1.3μm Single-Mode VCSEL-by-VCSEL Optical Injection-Locking for Enhanced Microwave Performance

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***Abstract*—Microwave performance of 1.3μm optically injection-locked single-mode VCSELs functioning at room temperature is presented. The experiment has been performed using two identical unpackaged VCSELs on two separate probe-stations. Three-fold increase in the 3-dB cut-off frequency of S_{21} spectra have been observed under VCSEL-by-VCSEL optical injection-locking.**

I. Introduction

Since their arrival a decade ago, the utilization of long wavelength VCSELs has been intensively investigated as reliable last-leg optical sources for short-haul optical communication and data transmission. Successful employment of single-mode long wavelength VCSELs in telecommunication systems faces many challenges, relatively low intrinsic cut-off frequencies being the most pertinent of them. Despite the appearance of VCSELs functioning at 25 [1] and 35 Gbit/s [2], optical injection-locking can be utilized to overcome obstacles such as direct-modulation induced frequency chirping [3] and non-linear distortion [4] as well as to increase the 3-db bandwidth of a VCSEL by increasing its intrinsic cut-off frequency. As VCSEL technology has grown mature [5], the need to thoroughly investigate the application of optical injection-locking for long wavelength VCSELs has become more pertinent. In this paper it is experimentally demonstrated that VCSEL-by-VCSEL optical injection-locking can provide an increase in the intrinsic cut-off frequency and this increase in 3-dB bandwidth is proportional to the injected optical power.

II. Experiment

Here, we present experimental results demonstrating the increase in the intrinsic cut-off frequency of the follower VCSEL. The experimental setup used to study the optical injection behavior of the follower VCSEL is shown in Fig.1. An optical circulator is used to inject optical power from the master VCSEL into the follower VCSEL. The follower VCSEL response is observed at the port 3 of the circulator. The VCSELs used in this experiment are 1.3 μm double intracavity conatct wafer-fused coplanar access monomode VCSELs [5] having a maximum free-running intrinsic cut-off frequency of 4GHz. The strongest advantage of using unpackaged on-chip VCSELs is that the constraints related to package parasitics and hence package cut-off frequency [6] are not encountered and are automatically eliminated. A device response exclusively characteristic of the device and independent of the parasitics can therefore be obtained. VCSEL-by-VCSEL optical injection-locking also helps in avoiding the usage of all sorts of polarization maintaining equipment which is otherwise necessary for injection-locking experiments.

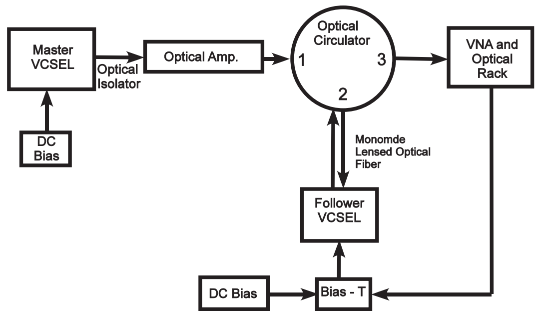

Fig. 1. Experimental Setup. The 1.3μm follower VCSEL was optically injection locked using a 3-port optical circulator. The S_{21} response of the injection-locked VCSEL was observed using an an HP-8510C vector network analyzer (VNA).

The follower VCSEL was biased at 5mA and directly modulated using an HP-8510C vector network analyzer (VNA). The detuning between the two VCSELs was kept at +0.925 nm, where detuning is defined as the difference between the master and follower wavelengths. The chosen detuning value was the one that maximized the RF gain. Due to this positive detuning the S_{21} curves for the optically injection-locked follower VCSEL are highly damped. The damping of the S_{21} curves of an injection-locked laser can be controlled by varying the detuning value between the two lasers. A negative detuning produces sharp resonance resulting in pronounced frequency peaks in the S_{21} curves [6]. The wavelength tuning for the master VCSEL was obtained by varying the master VCSEL bias current. Two separate probe stations (SÜSS Microtec and CASCADE Microtech) are used to collect optical power

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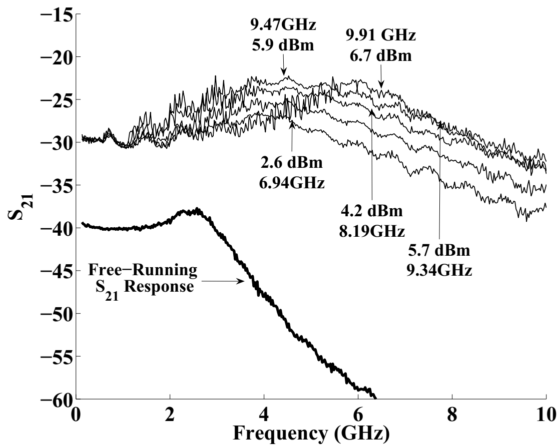

Fig. 2. Small Signal frequency response (S_{21}) of a 1.3μm wafer-fusion monomode injection-locked VCSEL for different incident optical powers. Corresponding cut-off frequencies are also indicated. The small signal frequency response of the same VCSEL in free-running mode is also presented for comparison.

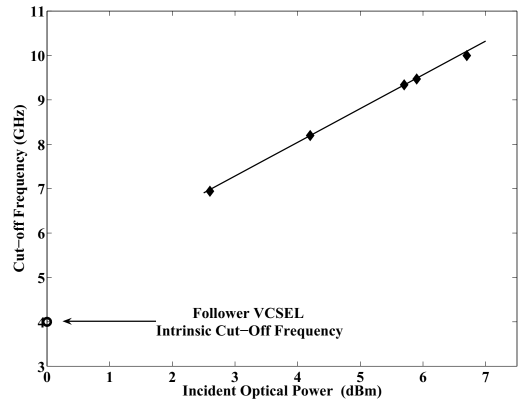

Fig. 3. Follower VCSEL intrinsic cut-off frequency as a function of incident power. The diamonds represent the measured intrinsic cut-off frequencies under optical injection-locking while the solid line is the data-fitted curve. The follower VCSEL intrinsic cut-off frequency is also presented as reference.

from master and follower VCSELs respectively. The optical power is injected into the optical circulator using FC/APC lensed optical fiber connectors. An Inphenix semiconductor optical amplifier (SOA) is used to vary the injected optical power level and hence the optical power incident on the follower VCSEL. The small signal frequency response is characterized using the VNA. An HP-83420A optical rack is used to directly integrate the follower output optical power to the VNA. The experiments are carried out at room temperature without follower VCSEL temperature regulation.

Free-running and Injection-Locked spectra for the follower VCSEL are presented in Fig.2. They demonstrate an increase in cut-off frequency with increasing injected power levels. Due to the utilization of on-chip VCSELs and probe-stations during this experiment the S_{21} curves are free of packaging parasitics' influence. No post-experiment mathematical operation is needed to extract the follower VCSEL's dynamic frequency response. We also present an RF gain of at least 10 dBs as a consequence of optical injection-locking. Fig.3 is a plot of follower VCSEL intrinsic cut-off frequency as a function of incident optical power. The cut-off frequency of the optically injection-locked VCSEL increases with incident optical power.

III. Conclusion and Discussion

In this paper we have demonstrated a significant increase in the cut-off frequency of a long wavelength VCSEL optically-injected by another long wavelength VCSEL. This technique might become important as the need for high bit rate, long wavelength VCSELs increases.

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