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Behavior of a new electronic circuit mimicking the edge-emitting semiconductor laser

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ABSTRACT

An electronic analog circuit of the edge-emitting semiconductor laser is proposed. It is powered with a sine wave, triangular wave and square wave. The numerical results are compared to the experimental one and an agreement is found. By using one parameter controlling the normalized reverse bias of the injection current, the Bifurcation diagram obtained when the electronic system is powered with the triangular wave shows that the system exhibits a period-doubling to chaos and this bifurcation diagram appears to be a shift compare to the one obtained with the sinusoidal wave.

1. Introduction

Lasers are classified into different groups depending on their excitation medium. Amount them, those with semiconductor medium called semiconductor lasers are interesting because they are very compact, low cost, the mirror cavity can be avoided and there is direct coupling between electrical energy and the light output. The gain is from 30 to 40% [1]. Some interesting classes of semiconductor laser are the Vertical Cavity Surface Emitting Lasers (VCSELs) and the Edge-Emitting semiconductor Lasers (EELs). In 1987, James and Moss designed an electronic circuit of a simple two-dimensional laser model with periodically modulated cavity-loss parameter. They focused on the two principal locked modes and the bifurcation structure, and made quantitative comparisons of their results with the theory due to Erneux et al. [2]. Also, an electronic device witch imitates the behavior of VCSELs described by the gain dependent current model of Danckaert et al. was built [3,4]. The electronic circuit presents the same dynamics as the real optical device. With electronic models, it is possible to construct some miniature and simple devices for laboratories. By doing so, this can help to simulate quickly and cheaply the behavior of semiconductor laser under various conditions. It also offers new electronic circuits for electronic and communication engineering.

The dynamical behaviors of nonlinear oscillators are important in many scientific fields; ranging from physics, chemistry, biology, engineering, electronic and metrology [5]. An analytic investigation of the torus bifurcation of the van der Pol oscillator subject to two periodic excitations with incommensurate frequencies was considered [6]. It has been shown that a Duffing oscillator subjected to square waves and triangle waves exhibits a period-doubling route to chaos and distinctly modified bifurcation structure [7]. Also, a Chua circuit powered by different types of periodic excitations including the saw tooth wave was shown to deliver new periodic regimes, crises and chaos [8]. A recent study showed that when a van der Pol oscillator is powered with sinusoidal waves, square waves and triangular waves, the bifurcation sequences are similar, but the range of a particular behavior and the bifurcation points are different. The experimental investigation using electronic components showed that the results are similar to those from the numerical simulations [9].

In this paper, we focus our attention on a design, realization and analysis of an electronic device model which is built from the equations of an edge-emitting semiconductor laser, subjected to sinusoidal, square and triangle waves. Both theoretical and experimental studies are carried out. The structure of the paper is as follows: In Section 2, the laser model and the electronic circuit are given. In Section 3 we present the behavior of the electronic circuit under DC current. Section 4 is devoted to the behavior of the

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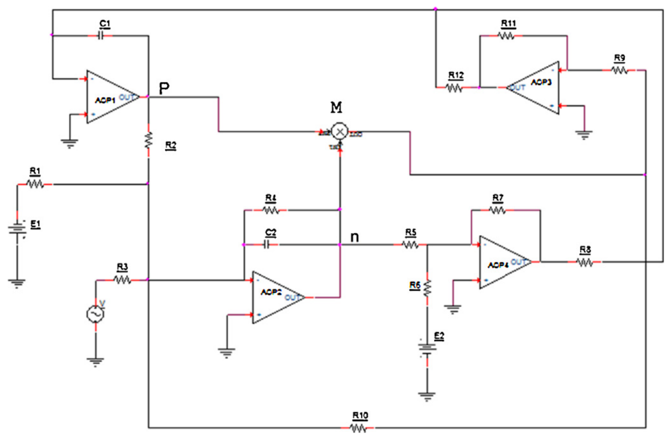

Fig. 1. Analog electronic circuit of an edge-emitting semiconductor laser.

electronic circuit powered by a DC plus sinusoidal signal. Section 5 presents the behavior of the electronic circuit powered by triangular and square wave signals. Finally the conclusion is given in Section 6.

2. Laser model and the analog electronic circuit

The rate equations which describe the dynamics of an edge-emitting semiconductor laser in terms of photon density P and the carrier density N inside the active layer are given [10,11]:

$$\frac{dP}{dt'} = \left[g\left(N - N_0\right)\left(1 - sP\right) - \frac{1}{\tau_p}\right]P + \frac{\beta N}{\tau_s} \tag{1a}$$

$$\frac{dN}{dt'} = I - \frac{N}{\tau_s} - g\left(N - N_0\right)\left(1 - sP\right)P \tag{1b}$$

here s represents the nonlinear gain suppression factor and β is the spontaneous emission factor. τ_s and τ_p are the carrier and photon life times. N_0 is the carrier density required for transparency and I is the injection current in the laser diode.

As injection current $I = I_{dc} + \xi f(t)$ where I_{dc} is the DC bias injection current and, ξ is the admittance. Let us set

$$t = \frac{t'}{\tau_p}; \quad p = \left(\frac{g\tau_s}{2}\right)P; \quad n = \frac{1}{2}g\tau_p N_{th}\left(\frac{N}{N_{th}} - 1\right)$$

$$\varepsilon = \frac{\tau_p}{\tau_s}; \quad \sigma = \frac{2s}{g\tau_s}; \quad \Phi = \frac{1}{2}gN_{th}\tau_p;$$

$$i_0 = \frac{gN_{th}\tau_p}{2}\left(\frac{I_{dc} - I_{th}}{I_{th}}\right); \quad \alpha = \frac{gN_{th}\tau_p}{2}\frac{\xi}{I_{th}}.$$

The dimensionless form of Eqs. (1a), (1b) and (2a), (2b) becomes:

$$\frac{dp}{dt} = \left[\left(2n + 1\right)\left(1 - \sigma p\right) - 1\right]p + \beta\left(n + \Phi\right) \tag{2a}$$

$$\frac{dn}{dt} = \varepsilon\left[i_0 + \alpha f(t) - n - \left(2n + 1\right)\left(1 - \sigma p\right)p\right] \tag{2b}$$

i_0 is the normalized reverse saturation current injected in the laser and α the control parameter of the injection current. Chembo and Woafo [11] studied Eqs. (2a) and (2b) and discard σ and β because of their very small order of magnitude (about 10^{-5}).

From the analog electronic component, we devise an electronic circuit for Eqs. (2a) and (2b). This circuit is displayed in Fig. 1, where operational amplifiers AOP1 and AOP2 are used in integrator configuration. The operational amplifiers AOP3 and AOP4 are used as inverters. M is an analog multiplier.

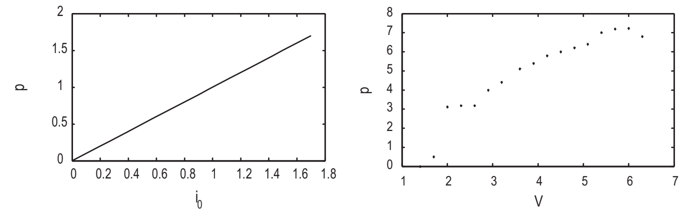

Fig. 2. Photons density as function of different values of DC current; at left hand, the simulation result for $\alpha = 0$, at right hand, experimental one; the DC voltage V varies from 1.4 V to 6.2 V.

When we apply the Kirchhoff laws, we obtain the following set of equations:

$$\frac{dp}{dt''} = \frac{R_{11}}{10R_{12}C_1R_9}np + \frac{R_7}{R_5R_8C_1}n + \frac{R_7E_2}{C_1R_6R_8} \tag{3a}$$

$$\frac{dn}{dt''} = \frac{E_1}{R_1C_2} - \frac{V}{R_3C_2} - \frac{1}{10R_{10}C_2}np - \frac{1}{R_2C_2}p - \frac{1}{R_4C_2}n \tag{3b}$$

Let $t = t''/\tau_p$, the system becomes

$$\frac{dp}{dt} = \frac{\tau_pR_{11}}{10R_{12}C_1R_9}np + \frac{\tau_pR_7}{R_5R_8C_1}n + \frac{\tau_pR_7E_2}{C_1R_6R_8} \tag{4a}$$

$$\frac{dn}{dt} = \frac{\tau_pE_1}{R_1C_2} - \frac{\tau_pV}{R_3C_2} - \frac{\tau_p}{10R_{10}C_2}np - \frac{\tau_p}{R_2C_2}p - \frac{\tau_p}{R_4C_2}n \tag{4b}$$

Equivalence between Eqs. (2a) and (2b) and Eqs. (4a) and (4b) under the condition $\sigma \approx 0$ [11], leads to the following equalities between the electronic components:

$$\frac{\tau_p}{10R_{12}C_1} = 2, \quad \frac{\tau_p}{20R_{10}C_2} = \varepsilon = \frac{\tau_p}{R_4C_2} = \frac{\tau_p}{R_2C_2}, \quad \varepsilon\alpha = \frac{\tau_p}{R_3C_2},$$

$$\varepsilon i_0 = \frac{E_1\tau_p}{R_1C_2}, \quad f(t) = -V$$

The results below are obtained for the following values of parameters $d = 1/23$, $b = 0.8$, $i_0 = 0.6$, $c = 0.5$, $\phi = 1.729$, $\beta = 1.0 \times 10^{-5}$, $\sigma = 1.16 \times 10^{-5}$, $\varepsilon = 2 \times 10^{-3}$. The corresponding values of resistors and capacitances are as follows:

$C_2 = 100\,\text{nF}$; $C_1 = 10\,\text{nF}$;

$R_1 = 10.67\,\text{k}\Omega$; $R_2 = 0.5176\,\text{k}\Omega$; $R_4 = 5.10\,\Omega$; $R_{12} = 120\,\Omega$;

$R_{11} = R_7 = R_6 = R_5 = 1\,\text{k}\Omega$;

$R_3 = 2.767\,\Omega$; $R_{10} = 2.2\,\text{k}\Omega$; $R_8 = 10\,\text{M}\Omega$; $R_9 = 17.893\,\Omega$;

$E_1 = 9.4\,\text{V}$; $E_2 = 8.2\,\text{V}$;

These values are chosen so as to match with the real edge-emitting semiconductor laser.

Let us power the electronic circuit with four types of excitations; DC current, DC plus sinusoidal signal, DC plus triangular wave signal and DC plus square wave signal.

3. Behavior of the electronic circuit under DC current

In this section, the analog electronic circuit of the edge-emitting semiconductor laser is powered with a DC current; for different values of the voltage V, we observed the behavior of the output P. The numerical simulations are performed using the fourth-order Runge–Kutta algorithm Fig. 2 shows the comparison between the numerical and the experimental results. The numerical result presents the P versus α which is related to I_{dc} and the experimental result represents the analog version of P versus the constant voltage. The experimental result shows that the threshold voltage of the analog device of the EEL is 1.4 V.