Temporal Dynamics of Semiconductor Lasers with Optical Feedback

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We measure the temporal evolution of the intensity of an edge emitting semiconductor laser with delayed optical feedback for time spans ranging from 4.5 to 65 ns with a time resolution from 16 to 230 ps, respectively. Spectrally resolved streak camera measurements show that the fast pulsing of the total intensity is a consequence of the time delay and multimode operation of the laser. We experimentally observe that the instabilities at low frequency are generated by the interaction among different modes of the laser. [S0031-9007(98)08077-6]

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Nonlinear systems with delayed feedback are of interest because they can be widely found in economy, biology, chemistry, and physics [1]. These systems are in principle infinite dimensional, and from this point of view, it is difficult to classify them *a priori* as deterministic dynamical systems because the existence and uniqueness of a solution have to be demonstrated for each particular model [2]. It is also difficult to separate the role of noise from determinism, because complex solutions display a Gaussian-Markovian behavior as if they were solutions of a Langevin equation [3,4], thus nonconventional measurement techniques are required [5].

During the past years, there has been particular interest in understanding the dynamical behavior of one such system: a semiconductor laser with optical feedback. It was experimentally shown that weak optical feedback may induce bistability [6], oscillations, and chaos [7]. At moderate feedback levels, a special dynamical regime occurs which is characterized by the appearance of aperiodic, fast reductions of the total intensity of the laser [8,9], followed by a slower recovery stage. The average time between such intensity drops is much longer than all characteristic times of the system itself, so they are called low-frequency fluctuations (LFF).

From numerical simulations it was recently proposed that LFF originate from a deterministic chaotic attractor which encompasses a large number of unstable fixed points, either saddle-node points or foci [9–11]. This chaotic attractor coexists with one or more stable fixed points. The trajectory, if in the chaotic attractor, wanders in phase space around the foci until it approaches a saddle. The collision with a saddle gives rise to a large, fast excursion in phase space until the evolution recovers towards the foci. Since this process lasts for several delay times, it generates a long-time scale dynamics which contributes to the lower part of the spectrum, and it was called "chaotic itinerancy with a drift" because it involves a drift in the laser frequency. Furthermore, the model—which assumes single-mode operation of the laser and very weak feedback—predicted that the temporal behavior of the laser intensity is characterized by pulses departing from zero intensity level and whose amplitude grows steadily until the collision with a saddle takes place leading to a sudden reduction of the intensity. However, recent measurements of the time-resolved spectrum showed that the laser operates multimode whenever LFF appear [12], breaking one of the basic assumptions of the model. In addition, statistical measurements of the intensity distribution with a sampling oscilloscope showed that the fast fluctuations in general take place around an average intensity value different from zero [13], thus disagreeing with the model.

Here we present measurements of both the total intensity and the time-resolved spectrum conducted with a single-shot streak camera which allowed us to unambiguously identify the physical mechanism of the fast pulsing. These results suggest an alternative interpretation of the process at the origin of the intensity drop in a semiconductor laser with optical feedback and confirm the results presented in [12,13].

These measurements are performed on an Hitachi HL 6314MG laser emitting about 630 nm, with a mode spacing of $\approx$135 GHz and a threshold current of 24 mA. An antireflection coated microscope objective is placed at the laser output to collimate the beam. An external mirror of 30% reflectivity is placed at a distance of 30 cm from the laser output (delay time $\tau = 2$ ns), reducing the threshold of the laser down to 22 mA. Part of the output beam is sent to a 2 GHz bandwidth silicon avalanche photodiode. The photodiode signal is monitored with a TDS620 digital oscilloscope (500 MHz analog bandwidth) and it can also be sent to a power spectrum analyzer (1.5 GHz bandwidth). The remaining portion of the laser output is detected by a single-shot streak camera system. This system is based on a streak tube with an S 20 photocathode having a radiant sensitivity of 20 mA/W

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at 630 nm and a P-11 phosphorous screen. A fiber-optics coupled gated image intensifier is used to intensify the output of the streak tube. The intensified image is detected with a two-dimensional, fiber coupled and thermoelectrically cooled charge-coupled device array. We operate the camera with different streak speeds, from about 4.5 to 65 ns/screen, to monitor the laser output on different time spans. The resolution of the system is 16 to 230 ps, respectively. The time resolution of the system and the linearity of the ramp at each speed are tested with a mode-locked Ti:sapphire laser. In order to maximize the signal to noise ratio of our measurements the input optics of the streak camera is removed, and the laser output is focused directly onto the photocathode. A cw He-Ne laser is used to determine the minimum sensitivity of the streak camera. This test rules out any possibility that in our experiments the camera might have been operated below the level at which a continuous signal can appear as a sequence of pulses as a result of a low number of photoelectrons and a high intensifier gain.

In Fig. 1 we show the total intensity as a function of time observed with the oscilloscope (Fig. 1a) and the streak camera (Fig. 1b). In both cases we note that the average intensity increases steadily with time until it suddenly drops to a minimum value. We can also observe that in both cases there are fast intensity pulses, partially filtered in the oscilloscope trace (Fig. 1a) by the limited bandwidth of the detection system. The streak camera measurement shows that the pulses disappear immediately following the drop of the total intensity. These pulses exhibit a marked pseudoperiodicity at the round-trip time of the optical field in the external cavity. However, there also exists pulsing at shorter time scales which suggests the influence of higher frequencies. We repeat the measurements for several values of injection current and feedback strength over hundreds of intensity drops in each case. As long as the system operated in the so-called LFF regime, the above qualitative behavior remained unaltered. However, the quantitative details change from one drop to another. In Fig. 2 we show intensity traces covering time spans of 21 ns taken with a time resolution of 70 ps (a)–(c) and time spans of 4.5 ns and 16 ps time resolution (d)–(f). Each trace corresponds to a different drop and starts at a different delay relative to the drop. These measurements confirm that up to our maximum time resolution there is no underlying dynamics and that Fig. 1b illustrates the relevant behavior of the total intensity.

In order to analyze the origin of the pulsing occurring at shorter times than the delay time, we conduct spectrally resolved measurements. We place a 0.3 m grating monochromator (Acton Research VM 503) with a resolution of 0.5 Å in front of the streak camera. Removing the

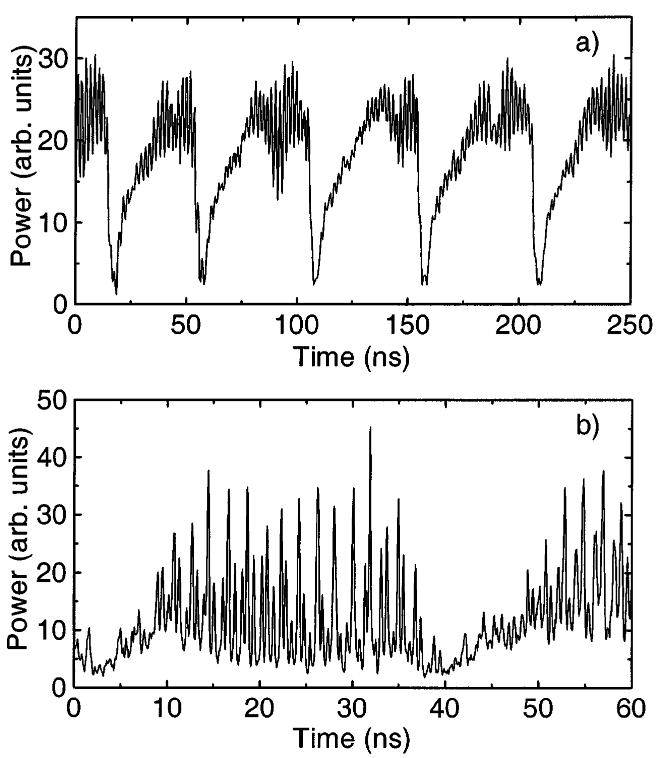

FIG. 1. Total intensity as a function of time taken with (a) the oscilloscope, and (b) the streak camera with a time resolution of about 230 ps. Note the pseudoperiodicity of the signal at the round-trip time in the external cavity (~2 ns).

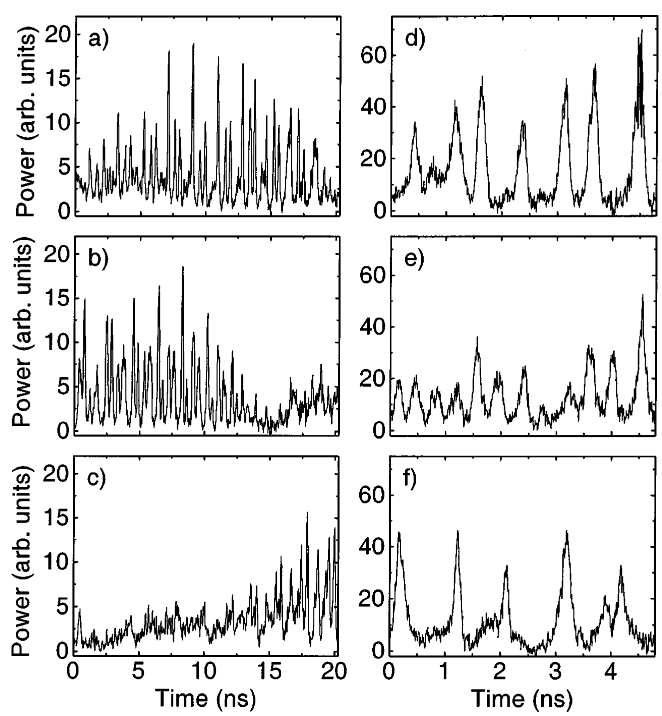

FIG. 2. Temporal evolution of the total intensity taken with the streak camera over different time spans: (a)–(c) 21 ns time span, 70 ps time resolution; (d)–(f) 4.5 ns time span, 16 ps time resolution. Different traces correspond to different drops, and the starting point relative to the drop is changing from one acquisition to the other.

output slit of the monochromator, we obtain a wavelength dispersed beam on the camera photocathode. In this way, we are able to record the time-resolved spectrum, with the horizontal axis of the streak image corresponding to wavelength, at the price of a lower signal to noise ratio due to the dispersion of the beam. The spectral resolution is ~40 GHz, enough to clearly resolve the resonances of the internal laser cavity although insufficient to resolve the external cavity resonances.

Figure 3 displays a typical time-resolved spectrum in the LFF regime taken with the streak camera with a resolution of 230 ps in time. We clearly observe that most of the time the system operates in multiple modes of the internal laser cavity, in agreement with the results of [12], and in general the dominant active modes are not consecutive ones. When a drop of the total intensity occurs (see times ≈5 and 35 ns), all modal intensities are below the photocathode sensitivity. However, after a delay of a few ns, we observe that several diode modes grow from the background. The modal evolution is controlled by the delay time, and until the next drop of the total intensity takes place, there is a transfer of energy among these modes.

Important dynamical information can be gained from the analysis of the temporal evolution of the relevant modal intensities. As shown in Fig. 4, each mode is pulsing with a repetition rate controlled by the external cavity round-trip time, but in general the phase of pulsation is different for different modes; in particular, the two dominant modes over a given time interval operate with different phases. The origin of the oscillations can be understood as a partial phase locking of the external cavity resonances within each internal cavity resonance. Since the modal intensities are pulsing with arbitrary phases one relative to the other, the total intensity displays fast pulsing (which looks irregular due to the exchange of energy among the modes) around a nonvanishing average level, in agreement with [13]. Finally, the analysis also reveals that shortly after two or more modes synchronize their amplitudes to pulse in phase, a drop in the total intensity occurs as soon as the pulses are big enough (see bottom panel in Fig. 4). It is worth noting that, in general, after each drop of the total intensity, both the number of modes and the respective phase of the pulsing change, and that the dominant modes just after the drop are not

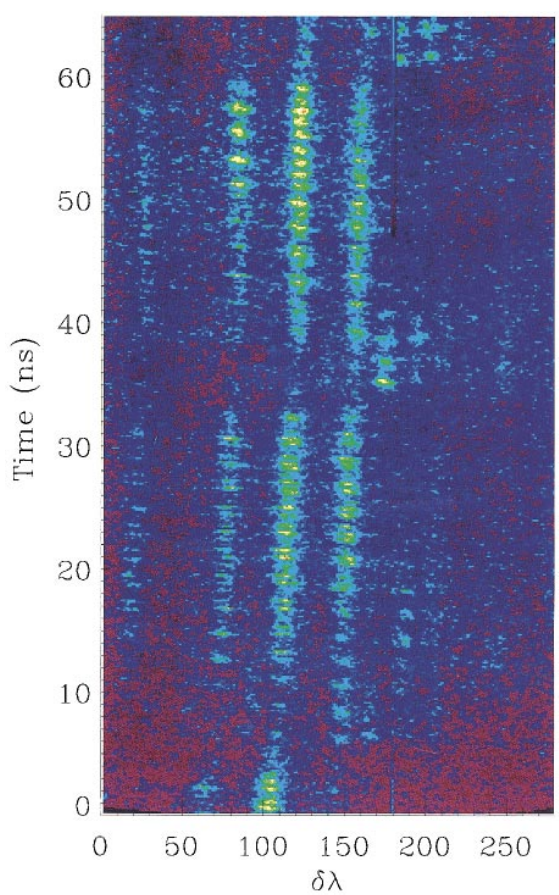

FIG. 3(color). Typical time-resolved spectrum in the LFF regime taken with the streak camera. The time span is 65 ns with a time resolution of ≈230 ps, while the frequency resolution is ≈40 GHz. The index in $\delta\lambda$ denotes the pixel on the CCD array, and the power is in false color, from purple (low power) to bright red (high power).

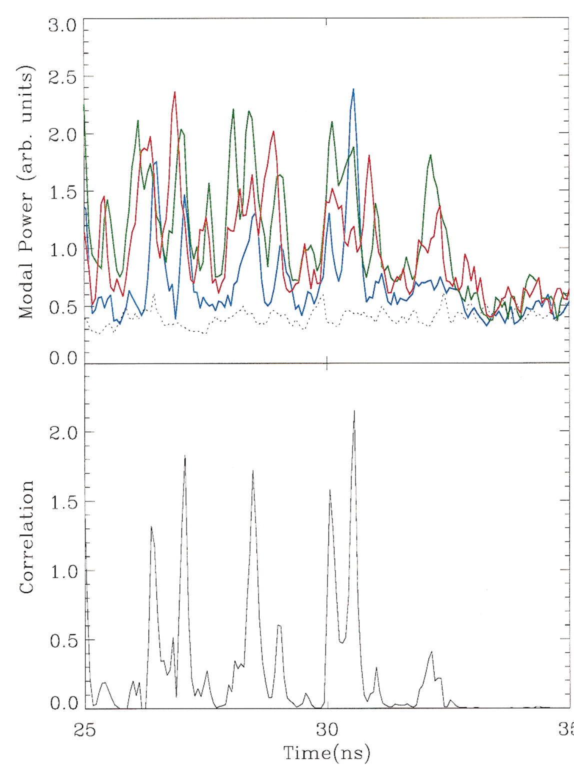

FIG. 4. Top panel (color): Modal intensity traces for the three dominant modes in Fig. 3 for times around the first drop. Blue corresponds to the mode at about $\delta\lambda = 60$, green to that at about $\delta\lambda = 100$, and red to the one at about $\delta\lambda = 150$. The dotted black line corresponds to the background level. Bottom panel: modal correlation defined as the product of the modal powers above the background level.

the dominant ones just before it. However, the repetitive feature is that a total intensity drop happens shortly after several modes start pulsing in phase.

It is worth noting that as the injection current is increased, the intensity drops become more frequent, and finally the signal in the oscilloscope looks almost random. This situation is commonly called "coherence collapse" (CC). In the CC regime, the signal observed with the streak camera does not show qualitative differences as compared to the LFF case, although now the signal fluctuates strongly at all times. In fact, the time-resolved spectrum in the CC regime does not show any "dark periods" where all modes are below the sensitivity limit of the streak camera. In addition, it appears that the different modes are no longer synchronized, as was the case in the LFF regime.

The above results disclose the fact that the interaction between the resonances of the internal cavity is at the origin of the total intensity drops. It is worthwhile noting that the operating modes are usually not consecutive ones, such as multimode instabilities in laser theory [14,15]. A physical interpretation can be based on a typical multimode laser instability. The system is essentially controlled by the delay time, which fixes a resonance frequency at τ^{-1}. For one laser mode, the external cavity modes tend to lock in phase during the buildup of the average total intensity, thus leading to pulses. If the delay is long enough the active material can recover before the next pulse is generated, and another laser mode is able to operate and it will grow from noise. The external cavity modes inside the bandwidth of this "new" operating mode tend also to lock in phase, but their locking phase will in general be different from that of the previously existing mode. In this way several electromagnetic modes are able to operate but their nonlinear coupling leads to an instability which gives origin to the drop of the total intensity and to fast variations of the material properties such as refractive index. As a consequence, there is a shift in frequency and later operation at other unrelated laser modes. The process then initiates again.

In conclusion, the fast pulsing observed in the total intensity with the streak camera is due mainly to the superposition of the intensities of different longitudinal laser modes and, for each mode, to a phase locking process of the external resonances. The intensity drops are the result of a multimode instability and the total intensity value is generally above the spontaneous emission level. The nonrepetitiveness of the signal from drop to drop leaves the question unanswered about the role of noise and the deterministic character of this particular system. Heuristically we can say that the whole process seems to be dominated by noise. However, the instability giving rise to each drop leads to a short stage of determinism during the recovery, but it is difficult to establish an unambiguous conclusion about the role of noise by just measuring the intensity and operation frequency of the laser.

Further details on the coherence collapse regime and the evolution of the system as the injection current is increased will be published elsewhere.

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[1] R. M. May, Nature (London) **261**, 459 (1976).
[2] I. Györi and G. Ladas, *Oscillation Theory of Delay Differential Equations: with Applications*, Oxford Mathematical Monographs (Clarendon, Oxford, 1991).
[3] B. Dorizzi, B. Grammaticos, M. Le Berre, Y. Pomeau, E. Ressayre, and A. Tallet, Phys. Rev. A **35**, 328 (1987).
[4] K. Ikeda and O. Akimoto, in *Coherence and Quantum Optics V*, edited by L. Mandel and E. Wolf (Plenum, New York, 1984).
[5] A. Hohl, H. J. C. van der Linden, and R. Roy, Opt. Lett. **20**, 2396 (1995).
[6] R. Lang and K. Kobayashi, IEEE J. Quantum Electron. **QE-16**, 347 (1980).
[7] J. Mork, B. Tromborg, and J. Mark, IEEE J. Quantum Electron. **QE28**, 3 (1992); B. Tromborg, J. H. Osmundsen, and H. Olesen, IEEE J. Quantum Electron. **QE20**, 1023 (1984).
[8] Ch. Risch and C. Voumard, J. Appl. Phys. **48**, 2083 (1977).
[9] I. Fischer, G. H. M. van Tartwijk, A. M. Levine, W. Elsässer, E. Göbel, and D. Lenstra, Phys. Rev. Lett. **76**, 220 (1996).
[10] T. Sano, Phys. Rev. A **50**, 2719 (1994).
[11] G. H. M. van Tartwijk, A. M. Levine, and D. Lenstra, IEEE J. Sel. Top. Quantum Electron. **1**, 466 (1995).
[12] G. Huyet, S. Balle, M. Giudici, C. Green, G. Giacomelli, and J. Tredicce, Opt. Commun. **149**, 341 (1998).
[13] G. Huyet, S. P. Hegarty, M. Giudici, B. de Bruyn, and J. G. McInerney, Europhys. Lett. **40**, 619 (1997).
[14] H. Risken and K. Nummedal, J. Appl. Phys. **39**, 4462 (1968); V. Benza and L. A. Lugiato, Z. Phys. B **35**, 383 (1979).
[15] L. M. Narducci, J. R. Tredicce, L. A. Lugiato, N. B. Abraham, and D. K. Bandy, Phys. Rev. A **33**, 1842 (1986).