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Low frequency fluctuations and multimode operation of a semiconductor laser with optical feedback

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Abstract

We experimentally investigate low frequency fluctuations (LFF) in a Fabry-Perot semiconductor laser with optical feedback from an external mirror. During LFF, the time resolved optical spectrum shows that many longitudinal modes of the solitary laser enter into the transients. After each LFF event, the excited solitary-laser modes recover similarly. However, the recovery for the power in each mode is much slower than the recovery of the total power. The intermode exchange of energy during the recovery indicates that a single-longitudinal mode description of such LFF behavior will not capture important underlying dynamics. The relevance of multimode dynamics is confirmed in a feedback experiment where the external mirror is substituted by a diffraction grating. © 1998 Elsevier Science B.V.

The effect of delayed feedback on dynamical systems has been studied in different branches of science such as physics [1], chemistry [2] and other fields [3]. These systems, which are commonly encountered in nature, often show a complex behavior and they challenge many intuitive and theoretical descriptions. Feedback was originally perceived as a stabilizing factor. It was introduced in several types of systems [4], but in many cases the result was strong fluctuations of the variables. This complexity makes such systems very interesting for general studies of nonlinear dynamics. In particular, optical feedback has been used for a long time in semiconductor lasers to stabilize the output and reduce the optical linewidth [5]. However, for a moderate level of feedback, as the injection current is increased the laser output becomes unstable and displays power drops [6], an example of which is shown in Fig. 1. These fluctuations of the intensity generate a broad feature at low frequencies in the power spectrum, hence they are usually called Low Frequency Fluctuations (LFF). For higher current level, the laser linewidth broadens up to tens of GHz, hence degrading the laser's coherence properties (the so-called ''coherence collapse'' regime) [7–9].

LFF induced by optical feedback are characteristic of many semiconductor lasers, including conventional edge emitters [6] and distributed feedback semiconductor lasers (DFB) [10,11]. The fact that LFF do not appear in other kinds of lasers under optical feedback is attributed to the strong amplitude-phase coupling that exists in semiconductor lasers due to the linewidth enhancement factor. However, to our knowledge, there is no information on the full optical spectrum in the LFF regime, probably because most of the studies on LFF have been focused on the

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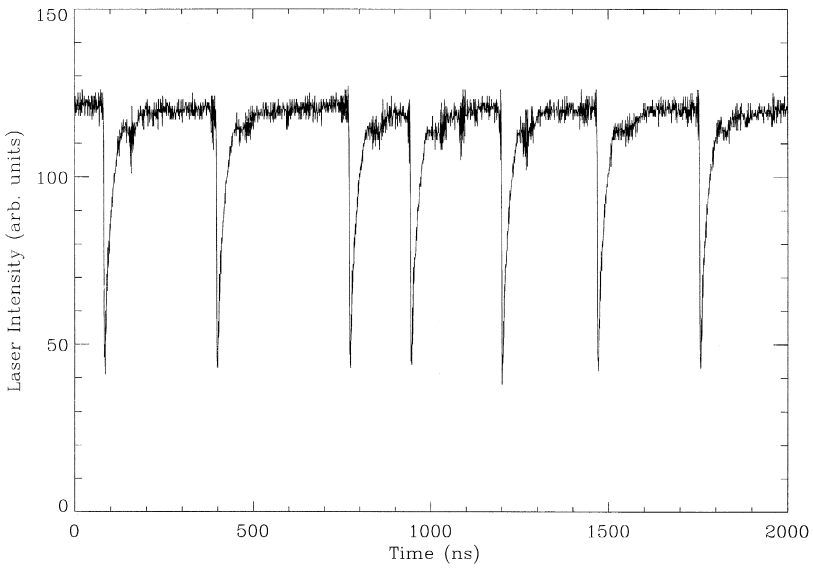

Fig. 1. Typical example of power drops observed in a semiconductor laser with optical feedback.

intensity dynamics. Also, we are not aware of any measurement of the phase and/or the frequency dynamics during the LFF, which may contribute important information on the behavior of the system.

From a theoretical point of view, the model commonly used to interpret the experimental observations is the one developed by Lang and Kobayashi (LK) for a single-mode semiconductor laser [12]. This model considers the temporal evolution of the complex amplitude of the electric field coupled to the carrier density, and the effect of the optical feedback is included in its first approximation by means of the re-injection of the field itself with a time delay corresponding to an external cavity round-trip. The main effect of this term is to couple the modulus and phase of the electric field, and its influence on the dynamics of the system has been extensively analyzed. From the numerical integration of the LK model, it has been shown that the laser power exhibits drops similar to those experimentally observed at low frequency [13,14]. In Ref. [14] it was numerically shown that, in the LK model, the laser emits fast pulses (typical FWHM of tens of ps) with irregular height and temporal spacing roughly corresponding to the period of the relaxation oscillations. Such pulses were observed with a streak camera in Ref. [15], in agreement with the numerical results. However, in a recent experiment [16] a statistical analysis of the intensity fluctuations showed clear discrepancies between the measured probability distribution of the intensity and the one obtained from the numerical integration of the LK model.

In this paper we show that, in the systems that we have studied, the emergence of LFF is associated with the excitation of additional longitudinal modes of the solitary laser [2]. We first measure in an edge emitter FP laser with optical feedback the correlation between the number of excited solitary laser modes and the number of drop per unit of time. In the LFF regime, the time resolved optical spectrum shows that the solitary laser modes are synchronized and they drop together. Following the drop, several modes become active, and they start to recover the power level they had just before the drop by means of intermode exchange of energy; as a consequence, the recovery of the power in each mode is much slower than the recovery of the total power, which indicates that the single-longitudinal mode description of such LFF behavior will not capture important underlying dynamics. We then replace the external mirror by a diffraction grating whose spectral reflectivity is high over a much narrower spectral range than the laser mode separation. When the output power displays drops, the side-modes become active. Therefore, the appearance of drops in our laser systems is connected to the excitation of multiple solitary laser modes. Since the characteristic time scale for the LFF is of the same order as the

[2] The term ''solitary laser mode'' deserves some explanation. As long as the feedback from the external mirror is present we could not in principle talk about modes of the laser cavity without feedback because the system will only recognize modes of the compound cavity. However, we can recognize two different time scales; one associated with the round trip inside the active medium, which is of the order of 10 ps; and a second one associated with the round trip time outside the medium which is about 1 ns. We study here the contribution to the dynamics from resonances which are more than 100 GHz apart, and therefore for sake of simplicity we call them ''modes of the solitary laser''

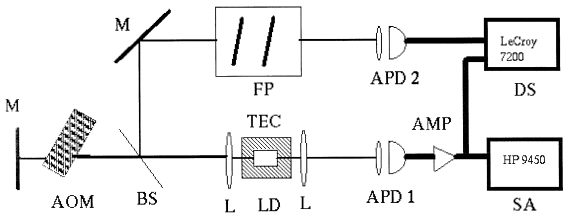

Fig. 2. Experimental setup: LD, laser diode; APD, avalanche photodiode; SA, RF spectrum analyzer; DS, digitizing oscilloscope; F-P, plane Fabry-Pérot; L, lens; M, mirror; BS, 50% beam splitter; AOM, acousto-optic modulator; TEC, thermoelectric cooler.

time scale for mode partition noise, the interaction among different laser modes may drastically alter the laser dynamics.

The experimental set-up is displayed in Fig. 2. An AlGaAs semiconductor laser (Hitachi HLP1400) emitting at 830 nm is mounted on a thermally stabilized plate. Its cavity length is 300 μm. A collimator placed at the output reduces the beam divergence. An external high reflectivity mirror is mounted on a PZT and placed at a variable distance with respect to the laser output. An acousto-optic modulator, between the external mirror and the laser, controls the amount of feedback without changing the alignment of the external cavity, which is known to modify the threshold for the appearance of LFF [17]. Two fast detectors (6 GHz bandwidth) are used. The first one (APD1) measures the total laser intensity as a function of time. The second one (APD2) is positioned behind a Fabry-Pérot (FP). The free spectral range of the FP equals 22 times the laser diode mode spacing, i.e. ≈ 3080 GHz and its finesse is around 200.

Fig. 3 is a schematic representation of the laser response as a function of feedback level. At high feedback level (a), the intensity is constant in time with a single laser mode. Intermediate feedback levels ((b) and (c)) lead to the appearance of low frequency fluctuations and several peaks in the optical spectrum are observed. The frequency separation among consecutive peaks is around 140 GHz which corresponds to the longitudinal mode spacing of the solitary laser. The main difference between (b) and (c) is the typical time interval between consecutive

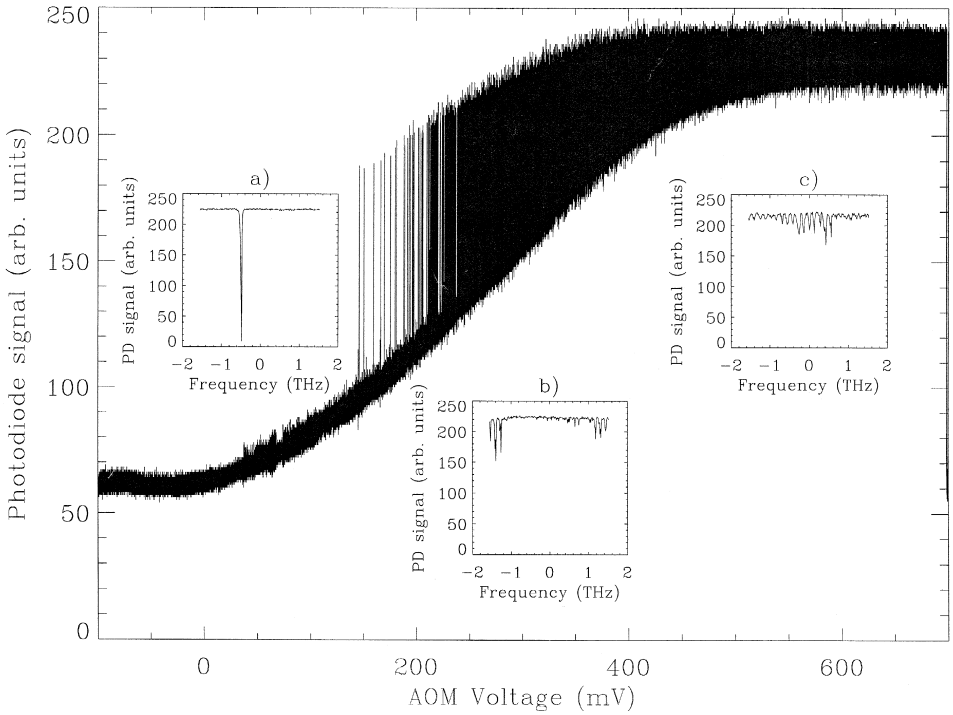

Fig. 3. Laser power versus feedback level for a current 5% above the solitary laser threshold, 81 mA. The feedback level is controlled by the AOM voltage, with maximum feedback level at $V = -100$ mV (threshold reduction of 27.5%) and minimum feedback level at $V = 700$ mV (threshold reduction of 5%). The insets show the optical spectrum corresponding to AOM voltages of: (a) 0 mV, (b) 200 mV and (c) 500 mV. The photodiode signal is inverted with respect to optical power, so low signal corresponds to high power.

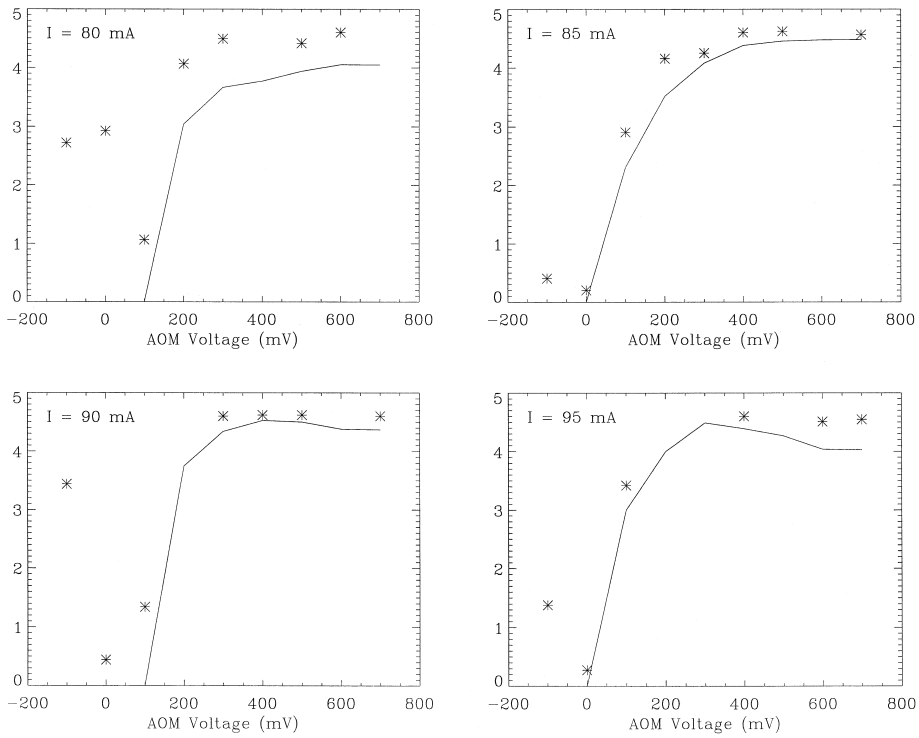

Fig. 4. Correlation between the number of drops in 1 ms and the number of excited solitary laser modes for ten different feedback levels (at 100 mV intervals) and different laser currents: (a) 80 mA, (b) 85 mA, (c) 90 mA and (d) 95 mA. Solid line: decimal logarithm of the number of drops. Symbols: number of excited solitary laser modes divided by 5.

drops, and also that for low feedback levels the minimum power during the drop reaches almost the spontaneous emission level. However, the shape of the drops is unchanged. Since LFF seem to induce multimode behavior, we measure the number of drops and the number of modes of the solitary laser above -20 dB with respect to the maximum peak as a function of feedback level (Fig. 4). In these measurements, the feedback phase was adjusted with the PZT in order to have either one ($I = 85$ mA and $I = 95$ mA) or several ($I = 80$ mA and $I = 90$ mA) solitary laser modes active just before the LFF appear. It is worth noting that when LFF start, several solitary laser modes become excited regardless whether the feedback phase was chosen to yield single- or multi-mode operation. In the LFF regime, the number of excited solitary-laser modes monotonically increases for decreasing feedback level and saturates at about 22 modes (independent of the feedback phase and limited by the FSR of our FP), showing that the presence of LFF is strongly linked to multimode behavior in this system.

Further information may be obtained from the time resolved spectrum. We fix the length of the FP and we record the total intensity and the intensity transmitted through the etalon simultaneously. The latter corresponds to the component of the optical spectrum at the transmission frequency of the FP, and its temporal behavior is the same after every drop of the total intensity. Therefore LFF do not correspond to mode hopping.

We record the time resolved spectrum for different current and feedback levels by repeating the above measurement for all frequencies inside a free spectral range (FSR) of the FP (now equal to 6 solitary laser modes, ≈ 900 GHz) and superposing the data recorded for every frequency. The appearance of an LFF triggers each measurement, which covers a time span of 190 ns with a time resolution of 1 ns. Following a drop of the total intensity (see Fig. 5), the active laser modes switch-off. As the power recovers, all solitary laser modes within the FSR of the FP (and possibly more due to aliasing) start emitting with their modal frequencies strongly blue-shifted. Interestingly we see that the maximal value of this shift can be almost equal to the solitary laser mode spacing [see Fig. 5(a) and 5(c)]. It is worth noting that, as the total power recovers, all the modal frequencies recover synchronously, with a recovery time below 50 ns, which is of the order of the recovery time for the total intensity. However, the modal frequencies approach the values they had before the drop exponentially instead of linearly as predicted by the single-mode LK equations.

In addition, the recovery for the modal powers takes longer than 200 ns. On this long time scale, the solitary laser modes exchange energy following dynamics similar

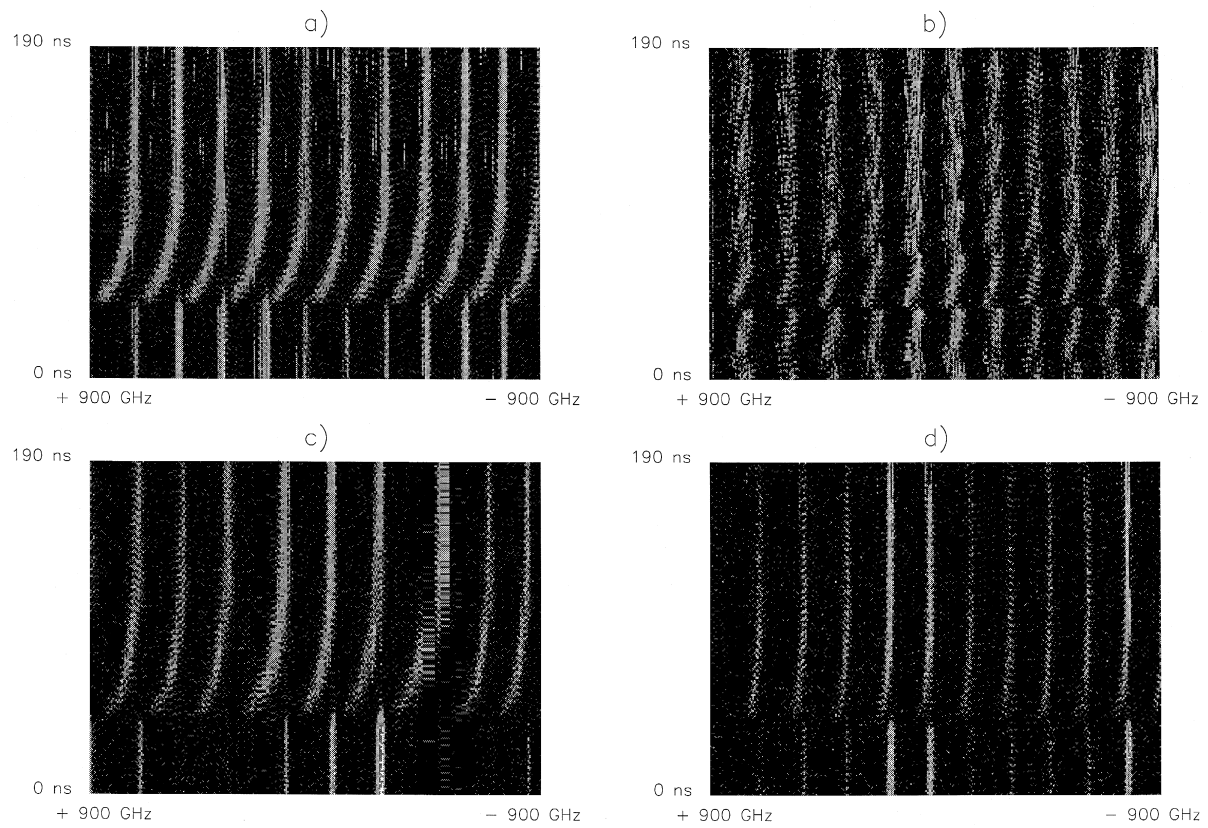

Fig. 5. Time resolved spectrum of the laser for currents: 87.9 mA with AOM voltages (a) 170 mV and (b) 380 mV, and 79 mA with AOM voltages (c) 170 mV and (d) 380 mV. Darker areas correspond to higher optical intensity.

to that observed during the switch-on transient of a laser [18]. It is worth noting that none of the solitary laser modes has an evolution which mimics that of the total power. If there were such a mode, one could then interpret the evolution of the system as dominated by this mode, the others becoming excited due to the nonlinear effects associated with the fast, large amplitude modulation of the master mode.

In Fig. 5(b), one can see the effect of multiple drops (every 20–25 ns). In this case, which is close to the so-called ''coherence collapse regime'', the time-resolved spectrum is more noisy because the drops are so frequent that the system is no longer able to completely recover its quasi-CW state after every drop.

Our experimental results cannot be interpreted within the single-mode LK model, since we have not found a master mode whose dynamics mimic those of the total power. Moreover, the experimental observation of dynamics on time scales between the duration of the drop and the time between drops cannot be disregarded. Because there is strong coupling among the modes on long time scales, it appears that, in order to describe our LFF, either an effective multimode description [19] or a partial differential equation to describe the compound cavity [20] would be required. Thus, the dynamical origin of such LFF may be substantially different from the single-mode situation, because the stability of the asymptotic solutions is greatly affected by the consideration of a multi-mode situation even if quasi-single-mode operation is recovered between drops.

To our knowledge, the model in Ref. [19] has not been studied in the parameter regime where LFF must appear. Our preliminary analysis indicates that even for only two modes, the inclusion of the feedback terms leads to a breaking of the usual antiphase dynamics [21]. Antiphase dynamics is the dominant effect in between LFF. However, each LFF breaks the phase locking of the modes, which start to oscillate in phase until the modal intensities reach the vicinity of their steady state values; at this point, antiphase dynamics is again observed.

In order to try to enforce single-mode operation even when the drops appear, we replace the external mirror by a diffraction grating in a Littman configuration. The grating resolution is about 30 GHz, i.e., almost five times smaller than the solitary-laser mode spacing. For a wide region of parameter space, the laser emission is stable and in a

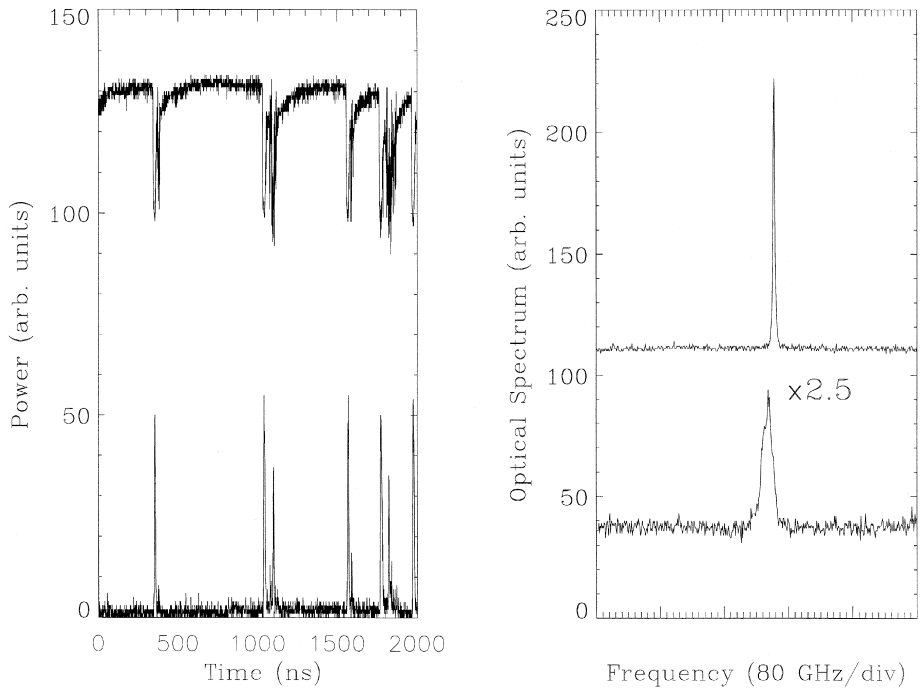

Fig. 6. Right panel: optical spectrum for the laser with feedback from a diffraction grating in the stable regime (upper trace, displaced upwards 75 units) and when drops occur (lower trace, magnified 2.5 times). Left panel: Time evolution during the LFF regime of the total power (upper trace) and power in the main-mode of the solitary laser (lower trace). The current is 98 mA, the AOM voltage is $V = 300$ mV, and the grating is set to feed back the fifth mode from the dominant one in the solitary laser.

single-mode, although unstable regime with power drops can be achieved for moderate feedback levels by setting the reflectivity peak of the grating slightly detuned from a solitary laser mode. A typical situation is depicted in Fig. 6, which displays the unstable regime corresponding to the grating's reflectivity peak detuned to the blue side of the operating frequency of the solitary laser by ≈ 700 GHz (i.e., five solitary laser mode spacings) and AOM voltage of 300 mV. Power drops can be observed, and the time-averaged optical spectrum shows one peak slightly blueshifted with respect to the grating's peak, with a larger linewidth than when the system is stable. However, if we monitor in real time the total intensity and the intensity of the dominant mode of the laser without feedback, we observe that following the drop, even such a distant mode becomes active. This same behavior is observed for the other solitary laser modes, thus supporting our observation that LFF induce multimode behavior.

In our experimental results, the appearance of LFF involves multimode operation of the system, and individual mode intensities recover more slowly than the total. In addition to the long-lasting intermode dynamics, there is no single mode which follows the total intensity. These experimental observations cannot be explained within a single-mode LK model, but instead they require a description which takes into account the multimode character of the solitary laser. Therefore the dimension of phase space required to describe such a process increases, which may thus lead to a completely new dynamical origin for the appearance of LFF in these systems.

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References

[1] K. Ikeda, H. Daido, O. Akimoto, Phys. Rev. Lett. 45 (1980) 709.
[2] V. Petrov, B. Peng, K. Showalter, J. Chem. Phys. 96 (1992) 7506.
[3] S.J. Schiff et al., Nature 370 (1994) 615; J. Starret, R. Tagg, Phys. Rev. Lett. 74 (1995) 1974.
[4] I. Györi, G. Ladas, Oscillation Theory of Delay Differential Equations, Oxford University Press, New York, 1991.
[5] A.P. Bogatov, P.G. Eliseev, L.P. Ivanov, A.S. Logginov, M.A. Manko, K.Ya. Senatorov, IEEE J. Quantum Electron. 9 (1973) 392.

[6] C.H. Risch, C. Voumard, J. Appl. Phys. 48 (1977) 2083.
[7] D. Lenstra, B. Verbeek, A.J. den Boef, IEEE J. Quantum Electron. 21 (1985) 764.
[8] J. Mork, J. Mark, B. Tromborg, Phys. Rev. Lett. 65 (1990) 1999.
[9] J. Mork, J. Mark, B. Tromborg, IEEE J. Quantum Electron. 28 (1992) 93.
[10] J. Mork, Ph.D. Thesis, Nonlinear Dynamics and Stochastic Behaviour of Semiconductor Lasers with Optical Feedback, Report # S48, March 1989, Technical University of Denmark. See Chap. 4, pp. 50–68.
[11] R.W. Tkach, A.R. Chraplyvy, J. Lightwave Technol. 4 (1986) 1655.
[12] R. Lang, K. Kobayashi, IEEE J. Quantum Electron. 16 (1980) 347.
[13] T. Sano, Phys. Rev. A 50 (1994) 2719.
[14] G.H.M. van Tartwijk, A.M. Levine, D. Lenstra, IEEE J. Sel. Topics Quantum Electron. 1 (1995) 466.
[15] I. Fischer, G.H.M. van Tartwijk, A.M. Levine, W. Elsässer, E. Göbel, D. Lenstra, Phys. Rev. Lett. 76 (1996) 220.
[16] G. Huyet, S. Hegarty, M. Giudici, B. de Bruyn, J.G. McInerney, Europhys. Lett. 40 (1997) 619.
[17] P. Besnard, B. Meziane, G.M. Stéphan, IEEE J. Quantum Electron. 29 (1993) 1271.
[18] S.E. Hodges, M. Munroe, W. Gadomski, J. Cooper, M.G. Raymer, J. Opt. Soc. Am. B 14 (1997) 180.
[19] A.T. Ryan, G.P. Agrawal, G.R. Gray, E. Gage, IEEE J. Quantum Electron. 30 (1994) 668.
[20] M. Homar, J.V. Moloney, M. San Miguel, IEEE J. Quantum Electron. 32 (1996) 553.
[21] J.Y. Wang, P. Mandel, Phys. Rev. A 48 (1993) 671.