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Low-frequency fluctuations and polarization dynamics in vertical-cavity surface-emitting lasers with isotropic feedback

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We investigate experimentally the polarization dynamics in vertical-cavity surface-emitting lasers exposed to isotropic time-delayed optical feedback. The existence of low-frequency fluctuations with and without the simultaneous excitation of polarization degrees of freedom is demonstrated. The appearance of polarization dynamics is shown to depend on the magnitude of the intrinsic dichroism of the device under study. If there is no polarization dynamics, low-frequency fluctuations of a single mode are observed.

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Semiconductor lasers have become one of the most important tools of today's information technology. Nevertheless, many features of these lasers are still not or only partially understood, with the behavior of a semiconductor laser exposed to optical feedback being one of these. In many applications, for example, fiber coupling, a nonnegligible amount of feedback is produced nearly inevitably [1]. Therefore, the understanding of semiconductor lasers under optical feedback is of great importance from a point of view of applications.

A semiconductor laser exposed to optical feedback is also a system of interest from the point of view of fundamental research, since it exhibits a broad variety of nonlinear dynamical behavior (see the contributions in Ref. [2]). One of the most intensely studied phenomena are the so called *low-frequency fluctuations* (LFF), observed first by Risch *et al.* [3]. These fluctuations manifest themselves as sudden dropouts followed by continuous recoveries in the output power of a semiconductor laser with time-delayed feedback at constant current. The term ''low frequency'' is hinting to the fact that the frequency of these fluctuations is slow compared to the characteristic time scales of the semiconductor material. The underlying structure of the slow dynamics has been shown to consist of fast pulsations on the time scale of the external cavity round-trip time and of irregular pulsations on a picosecond time scale [4–8].

The LFF have often been modeled using the Lang-Kobayashi equations [9–11], which describe the coupled dynamics of a single-mode laser field that is subjected to delayed optical feedback from an external mirror and the carrier density. In edge-emitting lasers, it has been shown experimentally that many of the longitudinal modes of the solitary laser are excited [5,12] when the LFF occur. The authors concluded that the description of the LFF by a single mode model is not appropriate. But also the observation of LFF of only one longitudinal mode has been reported if the dynamics was restricted to a single longitudinal mode by inserting an etalon into the external cavity [8,13] or by using a distributed-feedback laser [14]. These investigations motivated theoretical studies yielding the possibility of in-phase as well as out-of-phase dynamics of the involved modes [8,15]. However, in an edge-emitter the situation is very complicated, since many longitudinal modes might become active.

Vertical-cavity surface-emitting lasers (VCSELs) are rather novel devices with a very short cavity [16]. Hence, VCSELs operate in only one longitudinal mode. However, due to slight imperfections of the rotational symmetry of VCSELs, two orthogonal polarization modes with slightly different frequencies can exist [17,18]. Polarization selection and polarization competition was studied in free-running devices [17–19] and in devices with optical feedback [21,20]. If one restricts the experiments to regimes where no higher-order transverse modes are excited, there is the possibility of studying feedback-induced dynamics in a rather simple situation of single-mode or two-mode operation. In a former experiment [22] with isotropic feedback, LFF of the total power have been observed, with the dynamics of the two orthogonal polarized modes being in antiphase on a slow time scale. However, due to the restricted analog bandwidth of the experimental setup those investigations did not resolve the dynamics on time scales of the external cavity round-trip time and dependencies of the dynamics on the device parameters were not investigated in detail.

In this paper, we show that the dynamics of the polarization degrees of freedom during the LFF is strongly influenced by the differences in the gain-to-loss ratio of the two polarization components. This *amplitude anisotropy* or *dichroism* selects which polarization mode is the lasing mode at threshold in the solitary laser [17].

The experimental setup is shown in Fig. 1. The VCSELs investigated are gain-guided devices with an aperture diameter of 8 μm from EMCORE Corp. The emission is in the

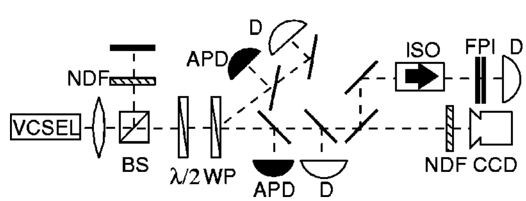

FIG. 1. Scheme of the experimental setup. For explanations see text.

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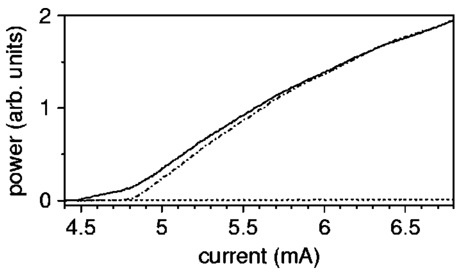

FIG. 2. Time averaged, polarization resolved power against current for a VCSEL with a large dichroism. Solid (dash-dotted) lines denote the mode with lower optical frequency with (without) feedback. The power of the mode with higher optical frequency is displayed by the dashed line for both cases. The feedback strength is −10 dB.

fundamental transverse mode up to more than two times the threshold current. The emission wavelength is around 845 nm. In order to stabilize and control the temperature, the lasers are mounted on a copper plate that is attached to a thermoelectric cooling system. The light is collimated by an aspheric, antireflection coated lens. A nonpolarizing beam splitter (BS) directs a fraction (66%) of the output power onto a highly reflective mirror that forms the external cavity. The external cavity round-trip time is 3 ns. The ratio of the light reflected back into the VCSEL is controlled by means of neutral density filters (NDF). The external mirror and the position of the collimation lens are adjusted to obtain mode-matched feedback. By measuring the Stokes parameters in each output branch of the BS, we confirmed that the polarization properties of the light in the external cavity is not altered by the BS. The output light of the VCSEL is split by a half-wave plate ($\lambda/2$) and a Wollaston prism (WP) into its orthogonal polarization components. In each branch after the WP, the power is measured by a low-bandwidth detector (D) and an avalanche photodiode (APD) with 1.8 GHz analog bandwidth. Time traces were obtained with a digital oscilloscope of 1.1 GHz analog bandwidth (sampling interval 125 ps) and rf spectra with a spectrum analyzer of 26 GHz bandwidth, respectively. The spectral characteristics are measured with a scanning Fabry-Perot interferometer (FPI) with a finesse of 200 and a free spectral range of 46 GHz. To avoid unintended back reflections into the VCSEL, an optical isolator (ISO) is placed in front of the FPI. The near field intensity distributions are observed with a camera.

Figure 2 shows the polarization resolved light-current characteristic (LI curve) of one of the devices under study with and without isotropic feedback. Due to birefringence, the orthogonal polarization modes of the VCSEL are frequency split [17,18,23]. In the device investigated in Fig. 2, the birefringence is 14 GHz and the mode with lower optical frequency is operating in the free-running mode and with feedback. In both cases, the mode with higher optical frequency is not lasing, i.e., the feedback does not change the lasing mode of this laser. The main axis and the ellipticity of the state of polarization of the lasing mode is not altered. For the case with feedback, we observe a reduction of the lasing threshold. The slope of the LI curve changes at the solitary laser threshold. By a measurement of the optical spectrum at

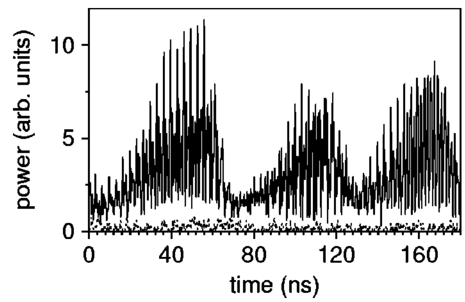

FIG. 3. Time series of the polarization resolved power at 4.59 mA (see Fig. 2).

lasing threshold one can extract the intrinsic dichroism, which is given by the difference of the linewidths of the lasing mode and the nonlasing mode [18], which can be observed due to amplified spontaneous emission. This method reveals a large dichroism of 4.5 GHz for the device studied in Fig. 2.

Directly at the reduced lasing threshold the laser output power is already fluctuating, but it is difficult to recognize a characteristic structure. The amplitude of the fluctuations grows continuously, if the current is increased. At an injection level of typically a few percent above the reduced threshold pronounced power drops followed by a slow recovery are present. Figure 3 shows an exemplary time trace. The characteristic features of this time trace resemble the shape of typical LFF occurring in edge-emitting semiconductor lasers (e.g., [2] and references therein). The power builds up on a time scale of ≈60 ns and then drops suddenly. The underlying structure of this slow dynamics consists of peaks of increasing height which are separated by the external cavity round-trip time (3 ns). The rf spectrum shows peaks at multiples of the external cavity frequency and a strong peak around 20 MHz corresponding to the LFF (Fig. 4), which is an indication for rather periodic dynamics on the slow time scale. The frequency of the peak corresponding to the LFF frequency is moving to higher values for increasing current, i.e., the duration of one LFF cycle shrinks.

In between the large-amplitude pulses separated by the external cavity round-trip time, peaks of lower amplitude exist. The separation of the latter ones is less than 1 ns. The corresponding frequency is at the limit of the bandwidth of our experimental setup, thus we cannot give definite information on their exact temporal development. The rf spectra (Fig. 4) indicate that there is dynamics on time scales below 1 ns. The latter is known for edge-emitting lasers [4–7].

The power in the polarization corresponding to the mode

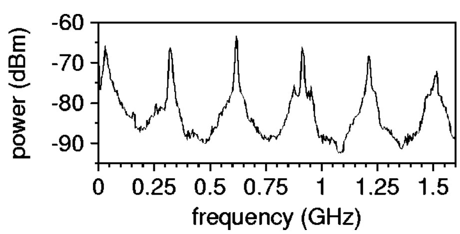

FIG. 4. rf spectrum of the mode with lower optical frequency corresponding to the time trace of Fig. 3.

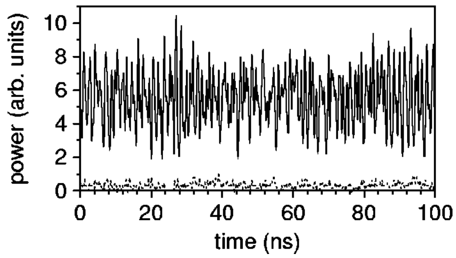

FIG. 5. Time series of the polarization resolved power at 5.14 mA (see Fig. 2).

with higher optical frequency remains on the spontaneous emission level. The optical spectrum shows one lasing mode and filtered spontaneous emission around the frequency of the nonlasing mode. The nonlasing peak is not amplified with respect to the case without feedback.

If the current is raised beyond the value of the solitary laser threshold, the height of the peak in the rf spectrum corresponding to the LFF decreases continuously within a range of about 0.1 mA until it cannot be distinguished anymore. The dynamics become more irregular (see Fig. 5). The rf spectra show that the dominant contributions to the fluctuations move to higher frequencies until they leave our measurement window (up to 1.8 GHz). The linewidth of the laser broadens up to more than 40 GHz, i.e., we observe coherence collapse [1]. The transition to coherence collapse was not observed experimentally in Ref. [22], but it is predicted by simulations [22]. Coherence collapse in VCSELs observed for devices of the same type and manufacturer has also been recently reported by other authors [24].

The dynamics observed up to twice the threshold current in this VCSEL are qualitatively independent of the substrate temperature and the feedback strength. Only for feedback strengths exceeding -10 dB and current values of twice the threshold current, polarization dynamics are observed in this device. Anticorrelated dropouts and bursts occur in the lasing and nonlasing mode, respectively. The peaks occur in groups separated by 100 ns, with single events in one group being separated by the external cavity round-trip time. In conclusion, the dynamics under isotropic feedback in this device are governed by one mode or polarization, respectively, except for very strong feedback and far above threshold.

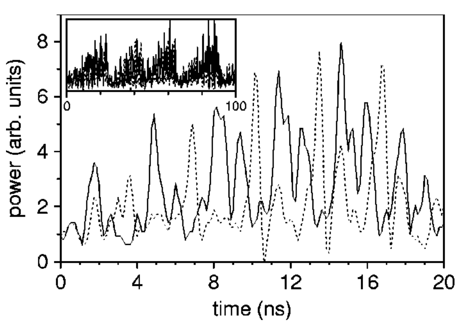

FIG. 6. Time series of the polarization resolved power at constant current 1% above the solitary laser threshold in a device with feedback and low intrinsic dichroism. The feedback strength is -10 dB. The inset shows a larger time interval of the same trace.

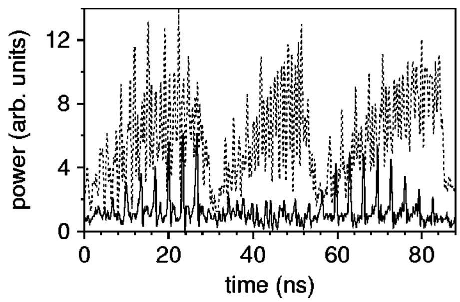

FIG. 7. Time series of the polarization resolved power at constant current 1% above the solitary laser threshold with feedback and intermediate dichroism. The feedback strength is -10 dB.

Figure 6 shows the polarization resolved time trace at constant current of another device with feedback. This device has a small dichroism (0.1 GHz). We observe LFF in both of the orthogonal polarization modes, which also both lase in the solitary device close to threshold. The dynamics in the orthogonal polarization directions are correlated on the slow time scale of the LFF cycles and anticorrelated on the time scale given by the external cavity. As for the device with large dichroism, we observe peaks of smaller amplitude between two larger peaks that are separated by the external cavity round-trip time. Also in this laser, the linewidth of the two modes broadens if the current is increased, but the maximum linewidth is smaller (20 GHz). LFF in VCSELs with a very low dichroism were considered theoretically in Ref. [25]. The paper predicts anticorrelated dynamics and the possibility of simultaneous dropouts of the two polarization modes, which matches our experimental results.

To point out the influence of the dichroism more clearly, we investigated the LFF for an intermediate dichroism value of 0.4 GHz. This regime was reached by adjusting the substrate temperature of the laser. The scenario is as follows (see Fig. 7): We observe LFF for the dominating mode, which is in this case the one with higher optical frequency. This is also the lasing mode of the solitary laser. The dynamics of the mode that is disfavored by the dichroism are different for different LFF cycles of the dominating mode. In many cycles, the power of the weaker mode remains on the spontaneous emission level. In some cycles also the weaker mode shows LFF, but with a smaller amplitude than in the dominating mode. In these cases, the dynamics are anticorrelated on the cavity round-trip time scale and correlated on the slow time scale of the LFF. In the rest of the cycles the weak mode also starts with pulsations, but these pulsations are damped before the LFF cycle of the dominant mode is completed, i.e., the slow dynamics become antiphased towards the end of the LFF cycle. The part of the time series displayed in Fig. 7 has been selected to demonstrate all of the three behaviors described above. The appearance of a burst in the normally suppressed polarization component at a LFF event in the dominant mode roughly matches the observations in Ref. [22].

Our investigations show a clear dependence of the polarization properties of the feedback dynamics in VCSELs on the intrinsic dichroism, which is characterizing the specific device and operating condition. The experiments suggest that the occurrence of the LFF is not depending on the dichroism, but that the dichroism determines the amount of polarization dynamics for isotropic feedback. For large dichroism, the LFF occur without the participation of the disfavored mode, i.e., we observe single-mode LFF. The feedback dynamics in the low dichroism case show anticorrelated polarization dynamics. The LFF in each of the orthogonal polarization modes look qualitative similar to each other and also to the LFF observed without polarization dynamics. From this observation one can conclude that the origin of the LFF in VCSELs is to some extent independent of polarization effects. This is supported by the fact that for intermediate dichroism (see Fig. 7) the LFF in the dominating mode always appear, i.e., they are independent of the presence or absence of the LFF in the weaker mode.

In conclusion, we have demonstrated LFF in VCSELs subject to isotropic optical feedback, including the observation of LFF of a single mode without any additional external anisotropies. The polarization properties of the feedback dynamics were shown to depend on the magnitude of the intrinsic dichroism of the specific device under study. We propose theoretical analysis of two-mode models of VCSEL devices as a promising approach to understand the relevance of multimode dynamics and the transition between single and multimode behavior in LFF.

Note added in proof. The dependence of the interplay of LFF and polarization dynamics in VCSELs with isotropic feedback on dichroism and birefringence was recently considered theoretically by Sciamanna *et al.* [26].

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