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Exponential recovery of low frequency fluctuations in a diode laser with optical feedback

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Abstract

We show that the recovery after each power drop on the chaotic low frequency fluctuations in a semiconductor laser with optical feedback follows an exponential envelope. The time constant for such exponential behavior was experimentally measured. This recovery time constant and the average time interval between consecutive drops have different dependences when measured as function of the pump current.
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1. Introduction

Nearly four decades ago, Risch and Voumard [1] reported that diode lasers submitted to moderate optical feedback show chaotic low frequency fluctuations as drops in their power output. Since then many laboratories have done experimental and theoretical work on this phenomena. Controlled studies are done using a reflecting mirror and making the so called external cavity that feeds back a delayed optical field into the very small laser chip cavity [2,3]. Thus, the feedback delay time, τ, which corresponds to the round trip time of the external cavity, is in the range of tens of nanoseconds when the reflecting surface is located a few meters from the laser. The irregular variation of time interval between power drops, T, is the main indicator of the chaotic LFF pulsations of the laser, as seen in Fig. 1.

Typically, the average value of T changes with the values of the feedback level and the laser pump current, going from the order of microseconds down to hundreds of nanoseconds. Simultaneously, underneath these slow time scale events, the laser dynamics has very fast (picosecond range) pulsations in its power output and population inversion [4–9]. Averaged in a time scale of nanoseconds, the LFF events reported to date have the shape of a sharp drop followed by a stepwise recovery [3,17,10,11]. The deterministic and random contributions to the origin of the LFF drops is still subject of studies and many works have been dedicated to the measurement and calculation of the properties of T [13,15–17]. Sukow et al. [16] have clearly established that the drops and recoveries within a LFF series are nearly constant, while T fluctuates. Liu et al. [10] studied the recovery process and established that the time interval between steps during the LFF recovery correspond to the external round trip or feedback time delay, τ. Their work also shows that within LFF time series, while the time between drops had a wide variance, the number of steps in the recovery was nearly constant. They study the number of steps within consecutive drops (that is, within the time T) as function of the current and external cavity length. Hegarty et al. [11] also reported that the fast population relaxation oscillations in diode lasers with optical feedback have the same repeated shape while the interdrop time, T, have large chaotic fluctu-

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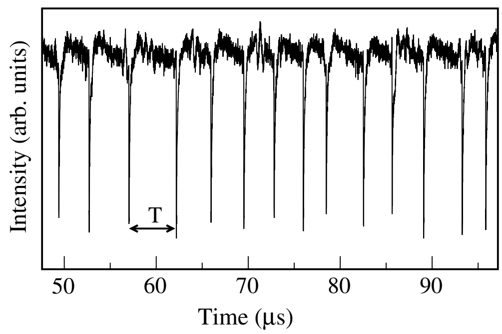

Fig. 1. Experimental laser power series with low frequency fluctuation drop events. The data correspond to filtered data series with pump current 19 mA, $\tau = 30$ ns and $\xi = 12\%$.

ations. They define as recovery time the time interval between switch-off and switch-on of the first peak on the ultrafast (subnanoseconds) dynamics and show the analogy with the turning-on of the laser. However, details or measurements for the recovery stage, after each drop, are missing in the literature. In the nanoseconds averaged time scale the ultrafast highly irregular pulses are not detectable and their effect merges within the other noise or fast deterministic fluctuations that eventually drives the LFF. The resulting averaged recovery of the LFF signal still have important physical behavior [17,12] to be studied quantitatively as function of the laser parameters.

The aim of this communication is to define and present quantitative measurements on this averaged stepwise recovery of LFF in a semiconductor laser with delayed optical feedback. A typical segment of the laser power time series of our experiments, filtered with 1 ns time window, is shown in Fig. 1. With the averaged signal we show that the LFF recovery occurs with an exponential time dependent envelope, having a time constant τ_0. A recovery time of the LFF events is defined as the time constant of these exponentials. This τ_0 is directly measured and is shown to be dynamically independent of the time T between drops. Such results can be foreseen in Fig. 2. To our knowledge, this exponential envelope and its time constant are proposed and systematically measured for the first time herein.

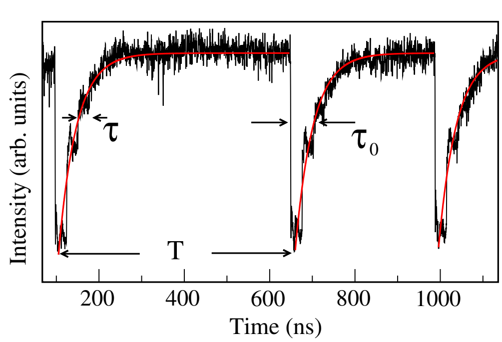

Fig. 2. Segment of experimental laser power with three low frequency fluctuation drop events. The feedback time τ, the interdrop time T and the time constant of the recoveries, τ_0, are shown. The smooth (color online) curves are exponential fittings using Eq. (1). The data correspond to filtered time series with pump current of 24 mA, $\tau = 30$ ns and $\xi = 12\%$.

2. Experiments

The laser in the experiments was an SDL 5401 GaAlAs, thermally stabilized to 0.01 K, and emitting at 850 nm. Its solitary threshold current was 17 mA. An external flat mirror distant between 0.9 m and 9.0 m was placed to create the optical feedback. Collimating lenses fixed the amount of feedback, which was measured by the threshold reduction parameter, ξ [5]. The intensity output is detected by a 1.5 GHz bandwidth photodiode and the power data series were filtered with the time averaging of 1 ns by a digital oscilloscope. Very long data series were also stored in a computer memory with a 12 bits AD acquisition system running at 100 MHz. Despite the filtering time of 1 ns the use of large round trip time delay permitted the distinct manifestation of the steps on the recovery of the LFF. This is seen in the short segments of the power series of Fig. 2 where τ is 30 ns.

Within Fig. 2 are indicated the external cavity round trip time, τ, the time between drops, T, and the recovery time constant of the drop envelope, τ_0.

To verify phenomenologically the exponential behavior on the recovery, after time t_i when a sharp drop occurs, the experimental laser power is fitted to the expression

$$P(t) = (P_0 - P_{\mathrm{L}})(1 - \exp\{-(t - t_i)/\tau_0\}) + P_{\mathrm{L}}, \tag{1}$$

where P_{L} is the minimum value of the laser power, just after the drop at time t_i and P_0 the value just before the drop $(i+1)$. Fig. 2 shows the fittings of exponentials curves (color on line), following Eq. (1), drawn over the experimental data. It is relevant to emphasize that a single value of τ_0 was used to fit the three consecutive drops presented in Fig. 2. Such is going to be our definition of recovery time in a LFF drop event.

A quantitative study of the experimental value of τ_0, was done with a best fitting computer program for the parameters of Eq. (1) runing over long experimental series. The fitting program first found the value t_i of a minimum, then determined P_0, P_{L} and finally searched for the best τ_0. From data series having more than 10^4 LFF drops, at each value of the injection current, the computer routine found the average of the recovery time, $\bar{\tau}_0$, which is shown in Fig. 3. In all these data the 100 MS/s or 60 MHz bandwidth of the signal filter would imply a time uncertainty of ± 10 ns on the value of each interspike time interval. However, if the intervals were equal, as in periodic events, 10^4 data points would reduce that source of uncertainity below 0.1 ns. Thus the significant variance on the interspike data is due to the chaotic nature of the phenomena.

For currents just above the solitary laser threshold the time constant $\bar{\tau}_0$ shows small variation with the current and a value close to three τ. Then, it decreases almost linearly with the current until the laser enters coherence collapse. The average time between drops, T, was also

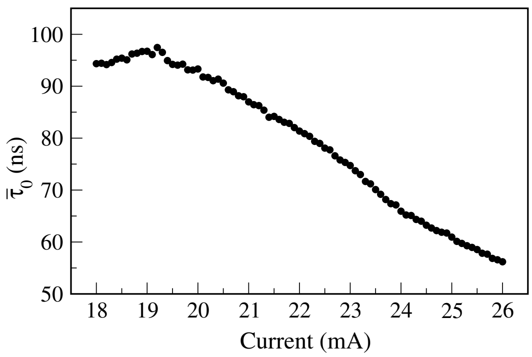

Fig. 3. Experimental average of the time constant τ_0 in low frequency fluctuating power series, as function of the pump current. The feedback parameter was $\xi = 12\%$ and the delay $\tau = 30$ ns.

extracted from the same experimental data series. The results are shown in Fig. 4.

Our measured $\overline{T}$, has a value of the order of $10^2\tau$ for low current, and behaves as described in previous work [10]. With external cavity of 0.9 m, which corresponds to $\tau = 6$ ns, the results obtained for $\bar{\tau}_0$ and $\overline{T}$ are shown in Figs. 5 and 6.

The two quantities, $\overline{T}$ and $\bar{\tau}_0$, are clearly distinct in their dependences on the pump current. Not only their order of magnitude, but mainly their rate of change with the current, given by the concavity of their dependences, are different. The most important difference appears for low currents. Near the solitary laser threshold current the average time between drops is known to have a sharp variation with the value of the pump current [13].

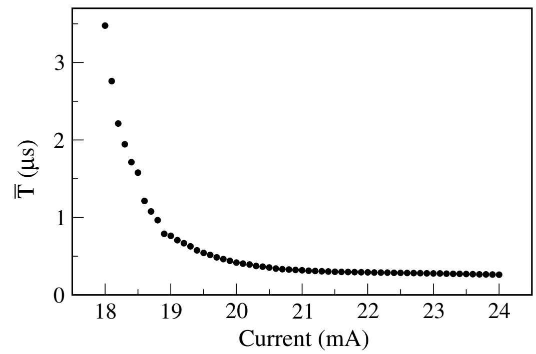

Fig. 6. Measured average time between drops, $\overline{T}$, for the diode laser with $\tau = 6$ ns delayed optical feedback and $\xi = 13.8\%$.

Further differences appear between the physical behavior of τ_0 and T when their variances are obtained as functions of the current. The results in Figs. 7 and 9 show the

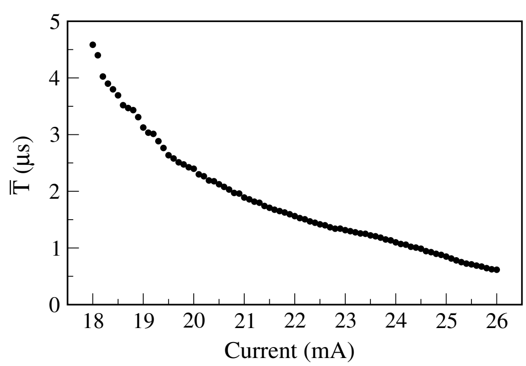

Fig. 4. Experimental average of the time T in low frequency fluctuating power series, as function of the pump current. The feedback parameter was $\xi = 12\%$ and the delay time $\tau = 30$ ns.

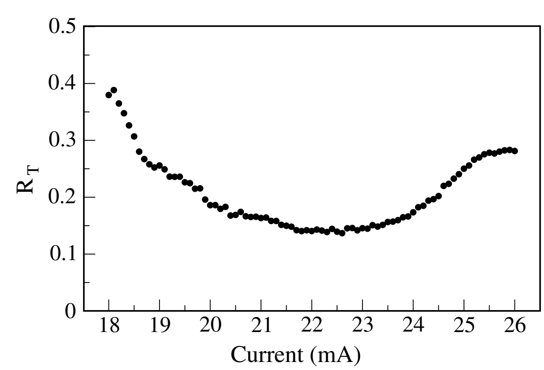

Fig. 7. Experimental normalized variance of the average time $\overline{T}$ in low frequency fluctuating power series, as function of the pump current. The feedback parameter was $\xi = 12\%$ and $\tau = 30$ ns.

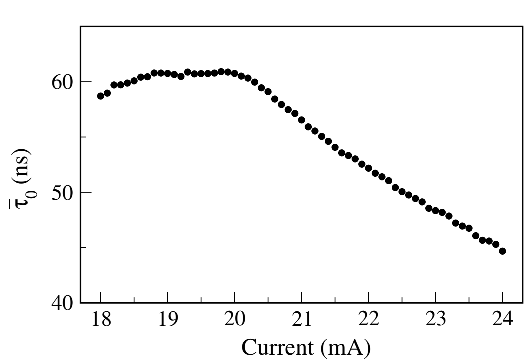

Fig. 5. Measured average of the recovery time constant, τ_0, for the diode laser with delayed optical feedback $\tau = 6$ ns and $\xi = 13.8\%$.

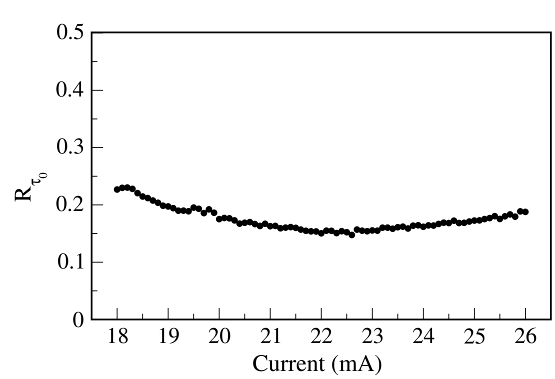

Fig. 8. Experimental normalized variance of the time constant τ_0 in low frequency fluctuating power series, as function of the pump current. The feedback parameter was $\xi = 12\%$ and $\tau = 30$ ns.

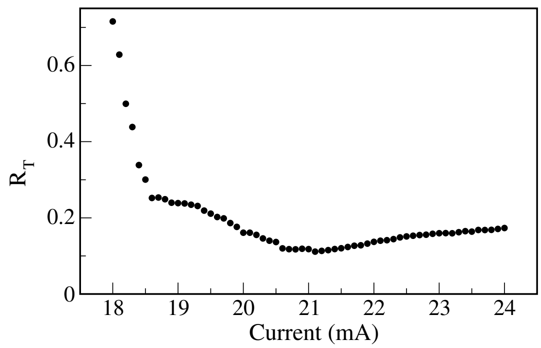

Fig. 9. Experimental relative variance of the time between drops, T, for the diode laser with $\tau = 6$ ns delayed optical feedback.

normalized variance, $R_T = \sigma_T/\overline{T}$, for the average time between drops. It has been previously studied [18] and present a minimum for intermediate values of the pump current. This can be interpreted as a manifestation of deterministic coherence resonance [18].

The value of $\overline{T}$ and the variance of T are strongly dependent on the noise in the system [13,14]. For low pump currents the main noise contribution is attributed to external or spontaneous emission origin [13,15], while deterministic noise, resulting from the fast chaotic dynamics, dominates at higher currents [4,18]. These regimes are seen in Figs. 6 and 9. It happens near the pump current of 19 mA where the shape of the current dependences drastically change. The corresponding normalized variances $R_{\tau_0} = \sigma_{\tau_0}/\bar{\tau}_0$ for the recovery time constant are shown in Figs. 8 and 10, respectively. In contrast to the relative variance of T, the relative variance of the time constant τ_0 is nearly constant. From this we infer that noise and fast fluctuations do not appear to affect τ_0. This is consistent with the definition of a quantity that is characteristic of the slow deterministic dynamics of the system.

Measurements done for external cavity lengths with $\tau = 6$ ns, 9 ns, 15 ns, 30 ns and 60 ns give approximately the same behavior for the relation between the recovery time constant and the time between drops. The value of R_{τ_0} remains nearly constant, below 30%, through the whole range of cavity lengths and pump currents investigated. A small concavity is observed only for relative variance of τ_0 with pump current in the data for cavity delay time of 30 ns (Fig. 8). For pump current near solitary threshold we have measured $\tau_0 \sim 3\tau$ to $\sim 10\tau$ and $\overline{T} \sim 10^2\tau$.

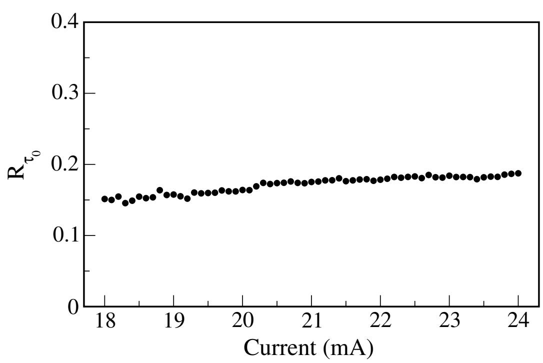

Fig. 10. Experimental relative variance of the recovery time constant τ_0 for the diode laser with $\tau = 6$ ns delayed optical feedback.

The numerical integration of the single-mode model of Lang and Kobayashi [19] equations give results for the recovery time τ_0 consistent with our experimental findings. Exponential recovery envelopes are obtained and the τ_0 dependence on the pump current goes according to Fig. 5. Earlier theoretical predictions of exponential recovery can be found in the literature [17]. Mork et al. [17] show that a simple return map model can predict stepwise recovery with exponential like envelope. A detailed study of the theoretical behavior of the recovery as obtained from the single-mode laser model is under investigation [20].

3. Conclusions

To summarize, a new experimental quantity on the dynamics of a semiconductor laser with optical feedback was introduced and studied: a time constant for the exponential recovery of the power drops in the Low Frequency Fluctuations. It is defined for the LFF signal averaged on a nanosecond time scale. The ultrafast pulsations present in the LFF are filtered out and this recovery definition is related to the slow dynamics (time scale longer than nanoseconds) of the system. The recovery time has specific dependence on the laser parameters, as shown here for the measurements as function of the pump current. Its relative variance is almost constant throughout the range of currents from threshold up to the onset of Coherence Collapse [5]. For comparison, the well studied [13,10,15–17] average time between drops, was also obtained for the same laser. Our results for low pump current confirm that the recovery is very insensitive to the effects of noise, in contrast to the average time between drops. The recovery envelope time constant, τ_0, may be useful as a relevant measurable quantity to be accounted for in calculations from theoretical models for the Low Frequency Fluctuations in chaotic diode lasers. A comparative study with numerical solutions of the Lang–Kobayahi equations [19] will be presented in a forthcoming publication [20].

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References

[1] Ch. Risch, C. Voumard, Journal of Applied Physics 48 (1977) 2083.
[2] H. Temkin, N.A. Olsson, J.H. Abelles, R.A. Logan, M.B. Panish, IEEE Journal of Quantum Electronics 22 (1986) 286.

[3] J. Mork, B. Tromborg, P.L. Christiansen, IEEE Journal of Quantum Electronics 24 (1988) 123.
[4] T. Sano, Physical Review A 50 (1994) 2719.
[5] G.H.M. van Tartwijk, D. Lenstra, Quantum and Semiclassical Optics 7 (1995) 87.
[6] I. Fischer, G.H.M. van Tartwijk, A.M. Levine, W. Elsäßer, E. GöNobel, D. Lenstra, Physical Review Letters 76 (1996) 220.
[7] G. Vaschenko, M. Giudici, J.J. Rocca, C.S. Menoni, J.R. Tredicce, S. Balle, Physical Review Letters 81 (1998) 5536.
[8] D.W. Sukow, T. Heil, I. Fischer, A. Gravielides, A. Hohl-AbiChedid, W. Elsäßer, Physical Review A 60 (1999) 667.
[9] A. Gavrielides, T.C. Newell, V. Kovanis, Physical Review A 60 (1999) 1577.
[10] Y. Liu, P. Davis, T. Takiguchi, Physical Review E 60 (1999) 6595.
[11] S.P. Hegarty, G. Huyet, P. Porta, J.G. McInerney, Optics Letters 23 (1998) 1206.
[12] G. Huyet, P.A. Porta, S.P. Hegarty, J.G. McInerney, F. Holland, Optics Communications 180 (2000) 339.
[13] A. Hohl, H.J.C. van der Linde, R. Roy, Optics Letters 20 (1995) 2396.
[14] M.C. Eguia, G.B. Mindlin, M. Giudici, Physical Review E 58 (1998) 2636.
[15] W.-S. Lam, O.N. Gudar, R. Roy, International Journal of Modern Physics B 17 (2003) 4128.
[16] D.W. Sukow, J.R. Gardner, D.J. Gauthier, Physical Review A 56 (1997) R3370.
[17] J. Mørk, H. Sabbatier, M.P. Sørensen, B. Tromborg, Optics Communications 171 (1999) 93.
[18] J.F.M. Avila, H.L.D. de S. Cavalcante, J.R. Rios Leite, Physical Review Letters 93 (2004) 144101.
[19] R. Lang, K. Kobayashi, IEEE Journal of Quantum Electronics QE-16 (1980) 347.
[20] J.F.M. Avila, H.L.D. de S. Cavalcante, J.R. Rios Leite (Unpublished).