Intermittency in the Coherence Collapse of a Semiconductor Laser with External Feedback

Joachim Sacher, Wolfgang Elsässer, and Ernst O. Göbel
Fachbereich Physik and Zentrum für Materialwissenschaften, Philipps Universität Marburg,
Renthof 5, D-3550 Marburg, Federal Republic of Germany
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We report the first experimental observation of type-II intermittency in an optical system. The type-II intermittency is observed in the light intensity of a GaAs/GaAlAs semiconductor laser with external feedback in the regime of the coherence collapse. We conclude the occurrence of a time-inverted type-II intermittency from the time distribution of the observed intensity breakdowns, with the injection current as control parameter. This interpretation is confirmed by a reconstructed Poincaré plot exhibiting the spiraling behavior of the type-II intermittency.

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Nonlinear dynamics and chaotic behavior are studied in many systems belonging to different areas like biology, chemistry, or physics. The interesting aspect of these studies is the search for universality in the behavior of nonlinear systems and their transition to chaos. Three universal transition routes from regular to chaotic motion have been discussed so far in many different systems: the period-doubling route, the Ruelle-Takens-Newhouse route (quasiperiodic route), and the intermittency route.[1,2] The intermittency route is characterized by short, irregular bursts, interrupting the nearly regular (laminar) motion. There are three different types of intermittency. Type I is associated with a inverse tangent bifurcation, type II with a Hopf bifurcation, and type III with a period-doubling bifurcation. Two of them are well established by experiments: type-I and -III intermittency.[3-5] Type-II intermittency, however, has been observed so far in an electrical system only.[6]

Nonlinear dynamics and chaotic behavior in laser systems has been investigated since the late 1970s. The three universal transitions to chaos have been found in some gas laser systems.[7] Opposite to these gas lasers, a solitary single-mode semiconductor laser cannot show chaotic behavior because it is fully described by only two independent parameters, the electric field and the carrier density. However, adding an additional degree of freedom, e.g., by an external cavity[8] or external light injection, allows the occurrence of chaotic instabilities. The investigation of these instabilities is of great practical importance also because of its application related aspects like, e.g., for fiber communication systems or for linewidth reduction.[9] The dynamics of instabilities in semiconductor lasers with external feedback have been studied by several groups.[10-13] Cho and Umeda[10] as well as Glas, Müller, and Wallis[11] have found correlation dimensions of the emitted light intensity which indicate deterministic chaos under strong feedback conditions. Mukai and Otsuka[13] have reported the occurrence of subharmonic frequencies in the light intensity of an external cavity system with a tilted external mirror. A particular interesting feature of an external cavity semiconductor laser is the occurrence of the so-called coherence collapse.[14-18] Coherence collapse means an enormous increase of the linewidth to typically 10–25 GHz under certain values of the external feedback. The linewidth of the laser is reduced for moderate levels of feedback; however, for strong levels the linewidth increases dramatically independent of the length of the external cavity. The origin of the coherence collapse is the occurrence of a bistability between the state of minimal gain and the state of minimal linewidth.[16,17] Numerical simulations have shown that this behavior is not noise induced.[15,18]

In the present paper we report a conclusive experimental demonstration of the occurrence of type-II intermittency in an external cavity semiconductor laser configuration with strong optical feedback and with the injection current as an external control parameter. We demonstrate the occurrence of a time-inverted type-II intermittency in this system by analyzing the light intensity fluctuations in the regime of the coherence collapse in time and frequency domain. To our knowledge, this is the first report of a type-II intermittency in an optical system.

Figure 1 shows the experimental setup. We use a temperature-stabilized GaAs/GaAlAs channeled substrate planar laser diode (Hitachi HLP1400, denoted as LD in Fig. 1). The external cavity (feedback part, on the right-hand side of the LD) consists of a high reflecting dielectric external mirror (98%) and an antireflection coated microscope objective to collimate the laser beam. The detection part is depicted on the left-hand side of the LD. The optical spectrum of the laser diode is measured using a 1-m Czerny-Turner grating monochromator and a scanning plane Fabry-Perot interferometer. The time-averaged laser intensity is measured by a slow *p-i-n* diode (PIN). The fluctuations of the laser intensity are detected employing a fast avalanche photodiode (APD, rise time ≤ 100 ps). Its electrical signal output is amplified and then analyzed in the frequency and in the time domain using a rf spectrum analyzer and a transient digitizer (bandwidth 600

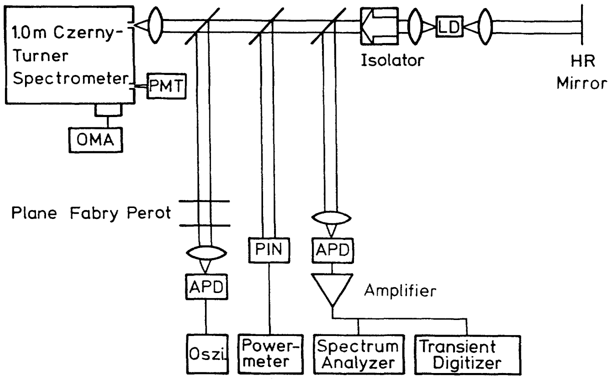

FIG. 1. The experimental setup consists of the feedback part on the right-hand side of the semiconductor laser (LD) and the detection part on the left-hand side.

MHz), respectively.

The light-power–injection-current characteristics (*p-i* characteristic) of the solitary laser diode and the external cavity laser diode are shown in Fig. 2. The *p-i* characteristic is strictly linear above the laser threshold without external feedback. With feedback, the threshold current is reduced 8% which is within the regime, where the coherence collapse occurs. The *p-i* characteristic with external feedback exhibits a kink in the current regime corresponding to the threshold of the solitary laser diode. The power spectrum of the emitted laser light at injection levels below and above the kink are depicted in the insets of Fig. 2. The power spectrum for a driving current below the regime of a kink exhibits a double-peak structure in the region of the inverse external cavity round-trip time. The frequency f_e of the narrow, low-frequency peak is determined by the length L of the external cavity: $f_e \simeq c/2L$ (=352 MHz in the present case). The origin of the high-frequency peak, which is shifted by 36 MHz with respect to the round-trip frequency f_e, is not completely understood at present; however, this feature is not important for the conclusions drawn in this paper. The upper inset in Fig. 2 shows a typical power spectrum for an injection current above the kink. The width of the peaks in the region of the inverse external cavity round-trip time has dramatically increased and a pronounced low-frequency noise occurs. This behavior is attributed to the occurrence of the coherence collapse. We have now analyzed the fluctuations of the light intensity in the time domain using a transient digitizer in order to understand the origin of the low-frequency noise. Figure 3 shows typical wave forms of the light output for a current value above the kink on a long-time [Fig. 3(a)] and a short-time scale [Fig. 3(b)]. The light intensity exhibits statistically distributed breakdowns with subsequent relaxations ($\tau_{\text{relax}} \simeq 40$ ns) to the equilibrium value. The frequency of the fast oscillating component ($\tau_e \simeq 2$ ns) in Fig. 3(b) corresponds to the external cavity frequency f_e. The low-frequency

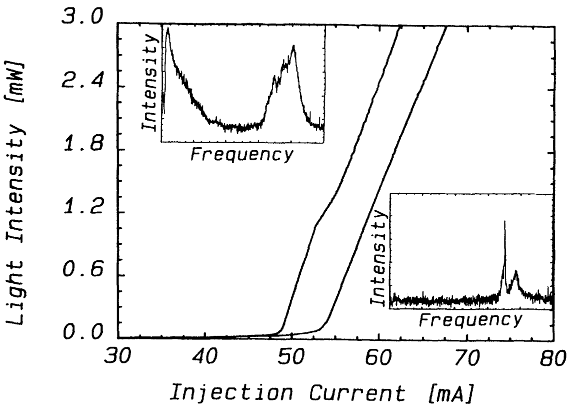

FIG. 2. Light-power–injection-current characteristics (*p-i* characteristic) of a semiconductor laser without optical feedback (right) and with optical feedback (left). The *p-i* characteristic with feedback exhibits a kink in the region of the threshold of the solitary laser. Lower inset: Typical power spectrum in the regime below the kink. Upper inset: Corresponding power spectrum in the regime slightly above the kink. The frequency scale of the insets ranges from 0 to 500 MHz, the intensity scale from −87 to −67 dBm.

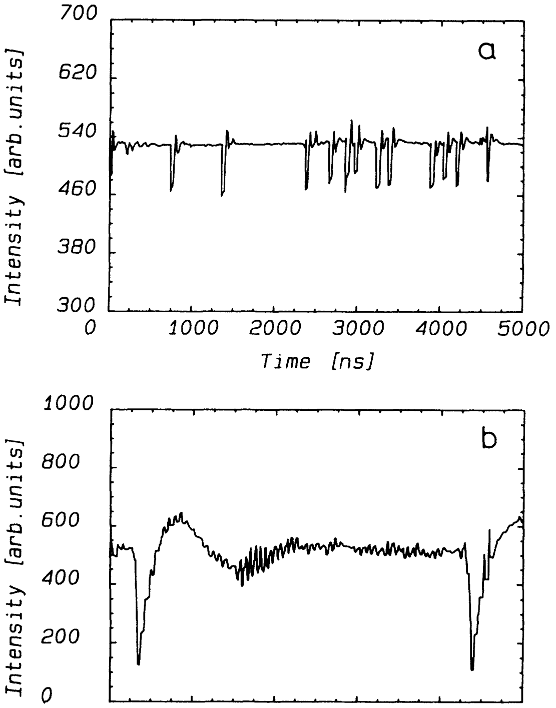

FIG. 3. Single shot time traces of the light intensity for a current value slightly above the kink. (a) Long-time behavior: The light output shows statistically distributed breakdowns. (b) Detailed behavior on a short-time scale: The light output breaks down and relaxes to the equilibrium value. The fast oscillation corresponds to the external cavity round-trip time.

noise is Fourier correlated to the frequencies of the breakdown events as proven by experiment. The temporal fluctuations of the laser intensity exhibit a behavior which is typical for intermittency. In the following we prove that the time behavior in our particular case is described by a time-inverted type-II intermittency.

Intermittency predicts a characteristic distribution of the mean time $\langle T\rangle$ of regular behavior of the laser light between two bursts. We have determined by a computer analysis of our data the mean time $\langle T\rangle$ as a function of the injection current. We have taken the normalized injection current

$$\epsilon = \frac{I - I_{\mathrm{th,ld}}}{I_{\mathrm{th,ld}}}$$

as control parameter which is justified by the fact that the onset of the intermittent behavior corresponds to the threshold of the solitary laser diode $I_{\mathrm{th,ld}}$. Figure 4(a) depicts the mean time $\langle T\rangle$ as a function of the normalized injection current ϵ in a double logarithmic plot. The mean time $\langle T\rangle$ decreases with an increase of the control parameter ϵ. We find in a double logarithmic plot a linear relation between the control parameter ϵ and the mean time $\langle T\rangle$ with a slope of -1.05, which is very close to a power-law[19] dependence

$$\langle T\rangle \sim \epsilon^{-1}$$

as predicted for type-II and -III intermittency, whereas for type-I intermittency $\langle T\rangle \sim \epsilon^{-1/2}$ is expected.[20] In order to further confirm type-II intermittency, we have investigated the statistical distribution of the occurrence of a breakdown; i.e., we have determined the probability of an event as a function of the time since the previous event. Type-II intermittency should exhibit a behavior $\sim T^{-2}$ for short times and an exponential tail for long times, very different to type-I intermittency, which predicts an increase of the probability for long times again.[20] We have evaluated a histogram [Fig. 4(b)] from the complete data set belonging to the control parameter of Fig. 3 to prove the predictions for the probability function. The experimental power law for short times ($t < 300$ ns) is difficult to confirm quantitatively; however, the expected exponential tail in the long-time regime is clearly indicated. The same results are observed for other values of the control parameter ϵ. This statistical analysis excludes type-I intermittency again. At this point, we are not able to decide experimentally whether the predicted scaling behavior of type-II or -III intermittency can be applied to our system. This, however, becomes possible when the development of the system in phase space is considered. We have followed the method of Bergé, Pomeau, and Vidal[2] to reconstruct a Poincaré plot by taking the successive extrema of the laminar signal between two intermittent events. In our case we have chosen the successive minima of the fast oscillation corresponding to the external cavity round-trip time between the two breakdowns in Fig. 3(b). We, consequently, plot the value of the emitted light intensity at the time corresponding to the Nth minimum as a function of the intensity at the $(N-1)$st minimum and obtain the Poincaré plot depicted in Fig. 5. This plot clearly exhibits spiraling behavior, which is characteristic for

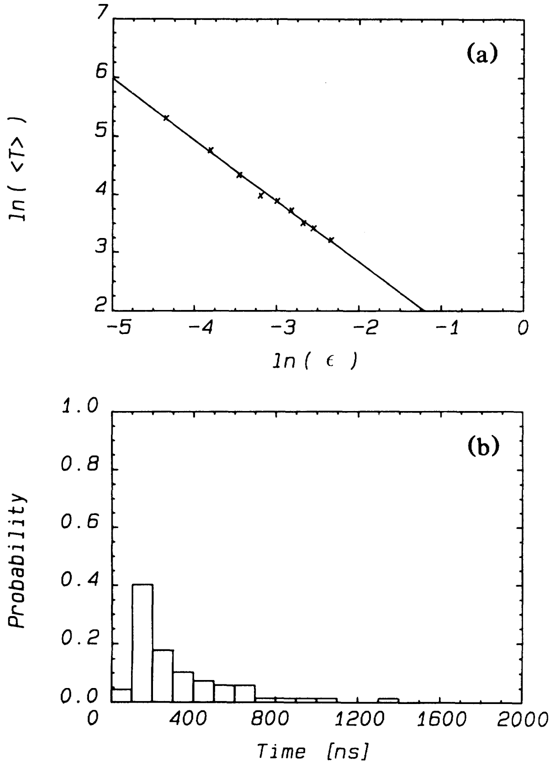

FIG. 4. (a) Double logarithmic plot of the mean time between two light intensity breakdowns as a function of the control parameter ϵ (normalized injection current). The slope is -1.05. (b) Probability distribution of the light intensity breakdown as a function of the time interval [Fig. 3(a)] between the events.

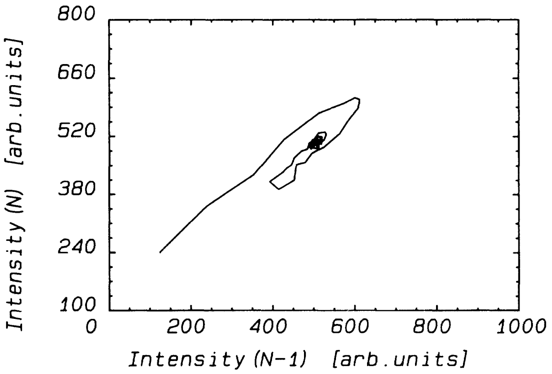

FIG. 5. Poincaré plot reconstructed from the experimental data of Fig. 3(b).

type-II intermittency.[20] However, the spiral is time inverted. This behavior means that the system is disturbed resulting in the breakdown of the light intensity and finally oscillates back to the equilibrium value, very similar to the Shilnikov model.[21] We call this behavior time-inverted type-II intermittency because it is time inverted with respect to the predicted behavior.

To summarize, we have observed a time-inverted type-II intermittency in the coherence collapse of a semiconductor laser with strong external feedback. The external control parameter ϵ of this system is the normalized injection current. We observe statistically distributed breakdowns of the light intensity in the time domain causing a pronounced low-frequency noise in the frequency domain. The mean time between two breakdowns is inversely proportional to the normalized injection current ϵ. The probability function of the time between the occurrence of a burst related to the previous burst decays exponentially for long times. Finally, the Poincaré plot exhibits the typical but time-inverted spiraling behavior of type-II intermittency. To our knowledge, this is the first conclusive observation of type-II intermittency in an optical system.

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[1] H. G. Schuster, *Deterministic Chaos* (VCH, Weinheim, 1988).

[2] P. Bergé, Y. Pomeau, and C. Vidal, *Order within Chaos* (Hermann, Paris, 1984).

[3] C. Jeffries and J. Perez, Phys. Rev. A **26**, 2117 (1982).

[4] P. Bergé, M. Dubois, P. Manneville, and Y. Pomeau, J. Phys. (Paris), Lett. **41**, L341 (1980).

[5] M. Dubois, M. A. Rubito, and P. Bergé, Phys. Rev. Lett. **51**, 1446 (1983).

[6] J.-Y. Huang and J.-J. Kim, Phys. Rev. A **36**, 1495 (1987).

[7] See, e.g., F. T. Arecchi, R. Meucci, G. Puccioni, and J. Tredicce, Phys. Rev. Lett. **49**, 1217 (1982); C. O. Weiss, A. Godone, and A. Olafson, Phys. Rev. A **28**, 892 (1983); R. S. Gioggia and N. B. Abraham, Phys. Rev. Lett. **51**, 650 (1983).

[8] R. Lang and K. Kobayashi, IEEE J. Quantum Electron. **16**, 347 (1980).

[9] R. F. Kazarinov and C. H. Henry, IEEE J. Quantum Electron. **23**, 1401 (1987).

[10] Y. Cho and T. Umeda, Opt. Commun. **59**, 131-136 (1986).

[11] P. Glas, R. Müller, and G. Wallis, Opt. Commun. **68**, 133 (1988).

[12] K. Otsuka and H. Kawaguchi, Phys. Rev. A **30**, 1575 (1984).

[13] T. Mukai and K. Otsuka, Phys. Rev. Lett. **55**, 1711 (1985).

[14] D. Lenstra, B. H. Verbeek, and A. J. den Boef, IEEE J. Quantum Electron. **21**, 674 (1985).

[15] K. Petermann, *Laser Diode Modulation and Noise* (Kluwar Academic, Boson, 1988), Chap. 9.3.4.

[16] J. Mork, B. Tromborg, and P. L. Christiansen, IEEE J. Quantum Electron. **24**, 123 (1988).

[17] N. Schunk and K. Petermann, IEEE J. Quantum Electron. **24**, 1242 (1988).

[18] G. C. Dente, P. S. Durkin, K. A. Wilson, and C. E. Moeller, IEEE J. Quantum Electron. **24**, 2441 (1988).

[19] J. O'Gorman, B. J. Hawdon, and J. Hegarty, Electron. Lett. **25**, 114 (1989), have reported a mean frequency of the low-frequency fluctuation which is proportional to ϵ.

[20] For comparison, see, e.g., Ref. 1, Chap. 4.

[21] A. Arneodo, P. Coullet, and C. Tresser, Commun. Math. Phys. **79**, 573 (1981).