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Chaos dynamics in vertical-cavity surface-emitting semiconductor lasers with polarization-selected optical feedback

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ABSTRACT

We study experimentally and numerically the dynamic states of chaotic oscillations in vertical-cavity surface-emitting semiconductor lasers (VCSELs) with polarization-selected optical feedback. We identify the regimes of fully-developed chaotic states, low-frequency fluctuations (LFFs), and coexistent states of LFFs and stable oscillation for the variations of the bias injection current and the optical feedback ratio. In particular, coexistent states of LFFs and stable oscillations are observed at higher optical feedback ratio and lower bias injection current. We draw maps of dynamic states in the space of the bias injection current and the optical feedback ratio. The qualitative agreement between the theory and the experiment is found.

1. Introduction

Vertical-cavity surface-emitting semiconductor lasers (VCSELs) have many advantages over conventional edge-emitting semiconductor lasers [1]. For examples, the laser has symmetrical beam profile, single longitudinal mode emission, very low threshold current, and wafer-scalable integration for laser arrays. Due to anisotropic structures of the laser materials that break a circular transverse symmetry, the output from a VCSEL shows a linearly-polarized oscillation along one of the two orthogonal polarization components (x- and y-polarizations) at a fixed bias injection current. However, the polarization direction of the laser oscillation is changed from the original direction (we here define the y-polarization as the original mode) to the counter one (x-polarization) for the increase of the bias injection current. Such polarization switching often accompanies time-dependent complex dynamics, where the laser exhibits simultaneous unstable oscillations of two polarization modes, polarization hopping, or emission of elliptically polarized light. Polarization instabilities in VCSELs are detrimental for polarization-sensitive laser applications. However, the study of the dynamics is still underway and several efforts have been made to understand the origins and mechanisms of polarization dependent characteristics in VCSELs [1–4].

Though VCSEL usually has a very high facet internal reflectivity of light over 99%, it is still very sensitive to self-optical feedback from external optical components. In addition to similar feedback-induced dynamics as observed in edge-emitting semiconductor lasers, VCSEL shows extra instabilities, for example, polarization instabilities depending on the bias injection current, feedback strength, and feedback cavity length. Several experimental and theoretical studies for the dynamics in VCSELs with optical feedback have been reported up to the present [5–16]. Also the dynamics of polarization-selected optical feedback in VCSELs have been studied [17–19]. Unstable oscillation of VCSELs induced by optical feedback is not only the effect, but also stabilization of VCSELs can be attained under certain feedback conditions. Indeed, polarization switching is much suppressed by strong polarization-selected optical feedback for some cases [17,18]. Low-frequency fluctuation (LFF) oscillations are typical phenomena in optical feedback instabilities in semiconductor lasers. On the other hand, fast chaotic oscillations, whose main frequency component is almost the same order as the laser relaxation oscillation, are also observable at a higher bias injection current. Another state is a coexistence of unstable and stable oscillations for the time development. However, there exist few reports for coexistent states in VCSELs subjected to optical feedback [13]. While, coexistent states of unstable LFFs and stable oscillations were commonly observed in edge-emitting narrow-stripe semiconductor lasers and broad-area semiconductor lasers subjected to optical feedback [20–22]. The systematic study is still lacked for the dynamics of polarization-selected optical feedback in VCSELs including the occurrence of coexistent oscillations.

In this paper, we experimentally investigate the dynamics in VCSELs with isotropic polarization-selected optical feedback. Fast chaotic oscillations, LFFs, and coexistent states are identified depending on feedback strength, feedback cavity length, and bias injection current. We also draw state maps for the dynamics, namely, chaotic oscillations, LFFs,

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and coexistent states, in the phase space of the bias injection current and the optical feedback strength. In particular, we experimentally identify the areas of coexistent states of LFF and stable oscillations in the phase space, which are also a function of the external optical feedback length. We also conduct numerical simulations for the dynamics by employing a spin-flip model, which is widely used for analyzing VCSEL dynamics and can well represent the dynamic behaviors for both solitary and optical feedback conditions. We obtain the good coincidences between the theory and the experiment.

2. Experimental setup

The experimental setup is shown in Fig. 1. A spatially single-mode VCSEL (SONY H05-3-3) that oscillated at a wavelength of 780 nm and a maximum power of 2.0 mW was used. The bias injection current of the laser was controlled by a stabilized current source driver and the laser temperature was stabilized at 25.0 °C by an automatic temperature control unit. The light-injection current (L-I) characteristic is shown in Fig. 2. The laser at first oscillated at the main polarization mode (y-mode) above the threshold current of 3.1 mA, but it switched to the orthogonal polarization mode (x-mode) at the bias injection current of 5.2 mA. After the switching, the laser stably oscillated at the orthogonal polarization mode. Thus the laser showed a typical polarization switching. Over the measured range of the bias injection current, the laser remained at a single spatial mode, i.e., the lowest spatial Gaussian mode. The laser output was collimated by a lens (CL) and went through a beam splitter (BS). One of the beams was reflected back to the VCSEL together with a polarizer (P), which selected the feedback polarization, and a neutral density filter (NDF), which controlled the feedback fraction. The external cavity length was a variable parameter, which was varied from 30 to 90 cm in the experiment. The other beam was fed into a polarization beam splitter (PBS), and the two polarization components were detected by detectors (D1 and D2: New Focus, 1554-50; bandwidth: 12 GHz) and were analyzed by a digital oscilloscope (OSC: Agilent DSO80804; analogue bandwidth: 8 GHz, sampling rate: 40 GSa/s). Two 30 dB optical isolators (ISO1 and ISO2) were used to prevent the reflection from the optical components and the detector surfaces.

3. Experimental results

Fig. 3 shows examples of L-I characteristics in the presence of polarization-selected optical feedback. The external mirror was positioned at 90 cm from the laser facet. Fig. 3(a) and (b) shows the results of y-polarization feedback for the feedback fractions of 0.5 and 2.0% in intensity, while Fig. 3(c) and (d) shows those x-polarization

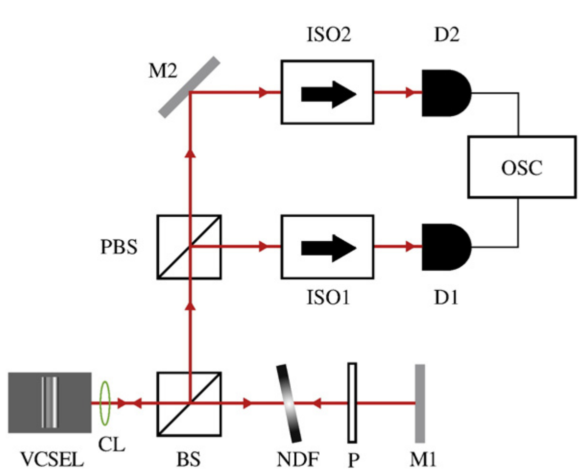

Fig. 1. Experimental setup. CL: collimating lens, BS: beam splitter, NDF: neutral density filter, P: polarizer, Ms: mirrors, PBS: polarization beam splitter, ISOs: optical isolators, Ds: detectors, and OSC: digital oscilloscope.

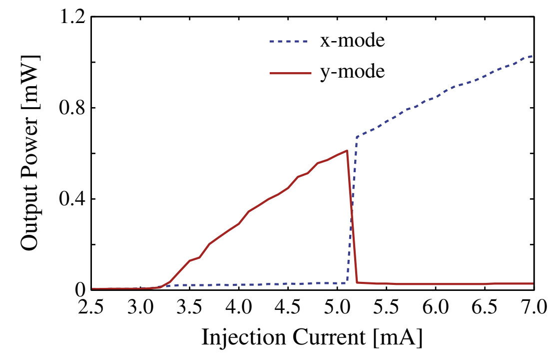

Fig. 2. Polarization resolved L-I characteristic of solitary laser.

feedback for the feedback fractions of 0.5 and 2.0%, respectively. The feedback strength was observed in the external optical loop, so that it was not the exact feedback fraction of light into the laser cavity as will be discussed later in section 5. It is noted that the thresholds are reduced less than that of the solitary oscillation due to the optical feedback. With the increase of feedback fraction in Fig. 3(a) and (b), the current at which polarization switching occurs increases (the initial current is 5.1 mA) and it finally disappears within the observed injection current range at higher optical feedback. Similar results have been reported in the previous papers [17]. The L-I plots are for the mean light intensities so that time variations, which actually exist, are averaged out in these characteristics. In contrast to y-polarization optical feedback, the switching current for x-polarization optical feedback decreases with the increase of the feedback fraction as shown in Fig. 3(c) and (d). In Fig. 3(d), the y-polarization mode, which is the initial main oscillation mode without optical feedback, is completely suppressed over the observed current range and behaves like a non-lasing mode as the time-averaged intensity due to rather stronger x-polarization optical feedback.

Fig. 4 shows time-resolved chaotic series in the presence of polarization-selected optical feedback at the bias injection current of 3.1 mA and the optical feedback length of 40 cm. At this bias injection current, the y-polarization mode is the main oscillation mode. Fig. 4(a)–(c) shows the results for y-polarization optical feedback. When the optical feedback is small enough at 1.0% in Fig. 4(a), the laser output of the y-polarization mode shows a fast chaotic variation. The counterpart output (x-polarization mode) also shows a chaotic oscillation with anti-phase manner to the y-polarization mode. With the increase of the optical feedback at 3.0% in Fig. 4(b), the output of the y-polarization mode shows typical LFFs and the orthogonal mode exhibits anti-phase oscillations to the y-polarization mode. At the higher feedback ratio of 6.0% in Fig. 4(c), the laser output power shows a different oscillation from ordinary chaotic states or LFFs. Both the polarization modes exhibit LFF oscillations at first, however they suddenly cease and show constant outputs. In this experiment, one state switches to the other after a certain duration and verse visa for the time development and each state lasted for several milliseconds. This phenomenon of the mixture of unstable and stable oscillations is called a coexistent state of chaotic oscillations. Such oscillations are frequently observed in other types of semiconductor lasers [20–22]. Fig. 4(d)–(f) shows the results for x-polarization optical feedback at the bias injection current of 3.1 mA. Though the original mode of the laser oscillation is the y-polarization mode, the x-polarization mode is strongly excited and the y-polarization mode is suppressed due to x-polarization optical feedback. To compare the oscillations for the y-polarization optical feedback, the same optical feedback ratios as those in Fig. 4(a)–(c) were used. Similar trends of the dynamics with the case of y-polarization optical feedback were observed in Fig. 4 (d)–(f), although the roles of the main- and sub-oscillation modes were reversed. For the x-polarization feedback, we also observed