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Linewidth narrowing caused by optical feedback in a multi-mode vertical-cavity surface-emitting laser

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Abstract

We have studied experimentally spectral characteristics of a multi-mode vertical-cavity surface-emitting laser that is subject to optical feedback. Appropriate alignment of the feedback mirror can suppress higher-order modes and significantly decrease the spectral linewidth of the laser.

Keywords: Vertical-cavity surface-emitting laser; Optical feedback; Spectral linewidth

Vertical-cavity surface-emitting lasers (VCSELs) have many advantages over conventional edge-emitting lasers, such as single-longitudinal-mode operation, low-divergence circular beam, low threshold current, and ease of making laser arrays. These features make VCSELs very useful in fiber-optical data communications, arrays applications, and highly integrated circuits [1]. Because of large lateral aperture, VCSELs can operate at multiple transverse modes when the injection current is increased. The oscillation of higher-order transverse modes leads to wide spectral linewidth and degrades the quality of beam profile. Therefore, suppression of higher-order modes in VCSELs has been an active research topic in recent years.

Similar to edge-emitting lasers, VCSELs are sensitive to optical feedback. Optical feedback is inevitable in applications of VCSEL, which can be produced by reflection from the end of optical fiber when the laser is coupled to the fiber or from the surfaces of optical components. Theoretical works on a two-mode VCSEL have shown that both the feedback level and the length of external cavity can be used for mode selection [2,3], and a long external cavity (>1 cm) results in chaotic pulsation [3]. Antiphase dynamics is demonstrated in a three-mode model with weak optical feedback [4]. Heinrich et al. observed in an oxidized VCSEL that low-order modes are suppressed as the feedback phase is changed by π for a 20 μm cavity length [5]. Quay et al. reported a decrease in coherence length under strong feedback in both single-mode and multi-mode regime, but the VCSEL is less sensitive to feedback in multi-mode operation [6]. Cheng et al. showed that single transverse mode operation can be obtained from a multi-mode VCSEL with a self-seeded optical feedback [7]. Chen et al. used a polarized feedback to achieve single transverse mode in one of the polarized states of a multi-mode VCSEL [8].

In this paper, we report our experimental study on the effect of optical feedback on a multi-mode commercial VCSEL. We have observed that optical feedback can either increase or decrease the linewidth of the VCSEL, depending on the alignment of feedback mirror. For appropriate alignment of the mirror, the linewidth can be significantly decreased.

We use a proton-implanted VCSEL (Honeywell SV3637-001) in our experiment. The aperture diameter of the laser is 16 μm. The operating wavelength of the laser is 827 nm. The experimental setup shown in Fig. 1 is on a vibration-isolated optical table. The temperature of the VCSEL is set at 18 °C using a temperature controller.

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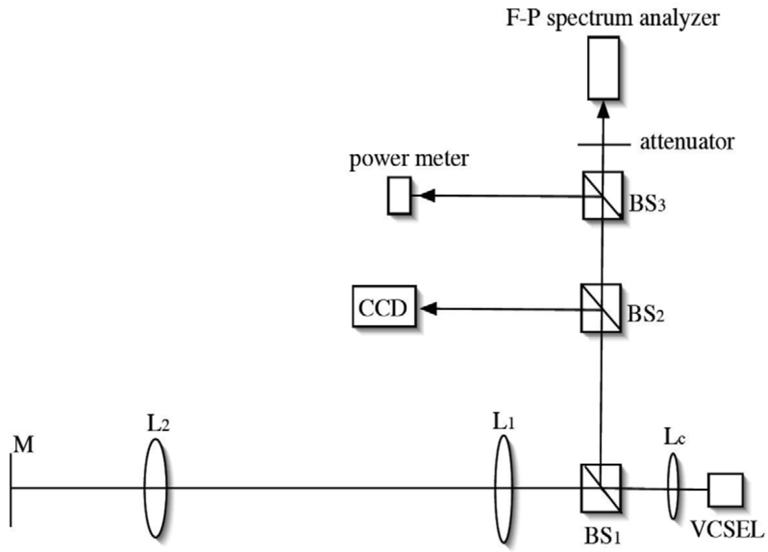

Fig. 1. Experimental setup. BS_1–BS_3: non-polarized beamsplitters; L_c: collimating lens; L_1 and L_2: intracavity lenses; M: end mirror that provides optical feedback.

The output of the VCSEL is coupled into an external cavity through a collimating lens L_c ($f_c = 8$ mm). The end mirror M of the external cavity creates optical feedback to the laser. The power reflectivity of the end mirror is 100%. To decrease divergence of the laser beam, two intracavity lenses L_1 and L_2, focal lengths 40 and 20 cm, respectively, are used to form a 4f system. The end mirror M is located at the back focal plane of L_2. The distance between the laser and the end mirror is 121 cm. In the external cavity, the laser beam is split at a non-polarized cubic beamsplitter BS_1. The light reflecting from BS_1 is used for monitoring. It is split at the second non-polarized cubic beamsplitter BS_2. Part of the light is sent to a CCD camera to observe beam pattern, another portion is split again between a power meter and a Fabry–Perot (F–P) scanning spectrum analyzer. The free spectral range of the F–P spectrum analyzer is 300 GHz. We place an attenuator in front of the spectrum analyzer and make sure that the spectrum analyzer does not produce unwanted feedback in the experiment.

The strength of the feedback signal is evaluated through the feedback power ratio R, which is expressed as $R = \rho^2 T_{BS}^2 T_{neu}^2 R_m = \rho^2 R_{ext}$ [6], where ρ is the coupling efficiency between the VCSEL and the external cavity, T_{BS} is the one-way transmittance of the beamsplitter BS_1, T_{neu} is the one-way transmittance of the neutral density filter inserted in the external cavity, R_m is the reflectivity of the end mirror, and $R_{ext} = T_{BS}^2 T_{neu}^2 R_m$ is the equivalent reflectivity of the external cavity. Using the method in Ref. [9], we measured the coupling efficiency between the laser and the external cavity is approximately 15%. The maximum value of R_{ext} is 25%. Therefore, the possible maximum value of R is -23 dB. At the maximum feedback level, the threshold current I_{th} is 2.5 mA, reduced approximately 10%. Compared to the feedback levels that result in coherence collapse [6,9], the strength of feedback in our experiment is relatively weak.

The threshold current of the free-running VCSEL, I_{th0}, is 2.8 mA. As the injection current is below 3.6 mA ($I/I_{th0} < 1.3$), the VCSEL operates with a single, linearly polarized fundamental mode. Its beam profile is approximately a Gaussian distribution. When the injection current is higher than 3.6 mA, a weaker mode with a higher frequency appears. The frequency difference between the two modes is of the order of 10 GHz, and the polarization of the second mode is perpendicular to the first mode. Hence, the two modes are orthogonal components of the fundamental transverse mode [10]. We name them as X and Y components, respectively. The beam profile of the Y component, however, has a three-lobe intensity distribution, as shown in Fig. 2a. It has been demonstrated by Fratta et al. that the two orthogonally polarized states of the fundamental mode may have different intensity profiles [11]. When the current is higher than 4.1 mA ($I/I_{th0} > 1.46$), more lasing modes appear in frequency structure obtained from the F–P spectrum analyzer. The frequency difference between the lowest frequency and highest frequency is more than 40 GHz. This indicates that higher-order transverse modes start oscillation. In the multi-mode domain, we evaluate spectral linewidth of the laser by using the frequency difference between the modes that have the lowest and highest frequencies, respectively. Fig. 2b shows the spectral linewidth of the free-running VCSEL from 3.0 to 7.0 mA. There are several discontinuities in the variation of the linewidth. Each discontinuity indicates onset of a new mode.

We use two different alignments of the end mirror M of the external cavity in our experiment. Near threshold we align the end mirror to optimally enhance the lasing mode—the X component of the fundamental mode. This alignment is named A1 in this paper. In the multi-mode domain, this alignment increases the spectral linewidth. Three examples of the frequency structures are given in