
COMMENTS

Comments are short papers which criticize or correct papers of other authors previously published in the Physical Review. Each Comment should state clearly to which paper it refers and must be accompanied by a brief abstract. The same publication schedule as for regular articles is followed, and page proofs are sent to authors.

Comment on “Andronov bifurcation and excitability in semiconductor lasers with optical feedback”

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In a recent paper [M. Giudici *et al.*, Phys. Rev. E **55**, 6141 (1997)] a new explanation is proposed for the so-called low-frequency fluctuation phenomenon occurring in the emission of semiconductor lasers in an external cavity. We argue that the experimental results of the commented paper do not conflict with existing theory, which has been thoroughly tested with experiments, and that the claims made are rather speculative. [S1063-651X(98)01409-3]

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In a recent paper [1] experimental results concerning low-frequency fluctuations (LFF) are reported. LFF occur when a semiconductor laser, pumped not too far above threshold, is subject to moderate amounts of delayed optical feedback from a distant reflector. LFF are characterized by a gradual buildup of the laser power over typically ten delay times, during which the power fluctuations increase until the power suddenly drops out to near zero and the process starts all over again. Since 1977 [2] the phenomenon of LFF has been a popular topic in the semiconductor laser and laser dynamics literature, as it has implications for both a practical and a fundamental understanding of semiconductor lasers: Weak feedback is most difficult to avoid in real systems, making it a very relevant issue for applications. The dynamics involved is potentially high dimensional (because of the delay effect), thus providing scientists with a rather easily accessible system to study high-dimensional optical chaos [3].

The main claims of [1] based on a phenomenological approach are that (i) noise plays a dominant role in LFF, (ii) LFF are the result of an Andronov bifurcation (the collision between stable fixed point and saddle point), and (iii) the semiconductor laser with optical feedback behaves as an excitable medium. In this Comment we argue that these claims cannot be made based on the experimental results. We will also argue that the experimental results in [1] fit well in the existing (and well-tested) theoretical explanation [4,5], which is not cited in [1]. We therefore briefly summarize it here.

After almost two decades of investigations on the manifestation and nature of the LFF phenomenon, it was shown by Sano [6] in 1994 that the standard Lang-Kobayashi (LK) equations [7] show LFF as a result of the merging of an attractor ruin of an external cavity mode and an antimode (saddle point). In order to verify this mechanism it was important that one of us could show [4] that before and after the

subsequent crisis, LFF in fact consists of irregular picosecond intensity pulses. This irregular pulsing behavior, underlying the LFF phenomenon, could be clearly demonstrated experimentally by us [5]. These observations are in very good qualitative and even quantitative agreement with the LK equations, also reported in [5]. The mechanism of the LFF can therefore be described as chaotic itinerancy with a drift: *En route* towards the minimum threshold state, i.e., the state where the laser benefits maximally from the feedback [8], the system shows chaotic multiattractor dynamics, while collisions of attractor ruins of destabilized compound cavity modes with antimodes exhibiting saddle-node instabilities cause the power dropouts.

In [1], the temporal resolution of the experiments is 500 MHz, which, in the best case, is barely enough to detect the fundamental round-trip time of the external cavity. In this case the round-trip frequency is between 300 and 1500 MHz. As is known from [5], important dynamical features have time scales up to several gigahertz. Thus relevant dynamics could not have been detected. This can be seen already from Fig. 2(b) of [1], where the power spectrum shows clearly frequency components corresponding to fast intensity dynamics. However, with respect to the time series in Fig. 2(a) of [1], the authors assume stable emission.

The analysis and interpretation of the experiments in [1] leave a few very important questions unanswered. The first analysis procedure is based on an averaging of the time evolution between consecutive dropout events exceeding a prefixed intensity threshold. It is then observed that in LFF fast oscillations between two events are washed out, leading to the conclusion that noise is dominating the dynamics. This notion is substantiated by plotting a histogram of the time between events. Whether the washing out of oscillatory structures in the LFF regime has any substantial implications is doubtful given the rigorous low pass filtering. We would

like to point out that similar histograms are obtained by numerically solving the LK equations, leading to the same scaling laws as were experimentally found in [9]. As was shown in Ref. [10], there are different regimes in parameter space concerning the effect of noise on the LFF characteristics. In a small region of parameter space (very close to threshold) noise has a large effect on the statistics of the power dropouts. This was tested by numerical integration of the LK equations with and without the inclusion of noise. Furthermore, the parameter range where noise is relevant in the experiments has been mapped by one of us and turns out to be small compared to the whole LFF regime [11,12]. The statement that noise is dominating the dynamics of LFF in general is therefore a rather crude simplification of the complete picture. The return map [Fig. 7(a) of [1]] shows a cloud of points, leading the authors of [1] to the conclusion that noise controls the dynamics. However, fully deterministic systems, such as systems exhibiting high-dimensional chaos induced by time-delay instabilities, also show these clouds.

In [1] it is argued that LFF arise through an Andronov bifurcation at the pump value separating regime I (constant intensity) from regime II (LFF). After observing that LFF are characterized by the existence of large intensity pulses (which means full LFF cycles), it is stated that “from a dynamical point of view, such behavior *may* correspond to a subcritical Hopf or an Andronov bifurcation” (emphasis by us). Thus the authors attempt to describe the LFF phenomenon in terms of limit cycle behavior (the large intensity pulses) born out of a bifurcation involving only one or two

fixed points. In this global dynamics picture, the conditions for a subcritical Hopf bifurcation were never observed in the experiment, while the properties of an Andronov bifurcation seem to fit the description qualitatively. An Andronov bifurcation takes place when saddle points collide with a stable fixed point. After the observation that such saddle-node collisions do not occur upon increasing the pump in the LK model, it is simply stated that a “better description than the LK equations is required.” In our opinion, this is a premature and unjustified denouncement of the LK model. In fact, it has not been demonstrated that the transition from regime I to regime II does *not* occur within the LK model. In [4,5] it is shown that these large pulsations, seemingly starting at a stable state, are the result of the rigorous low pass filtering. It is very doubtful that this experimental artifact necessitates a new theory. Before proposing a new explanation and interpretation of LFF, the authors should have made clear what experimental result in [1] conflicts with the existing (and thoroughly tested) theory.

We would like to point out that the results of the excitation experiments do not contradict the existing theory either. The amplitude of the current pulses is comparably large for the claimed excitation case [‘Fig. 3(c) in [1]]. Being 10 mA, i.e., even larger than the LFF regime (which typically spans 5 mA), it is not very surprising to kick the system in the direction of an antimode, thereby inducing a collision.

We conclude that the experimental results in [1] are in agreement with the existing theory [4–6] and do not necessitate a new explanation and interpretation.

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