Experimental Observation of Chaotic Dynamics in Two Coupled Diode Lasers Through Lateral Mode Locking

Rui Santos and Horacio Lamela, Member, IEEE

Abstract—The nonlinear and chaotic phenomena in lateral coupled diode lasers have been widely studied theoretically. In this work an experimental analysis of the complex nonlinear and chaotic dynamic regimes experimentally observed in these devices and the mechanisms that produces it is made. This analysis is set by means of the RIN electrical spectrum and of the high resolution Fabry–Perot optical spectrum. A mapping of the nonlinear occurrences in these devices is obtained and a study of the relation between the relaxation oscillation frequency and the lateral locking frequency is achieved.

Index Terms—Chaos, lateral mode locking, nonlinear dynamics, semiconductor laser arrays.

I. INTRODUCTION

COMPLEX nonlinear dynamics and chaotic behavior in semiconductor lasers has been studied for several years. These devices cannot show chaotic behavior because their functioning is fully described by two independent quantities: the electric field and the carrier density. However, by adding an additional degree of freedom, chaotic instabilities may occur. This phenomenon occurs when the semiconductor laser is externally influenced by: 1) external cavity; 2) external light injection; and 3) external modulation [1]. The external cavity nonlinear dynamics are due to a delayed feedback condition. In this case a multi degree of freedom situation occurs due to the nature of the delay and of the external cavity characteristics [1]. In the case of external light injection a rigorous theoretical and experimental study was developed. In these studies several period-doubling cascades separated by chaotic regimes were found. These occurrences take place either when the detuning between the master and slave lasers is approximately zero or double the relaxation oscillation frequency [1], [2]. For external modulation of the injection current period double route to chaos was experimentally reported [3] and theoretically investigated [4]. In this case the observed route to chaos was through period doubling bifurcations and a period three truncation of the Feigenbaum sequence may occur [3], [4]. Besides this, in external modulation of the current injection virtual hopf noise phenomena through noise precursors were experimentally observed in the onset of the period doubling [5].

Theoretical studies concerning the dynamics of two lateral coupled diode lasers (LCDL) showed that these devices presented, intrinsically, instabilities and chaotic behavior. Winful et al. [6] developed a time-dependent coupled mode theory and indicated that these devices were intrinsically unstable and that the laser output is generally chaotic [6]. This chaotic behavior was assigned to the competition between the array supermodes and strength of the coupling [7]. In the same investigation area, Hess and Schöll [8] developed a spatio-temporal model for the analysis of the dynamics of LCDL. In this work the authors performed a study of the stability of these devices for different separations between the laser waveguides and concluded that for devices with strong coupling (separation between laser ridges \( \leq 5 \mu m \)) the output oscillates chaotically. This chaotic feature vanishes when the laser waveguides are separated by more than 14 \( \mu m \) [8]. This unstable behavior was also predicted by Lamela et al., using the analysis of a BPM spatiotemporal model and a rate equations model [9]. Where the instabilities were described as an effect of the intrinsic coupling between waveguides, which produces an oscillating frequency that was characterized for several separation distances between the laser ridges, and a modulation scheme, at these frequencies was proposed [9]. Very recently nonlinear dynamics of two laterally coupled semiconductor lasers has been studied by a bifurcation analysis of the composite cavity modes of these devices [10]. Besides this, these devices have been proposed for frequency modulation beyond the intrinsic relaxation oscillation frequency of a single diode laser. This was theoretically predicted by Winful et al. by modulating the out-of-phase mode [11]. Experimental observation of modulation of these devices beyond the relaxation oscillation frequency was reported via the locking of the two lateral modes (in-phase and out-of-phase) characteristic of these devices [12] and experiments of transmission signals at this locking frequency were also achieved [13].

Recent experimental characterizations of the dynamics of LCDL devices showed that nonlinear and chaotic functioning as well as stable operation, are observed in the same device of two lateral coupled diode lasers (LCDL) [14].

In previous experimental work it was found that the LCDL devices are characterized by a second resonance oscillation frequency beyond the relaxation oscillation frequency that is im-
posed by the lateral mode coupling between the fields emitted by twin lasers (lateral locking frequency) [12]. The coupling between the lateral modes depends on both the relative current applied to each one of the laser waveguides and on the distance between the ridges [15]. The relative bias current is responsible for the change in the frequency of the second resonance and in the lateral phase-locking conditions. The lateral distance separation characterizes the frequency range of the second resonance. This implies that the system has a new degree of freedom corresponding to the second resonance frequency which, can lead, under certain circumstances, to nonlinearities [1], [16]. This feature can be understood as the degree of freedom, responsible for the nonlinearities in external optical injection [1], [2], [16].

It is the aim of this work to study and clarify the nonlinear and chaotic behavior experimentally observed in LCDL devices and theoretically predicted by different authors.

In order to define the mechanism that induces the nonlinear dynamics in lateral coupled diode lasers, in this paper a detailed experimental study is presented. In Section II a description of the main characteristics of the LDCL device and of the experimental setup used to perform this study is made. In Section III an analysis of both the RIN and of the high resolution optical spectrum used to identify the nonlinear regimes is shown. Once the regimes are defined and characterized, a detailed study of the proper frequencies (second resonance and relaxation oscillation frequency) of the device is made. In order to do so an analysis of the variation of the relaxation oscillation frequency with the bias currents applied and its relation with the second resonance frequency was performed. Also in this section, a detailed mapping of the nonlinear regimes observed and the transitions between each regime is presented. Conclusions are given in Section IV.

II. EXPERIMENTAL SETUP

The lateral coupled diode laser device under study is a twin 500-μm-long Fabry–Perot laser laterally optically coupled with independent bias on each ridge fabricated on a 1330 nm AlGaInAs/InP structure on SI-InP substrate with p-type contact up. Horizontal confinement of the optical field is achieved etching down to within 350 nm of the top p-type waveguide layer, forming two ridge waveguides with 4 μm width, spaced 4 μm from one another [considering that the metal layer is part of the ridge width as seen in Fig. 1(a)]. The active region is composed by 5 AlGaInAs quantum wells embedded in 100 nm p- and n-type waveguide layers. Facets were left as cleaved. In Fig. 1(a) a SEM picture of the LCDL device fabricated under the FALCON TMR project is shown. More details on the static characteristics of these devices can be found in [17]. The laser chip is mounted on a sub-mount with a ”K” connector for RF modulation (up to 40 GHz). This device presents a threshold current for single ridge operation of 30 mA in ridge 1 and 33 mA in ridge 2 [12]–[15]. This difference between the threshold currents is due to a small variation in the reflectivities of each waveguide caused during the cleavage process. When both laser ridges are biased and ridge 1 is biased below threshold, the threshold current of ridge 2 decreased due to the decrease in losses. This effect occurs because injecting current into ridge 1 acts as a source of carriers that reduces carrier diffusion in the interridge spacing [17], [18]. By biasing ridge 2 above threshold, it was seen that the relaxation oscillation

Fig. 1. (a) SEM picture of a generic LCDL of cleaved facets showing gold contacts on top of the ridges, and ridge dimensions of 3.65 μm width, and 4.77 μm separation. (b) Spectrally resolved far field (top) and integrated spectrum (bottom) with separation between the in-phase and out-of-phase spectrum of 8 GHz. (c) Frequency response corresponding to a separation between lateral modes of 8 GHz.
frequency of ridge 2 depends on the bias applied to ridge 1. This dependence presents two different linear segments: the first one when only the out of phase lateral mode is present and the second one when both in-phase and out-of-phase lateral modes coexist [as in Fig. 1(b), top] [18]. The emission wavelength was found to be around 1335 nm [Fig. 1(b), bottom]. It can be observed in this figure that each longitudinal mode is formed by the in-phase and out-of-phase lateral modes [Fig. 1(b), top]. This emission characteristic was previously reported in [12] and [19]. The frequency separation of the lateral modes implies the existence of a second resonance peak at the frequency response of these devices which, in this case, was approximately 8 GHz [Fig. 1(c)].

The experimental setup to perform this study is described in Fig. 2 where the output of the LCDL device was divided by means of a beam splitter in order to simultaneously measure the RIN spectrum and the lateral side bands around one longitudinal mode. This allows the observation of the RIN power spectrum for identification of the characteristic frequencies of the device, simultaneously with the evolution of the lateral modes spectrum at each operation region. Both ridges of the device were biased separately and the device was stabilized in temperature ($T = 25^\circ\text{C}$). One of the light beams was coupled to a monomode fiber which was connected to an optical isolator, in order to avoid optical feedback into the laser device, and finally connected to a 10–90 optical splitter. The 90% branch was connected to a U2T high speed photodiode and the 10% branch was used to measure the DC optical power. The output of the photodiode was connected to a 30 dB low noise amplifier, with a bandwidth from 1 to 40 GHz, and this was connected to an Anritsu MS2668C spectrum analyzer. Since these devices are multi-longitudinal mode, the other beam was passed through a monochromator to spatially separate each longitudinal mode. At the output of the monochromator one of the longitudinal modes, and the adjacent lateral modes, were coupled in a monomode fiber and were analyzed using a scanning Fabry–Perot (FP). The Free Spectral Range (FSR) of the Fabry–Perot was set at 30 GHz. This allows us to obtain a fine measurement of the lateral side bands of each longitudinal mode with spectral resolution of 30 MHz.

III. NONLINEAR DYNAMICS AND CHAOS IN LCDL

Representative nonlinear regimes observed in this device are presented in Fig. 3. For a bias current applied to ridge 1 of 36 mA and of 58 mA to ridge 2 the optical spectrum is composed of the two locked lateral modes separated by 7 GHz. This implies that the RIN spectrum presents a second resonance peak at the same frequency separation as the lateral modes (7 GHz) [Fig. 3(a)], which is a signature of the lateral coupled diode laser devices. At this bias condition a stable period single due to lateral locking is observed. Increasing the current applied to ridge 1 to 38 mA [Fig. 3(b)], the device is also in the locking region and it is observed that both in the optical spectrum and the RIN spectrum the lateral modes are separated by 7.1 GHz and a new frequency, corresponding to an undamping of the relaxation oscillation frequency, appears at 3.55 GHz. This indicates that the device is in a period doubling operation region. Period quadrupling is found at the bias conditions of 42 mA for ridge 1 and 58 mA for ridge 2 [Fig. 3(c)]. The separation between the locked lateral modes is found at a frequency of 7.5 GHz and the nonlinear low harmonics with a separation of 1.88 GHz, as can be observed in both the RIN and the optical spectrum. For bias conditions of 42 mA in ridge 1 and 62 mA in ridge 2 a chaotic nonlinear regime is found [Fig. 3(d)]. In this case the RIN spectrum is characterized by a broadband ($\sim$10 GHz) spectrum over a period doubling regime. In the Fabry–Perot spectrum the lateral modes present a separation of 8 GHz and a period doubling is found at 4 GHz above a broadband chaotic spectrum.
Once the regimes are described a study of the relation between the proper frequencies of this device is made. The evolution of the resonance frequency was determined by the measurement of the small signal bandwidth of the device [Fig. 1(c)], as described in [12]. The small signal modulation was applied to a fixed biased ridge 2 while the bias applied to ridge 1 was varied. The fixed bias points applied to ridge 2 were chosen so that, nonlinearities occurred. The bias applied to ridge 2 was 55 mA [Fig. 4(a)], and the bias of ridge 1 was varied so that period doubling and period quadrupling were observed. From the measurements it was found that the second resonance (corresponding to the frequency separation between the locked lateral modes) was, approximately, at double the relaxation oscillation frequency. This result is in accordance with previous studies on external injection semiconductor lasers, since at double the relaxation oscillation frequency the laser is more sensitive to external perturbations and nonlinearity regimes occur [2]. It must be noted that the device is in the lateral locking region (lasing both in-phase and out-of-phase lateral modes) when the nonlinearities are observed.

Finally we present the evolution of the nonlinear regimes as a function of the bias conditions applied to each one of the LCDL ridges [plotted in Fig. 4(b)]. When the bias applied in ridge 2 is lower than 51 mA, and for any bias applied to ridge 1, the device behaves in a stable lateral locking operation and no nonlinear behavior is found. For bias currents applied to ridge 2 higher than 51 mA period doubling, quadrupling and chaotic regimes are observed. The first nonlinear regime to appear is period doubling. Increasing the current applied to ridge 2, period quadrupling and chaotic regimes are experimentally observed. In these devices the route to chaos seems to be via period doubling. These results indicate that both stable and nonlinear regimes are observed in the same LCDL device. The mechanism that produces nonlinear operation is the interaction between the relaxation oscillation frequency and the lateral locking frequency.
IV. CONCLUSION

In conclusion, we have for the first time, to our knowledge, experimentally obtained a detailed characterization and mapping of the nonlinearities observed in LCCL devices. Analyzing the optical spectrum and the RIN spectrum it was demonstrated that stable and nonlinear operation of the same LCCL device occur. Stable operation is characterized by the simultaneous emission of both the in-phase and out-of-phase lateral modes. In this operation regime a single frequency is observed in the RIN spectrum corresponding to the frequency difference between the in-phase and out-of-phase lateral modes. When this frequency doubles the relaxation oscillation frequency nonlinear regimes takes place. The first nonlinear regime to appear is period doubling followed by period quadrupling and chaos. This indicates that the route to chaos, in these devices, is via period doubling.

ACKNOWLEDGMENT

The authors acknowledge device fabrication by Prof. M. Pessa, ORC (Tampere, Finland), and RF submounts by J.P. Vilcot, IEMN (Lille, France).

REFERENCES


Rui Santos received the degree in optoelectronics and lasers from the School of Sciences, University of Porto, Spain, in 2000. From 2000 to 2003 he was working as a pre-doc in the FALCON-TMR European Project. He is currently working toward the Ph.D. degree at the Universidad Carlos III de Madrid, and he is a Lecturer of the Tecnologia Electronica Department. His research interests are high-speed semiconductor laser dynamics, optical communications and nonlinear and chaotic dynamics in semiconductor lasers arrays.

Horacio Lamela (M’98) received the Industrial Engineering degree from the Universidad Politécnica de Madrid (UPM) in 1980, the Diplome d’Etudes Approfondies (DEA) from the University of Paris XI in 1981, and the Diploma d’Etudes Approfondies (DEA) from the University of Paris XI in 1981, and the Doctorate-Ingenieur degree in optical interferometry from the Conservatoire d’Arts et Metiers of Paris, France, in 1985. From May 1985 to November 1987, he was with the Massachusetts Institute of Technology, Cambridge, as a Postdoctoral Fellow with the Electrical Engineering and Computer Sciences Department, Visiting Scholar through Fulbright-MEC Commission at the Research Laboratory of Electronics. He is presently a full Professor with the Departamento de Tecnologia Electronica and leader of the Optoelectronics and Laser Technology Group at Universidad Carlos III de Madrid. He is a Lecturer of the Tecnologia Electronica Department. His research interests are high-speed semiconductor laser dynamics, dual mode lasers for millimeter and THz generation, optoelectronic neural networks and interferometric fiber optic sensor for industrial and biomedical applications.