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Optical spectrum behaviour of a coupled laser system under chaotic synchronization conditions

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Synchronization characteristics of two bidirectionally coupled semiconductor lasers, one operating in a chaotic regime with low-frequency fluctuations and the other with free laser beam emission, were experimentally investigated. The chaotic synchronization regimes and optical spectral behavior of the coupled system were analyzed with respect to the optical spectra emitted initially by the two uncoupled lasers operated under the same feedback conditions. It was observed that the number of synchronization regimes that can be obtained and their stability depend on the similarity of spectral structures of the uncoupled lasers emissions. The dominant active laser modes of the coupled system emission coincide with the laser modes of the one or both uncoupled laser emissions, depending on the operating synchronization regime. We have associated changes in the optical spectrum of the coupled system with the synchronization regimes. The repartition of power between the active modes of a coupled system allows identification of the synchronization regime.

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1 INTRODUCTION

The semiconductor laser devices that have nonlinear dynamics are interesting as physical systems and are useful in engineering applications, particularly in external optical feedback conditions. The external feedback generates qualitatively different phenomena out of which the most studied is the chaotic behavior. The intensity of the optical feedback, the level of the injected current and the diode temperature significantly influence the chaotic evolution of the system. When the laser operating current is near to the laser emission threshold, the time evolution of the beam intensity shows low-frequency fluctuations (LFFs) [1].

An external-cavity semiconductor laser (ECSL) system with optical feedback is typically used to generate chaotic laser emission in the LFF regime [1]. The LFF frequencies can be changed by applying a controlled variation to an accessible parameter of the ECSL system. The chaotic behavior may have applications in secure optical communications by synchronizing two such systems – one, defined as “master”, and the other as “slave”. An encoded digital message attached to the chaotic optical carrier can be recovered by coupling the chaotic transmitter with a similar ECSL or solitary laser receiver [2]. This coupling may be accomplished in unidirectional or bidirectional fashion, leading to different synchronization regimes [3]. The quality of the recovered message depends on the retardation time that is required for the receiver dynamics to synchronize with the transmitter [4, 5]. It also depends on the similarity of the modal power distributions in the emission spectra (operating frequencies) of the laser systems [2]. The retardation time has a value that is close to the time of flight of the laser light-beam needed to travel the optical path between the two semiconductor lasers [6, 7]. Three different synchronization regimes can be obtained - depending on the retardation time, such as: lag synchronization (LS) when the slave dynamics follow the master dynamics; zero-lag synchronization (ZLS), when there are no delay times between the two dynamics; and anticipated synchronization (AS), which is obtained only in a bidirectional coupling, when the slave fluctuations are produced before the master ones [3].

In this paper we analyze from the point of view of the optical spectrum, the general case of bidirectional synchronization of an ECSL chaotic system with a solitary laser used as master and slave [6, 8]. Two commercially available semiconductor lasers (SL) which have the same technical specifications were used.

2 EXPERIMENTAL SETUP

We have developed an experimental setup consisting of an ECSL chaotic laser system with LFF dynamics, used as master, and optically coupled, in a bidirectional fashion, with a solitary SL which has a free emission and is used as slave. We utilized two continuous wave Fabry-Perot semiconductor lasers (Mitsubishi, ML101J8) that are operated near the laser threshold currents, as shown in Figure 1 [9], emitting at 661 nm laser beams having the powers around 2 mW. The se-

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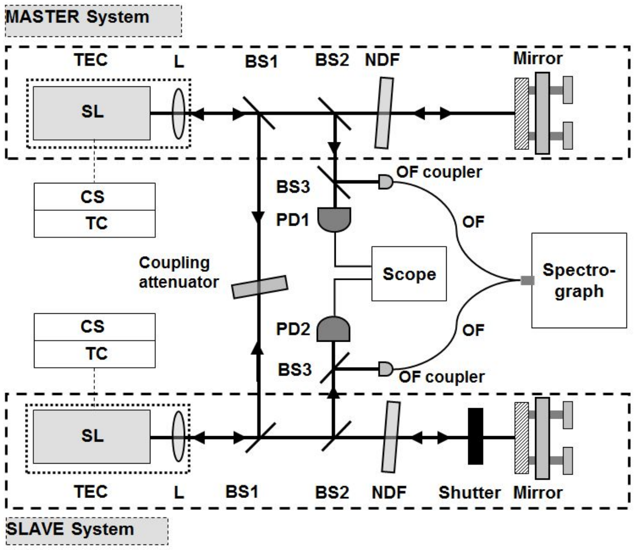

FIG. 1 Experimental set-up of bidirectionally coupled system. SL - Semiconductor lasers; SL mounts with thermo-electric cooler TEC; current sources and temperature controllers CS and TC, respectively; L - collimation systems; BS - beam-splitters; NDF - neutral density filters; PD - photodetectors; OF - optical fibers.

lected lasers are commercially available and have almost identical manufacturer's specifications for optimal operation: output powers of 40 mW at a wavelength of 663 nm and 24°C case temperature. The injection currents are $I_M = 109$ mA for master and $I_S = 110$ mA for slave with threshold currents of $I_M^{th} = 54$ mA and $I_S^{th} = 53$ mA, respectively. Two identical mechanical mounts (TEC) that include collimation optical systems (L) are used to operate the laser diode in the same conditions. The optical feedback was obtained in both systems by placing mirrors of 98% reflectivity in the optical paths of the laser emissions. The slave system was used under feedback conditions only in the alignment stage. The feedback intensity could be adjusted in the chaotic system by controlling a neutral density filter (Thorlabs, NDC-50C-4M) with variable transmittance. The feedback intensity level measured by feedback coefficient was adjusted until well-delimited intensity fluctuations were obtained in the laser emission at a specific set of initial operating parameters.

The feedback coefficient is determined by the sum of the attenuations introduced in the optical path by the two beamsplitters, BS1 and BS2, with fixed transmittances of 66% and 82%, respectively, and the neutral density filter (NDF). The feedback coefficient represents about 1% of the output power of the laser, but less than this power fraction is injected into the laser active medium. The actual level of the feedback intensity was estimated to be one tenth of the calculated feedback coefficient, due to diffraction effects in the collimating system that generate a focal spot with large dimensions relative to the active medium dimensions - and also to other causes of light loss [8]. Two photodetectors, PD1 (Becker&Hickl, APM-400-P), and PD2 (Laser 2000, ET-2030A) with rise times of less than 500 ps, convert the detected optical signal into electrical impulses. A Tektronix DPO7254 digital scope with a bandwidth of 2.5 GHz was used to acquire simultaneously the master and slave signals. The wavelength was measured with a spectrograph (Princeton Instruments; Acton SpectraPro 2750), with an optical resolution of 0.02 nm. In this case, the recorded optical spectrum represents an average over ten consecutive spectra, each registered during an exposure time of 500 µs. A coupling attenuator was used to control the optical injection strength between the two lasers placed at a distance apart of about 66 cm. As a measure of the optical injection strength, a coupling ratio (CR) defined as the ratio of the master optical injection and solitary laser output power is introduced.

3 RESULTS AND DISCUSSION

The correspondence between the initial emission spectra of the uncoupled chaotic lasers, the synchronization regimes and the optical spectrum of the coupled system was analyzed.

The initial operating parameters (injection currents and case temperatures) were chosen so that the optical spectra of the two solitary lasers are quasi-identical at injection currents near the threshold currents of the laser emissions. This condition is necessary in order to achieve the dynamics synchronization of the two laser systems in the LFF chaotic regime. In this respect, two sets of operating parameters were identified - for which the two emission spectra of the solitary lasers are quasi-identical (Figures 2(a), 3(a) and 4, the inset pictures).

The slave system was operated under the same external optical feedback conditions as the master system only when used in the alignment stage of the coupled system - having in mind, at the same time, the use of its optical spectrum as a reference spectrum in the analysis process. The two ECSL systems were aligned to each other so that one obtains the maximum output power of each coupled system. After that, the slave external cavity was misaligned (zero value of feedback coefficient), and the coupling ratio was adjusted until stable LFFs were obtained in the laser emissions of the coupled system. The master optical injection induces in the slave laser emission LFF dynamics that are synchronized with the master one. The synchronization can be performed in a lag, zero-lag or an anticipated [3] regime – as a function of the initial operating parameters and coupling conditions.

Special attention has been paid to obtaining the three distinct synchronization regimes. The alignment conditions of the ECSL systems, together with those concerning the bidirectional coupling of the ECSL system and solitary laser, were analyzed.

Mirror alignment was performed for each ECSL system, in order to obtain a maximum output power level for the initial operating parameters and for a higher feedback coefficient. After that, the NDF transmission of each system was decreased until stable LFF fluctuations were obtained in the laser intensity time series. The NDF transmissions were fixed in such a way as to obtain the same feedback coefficients in both systems.

When the mirror is configured to give the maximum feedback intensity and maximum output power, respectively, without misalignment, the laser emission exhibits a constant intensity time-series, without fluctuations.

In the first instance, it was observed that the two ECSL uncoupled systems aligned in this way showed quasi-identical optical spectra with narrowed bandwidth, for each set of initial operating parameters and a proper chosen external cavity length. The optical spectrum of the coupled system is identical with the initial spectra, and the lag regime is the only stable synchronization regime obtained in all cases analyzed.

On the other hand, it was observed that the number of synchronization regimes that can be evidenced, starting from a specific set of initial operating parameters and external cavity length, increases for higher NDF transmissions, at the same ECSL output powers as used in the previous alignment. In this case, the laser emission had a large bandwidth and the ECSL power decrease was achieved by mirror misalignment - which easily affects the output power level emitted by the system, diminishing it by about 10%. In this way, in order to obtain the LFF chaotic emission, the external mirrors used at normal incidence were aligned slightly away from the position for which the maximum laser output power is obtained. The difference between the two types of alignment is given by the laser power distribution in the laser spot, which is higher for mirror misalignment case (higher NDF transmission). The calculated feedback coefficient is much higher than in the first case of alignment but, due to the focal point movement on the emitting area of the semiconductor, the actual feedback coefficient is lower. It was estimated by comparing the ECSL powers with those from the first case of alignment, and it was maintained at the same value in all the cases analyzed.

It is important to mention that, in the mirror misalignment case, the optical spectra of the two ECSL systems can be more or less overlapped - by properly choosing the alignment conditions.

Combining the initial set of operating parameters with two properly chosen ECSL cavity lengths, three cases of laser emission of the master and slave systems, both used in the ECSL configuration, were obtained. So, we found master and slave ECSL system emissions with different, similar and quasi-identical optical structures. Two external cavity lengths, L_1 = 64.1 cm and L_2 = 48.3 cm, respectively, were used. In the cases analyzed, laser emissions with different optical spectra imply emissions with close spectral ranges, which are superimposed on a narrow bandwidth. Use of the word 'similar' means laser emissions with the same spectral range and modal structure but with different modal power distributions. Use of the phrase 'quasi-identical optical spectra' means laser emissions with the same spectral range, modal structure and ratio of the modal power distributions.

In the three cases of laser emissions that were analyzed, the synchronization regime obtained for the initial set of operating parameters was also different from one case to another. Lag synchronization was obtained in the case of emissions with different optical spectra (Figure 2); anticipated synchronization was obtained in the case with similar optical spectra (Figure 3); and zero-lag synchronization was obtained in the case with quasi-identical spectra (Figure 4). Two other synchronization regimes were obtained for each of the first two analyzed cases of laser emissions, with different and similar optical spectra, by slightly adjusting the initial operating parameters. In the case with quasi-identical spectra, in all analyzed situations, when the master chaotic system has been synchronized with the solitary slave laser, the zero-lag synchronization was the only regime obtained.

Figure 2 shows the coupled system emission with master and slave different spectral ranges. The optical spectra (a), intensity time series (b), and associated power spectra (c) of the two laser systems are represented for the three synchronization cases, (I) lag, (II) zero-lag and (III) anticipated. The measurements were performed for L_1 at $I_M = 1.07\times I_M^{th}$, $T_M = 22.5°C$ and $I_S = 1.056\times I_S^{th}$, $T_S = 24°C$.

In Figure 2(a), the inset picture shows the master (black line) and slave (light grey line) spectra without optical feedback, while the large figure shows the master and slave spectra of the uncoupled lasers with feedback. The optical spectra of the two solitary lasers show an initial shift of 0.15 nm. The optical spectrum of the coupled system is represented for the three synchronization cases, with the filled area corresponding to the first synchronization regime.

The initial emission spectra of the uncoupled ECSL chaotic systems have shown multimode structures with modes that are active in different spectral ranges that overlap in a small wavelength region of 1 nm in extent, i.e. from 661.2 to 662.2 nm. The optical spectrum of the coupled system has a multimode structure, where the dominant active modes overlap with those of the optical spectra of the two uncoupled chaotic systems (Figure 2(a) (I-III)). The first synchronization regime obtained for the initial set of operating parameters was the lag regime, and it was obtained for a coupling ratio of 1.2% (Figure 2(b) (I)). The coupling ratio value was identified (*via* several checks) in order to achieve a good degree of synchronization of the two-laser dynamics and to obtain regular LFF fluctuations in the coupled system dynamics, respectively. Two other synchronization regimes were obtained by slightly changing the output power levels of the two lasers and the coupling attenuator transmission. To obtain the zero-lag synchronization regime (Figure 2(b) (II)) the previous operating parameters were adjusted so that the master power decreases and slave power increases. The new values of the operating parameters therefore became $I_M = 0.98\times I_M^{th}$ (decreased by 4.86 mA) and $T_M = 22.5°C$, and $I_S = 1.04\times I_S^{th}$ (decreased by 0.53 mA) and $T_S = 23.7°C$ (decreased by 0.42°C). The changing of the operating parameters has the result a loss in the quality of the synchronization that could be reestablished by increasing the attenuator transmission. The new coupling ratio became 3.0%. The anticipated regime (Figure 2(b) (III)) was obtained by changing the operating parameters with respect to the previous case, so that the master current and slave temperature were decreased by 0.53 mA, and 0.1°C, respectively. The coupling ratio became 2.0% due to the slave output power increasing and the master output power decreasing. The dominant modes of the coupled system laser emission overlap with: the modes of the master emission in the LS case (Figure 2(a) (I)); the master and slave laser modes in the ZLS case (Figure 2(a) (II)); and the slave laser modes in the AS case (Figure 2(a) (III)).

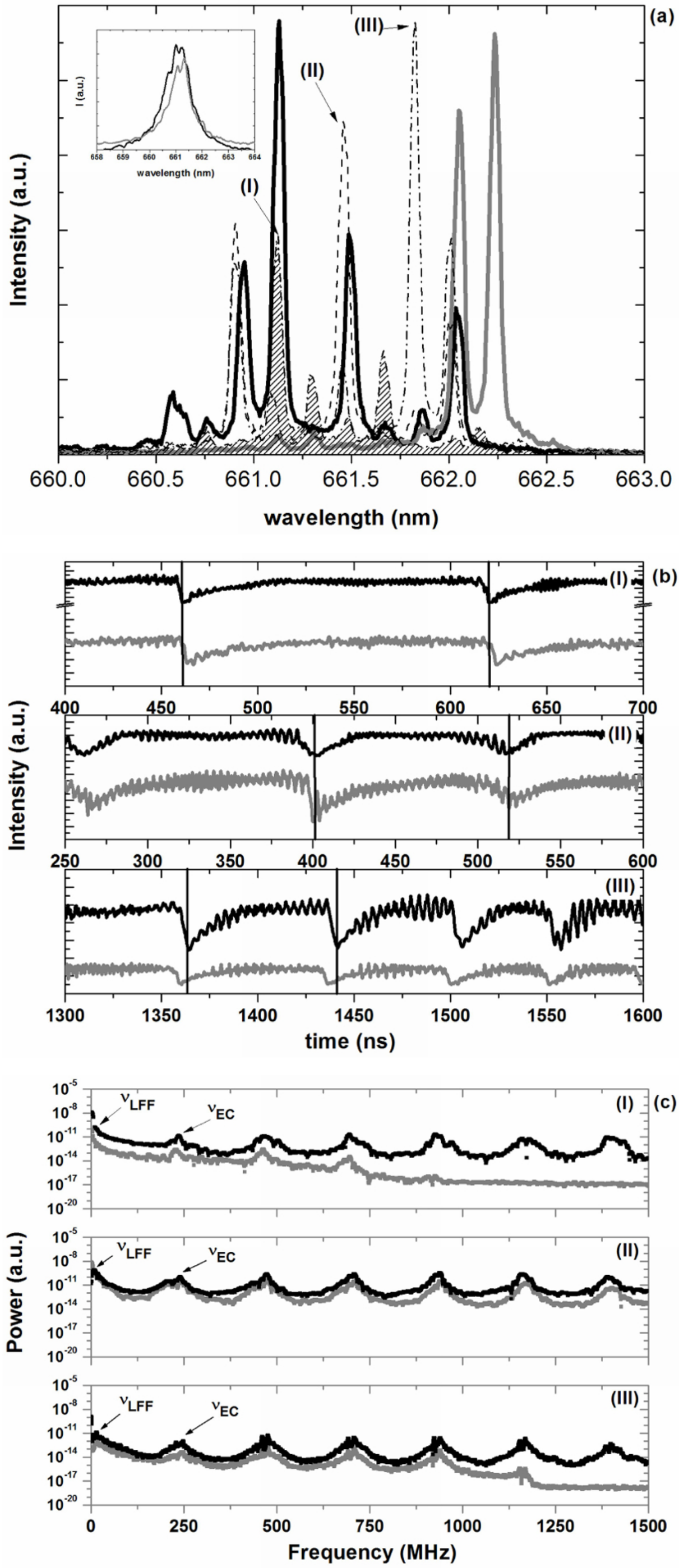

FIG. 2 Synchronization characteristics of the laser dynamics for master and slave systems with different spectral ranges. Optical spectra (a), intensity time series (b) and power spectra (c) are shown for lag (I), zero-lag (II), and anticipated (III) synchronization cases. The black line denotes the master and the light grey line the slave. In (a) the inset picture shows the optical spectra of the master and slave uncoupled systems without external feedback - while the large figure shows the same spectra with feedback; the filled area corresponds to the first synchronization regime obtained for the initial operating parameters.

Figure 2(c) shows power spectra associated with the laser intensity time series, and provides information concerning the frequency of periodic oscillations of the laser intensity. The LFF frequency is given by the periodicity of the power dropouts - and it is different in going fromone synchronization regime to another (Figure 2(b)), having values up to 100 MHz. The frequency values change when the operating parameters and feedback intensity change. LFFs represent envelopes for fast oscillations for which the frequency is determined by the external cavity length. This frequency has values in the range of hundreds of MHz to GHz. The power spectra in the three cases of synchronization show the same frequency components, which indicate the master and slave dynamics synchronization. The first peak represents the LFF frequency (υ_{LFF}), and the second is the frequency of the external cavity oscillations (υ_{EC}), where $\upsilon_{EC} = 1/\tau$, and $\tau = 2L_{EC}/c$; τ is the round-trip time in the external cavity, L_{EC} is the external cavity length, and c is the light speed in air. In Figure 2, the external cavity length was of 64.1 cm which determines a round-trip time of 4.2 ns, and a frequency of $\upsilon_{EC} = 239$ MHz, respectively. The next peaks are located at integer multiples of υ_{EC}, representing its harmonics. The retardation time which the slave dynamics synchronizes with the master is of 4.4 ns, which corresponds to the optical pathlength of 66 cm between the lasers [6].

Figure 3 shows the coupled system emission case with the same master and slave spectral range, and similar modal structures. As in the previous case, the coupled system shows the same synchronization regimes (Figure 3(b)) and optical spectrum behavior with the difference given by the higher stability of the coupled system in the anticipated synchronization regime, which was the first synchronization regime. The emission spectra of the uncoupled lasers (Figure 3(a)) were obtained at the same external cavity length, $L_1 = 64.1$cm, as in the previous case, but at a different set of initial operating parameters. The values of the parameters were $I_M = 1.024 \times I_M^{th}$, $T_M = 22.5$°C, $I_S = 1.020 \times I_S^{th}$, and $T_S = 23.8$°C, and a coupling ratio of 2.4%. The other two regimes of synchronization, ZLS and LS, were obtained after the operating parameters have been changed. Three operating parameters were modified to obtain the zero-lag regime, $I_M = 1.046 \times I_M^{th}$ (increased with 1.23 mA), $I_S = 1.056 \times I_S^{th}$ (increased with 2.00 mA) and $T_S = 24.1$°C (increased by 0.3°C), and are calculated with the above mentioned parameters. The coupling ratio was 2.1%. For lag regime, the modified parameters were $I_M = 1.033 \times I_M^{th}$ (decreased by 0.75 mA), and $I_S = 1.034 \times I_S^{th}$ (decreased by 1.22 mA) calculated in relation to the previous parameters. The coupling ratio was of 2.1% as in the previous case.

The observed tendency of the optical spectrum of the coupled system was the same as well. The optical spectrum showed a dominant mode that corresponds to the laser modes of the system emission for which power dropouts are manifest first in the intensity time series (Figure 3(b)). The power spectra show the same frequency components, which indicate the synchronization of the master and slave dynamics.

In the last case analyzed, with master and slave laser emissions having quasi-identical spectra structures (Figure 4), the coupled system showed a strong stability in the zero-lag synchronization regime. The initial operating parameters were the same as in the previous case $I_M = 1.024 \times I_M^{th}$, $T_M = 22.5$°C,

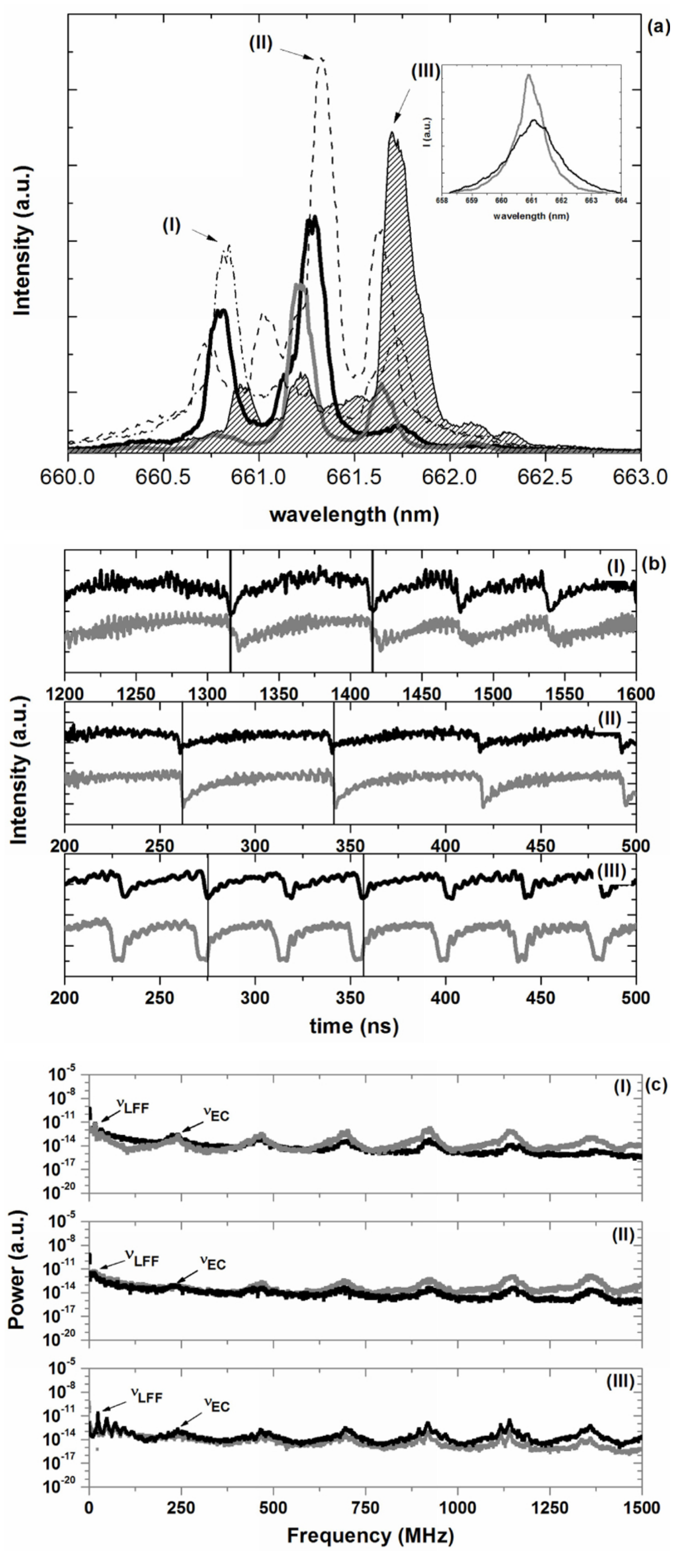

FIG. 3 Synchronization characteristics of the laser dynamics for master and slave systems with similar modal structures. The optical spectra (a), intensity time series (b) and power spectra (c) are shown for lag (I), zero-lag (II), and anticipated (III) synchronization cases. The black line denotes the master and the light grey line the slave. In (a) the inset picture shows the optical spectra of the master and slave uncoupled systems without external feedback -while the large figure shows the same spectra with feedback; the filled area corresponds to the first synchronization regime obtained for the initial operating parameters.

$I_S = 1.020 \times I_S^{th}$, and $T_S = 23.8°C$, but we have used a smaller external cavity length, $L_2 = 48.3$ cm. The coupling ratio was

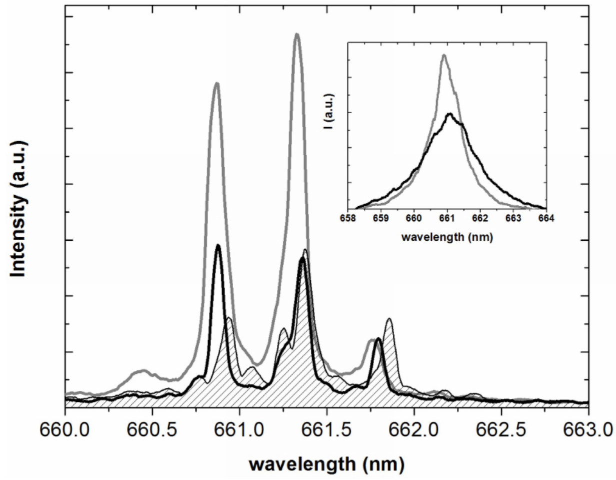

FIG. 4 Spectral characteristics of the laser dynamics for master and slave systems with quasi-identical modal structures. The optical spectrum (filled area) corresponds to the zero-lag synchronization regime obtained for the initial operating parameters. The inset picture shows the optical spectra of the master and slave uncoupled systems without external feedback, while the large figure shows the same spectra with feedback. The black line denotes the master and light grey line the slave.

of 2.0%. In all the other sets of operating parameters that were analyzed - no other synchronization regime was obtained when the master system was synchronized with the slave.

4 CONCLUSIONS

In this paper, the synchronization characteristics of an ECSL chaotic system with a solitary semiconductor laser were analyzed with respect to the similarity of the optical spectra of the two uncoupled lasers emissions. The chaotic regimes of synchronization were obtained for master and slave laser emissions with different spectral ranges, and with similar and quasi-identical modal structures by a proper choice of the master and slave operating parameters, master external-cavity length and alignment conditions. Three stable synchronization regimes, lag, zero-lag and anticipated, were obtained for different and similar optical spectra - and a single stable regime was obtained for quasi-identical optical spectra. It was observed that the coupled system emission is more stable in a synchronization regime when the spectral structures of the two laser emissions tend towards being identical.

The optical spectrum of the coupled system displays a combination of master and slave modes. In all the synchronization cases analyzed, we have identified the same spectral behavior in the coupled system - which shows a dominant mode corresponding to the modes of the system (master or slave) whose power dropouts appear first in the intensity time series. The synchronization regimes of the coupled system can be characterized using optical spectrum analysis. The result is that the modal power distribution of the active modes of the coupled system allows identification of the synchronization regime.

The reported results are of interest in optical secure communications based on synchronization of chaotic lasers, where the synchronization regime [3] plays an important role.

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