Novel cascaded injection-locked 1.55-µm VCSELs with 66 GHz modulation bandwidth

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Abstract: We demonstrate a novel cascaded configuration of optically injection-locked (COIL) VCSELs, which enables a wide and tailorable direct modulation bandwidth. Up to 66 GHz bandwidth is achieved using VCSELs with an original, free-running 10 GHz bandwidth. Different configurations of cascading are discussed in detail with the focus on optimizing the modulation bandwidth. We also discuss scaling capability of this technique to achieve tailorable modulation response.

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

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1. Introduction

There is an ever-increasing demand of very high-speed, low-cost optical transmitters to transmit analog and digital signals over optical fibers. High-speed transmitters are enabling components for not only the RF and millimeter-wave applications, but also next generation 100-Gb/s Ethernet and local area networks (LANs). Over the past ten years, much effort has been put into developing wide-bandwidth lasers and modulators. Devices working at wavelength around 1.55 µm are preferred due to more mature technologies of

#87159 - $15.00 USD Received 4 Sep 2007; revised 16 Oct 2007; accepted 20 Oct 2007; published 25 Oct 2007

the link and other components. The largest bandwidth reported of directly-modulated diode lasers at 1.55 μm is 30 GHz measured from a multiple-quantum-well laser [1] as well as a DBR laser [2]. The nonlinear gain effect and the carrier transport lifetime of the material system at 1.55 μm are the main hurdles that prevent the modulation speed being engineered even higher. On the other hand, the external modulators are demonstrated with impressive achievements. Up to 105 GHz and 150 GHz modulation have been shown on a Ti:$LiNbO_3$ traveling wave modulator [3] and a polymer electro-optic modulator [4], respectively. However, the half-wave voltage, V_π, is currently still very high, making it difficult for system applications. Long-term stability of polymer materials is still undergoing development. In addition, overall design and fabrication process of these devices are complex and costly. Therefore, a very high-speed, direct-modulated laser is highly desirable for the rapidly-growing applications.

Optical injection locking (OIL) has been shown as a very effective technique to increase the resonance frequency [5, 6]. A record resonance frequency of 72 GHz was reported on a directly modulated injection-locked DFB laser [5]. High-speed vertical-cavity surface-emitting lasers (VCSELs) are also of great interests for many applications due to their cost-effective fabrication. Although the modulation speed of VCSELs is limited by device parasitics to ~20 GHz, the dynamic performance can be drastically improved by applying strong optical injection locking [6, 7]. However, for both types of lasers under OIL, a significant reduction in the modulation efficiency is seen between low frequencies and the resonance frequency. As a result, the 3-dB bandwidth is typically much lower than that of the resonance frequency.

By leveraging the bandwidth enhancement property of directly-modulated VCSEL under OIL, we recently proposed and demonstrated preliminary results of a novel cascaded injection-locked VCSEL configuration to attain tailorable and broad modulation bandwidth of 50 GHz [8]. This configuration had never been investigated before. In this paper, we present a more comprehensive study on the cascaded OIL configurations of two VCSELs to achieve a wide and tailorable modulation bandwidth. A record bandwidth of 66 GHz is attained by cascading two OIL VCSELs. Finally, we discuss the scaling capability of this approach to achieve ultra-high bandwidth modulation (> 100 GHz) eventually. This leads to a structure of multiple COIL slave lasers in a daisy chain, all being injection-locked by a single master laser, with modulation signal applied directly to one or multiple slave lasers.

2. Cascaded optical injection locking (COIL)

The resonance frequency enhancement of an OIL laser is primarily due to the red-shifted cavity resonance of the slave laser, which resulted in the amplification of the modulation sideband of either the master or the slave laser [7]. The frequency difference between the injection-locked laser mode (same as the master mode) and the cavity mode corresponds to the resonance frequency in the RF domain. In this paper, we extend the typical OIL configuration by adding one more slave laser, injection-locked by the same master laser but with a different detuning, to achieve an even larger difference between the OIL mode and the cavity mode. Hence a second resonance peak is created in the modulation response at an even higher frequency.

This COIL idea is schematically illustrated in Fig. 1. The first slave laser, colored in blue, is injection-locked and directly modulated, while the second slave laser, colored in red, is kept under CW operation while injection-locked by the output of the first stage. The slave laser is lasing at the master mode when it is injection-locked shown in gray, while its cavity resonance is red-shifted and exhibit amplified spontaneous emission in the optical spectrum, shown in blue and red for the first stage and the second stage, respectively. When the modulation lower sideband (with lower frequency) scans over the cavity mode and experiences the amplification, a resonance peak shows up in the

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frequency response at the frequency corresponding to the spacing between the OIL mode and the cavity mode as labeled in the Fig. 1. Since the resonance peak is due to the amplification of the sideband by the slave laser cavity, a second resonance peak exhibits even though the second slave laser is not modulated. Therefore, by repeatedly utilizing the cavity effect based on the understanding of OIL dynamics, it is promising to achieve high-speed devices using COIL.

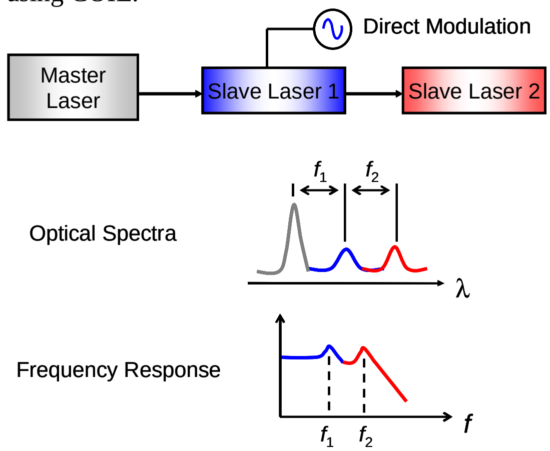

Fig. 1. A schematic explaining the idea of cascaded optical injection locking (COIL).

3. Experiments and results

Experiments are performed to verify the COIL idea. The measurement setup is shown in Fig. 2. A commercial DFB laser is used as the master laser with maximum output power ~ 40 mW. The VCSELs are single mode at 1.55 μm with buried tunnel junction (BTJ) structure designed for high speed operation [9]. They all have threshold current ~ 0.6 mA and > 1 mW output power. The VCSELs are mounted on copper blocks 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 probes. 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 photodetector with 3-dB bandwidth of 84 GHz. A 110-GHz vector network analyzer (VNA), Agilent E8361A, is used to test the small-signal frequency response. All the frequency response shown in this paper is corrected for RF cable loss only.

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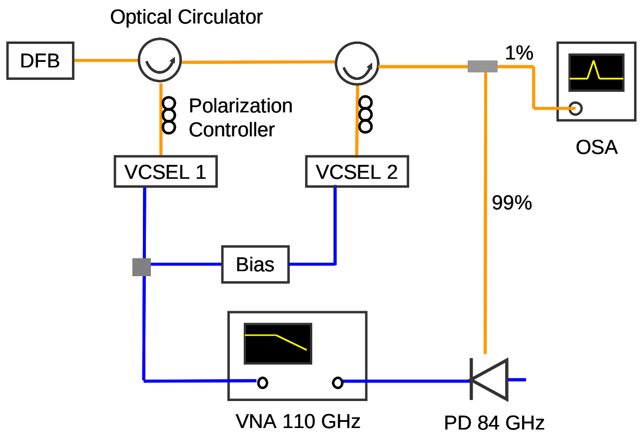

Fig. 2. Experimental setup. Orange lines are optical paths, while blue lines are electrical paths. ML: master laser, PC: polarization controller, OSA: optical spectrum analyzer, VNA: vector network analyzer, PD: photodetector.

The frequency response of a free-running VCSEL is shown in Fig. 3. The device is biased at 3.3, 5, 6.7 and 8.3 times of the lasing threshold. They are designed for 10 Gb/s transmission. The 3-dB bandwidth is about 10 GHz. Both VCSELs used in the experiment show the same modulation characteristics.

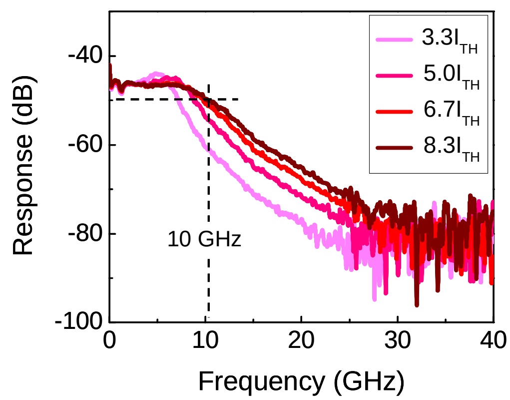

Fig. 3. Frequency response of a free-running VCSEL at various biasing levels.

It has been demonstrated that the frequency response of an injection-locked laser can be tailored by adjusting the wavelength detuning ($\lambda_{master} - \lambda_{slave}$) between the master and the slave laser [6]. On the blue detuning side ($\lambda_{master}<\lambda_{slave}$), the frequency response possesses a sharp resonance peak at a high frequency, but usually associated with a droop in the middle frequencies [5]. According to OIL dynamics, a third pole in the transfer function, which can be derived from injection-locking rate equations, causes a significant reduction in the modulation response between low frequencies and the resonance peak. Therefore, even though the resonance frequency can be maximized in this condition, the modulation bandwidth is limited at a relatively low frequency. On the red detuning side ($\lambda_{master}>\lambda_{slave}$), however, the response is flatter and the resonance peak is damped, but at a lower frequency. This would help obtain a better performance in terms of modulation bandwidth, but the ultimate limit is reduced. Therefore, based on the detuning dependence stated above, there could be two possible configurations to realize COIL, both with the

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purpose to widen the bandwidth.

If one follows the concept described in section 2 directly, the second stage should be detuned to generate a resonance peak at a higher frequency, thus extending the bandwidth even further. In this case, to alleviate the bandwidth limit caused by the third pole of the first stage, OIL on the first stage should be kept at a red detuning condition to attain a flat response. It should also be noted that the resonance frequency enhancement of OIL laser is determined by the injection ratio (P_{master} / P_{salve}) [6], the second VCSEL needs to be locked with a higher power. However, due to coupling and other link loss, the master laser power is usually significantly reduced when it reaches the second stage. Therefore, to maintain a high injection ratio for the second stage, the second VCSEL needs to be biased at a low current level, thus emitting less power. Figure 4 shows the frequency response. Dashed gray line is the response from the first OIL stage only, under an injection ratio of ~14 dB. Since it is red-detuned, no severe droop is observed. Then the second VCSEL is injection-locked with an injection ratio of ~ 16 dB. As expected, the response of two-stage OIL is ameliorated as shown in the solid red line in Fig. 4, and a 3-dB bandwidth of 66 GHz is achieved. This is the highest bandwidth reported of a direct modulated semiconductor laser, to the best of our knowledge.

On the other hand, the first stage can be detuned to the blue side to reach a high resonance frequency, and then the second stage is utilized to compensate the efficiency reduction in the middle frequencies caused by the third pole. The frequency response is shown in Fig. 5. Figure 5(a) shows the frequency response of both one-stage (dashed gray) and two-stage (solid red) OIL VCSELs. The first VCSEL is modulated as well as injection-locked by the master laser with an injection ratio of ~ 12.5 dB and a blue detuning so that the resonance peak is pronounced at 60 GHz as indicated by the gray dashed line in Fig. 5(a). However, the modulation efficiency drops about 20 dB up to 40 GHz. As the second VCSEL is biased and injection-locked by the output of the first stage with an injection ratio ~11 dB and a proper detuning value, a second peak shows up at a frequency between DC and the first resonance peak, and helps increase the modulation efficiency dramatically in the middle frequencies. Similarly as the first stage, the exact location and damping of the second peak can be tuned by adjusting the injection ratio and the detuning value of the second stage. Even though the response is improved by putting in a second VCSEL, the 3-dB bandwidth is still limited by the fast roll-off due to the third pole from the first OIL stage. However, there are totally four parameters, injection ratios and detuning values of two OIL stages, can be tuned to tailor the overall response. If the master laser can be red-detuned for the first stage to relive the dipping at frequencies below the resonance, the compensation brought in by the second stage can be more effective. This is shown in Fig. 5(b) as the first stage is detuned to exhibit a flatter and damped response. And then with the assist from the second stage, a 3-dB bandwidth of 50 GHz is achieved.

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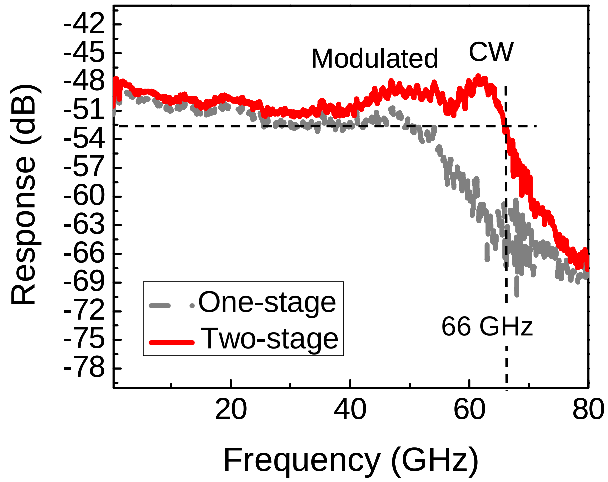

Fig. 4. Frequency response of COIL. The first modulated VCSEL is red-detuned to provide a flat response while the second VCSEL is locked at a longer wavelength to extend the bandwidth. 3-dB bandwidth of 66 GHz is obtained.

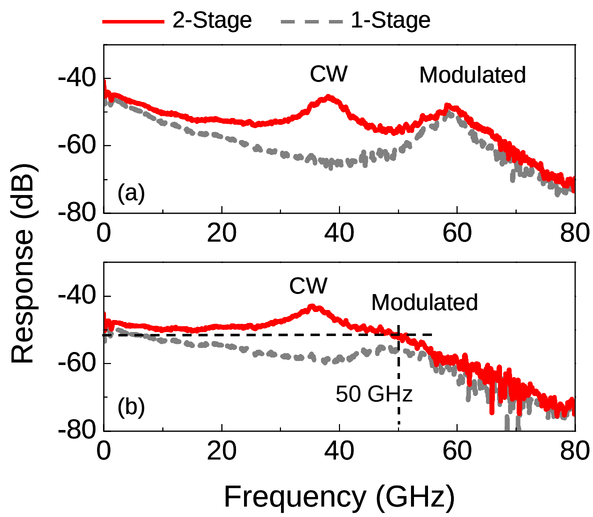

Fig. 5. Frequency response of COIL. (a) The first modulated VCSEL is blue-detuned. Cascading effect is clearly shown by the two resonance peaks. (b) The first modulated VCSEL is red-detuned. A flat response with 3-dB bandwidth of 50 GHz is achieved.

Therefore, as demonstrated above, the first configuration starts with a flat response of the first stage and extends the bandwidth by adding in a second stage. In this case, the second slave laser needs to be locked at a longer wavelength to provide the extra bandwidth, which in turn desires a higher injection ratio. Alternatively, the second configuration takes the advantage of the large resonance frequency on the blue detuning side and uses the second stage to compensate the drop in the middle frequencies, thus resulting in an overall wide-bandwidth response. So the first slave laser is locked at a longer wavelength relative to the second one, which requires a higher injection ratio for the first OIL stage. Both configurations show very impressive improvement on the bandwidth enhancement, even though the first one shows larger bandwidth than the second one (66 GHz vs. 50 GHz), but with higher injection ratio too. They open up great flexibility and tunability for COIL to be employed as an effective technique for high-speed applications.

4. Conclusion and discussion

In conclusion, we present a novel COIL idea, which is promising to attain wide-bandwidth direct-modulated laser transmitters using relatively low-cost and low-speed devices. Two possible configurations that can be employed to achieve broadband modulation by cascading two stages are shown in detail. Demonstrated on two 1.55-μm VCSELs, a record 3-dB modulation bandwidth of 66 GHz is obtained. Furthermore, the frequency response can be easily tailored by adjusting the injection-locking parameters of the two stages.

In addition, this system has the scaling-up potential to eventually reach ultra-wide band modulation (> 100 GHz) by cascading more slave lasers in a daisy chain structure, as long as the master laser has enough power to stably lock the slave laser that has the largest detuning value, as shown schematically in Fig. 6. In such a multi-stage scenario, to further simplify the structure and reduce the size and the cost, the circulators could be possibly replaced by power splitters between different stages. Integration of all the slave lasers on a same chip might be considered as a more practical solution. For an integrated device, the modulation signal can be applied simultaneously to all the slave lasers. This would provide equal distribution of the RF signal to all the devices, thus avoiding the loss of the signal during transmission from one stage to another. Therefore, the modulation efficiency may possibly be enhanced, especially at high frequencies.

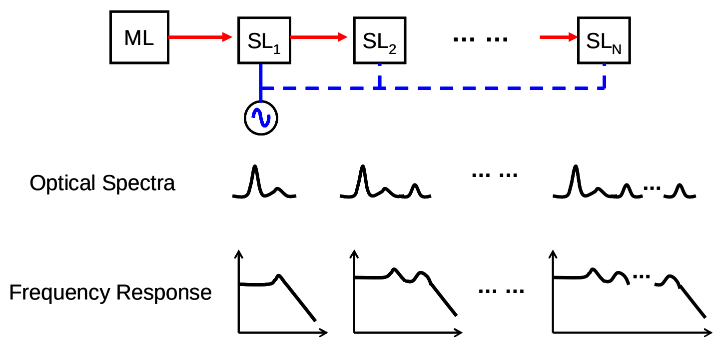

Fig. 6. Schematic of a multiple COIL transmitter with optical spectra and frequency response shown after each cascaded stage. The modulation signal can be applied directly to the first slave laser only or to all the slave lasers simultaneously. (ML: master laser, SL: slave laser)

Acknowledgements

We acknowledge DARPA aPropos/Army Research Office under #W911NF-06-1-0269 and German Research Council (DFG).