On the mechanism of the LFF phenomenon in the coherence collapse of semiconductor lasers: There is hope for Sisyphus !

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ABSTRACT

The origin of Low Frequency Fluctuations (LFF), occurring for semiconductor lasers with delayed optical feedback from an external mirror, has been intensively discussed within the last ten years. One of the key questions has been whether the LFF are a deterministic or a noise induced phenomenon. We present experimental evidence for a deterministic mechanism by demonstrating the two major predictions of this model: irregular pulsing of the intensity on picosecond timescales underlying the LFF dynamics, and the existence of stable compound cavity modes with high gain within the LFF regime. We present a systematic investigation of the dynamical regimes with respect to both, feedback rate and injection current. We demonstrate that stable emission can indeed be achieved for a wide parameter range within the LFF regime.

Keywords: nonlinear dynamics, semiconductor laser, coherence collapse

1. INTRODUCTION

Semiconductor lasers are very sensitive to optical feedback. This fact is known for about twenty years[1] and has attracted a lot of interest since then. The sensitivity to feedback manifests itself in a sudden increase of the lasers spectral linewidth from about 100 MHz to typically several tens of GHz for delay times not much smaller than the relaxation oscillation period and for moderate feedback levels. Therefore, the name coherence collapse has been coined for these feedback effects[2] . In a lot of studies since then, it has turned out that underlying the linewidth increase a variety of dynamical phenomena occur (e.g.[3–7]). A very striking phenomenon within the coherence collapse which has attracted a lot of interest is the effect of irregular drop-outs of the laser intensity on micro- to nanosecond timescales, the so-called Low Frequency Fluctuations (LFF). This name originates from the fact that the time intervals between consecutive drop-outs are long compared to the other dynamical timescales involved in semiconductor laser dynamics like the frequency of the relaxation oscillations or the external cavity round-trip time.

During the last years, the mechanism underlying the LFF has been lively discussed. Considering the influence of noise, the LFF have been treated in terms of a first passage time problem[8,9] . A multimode traveling wave model has been proposed in[10,11] ,explaining the LFF phenomenon as a dynamical bistability. However, this model leaves the question open, whether the origin of the drop-outs is noise or deterministic fluctuations. Furthermore, the responsible mechanism has been attributed to cavity misalignment[12] . In[13] it has been shown that the statistics of the drop-outs and its current dependence is consistent with those of deterministic intermittency phenomena. Very recently, some of the problems concerning the models mentioned above have been discussed by considering the statistics of the LFF power drop-out events[14] .

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In 1994, the LFF have been attributed to another deterministic mechanism linked to chaotic itinerancy with a drift.[15] This deterministic explanation of the LFF which was later extended by van Tartwijk et al.[16] is based upon an analysis of the Lang-Kobayashi equations[1] , i.e. two coupled delay-differential equations describing a single-mode semiconductor laser subject to weak or moderate optical feedback from an external cavity.

In this paper, we present experimental evidence for the latter deterministic mechanism by demonstrating an irregular pulsing behavior on picosecond timescales underlying the LFF dynamics, and furthermore, the coexistence of LFF behavior and stable emission on a compound cavity mode with high gain. These experimental results coincide with theoretical predictions made by[16,17] on the basis of the deterministic model. Furthermore, we present a systematic investigation of the dynamical behavior of the system in dependence on the two for the dynamics of the system most relevant parameters, the injection current and the optical feedback strength. By varying these two parameters over a wide range, we have obtained a phase space diagram mapping the different dynamical regimes of the system. In particular, three different dynamical regimes can be identified: the LFF regime, the regime of coexistence of LFF and stable emission, and the regime of fully developed coherence collapse. Finally, we discuss the influence of noise on the switching to a state of stable emission and on the respective escape time from such a stable mode.

The analysis of the Lang-Kobayashi equations shows that the eigenmodes of the system consisting of the semiconductor laser cavity and the external cavity always occur in pairs of fixpoints. One solution corresponds to constructive interference of the coupled cavities and is usually referred to as compound cavity mode, the other solution corresponds to destructive interference of the coupled cavities and, thus, is called anti-mode. The strong nonlinearities of the semiconductor material, as expressed by the linewidth-enhancement factor[18] , make the various compound cavity modes and anti-modes lie on an ellipse around the solitary laser mode in the frequency-inversion space[16] : a linear stability analysis shows, that the modes and anti-modes are destabilized for a wide feedback range, the anti-modes via a saddle-node instability, the modes via Hopf-bifurcations, except for at least one mode on the low-frequency, high-gain side of the ellipse which always remains stable[17] . According to the deterministic model, the chaotic itinerancy takes place along the attractor ruins of the destabilized compound cavity modes with a drift towards the stable high-gain mode. Linked to this dynamics is the emission of irregular picosecond-pulses[16,19] which build up during the itinerancy. However, as the trajectory itinerates towards the high gain part of the ellipse the attractor ruins of the modes and the anti-modes approach and a crisis occurs: the trajectory hits an anti-mode. The characteristic drop-outs of the emitted power, then, are associated with such a crisis bouncing the trajectory away from its moving drift towards one of the stable high gain modes and reinjecting the trajectory into the lower gain part of the ellipse. This is the reason why van Tartwijk et al. coined the name 'Sisyphus effect' for the LFF dynamics[16] . In the following the experiments will be discussed which give evidence for this deterministic mechanism. The experiments will also show that stable emission can be reached under some conditions and thus, that 'there is hope for Sisyphus'.

2. EXPERIMENTAL SETUP

The experiments have been performed using a bulk GaAs/GaAlAs laser (Hitachi HLP 1400) emitting light at $\lambda = 840$ nm. This type of laser diode with its parameters and dynamical properties is the most studied in experiments on external optical feedback. In fact, most of the model calculations and experimental investigations concerning the coherence collapse and, in particular, the LFF regime have been done for this type of laser diode. Figure 1 shows the experimental setup. The laser diode is driven by an ultra low noise dc-current source, the temperature is stabilized to better than 0.01 K. On the right hand side of the laser diode (LD) we have depicted the external cavity. It is realized by an AR-coated microscope objective (MO) which collimates the beam, a high reflection mirror of interferometric flatness better than $\lambda/200$,

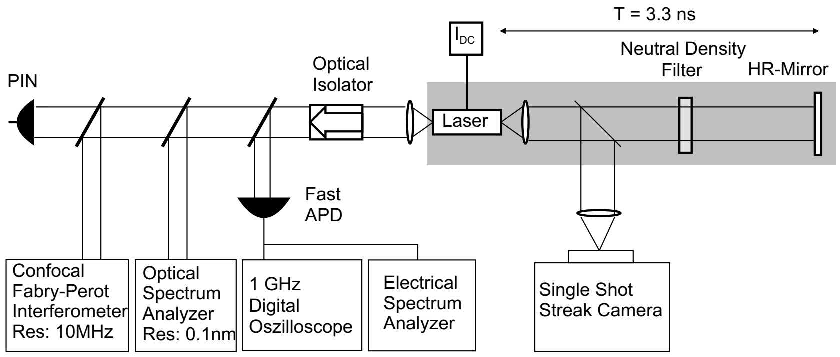

Figure 1. Experimental set-up, depicting with a grey background the external cavity configuration, and the detection scheme

and a neutral density filter to vary the optical feedback strength. The delay time τ of the external cavity amounts to $\tau = 3.3\,ns$ which corresponds to an external-cavity mode spacing of 300 MHz. Optionally, an etalon with a transmission FWHM of $5nm$ can be placed within the external cavity to restrict the emission to mainly one longitudinal diode mode. The time averaged laser intensity is measured by a slow p-i-n photodiode. Both, the time series of the intensity and the optical spectrum of the laser are simultaneously measured with two different resolutions in order to account for the wide temporal and optical scales of the investigated dynamics. The intensity dynamics is detected by a single-shot streak camera system and a fast avalanche photodiode (APD) with larger than 3 GHz bandwidth. The power spectrum of the APD signal is recorded by an electrical spectrum analyzer of 0.1 kHz to 21 GHz bandwidth. The corresponding time series are low-pass filtered with the cut-off frequency at 1 GHz and detected by a fast digitizing oscilloscope of the same bandwidth. The streak camera system allows to highly resolve the temporal dynamics with $10ps$ resolution and within time windows of up to $7.3ns$ total length. These so obtained time traces contain single shots of the intensity dynamics detecting the whole relevant bandwidth from dc-levels up to $\sim 100GHz$. The optical spectrum is detected by a grating spectrometer with a resolution of 0.1 nm in order to resolve the longitudinal diode modes, and a confocal scanning Fabry-Pérot interferometer to resolve the compound cavity modes. The free spectral range of the interferometer amounts to 2 GHz, which corresponds to a resolution of 10 MHz. The optical isolator shields the laser from unwanted reflections from the detection branch.

3. EXPERIMENTAL RESULTS AND DISCUSSION

Before we discuss the dynamical behavior of the semiconductor laser with feedback, the influence of the feedback on the L/I-characteristic is described. Fig. 2 depicts the L/I-characteristic, showing the emitted power versus the injection current for the solitary laser and the laser with moderate amount of optical feedback. The effect of the feedback is twofold, first the threshold current is reduced with respect to the

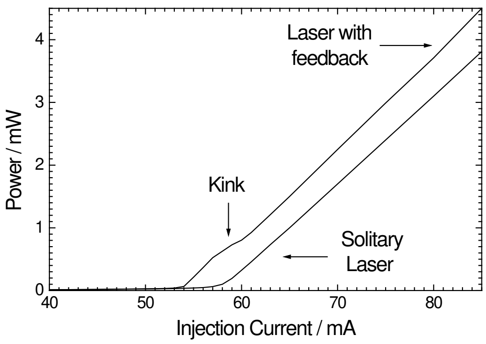

Figure 2. Emitted power versus injection current for a semiconductor laser without and with optical feedback

solitary laser, here by $\sim 6\%$, second, a pronounced kink of the L/I curve in the vicinity of the solitary laser threshold occurs. Typically, the LFF dynamics can be found for injection currents around this kink. Fig. 3 depicts a $500ns$ long time series of the laser intensity obtained with the fast photodiode and the fast digitizing oscilloscope for an injection current of $I = 60.0mA$ corresponding to 1.04 times the solitary laser threshold $I_{th,sol}$. It shows the typical irregular behavior with fast drop-outs of the intensity and a

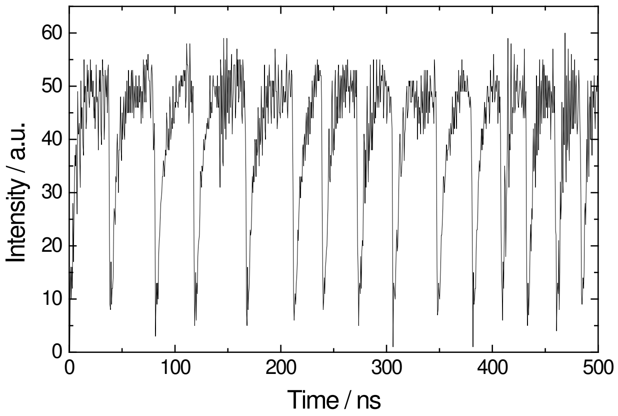

Figure 3. Typical LFF dynamics obtained for $I = 60.0mA$ with the $1GHz$ digitizing oscilloscope

somewhat slower relaxation back to higher intensities. The times in between the drop-outs depend strongly on the injection current, decreasing for increasing current, ending up in a dynamical regime where different drop-out events cannot be distinguished anymore, the so-called fully developed coherence collapse. As has been demonstrated recently, the resolution of the detection with a bandwidth of $1GHz$ hides faster dynamics underlying the behavior shown in Fig.3[19] . With the single-shot streak camera an irregular pulsing behavior on picosecond timescales can be found confirming the prediction of[16] . Fig. 4 depicts a typical streak camera trace, also obtained for an injection current of $I = 60.0mA$. It shows separate pulses with a

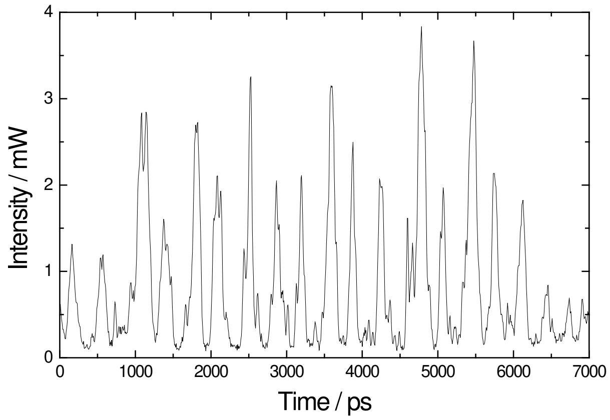

Figure 4. Typical pulsing behavior within the LFF regime obtained for $I = 60.0mA$ with the single-shot streak camera

temporal width of $50..200ps$ and a pulse separation of typically $200ps..1000ps$. In between the pulses the intensity breaks down to nearly zero. The property of the streak camera to detect the huge bandwidth from dc to $\sim 100GHz$ allows even to absolutely scale the power of the pulses. This pulsing behavior is typical for the whole dynamical process of the LFF. This is confirmed by Fig. 5 which depicts a statistics how often different intensities are emitted by the laser. It has been obtained by analyzing 20 arbitrarily triggered

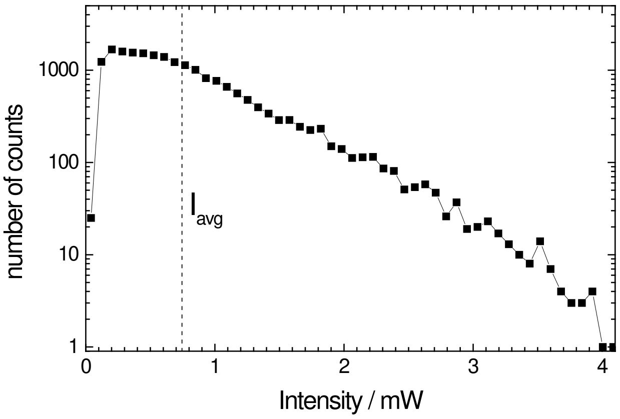

Figure 5. Statistical distribution of the different intensity values which are emitted by the laser. The dotted line denotes the average intensity.

streak camera traces and thus getting a statistics over about 20,000 intensity values. The statistical diagram shows a maximum at very low intensities and then a monotonuously decreasing distribution confirming two main dynamical properties: first, the very low intensities are pronounced indicating the sustained pulsing behavior, with nearly zero intensity in between the pulses, and the existence of high pulse intensities up to five times the average intensity. This statistical distribution shows a qualitatively similar behavior for the whole current range in which the LFF occur and even for the fully developed coherence collapse. These results are in very good agreement with the predictions of the deterministic model.[16]

Besides the fast pulsing behavior, the second major prediction which has been made based on the analysis of the Lang-Kobayashi equations is the existence of stable compound cavity modes. A stability analysis yields that the maximum gain modes and possibly a few neighbouring modes are stable.[17] Thus, a key question in this context is: do stable modes exist and if they do, how long are the escape times from it ? The answers to these questions clarify in how far the assumption of a deterministic mechanism holds and if the treatment of the LFF in terms of a first passage time problem is justified. In order to answer these questions experimentally we have extended the experiment in the following way. We have build up an interferometically stable cavity with a feedback mirror of interferometric flatness better than $\lambda/200$. The feedback strength γ is adjusted using a high precision variable neutral density filter. Subsequently, the injection current I is increased starting below threshold over the whole accessible range. The resulting dynamical behavior is investigated and classified in dependence on the injection current. Repeating this procedure for several different values of feedback strength, we have obtained a map of the dynamical behavior of the semiconductor laser subject to optical feedback in the γ-I-space, which is depicted in Fig. 6. Increasing the injection current along the vertical dotted line from "A" to "B" as depicted in Fig. 6 corresponding to a relative feedback strength of 0.3, one reaches every dynamical regime present in the γ-I-space: After passing the feedback reduced laser threshold, the system enters a regime of stable emission on one longitudinal diode mode and several external-cavity modes. The mode beatings of the external-cavity modes appear as sharp peaks in the power spectrum. The LFF regime is reached by increasing the injection current by approximately 3 mA. There, a dominant low frequency contribution builds up in the power spectrum; the compound cavity mode beatings broaden significantly. Increasing the injection current further, the time intervals between the drop-outs decrease, giving rise to the behavior depicted in Fig. 3. Finally, a continuous transition to the fully developed coherence collapse takes place accompanied by a broad power spectrum and completely irregular intensity time series. The most striking aspect of this phase space diagram is the existence of a large region within the LFF regime, where discrete transitions

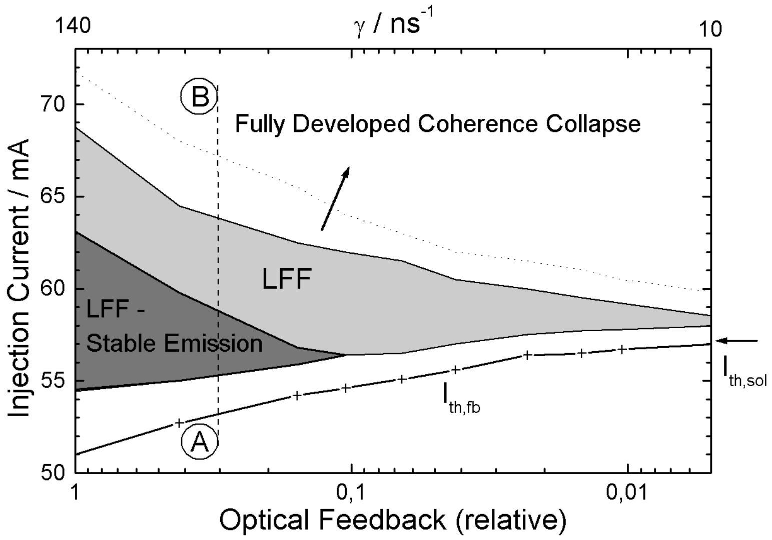

Figure 6. Phase space diagram: dynamical regimes depending on amount of feedback and injection current

between LFF and stable emission occur.

In the following, we will discuss this coexistence region embedded in the LFF regime. Fig. 7 depicts one typical transition from the LFF state to the stable emission state occurring at the time of $3\,\mu$s. In

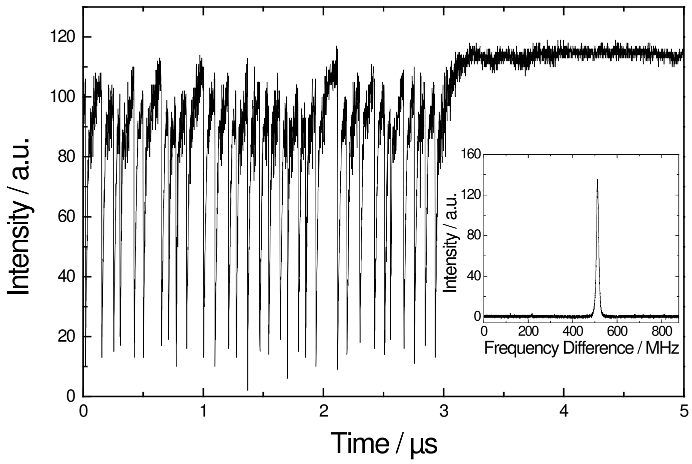

Figure 7. Typical transition from LFF dynamics to stable single mode emission: dynamics detected by the fast photodiode. The inset shows the Fabry-Perot spectrum for stable emission.

order to verify that the stable emission state corresponds to a single compound cavity mode with high gain, we have characterized the emission in the stable state. First, we find that the intensity of the laser stabilizes on a higher level than the LFF. Accordingly, the transition to stable emission is characterized by a sudden increase in the time averaged intensity, which is recorded by the p-i-n photodiode. Second, the power spectrum shows no components and is found to be completely flat. Third, in the Fabry-Pérot spectrum we find one single peak indicating emission on a single compound cavity mode. The inset of Fig.7 depicts the optical spectrum of the stable emission state showing a single sharp peak whose width is limited by the resolution of the Fabry-Pérot interferometer only. The escape times from such a stable mode can exceed one minute which is more than 10^8 times longer than the typical time intervals between two subsequent LFF events under identical conditions. Thus, we have demonstrated that a semiconductor laser subject to optical feedback can remain stable on a single high-gain compound cavity mode within the LFF regime for very long times. This measurement gives evidence for the existence of the stable high gain modes which has been predicted in[17] . The trajectory of the system reaches the stable mode after its chaotic intinerancy. And so, despite greek mythology, "There is hope for Sisyphus: he can reach his goal and remain there".

The stable states prolong for stronger feedback and higher injection current. Only for a very small regime of a few tenth of mA above laser threshold the escape times are comparable to the time interval between two subsequent LFF events. Increasing the injection current, the periods of stable emission prolong by several orders of magnitude, while the time intervals between the LFF drop-outs shorten. This means, on the one hand, that in the parameter region very near to threshold the spontaneous emission noise can kick the trajectory off the stable mode as it is described in[9] . For higher currents, on the other hand, the escape times from the stable modes by far exceed the time intervals between consecutive drop-outs. We interprete this observation such, that the influence of the spontaneous emission noise is reduced with increasing current and, thus, does only very rarely suffice to push the trajectory away from the stable mode. If the trajectory is ejected from the stable mode by an external perturbation or noise, the system undergoes a large number of LFF cycles before it returns to one of the stable modes by itself. For high injection currents within the coexistence regime the stable modes are reached only very rarely. However, if stable emission occurs, the escape times become very long. This behavior indicates that the probability to reach the stable mode in this parameter region is reduced with increasing injection current. Nevertheless, the trajectory can remain on the stable mode, because the level of the spontaneous emission noise is too low to kick the trajectory off the stable mode. Outside the coexistence region, finally, the trajectory does not reach the stable mode any more and the system shows nothing but LFF behavior. To sum up, the relative duration of the stable emission state and the LFF state strongly varies with the position of the system in γ - I - space.

An open question is still, if the transition from the LFF dynamics to a stable mode can happen deterministically or if noise is necessary to reach it. We have performed model calculations without noise, using a modified Lang-Kobayashi model which incorporates the lateral dimension of the active area[21] . We find that in certain parameter ranges transitions to a stable mode can indeed occur after a long period of LFF and that the system can even stay in that mode permanently. This is illustrated by the temporal evolution of the round-trip phase difference $\Delta(t)$. The compound cavity modes appear as integer multiples of $\Delta(t)/2\pi$ and thus, the drop-outs and the drift along the ellipse is manifested in the dynamics of Δ. Fig. 8 depicts a $600ns$ long time window of the temporal evolution of Δ, obtained for $I = 1.15 I_{th,sol}$, $\gamma = 0.1$ and $\tau = 1.0\,ns$. At $t = 700ns$ the transition to the stable high gain mode which corresponds to the largest

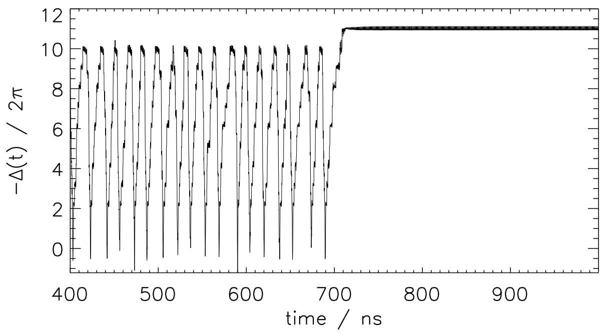

Figure 8. Modelled dynamics of the round-trip phase difference showing a transition to a stable mode

value of $\Delta(t)/2\pi$ can be recognized. Thus, we can demonstrate that the transition to a stable compound cavity mode with high gain might even occur without noise.

We have performed the experiments presented in this paper without and with an etalon placed within the external cavity[20] . Without the etalon the optical spectrum exhibits various longitudinal modes of the solitary laser in the LFF regime. With the intracavity etalon the emission is dominated by only one diode mode even within the LFF regime. We have generated the same phase space diagram for the different dynamical regimes and we have found some slight quantitave but no qualitative changes. Shape, size, and position of the various dynamical regions in the γ - I - space including the coexistence regime remain essentially unchanged. We interpret this such, that the various diodes modes are excited by the strongly fluctuating intensity with the drop-outs and the picosecond-pulsing, however, these modes play only a passive role for the LFF dynamics and are not essential for its explanation.

4. CONCLUSIONS

In conclusion, we have presented experimental results that give evidence for the deterministic 'Sisyphus effect' as the relevant mechanism causing the Low Frequency Fluctuations in semiconductor lasers subject to optical feedback. Our experiments show that underlying the well-known LFF phenomena on nanosecond to microsecond timescales is an irregular pulsing behavior on picosecond timescales. The picosecond pulsing behavior dominates the dynamical behavior as has been shown by an intensity statistics over 20 arbitrarily triggered streak traces. Thus, we have demonstrated one main feature of the mechanism, interpreting the LFF as chaotic itinerancy with a drift. Furthermore, we could give evidence for the existence of stable compound cavity modes with high gain within the LFF regime. These modes have also been predicted based on an analysis of the Lang–Kobayashi equations. We can experimentally demonstrate the existence of these stable modes. By performing systematic investigations of the dynamical regimes depending on the injection current and the amount of optical feedback we find that the coexistence of stable emission and LFF occurs for wide parameter ranges. Both, the importance of spontaneous emission noise and the probability to reach the stable mode strongly vary over the coexistence region. We find that the escape times from the stable modes can exceed minutes which is many orders of magnitude longer than the drop-out typical separation. Thus, we give evidence for two major predictions of the deterministic model and conclude, that, though noise can modify the dynamical behavior in some parameter regimes, it is not crucial to explain the the LFF phenomenon.

5. ACKNOWLEDGEMENTS

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