107-GHz Resonance Frequency of 1.55-µm VCSELs Under Ultra-high Optical Injection Locking

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Abstract: We demonstrate a record resonance frequency enhancement of 1.55-µm VCSELs from 10 GHz to 107 GHz under ultra-high optical injection locking. Detuning and injection-ratio dependence are characterized to show the broad applicability of the technique.

OCIS codes: (140.3520) Lasers, injection-locked; (060.4080) Modulation; (250.7260) VCSELs;

1. Introduction

To satisfy the growing need for larger transmission speed and data capacity in optical communication systems, much research has been carried out to increase the direct modulation bandwidth of semiconductor lasers. In a typical diode laser, the relaxation oscillation (resonance) frequency is a necessary but not sufficient figure-of-merit to determine its maximum direct modulation bandwidth. It has been demonstrated that optical injection locking (OIL) can significantly increase the resonance frequency of a directly-modulated laser [1, 2]. A resonance frequency of 72 GHz was reported on a DFB laser previously [1]. High-speed vertical-cavity surface-emitting lasers (VCSELs) are also of great interests for many applications in short-haul communication systems due to their cost-effective fabrication and simple testing process. Although the modulation speed of 1.55-µm VCSELs is limited by device parasitics to < 20 GHz, the dynamic performance can be drastically improved by applying strong optical injection locking [2]. Recently, cascaded optical injection locking (COIL) was proposed to leverage the resonance enhancement, and ultimately to achieve broadband modulation from a series of injection-locked VCSELs [3]. However, obtaining an ultra-wide modulation bandwidth requires an ultra-high resonance frequency OIL VCSEL as the first stage. Therefore, studies on the resonance enhancement of a directly-modulated laser under ultra-high injection locking is still of great importance and interest. In this paper, we demonstrate a record resonance frequency of 107 GHz from a directly-modulated 1.55-µm injection-locked VCSEL. Detailed characterization is carried out showing the small-signal frequency response as a function of both the detuning value ($\Delta\lambda = \lambda_{\mathrm{master}} - \lambda_{\mathrm{slave}}$) and the injection ratio ($P_{\mathrm{master}} / P_{\mathrm{slave}}$). No fundamental limit is observed for the resonance frequency under injection locking.

2. Experimental setup

The experimental setup is shown in Fig. 1. A commercial DFB laser is used as the master laser with maximum output power ~ 40 mW. The VCSEL is single mode (side polarization mode suppression ratio > 40 dB) at 1.55 µm with buried tunnel junction (BTJ) structure designed for high-speed operation (3-dB bandwidth of ~ 10 GHz) [4]. The threshold current is 0.6 mA, and the output power is > 1 mW. The VCSEL is mounted on a copper block and temperature controlled by thermal electric coolers (TECs). The emitted light is coupled into tapered fiber, hence can be injection-locked through an optical circulator. Polarization controller is used to match the master polarization to the VCSEL preferred polarization to maximize the locking stability. Biasing and modulation signals are delivered to the VCSELs through high-speed 1-mm coaxial microwave signal-ground probe. A small amount of the output light is sent to an optical spectrum analyzer (OSA) to monitor the locking condition. The majority of the light is detected by a photo-detector (PD) with 3-dB bandwidth of 84 GHz. A 110-GHz vector network analyzer (VNA), Agilent N5250A, is used to test the small-signal frequency response. All the frequency response shown in this paper is corrected for RF cable loss only. The VCSEL parasitic response is not de-embedded.

3. Results and conclusion

Fig. 2 shows the (a) frequency response and (b) optical spectra of the VCSEL at various detuning values under a constant external light injection of 16 dB. Free-running response is also shown as a reference. The VCSEL is biased at 2 mA ($3.3\times I_{\mathrm{th}}$) with 0.43 mW output power and a 6-GHz resonance frequency. As the master wavelength is tuned from -0.748 nm to -0.906 nm as shown in Fig. 1(b), the resonance peak increases from 92 GHz to 107 GHz with a reduced damping factor. Correspondingly, the cavity mode shown in the optical spectra is suppressed as $\Delta\lambda$ increases. Fig. 3 shows the (a) frequency response and (b) optical spectra of the VCSEL at different injection ratio levels. At each injection ratio, the detuning is adjusted so that the RF gain of the resonance peak is about ~20

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dB (similar damping factor). Correspondingly, in the optical domain, shown in Fig. 3(b), the cavity modes for different injection ratio conditions are all aligned with similar optical gain. As shown theoretically [5], the maximum resonance frequency enhancement increases with injection ratio. Therefore, even higher resonance frequency is expected with a higher injection ratio. Additionally, it is promising to achieve broadband response up to 110 GHz using COIL configuration with multiple cascaded slave VCSELs.

In conclusion, we demonstrate dynamically tunable resonance frequency >100 GHz of 1.55-μm VCSELs under ultra-high optical injection locking. It brings the possibility of achieving cost-effective ultra-wideband modulation for next generation high-speed communication systems.

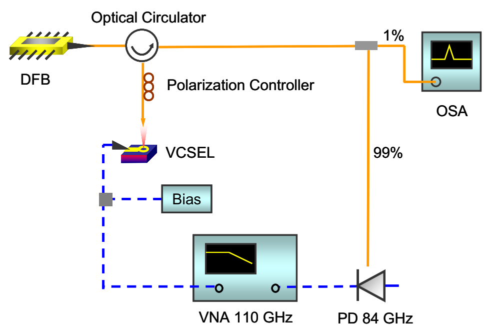

Fig. 1 Experimental Setup (VNA: vector network analyzer, PD: photo-detector, OSA: optical spectrum analyzer)

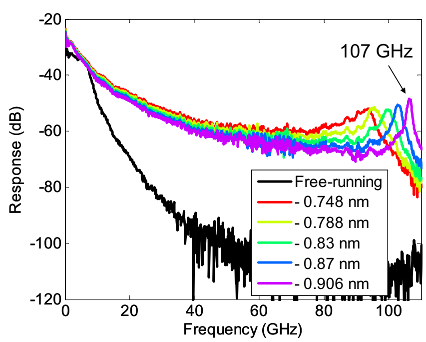

Fig. 2 (a) Frequency response of an OIL VCSEL at various detuning values. A record resonance frequency of 107 GHz is shown.

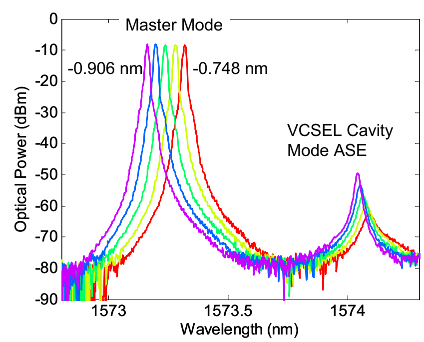

Fig. 2 (b) Optical spectra of an OIL VCSEL at various detuning values. The master laser wavelength is tuned.

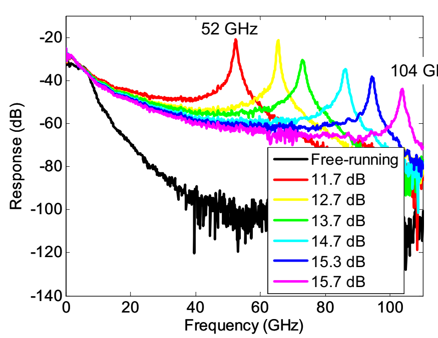

Fig. 3 (a) Frequency response of an OIL VCSEL under various injection ratio levels. The detuning is adjusted to result in a resonance peak with ~ 20 dB gain for all the cases.

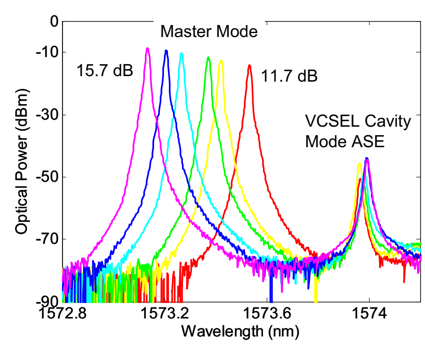

Fig. 3 (b) Optical spectra of an OIL VCSEL under various injection ratio levels. Both the power and the wavelength of the master laser are tuned.

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