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Modulation of distributed feedback (DFB) laser diode with the autonomous Chua's circuit: Theory and experiment

Jimmi Hervé Talla Mbé [a,b,c,*], Paul Woafo [b,c]

[a] Laboratory of Condensed Matter, Electronics and Signal Processing, Department of Physics, University of Dschang, P.O. Box 67, Dschang, Cameroon
[b] Laboratory of Modeling and Simulation in Engineering, Biomimetics and Prototypes, Department of Physics, University of Yaoundé I, P. O. Box 812, Yaoundé, Cameroon
[c] African Center of Excellence for Information and Communication Technologies (CETIC), Polytechnic School of Yaoundé, P.O. Box 8390, Yaoundé, Cameroon

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ABSTRACT

We report on a simple way to generate complex optical waveforms with very cheap and accessible equipments. The general idea consists in modulating a laser diode with an autonomous electronic oscillator, and in the case of this study, we use a distributed feedback (DFB) laser diode pumped with an electronic Chua's circuit. Based on the adiabatic P-I characteristics of the laser diode at low frequencies, we show that when the total pump is greater than the laser threshold, it is possible to convert the electrical waveforms of the Chua's circuit into optical carriers. But, if that is not the case, the on-off dynamical behavior of the laser permits to obtain many other optical waveform signals, mainly pulses. Our numerical results are consistent with experimental measurements. The work presents the advantage of extending the range of possible chaotic dynamics of the laser diodes in the time domains (millisecond) where it is not usually expected with conventional modulation techniques. Moreover, this new technique of laser diodes modulation brings a general benefit in the physical equipment, reduces their cost and congestion so that, it can constitute a step towards photonic integrated circuits.

1. Introduction

For many applications, laser light needs to be modulated. There are two main types of modulation, external and direct modulations. The external modulation consists in copying the RF signal from a function generator to a light by using an external component known as modulator, for example Mach-Zehnder and acousto-optical modulators. On the other hand, in direct modulation, the function generator immediately feeds the laser. If external modulation can be applied to a wide variety of lasers and the modulation bandwidth extended to tens of GHz, direct modulation is typically used for laser diodes with limited bandwidth up to a few GHz. However, direct modulation is cheaper and specially in the applications which do not ask for very high speeds of modulation. In addition, laser diodes have become the world largest laser sources because they are also cheap, easy to manufacture, small in size, and therefore easy to be integrated in electronic devices. They are found everywhere due to their disparate areas of application such as medicine, as pumping sources of other lasers, material processing, data storage systems, printing, monitoring of welding, spectroscopy, telecommunication, to name just a few [1,2].

Under external perturbations, laser diodes are capable of generating a variety of instabilities such as regular, pulse, bursting, and chaotic oscillations [3,4]. If these instabilities were initially viewed as undesirable phenomena, and were devoted to control, they have now received important considerations for research and technology. For instance, optical pulses are important for communication based applications [5,6]. Bursting oscillations and their different variations are found in many biological and chemical systems such as enzymes, nerves, and heart cells, so that optical bursting can be used to mimic them, and for biological sensing, or bioinspired information processing [7]. Optical chaotic signals are exploited for chaos based communication [8–11], random bit generation [12–14], and chaotic radar [15].

In addition to noise, the major sources of instability in laser diodes are the delay feedback [7,16] and direct current modulation [17–23]. Despite the fact that the delay feedback offers broader application fields, and are robust for chaos encryption applications [7], the current modulation seems to be more stable and easier to implement experimentally. Moreover, both sources sometimes induce similar dynamics in laser diodes like for example, the

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* Corresponding author at: Laboratory of Condensed Matter, Electronics and Signal Processing, Department of Physics, University of Dschang, P.O. Box 67, Dschang, Cameroon.

E-mail address: jhtallam@yahoo.fr (J.H. Talla Mbé).

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sequence of pulses gathered in package, appearing regularly, and known as pulse packages [19,24]. The majority of function generators used experimentally in laser diode current modulation are heavy, bulky, and can offer up to three functions namely, sine, square, and triangular. These characteristics can be disadvantageous in some applications where autonomy, small size and volume are required such as in embedded systems. Therefore, replacing the function generators by autonomous oscillators is an eventual solution because they are cheap compared to function generators, small in size, offer low energy consumption, and are capable for some of them of generating a variety of complex electrical signals like period-n $(n = 1, 2, \ldots)$, pulses, bursting, and chaotic oscillations. The aim of this paper is to experimentally perform this type of laser diode modulation.

Indeed, the idea of directly modulating a laser diode with an autonomous oscillator really emerged recently [20,25–28]. Nevertheless, it is important to note that previously, some experimental setups where an autonomous oscillator contributed to the pumping of the laser diode were already considered [29–31]. The authors of [29] addressed on oscillation death in a diode-laser-pumped Nd: YAG laser mutually coupled to a Rössler's oscillator. In [30,31], it was reported a conversion from electrical chaotic signal to optical chaotic signal by the use of a hybrid system which consisted of a laser diode driven by a resonant tunneling diode cascaded by a sinusoidal signal; optical pulses were also obtained when the sinusoidal signal was replaced by noise [32]. But, the study of the dynamical behavior of the laser diode directly modulated by autonomous circuits was not addressed by these authors. In [20,25], using a Rössler's oscillator and respectively a Van der Pol's oscillator, it was theoretically demonstrated that it is possible to recover the dynamics of VCSELs (vertical cavity surface-emitting lasers) and EELs (Edge-emitting lasers) when they are supplied with a high frequency sinusoidal pump. Besides, using other oscillators, numerical investigations were also reported, such as ring lasers driven by a Chua's oscillator [26] and VCSELs under Nana et al. oscillator [27]. Interesting results were for example the generation of bursting oscillations, period-doubling route to chaos at high modulation frequencies (in the range of GHz), with the possibility of encrypting digital messages. But, these numerically results assumed that the autonomous oscillators cited above run at high frequencies (beyond about 100 MHz), which on a practical point of view requires electronic components that are not yet available. Moreover, an experimental issue on the idea was recently done by Momo and Woafo, but on an analog electronic model of an EEL driven by a Kingni et al. oscillator [28]. It is therefore necessary to carry out experiments on a real laser diode driven by a constructed autonomous circuit. Although, this does not solve the question of high frequencies, modulating laser diodes with even low or intermediate frequency signal may lead to applications such as control of group velocity, optical microscopy and quantum information processing and of which we will discuss later.

In this paper, we address on the point by studying experimentally and confirm theoretically the dynamical behavior of the DFB laser diode under the modulation of the electronic Chua's circuit. Our attention is focused on these elements because of the following reasons. The Chua's circuit is a simple autonomous nonlinear oscillator capable of exhibiting a variety of bifurcation scenarios, and chaotic phenomena encountered in other circuits. Indeed, it was the first circuit implementation specially designed to exhibit chaos [33,34]. On the experimental point of view, the Chua's circuit can be implemented easily using available and inexpensive electronic components. For the DFB laser diodes, despite the fact that they can require a threshold current higher than other laser diodes, they produce an optical output with very low bandwidth, offering therefore the possibility to fix their wavelength at a desired value such as the telecommunication one for example [35,36]. They are also counted among the main optical sources in many experimental research works as those carried out at low frequencies [37–41].

The outline of the paper is as follows. The experimental setup and the modeling are given in Section 2. The coupling between the laser and the electronic circuit is also emphasized. Experimental and numerical time-dynamics of the system are presented in Section 3. In Section 4, we discuss about applications. A conclusion ends the article.

2. System and model

Our system is displayed in Fig. 1: a commercial butterfly continuous wave multi quantum well distributed feedback laser diode (Mitsubishi $FU-68PDF-V10M59B$) with telecom wavelength $\lambda_L = 1549.32$ nm and a polarization maintained terminal pigtail. That laser placed on a mount fixture (IXL Lightwave $LDM-4980$), is fed with a pumping $V_{pump}(t) = -V_{dc} - \zeta V_k(t)$, which is a combination of V_{dc} supplied by a bias voltage source and a time-varying voltage $V_k(t)$ provided by an autonomous oscillating Chua's circuit (Fig. 1b). V_k, $k = 1, 2$ is the voltage difference at the electrodes of capacitor C_k, and $\zeta = r/R$ is the coupling coefficient used to adjust the laser pumping so that it does not exceed the maximum value which is 3.5 V. The collection of V_{dc} and $V_k(t)$ is performed by a summing circuit made of an Op-Amp ($TL081CP$) with three resistors (one R and two r). Since the laser is configured to operate with negative voltages, the summing circuit is built as an inverter.

In order to match the impedances between different elements of the system, the summing circuit is sandwiched with two voltage follower circuits (Fig. 1a). The optical signal generated by the laser is converted into a photocurrent by an InGaAs fast photodiode (Thorlabs $PDA10CF-EC$), with a bandwidth of 700–1800 nm, and having an electrical/optical conversion factor of 0.95 A/W. The output of that photodiode is visualized thanks to a 100 MHz digital oscilloscope (RIGOL $DS1102E$), with a sampling rate of 1G samples/s. The whole setup was thermalized to the room temperature without any specific control, since we are concerned with the deterministic dynamics of the system.

It is important to note that the frequency of the Chua's circuit is of the order of kHz, while the relaxation oscillation frequency (f_{ro}) of the laser diode is in the range of GHz. This large difference in frequency of 6-order of magnitude between these devices can be confusing. Indeed, like any other laser diode, a DFB laser has an intensity versus frequency characteristics similar to a high-pass filter [17,18] (see Fig. 2a), with a cut off frequency in the range of GHz (in our case 2 GHz, given by the manufacturer) but, starting at very low frequency range, some Hz. Thus, the laser diode can operate at frequencies lower than its cut-off value, which is close to the relaxation oscillation frequency. This reveals that the laser diode can be pumped with circuits of high, low or very low frequency such as the Chua's circuit and could be of great interest on the fundamental point of view in lasers physics but also for various area of applications.

The first main element of the setup is the Chua's circuit (Fig. 1b). It is a simple autonomous nonlinear oscillator made of three energy storing components (two capacitors C_1 and C_2, and one coil L), one linear resistor R_c, and one non-linear resistor also known as Chua's diode (boxed part of Fig. 1b). The Chua's diode consists of two Op-Amps and six resistors $R_m, m = 1, 2, 3, 4, 5, 6$. Its current versus voltage characteristics $i_{NL} = f(V_1)$, which is a piece-wise linear function, with breakpoint B_s is shown in Fig. 2b. The state equations of the Chua's oscillator are obtained through application of Kirchhoff's laws: