Optically Injection-Locked VCSEL as a Duplex Transmitter/Receiver

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***Abstract*—We propose and experimentally demonstrate a novel communication system scheme with an optical injection-locked vertical-cavity surface-emitting laser (OIL-VCSEL) acting both as a transmitter and as a receiver, under an identical forward-bias condition. We show that an OIL-VCSEL can function as a receiver with a small signal modulation bandwidth of ~20 GHz, and for large signal digital modulation with data rate as high as 12 Gb/s.**

***Index Terms*—Optical injection-locking (OIL), vertical-cavity surface-emitting laser (VCSEL).**

I. INTRODUCTION

SINCE its first demonstration in 1976, optical injection-locking (OIL) has been actively investigated in various applications in optical communications and microwave photonics [1]. Most injection-locked systems that involve data transmission use locked lasers as transmitters [2]. In this letter, we explore a novel OIL scheme with an injection-locked vertical-cavity surface-emitting laser (VCSEL) functioning both as a transmitter and as a receiver, both for the same forward-bias condition. Small signal measurements are performed on both the VCSEL as a transmitter and as a receiver, with an injected power up to 9.5 dBm, which corresponds to an injection ratio of 5.1 dB. We also perform large signal digital modulation with data rates as high as 12 Gb/s, utilizing the VCSEL as a detector. To the best of our knowledge, this is the first proposal and demonstration of an injection-locked VCSEL functioning both as an electrical-to-optical and an optical-to-electrical converter. This discovery can lead to new and simpler optical communications systems, ranging from metro networks to short optical interconnects.

In this letter, half-duplex operation is experimentally demonstrated. We further propose a cost-saving communication system using a full-duplex VCSEL in the home, and a conventional transmitter/receiver in the central office (CO), as depicted in Fig. 1. The full-duplex configuration would be achievable if the data is either time-division multiplexed or frequency-division multiplexed, as allowed by many communication protocols. As our system relies on injection-locking for both the transmitter and receiver operation, it is essential for the CO master laser wavelength to be within locking range of the VCSEL; this corresponds to ensuring that the VCSEL is temperature stabilized to within a ~10°C range for a 1-nm locking range.

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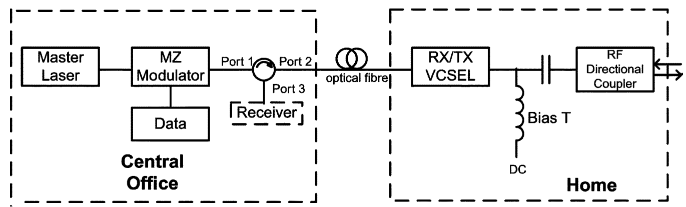

Fig. 1. Proposed full-duplex system with an OIL-VCSEL in the home.

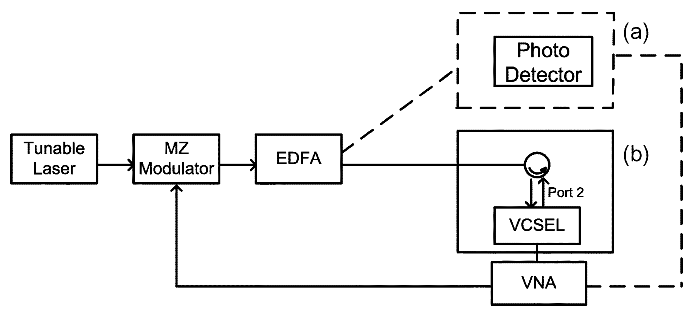

Fig. 2. Experimental setup for measuring the OIL-VCSEL functioning as a receiver. (b) VCSEL as receiver is compared with (a) u^2t photodiode, with a responsivity of 0.6 A/W.

II. TRANSMITTER/RECEIVER OIL-VCSEL S21

A. Experimental Setup

The transmitter/receiver VCSEL used in these experiments is a 1.57-μm InGaAlAs–InP buried tunnel junction VCSEL [3]. The VCSEL threshold is 0.5 mA, and was operated at a forward bias of 2 mA for both the transmitter and receiver experiments. The VCSEL was temperature controlled to 25 °C. The VCSEL was probed with a 50-GHz probe and bias-T, with the AC port of the bias-T serving as the microwave signal input in the VCSEL-transmitter case (similar to [1]), and as an output in the VCSEL-receiver case.

The experiment setup for using the VCSEL as a receiver is shown in Fig. 2. An HP 8164A tunable laser was used as the master laser, and the light was externally modulated with a 10-Gb/s Mach–Zehnder (MZ) modulator with a $V_\pi = 2$ V. The modulator output was amplified by an erbium-doped fiber amplifier (EDFA), fed through a polarization-maintained (PM) circulator, then coupled into the VCSEL using an antireflection-coated lensed PM fiber, which was aligned using a piezo-electric nano-positioning stage (coupling loss of 2.1 dB). The polarization of the injected light was adjusted

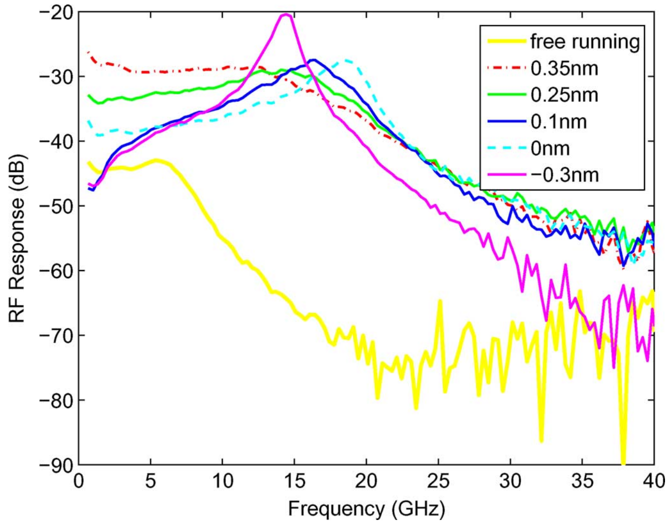

Fig. 3. Frequency response of the OIL-VCSEL transmitter at 0.6-dB injection ratio, forward-biased at 2 mA.

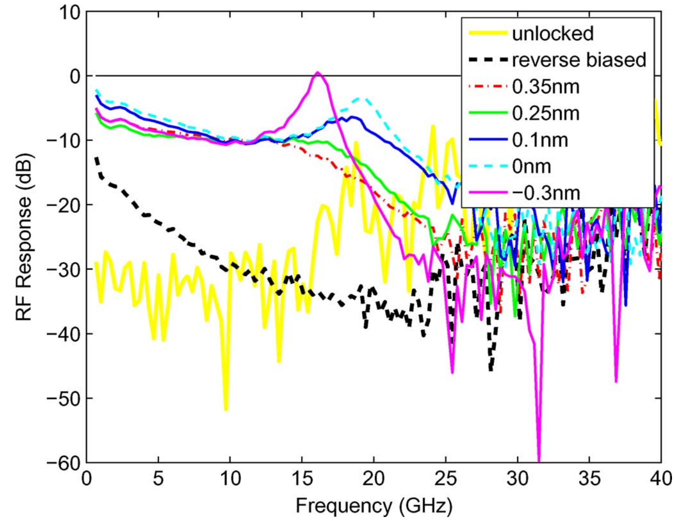

Fig. 4. Frequency response of the VCSEL as a receiver: unlocked, 2-mA bias; injection-locked at a 0.6-dB injection ratio, 2-mA forward bias; reverse biased at -1 V. The data is the S21 relative to the response of the u^2t PD. Coupling losses have been de-embedded.

to match the fundamental polarization mode of the VCSEL, as in [4]. An Agilent E8361A 67-GHz Network Analyzer (VNA) was used to characterize the small signal frequency responses (S21). In the experiments for the VCSEL receiver, two sets of S21 measurements were performed: first, the S21 of the link consisting of the modulator, EDFA, and a 50-GHz u^2t *photonics* photodetector (PD), as shown in Fig. 2(a); and second, for the link consisting of the modulator, EDFA, and the injection-locked VCSEL, as shown in Fig. 2(b). For the measurement shown in Fig. 4, the S21 data shown is the difference of these two measurements, with VCSEL coupling loss excluded. This yields the response of the OIL-VCSEL, relative to the commercial PD.

B. Results and Discussions

We obtain frequency responses for various injection conditions, for each configuration. Figs. 3 and 4 show a comparison of the frequency responses of the directly modulated OIL-VCSEL and the OIL-VCSEL receiver, under the same injection ratio of 0.6 dB, for the same detuning values, for a 2-mA forward bias. The injection ratio is defined as the power incident on the VCSEL, minus the VCSEL output power, with the coupling losses accounted for. Wavelength detuning is defined as the wavelength difference between the master and the follower lasers [1].

In Fig. 4, the OIL-VCSEL receiver scheme, the curves represent an S21 of the VCSEL detected signal relative to the u^2t PD, with the line at 0 dB representing the u^2t PD response. When injection-locked, the VCSEL functions as a detector with a bandwidth of $\sim$20 GHz. For frequencies below 15 GHz, the response is > -10 dB, i.e., the OIL-VCSEL has about a 10$\times$ lower responsivity than the u^2t PD. For the unlocked VCSEL case, the response is negligible, indicating that a conventional forward-biased VCSEL does not function as a receiver. This is similar to the operation of a resonant cavity-enhanced (RCE) PD [5], where wavelengths mismatched to the Fabry–Pérot modes are reflected. When reverse biased at 1 V, the response is frequency-limited by the depletion capacitance of the VCSEL pn-junction; the device was not designed for high-speed photodetection.

In both transmitter and receiver configurations, similar trends are observed as the master wavelength is tuned from the red to the blue side relative to the free running follower (i.e., detuning ranging from 0.35 to -0.3 nm): 1) the laser resonance frequency increases, and 2) the damping decreases. In the case of the VCSEL operating as transmitter, this behavior is consistent with what has been observed experimentally [1] and described theoretically [6]. In the OIL-VCSEL receiver case, the response in Fig. 4 agrees qualitatively with the predicted carrier population response predicted in [6], indicating that the response of the OIL-VCSEL receiver is dictated by the injection-locking dynamics. As shown in the experimental results, detection is only possible under the injection-locking condition, within the locking bandwidth. The wavelength response characteristic is determined by the locking dynamics, rather than the RCE effect, as found in reverse-biased VCSELs such as in [7]. When injection-locked, the VCSEL's lasing wavelength matches that of the external field, thus the external light is coupled into the cavity, modifying the VCSEL's operating conditions. This process is accurately described by the injection-locked rate equations [6], showing that the carrier density in the laser is depleted due to the external field increasing the rate of stimulated emission. This leads to an measurable electrical signal at the VCSEL contacts. In contrast to RCE PDs [5], this effect is observable under forward-bias rather than reverse-bias.

Measurements were also performed for various injection ratios, ranging from -7.4 to 5.1 dB. For an increasing injection ratio, we observe that the resonance frequency increases in both cases. This indicates that the OIL-VCSEL receiver bandwidth can be enhanced for a higher injected power. This can be viewed as a trade-off resulting in a lower power budget.

III. OIL-VCSEL Receiver—Digital Modulation

A. Experimental Setup

The OIL-VCSEL functioning as a receiver is characterized under large signal conditions. The master laser is externally modulated with a 10-Gb/s MZ modulator using an Anritsu

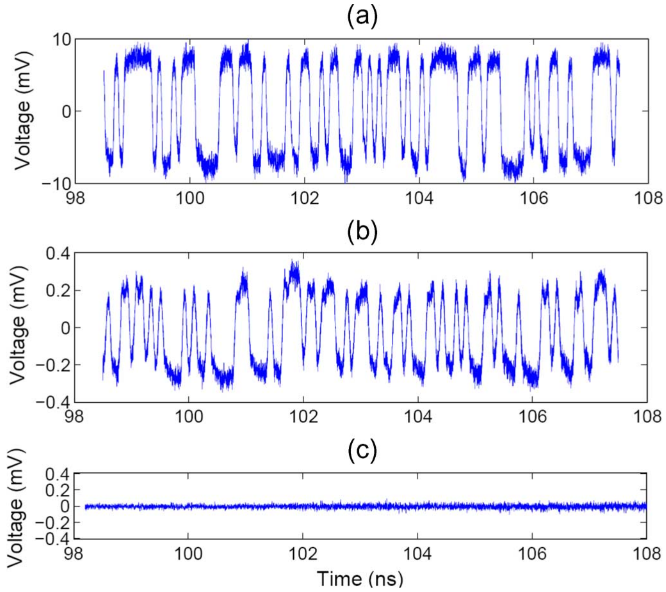

Fig. 5. Modulation waveforms at 12 Gb/s. (a) Using the u^2t detector; (b) OIL-VCSEL receiver for a 0.6-dB injection ratio, 0.25-nm detuning; (c) free-running VCSEL. Waveform data was averaged 256 times.

MP1763B Pulse Pattern Generator with a pseudorandom binary sequence of 2^{15} at bit rates ranging from 1 to 12 Gb/s, with a peak-to-peak voltage of 1.5 V. Two measurements were performed using a 50-GHz HP 83480A Digital Communications Analyzer: first, the electrical signal from the OIL-VCSEL receiver; and second, the signal from the u^2t PD. This allowed a comparison of the received signals of the two detectors.

B. Results and Discussions

Fig. 5 shows experimental modulation waveforms with a bit rate of 12 Gb/s. A comparison is made between the u^2t PD, the OIL-VCSEL, and the unlocked VCSEL as a receiver. For the case of the unlocked VCSEL, there is very little received signal, as shown in Fig. 5(c). As shown in (b), the transmitted data can clearly be detected by the OIL-VCSEL, although with a lower amplitude in comparison with the u^2t PD (a). The amplitude of the digital data received by the OIL-VCSEL is approximately 13 dB lower (by a factor of $\sim 25\times$) than that of a commercial detector, in agreement with the small-signal measurement (10 dB). As an example power-budget for our proposed full-duplex VCSEL system, a 10-dBm transmitter with an injected power of 0 dBm would leave a 10-dB power budget, which is enough for a communication distance of 100 km.

Eye diagrams were constructed using the waveform data collected, as shown in Fig. 6, for the signals detected by the OIL-VCSEL receiver for various data rates, injection power, as well as wavelength detuning. Open eye diagrams were obtained for bit rates from 1 to 12 Gb/s. The maximum bit rate that was possible to test in this experiment was equipment limited by the 10-Gb/s modulator and the 12-Gb/s pattern generator. Future investigations are required to determine if this scheme can function at higher data rates. Since this is the first observation and an early demonstration of the half-duplex operation in an OIL-VCSEL system, bit-error-rate measurements have not yet been performed.

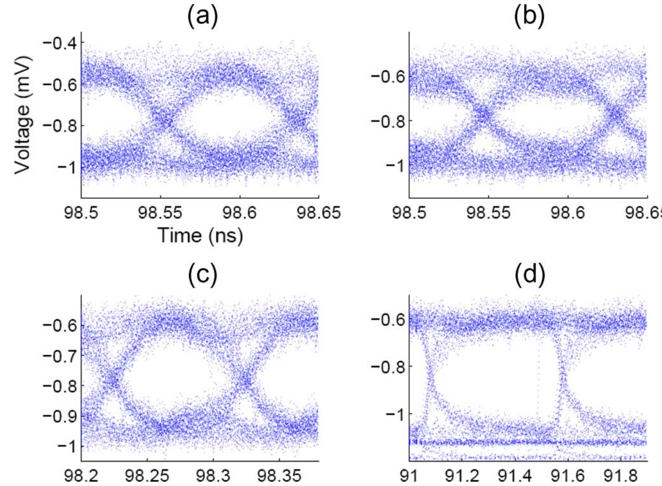

Fig. 6. Experimental eye diagrams for the injection-locked VCSEL receiver: (a) 12 Gb/s with 0.6-dB injection ratio and 0.25-nm detuning, biased at 2 mA; (b) 12 Gb/s with 5.1-dB injection ratio and −0.2-nm detuning, biased at 4 mA; (c) 10 Gb/s with 0.6-dB injection ratio and −0.1-nm detuning, biased at 2 mA; (d) 2 Gb/s with 5.1-dB injection ratior and −0.2-nm detuning, biased at 4 mA.

IV. CONCLUSION

We report a novel scheme of an optically injection-locked VCSEL that can behave as both a transmitter and a receiver, under an identical bias condition. The OIL-VCSEL receiver's performance was evaluated both in small signal and large signal modulation. This discovery has the potential to significantly reduce cost for transponders in optical communication systems.

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