High-Speed Laser Transmitters Using Cascaded Optical Injection Locking

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Abstract We demonstrate high-speed laser transmitters with relatively low-frequency devices using cascaded optical injection locking. Tailorable frequency response with a bandwidth of 52 GHz is obtained by adjusting locking parameters of the two slave lasers independently.

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Introduction

Optical injection locking (OIL) is a very effective technique to increase the resonance frequency, hence the bandwidth of directly-modulated semiconductor lasers. This has been demonstrated on DFB lasers and VCSELs [1, 2]. The physics of the resonance enhancement was also studied and shown that the slave laser cavity essentially works as a red-shifted optical amplifier in the high-power injection regime, thus providing strong single-sideband amplification of the modulation signal up to frequency range that is one order of magnitude higher than that of free-running lasers [3]. Recently, we proposed and demonstrated a novel cascaded OIL (COIL) configuration, where one master laser is used to lock two slave lasers in series. In this work, we demonstrate the bandwidth enhancement up to 52 GHz of two-stage COIL using 1550-nm VCSELs, by modulating either the slave laser directly or the master light externally. The shape of the frequency response can be easily adjusted by tuning the injection ratios (P_{master} / P_{slave}) and the detuning values ($\lambda_{\text{master}} - \lambda_{\text{slave}}$) of the two OIL stages as desired by different applications.

Experimental Setup

Fig. 1 shows the experimental setup of cascaded optical injection locking (COIL). The modulation signal is delivered by either directly modulating the first VCSEL, shown by path (a), or by externally modulating a Mach-Zehnder modulator (MZM), shown in path (b). The master laser is a CW DFB laser with output power up to 40 mW for strong injection study. The VCSELs used as slave lasers are ~1.55 µm with buried tunnel junction (BTJ) structure designed for high speed operation (10 GHz) [4]. Optical injection locking is configured using optical circulators. All the optical components are polarization maintaining (PM). The frequency response is measured by Agilent E8361A network analyzer. The RF cable used in the system has a 3-dB bandwidth about 40 GHz and the photodetector has a 3-dB bandwidth about 34 GHz. No bias or temperature control is applied to the MZI during the experiment. 10% of the output signal is fed to an optical spectrum analyzer to monitor the injection locking condition.

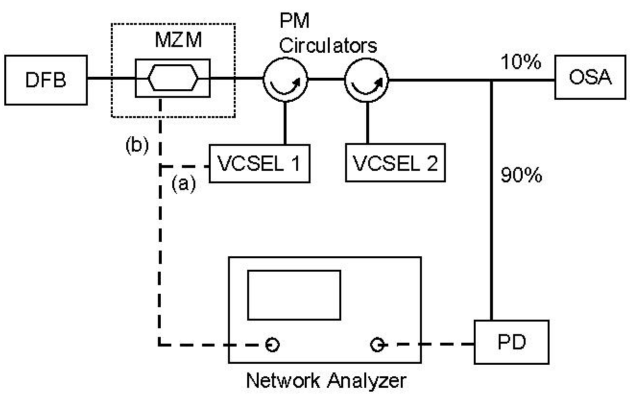

Fig. 1 Experimental Setup (a) direct modulation on the slave laser (b) external modulation on the master laser (MZM: Mach-Zehnder modulator, PM: Polarization maintaining, PD: Photodetector, OSA: optical spectrum analyzer)

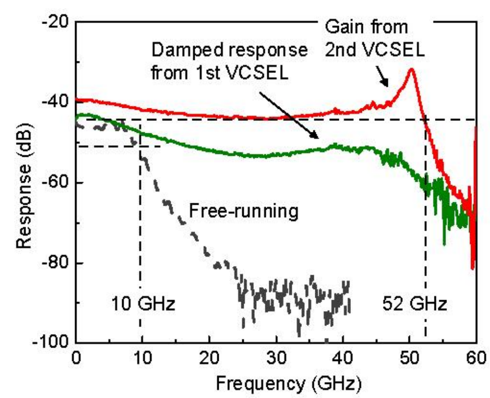

Fig. 2 Frequency response of COIL when the VCSEL is modulated. The first stage is red-detuned to result in a damped response. 3-dB bandwidth of 52 GHz is obtained.

Results

Fig. 2 shows a wide band flat response of a COIL transmitter when the VCSEL is directly modulated shown by (a) in Fig. 1. In this case, the first VCSEL is locked at a red-detuning condition. Hence a damped resonance ~40 GHz is obtained shown in green in Fig. 2. 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 52 GHz is obtained shown in red in Fig. 2. In this case, even thought the first VCSEL is directly modulated, it is noted that the second VCSEL is kept under CW operation and the modulation signal is provided by an equivalent modulated-master light to it. This observation can be extended to a new scheme shown in Fig. 1 by path (b), where the modulation signal is carried by the master laser for both VCSELs. A MZM is used to modulate the master light.

Fig. 3 and 4 show the measured frequency response. The dashed dark lines show the link response without any OIL VCSELs, which is equivalent to the response of the MZM. It has a 3-dB bandwidth about 25 GHz. When the first VCSEL is turned on and injection-locked by the modulated master light, the modulation efficiency is boosted up and the bandwidth has increased > 35 GHz, as shown by the green lines in the two figures. When the second VCSEL is also turned on and tuned to a proper wavelength, the total response can be gained up to ~ 50 GHz as shown by the red curves. The resonance peaks are due to the RF amplification from the shifted VCSEL cavities. The shape of the resonance peaks, thus the shape of the total response of a COIL transmitter, can be tailored by adjusting the locking conditions of the VCSELs. The tailoring capability of the total response is illustrated by the difference of Fig. 3 and 4.

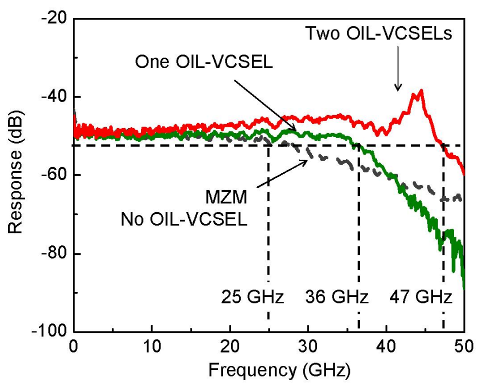

Fig. 3 A damped frequency response of externally modulated COIL. Bandwidth of ~ 47 GHz is achieved.

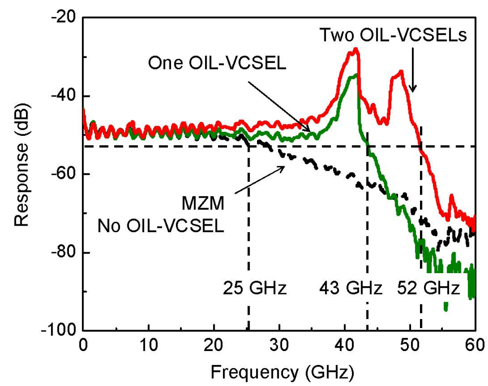

Fig. 4 A resonant frequency response of externally modulated COIL. Bandwidth of ~ 52 GHz is achieved.

Conclusions

We present 52-GHz modulation bandwidth of a COIL laser transmitter using low-cost, low-frequency devices. There is no apparent distinction between the master modulation and slave modulation schemes for bandwidth improvement. The modulation response can be tailored to different desired shapes for different applications by adjusting the injection-locking parameters of the slave lasers independently.

Acknowledgements

We acknowledge DARPA aPropos/Army Research Office under contract # W911NF-06-1-0269.

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Xiaoxue Zhao received her BS degree in electronics from Peking University, Beijing, P.R. China, in 2003, and is currently pursuing her Ph.D. degree in electrical engineering and computer science at the University of California, Berkeley. Her research interests are in microwave photonics, high-speed modulation characteristics of diode lasers, optical injection locking, and optical communication.