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Cascaded Injection-Locked 1.55-µm VCSELs for High-Speed Transmission

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Abstract: We demonstrate high-speed laser transmitters with low-frequency components using a novel cascaded injection-locking scheme. Tailorable RF response with bandwidth about 52 GHz can be obtained by adjusting locking parameters of the two slave lasers independently.

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

1. Introduction

Very high-speed, low-cost optical transmitters are critical components for next generation 100-Gb/s Ethernet and local area networks (LANs). Optical injection locking (OIL) has been shown as a very effective technique to increase the resonance frequency, hence the bandwidth of a directly-modulated semiconductor laser [1-3]. We have shown that the VCSEL cavity essentially works as a red-shifted high-Q optical amplifier under high-power optical injection [3], thus providing strong single-sideband amplification of the modulation signal up to frequency range that is close to one order of magnitude higher than that of free-running VCSELs [2]. In this work, we leverage the bandwidth enhancement of OIL-VCSELs, and demonstrate a novel configuration with modulation characteristics that is scalable and tailorable using cascaded OIL-VCSELs.

2. Experimental setup and results

Fig. 1 shows the schematic of cascaded OIL-VCSEL transmitters. Fig. 1(a) and (b) depict two different modulation schemes. The modulation is imposed onto the first VCSEL via direct current modulation in (a), whereas the modulation is delivered by externally modulating a Mach-Zehnder modulator (MZM) in (b). In both cases, the master laser is a commercial CW DFB laser (60 mW max). The VCSELs are ~1.55 µm (~1 mW) with buried tunnel junction (BTJ) structure designed for high speed operation [4]. They are wire-bonded onto SMA mounts with a limiting parasitic response of ~10 GHz.

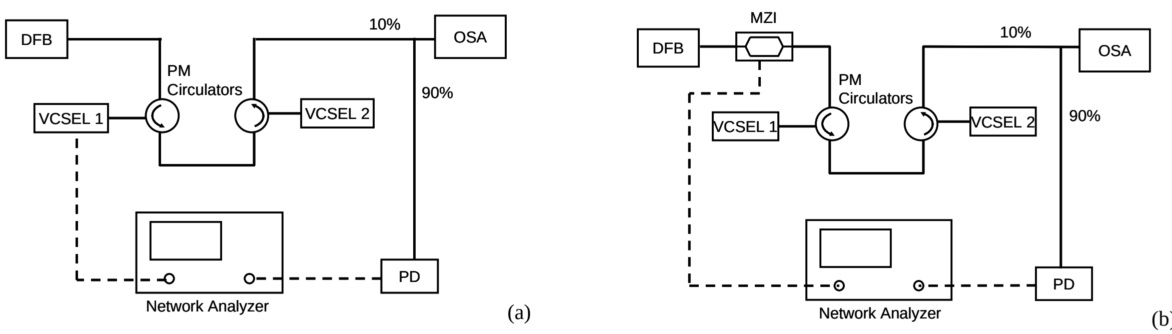

Fig. 1 Schematic of cascaded injection-locked VCSEL transmitters. (a) Modulation signal provided by the direct modulation on the first VCSEL (b) Modulation signal provided by the external modulation on the MZM (PM: polarization maintaining, PD: photodetector, OSA: optical spectrum analyser, MZM: Mach-Zehnder Modulator) Solid lines: optical path; dashed lines: electrical path

Fig. 2 shows the frequency response of the first scheme indicating in Fig. 1(a) without correction for VCSEL parasitics. The free-running VCSEL has a bandwidth up to 10 GHz. With the first VCSEL being injection-locked by a CW master laser and the second VCSEL unbiased, a bandwidth enhancement up to 30 GHz is obtained. The raw data of this modulation without de-embedding the cable and detector loss (32GHz) is shown by the dashed line in Fig. 2(a). To further enhance the modulation response, a second VCSEL can be cascaded and injection-locked by the output of the first OIL-VCSEL. The detuning value needs to be adjusted (by adjusting the slave laser wavelength) so that the second VCSEL cavity is locked at a redder wavelength to the master to give enhancement at frequencies greater than the resonance frequency that is already achieved by the first OIL-VCSEL. The frequency response with cascaded OIL-VCSELs is shown in Fig. 2(a) in solid lines. Different lines are conditions with different detuning values. The cascading effect is clearly seen by the two peaks. The frequency response can be tailored to have either damped low resonance frequency or peaked high resonance frequency by adjusting the injection power and the detuning values [1, 2]. Therefore, in this cascaded configuration, there are four independent parameters can be tuned to have a desired response.

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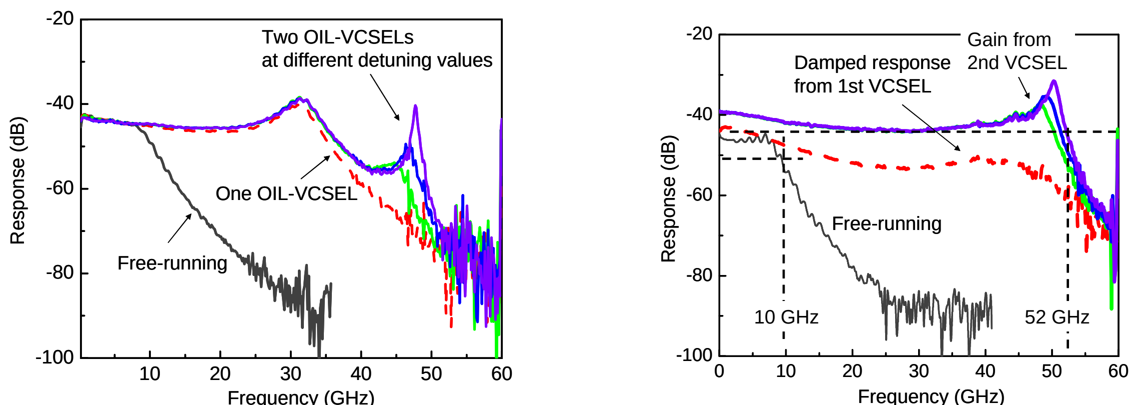
For digital transmission, a flat response with large bandwidth is preferred. Figure 2 (b) shows how this can be attained by adjusting the two slave laser OIL parameters. In this case, we adjust the first VCSEL to lock at a red-detuning condition ($\lambda_{master} > \lambda_{slave}$). A damped resonance ~40 GHz is obtained shown by the dashed line in Fig. 2(b). Although the bandwidth is limited by the droop in the middle of the response, the response does not drop fast at high frequency. Adding a second VCSEL, the total response efficiency is increased and a flat response up to 50 GHz is obtained in Fig. 2(b). A 3-dB bandwidth of 52 GHz is achieved using low-frequency (10 GHz) devices.

The detuning dependence of the cascaded structure is the same as that for a single directly-modulated OIL-VCSEL as demonstrated in [3]. However, it is noted that the second VCSEL is actually kept under CW operation and the modulation signal is provided by an equivalent modulated-master light to the second VCSEL. This observation can be extended to a new scheme shown in Fig. 1(b) where the modulation signal is carried by the master laser even for the first VCSEL. A MZM is used to provide the modulation because the high power DFB laser used in the experiment can not be directly modulated.



(a) (b)

Fig. 2 Frequency response of the first scheme shown in Fig. 1 (a) where the first slave VCSEL is directly modulated. (a) peaked response showing the cascading effect (b) damped response tailored by adjusting the injection power and the detuning values of the two OIL-VCSELs.

In Fig. 3, the dashed dark line shows the link response without any OIL-VCSELs having a 3-dB bandwidth of 25 GHz. When the first VCSEL is turned on and injection-locked by the modulated master light, the modulation response is increased and bandwidth increases to 36 GHz. Adding a second OIL-VCSEL, the bandwidth is further increased to 47 GHz. The data is again raw data without de-imbedding. The shape of the resonance peaks and total response can be tailored by adjusting the injection power as well as the detuning values of the two VCSELs.

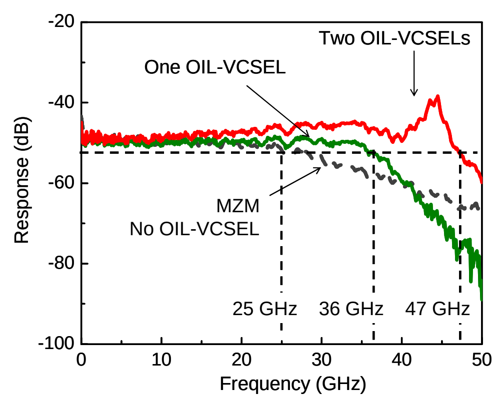


Fig. 3 Frequency response of the second scheme in Fig. 1 (b) where the signal is from external modulation of the master laser. Bandwidth of ~ 47 GHz is achieved using two OIL-VCSELs.

3. Conclusion and Discussion

We present a novel cascaded OIL-VCSEL scheme, which is promising to attain very high-speed laser transmitters using low-cost low-frequency devices. There is no apparent distinction between the master modulation and slave modulation schemes for bandwidth improvement. We show a tailorable modulation response with two slave lasers. This scheme is promising for scaling up by cascading more VCSELs in a daisy chain.

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