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Chaotic behaviour in the emission of semiconductor lasers optically coupled with an external cavity

I. R. ANDREI*, C. M. TICOS, M. BULINSKI[a], M. L. PASCU
National Institute for Lasers, Plasma, and Radiation Physics, PO Box MG 36, 077125, Bucharest, Romania
[a]*University of Bucharest, Faculty of Physics, Department of Optics, PO Box MG11, 077125, Bucharest, Romania*

An experimental analysis of phenomena observed in the laser emission of a semiconductor laser operating with an external cavity system in the low-frequency fluctuations regime has been carried out. The chaotic behaviour of the semiconductor laser emission with external feedback is influenced by laser parameters. The optical feedback coefficient, the injection current and diode temperature greatly influence the chaotic system evolution. In this paper we present data about the control of the chaotic dynamics of semiconductor lasers for different sets of experimental parameters.

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1. Introduction

Semiconductor laser (SL) is one of the most important devices in information technology having a wide area of applications, from information storage media to information transmission and encoding on optical carriers. When subjected to optical feedback from an external reflector, the SL shows a rich variety of dynamic phenomena [1-5]. When the light emitted by SL is redirected into the laser cavity as feedback from an external reflecting surface, the configuration is known as external-cavity semiconductor laser (ECSL). If the extended cavity length is smaller than the output coherence length, the system will behave as a laser with a compound cavity. When the length is increased some chaotic phenomena appear [6]. The amount of optical feedback greatly influences the system dynamics. Near the lasing threshold, the time evolution of the light intensity shows a pattern of low-frequency fluctuations (LFF) [7-9]. All these phenomena cause problems for some practical applications; for example in interferometric applications they can degrade the modulation response characteristics and increase noise intensity in a diode-to-fiber optical coupling [10].

Chaotic behaviour of SL with external feedback conditions is influenced by some of the intrinsic properties of the lasers. Broad gain spectrum (~5nm) which allows excitation of different longitudinal modes of the diode cavity, small changes of driving parameters and strong dependence of the active medium refractive index on the excited carrier density or temperature are the most important factors [11].

One of the most intensely studied issue on the chaotic dynamics of ECSL is the regime of LFF. A typical ECSL with weak optical feedback operated slightly above the lasing threshold, runs into an unstable regime, manifested as a cyclic dropout almost to zero of the output light intensity [12]. The time intervals between these dropouts are uncorrelated and depend on the control parameters of the ECSL, having a rate of gradually return to full power of about tens to hundreds of nanoseconds. The experimentally observed emitted light oscillates during the emission, chaotically in time at a high frequency but with much smaller amplitude compared with the average value of the emitted laser beam power. This complex laser dynamics with two time scales is described as high-dimensional chaos, or hyperchaos [13]. The chaotic behaviour of an ECSL working in LFF regime can be controlled by different parameters such as injection current, temperature, external cavity length, external feedback, or variations in the external cavity length.

In the present article we aimed to experimentally evaluate the LFF dynamics with respect to the operation parameters of the ECSL system. The parameters are the injection current, laser temperature, external optical feedback and cavity length. The measurements are made for an average optical feedback. Medium feedback levels generate line broadening and the coexistence of the LFF and the so called coherence collapse (including sub-harmonic bifurcation, intermittent behaviour and self-pulsation).

2. Experimental setup

The experimental setup is schematically shown in Fig. 1.

A semiconductor laser is stabilized using a Lightwave LDC-3724B current controller and a Lightwave LDM-4412 temperature controller. The laser is subjected to delayed optical feedback from a holographic grating (2400 lines/mm). The ECSL system comprises a Mitsubishi semiconductor laser ML101J8.

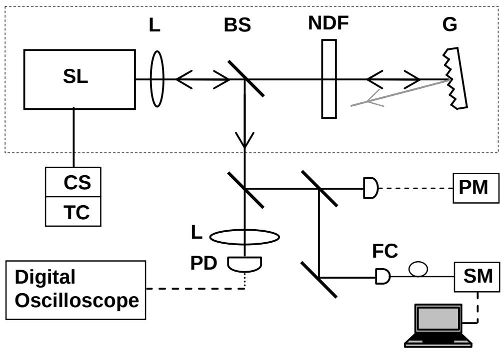

Fig. 1. The ECSL experimental setup: SL, semiconductor laser; PD, amplifying photo-detector; SM, spectrometer; PM, powermeter; CS, current source; TC, temperature controller; G, grating; NDF, neutral density filter; BS, beamsplitter; L, lens; FC, fiber coupler.

The total optical power of 40 mW is obtained for operation in continuous wave (CW) with λ=663 nm at I=109mA and T=24°C. The laser alone has a threshold current at I_{0th}=54 mA at 24.0°C. The emitted radiation is in fact a single transversal mode beam with FWHM = 0.04nm at I=1.16*I_{0th}. The external cavity is formed between the grating and the reflecting face of the semiconductor laser cavity itself. The laser beam is collimated using a lens with f=5 mm and 0.50 NA inserted in the laser head. The feedback strength (expressed by feedback coefficient γ) is controlled by a neutral density filter (NDF) which can vary its transmission from 0 to 100% by rotating it about its axis. A fraction, 0.16, of the intensity in the external cavity is coupled out through a beam splitter, for real-time monitoring. The signal is picked up by a Si-based amplifying photodiode with a bandwidth of 75 kHz to 1.2GHz and rise time < 0.5 ns. A Tektronix DPO7254 Digital Oscilloscope (analog bandwidth of 2.5 GHz) is used to display the temporal evolution and records the time series of the laser emission. The sampling rate used was 10GS/s. The total power in the external cavity was monitored by sending a fraction of 2% into a low rise time powermeter (resolution of 1nW). The wavelength was measured with an OceanOptics HR4000 Spectrometer (optical resolution of 0.4nm). The laser was operated selectively on few single longitudinal modes throughout the experiments by adjusting the angle of the grating in the first diffraction order.

3. Results and discussion

The study of the chaotic dynamics refers to the nonlinear temporal evolution analysis of the laser emission, subject to the application of an average optical feedback of only a few percent of the laser power. Fig. 2 (a) shows the intensity time series for an injection current of I=1.04*I_{0th}, external cavity length of L_{EC}=31.5cm, case temperature of T=24°C and optical feedback of γ=10%. Cyclic drop-out to almost zero of the envelope of light intensity (LFF) can be observed in Fig. 2 (a). It appears like a self-modulation of the light intensity, which reproduces a frequency υ_{LFF}=12.1 MHz. This frequency may be observed in the Fourier power spectrum of the time series, shown in Figs. 2 (b) and (c).

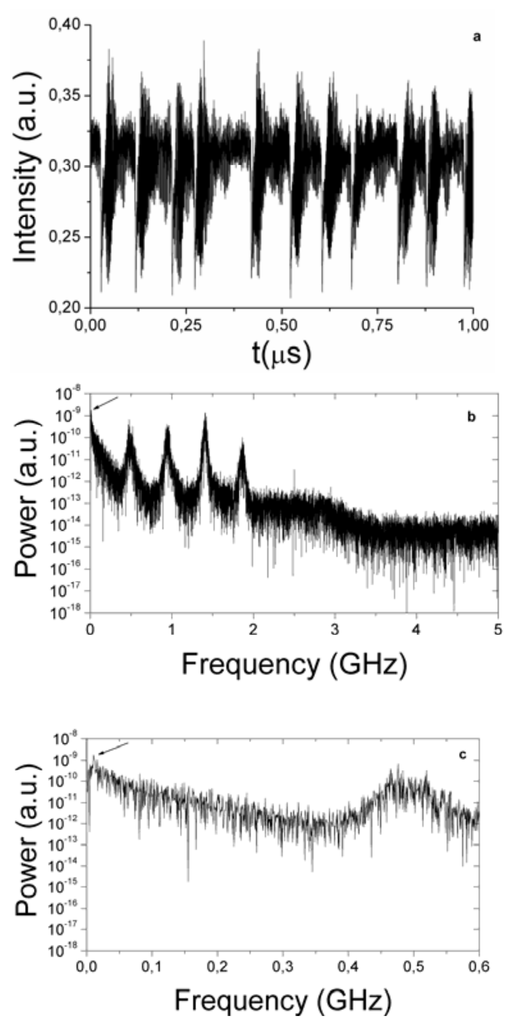

*Fig. 2. Laser emission at LFF regime. a) intensity time series of a SL subject to constant feedback ratio, γ=10%, I=1.04*I_{0th}, T=24°C, L=31.5cm; (b) the power spectra corresponding to 2 (a); c) zoom –in of 2 (b); the arrows point to the LFF frequency of 12.1 MHz.*

The power spectrum indicates the presence of other oscillations of higher frequency, which can be observed in a zoom-in sequence of the time series, as shown in Fig. 3. This sequence shows the laser output between two consecutive dropouts and has a duration of 54ns. As can be seen, there are two types of oscillations of different amplitudes and characteristic time periods [14].

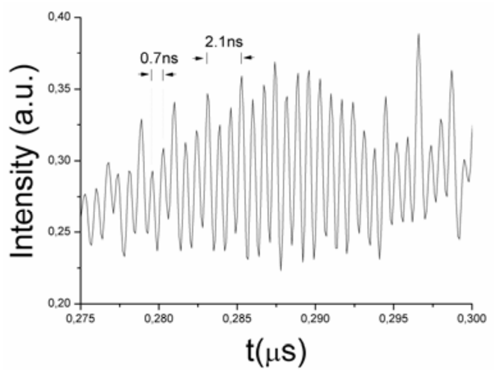

Fig. 3. Short time series of 54ns from time series shown in Fig. 2 (a); Two time scale are evidenced 2.1ns (υ_{EC}=476MHz) corresponding to the period of the external cavity modes and 0.7ns ($\upsilon_{SC}\approx$1.43GHz) corresponding to the duration of the fast pulsation from the short external cavity.

Thus, the dominant intensity components present a time period τ of about 2.1ns. In the ECSL cases the relationships τ_{EC}=2L/c and υ_{EC}=1/τ provide correspondence between τ_{EC} - the round trip time of the external cavity, L_{EC} - the external cavity length, and υ_{EC} - the frequency of the modes corresponding to the specified cavity length L_{EC}. The frequency which corresponds to the time period of τ_{EC} =2.1ns is υ_{EC}=476MHz and the cavity length is L_{EC}=31.5cm. This frequency appears in the power spectrum as the first peak after the LFF peak. At the same time, the next peaks are located at integer multiples of υ_{EC}, representing its harmonics. This means that the laser system oscillates on several modes of the extended cavity. We refer to these frequencies as the high frequency fluctuations (HFF) [15]. In Fig. 3, it can be observed that the dominant oscillations are accompanied by secondary oscillations of lower amplitude, but characterized by a time period shorter than one nanosecond, respectively 0.7ns. It corresponds to a frequency of υ_{SC}=1.43 GHz and to an associated length of L_{SC}=10.5cm of what we call a short external cavity (SC). In our experimental arrangement this distance corresponds to the beamsplitter position used to couple out the radiation from cavity for detection purposes. The beamsplitter is positioned at 45^o with respect to the ligth propagation direction in the extended cavity. It is possible that a fraction of less than 1% of the output power of the laser could be re-injected within the laser junction, under certain alignment conditions and presence of external feedback. This mode of operation is demonstrated in Fig. 4 where the power spectrum corresponds to the laser beam intensity time series for I=1.07*I_{0th}, T=15^{o}C and γ=0%. This power spectrum presents a first peak oscillation frequency at $\upsilon_{SC}\approx$1.43GHz and a harmonic at $\upsilon\approx$2.86GHz, which is also noticeable in the power spectrum of Fig. 2 (b). Given these observations, we can assume that the slight variations of the HFF peak intensities of the power spectrum in Fig. 2 (b) are due to the overlapping of the oscillation modes of the two cavities. The main one, is due to feedback from the grating, and the second one is generated by reflection on the beamsplitter. The low amplitude oscillation series shown in Fig. 3 are found in the power spectrum shown in Fig. 2 (b), as the HFF envelope which peaks at υ=1.43GHz. In addition, the external cavity and short cavity may function as coupled cavities. This is possible to observe through the distribution of dominant peaks, raported at the secondary peaks, at same time period of the latter (0.7ns).

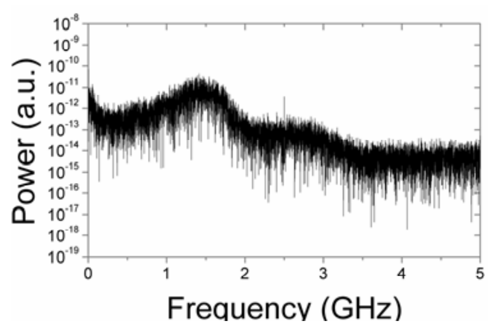

*Fig. 4. The corresponding power spectra of an intensity time series case without long external cavity coupling. Operating parameters of the ECSL system: constant feedback ratio (γ=0%), I=1.07*I_{0th}, T=15^{o}C; the power spectra show two peaks $\upsilon_{SC}\approx$1.43GHz and its harmonic $\upsilon\approx$2.86GHz.*

Next, we will detail the results elaborated for the chaotic dynamic behavior study. The analysis of the obtained results was done in terms of those discussed above, for different operating values of the ECSL system. The dependence on a particular parameter was measured keeping all the other parameters constant. The last measurement was devoted to study the parameter dependence of the chaotic dynamics on the external cavity length. In this case L_{EC} was kept fixed at 31cm. The considered parameters were: the injection current, adjusted between 0.98*I_{0th} and 1.07* I_{0th}; the temperature of the laser junction, with values between 15^{o}C and 30^{o}C; the feedback coefficient, adjusted to achieve a feedback between 1% and 15% of the output power level; and the cavity length, increased between 1*L_{EC} and 2.33*L_{EC}.

The measurements show that the chaotic dynamics of the ECSL system emission have the same main features as in the case of Fig. 2 (the exception is the L_{EC} dependency case). Thus, the power spectra associated to recorded time series have shown a single peak at frequencies under 100MHz, corresponding to the LFF fluctuations, up to four peaks corresponding to the υ_{EC} and its harmonics. Also a peak envelope similar to that in Fig. 2 (b), corresponding to the duration of the fast oscillations was observed. The average frequency of the LFF and HFF regimes, and the number and amplitude in the power spectra of the latter, varied along with the output power of ECSL system. A pronounced tendency of increasing the LFF frequency with the power is observed when the injection current or the temperature is increased. In the feedback dependency case, the LFF values are fluctuating. They do not have a particular tendency, i.e., they alternate in the range 13÷34MHz, for I=1.04*I_{0th}, T=24^{o}C, L=30cm and γ adjusted between 1% and 15%. This case corresponds to an operation with more pronounced fluctuations in intensity due to emission near the laser threshold. At the same time, in the current, temperature or feedback dependency, the LFF fluctuations may disappear entirely, followed by a coherence collapse. This occurs when the current – temperature – feedback combination set provide a total power of the ECSL system below ~ 0.15mW and above ~ 4mW. In terms of υ_{EC} values, they oscillate around the 480MHz with fluctuations of up 10% (if a parameter is varied). The number of the υ_{EC} harmonics was 3 in all studied cases. The υ_{EC} frequencies have vanished from the power spectra only for ECSL emission power values below 0.15mW.

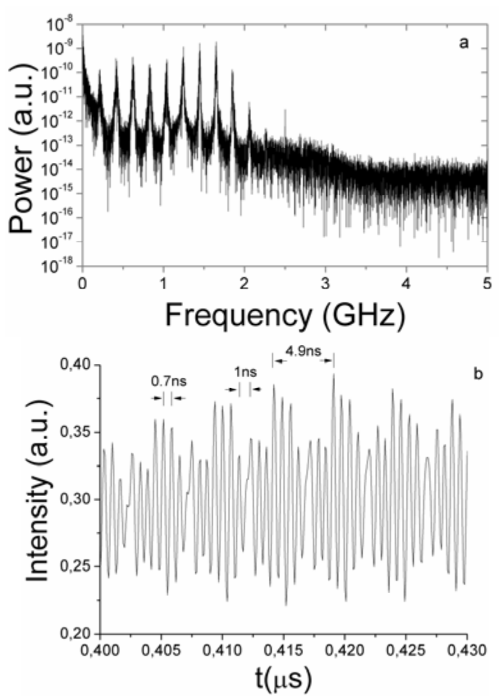

Fig. 5. (a) Power spectra corresponding for feedback ratio (γ=10%), $I=1.04*I_{0th}$, T=24°C, and L=70cm, in the LFF regime; (b) Zoom on intensity time series; two time scale are evident 4.9ns (υ_{EC}=204MHz) corresponding to the period of the external cavity modes and 0.7ns (υ_{SC}≈1.43GHz) corresponding to the duration of the fast pulsation from the short external cavity.

A special case was the study of chaotic dynamics dependence on cavity length. In this case the LFF frequencies have fluctuated slightly around 11MHz, value obtained for $I=1.04*I_{0th}$, T=24°C, γ=10% and L adjusted between $1*L_{EC}$ and $2.33*L_{EC}$. The υ_{EC} frequencies values have decreased with increasing cavity length, due an increase in the round trip time within the external cavity. At the same time the harmonics number steadily increased. In the $2.33*L_{EC}$ case (Fig. 5 (a)) the harmonics number nearly tripled compared to the single L_{EC} case (Fig. 2 (a)). The υ_{EC} frequency decreased from about 476MHz (2.1ns) to 204MHz (4.9ns). The 4.9ns time period corresponds to a series of three dominant oscillations in the intensity time series (Fig. 5 (b). These three dominant oscillations together with other secondary oscillations form, in this case ($L=2.33*L_{EC}$), a group of seven oscillations with a time period of 1ns. Inside this group of seven oscillations the characteristic time period is 0.7ns, corresponding to the short cavity modes. The length of the short cavity remained unchanged during the measurements. Inside of the group formed by the dominant and secondary oscillations, the number of the oscillations changes with cavity length variation. This number is approximately equal with the ratio between the lengths of the external cavity and of the short cavity.

The HFF frequencies distribution in the power spectra is uniform in the 0÷2.2 GHz band, regardless their number in the power spectra. The harmonics number increased with two units for any cavity length increasing with 10cm, i.e. from 4 in the case L=30cm the harmonic number increase at 11 in the case with L_{EC}=70 cm.

4. Conclusions

The experimental observations made on the emission of an ECSL system showed its nonlinear character. This was manifested in the form of low-frequency fluctuations (LFF). High resolution temporal analysis and the Fourier analysis of intensity time series have evidenced the effect that the optical elements of the external cavity may have on the laser emission dynamics. The influences are manifested like a competition between external and secondary cavities modes. This mode competition can have a constructive or destructive influence on emission dynamics. It is possible that secondary oscillations of the secondary cavity determine the temporal period of the dominant oscillations of the extended cavity, and by this the frequency structure of the power spectrum.

The harmonics distribution and their number in the length cavity dependency is not fully elucidated, and this behaviour remains a target for future investigation; it is needed to be fully clarify the mixing effect of the oscillation modes generated by the extended and secondary cavities. It must be shown if these secondary oscillations influence the dynamics of low frequency fluctuations, or not.

Acknowledgments

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*Corresponding author: ionut.andrei@inflpr.ro