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Characterization of chaotic emission of a laser diode in optical feedback conditions produced by different external reflectors

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The external-cavity semiconductor laser (ECSL) system is obtained when the radiation emitted by a semiconductor laser is redirected into the laser cavity as feedback from an external reflecting surface. In the present work, we experimentally evaluated the chaotic dynamics of the laser diode emission at the low-frequency fluctuation (LFF) regime using different external optical reflectors in the ECSL system. The stability of the LFF regime was analyzed using the same function parameters of the ECSL system and considering selective and unselective external reflectors with respect to the wavelength. We show that a stable LFF regime is obtained for selective reflector with single-mode emission; for selective and unselective with multimode emission, but at higher laser power if compared with the single-mode case. Unstable LFF regimes were obtained for multimode laser emission using selective or unselective reflector at laser power levels similar to single-mode laser emission case.

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1. Introduction

A laser diode (LD) shows a multitude of dynamic phenomena described as chaotic dynamics, when subjected to optical feedback from an external reflector [1]. When the radiation emitted by LD is redirected into the laser cavity as feedback from an external reflecting surface, the set-up configuration is known as external-cavity semiconductor laser (ECSL). Chaotic behavior of LD in external feedback conditions is influenced by some of the intrinsic properties of the laser. Broad gain spectrum which allows the excitation of different longitudinal modes of the laser 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.

One of the most studied issues on the chaotic dynamics of ECSL is the regime of low-frequency fluctuations (LFF) which is an unstable regime, behaving as a cyclic dropout (to almost zero) of the output light intensity; this is evidenced when a typical ECSL with weak optical feedback operates slightly above the lasing threshold [2]. The time intervals between the dropouts are uncorrelated and depend on the control parameters of the ECSL, having a rate of gradually return to full power from a few to hundreds of nanoseconds [3, 4]. The chaotic behavior of an ECSL working in LFF regime can be controlled by varying different parameters such as the injection current, the temperature, the external cavity length, and the external feedback. The level of the optical feedback intensity greatly influences the system dynamics [5].

In this paper we report experimental measurements on the chaotic dynamics of a LD emission, at LFF regime, with respect to the external optical reflector type used in the ECSL system. External reflector was in our case, a ruled grating with 1200 groves/mm, a totally reflecting mirror and a holographic grating with 2400 lines/mm, respectively. The measurements were made for a medium level of the optical feedback intensity. Medium feedback, near the lasing threshold, generates under certain conditions the coexistence of the LFF with the so called coherence collapse (including intermittent behavior and self-pulsation) [6, 7]. The solitary laser operate at the threshold, in multimode regime; when the blazed grating was used it was selectively adjusted on a few single longitudinal modes by modifying the incidence angle on it (the grating is blazed in the first order at $\lambda = 500$ nm).

The chaotic LFF characteristics of the laser emission were analyzed with respect to the spectral structure of the laser beam. LFF chaotic emission was obtained using the same parameters for laser operation, in all three cases of used reflectors; the mirror and holographic grating were mounted at normal incidence. The measurements were performed in blazed grating case for different angles of incidence on the grating. The holographic grating was tested in the zero diffraction order due to the low efficiency in the first diffraction order. To obtain LFF chaotic emission, the reflectors used at normal incidence were aligned slightly out of the position for which the maximum laser output power is obtained. When the external reflector is configured to give the maximum feedback and maximum output power, respectively, without a misalignment, the laser emission exhibits a constant intensity time series without fluctuations; the adjustment of the external reflector position easily affects the output power levels emitted by ECSL laser system by reducing it with about 9%. The performed measurements have shown the different behaviours of the chaotic dynamics in the selective and unselective feedback cases. The differences are visible in the frequencies numbers corresponding to the LFF oscillations, which are observed in the power spectra on low frequency band up to 100 MHz.

2. Experimental setup

In Fig. 1 is shown the experimental setup which contains a laser diode (Mitsubishi, ML101J8) and an external cavity limited by an external reflector (ER). The laser is subjected to delayed optical feedback from the external reflector and it is stabilized using a current controller (Lightwave, LDC-3724B) and a temperature controller (Lightwave, LDM-4412). A lens system with f=5 mm and NA = 0.50 inserted in the laser diode mount is used to collimate the laser beam. The maximum optical power (40 mW) of the solitary laser diode is obtained for operation in continuous wave at the optimal operation parameters, I=109 mA and T=24 ^{o}C, with I_{0th}=54 mA. The utilized laser diode was in fact a single-mode AlGaInP laser with FWHM = 0.04 nm which oscillates at λ= 663 nm when operated at the optimal parameters. The external cavity length was kept constant at 30 cm ± 0.1cm during the experiments for the all utilized external reflector cases.

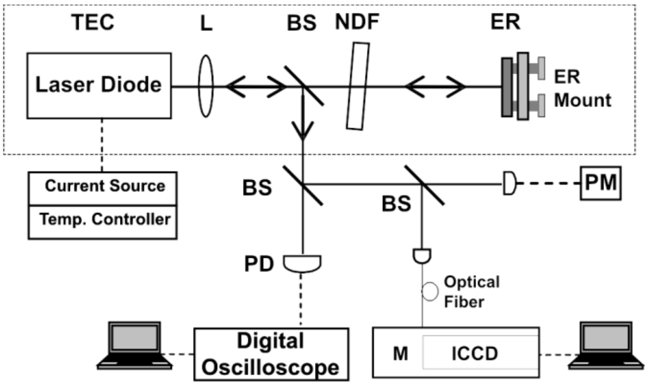

Fig. 1. The ECSL experimental set-up: TEC, thermoelectric cooler; L, collimation system; BS, beamsplitter; NDF, neutral density filter; ER, external reflector; PD, photo - detector; SM, spectrometer; PM, powermeter.

A neutral density filter (NDF) inserted in the cavity is used to control the feedback level. The NDF can vary its transmission by rotating it around its own axis; it was kept in fixed position during the measurements. The feedback intensity could vary during the experiments, in these conditions, function of the light intensity reflected by the external reflector. In fact, the optical feedback calculated at the external cavity level represents up to 20 % of the total output power of the ECSL system emission, but not all of this power fraction is injected into the laser active medium [8,9]. A fraction of 0.16 of the intensity output power is coupled out through a beam splitter for real-time monitoring. The signal is analyzed using an amplifying photodiode (PD) with a bandwidth ranging from 75 kHz to 1.2GHz and the rise time < 0.5 ns. A digital oscilloscope (Tektronix, DPO7254) with 2.5 GHz analog bandwidth is used to display the temporal evolution and allows recording 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 0.02 into a low rise time powermeter (resolution 1 nW). A monochromator (Princeton Instruments, Acton SpectraPro 2750) having the optical resolution of 0.02 nm was used to analyze the optical spectrum.

When the laser was operated using a blazed grating in the ECSL, the output from the ECSL was either single mode or contained a few single longitudinal modes function of the incidence angle on the grating. In the mirror or holographic grating cases which were operated at normal incidence, in the LFF regime, the laser emission has shown a multimode structure.

3. Results and discussions

Chaotic behavior characterization of the ECSL laser emission consists in determining the LFF stability function of the dominant LFF frequency for all three external optical reflectors which were used. This was made by analyzing the power spectra obtained by applying Fast Fourier Transform on the intensity time series of the laser emission. The power spectrum allowed to determine the frequency components in the low frequency band. A single dominant frequency corresponds to a stable LFF regime. The unstable/random LFF regime is obtained by the superposition of two or more independent LFF oscillations; the number of the LFF oscillations is indicated by the number of dominant frequencies in the power spectrum of the emitted beam. Eventually, the LFF behavior is correlated both with spectral structure and output power of the laser beam for each case.

The experimental measurements were performed by changing the external reflector from the ECSL setup. The operation parameters of the solitary laser in the LFF regime were I= 55 mA, T=20^{o}C and I_{th}=53 mA, with a total output power of P_0=1.2 mW. The solitary laser was operated during the experiments at an injection current near lasing threshold, I=1.038*I_{th}. In Fig. 2a it is shown the optical spectrum of the laser diode in the absence of the optical feedback. In this case the FWHM is about 1nm. When the external cavity is aligned takes place the amplification of radiation. When the external optical feedback is applied, the energy accumulated in the semiconductor active medium is increased; at the same time a decrease of the laser treshold takes place (about 9% compared to solitary laser) which leads to an increase of the emitted laser beam power. In Figs. 2b-d are given the optical spectra for all external reflectors which were used.

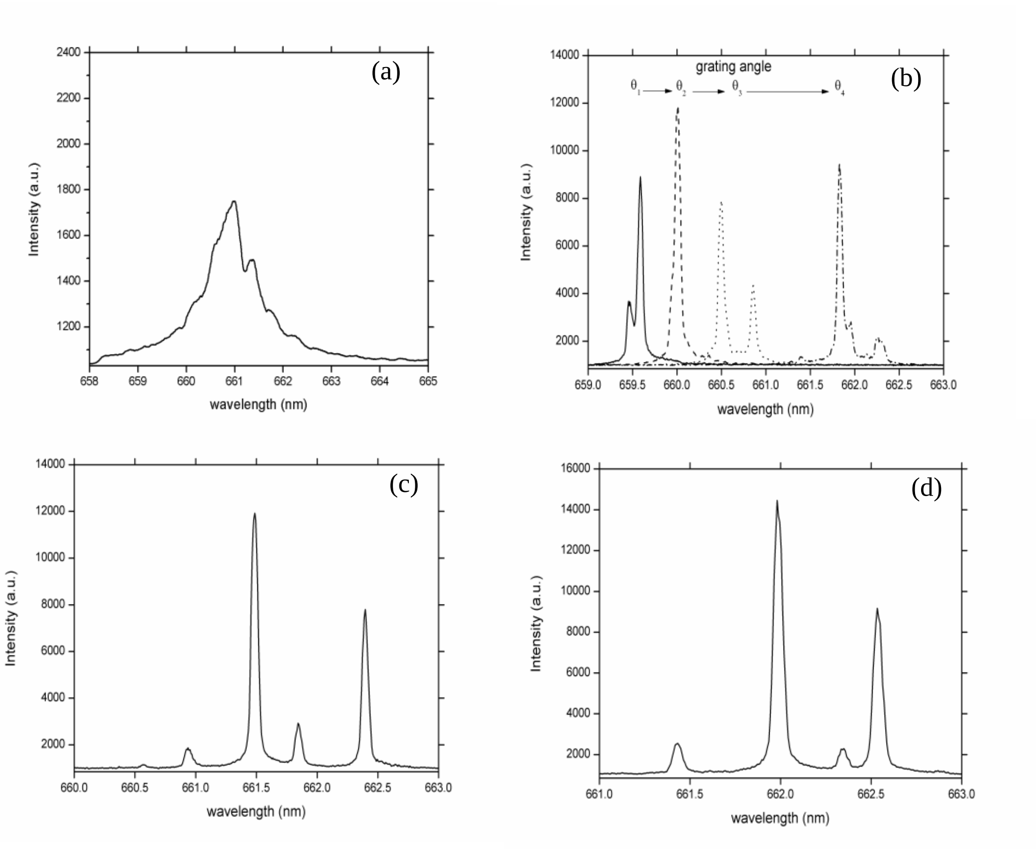

Fig. 2. Laser beam optical spectra for: a) solitary laser, in absence of the optical feedback; b)-d) blazed grating, mirror and holographic grating cases.

In Fig. 2b, blazed grating case respectevly, are shown four optical spectra which are obtained for four different grating angles; two cases are selected for single-mode emission (θ_1 and θ_2 cases) and two cases for multimode emission (cases θ_3 and θ_4). The laser emission shows a multimode structure with a mode spacing of $\Delta\lambda$~0.550 nm, which is specific to the laser diode that was used, with emission at λ = 663 nm and with active media length of ~0.4 mm. In the optical spectra associated to grating angles θ_1 and θ_4 (Fig. 2b), respectively, there is a mode bifurcation lower than the $\Delta\lambda$ mode spacing. These bifurcations are always accompanied by an unastable LFF regime and this is emphasizing as the two peaks tend to become equal in intensity; if the difference between the intensities of the two peaks is large, as in the two above mentioned examples, the LFF instability is reduced or may be not even observed. One source of this behavior, under optic feedback conditions, may be unwanted optical reflections caused by optical components or by the fact that the colimation system generates on the output face of the laser diode a spot with dimensions 800×800 μm that are larger than the real laser diode surface dimension which is about 30×5 μm [8]. This is why one may angularly adjust an external reflector utilised at normal incidence around this position without walking off the optical feedback condition. In LFF emission regime the optical spectra show a multimode structure for mirror and holographic grating as may be seen in Figs. 2c, and Fig. 2d, respectively.

The optical signal recording was made simultaneously for both optical spectra and power spectra analysis. Thus, for the optical spectra shown in Fig. 2b were calculated power spectra of the intensity time series represented in Fig. 3, differentiated by the grating angle. The power spectra shown in Fig. 4 are associated to the optical spectra from Figs. 2c and 2d.

The power spectra indicate for selective feedback case with single-mode emission (Fig. 3, cases θ_1 and θ_2) and multimode emission (Fig. 3, case θ_4) the presence to a single LFF frequency, but the last case having a single dominant mode. The power spectrum shows two LFF frequencies for selective feedback with multimode emission, but with two dominant modes (Fig. 3, case θ_3), which indicates an instability of the LFF laser emission. This instability corresponds to a low value of laser power, $P = 1.6*P_0$, compared with that from multimode emission shown in Fig. 3θ_4, where $P = 2.4*P_0$, but which is comparable with the output power of the single-mode laser emission from Fig. 3θ_2, where the LFF emission is stable. This shows that to the LFF emission stability contribute both the power level of the laser emission and the single-mode or multimode nature of it. We can claim from this reason that the LFF regime stability, under multimode laser emission conditions, is obtained only when the laser power exceeds a particular level, corresponding to the function parameters set for the ECSL system, and higher than the one corresponding to the single-mode emission. We did not observe influences on the LFF emission stability in the cases of modes bifurcation at intervals < Δλ (Figs. 2b, θ_1 and θ_4 grating angle positions), where higher differences between the two peaks intensities were obtained.

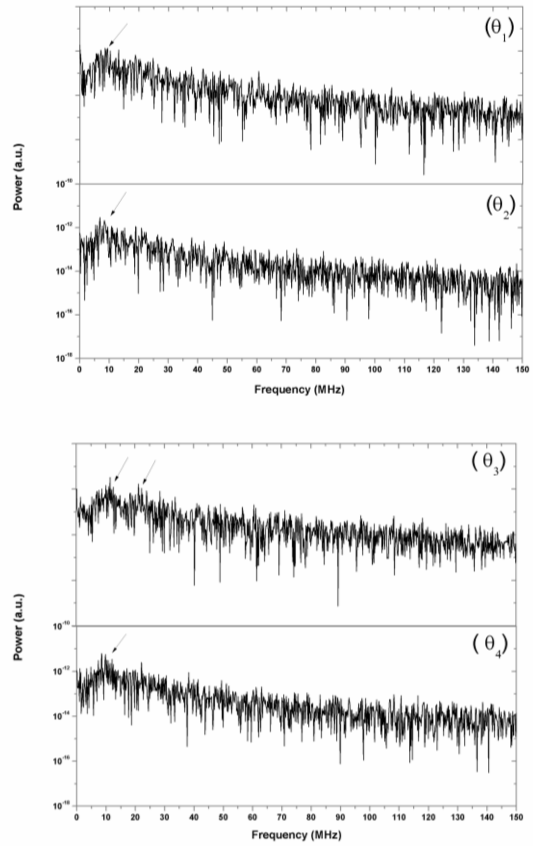

Fig. 3. Power spectra for selective optical feedback. Blazed grating case: (θ_1) a single LFF frequency, $P=1.4*P_0$; (θ_2) a single LFF frequency, $P=1.6*P_0$; (θ_3) two LFF frequencies, $P=1.6*P_0$; (θ_4) a single LFF frequency, $P = 2.4*P_0$; the arrows indicate the LFF frequencies.

The laser emission of the ECSL system has a multimode structure in the unselective feedback case, usually with 4-5 active modes out of which at least two are dominant modes (Figs. 2c and 2d, respectively). The power spectrum indicates a single LFF frequency in the mirror case (Fig. 4a) and the laser power is $P = 2.5*P_0$ and it is equivalent to that obtained for the selective feedback with multimode emission (Fig. 3 θ_2). Unlike selective feedback case, where a part of energy is lost via the zero diffraction order, in the unselective feedback case all the energy is returned in the laser emission area. The unselectivity with respect to the wavelength, in the mirror case, is compensated with the higher amount of energy injected into the laser active medium, which determines the intensity amplification of a large number of wavelengths.

Fig. 4b shows the power spectrum of the intensity time series of ECSL laser emission having as external reflector the holographic grating. Due to the low efficiency in the first diffraction order, the optical feedback was obtained using the reflection of the zero diffraction order (normal incidence). For this ECSL configuration the obtained laser power was $P = 1.8*P_0$. The power spectrum in Fig. 4b shows the presence of several frequencies of which at least two are associated with LFF. In this case the LFF chaotic dynamics of the laser emission shows a high instability, evidenced by high frequency fluctuations (~ 35 MHz) modelled at another of low frequency (~ 5 MHz).

It is important that the chaotic LFF regime to be stable, namely a single dominant LFF to be provided, from the point of view of the ECSL system aplications, especially in chaotic coupling. This is posible, as mentioned above, in single-mode (selective feedback) or multimode (selective and unselective) operation, but in the last case at laser beam powers higher than in the single-mode functioning. In single-mode and multimode cases the provided power ranges are specific to each set of functional parameters for the chosen ECSL system.

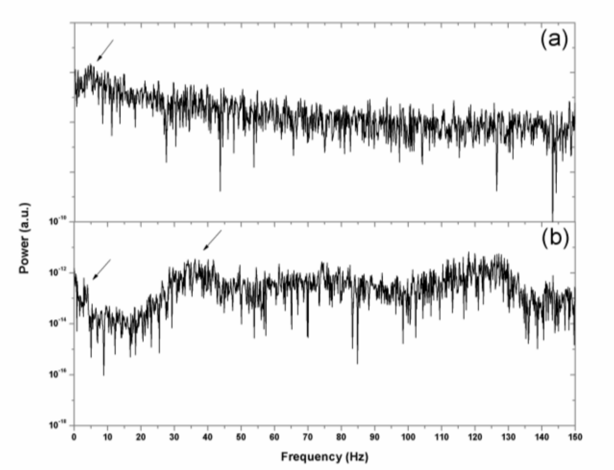

Fig. 4. Power spectra for unselective optical feedback. Mirror case (a), a single LFF frequency, $P=2.5*P_0$; holographic grating case (b), two LFF frequency, $P=1.8*P_0$; the arrows indicate the LFF frequency.

4. Conclusions

In the present paper it was analyzed the LFF chaotic behavior of an ECSL system laser emission when the external reflector is changed. As external reflectors were used a grating blazed in the first diffraction order, a mirror and a holographic grating used in zero diffraction order, respectively.

The measurements have shown that the LFF chaotic regime is stable in the selective feedback case for single-mode and multimode emission, but in the last case for output power values higher than in the single-mode emission. Also, stable LFF regime was obtained for unselective feedback, mirror case, but at power values higher than in the selective feedback case.

Unstable LFF regimes were obtained in the selective feedback case with multimode emission, when the output power value of the ECSL system was equivalent to the value obtained in the single-mode emission, and in the unselective feedback case when was used the holographic grating. In this last case the laser emission has shown a multimode structure with power values of the ECSL system equivalent with those obtained in the selective feedback case with single-mode emission.

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