Microwave Performance of Optically Injection-Locked VCSELs

Lukas Chrostowski, *Member, IEEE*, Xiaoxue Zhao, *Student Member, IEEE*, and
Connie J. Chang-Hasnain, *Fellow, IEEE*

Invited Paper

***Abstract*—The optical injection-locking technique has been demonstrated to enhance the microwave performance of fiber-optic links based on vertical-cavity surface-emitting lasers (VCSELs). We report recent advances of a comprehensive study on VCSELs under ultrahigh injection-locking conditions. The performance improvements include ∼20-dB increase of both spur-free dynamic range and RF link gain, a factor of 5–10 increase in resonance frequency, as well as ∼20-dB reduction in laser noise.**

***Index Terms*—Injection-locked lasers, microwave photonic links, optical fiber communication, optical injection locking (OIL), vertical-cavity surface-emitting lasers (VCSELs).**

I. INTRODUCTION

SINCE THEIR inception, semiconductor diode lasers have been unique light sources with excellent spectra and beam properties and a capability to be directly modulated at a very high speed. This modulation capability has led them to be used for major applications such as optical fiber communications.

For analog fiber-optic transmission, a faithful reproduction of the signal is desired, with negligible distortion, low noise, and a high RF link gain. In addition, a large modulation bandwidth ($>$10 GHz) is desirable. External optical modulators are typically used for high-performance links. This solution, though effective, is costly and bulky. In contrast, directly modulated lasers are more desirable on these two accounts. In particular, vertical-cavity surface-emitting lasers (VCSELs) [1]–[3] are very promising for applications where low cost, small size, and low power dissipation are required as much as high signal fidelity. However, directly modulated lasers, including VCSELs, suffer from high distortion near the resonance frequency and can, therefore, only be used at low RF frequencies [4] (e.g., $<$1 GHz). The distortion physically originates from the nonlinear characteristics of the laser, dominated by the carrier–photon interaction. To avoid performance degradation due to this phenomenon, it is desirable to have the laser resonance frequency greatly exceed the highest RF frequency of use.

The modulation frequency response of a diode laser is governed by the rate that electrons and holes recombine at the laser junction (carrier lifetime), and the rate that photons are generated and escape from the laser (photon lifetime). To date, the highest reported experimental resonance frequency is ∼31 GHz for a diode laser [5], and ∼15 GHz for a VCSEL [6]. 20-Gb/s transmission has also been reported with VCSELs [7]. To increase the resonance frequency (f_r) beyond these values, optical injection locking (OIL) could be an effective method for improved microwave performance [8]. Injection locking has been used to improve the performance of distributed feedback (DFB) lasers [9]. A monolithic injection-locked two-section DFB laser attained a resonance frequency of 25 GHz [10]. A 30-GHz resonance frequency was observed in the optical spectrum of an injection-locked DFB [11].

In this paper, we report a systematic and comprehensive study of experimental and theoretical results demonstrating that injection-locked VCSELs are a promising candidate for high-bandwidth microwave transmitters. Using OIL, VCSELs have exceeded the performance of all directly modulated lasers demonstrated to date. We show that f_r of a VCSEL can be increased from $<$10 GHz in the free-running mode to $>$50 GHz, currently limited by our equipment [12]. The increased f_r reduces the nonlinear distortion and laser noise in the communication band (e.g., $<$40 GHz) [13]. Finally, injection locking also increases the RF link gain by as much as 20 dB.

This paper is organized as follows. Section II introduces OIL. Section III describes the resonance frequency enhancement and frequency response of VCSELs. Section IV describes the RF link gain enhancement due to OIL. Section V discusses the laser distortion and measured spur-free dynamic range (SFDR). Section VI discusses the laser relative intensity noise (RIN).

II. OIL

OIL was first demonstrated in 1976 using edge-emitting semiconductor lasers [14] and, in 1996, using VCSELs [15]. The injection-locking technique uses one laser (master) to optically lock another laser (follower), which can be directly

---

Manuscript received June 9, 2005; revised September 21, 2005. This work was supported by the National Science Foundation under Award ECS-0123512 and by the Defense Advanced Research Projects Agency under Award F30602-02-2-0096.

L. Chrostowski was with the Department of Electrical Engineering and Computer Science, University of California at Berkeley, Berkeley, CA 94720 USA. He is now with the Electrical and Computer Engineering Department, University of British Columbia, Vancouver, BC, Canada V6T 1Z4.

X. Zhao and C. J. Chang-Hasnain are with the Department of Electrical Engineering and Computer Science, University of California at Berkeley, Berkeley, CA 94720 USA (e-mail: cch@eecs.berkeley.edu).

Digital Object Identifier 10.1109/TMTT.2005.863066

modulated. This technique is an effective method to significantly increase the laser resonance frequency and bandwidth [9], [16], reduce nonlinear distortions [17], and reduce frequency chirp [18].

Using a VCSEL as the follower and a high power (∼40 mW) DFB laser as the master, we can achieve injection locking with an ultrahigh injection ratio, i.e., the master laser power being much higher than that of the follower. The motivation for using a high injection ratio is that the resonance frequency is expected to scale approximately as the square root of the injection ratio [19]. No limit has been predicted to the increase in frequency response. This is a major difference from previous experiments by other research groups.

Another major distinction between our study and other previous research is that we insisted on using pure single-mode lasers as both master and follower lasers. Both lasers have single transverse, longitudinal, and polarization modes. The reason we have chosen single-mode lasers is because our experiments with multimode follower lasers in the ultra-strong injection regime have shown inconsistent results due to an overlap in the locking ranges, which leads to mode competition. Furthermore, the single-mode system is easier to model [20]. The use of a multimode master laser has not been investigated by our group.

Let us first define two major control parameters used in this series of experiments: injection ratio and wavelength detuning. The injection ratio is $P_{\text{master}}/P_{\text{follower}}$, where P is optical power; it is measured as the ratio of optical power estimated to be incident on the VCSEL versus the output power of the free-running VCSEL. Wavelength detuning is $\lambda_{\text{master}} - \lambda_{\text{follower}}$, where λ is the optical wavelength; it is measured as the wavelength difference of the master DFB laser and the free-running VCSEL. We have previously shown that as the injection ratio is increased, the wavelength detuning range for the stably locked region is increased [8]. In the current ultrahigh injection experiments, a locking bandwidth of >2 nm was observed. As the injection ratio is increased, we found that larger performance improvements can be achieved (details discussed below). In addition, the performance enhancement becomes less sensitive to unintentional variations of the power ratio or detuning, showing the effectiveness and robustness of the technique [8]. In particular, VCSELs have a short cavity, thus a higher coupling rate coefficient $k_c = c\sqrt{1-R}/2$ nL (approximately 1×10^{12} s^{-1}) with which a much higher effective injection ratio can be attained. Due to these advantages, we have shown dramatic enhancements using injection-locked VCSELs in the resonance frequency [21], [22], significant reduction in optical chirp [8], laser noise [23], and nonlinear distortions [24], and promise for un-cooled operation [25]. Thus far, we find that the performance continues to improve with injection ratio. Thus far, no upper bound was observed within our instrumentation limit.

An explanation for these performance enhancements has recently been studied by several groups [19], [20]. Our understanding of the effects is as follows: under injection locking, the threshold current of the follower laser is reduced. The refractive index of the active region is increased due to the reduction in carrier density (by the Kramers–Kronig relationship), which thus red shifts the cavity resonance in spite of the fact that the lasing wavelength is locked by the master laser at the original cavity wavelength. The shift in the wavelength of the laser cavity mode strongly depends on the wavelength detuning. As well, the difference between the OIL lasing wavelength and OIL cavity wavelength depends on injection ratio; the higher the injected stimulated emission, the larger the difference. The enhancement in relaxation oscillation was attributed to a new resonance, which has a frequency being the difference in cavity wavelength versus the lasing wavelength [19]. This leads to injection-induced population pulsations at the new resonance frequency [23], and the detuning plays a major role in determining this resonance frequency. The enhancement in the RF gain occurs when the follower laser is modulated at a frequency less than or equal to the difference; in this case, one sideband (longer wavelength side) of the modulated signal is greatly amplified by the interaction of the signal with the cavity mode. This, we believe, is the origin of the RF gain under an ultrahigh injection ratio. The details of this theory are under development [26].

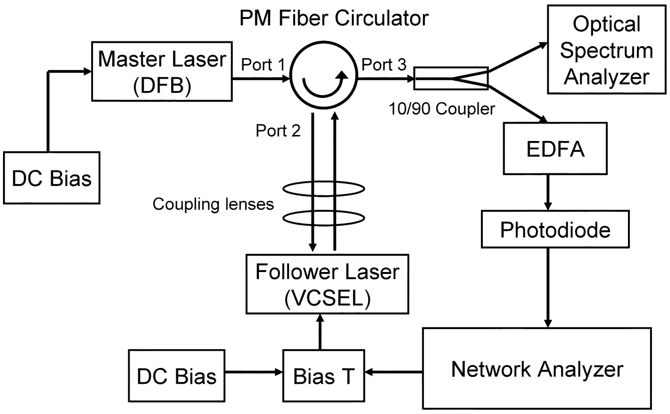

Fig. 1. Experimental setup. The 1.55-μm VCSEL was injection locked by a DFB laser through a PM circulator. The frequency response was characterized by an Agilent E8364A 50 GHz network analyzer. The injection locking spectrum was observed by an optical spectrum analyzer.

The experimental setup used for the studies is shown in Fig. 1. Two lenses ($f = 4.5$ mm) on micropositioning stages were used to couple the light between the VCSEL and port 2 of the fiber circulator. The circulator is used to prevent optical feedback to the master laser.

The master laser is an Ortel DFB laser (RIN <−165 dB/Hz) with a polarization maintaining (PM) single-mode fiber output. Its light was injected to the VCSEL via a PM circulator. The wavelength detuning and injection ratio were adjusted by tuning the DFB temperature and bias current. The polarization of the DFB signal is adjusted to match that of the VCSEL by rotating the circulator port-2 fiber.

Two types of VCSELs were used in this study as follower lasers. The first type were 1.55-μm InGaAlAs/InP buried tunnel junction (BTJ) VCSELs with five quantum wells, typically with >25–30-dB side-mode suppression ratio under continuous wave (CW) operation [27] manufactured by Vertilas GmbH, Munich, Germany. The typical f_r was approximately 6 GHz at ∼2× threshold bias. The second type of VCSELs were tunable 1.55-μm VCSEL with a threshold approximately 1 mA manufactured by Bandwidth9 Inc., Fremont, CA [28].

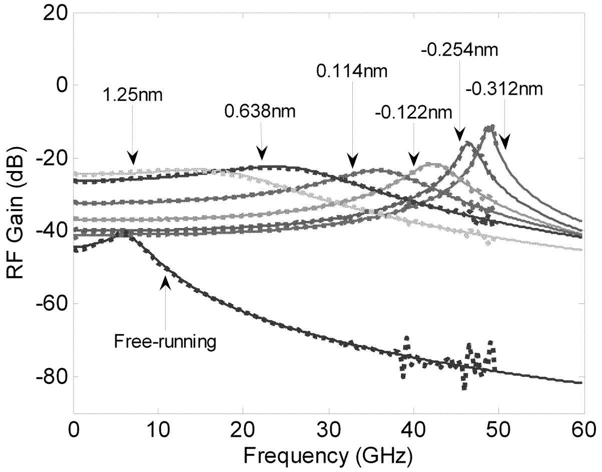

Fig. 2. Small-signal frequency response ($S21$) of free-running and injection-locked BTJ VCSEL #1 for varied wavelength detuning values. The free-running f_r ($\sim$7 GHz, 2-mA bias) is also shown as the reference. The injection ratio is fixed at 13.8 dB. Thick dotted curves are calibrated $S21$ data, while the thin solid curves are curve-fitted data.

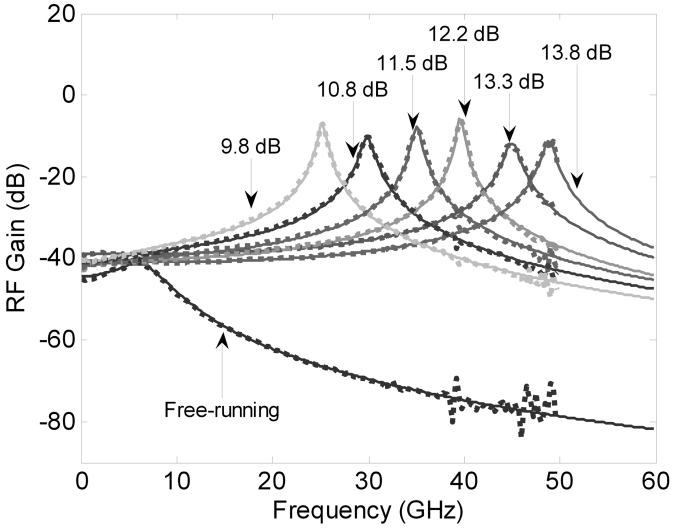

Fig. 3. Small-signal frequency response ($S21$) of free-running and injection-locked BTJ VCSEL #1 for varied injection ratio ranging from 9.8 to 13.8 dB. The detuning is for negative wavelength detuning at the edge of locking.

III. Frequency Response of Injection-Locked VCSELs

Here, we present experimental results demonstrating a drastic frequency-response enhancement in VCSELs. The follower lasers used in this experiment and in Section IV are the Vertilas GmbH BTJ VCSELs. The VCSEL was biased at 2 mA ($\sim 2\times$ threshold) and directly modulated. The small-signal frequency response ($S21$) was characterized using an Agilent E8364A 50-GHz network analyzer.

The modulated VCSEL output was amplified using an erbium-doped fiber amplifier (EDFA) and detected using a 50-GHz u^2t Photonics waveguide photodiode. Simultaneously, we observed the injection-locking optical spectrum, as well as measured the RF gain without EDFA amplification by modulating the laser with a 1-GHz single tone. The $S21$ data have been calibrated with the device and packaging parasitic response deembedded [21]. The experiments were conducted at room temperature without VCSEL temperature stabilization.

One distinct feature of optically injection-locked lasers is that the damping and resonance frequencies can be independently controlled by adjusting the injection ratio and wavelength detuning. Thus, a nearly arbitrary choice of damping rate and resonance frequency is possible. One can customize the frequency response to yield a flat response (highly damped) or one with a sharp resonance (undamped). Recent numerical simulations confirm these phenomena [20].

Representative $S21$ spectra are shown in Figs. 2 and 3. Fig. 2 shows the $S21$ spectra for a free-running VCSEL and when it is injection locked at a fixed injection ratio of 13.8 dB for various detuning values. The f_r is enhanced to 50 GHz, limited by our instrumentation, from the free-running 6 GHz. The lowest damping (sharpest resonance peak) occurs for the most negative wavelength detuning values (-0.312 nm, i.e., the master laser has a shorter wavelength). As the detuning increases (i.e., the master laser is tuned to the longer wavelength side), the resonance peak is more damped out, and flatter $S21$ responses are observed together with an increasing RF gain. The highest injection-locked f_r observed for this injection power is $\sim$50 GHz.

In the experiments, we defined the edge of the locking range on the negative wavelength detuning side to be that where a 30-dB optical side-mode suppression ratio was observed. The negative wavelength locking edge is actually a gradual transition via a Hopf bifurcation [29], and detuning past this boundary results in the appearance of a second optical mode. For continued negative detuning, the resonance frequency continues increasing, but the laser response becomes less damped and a dip in low frequency appears in the $S21$ curve. Thus, for further detuning, the laser undergoes undamped oscillations at the resonance frequency and becomes less suitable for broad-band applications.

Fig. 3 shows the $S21$ spectra for the same VCSEL with a varied injection ratio. The data is taken at the edge of locking for a negative wavelength detuning. The resonance frequency is shown to increase from 25 to 50 GHz for an injection ratio ranging from 9.8 to 13.8 dB.

In this study, a set of four lasers was tested. Fig. 4 shows the maximum f_r obtained at the lowest (negative) detuning as a function of the injection ratio for all four VCSELs tested. The resonance frequency increases with the injection ratio and all lasers have f_r higher than 45 GHz. The variation in the curves is attributed to optical coupling differences, as well as variations in laser-mode behaviors under injection locking. For even higher injection ratios, a flat frequency response was observed, indicating a resonance frequency beyond 50 GHz was present. No upper bound in the enhancement has been observed. In comparison to experiments performed on edge-emitting lasers, VCSELs have a higher coupling coefficient, and the slope of the resonance enhancement versus the injection ratio is higher.

The resonance frequencies observed by other groups is also plotted in Fig. 4. The first experimental demonstration of resonance frequency enhancement (with a measured $S21$) was by Meng *et al.* in 1998 [9], [17] using a DFB laser. Other

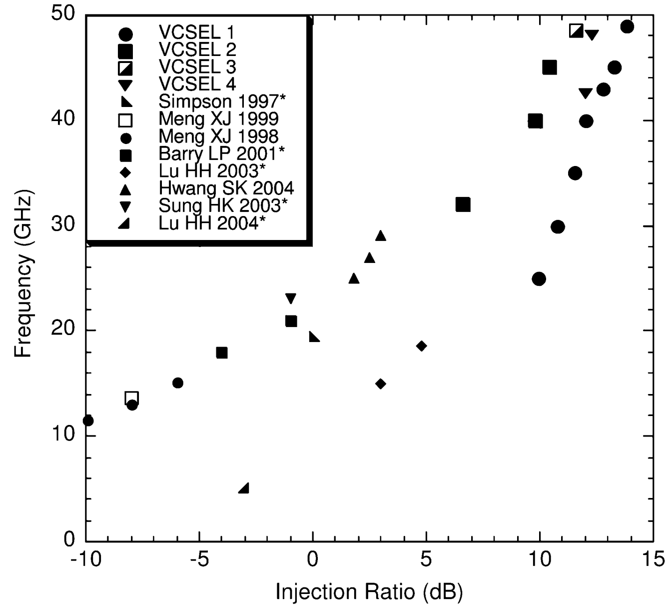

Fig. 4. Comparison of the resonance frequencies reported in literature. The experiments in this paper are for the four VCSELs (labeled VCSEL 1–4). The points are the maximum resonance frequencies (determined from curve-fitted measured small-signal frequency response) for the four VCSELs versus injection ratio. All lasers show >45-GHz resonance frequency. The other points are for experiments by other groups (referred by author/date). For points marked with an asterisk $(*)$ in the legend, the injection ratio was estimated based on provided information.

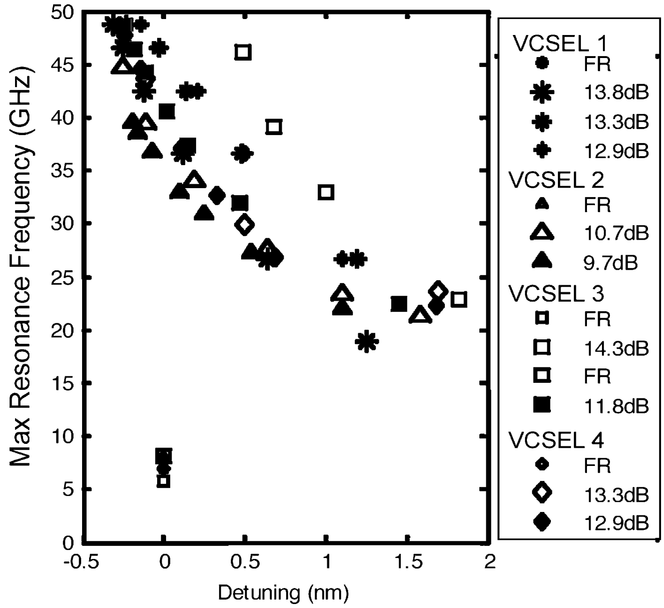

Fig. 5. Resonance frequency of four VCSELs versus wavelength detuning. Large resonance frequencies were obtained at small and negative wavelength detuning values. (Legend: FR is free running, decibel values are injection ratios.)

groups performing similar experiments have included: Lu *et al.* in 2003 with a DFB laser [30], and Barry *et al.* in 2001 with a Fabry–Perot (FP) laser [31]. Using an optical probe technique to determine the modulation bandwidth, enhancements in FP lasers were demonstrated by Simpson and Liu in 1997 [32], and in DFB lasers by Hwang *et al.* in 2004 [11]. Monolithic injection locking of DFB lasers has shown resonance frequencies of 23 GHz [10]. Finally, injection locking using VCSELs has been used by Lu *et al.* in 2004 for radio-over-fiber systems utilizing the enhanced resonance frequency [33]. As can be seen in Fig. 4, there is a substantial variation in the injection ratios for the various experiments summarized. The variation is attributed to difficulties in experimentally determining the injection ratio due to: 1) coupling loss; 2) varying device parameters such as reflectivity; 3) photon lifetime; and 4) coupling rate. Finally, different authors have used different definitions for the injection ratio. However, the trend is clear; the higher the injection ratio, the higher the resonance frequency.

Fig. 5 shows f_r as a function of detuning for the four lasers studied. The lasers exhibited similar detuning dependence and locking range, demonstrating the robustness of this technique.

IV. RF Link Gain Enhancement of OIL VCSELs

Figs. 2 and 3 reveal an interesting phenomenon for VCSELs under ultrahigh injection locking. A very large modulation efficiency (RF gain) enhancement is attained at lower frequencies for typically positive wavelength detuning (i.e., master wavelength is longer than follower wavelength). This had never been predicted before our study [24]. The reason for the RF gain effect and its dependence on detuning is currently under investigation.

This effect is studied more comprehensively here. The modulation efficiency of the free-running BTJ VCSEL used in Section III is 0.22 W/A [27]. For a large injection ratio ($\sim$14 dB), the enhancement is up to 20 dB at large positive detuning ($\sim$1.2 nm), resulting in a modulation efficiency of 2.2 W/A, or an equivalent 2.75 photons generated per electron–hole pair.

Under a fixed injection ratio, the RF gain varies with detuning. The minimal value is at small or negative wavelength detuning associated with frequency response curves showing a sharp resonance peak. On the other hand, the maxima RF gain is obtained at large positive wavelength detuning values accompanied by frequency-response curves with high damping rates, as shown in Fig. 2. Hence, there exists a tradeoff between f_r and RF gain. Fig. 6 shows the RF gain as a function of wavelength detuning. The correlation between RF gain enhancement and wavelength detuning is clearly visible. However, we achieved a large wavelength detuning range with RF enhancement for VCSELs with ultrahigh injection.

The maximum RF gain enhancement keeps increasing as we increase the injection ratio. Fig. 7 shows the enhancement versus injection ratio. The RF gain was measured for a small-signal input of -20 dBm at 1 GHz. The modulation efficiency also increases with increased injection ratio, reaching a maximum of $\sim$2.2 W/A at the highest injection ratio studied. In this case, the system link gain was -41 dB when the laser was free running, and increased to -19 dB when it was injection locked at an injection ratio of $\sim$10 dB. The optical coupling in our experiments was not completely optimized, resulting in a poor free-running VCSEL RF link gain of -41 dB. In comparison, a single DFB with a slope efficiency of 0.36 W/A achieved a link gain of -10.5 dB [34]; thus, with optimal coupling, we expect that the

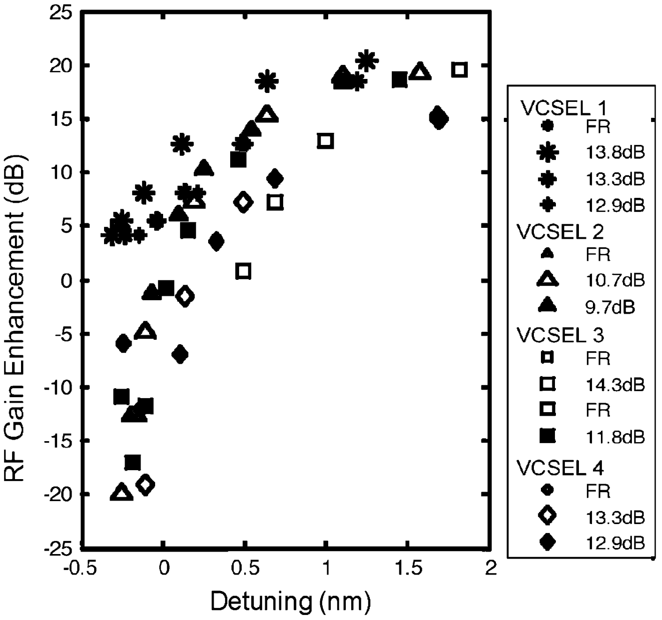

Fig. 6. RF gain measured at 1 GHz for four VCSELs versus wavelength detuning. As high as ~20-dB RF gain is found for large detuning cases. (Legend: FR is free running, decibel values are injection ratios.)

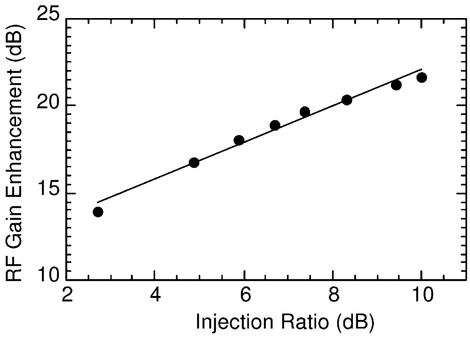

Fig. 7. Experimental RF gain enhancement versus injection ratio for VCSEL 5. The detuning values chosen were those that resulted in the highest RF gain, i.e., at the positive wavelength locking edge.

link gain can be further improved by ~10 dB, above the 20-dB enhancement due to ultra-strong injection locking.

The RF gain can be numerically validated by simulations by varying some of the laser parameters. However, the effect has not yet been satisfactorily explained. The enhancement is possibly due to the optical cavity frequency being shifted away from the lasing wavelength due to injection locking. The cavity shift can be much larger (~100 GHz) than the cavity bandwidth determined by photon lifetime (~10 GHz), leading to modified laser dynamics. As well, the carrier density is significantly reduced, thus the device operates at a higher differential gain regime.

In addition to small-signal response, we recently performed large-signal modulation experiments. In the lasers tested, an optical extinction ratio of ~20 dB was attainable [28] for the ultra-strong injection ratio cases with greater than 30-GHz f_r.

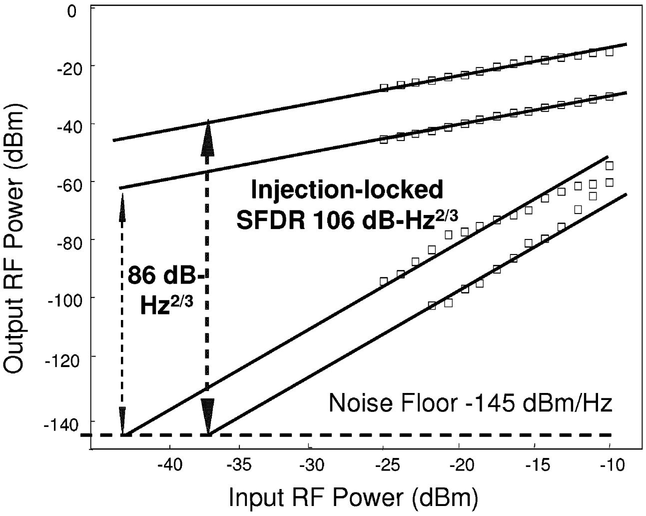

Fig. 8. Two-tone SFDR improvement at 50 °C ~0.2-nm detuning and 1.0-GHz modulation. Two-tone frequency spacing = 10 MHz. Inner lines for free running and outer lines for injection locked.

V. DISTORTION AND DYNAMIC RANGE OF OIL VCSELS

Typical optical link linearity is characterized by the SFDR. It is defined as the signal-to-noise ratio at the input RF power for which the system noise floor equals the largest distortion spur power. Distortion occurs from several sources, including second- and third-order harmonics of the signal, and the intermodulation distortion (IMD). For device studies, the standard technique is to characterize the third-order intermodulation (IMD3) products due to two-tone modulation.

Nonlinear distortion has been shown to be inversely proportional to the resonance frequency [4]. Hence, with the increased f_r, injection-locked lasers are promising for exhibiting reduced nonlinear distortion. Experiments and simulations showing decreased distortion and improved IMD3-limited SFDR using injection locking are described here.

The highest IMD3 SFDR reported for a direct-modulated diode laser at ~1 GHz is 125 dB · Hz$^{2/3}$ for <1 GHz for a 1.3-μm DFB laser [36], and 113 dB · Hz$^{2/3}$ at 0.9 GHz for an 850-nm VCSEL [37].

Here, we demonstrate both experimentally and theoretically that large SFDR improvements can be attained for a wide range of modulation frequencies from 0.6 to 3.0 GHz for an OIL VCSEL [13]. We also observed a linear relationship between dynamic-range enhancement and the injection ratio. We attribute these major improvements to an ultrahigh injection ratio.

A. Experiments

Fig. 8 shows that a significantly improved IMD3 SFDR of ~106 dB · Hz$^{2/3}$ at 1 GHz [25] was obtained for an injection-locked 1.55-μm VCSEL. This was measured using two-tone modulation. A 20-dB enhancement in the SFDR was attained.

The experimental setup for the distortion measurements is similar to that shown in Fig. 1, except that two RF synthesizers were used to directly modulate the VCSEL, and the output signal was characterized using an HP71400C lightwave analyzer. The VCSEL used for this experiment was a

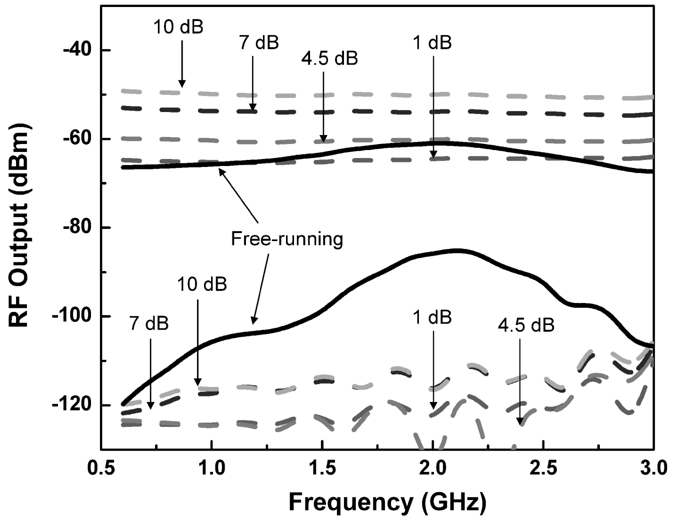

Fig. 9. Experimental modulation response and two-tone IMD3 distortion versus carrier frequency with RF input -8 dBm and $D_f = 10$ MHz. Data were taken for free-running, as well as injection-locked laser at different injection ratios (in decibels).

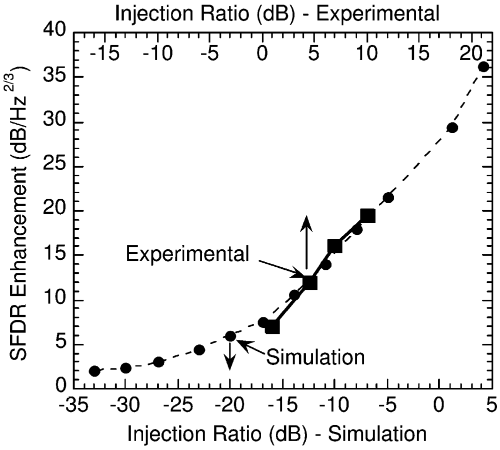

Fig. 10. Experimental SFDR enhancement versus injection ratio (square data points, top x-axis) at half the resonance frequency (1 GHz) for a VCSEL at various injection ratios relative to the free-running case. Numerical simulation of SFDR enhancement (circle data points, bottom x-axis) at half the resonance frequency (2.4 GHz). The data are plotted on two separate x-axes (same scale) to demonstrate that the experiment and the simulation match in trend and slope.

Bandwidth9 Inc. tunable VCSEL. This VCSEL was biased at 2 mA, and directly modulated with RF signals at a 10-MHz spacing. It was found that the device suffered from parasitic response due to the wire bonding and ceramic packaging. Thus, the RF input power was adjusted to compensate for the parasitic power loss at different frequencies. The parasitic response was determined by the technique described in [21].

The VCSEL's free-running f_r was 2 GHz and, with injection locking, it was increased to 10, 15, 20, and >22 GHz for injection ratios of 1, 4.5, 7, and 10 dB, respectively. Wavelength detuning values were chosen to be close to the positive edge (the master laser is on the longer wavelength side of the free-running VCSEL) at which RF gain enhancement tends to be larger [35]. For a -8-dBm two-tone input at frequencies from 0.6 to 3.0 GHz, the output powers at one of the fundamental frequencies and at one of the IMD3 product frequencies are shown in Fig. 9 for the free-running condition (solid lines) and for various values of injection ratio (dashed lines).

It is interesting to note that, for the free-running laser, the IMD peaks at the resonance frequency, and a "shoulder" is observed at half f_r; in this case, 1.0 GHz [29]. We observed a very large modulation efficiency enhancement with increasing injection ratio ranging from 0.5 dB for the low injection ratio to as high as ~16 dB for the highest injection ratio 10 dB. In addition, the distortion is reduced by from 11 to 19 dB. The measured distortion is source instrument limited, as evidenced by the similar oscillations that we observed in the measurement of the IMD of two synthesizers.

The SFDR enhancement is determined by the RF gain enhancement plus one-third of the distortion reduction; thus, the RF gain significantly contributes to the SFDR enhancement. Fig. 10 shows the SFDR improvement for varying injection ratios. The experiment demonstrates that an increasing injection ratio leads to an increasing SFDR. Note that this SFDR improvement does not include the potential reduction in RIN [39]. We were unable to measure RIN accurately in this case because of high coupling loss. Hence, the SFDR improvement reported here can be considered as a lower bound.

B. Simulations

Theoretical predictions for the distortion of an injection-locked laser have shown that a small reduction in distortion is possible for some injection conditions [40]. The injection conditions studied, however, were for a low effective injection ratio, limited to typical edge-emitting laser injection-locking parameters. In the case of surface-emitting lasers, since the cavity length can be ~300× smaller than the edge emitters, even with a 99% reflectivity, the coupling coefficient k_c can be ~20× larger. We performed numerical simulations for the case of the injection-locked VCSEL under very strong injection conditions, and demonstrate that a very large distortion reduction is possible. We also confirm RF link gain enhancement.

Simulations of $S21$ and IMD3 of both the free-running and injection-locked laser have been performed using laser rate equations [8]. The master laser was assumed to be noise free. The free-running f_r is 4.8 GHz. The parameters used for the simulations were: 1) coupling rate $k_c = 3.8 \times 10^{12}\ \mathrm{s}^{-1}$; 2) photon and carrier lifetime $t_p = 2 \times 10^{-12}$ s; $t_s = 2 \times 10^{-9}$ s; 3) linewidth enhancement factor $\alpha = 3$; 4) differential gain $(dg)/(dn) = 2 \times 10^{-16}\ \mathrm{cm}^2$; and 5) a bias of 4 mA. In the simulation, a frequency spacing of 100 MHz was chosen to reduce the numerical computation time by 10× where, as in the experiment, a 10-MHz spacing was used. The distortion simulated only considers the distortion originating from the rate equations (i.e., due to the relaxation oscillations). Other origins of distortion, such as lateral carrier diffusion and spatial hole burning, have not been considered, as it has been numerically predicted that they have a negligible effect on injection-locking performance [41]. These effects, however, may become important when investigating distortion enhancement at even higher injection ratios.

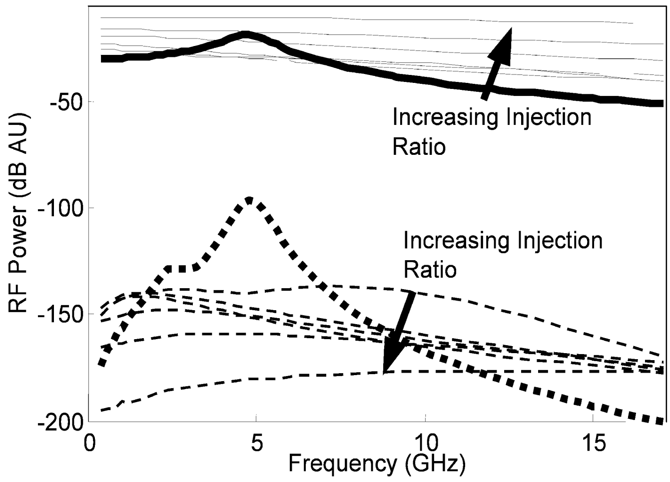

Fig. 11. Numerical simulation results for modulation response $S21$ and two-tone IMD3 versus frequency. The two-tone spacing is $\Delta f = 100$ MHz.

Fig. 11 shows the simulated results for the signal and distortion frequency response. The thick curves are the $S21$ (top solid) and IMD3 (bottom dotted) of the free-running laser, while the thin curves are those under various injection ratios. The wavelength detuning is chosen to be at the positive edge of locking. As can be seen, the modulation efficiency is increased as the injection ratio increases; meanwhile, the IMD3 is suppressed, which is consistent with the experimental results. For very high injection ratios, substantial suppression of the IMD3 is observed.

The simulation results for the SFDR improvement versus injection ratio are shown in Fig. 10. They are plotted for the 2.4-GHz signal (which is half of the free-running resonance frequency of 4.8 GHz) as a function of injection ratio for a wavelength detuning that is near the positive edge of the locking range. For consistency, the comparison between the experimental and numerical results was done at half the resonance frequency.

The experimental and simulation results are comparable in trend. The simulation predicts that a very large dynamic range can be achieved for a high injection ratio. The slope of the enhancement versus injection ratio is ~1 dB/dB. This suggests that experimentally increasing the injection ratio ~8 dB higher (i.e., ~18-dB injection ratio) would result in an SFDR enhancement of 30 dB.

The discrepancy on absolute enhancement versus injection ratio between simulation and experiment is in part due to the difficulty in accurately measuring the injection ratio parameter. The injection ratio is defined as the ratio between injection power into the VCSEL versus the free-running power. In the case of the VCSEL, the high reflectivity mirror may be increasing the coupling loss; thus, a higher injection power would be required to achieve the predicted results. As well, the VCSEL parameters chosen for the rate equation do not necessarily accurately describe the VCSEL used in the experiment. Further studies to determine the VCSEL parameters and injection ratio could be performed using the injection-locking four-wave mixing technique described in [42].

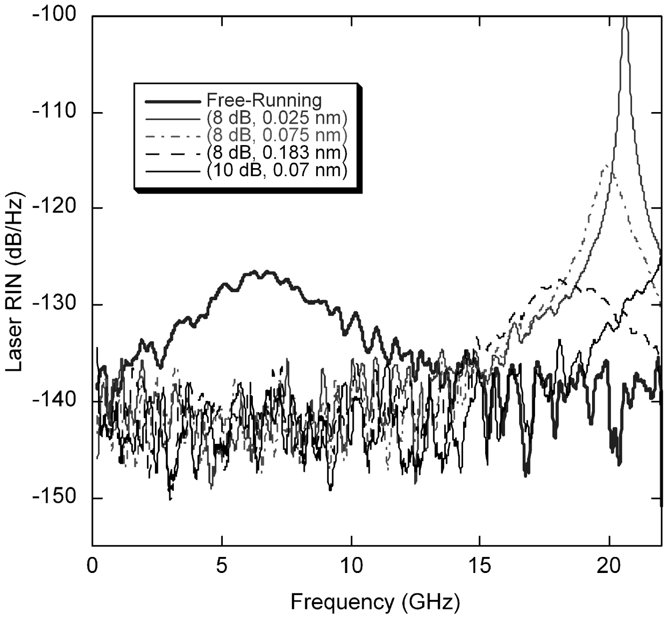

Fig. 12. Experimental results of the laser RIN. The thick curve is the RIN for the free-running laser. Legend indicates (injection ratio, wavelength detuning) values. The thin curves are RIN for injection-locked VCSELs at two injection ratio values for varied wavelength detuning values.

VI. RIN OF OIL VCSELs

OIL has been reported to reduce laser RIN for VCSELs and FP edge-emitting lasers [23], [43]. For a RIN-limited radio-over-fiber system, this implies an even higher SFDR. In this experiment, a Vertilas BTJ VCSEL VCSEL was used and biased at 1 mA. Due to the high fiber coupling loss, the optical signal was too weak to directly observe the laser noise (<-10 dBm). An EDFA followed by an optical filter were used to amplify the noise signal. An HP 71400C lightwave signal analyzer was then used to measure the RIN of the injection-locked VCSEL.

The RIN spectra of the injection-locked VCSEL at different injection conditions are shown in Fig. 12. The RIN spectrum of the free-running VCSEL is also shown as the reference at a 1-mA bias (~2× threshold for this device). The RIN peaks of both free-running and injection-locked conditions are in agreement with resonance frequencies in the small-signal modulation response of the laser. For an injection ratio of 8 dB, RIN data for varied detuning is shown. As the detuning is reduced (to shorter wavelength side), the resonance frequency is increased and less damped. A large RIN reduction at the low frequency regime (0–13 GHz) is observed due to increased f_r. However, it is relatively constant over a large frequency span, even at the very low-frequency region, and is limited by EDFA noise. At higher injection ratios (10 dB), the resonance frequency increases beyond the instrumentation limit, and the noise is reduced over nearly the entire visible frequency band. The RIN reduction can be intuitively understood as the following: when the laser is injection locked, fewer carriers are needed to achieve lasing threshold. The spontaneous emission of the laser and, therefore, its noise, is reduced. However, the increased resonance frequency enhancement is the most important reason that the noise value is decreased at the low-frequency regime since the noise peak is moved to higher frequencies. The combination of these two factors results in the RIN reduction of an injection-locked laser.

TABLE I
MICROWAVE PERFORMANCE OF OIL VCSELs.
($*$LIMITED BY AVAILABLE INSTRUMENTATION)

Performance Metric	**Enhance-ment**	**OIL VCSEL**	**OIL DFB**
Resonance Frequency	5-10 X	50 GHz*	30 GHz [11]
Intrinsic Modulation BW	5+ X	> 50 GHz	35 GHz [11]
Modulation Efficiency	10 X	2.2 W/A	
RF Link Gain	20 dB	-19 dB	
Spur-free Dynamic Range	20 dB	106 dB-Hz$^{2/3}$	100 dB-Hz$^{2/3}$ [17]
Relative Intensity Noise	15 dB	-140 dB/Hz*	-170 dB/Hz [30]

VII. CONCLUSION

To summarize, we have reported a thorough study on the microwave performance of OIL VCSELs. The use of an ultrahigh injection ratio results in a high resonance frequency, which leads to significant performance improvements including enhancements in bandwidth, RF link gain, dynamic range, and reduction in laser noise. The performance and enhancements of OIL VCSELs is summarized in Table I. All enhancements, except the 50-GHz resonance frequency, were obtained for a large positive wavelength detuning, for high injection ratio, and are observable simultaneously. For the large detuning values, the resonance frequency was enhanced to $\sim$30–40 GHz.

A record resonance frequency of 50 GHz is achieved with polarization-maintained injection locking of a BTJ 1.55-μm VCSEL. We demonstrated this behavior for four devices with all devices showing an initial free-running resonance frequency below 10 GHz. The intrinsic bandwidth of the injection-locked VCSEL is $>$50 GHz. We show that the resonance frequency scales with increasing injection ratio, and is expected to increase for even higher injection ratios.

Under the ultra-strong injection conditions, we attain up to 20-dB RF link gain enhancement. This corresponds to a modulation efficiency enhancement from 0.22 to 2.2 W/A. The modulation efficiency increases with increasing injection ratios.

We demonstrated both experimentally and numerically that injection locking is effective in reducing distortion, thereby improving the SFDR of a directly modulated laser. An OIL VCSEL with an IMD3 SFDR of 106 dB $\cdot$ Hz$^{2/3}$ at 1 GHz was achieved, representing an SFDR increase of 20 dB. A large dynamic range was observed as well over a wider frequency band of 0.6–3.0 GHz. The SFDR improvement is shown to linearly increase with injection ratio. Similarly, the SFDR enhancement increases with increasing resonance frequency and RF gain. We expect that a 30-dB enhancement could be observed with a higher injection ratio.

Injection locking was shown to reduce laser noise. The VCSEL RIN peak was moved to higher frequency, leaving a low noise ($\sim\!-140$ dB/Hz) over a very broad frequency band (0–13 GHz). The RIN reduction was $\sim$15 dB at the free-running f_r (6 GHz). This reduction in laser noise was not taken into account when determining the SFDR enhancements, thus an even larger enhancement is expected if laser noise was taken into account.

The results suggest that OIL VCSELs are a promising high-performance solution for microwave photonic applications. OIL VCSELs may find applications in low-cost radio-over-fiber distribution systems such as cellular telephone signals (global system for mobile communications (GSM) requires $\sim$90 dB $\cdot$ Hz$^{2/3}$ dynamic range) and wireless local area networks (WLANs) (802.11 x). For injection locking to offer the enhancements described in this study, the resonance frequency must be increased to a very high value, which is achieved by using an ultrahigh injection ratio.

ACKNOWLEDGMENT

The authors would like to thank Prof. M.-C. Amann, R. Shau, M. Ortsiefer, all with Vertilas GmbH, Munich, Germany, for providing the BTJ VCSELs, as well as Dr. W. Yuen and R. Stone, both with Bandwidth9 Inc., Fremont, CA, for the tunable VCSELs. The authors acknowledge M. Moewe, University of California at Berkeley, for performing the RIN measurements. The authors thank Prof. M. C. Wu, University of California at Berkeley, Dr. S. Pappert, Defense Advanced Research Projects Agency (DARPA), Arlington, VA, and Prof. R. Tucker, University of Melbourne, Melbourne, Australia, for stimulating discussions.

REFERENCES

[1] H. Soda, K. Iga, C. Kitahara, and Y. Suematsu, "GaInAsP–InP surface emitting injection-lasers," *Jpn. J. Appl. Phys.*, vol. 18, pp. 2329–2330, 1979.

[2] J. L. Jewell *et al.*, "Low-threshold electrically pumped vertical-cavity surface-emitting microlasers," *Electron. Lett.*, vol. 25, pp. 1123–1124, 1989.

[3] D. L. Huffaker, D. G. Deppe, K. Kumar, and T. J. Rogers, "Native-oxide defined ring contact for low-threshold vertical-cavity lasers," *Appl. Phys. Lett.*, vol. 65, pp. 97–99, 1994.

[4] K. Y. Lau and A. Yariv, "Intermodulation distortion in a directly modulated semiconductor injection laser," *Appl. Phys. Lett.*, vol. 45, no. 10, pp. 1034–1036, 1984.

[5] S. Weisser *et al.*, "Damping-limited modulation bandwidths up to 40 GHz in undoped short-cavity In0.35Ga0.65As–GaAs multiple-quantum well lasers," *IEEE Photon. Technol. Lett.*, vol. 8, no. 5, pp. 608–610, May 1996.

[6] K. L. Lear *et al.*, "High-speed vertical cavity surface emitting lasers," in *Proc. IEEE/LEOS Summer Topical Meeting*, vol. 1997, pp. 53–54.

[7] D. M. Kuchta, P. Pepeljugoski, and Y. Kwark, "VCSEL modulation at 20 Gb/s over 200 m of multimode fiber using a 3.3 v SiGe laser driver IC," in *LEOS Summer Top. Meeting*, Jul. 30–Aug. 1, 2001, pp. 49–50.

[8] C. H. Chang, L. Chrostowski, and C. J. Chang-Hasnain, "Injection locking of VCSEL's," *J. Sel. Topics Quantum Electron.*, vol. 9, no. 5, pp. 1386–1393, Sep.–Oct. 2003.

[9] X. J. Meng, C. Tai, and M. C. Wu, "Experimental demonstration of modulation bandwidth enhancement in distributed feedback lasers with external light injection," *Electron. Lett.*, vol. 34, no. 21, pp. 2031–2032, 1998.

[10] H.-K. Sung *et al.*, "Modulation bandwidth enhancement and nonlinear distortion suppression in directly modulated monolithic injection-locked DFB lasers," in *Int. Topical Microw. Photon. Meeting*, 2003, pp. 27–30.

[11] S. K. Hwang, J. M. Liu, and J. K. White, "35-GHz intrinsic bandwidth for direct modulation in 1.3-μm semiconductor lasers subject to strong injection locking," *IEEE Photon. Technol. Lett.*, vol. 16, no. 4, pp. 972–974, Apr. 2004.

[12] L. Chrostowski, X. Zhao, C. Chang-Hasnain, R. Shau, M. Ortsiefer, and M.-C. Amann, "50 GHz directly-modulated injection-locked 1.55 μm VCSELs," presented at the Opt. Fiber Conf., 2005.

[13] X. Zhao, L. Chrostowski, and C. J. Chang-Hasnain, "Dynamic range enhancement in 1.55 m VCSEL's using injection-locking," in *Microw. Photon. Conf.*, 2004, pp. 111–114.

[14] K. Kobayashi and R. Lang, "Suppression of the relaxation oscillation in the modulated output of semiconductor lasers," *IEEE J. Quantum Electron.*, vol. QE-12, no. 3, pp. 194–199, Mar. 1976.

[15] H. Li, T. L. Lucas, J. G. Mclnerney, M. W. Wright, and R. A. Morgan, "Injection locking dynamics of vertical cavity semiconductor lasers under conventional and phase conjugate injection," *IEEE J. Quantum Electron.*, vol. 32, no. 2, pp. 227–235, Feb. 1996.

[16] J. Wang, M. K. Haldar, L. Li, and F. V. C. Mendis, "Enhancement of modulation bandwidth of laser diodes by injection locking," *IEEE Photon. Technol. Lett.*, vol. 1, no. 8, pp. 34–36, Aug. 1996.

[17] X. J. Meng, C. Tai, and M. C. Wu, "Improved intrinsic dynamic distortions in directly modulated semiconductor lasers by optical injection locking," *IEEE Trans. Microw. Theory Tech.*, vol. 47, no. 7, pp. 1172–1176, Jul. 1999.

[18] S. Mohrdiek, H. Burkhard, and H. Walter, "Chirp reduction of directly modulated semiconductor lasers at 10 Gb/s by strong CW light injection," *J. Lightw. Technol.*, vol. 12, no. 3, pp. 418–424, Mar. 1994.

[19] A. Murakami, K. Kawashima, and K. Atsuki, "Cavity resonance shift and bandwidth enhancement in semiconductor lasers with strong light injection," *J. Quantum Electron.*, vol. 39, no. Oct., pp. 1196–1204, 2003.

[20] S. Wieczorek, W. W. Chow, L. Chrostowski, and C. J. Chang-Hasnain, "Improved semiconductor-laser dynamics from induced population pulsation," *Phys. Rev. A, Condens. Matter*, 2005, submitted for publication.

[21] L. Chrostowski, X. Zhao, and C. J. Chang-Hasnain, "Very high resonance frequency (>40 GHz) optical injection-locked 1.55 μm VCSELs," in *Microw. Photon. Conf.*, Oct. 2004, pp. 255–258. vol. 2004.

[22] X. Zhao *et al.*, "28 GHz optical injection locked 1.55 m VCSELs," *Electron. Lett.*, vol. 40, no. 8, pp. 476–478, Apr. 2004.

[23] L. Chrostowski, C. H. Chang, and C. J. Chang-Hasnain, "Reduction of relative intensity noise and improvement of spur-free dynamic range of an injection locked VCSEL," in *Lasers Electro-Opt. Soc. Conf.*, vol. 2, Oct. 27–28, 2003, pp. 706–707.

[24] ——, "Enhancement of dynamic range in 1.55 μm VCSEL's using injection locking," *IEEE Photon. Technol. Lett.*, vol. 15, no. 4, pp. 498–500, Apr. 2003.

[25] ——, "Injection-locked 1.55 μm tunable VCSEL for uncooled WDM transmitter applications," *IEEE Photon. Technol. Lett.*, vol. 16, no. 3, pp. 888–890, Mar. 2004.

[26] R. Tucker, private communication, 2005.

[27] M. Ortsiefer *et al.*, "High-speed modulation up to 10 Gbit/s with 1.55 μm wavelength InGaAlAs VCSELs," *Electron. Lett.*, vol. 38, no. 20, pp. 1180–1181, 2002.

[28] G. S. Li, R. F. Nabiev, W. Yuen, M. Jasen, D. Davis, and C. J. Chang-Hasnain, "Electrically-pumped directly-modulated tunable VCSEL for metro DWDM applications," in *Eur. Opt. Commun. Conf.*, vol. 12, 2001, pp. 1686–1688.

[29] S. Wieczorek, B. Krauskopf, and D. Lenstra, "A unifying view of bifurcations in a semiconductor laser subject to optical injection," *Opt. Commun.*, vol. 172, no. 1–6, pp. 279–295, Dec. 15, 1999.

[30] H.-H. Lu, H. H. Hunag, H. S. Su, and M. C. Wang, "Fiber optical CATV system-performance improvement by using external light-injection technique," *IEEE Photon. Technol. Lett.*, vol. 15, no. 7, pp. 1017–1019, Jul. 2003.

[31] L. P. Barry, P. Anandarajah, and A. Kaszubowska, "Optical pulse generation at frequencies up to 20 GHz using external-injection seeding of a gain-switched commercial Fabry–Perot laser," *IEEE Photon. Technol. Lett.*, vol. 13, no. 9, pp. 1014–1016, Sep. 2001.

[32] T. B. Simpson and J. M. Liu, "Enhanced modulation bandwidth in injection-locked semiconductor lasers," *IEEE Photon. Technol. Lett.*, vol. 10, no. 9, pp. 1322–1324, Sep. 1997.

[33] H. H. Lu, P. C. Lai, and W. S. Tsai, "Radio-on-multimode fiber systems based on VCSEL's and external light injection technique," *IEEE Photon. Technol. Lett.*, vol. 16, no. 4, pp. 1215–1217, Apr. 2004.

[34] C. H. I. I. I. Cox, H. V. Roussell, R. J. Ram, and R. J. Helkey, "Broadband, directly modulated analog fiber link with positive intrinsic gain and reduced noise figure," in *IEEE Int. Microw. Photon. Topical Meeting*, 1998, pp. 157–160.

[35] X. Zhao, L. Chrostowski, and C. Chang-Hasnain, "Extinction ratio of injection-locked VCSELs," presented at the IEEE Lasers Electro-Opt. Soc. Meeting, 2004.

[36] S. A. Pappert, C. K. Sun, R. J. Orazi, and T. E. Weiner, "Microwave fiber optic links for shipboard antenna applications," in *Proc. IEEE Int. Phased Array Syst. Technol. Conf.*, Piscataway, NJ, 2000, pp. 345–8.

[37] H. L. T. Lee, R. V. Dalai, R. J. Ram, and K. D. Choquette, "Dynamic range of vertical-cavity surface-emitting lasers in multimode links," *IEEE Photon. Technol. Lett.*, vol. 11, no. 11, pp. 1473–1475, Nov. 1999.

[38] J. Wang, M. K. Haldar, and F. V. C. Mendis, "Formula for two-carrier third-order intermodulation distortion in semiconductor laser diodes," *Electron. Lett.*, vol. 29, no. 15, pp. 1341–1343, 1993.

[39] G. Yabre, H. De Waardt, H. P. A. van den Boom, and G. D. Khoe, "Noise characteristics of single-mode semiconductor lasers under external light injection," *IEEE J. Quantum Electron.*, vol. 36, no. 3, pp. 385–393, Mar. 2000.

[40] G. Yabre and J. Le Bihan, "Reduction of nonlinear distortion in directly modulated semiconductor lasers by coherent light injection," *IEEE J. Quantum Electron.*, vol. 33, no. 7, pp. 1132–1140, Jul. 1997.

[41] J. Y. Law, G. H. M. van Tartwijk, and G. P. Agrawal, "Effects of transverse-mode competition on the injection dynamics of vertical-cavity surface-emitting lasers," *Quantum Semiclassical Opt.*, vol. 9, no. 5, pp. 737–747, 1997.

[42] T. B. Simpson, J. M. Liu, A. Gavrielides, V. Kovanis, and P. M. Alsing, "Period-doubling route to chaos in a semiconductor laser subject to optical injection," *Appl. Phys. Lett.*, vol. 64, no. 26, pp. 3539–3541, 1994.

[43] X. Jin and S. L. Chuang, "Relative intensity noise characteristics of injection-locked semiconductor lasers," *Appl. Phys. Lett.*, vol. 77, no. 9, pp. 1250–1252, 2000.

Lukas Chrostowski (M'98) was born in Warsaw, Poland, in 1975. He received the B.Eng. degree in electrical engineering from McGill University, Montreal, QC, Canada, in 1998, and the Ph.D. degree in electrical engineering and computer science from the University of California at Berkeley, in 2004.

Since January 2005, he has been an Assistant Professor with the Electrical and Computer Engineering Department, University of British Columbia, Vancouver, BC, Canada. His research interests are in the area of opto-electronics and include injection locking of VCSELs for high-speed analog and digital modulation, VCSEL fabrication, characterization, design and modeling, and optical communication systems.

Xiaoxue Zhao (S'04) was born in Beijing, China, in 1981. She received the B.S. degree in electronics from Peking University, Beijing, China, in 2003, and is currently working toward the Ph.D. degree in electrical engineering and computer science at the University of California at Berkeley.

Her research interests are in microwave photonics, high-speed modulation of VCSELs, distortion reduction using OIL, and optical communication systems.

Connie J. Chang-Hasnain (M'88–SM'92–F'98) received the B.S. degree from the University of California at Davis, in 1982, and the M.S. and Ph.D. degrees from the University of California at Berkeley, in 1984 and 1987, respectively, all in electrical engineering.

From 1987 to 1992, she was a Member of Technical Staff with Bellcore. From April 1992 to December 1995, she was an Associate Professor of electrical engineering with Stanford University, Stanford, CA. Since January 1996, she has been a Professor with the Department of Electrical Engineering, University of California at Berkeley. Since 2004, she has been the Director of the Center for Optoelectronic Nanostructured Semiconductor Technologies (CONSRT). She has coauthored 283 research papers in technical journals and conferences and six book chapters. She holds 26 patents. Her research interests are nanostructured materials, nanoopto-electronc and microopto-electronic devices, and their applications.

Prof. Chang-Hasnain is a Fellow of the Optical Society of America (OSA) and the Institution of Electrical Engineers (IEE), U.K. She is an associate editor for the JOURNAL OF LIGHTWAVE TECHNOLOGY. She was named a Presidential Faculty Fellow, a National Young Investigator, a Packard Fellow, a Sloan Research Fellow, and an Outstanding Young Electrical Engineer of the Year by Eta Kappa Nu. She was the recipient of the 1994 IEEE Lasers and Electro-Optics Society (IEEE LEOS) Distinguished Lecturer Award, the 2000 Curtis W. McGraw Research Award presented by the American Society of Engineering Education, the 2003 IEEE William Streifer Scientific Achievement Award, and the 2005 Gilbreth Lecturer Award presented by the National Academy of Engineering. In 2005, she was elected an Honorary Member of the A. F. Ioffe Institute.