Observation of low-frequency fluctuations in vertical-cavity surface-emitting lasers

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Low-frequency fluctuations, which are typical irregular oscillations in edge-emitting semiconductor lasers, are experimentally observed for the y-polarization mode (y is the direction along the optical axis of a laser material) in a vertical-cavity surface-emitting laser with optical feedback.

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Vertical-cavity surface-emitting lasers (VCSELs) are attractive as compact light sources in optical communications and optical information processing because of their advantages over edge-emitting semiconductor lasers, such as single-longitudinal-mode emission, low threshold current, high modulation bandwidth, circular beam output, and ease of fabrication of the array structure. VCSELs have also attracted many researchers from the point of view of fundamental studies of laser dynamics induced by polarization switching and competition among spatial oscillation modes. Since a VCSEL has a circular aperture, the polarization direction of the laser oscillation is not uniquely decided, resulting in complex polarization dynamics. The light emitted from a VCSEL is generally reported to be linearly polarized and oriented along the crystal axis, but the polarization direction may change from the primary mode (along the crystal axis in the laser medium) to the perpendicular mode, depending on the oscillation condition. As one of the physical origins of the polarization dynamics, polarization switching as a result of the birefringence in VCSELs has been discussed.[1,2] Although the difference in the refractive index between the crystal axis and its perpendicular component in a laser medium as a result of birefringence is very small (the refractive-index difference is of the order of 10^{-3} to 10^{-4}), it affects the dynamics of the laser oscillations somewhat because of its spatial dependence on the carrier distribution (spatial hole-burning effect). The coexistence of orthogonally polarized states has also been reported.[3,4]

Edge-emitting semiconductor lasers are stable in nature; however, VCSELs themselves are unstable even in solitary operation, and instabilities in the laser output are induced by irregular or chaotic polarization and spatial-mode switching. In addition to these dynamics in VCSELs, we can observe various instabilities of laser oscillations in the presence of optical feedback. VCSELs have a distributed-feedback mirror structure of the facet and a high reflectivity of more than 99%, much higher than those of edge-emitting semiconductor lasers (~10%). Despite the high reflectivity, VCSELs are very sensitive to external optical feedback because of lower photon numbers in the cavity and a larger light-emitting area than edge-emitting semiconductor lasers. Therefore, VCSELs are also sensitive to optical feedback from an external reflector such as an edge-emitting semiconductor laser. The dependence of the dynamics on an external feedback fraction varies from one VCSEL to another because of the unique device structure of each; however, we can expect chaotic dynamics similar to those for edge-emitting semiconductor lasers, in addition to particular dynamics that originate from the VCSEL structures.[5] Up to now, a few experimental studies of the effects of optical feedback in VCSELs have been reported. These studies were mostly concerned with spectral broadening of the laser oscillations as a result of optical feedback observed with, for example, a Fabry–Perot spectrometer.[6–9] Also, theoretical works on feedback-induced instabilities have been published.[10,11]

Recently, Masoller and Abraham theoretically discussed low-frequency fluctuations (LFFs) of VCSELs in the presence of optical feedback.[12] LFF is a typical feature induced by optical feedback in ordinary edge-emitting semiconductor lasers, and it is also expected to be observed in VCSELs. However, to our knowledge it has been experimentally reported yet. In this Letter we present the experimental observation of LFFs in a VCSEL. At a long external cavity length and with high reflectivity of an external mirror, we observed LFFs in the y-polarization mode of a VCSEL. In an index-guided cylindrical disk-contact VCSEL, the directions of the orthogonal polarization states are identified by subscripts x and y. Here, the y direction is assumed to be that of the optical axis of the laser material. From analysis of the output time series and their spectra, the laser shows LFF properties quite similar to those observed in edge-emitting semiconductor lasers.

The laser used in the experiment was a disk-contact VCSEL (EMCORE MODE 8085-2800) that oscillated at a wavelength of 844.7 nm and had a maximum power of 3 mW. The diameter of the VCSEL was 16 μm. The external mirror was positioned ~1900 mm from the laser facet, and the fraction of the optical feedback could be varied by use of a neutral-density filter in front of the reflector. The bias injection currents of the laser were controlled by a stabilized current source driver, and the laser temperature was stabilized at 25.9 °C by an automatic temperature-control circuit. The output intensity of

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the laser was detected by a high-speed photodetector (New Focus 1537M-LF; bandwidth, 6.0 GHz). Irregular waveforms were analyzed by a rf spectrum analyzer (Hewlett-Packard HP 8595E; bandwidth, 6.5 GHz) and a fast digital oscilloscope (HP 54845A; bandwidth, 1.5 GHz). Also, the optical output was analyzed by a Fabry–Perot spectrometer (free spectral range of 10 GHz).

Figure 1 shows the light–intensity characteristics of the VCSEL. The threshold current was 4.5 mA, as shown in Fig. 1(a) for solitary operation. We can observe a change of the polarization state for injection currents higher than 7 mA, although it is not sharp switching. The change of the polarization state with increasing injection current is a typical feature of VCSEL oscillations. The spatial mode was almost single (fundamental, i.e., LP01 mode) in our experiments as long as the bias injection current was less than 7 mA. In the presence of optical feedback, the threshold was reduced, as shown in Fig. 1(b). The external feedback rate was 18.8% (calculated simply from reflectivity of optical components), and the other losses such as diffraction and absorption of light through optical components were not taken into account for the feedback rate. The threshold current was reduced by 22%. In the case of optical feedback, the trend of the light–intensity characteristics was changed, and the output power of the y mode still was higher than that of the x mode within the range of the observed injection current.

LFFs were experimentally observed in the VCSEL with optical feedback. Figure 2(a) shows a single-shot time series of LFFs for the y-polarization component. The injection current of the laser was biased at 5.0 mA, and the reflectivity of the external mirror was the same as the one in Fig. 1(b). Usually, dropout events in LFFs occur irregularly in time; however, they seem rather quasi-periodic in Fig. 2(a). The occurrence and frequency of LFFs are functions of the laser parameters, and either quasi-periodicity or nonperiodicity of LFF oscillations depends on the bias injection current. Indeed, periodic LFFs tend to be observed at a higher injection current above the laser threshold in ordinary edge-emitting semiconductor lasers.[13] The average frequency of LFFs was read to be ~7.8 MHz in Fig. 2(a). In the observed waveform, the time series does not show clear power dropouts typically observed in LFFs of edge-emitting semiconductor lasers. At the injection current of 5 mA, the observed spatial mode was almost single (fundamental mode) even in the presence of optical feedback. The output power of the x-polarization mode was less than 10 μW and was scarcely observed by our detector.

It is difficult to investigate the detailed LFF structure from Fig. 2(a), so an averaged one-shot LFF waveform over 256 events was calculated. The result is shown in Fig. 2(b). In the averaging, a trigger point for the average was automatically set to take the local minima of the optical power after dropouts in the digital oscilloscope. We also examined an average over the samples with computer software. The results both automatically averaged by the oscilloscope and calculated on the computer almost coincided with each other. Power dropout and stepwise power recovery are the typical features of LFF that are usually observed in edge-emitting semiconductor lasers. However, these features were not clearly visible in Fig. 2. The time duration between successive underspikes is equal to 12.8 ns, and the value is quite similar to the calculated round-trip time of light within the external mirror (12.7 ns). Therefore, it is concluded that the sequence of these underspikes corresponds to the stepwise power recovery that is due to the oscillation modes generated by the external mirror.

Since the output power of the x component was very low [see Fig. 1(b)], we could not observe the corresponding oscillation for the y component. From examination of the other parameter conditions for the

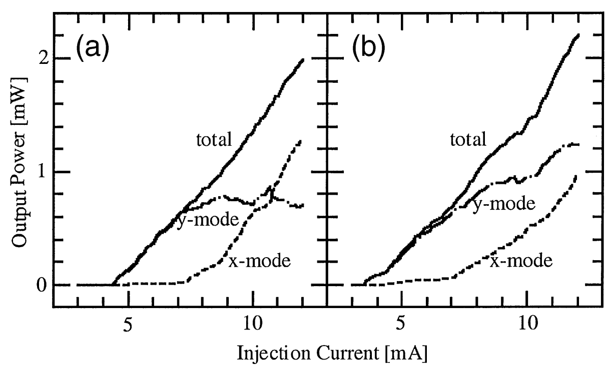

Fig. 1. Light–intensity characteristics of total and x- and y-polarization modes (a) without and (b) with optical feedback. The external feedback rate is 18.8%.

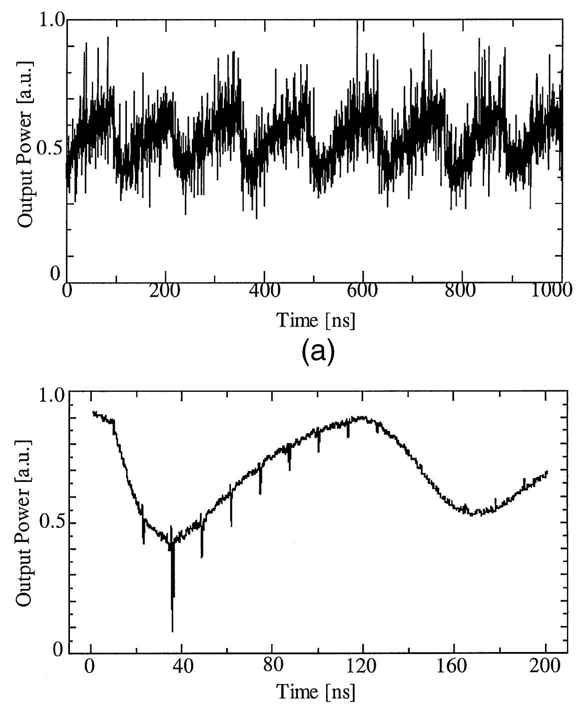

Fig. 2. Time series of LFF output power for the y-polarization component at a bias injection current of 5 mA. (a) Single-shot time series and (b) averaged one-shot LFF waveform.

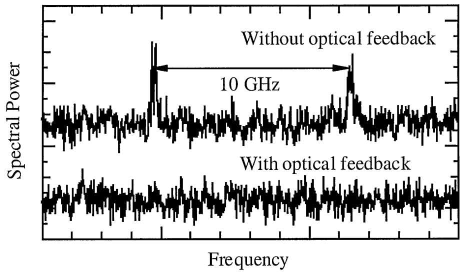

Fig. 3. Fabry–Perot spectra with and without optical feedback.

external mirror and the bias injection current, one of the irregular output powers corresponding to the polarization components tended to compensate for the other. However, clear out-of-phase oscillations of x- and y-polarization modes were not confirmed by the present experiment. The time-dependent nature of the dual polarization behavior is not discussed here, but a detailed investigation would be interesting and is left for future study. Not only in LFFs but also in ordinary chaotic oscillations with high-frequency fluctuation, there exists phase sensitivity of the external mirror variation that is compatible with optical wavelength. The dynamics of LFFs in the system was also affected by the phase. However, the aim of this Letter is the demonstration of the existence of LFFs in VCSELs, and the effect of phase will be treated in a future paper.

One of the typical features of LFFs is a coherence collapse of the laser oscillations. We examined the optical spectrum in the presence of optical feedback. Although it is not shown here, we observed a slight broadening of the oscillation spectrum with the rf spectrum analyzer for the optical feedback. The laser oscillated at a single longitudinal mode both with and without optical feedback, and the oscillation frequency remained unchanged by the optical feedback within the range of the resolution of the spectrum analyzer of 0.05 nm. However, the coherence was completely destroyed by the optical feedback. Figure 3 shows the optical spectra with and without optical feedback observed by the Fabry–Perot spectrometer. In the absence of optical feedback, the laser oscillated while keeping its coherence; however, for the optical feedback, the coherence is completely destroyed, and we cannot see any spectral component as shown in Fig. 3. Coherence collapse is a typical feature of chaotic laser oscillation in a LFF regime.

Other than polarization and spatial-mode dynamics, which are typical instabilities of VCSELs with broad-area emitting structures, these structures are expected to show dynamics similar to those in edge-emitting semiconductor lasers. Indeed, LFFs in a VCSEL with optical feedback have been observed experimentally for what is believed to be the first time. Masoller and Abraham theoretically studied the dynamics of VCSELs with optical feedback and showed the possibility of the occurrence of LFFs.[12] However, they did not take into account the spatial structure of VCSELs in their equations. Instead, they considered the circular polarization modes and the spin decay rate. In reality, spatial diffusions of carriers in the radial direction in the active layer that should be involved in the carrier density equation play an important role in the polarization dynamics of VCSELs. Therefore, not only detailed experimental investigation of LFF dynamics in VCSELs but also theoretical study of the origin of LFFs is required.

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