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Long Wavelength VCSEL-by-VCSEL Optical Injection-Locking

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Abstract—VCSEL-by-VCSEL optical injection-locking to obtain high cut-off frequencies of 1.3 μm Vertical-Cavity Surface-Emitting Lasers (VCSELs) is demonstrated. A detailed physical explanation of the underlying mechanism is presented. VCSELs from the same wafer have been used in a master-follower configuration. Two probe stations are used in this experiment to power-up two VCSELs simultaneously. Polarization insensibility of the injection-locking is demonstrated and a novel architecture is proposed to achieve cut-off frequency doubling. For the first time a high cut-off frequency is achieved through optically injection-locking the satellite mode of a long wavelength VCSEL. Injection-locking spectra with variable injection-powers and variable detuning values have been obtained and methods have been proposed to obtain high cut-off and/or resonance frequencies. A rate-equation based model is presented. Simulations have been carried out using this model. Finally, a linear increases in the follower VCSEL cut-off frequency with increasing injected-power is demonstrated by using a semiconductor optical amplifier.

Index Terms—1.3 μm VCSEL, Optical Injection-Locking, Probe Station Testing, Microwave Response of VCSELs

I. INTRODUCTION

SEMICONDUCTOR lasers are integral components of telecommunication and data communication systems. Their deployment in high-speed telecom and datacom links requires the utilization of external modulators. This is done in order to address two main performance issues related to semiconductor optical sources namely the frequency-chirping under direct modulation and the intrinsic modulation frequency limits imposed by the device structure. The employment of external modulators however renders the system expensive.

Optical injection-locking can be used to overcome these intrinsic limitations of semiconductor lasers. Adler first studied the locking phenomenon in electronic oscillators in 1946 [1]. Pantell then extended the concept of injection-locking of oscillators to optical injection-locking of laser oscillators in 1965 [2]. Optical injection-locking was then demonstrated for He-Ne lasers [3], for CO_2 lasers [4] and for semiconductor lasers [5] over the following two decades. Several optical injection-locking studies regarding

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semiconductor lasers have reported frequency-chirp reduction [6], [7], [8], increased RF link gain [8], [9], improved relative intensity noise [10], [11], [12], [13] and diminished non-linear distortion [8], [14]. Despite all these advances regarding this very potent combination of semiconductor lasers and optical injection-locking, the phenomenon and its practical applications could not get any commercial breakthrough. In our opinion, the major reason was the non-integrability of the optical injection-locking laboratory experimental setup into a single chip or even a single module. External modulators continue to be used despite all the improvements demonstrated by the utilization of optical injection-locking. Simply because they are the most cost-effective solution providing the required performance.

With the arrival of Vertical-Cavity Surface-Emitting Lasers (VCSELs) on the commercial scene as low-cost, integrable sources, the efforts to revive the optical injection-locking phenomena were once again undertaken and follower VCSEL resonance frequencies ranging from 27 Ghz to 107 GHz have been reported in recent years [8], [15], [16], [17]. The problem of non-integrability however is still unresolved due to the utilization of a distributed feedback (DFB) laser as master optical source to injection-lock a follower VCSEL. The DFB lasers have horizontal optical cavities. This physical asymmetry renders the monolithic integration more complicated while the utilization of a powerful DFB laser compromises the economy of the setup by increasing the cost dramatically and fails the purpose of using a VCSEL in the first place. Clearly the solution to afore-mentioned problems would be to try a VCSEL-by-VCSEL optical injection-locking approach.

We present here, for the first time, a complete study of the microwave behavior of a VCSEL-by-VCSEL optically injection-locked system. Our objective is to explore the possibilities of VCSEL-by-VCSEL optical injection-locking with the final intent to have an integrated low-cost high-speed communications module. In place of working with a master DFB laser and a follower VCSEL, we have decided to work with two identical VCSELs used in the familiar master-follower configuration. In this paper we present the modified rate equations quantifying the follower VCSEL behavior under external light injection. A novel architecture using a 50-50 coupler is proposed along with the familiar optical circulator architecture. We then present the several experimental results obtained through working in different detuning and

injection regimes. A comprehensive physical explanation to interpret the results thus obtained is also given. Finally damped frequency responses of an injection-locked follower VCSEL are presented for various increasing injected-power levels to demonstrate the effective bandwidth enhancement of the system through proper choice of the detuning mechanism.

II. THEORY AND PHYSICAL EXPLANATION

The increase in resonance frequency is a combination of two factors extraneous to the follower laser and dependent on the injected light.

1) The injection of photons in the follower laser cavity changes the carrier-photon equilibrium inside the cavity. The free-running follower laser cavity resonance that is represented by the photon and carrier densities is redefined due to external light injection. The increase in photon density affects the carrier density inside the follower laser cavity. The change in cavity resonance frequency due to carrier population density variation can be quantified using "α_H"; the linewidth enhancement factor that indicates the carrier-variation induced refractive index change and hence the amplitude-phase coupling.

The consequence of the external photon-injection is hence a downshift in the laser cavity resonance frequency denoted as $\omega_{Downshifted}$ in this text.

2) The second factor takes into account the difference between the master and the follower lasing frequencies. This difference is known as "frequency detuning" and could be defined as

$$\Delta\omega \quad = \quad \omega_{master} - \omega_{follower} \qquad (1)$$

The detuning is said to be positive if the master laser has an emission frequency greater than that of the follower laser and is said to be negative if the reverse is true. Once locked the follower laser emits at the same frequency as the master laser. The output frequency of the follower laser hence becomes identical to that of the master laser.

The follower laser, therefore, in effect is experiencing two different phenomena at the same time. The external light injection has offset the cavity mode to a lower resonance frequency while the detuning has led to a high emission frequency. It is the difference between ω_{master} and $\omega_{Downshifted}$ that determines the value of enhanced resonance frequency, $\omega_{EnhancedResonance}$ of an optically injection-locked laser. The interference between ω_{master} and $\omega_{Downshifted}$ generates a beat note whose value could be given as

$$\omega_{EnhancedResonance} \quad = \quad \omega_{master} - \omega_{Downshifted} \quad (2)$$

The resonance peak observed in S_{21} curves of an optically injection-locked slave laser is in fact the beat-note between the downshifted cavity resonance frequency, $\omega_{Downshifted}$, and the master laser emission frequency ω_{master}. This beat-note is amplified due to resonance when the modulating frequency
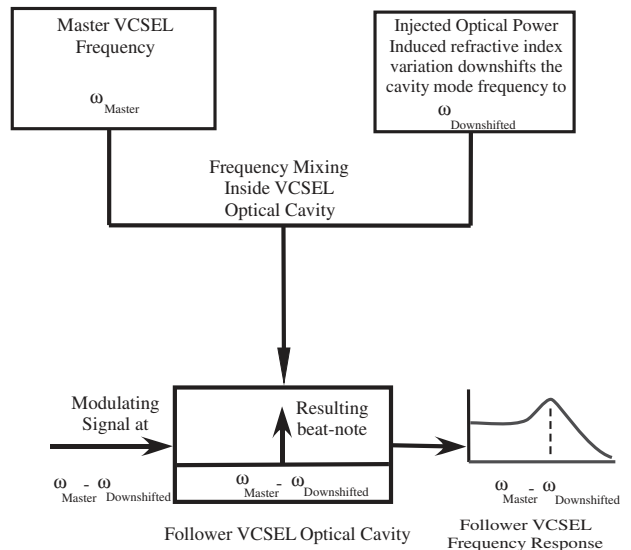

Fig. 1. A schematic diagram representing the physical phenomenon of resonance frequency enhancement of the follower VCSEL due to optical injection-locking. The beat note $\omega_{master} - \omega_{Downshifted}$ created due to frequency-mixing inside the follower VCSEL optical cavity is amplified due to resonance when a signal with a same frequency value is applied to modulate the follower VCSEL.

becomes equal to it. Fig. 1 represents the physical phenomena taking place during the optical injection-locking procedure schematically.

(2) explains the high resonance frequencies for optically injection-locked follower lasers operating in positive frequency detuning regime. A positive frequency detuning value leads to a high resonance frequency. These high resonance frequencies, obtained through operating in positive frequency detuning regimes, however, do not help in increasing the overall 3-dB bandwidth of the system because the resonance is pronounced so far on the frequency spectrum that the S_{21} curve has already tapered down to below 3-dB of the DC gain [16].

When the follower laser is injection-locked in the negative frequency detuning operation regime, quite logically the enhancement in the optically injection-locked follower laser frequency is not colossal. However, this resonance, by virtue of not being very high in frequency, falls within the operating limits of the lasing device and increases the overall bandwidth of the system along with the DC gain. Furthermore Murakami et al. [18] have shown that the carrier population density induced variation in the cavity resonance can be mathematically described as follows:

$$\omega_{Shifted} \quad = \quad \frac{\alpha_H}{2} \cdot a_0 \cdot \Delta N \qquad (3)$$

where a_0 represents the differential gain and ΔN is the variation in the carrier population density.

(3) shows that the value of $\omega_{Shifted}$ depends on ΔN. Since this variation is affected by injecting optical power from the master laser inside the follower laser cavity, varying the injected power varies the cavity resonance frequency of the optically injection-locked laser. An increase in photon population

inside the follower laser cavity through optical injection down-shifts the cavity resonance frequency and (ref. (2) and (3)) increases the $\omega_{EnhancedResonance}$. The $\omega_{EnhancedResonance}$ therefore is directly proportional to the injected optical power. Numerous authors have already presented S_{21} curves of optically injection-locked follower lasers to demonstrate this effect [8], [17], [15].

III. DEVICE CHARACTERISTICS

The VCSELs used in this experiment are double intracavity contact 1.3 μm single-mode VCSELs with coplanar access. The InP-based optical cavity consists of four InAlGaAs quantum wells (ref. Fig. 2). The top and bottom distributed Bragg reflectors (DBRs) comprise of 21 and 35 pairs respectively and are grown by metal-organic chemical vapor deposition (MOCVD) epitaxy method. Using the technique of localized wafer fusion, the top and the bottom AlGaAs-GaAs DBRs are then bonded to the active cavity wafer and the tunnel junction mesa structures [19], [20]. Using VCSELs with double intracavity contacts has its own advantages. These contacts are much nearer to the active region than the classical contacts. Their utilization combined with the presence of tunnel junction allows to have lower series resistance as compared to oxidized-aperture VCSELs. Due to this proximity to the active region these VCSELs tend to have a high quantum efficiency. The devices used in this experiment have an average threshold of 1mA. Their location near the active region results in no current passage through DBRs.

For this series of experiments, we have decided to use un-packaged, un-cooled, on-chip VCSELs. This method is advantageous in certain regards. It provides direct electrical-acces to the VCSEL optical cavity and the device performance is not curtailed by package-induced parasitics. VCSELs from the same wafer have been used to investigate the possibility of VCSEL-by-VCSEL optical injection-locking. That helps avoid using the polarization maintaining techniques that are necessary to use in case of non-identical master and follower lasers.

Another problem that surfaces while working at high frequencies is the introduction of parasitic inductances and capacitances due to device packaging. The high frequency performance of the component is affected by these parasitics since at high frequencies the reactance values for the capacitors and inductors are non longer negligible. At high frequencies, instead of reaching the VCSEL optical cavity, the incoming signal is routed through the parasitic components. This undesired bypassing effect severely degrades the output of the component. In most cases, the component cut-off frequency is dictated by the packaging parasitic cut-off bandwidth. Post-experimental treatment of the data thus acquired is necessary to extract useful information [8], [15], [21]. Using on-chip components eliminates the packaging and hence the parasitics effects associated to it. In order to obtain the true VCSEL optical cavity small-signal response under
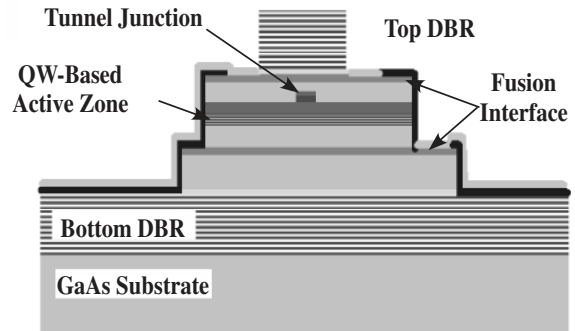

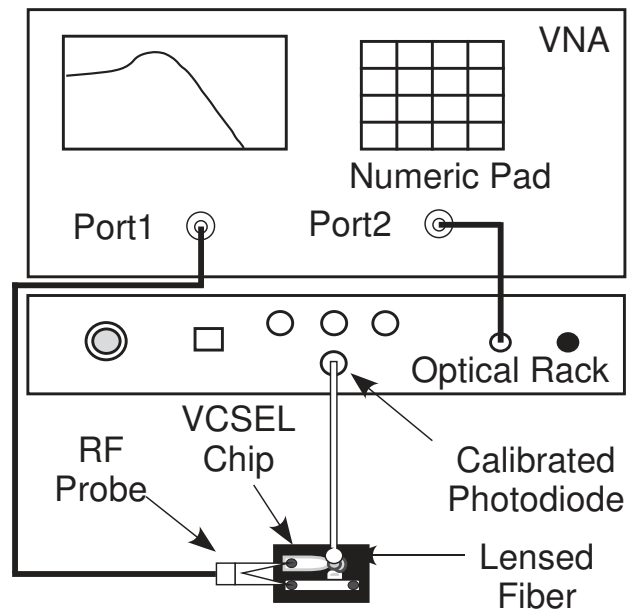Fig. 2. Schematic of the 1.3 μm structure used in optical injection-locking experiments.

Fig. 3. Schematic representation of the experimental setup used to measure the S_{21} response of an on-chip VCSEL using a vector network analyzer. A lensed fiber is used to collect the optical power emitted by the VCSEL. The VCSEL optical output is converted to electrical signal by a pre-calibrated photodiode integrated to the vector network analyzer by means of an optical rack.

external light injection it was decided to use on-chip VCSELs.

On the other hand, coupling optical power from the small emission window of a VCSEL to a lensed single-mode fiber becomes challenging at times due to low optical power emission levels of the VCSELs and due to the miniscule nature of the components deployed in this experiment. In our opinion however, the results thus obtained justify the extra effort employed.

IV. MEASUREMENTS

A. Working Environment

In order to power-up the VCSELs, probe stations have been used. Since the intent of the experiments has been to investigate the VCSEL-by-VCSEL optical injection-locking
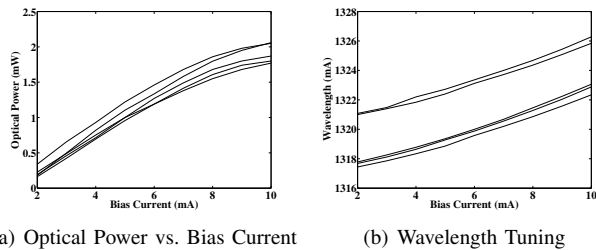
(a) Optical Power vs. Bias Current (b) Wavelength Tuning

Fig. 4. The L-I curves for the set of VCSELs used in this expriment. Representative wavelength-bias current tuning curves are also given.
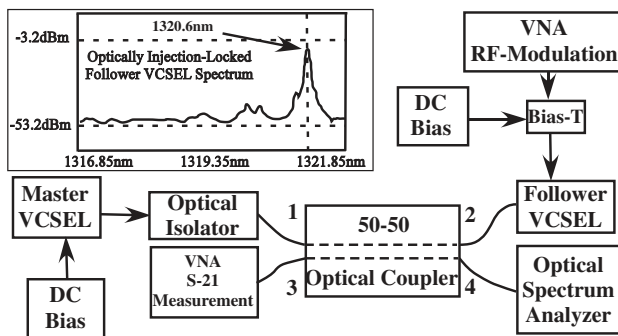

Fig. 5. The proposed architecture employing a 4-port optical coupler for injection-locking experiments.
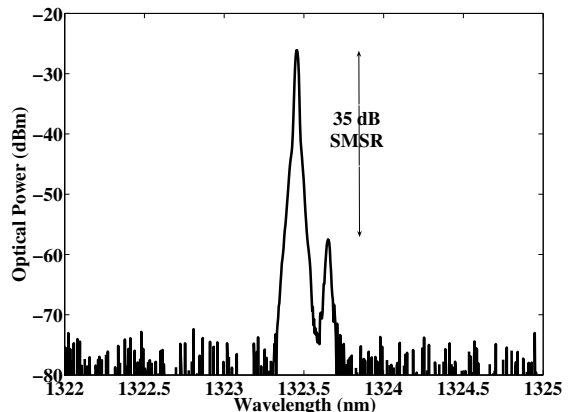

Fig. 6. Optical spectrum of the follower VCSEL used in the injection-locking experiment utilizing the 4-port coupler. A smaller secondary mode could also be observed to the right of the fundamental lasing mode. The side-mode suppression ratio (SMSR) is noted to be about 35 dBs.
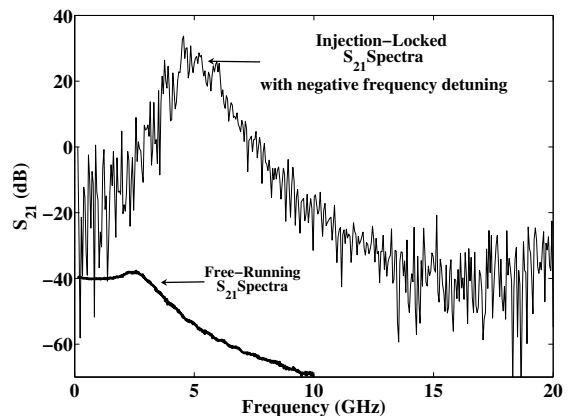

Fig. 7. A comparison of the S_{21} spectra of free-running and optically injection-locked 1.3 μm single-mode VCSELs. The follower VCSEL was locked using the architecture shown in Fig. 5. The measurements were taken in the negative frequency detuning regime.

phenomenon, two probe stations have been used simultaneously to power-up the master and the follower lasers at a time. Furthermore, the follower VCSEL probe station has been connected to an HP-8510 Vector Network Analyzer (VNA). This VNA has been used to serve two purposes.

1) To provide modulation signal to the optically injection-locked follower VCSEL.
2) To observe the S_{21} response of the optically injection-locked follower VCSEL under external light injection.

An optical rack has been integrated to the VNA. This rack consists of a high-speed photodiode calibrated to the VNA. The probes were calibrated using the VNA before the experiment to obtain the parasitics-free VCSEL optical-cavity small-signal response. On the output side of the injection-locked system, the light emitted from the follower VCSEL was gathered using an unsheathed lensed single-mode fiber. This fiber was then connected to the optical rack containing the photodiode already calibrated to the VNA. A schematic representation of the experimental setup used to measure the on-chip VCSELs' S_{21} response is presented in Fig. 3.
No temperature regulation or compensation mechanism was employed in course of this experiment and all the experiments were carried out at room temperature. The output optical powers and the emission spectra of the VCSELs utilized in this experiment are given in Fig. 4.

B. Architectures Used for Injection-Locking Experiments

The standard architecture used for injection-locking experiments is a polarization-maintaining circulator. In our opinion the utilization of polarization-maintaining circulator was rendered necessary due to the fact that two fundamentally different laser sources with inherently different polarizations, namely a DFB laser and a VCSEL, were being used in these experiments [8], [15], [22]. We decided to use a non-polarization maintaining 3-dB 4-port coupler to investigate this hypothesis. A schematic representation of the experimental setup is presented in Fig. 5. The fundamental supporting argument was that the choice of two identical VCSELs functioning at approximately same bias currents would have the same polarization. The follower VCSEL optical spectrum is given in Fig. 6. The side-mode suppression ratio between the fundamental and the satellite mode is about 40 dBs. We decided to injection-lock the follower VCSEL satellite mode with master VCSEL fundamental mode since we had decided not to use the semiconductor optical amplifier. This technique hitherto had been limited to optical computing applications [23]. The results thus obtained are given in Fig. 7.

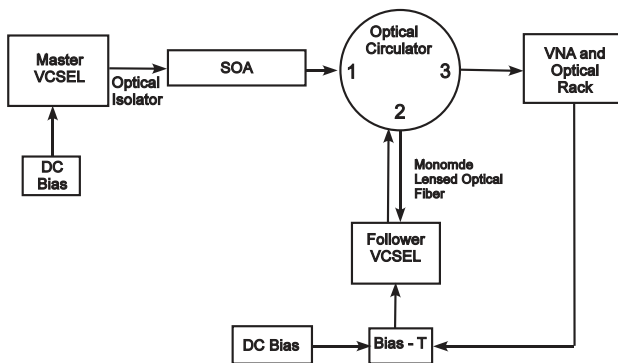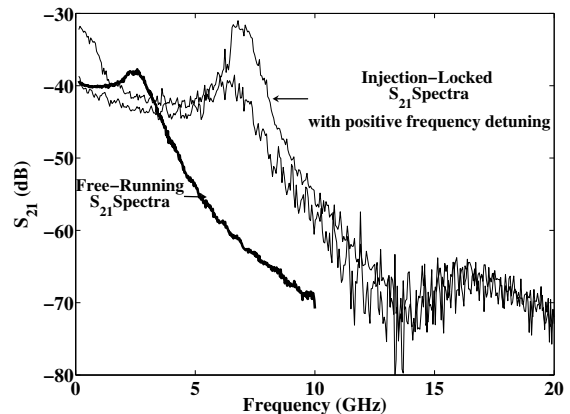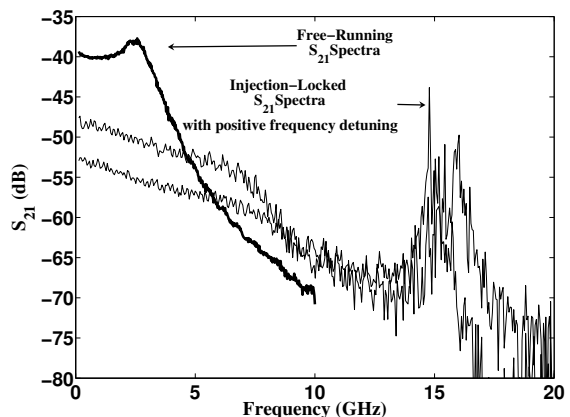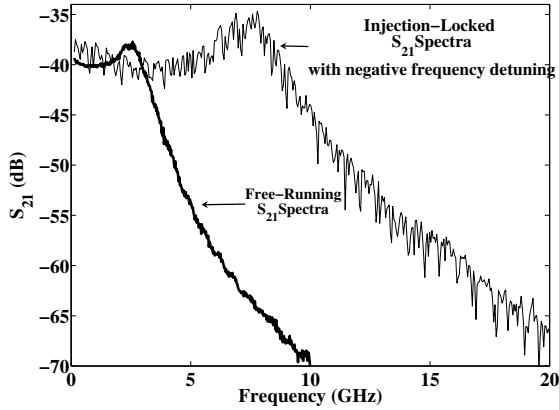In order to investigate the variation in optically injection-

Fig. 11. Small-signal frequency response (S_{21}) of free-running and injection-locked VCSEL spectra: The injection-locked spectrum was obtained by locking the follower laser at a negative frequency detuning value (a wavelength detuning +0.101 nm). The injected optical power is 13.9 dBm.
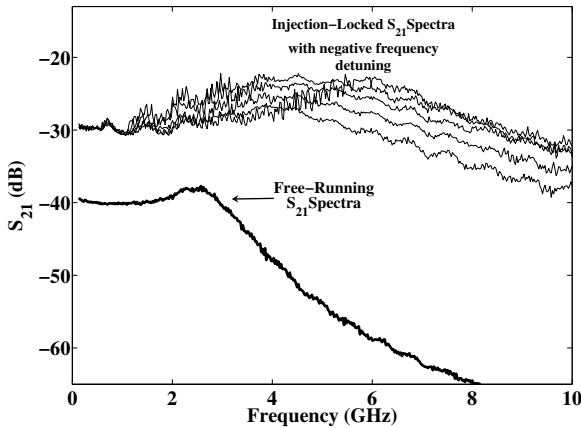

Fig. 13. follower VCSEL intrinsic cut-off frequency as a function of incident power. The diamonds represent the measured intrinsic cut-off frequencies under optical injection-locking while the solid line is the data-fitted curve. The follower VCSEL intrinsic cut-off frequency is also presented as reference.

VI. SIMULATIONS USING RATE EQUATIONS

The optically injection-locked follower VCSEL response is modeled by re-writing the classical rate equations by taking into account the frequency detuning between the two VCSELs, the phase difference thus induced and the optical power coupling rate that determines the effective injected optical power [24]. These modified rate equations are given below. The Langevin forces that typically quantify laser noise in these rate equations have been omitted for simplicity.

$$
\begin{aligned}
\frac{dS}{dT} &= \frac{\Gamma \cdot v_g \cdot a_0 \cdot (N - N_{tr})S}{1 + \epsilon S} - \frac{S}{\tau_p} \\
&+ 2\kappa_c \sqrt{S \cdot S_{inj}} \cos(\Delta f t - \phi(t)) + \Gamma B \beta N^2 \quad (4)
\end{aligned}
$$

$$
\begin{aligned}
\frac{dN}{dT} &= \frac{\eta I}{q \cdot V_{act}} - (A + BN + CN^2) \cdot N \\
&- \frac{v_g \cdot a_0 \cdot (N - N_{tr})}{1 + \epsilon S} S \quad (5)
\end{aligned}
$$

$$
\begin{aligned}
\frac{d\phi}{dT} &= \frac{\alpha_H}{2} \cdot v_g \cdot a_0 \cdot \frac{(N - N_{tr})}{1 + \epsilon S} - \frac{\alpha_H}{2\tau_p} \\
&+ \kappa_c \sqrt{\frac{S_{inj}}{S}} \cdot \sin(\Delta f t - \phi(t)) \quad (6)
\end{aligned}
$$

Where S, N and ϕ are photon density, carrier density and the follower laser phase respectively. N_{tr} is the transparency carrier density. κ_c and β are the optical-coupling and the spontaneous emission coefficients. ϵ, Γ and α_H denote the compression, confinement, and amplitude-phase coupling (Henry) factors. A, B and C are non-radiative recombination, bimolecular recombination and Auger's recombination rates respectively. τ_p is the photon lifetime. V_{act} is the volume of the active region. I denotes the bias current. S_{inj} represents the injected photon density, α_o the differential gain, v_g the group velocity and Δf the frequency detuning between the master and the follower lasers. The value for the optical coupling coefficient κ_c has been calculated using the relation

Fig. 12. Small Signal frequency response (S_{21}) of a 1.3 μm wafer-fusion single-mode 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.

were obtained. The increase in effective bandwidth is due to increase in photon population density that downshifts the cavity-mode frequency hence increasing the value of $\omega_{EnhancedResonance}$ (ref. (2)). The high damping of the curves however is due to the selection of negative frequency detuning (positive wavelength detuning of 0.152 nm) regime. The 3-dB bandwidth has shown a two-fold increase for this last set of curves depicted in Fig. 12. Since the frequency detuning for these particular measurements is kept constant, the resonance frequency and hence the cut-off frequency follows the variation in injected optical power. The injected-power levels corresponding to the progressive optically injection-locked follower VCSEL S_{21} spectra are 6 dBm, 9 dBm, 10.2 dBm, 11.5 dBm and 12.3 dBm repectively. Fig. 13 shows the linear variation of the 3-dB bandwidth with increases injection power levels.
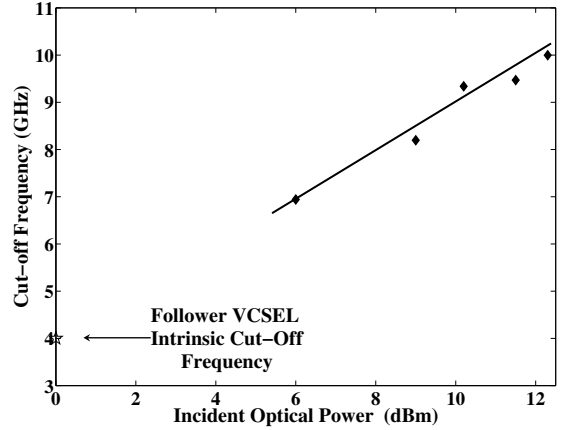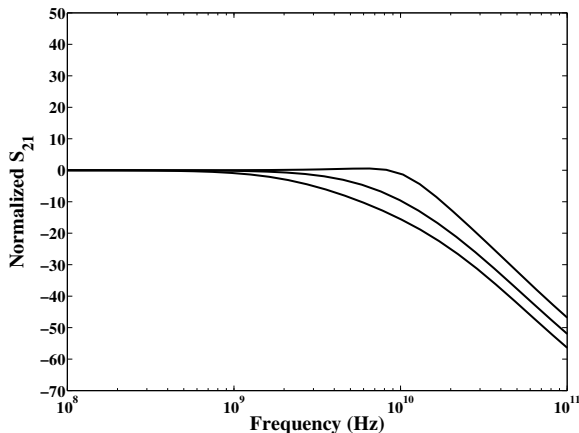
Fig. 14. Optically Injection-Locked follower VCSEL S_{21} response using the modified rate equations (4,5,6). These highly damped simulation responses have been obtained by keeping a constant injection-ratio and by working on the edge of the negative frequency detuning.
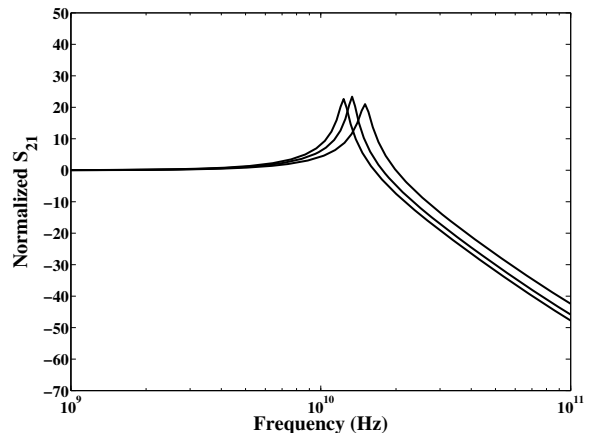

Fig. 15. Optically Injection-Locked follower VCSEL S_{21} response using the modified rate equations (4,5,6). These under-damped simulation responses have been obtained by keeping a constant injection-ratio and by working on the edge of the positive frequency detuning.

$$\kappa_c = \frac{v_g}{2L_{eff}} \qquad (7)$$

where L_{eff} is the effective cavity length. Since the cavity length for the VCSELs is very small as compared to DFB lasers, the value of coupling coefficient is consequently higher which enables in attaining much higher effective injection-ratios [8].

These equations were solved using MATLAB with the ODESolver45 based on the Rung-Kutta numerical algorithm. The parameters used in the simulations are outlined in Table. I. The simulation curves thus obtained are given in Figs. 14, 15 and 16. Three visibly distinct responses for the optically injection-locked follower VCSEL have been presented. The over-damped, critically-damped and under-damped responses have been obtained by varying the detuning frequency between the master and follower VCSELs.

Fig. 14 gives the S_{21} responses obtained by working at the negative frequency detuning edge. As a result the S_{21} responses are highly damped. On the other hand Fig. 15 refers to the S_{21} responses obtained by doing simulations at the edge of the positive frequency detuning range. These responses are under-damped with sharp resonance frequencies varying from 10 GHz to 20 GHz. The third set of simulations, as depicted in Fig. 16, was obtained by working with small negative detuning frequency values. As a result of the negative frequency detuning values being small, the S_{21} curves thus obtained are critically-damped.

These simulation results depict the detuning frequency and the injection-ratio dependence of the optically injection-locked follower VCSEL microwave behavior. By varying the detuning-frequency and the injection-ratio properly under-damped, over-damped and critically-damped S_{21} responses with varying resonance frequencies and hence 3-dB band-widths can be obtained.
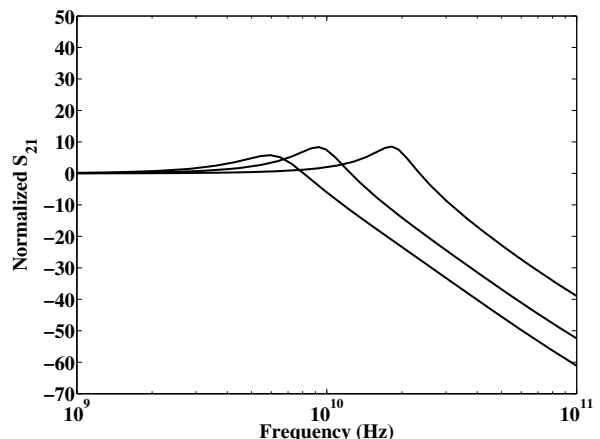
Fig. 16. Optically Injection-Locked follower VCSEL S_{21} response using the modified rate equations (4,5,6). These critically-damped simulation responses have been obtained by gradually increasing the injection-ratio while working with a slightly negative frequency detuning.

VII. CONCLUSION

We have reported a thorough study of VCSEL-by-VCSEL optical injection-locking. The intent was to move toward compacter, lighter, low-cost, high-speed systems that could be monolithically fabricated or integrated into communication modules. The injection-locking experiments reported here were carried-out using two probe stations to power-up the master and follower VCSELs. The advantage of such a setup was a parasitics-free S_{21} response that needed no post-experimental treatment. The injection of optical power in the fibered components however became challenging at times. The back-reflections from the open-ended unsheathed lensed fiber used to collect optical power hinder the obtention of smooth S_{21} curves. This could be overcome by using anti-reflection (AR) coated conical and ball lensed fibers that gather a maximum of light without perturbing the VCSEL emission.

TABLE I
VCSEL INTRINSIC PARAMETERS

Parameter	Symbol	Value	Units
Intrinsic Efficiency	η_i	0.8	-
Carrier Lifetime	τ_e	0.61	ns
Photon Lifetime	τ_p	6.4	ns
Threshold Carrier Density	N_{th}	5.33×10^{18}	cm^{-3}
Transparency Carrier Density	N_{tr}	3.24×10^{18}	cm^{-3}
Non-Radiative Recombination Rate	A	1.1×10^8	s^{-1}
Bimolecular Recombination Rate	B	1.0×10^{-10}	cm^3/s
Auger's Recombination Rate	C	3.6×10^{-29}	cm^6/s
Differential Gain	a_0	4.8×10^{-16}	cm^2
Gain Compression Factor	ϵ	2.2×10^{-17}	cm^3
Phase-Amplitude Coupling Factor	α_H	5	-
Coupling-Rate Coefficient	κ_c	1.5×10^{13}	s^{-1}

We have hypothesized that the necessity of employing polarization control and polarization matching in previous injection-locking experiments using VCSELs was due to the dissimilarity between the two optical sources. Ideally, the deployment of two identical VCSELs should result in successful optical injection-locking without polarization control. Results to this effect have been presented in this article since no polarization control mechanism was applied to obtain the S_{21} curves presented.

The enhancement of effective bandwidth by injection-locking the secondary mode paves the way for the realization of low-cost, high-speed, VCSEL-by-VCSEL, optically injection-locked communication modules. While working with devices, whose intrinsic cut-off limit is about 4 GHz, it has been demonstrated that VCSEL-by-VCSEL injection-locking can be used to have effective bandwidths up to 12 GHz. With the progress of vertical-cavity semiconductor optical amplifier technology [25], [26] combined with the advances in wafer-fusion fabrication techniques, integrated VCSEL-by-VCSEL optically injection-locked modules for high-speed applications seem to be not a distant possibility. Consequently VCSELs could be employed for applications that require direct intensity modulation at high frequencies such as "fiber to the home" (FTTH) or gigabit LAN. The simulations depict that the resonance frequency and the cut-off frequency of an optically injection-locked follower VCSEL can be controlled by varying the injection ratio S_{inj}/S and the frequency detuning Δf. Increasing injection-ratios tend to enhance the cut-off frequency while the varying frequency detuning can be used to control the damping of the resonance frequency. In this fashion, over-damped, under-damped or critically damped S_{21} reponses can be obtained.

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