Experimental demonstration of suppression of low-frequency fluctuations and stabilization of an external-cavity laser diode

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Received December 22, 1999

We demonstrate experimentally all-optical stabilization of a single-mode laser diode subject to external optical feedback operating in the low-frequency fluctuations (LFF) regime, by the technique of applying a second delayed optical feedback. We interpret our results as suppression of LFF through destruction of the antimodes responsible for the LFF crises and stabilization of the laser through creation of new maximum gain modes, in agreement with recent theoretical predictions. © 2000 Optical Society of America

OCIS codes: 140.1450, 140.2020, 140.5960, 190.3100.

When they are subjected to external optical feedback, semiconductor lasers exhibit a large variety of dynamic instabilities, including coherence collapse[1] and low-frequency fluctuations (LFF's),[2] which can lead to severe degradation of their temporal characteristics and increase their typical optical linewidths from 100 MHz to several tens of gigahertz. The LFF regime is typically observed when laser diodes are pumped near threshold and subjected to moderate optical reinjection from a distant reflector. The dominant features of this instability are sudden dropouts of the optical power, followed by gradual, stepwise recoveries that occur at aperiodic intervals, leading to a dramatic increase in low-frequency noise in the rf spectrum. Sano[3] showed through analytical and numerical investigation of the Lang–Kobayashi equations[4] that LFF power dropouts are due to crises between external-cavity modes and antimodes, leading to collisions of the system trajectory in phase space with the saddle-type antimodes. Each dropout is preceded by a chaotic itinerancy of the trajectory among attractor ruins of external-cavity modes, with a drift toward the maximum gain mode.

The idea of using a second delayed optical feedback was initially proposed as a means to stabilize a chaotic laser diode pumped far above threshold in the coherence collapse regime.[5] Rogister *et al.*[6] investigated this scheme theoretically at pumping levels near threshold, paying close attention to the steady-state solutions. Relying on Sano's deterministic theory of LFF in a single-mode laser diode,[3] this method uses the second, delayed optical feedback to suppress LFF by destroying the antimodes that are responsible for the LFF crises or by pushing them far away from the external-cavity modes, with the consequence that the dropouts can no longer occur. Stabilization is also achieved as the laser locks onto new, stable maximum gain modes that are created as the second-feedback strength increases. Important advantages of this method are that one can apply it, unlike most existing control or stabilization techniques, without changing any parameters of the laser or the first external cavity.

In this Letter we describe what is believed to be the first experimental realization of this technique. We show that LFF is suppressed by destruction of the antimodes that are responsible for the crises and that the laser is stabilized by creation of new, stable maximum gain modes, in agreement with the theoretical results presented in Ref. 6.

In the experiment we use a laser diode (SDL 5301) operating at $\lambda = 780$ nm. The laser is biased at a pump current of $I = 25.0$ mA, just below solitary threshold. As illustrated in Fig. 1, the laser beam is collimated by a lens (CL) and directed to a holographic grating (GR). The zeroth order of the grating is used to monitor the system's behavior. The grating's first-order beam goes into the double cavity, which is formed by a nonpolarizing beam splitter (NPBS) and two 99%-reflectivity mirrors. The double-cavity system (contained within the dashed box) is protected

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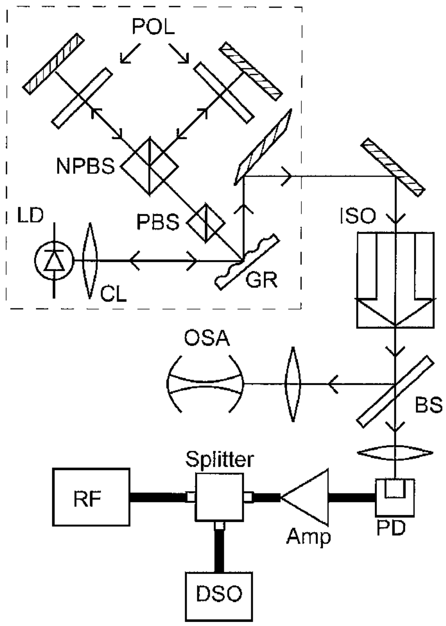

Fig. 1. Experimental setup. See text for definitions.

from parasitic feedback from the detection branch by a optical isolator (ISO). External-cavity optical lengths are $L_1 = 21$ cm and $L_2 = 19$ cm, respectively. The grating narrows the cavity bandwidth to 50 GHz, causing the laser to oscillate in a single solitary laser mode. The laser output is monitored by a scanning Fabry–Perot interferometer [OSA (Newport SR-240C; free spectral range, 2000 GHz; finesse, $>17,000$)] and a fast ac-coupled photodiode [PD (Hamamatsu C4258; 8-GHz bandwidth)]. The photodiode signal is amplified and connected to a 500-MHz bandwidth digitizer (DSO; Tektronix RTD 720) and a rf spectrum analyzer [RF (Hewlett-Packard HP 8596E)]. The feedback strengths of each external cavity are controlled independently by a polarizing beam splitter (PBS) and two polarizers (POL). The feedback strengths are characterized through the fractional threshold reduction $\Delta I = (I_{\mathrm{th}} - I)/I_{\mathrm{th}}$ that is induced by each cavity acting alone. This choice is convenient because experimental fractional threshold reductions can be directly compared with theoretical normalized feedback strengths.

Figure 2 shows the experimentally observed optical spectra as a function of ΔI_2, the threshold reduction that is due to the second cavity only. The horizontal axis has its origin at the frequency of the first mode that lases, as the strength of the first feedback increases from zero when there is no second feedback. In the figure the strength of the first feedback is fixed so that it corresponds to a threshold reduction of $\Delta I_1 = 7.1\%$, such that the laser displays LFF in seven external-cavity modes when it is not subjected to a second feedback [trace (a)]. Increasing slightly the strength of the second feedback [$\Delta I_2 = 0.44\%$; trace (b)] results in stabilization of the sixth external-cavity mode of the first cavity. The limited resolution of the Fabry–Perot interferometer, however, does not allow us to measure the linewidth of this stable mode. We attribute this first stabilization to the destruction of the antimode that is responsible for the LFF crises since, in this case, we do not observe a large frequency shift to lower frequencies as has been numerically observed when the laser locks into a new maximum gain mode.[6] For $\Delta I_2 = 1.58\%$ [trace (c)], the system loses stability and once again displays LFF. For a threshold reduction of $\Delta I_2 = 6.42\%$ [trace (d)] the optical spectrum exhibits two peaks, and the rf spectrum reveals that they are associated with periodic oscillations. Increasing further the second-feedback strength [trace (e)], we find that the system exhibits complex dynamics until $\Delta I_2 = 10.4\%$ [trace (f)], at which the laser again becomes stable. We interpret this as a locking of the system onto a newly created, stable maximum gain mode that is well separated in frequency from the original seven external-cavity modes of the first cavity. Further increases of the second-feedback strength lead to a continuation of this pattern, with stabilization of increasingly distance modes interspersed with regions of complex behavior, in agreement with the theoretical predictions.[6]

Time series and rf spectra that correspond to the first two steps in the bifurcation cascade are shown in Figs. 3 and 4. When the laser is subjected to the first optical feedback only, the power clearly exhibits strong dropouts [Fig. 3(a)], and the rf spectrum presents peaks at multiples of the first external-cavity frequency [Fig. 3(b)]. When the laser is stabilized by the second feedback, the intensity shows only small fluctuations that are caused by spontaneous-emission noise [Fig. 4(a)], and the rf spectrum is flat [Fig. 4(b)].

We have observed that the control of the method is robust, limited only by the mechanical stability of the system. In agreement with theory,[6] the method works for every first-feedback strength that is accessible in our experiment. Thus the method should not be affected by the addition of absorptive elements inside the first cavity. The method also works for a broad

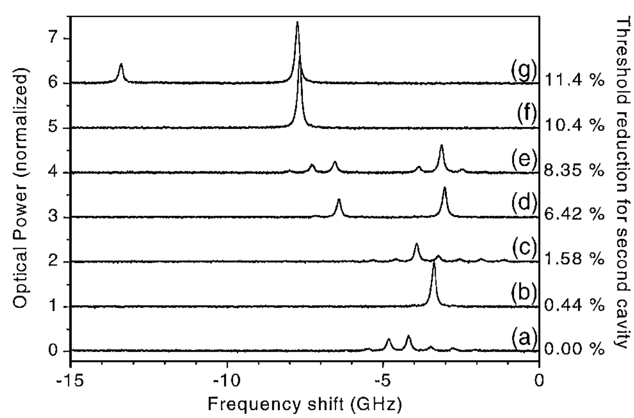

Fig. 2. Experimental optical spectra measured in double-cavity configuration as a function of threshold reduction ΔI_2 owing to the second-feedback strength. (a) LFF is observed in the absence of the second feedback. Increase of the second-feedback strength leads to stabilization [(b) and (f)] interspersed with unstable regions [(c)–(e) and (g)]. The optical spectra have been normalized with respect to the maximum of trace (b).

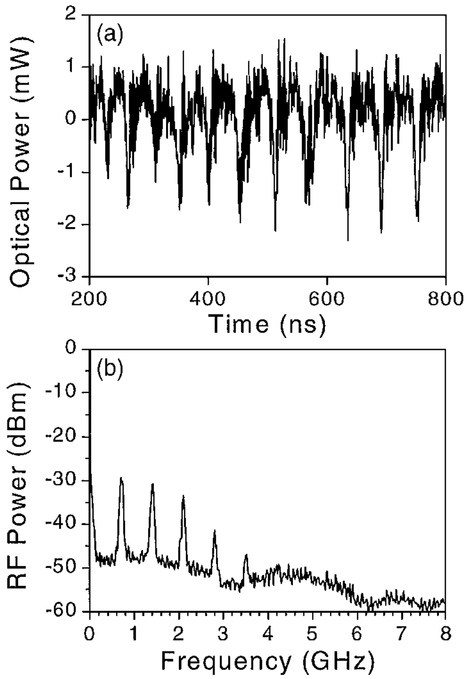

Fig. 3. LFF is observed in the absence of a second optical feedback ($\Delta I_2 = 0$). (a) Fluctuations of the optical power around its average. (b) rf spectrum.

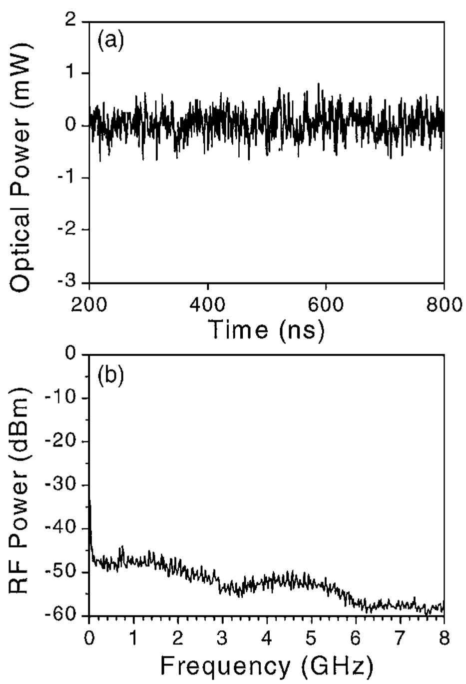

Fig. 4. Stabilization of the laser by the second optical feedback ($\Delta I_2 = 0.44\%$). (a) Fluctuations of the optical power around its average. (b) rf spectrum.

range of cavity lengths. Dispersive elements, which affect the optical lengths, can therefore be added to the cavities.

Every feature observed in the theoretical bifurcation cascade [Fig. 2(b) in Ref. 6] is also observed experimentally here (Fig. 2), despite the differences in cavity length and first-feedback strength between the two cases ($L_1 = 15$ cm, $L_2 = 3$ cm, and $\kappa_1 = 4.6 \times 10^{-3}$ in Ref. 6). Moreover, by varying the first-feedback strength in our experiment and by varying not only the first-feedback strength but also the lengths of the two cavities in our simulations, we have found that the strengths of the second feedback that are needed to stabilize the laser for the first time are in every case small and comparable: For instance, $\Delta I_2 = 4.4 \times 10^{-3}$ in this study and $\kappa_2 = 3 \times 10^{-3}$ in Ref. 6. By contrast, the successive regions of stability are broader when the cavity lengths are close, as can be illustrated by comparison of our Fig. 2 with Fig. 2(b) of Ref. 6

In conclusion, we have demonstrated experimentally all-optical stabilization of LFF by use of a second-optical feedback, which suppresses LFF through destruction of antimodes that are responsible for the crises and stabilizes the laser through creation of new maximum gain modes. Our experimental results are in good agreement with theoretical analysis. This technique is remarkable in that it does not require modification of the laser or the first optical feedback parameters. Furthermore, stabilization can in principle be achieved regardless of the strength of the first feedback.

This work was funded by the Inter-University Attraction Pole program (IAP IV/07) of the Belgian government. D. W. Sukow acknowledges the support of the National Research Council and the U.S. Air Force Office of Scientific Research. F. Rogister's e-mail address is Rogister@telecom.fpms.ac.be.

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