Greatly enhanced modulation response of injection-locked multimode VCSELs

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Abstract: We report greatly enhanced modulation response of multimode vertical-cavity surface-emitting lasers (MM-VCSELs), for the first time, using optical injection locking. A 3-dB bandwidth of 38 GHz and 54 GHz resonance frequency are achieved using a MM-VCSEL with a 3 GHz free-running bandwidth. We show that transverse mode selection can be attained with optical injection locking through frequency and spatial detuning.

OCIS codes: (060.4080) Modulation; (140.3520) Lasers, injection-locked; (140.5960) Semiconductor lasers; (250.7260) VCSELs

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1. Introduction

Recently, increased demands on performance and cost are being placed on high-speed transmitters for short-reach (< 1 km) fiber-optic communications. Multimode (MM) VCSELs provide the ideal device to meet these demands due to their low cost of manufacture and performance advantages over electrical cables [1,2]. However, to meet the demands of the future, 100G Ethernet and millimeter-wave analog fiber links, higher modulation speed and longer transmission distance are needed. Modal dispersion and mode competition noise however limit the speed and transmission distance of MM lasers [3,4]. These problems however can be eliminated by using a single-mode laser but with a tradeoff in cost for performance.

Optical injection locking (OIL) of single-mode (SM) VCSELs has previously been demonstrated to improve both modulation speed and transmission distance [5-8]. 107 GHz resonance frequency and 80 GHz intrinsic 3-dB bandwidth for an OIL SM VCSEL has been experimentally demonstrated. Injection locking of multimode Fabry-Perot (FP) lasers has also been shown to increase the 3-dB bandwidth by a factor of 2 [9]. However, further improvement of multimode FP lasers is limited by the spacing between the adjacent longitudinal modes, which limits the locking range thus the bandwidth of the frequency response. Previous work has also studied MM VCSELs under weak optical injection showing higher-order mode suppression and polarization switching, however no frequency response was reported [10,11].

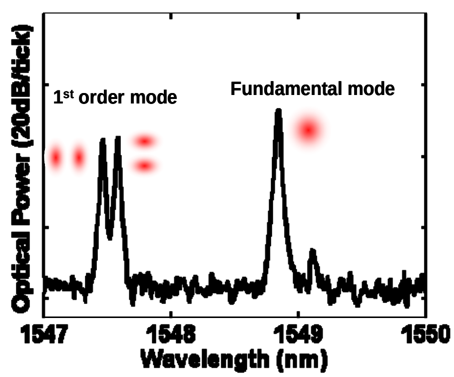

Fig. 1. Optical spectra of 10 µm MM VCSEL. The tranverse modes are spectrally and spatially distinct.

In this paper, we investigate optical injection locking of MM VCSELs to improve device performance under direct modulation. We show a 54 GHz resonance frequency and 38 GHz 3-dB bandwidth for an OIL MM VCSEL with a free running bandwidth of 3 GHz. Leveraging the spectrally and spatially well separated transverse modes of MM VCSELs (Fig. 1) we also show a tailorable frequency response. We believe that this result can provide an excellent solution for low-cost upgrades of existing short-reach optical networks.

2. Resonance frequency and 3-dB bandwidth enhancement

The experimental setup (Fig. 2) is similar to previous single-mode optical injection locking experiments with the single-mode slave laser being replaced by a MM VCSEL. We use a commercial off-the-shelf CW DFB laser with a maximum output power of ~80 mW as the master laser. A high-speed MM VCSEL designed with a buried tunnel junction (BTJ) structure to confine both current and light is employed as the slave laser [12]. The MM VCSEL has a 10 µm aperture, 6 mA lasing threshold and a maximum output power of ~ 5 mW at 25-mA bias. Output of the MM VCSEL is coupled via a cleaved SM fiber with a coupling loss of ~ 5 dB. Through the optical circulator and polarization controller the master laser injection locks the slave laser. Modulation is then directly imposed on the MM VCSEL by means of a high-speed RF probe. The output of the circulator is split to an optical spectrum analyzer to record the optical spectra and to a photodetector so small-signal frequency response (Agilent E8361A) can be tested. To achieve high injection power ratio, P_{Master}/P_{Slave}, while still maintaining multimode behavior, the VCSEL was biased at 10 mA with 1.2 mW output power. As seen in Fig. 3(a) (black trace), the VCSEL emits a fundamental mode, the longer wavelength mode, and a first-order mode, which has degenerate polarization modes.

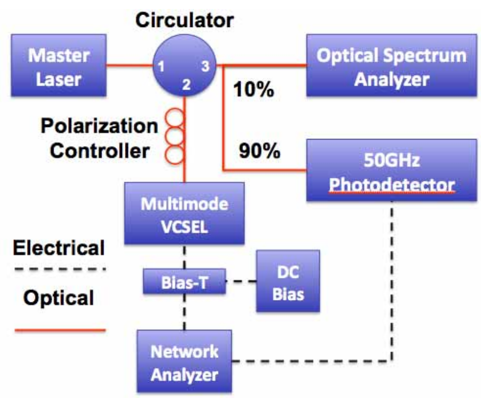

Fig. 2. Schematic of experimental setup

In the first experiment, we investigate resonance frequency enhancement of the MM VCSEL with respect to the free running case. As the fundamental mode has similar spatial characteristics to the injected light and a single dominant polarization mode, it is selected for this experiment. Similarly to the single-mode case, to get resonance frequency enhancement the master laser wavelength is shorter than the slave laser wavelength ($\Delta\lambda=\lambda_{Master}- \lambda_{Slave}$ is negative). Figure 3(a) shows the optical spectra for various detuning values when the master laser is detuned to wavelengths shorter than the slave laser wavelength while the injection power ratio (~8.1 dB) is held constant. The higher-order mode is suppressed under strong optical injection locking, effectively making it a single-mode laser. The side mode suppression ratio are 49.4, 37.2, 28.1, and 24.4 dB, for -0.245, -0.293, -0.341, and -0.365 nm detuning values, respectively. Figure 3(b) shows the resulting small signal modulation responses. The resonance frequency enhancement is significant comparing to the free running (black trace) case MM-VCSEL. Note that the data shown in Fig. 3(b) include the VCSEL device parasitics (estimated to be 10 GHz), and the measurement system parasitics such as the electric probe (40 GHz), photo-detector (50 GHz) and the bias tee (50 GHz). The ripples in the frequency response are caused by reflections off of the cleaved fiber, and can be reduced by switching to a lensed fiber. Low frequency roll-off in the response can be attributed to an additional real pole in directly-modulated OIL systems, which acts as a low-pass filter [13]. The 54 GHz resonance frequency is a record value achieved for directly modulated MM VCSEL, to the best of our knowledge.

For the case when the master laser wavelength is detuned to a longer wavelength ($\Delta\lambda$ is positive) than the slave laser fundamental mode, a flat frequency response can be achieved with a large 3-dB bandwidth enhancement. Figure 4(a) shows the optical spectra for such cases. The injection power is again held constant (9.03 dB) and the master laser is detuned to longer wavelengths than the slave laser. The higher order mode is suppressed in this case also with a side mode suppression ratios of >70dB for detuning values of 0.208, 0.582, and 0.778nm. Corresponding frequency responses are shown in Fig. 4(b), with a record 38 GHz 3-dB bandwidth at $\Delta\lambda$ =0.21nm. Note again that the data shown in Fig. 4(b) includes the system parasitics and has rippling due to the cleaved fiber similarly to Fig. 3(b).

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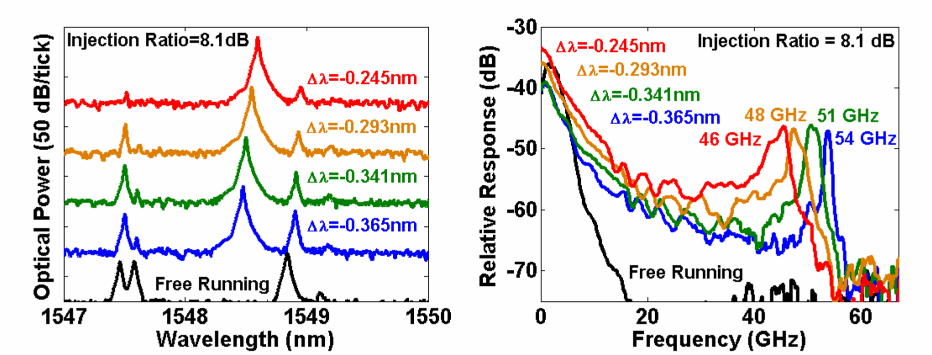

Fig. 3. (a), Optical spectra and (b) frequency response of 10 µm 1550-nm multimode VCSEL under optical injection with constant injection ratio (~8.1 dB) and negative detuning. Black traces are free running MM VCSEL. The frequency response curves are raw data which includes VCSEL parasitics (10 GHz) and measurement system parasitics such as the electric probe (40 GHz), photo-detector (50 GHz) and the bias tee (50 GHz). The ripples in the frequency response are caused by reflections off of the cleaved fiber, and can be reduced by switching to a lensed fiber.

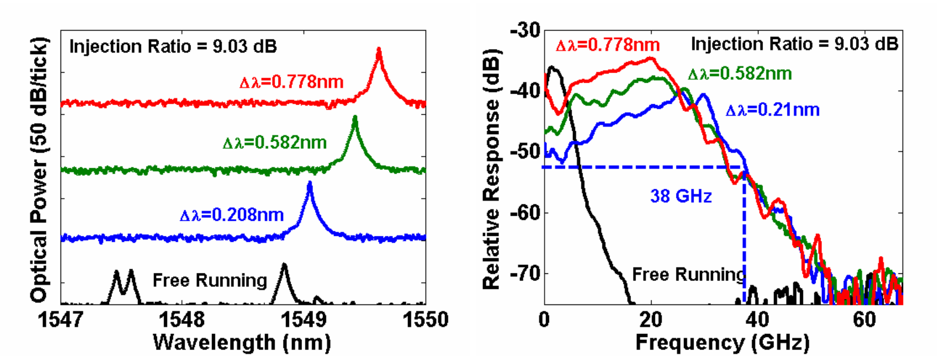

Fig. 4. (a). Optical spectra and (b) frequency response of 10 µm 1550-nm multimode VCSEL under optical injection with constant injection ratio (~9.03 dB) and positive detuning. Black traces are free running MM VCSEL. The frequency response curves are raw data and include the system parasitics similar to Fig. 2(b). The ripples in the frequency response are caused by reflections off of the cleaved fiber, and can be reduced by switching to a lensed fiber.

3. Spatial detuning

In the previous section we explored optically injection locking the fundamental mode due to its spatial mode profile being similar to the single-mode case. In this section we investigate injection locking of higher order transverse modes and spatial detuning to preferentially select modes. A 15 µm aperture MM VCSEL biased at 12 mA with 1 mW output power and a lensed SM fiber are used for this experiment to provide a highly multimode slave laser and to provide better selective coupling respectively. Additionally, the master laser was replaced with an external cavity tunable laser with an erbium-doped fiber amplifier (EDFA) to achieve high injection ratios due to the large coupling loss. In Fig. 5(a) we see the optical spectra for the MM VCSEL where output coupling is optimized (~12 dB coupling loss). The first order mode is the dominant mode in this case. Optically injection locking to achieve resonant frequency enhancement on this mode results in a double peaked frequency response due to the degeneracy of the polarization modes (Fig. 5(b)).

Spatially scanning the lensed fiber across the aperture of the VCSEL to make the fundamental mode the dominant mode, results in the data shown in Fig. 6(a) (black trace). Optically injection locking the dominant (fundamental) mode now results in the single peak resonance frequency enhancement. 30 GHz resonance frequency is achieved at a detuning of

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-0.136nm with 40 dB higher-order mode suppression (Fig. 6(b)). This result shows that performance enhancement is possible by spatially selecting preferable spectral characteristics of the MM VCSEL

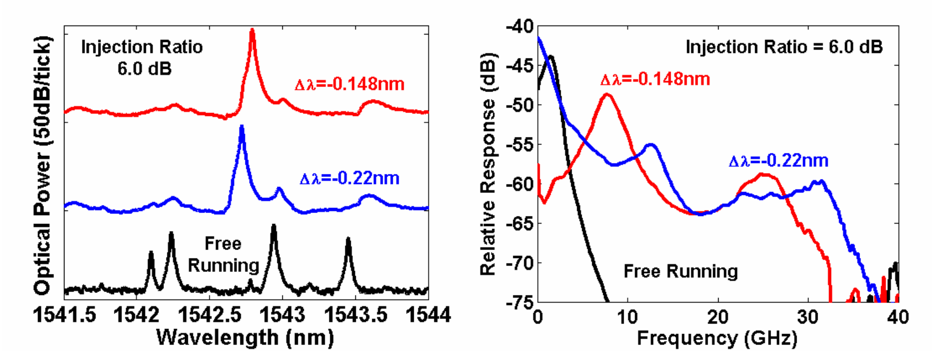

Fig. 5. (a). Optical spectra and (b) frequency response of 15 μm 1550-nm multimode VCSEL under optical injection with constant injection ratio (~6 dB) and negative detuning with 1st order mode selected as the dominant mode. Dual peak in frequency response is due to dual polarization modes of the 1st order mode. Black traces are free running MM VCSEL. The frequency response curves are raw data and include the system parasitics similar to Fig. 2(b).

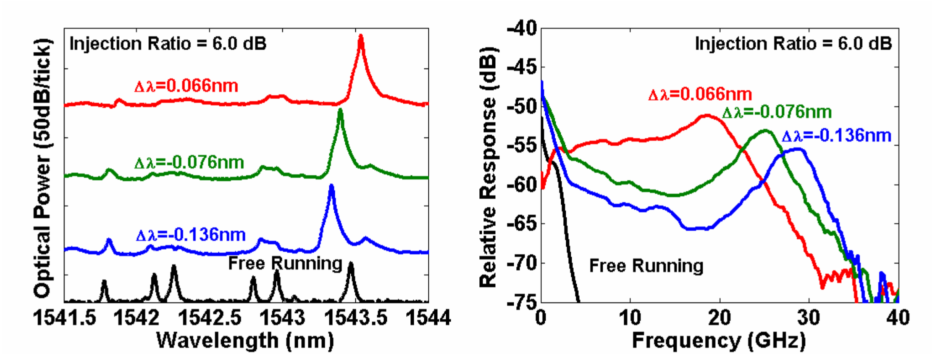

Fig. 6. (a). Optical spectra and (b) frequency response of 15 μm 1550-nm multimode VCSEL under optical injection with constant injection ratio (~6 dB) with fundamental mode selected as the dominant mode. .Black traces are free running MM VCSEL. The frequency response curves are raw data and include the system parasitics similar to Fig. 2(b).

4. Conclusion

Record resonance frequency and 3-dB bandwidth enhancement are shown for a directly modulated multimode 1550-nm VCSEL under optical injection locking. Spectral detuning for transverse mode selection was also shown to improve performance and provide tenability of frequency response. Results are limited only by system parasitics and maximum master laser output power, which if alleviated will result in performance similar to a single-mode OIL VCSEL. Furthermore, this technique will also improve performance for 850 nm and 980 nm MM VCSELs.

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