β	Spontaneous emission coupling factor
τ_p	Photon lifetime
η	Differential quantum efficiency per facet
λ_0	Lasing wavelength
Q	Electron charge
H	Planck's constant
C	Light velocity (vacuum)

Accordingly with [5], the standard rate equations that use a linear gain-saturation term of the form (1-ε)S can possess three dc solution regimes for nonnegative values of injection current, which two of them are nonphysical solutions, characterized for negative power and high power solutions. For the parameter values used in this paper, the nonphysical solutions would happen above a injection current value between 0.5 and 2A [5], which is higher than typical values applied in these simulations

III-SIMULATION

A. LED

In fig.1 can be seen the LED block, with other blocks like signal generator and scope. The user can change quickly the parameters of a LED block, as shown in fig.2.

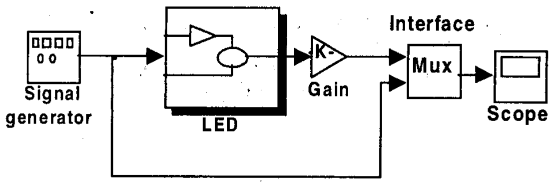


Fig. 1 - Structure used to simulate the behavior of a LED

Parameters values used to the simulations of this work are also shown in figs. 2 and 5. Using this structure to simulate the behavior of a LED, and plotting the optical power emitted when the input is a test square wave, the output aspect can be seen in fig 3.

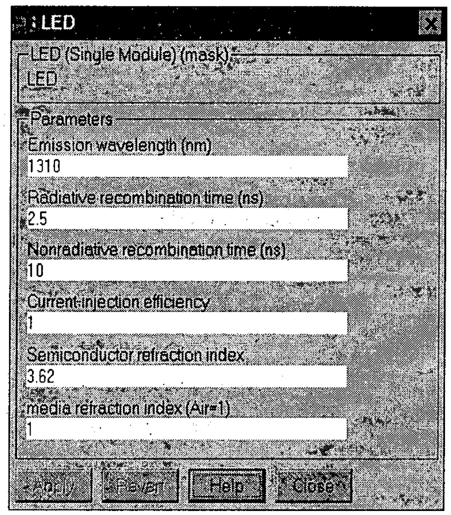


Fig.2 – Dialog box to the LED parameters.

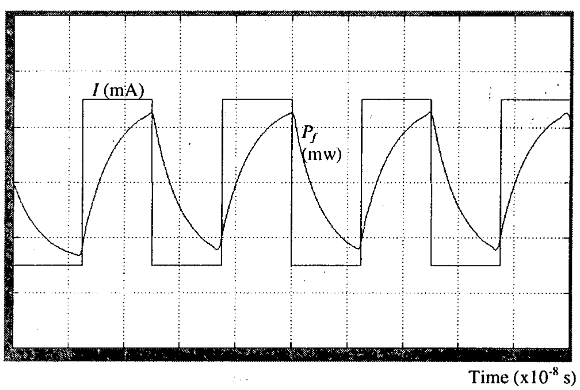


Fig.3 – Simulation Results to the LED.

B. *Fabry-Perot LASER (multimode)*

The block diagram to the simulation of the LASER diode is shown below. This is a model of multimode Fabry-Perot LASER described by the equations (8) – (12).

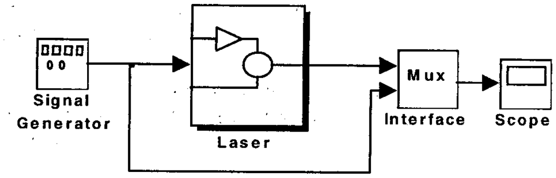


Fig.4- Structure used to simulate a LASER diode.

Activating the LASER block, the following Dialog box will open, allowing the user to adjust the parameters seen in the fig. 5.

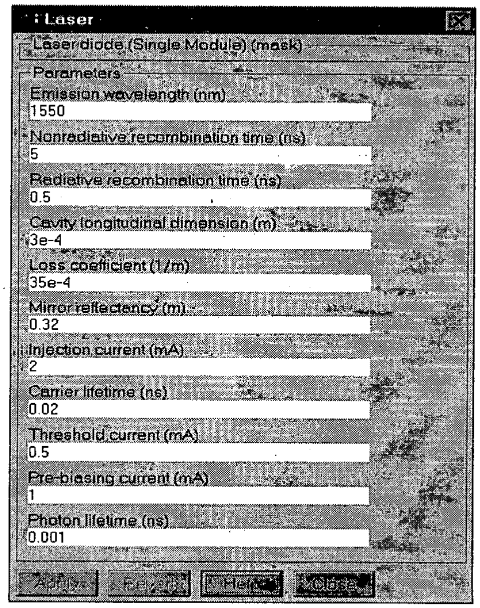


Fig.5- Dialog box with LASER diode parameters.

The results of simulation (fig. 6), show the behavior of a LASER diode, with a square wave current of input signal.

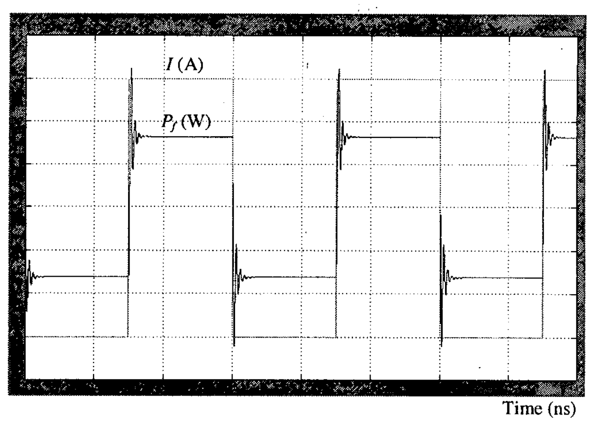


Fig.6- Simulation Results to the LASER Diode

Note: To permit the simulation of the Fabry-Perot LASER, as well as the QW LASER, to be discussed in the following session, was necessary to adjust the time *step* in "simulations parameters" dialog box, to "fix" (Runge-Kutta method), using a time step lower than the default, to guarantee the stability of digital simulation.

C. Quantum-Well LASER

The block diagram related to the simulation of the LASER diode is shown in the fig. 7.

Fig. 8 illustrates the dialog box for input parameters, activated by double clicking the Rate equation block, allowing the simulation of QW LASER for different materials and structures.

Accordingly with (13)-(15), the "rate equations" block in fig 7 is composed by the structure shown in fig.9.

Fig.10 shows the plot of optical power output corresponding to the values given in fig.9 (default values), where the injected current varies between 0 and 10 mA with a period of 40 nS (25 Mhz). It Can be observed in this figure that there is a significant delay in the response, considering that the lower level of the injected current is below the threshold current to cause lasing. To other experienced simulations, varying the injected current between 8 and 10.5 mA, the output optical power follows the shape of the input signal in a better manner, with less delay, with a consequence that a greater operating frequency could be used. However, the rising of the superior level of the injected current, the overshoot becomes bigger, indicating a reduction in the relative stability of the system.

Fig.13 shows the relation between the photons density S, carrier density N and the optical output power to the same injection current used in fig. 12.

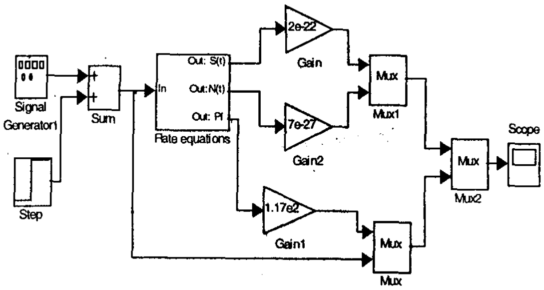


Fig.7 – Block diagram used to simulate a QW LASER

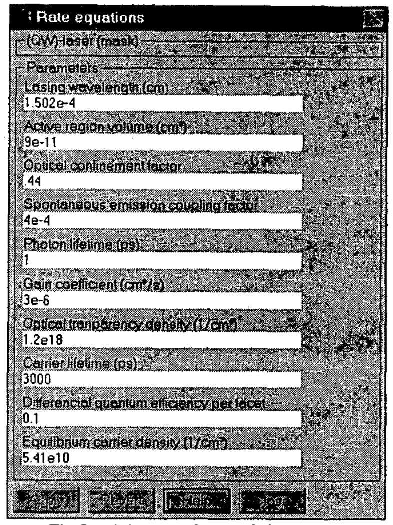


Fig.8 - Dialog box for the QW LASER

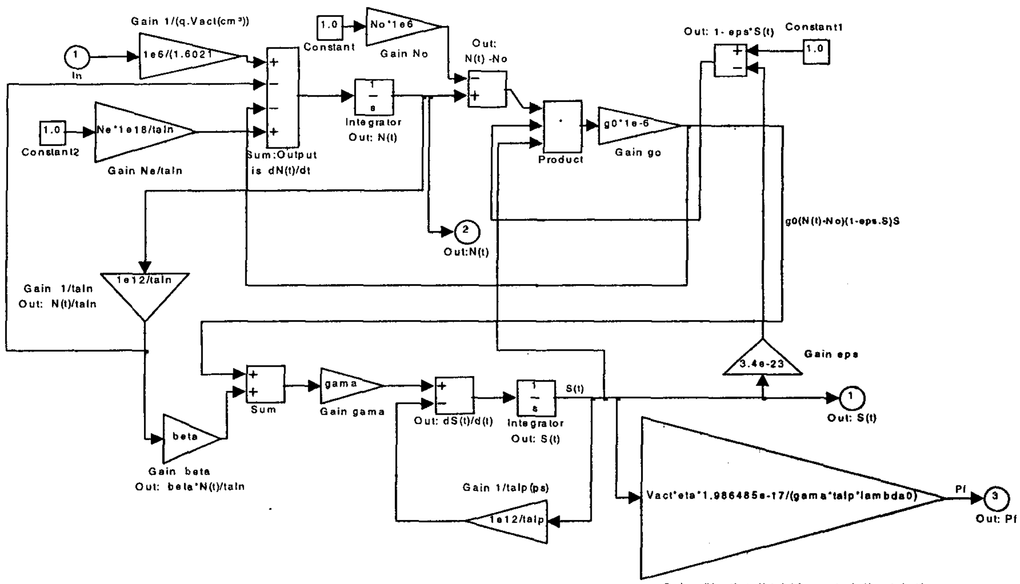
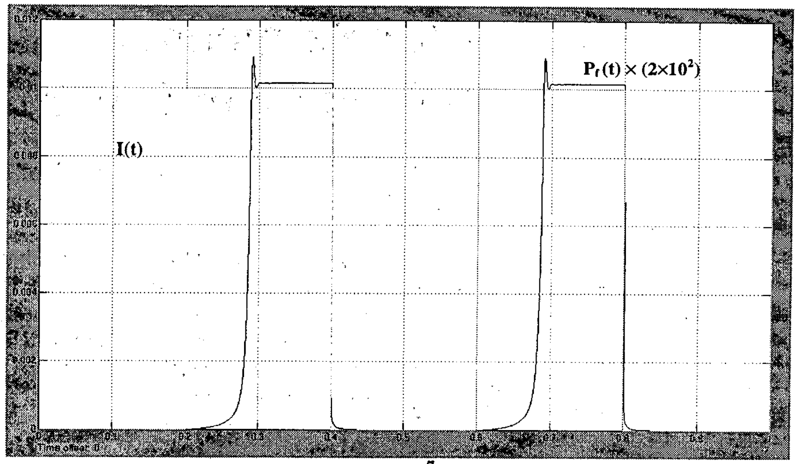
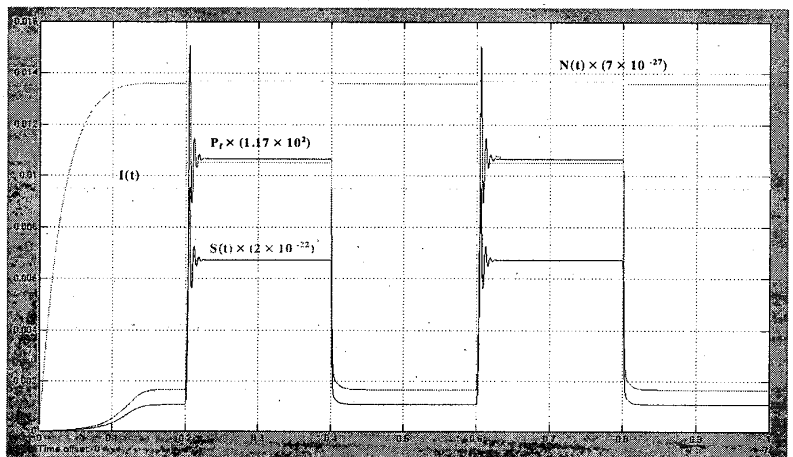


Fig 9 – Block diagram of "rate equations" module in time domain.



time (10^{-7} s)

Fig 10- Optical Output Power to a input current varying between 0 and 10 mA



time (10^{-7} s)

Fig. 11– Variation of the photons density *S*, Carriers density *N* and Optical output Power to an input current varying between 9.5 e 10.5 mA .

IV - Conclusions

The Simulink™ blocks described here have been used as a teaching tool for undergraduating students in basic courses of optical fiber communications at UFPa. The facilities of the computer simulation allows a better understanding of the theory, improving the student's yield, and the flexibility of the software permits the investigation of the influence of various parameters, proving to be a good didatic complement.

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