Optical Properties and Modulation Characteristics of Ultra-Strong Injection-Locked Distributed Feedback Lasers

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***Abstract*—The optical properties and the frequency responses of ultrastrong (injection ratio > 10 dB) injection-locked distributed feedback lasers are investigated experimentally and theoretically. We have observed three distinctive modulation regimes under different frequency detuning between the master and the slave lasers. At large negative frequency detuning, the laser exhibits enhanced modulation efficiency at low frequencies. At intermediate frequency detuning, a flat frequency response with large 3 dB bandwidth is observed. At large positive frequency detuning, the modulation response shows a pronounced resonance peak at high frequencies. These phenomena can be explained by the resonance enhancement of the slave laser cavity mode, with the resonance frequency equal to the difference between the injection-locked frequency and the cavity mode. The experimental results agree well with theoretical calculations based on three coupled rate equations. Depending on the applications, the injection locking conditions can be optimized to achieve high RF link gain, broadband, or high resonance frequency operations.**

***Index Terms*—Directly modulated semiconductor laser, optical injection locking, modulation response.**

I. Introduction

Optical injection locking of semiconductor lasers has been widely investigated because they exhibit many advantages over free-running lasers, including the reduction of mode partition noise [1], chirp [2]–[4], relative intensity noise (RIN) [5], [6], and nonlinear distortions [7], [8]. It has also been used to provide direct optical phase modulation [9]. More recently, optical injection locking has been employed to enhance the resonance frequency and modulation bandwidth of the slave laser [10]–[13].

Historically, most of the experiments performed in the 1980s were in the weak injection regime ($R < -10$ dB) [1], [9], [14]–[17]. Injection ratio R is defined as the power ratio between the injected power and the lasing power of the free-running slave laser measured inside the laser cavity. In the 1990s, owing to the advances in high-power semiconductor lasers, strong optical injection (-10 dB $< R < 0$ dB) has been investigated. The enhancement of resonance frequency [10] and modulation bandwidth [5], [11], [18]–[21] becomes significant. This enhancement has been predicted theoretically, based on rate equation simulations [10]. Recently, Murakami *et al.* [12] provided a simple physical picture of the enhancement process. Under optical injection locking, the slave laser is forced to oscillate at the master laser frequency and not at the cavity mode. When the slave laser is modulated, as the modulation sideband overlaps with the cavity mode, the modulation response is enhanced. This resonance frequency is equal to the detuning between the master frequency and the shifted cavity mode. It is to be noted the cavity mode will shift under injection locking due to a change of carrier concentration in the slave cavity. Ultimately, the detuning is limited by the stable locking range. Since the locking range is proportional to the injection ratio [22], [23], higher resonance frequency can be achieved with large R. Using an injection ratio of 13.8 dB, measured at the outside of the laser cavity, Chrostowski *et al.* has demonstrated a resonance frequency of >50 GHz in vertical-cavity surface-emitting lasers (VCSELs) [24], [25].

In this paper, we report on the dynamic performance of distributed feedback (DFB) lasers under even higher injection ratios ($R > 10$ dB). To distinguish this from the previous *strong* optical injection with R between -10 and 0 dB, we call this regime *ultra-strong* optical injection. The dynamic response of the slave laser exhibits three distinctive regimes of operation under various frequency detuning between the master laser and the free-running slave laser. The injection condition can be optimized for: (1) high modulation efficiency; (2) broadband operation; or (3) high resonance frequency. Experimentally, a record high resonance frequency of 72 GHz has been achieved [26]. The experimental observation agrees well with the theoretical calculations based on three coupled rate equations.

II. Experimental Setup

The experimental setup is shown in Fig. 1. An external-cavity tunable laser (ECTL) is employed as the master laser. An erbium-doped fiber amplifier (EDFA) boosts up the injection power (maximum output power = 25 dBm). The injection ratio is controlled by a variable optical attenuator. Polarization matching between the master and the slave lasers is realized by a fiber polarization controller. Light from the master laser is coupled to the slave laser via an optical circulator (with >40 dB isolation) and a fiber pig-tailed optical pickup head. The output from the slave laser is collected by the same pickup head and

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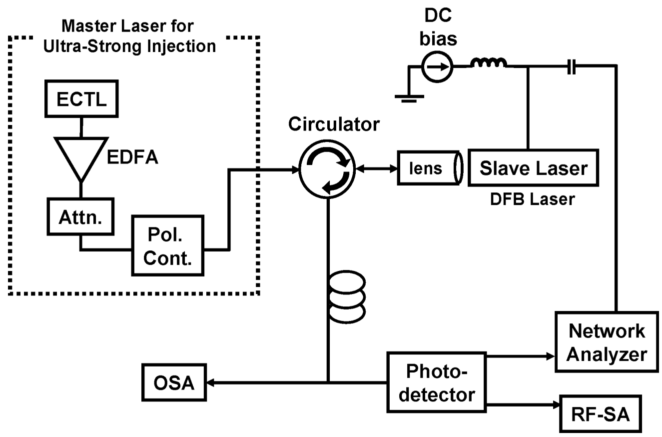

Fig. 1. Experimental setup for ultrastrong optical injection locking. The optical spectrum and the frequency responses are monitored simultaneously. Attn.: variable optical attenuator; Pol. Cont.: polarization controller.

separated from the master output by the circulator. The circulator prevents undesired feedback from the slave laser to the master laser, as well as protects the slave laser from the back-reflected light. The slave laser is a DFB laser with two electrically isolated gain sections. Only the section facing the coupling lens is pumped while the other section is left unbiased.

The optical and the RF spectra of the slave laser are continuously monitored to ensure stable single-mode operation throughout the measurements presented in this paper. The optical output of the injection-locked laser is characterized by an optical spectrum analyzer (OSA) with a resolution of 0.01 nm ($= 1.25$ GHz). To measure the frequency responses, modulation signals from a network analyzer are applied to the slave laser through a bias-tee. The output is sent to a high-speed (34 GHz) photodetector, followed by the network analyzer or an RF-spectrum analyzer (RF-SA).

III. Experimental Results

Fig. 2(a)–(c) show the measured optical spectra under various frequency detuning values. Fig. 2(d)–(f) depict the corresponding frequency responses. The threshold current of the free-running slave laser is 9 mA. It is dc-biased at 19 mA ($= 2.1\ I_{\rm th}$) for all measurements. The lasing wavelength at this bias current is thermally stabilized at 1545.91 nm by a heat sink with temperature controller. The output power of the free-running slave laser is measured to be -3 dBm at the output fiber.

The free-running optical spectrum is shown by the dotted line in Fig. 2(a). It exhibits stable single-mode operation with side mode suppression ratio (SMSR) of >50 dB. The frequency response in Fig. 2(d) shows a relaxation oscillation frequency of 4.2 GHz for the free-running laser. To achieve ultrastrong injection-locking, the optical power of the master laser is boosted by an EDFA to attain an injection ratio of $R = 12$ dB. The frequency detuning Δf is varied systematically by piezotuning of the ECTL while maintaining the injection ratio at a constant value. The frequency detuning Δf is defined as the frequency difference between the master and the free-running slave lasers ($\Delta f = f_{\rm master} - f_{\rm free,slave}$). The injection-locking range is measured by observing the optical spectra in OSA and the beat frequency in RF-SA. The measured locking range is marked by the thin vertical lines at $\lambda = 1545.71$ and 1546.30 nm in Fig. 2(a)–(c). The area between the two vertical lines is the stable locking range. The lower and the upper limits of frequency detuning values are -48.75 and 25 GHz, respectively. The line at $\lambda = 1545.91$ nm represents the zero-detuning frequency ($\Delta f = 0$). The asymmetry of the locking range is due to the nonzero linewidth enhancement factor (Henry's factor) [22], [27].

Experimentally, the transition from locked to unlocked states at the negative detuning edge was easily observed through a sudden jump in lasing frequency. However, because there is no such wavelength hop at the positive detuning edge, the locking range for the positive detuning edge is defined as the frequency detuning at which the SMSR between the injection-locked peak and the residual cavity mode is 35 dB. Within this range, no unstable locking or unlocked phenomena such as four-wave mixing, pulsation, or chaos were observed. The slave laser is still locked to the master laser despite the existence of the cavity mode.

In the large negative locking regime ($\Delta f = -42$ GHz), where the master laser is injected on the longer wavelength side of the free-running slave laser, the optical spectrum in Fig. 2(a) shows a single-mode operation with SMSR >50 dB. The corresponding frequency response exhibits an enhanced amplitude response at low frequency (dc to $\sim$3 GHz). The increase of the amplitude response results from a cavity resonance effect. Since the cavity mode is very close to the injected frequency, the resulting resonance frequency is low.

When the master laser is tuned toward the center of the locking range ($\Delta f = -14$ GHz), a single-mode spectrum is maintained with an SMSR of 45 dB. The cavity mode is believed to be hidden under the envelope of the injection-locked spectrum due to its small amplitude and the limited resolution of the OSA. The corresponding frequency response in Fig. 2(e) exhibits a 3 dB bandwidth of 21 GHz, which is more than fourfold increase over the relaxation oscillation frequency of the free-running laser. This broad 3 dB bandwidth originates from the moderate resonance enhancement of the cavity mode. This resonance compensates the RC roll-off of the free-running laser. Therefore, the flat frequency response and broad 3 dB modulation bandwidth are observed.

Finally, the master laser is tuned to the positive detuning edge. The cavity mode becomes observable, showing a reduced SMSR and increased wavelength spacing between injection-locked frequency and the cavity mode. As shown in Fig. 2(c), the wavelength of the cavity mode is shifted to longer wavelength compared with the original wavelength of the free-running slave laser. This results from the carrier density-dependent refractive index change in the injection-locked laser [12], [22]. The injection of photon from the master laser depletes the carrier in the slave laser. The difference between the injection-locked wavelength and the cavity mode is measured to be 0.264 nm (=33 GHz). Correspondingly, a resonant peak is observed at 33 GHz in the frequency response, as shown in Fig. 2(f). The resonance peak originates from the resonance enhancement of

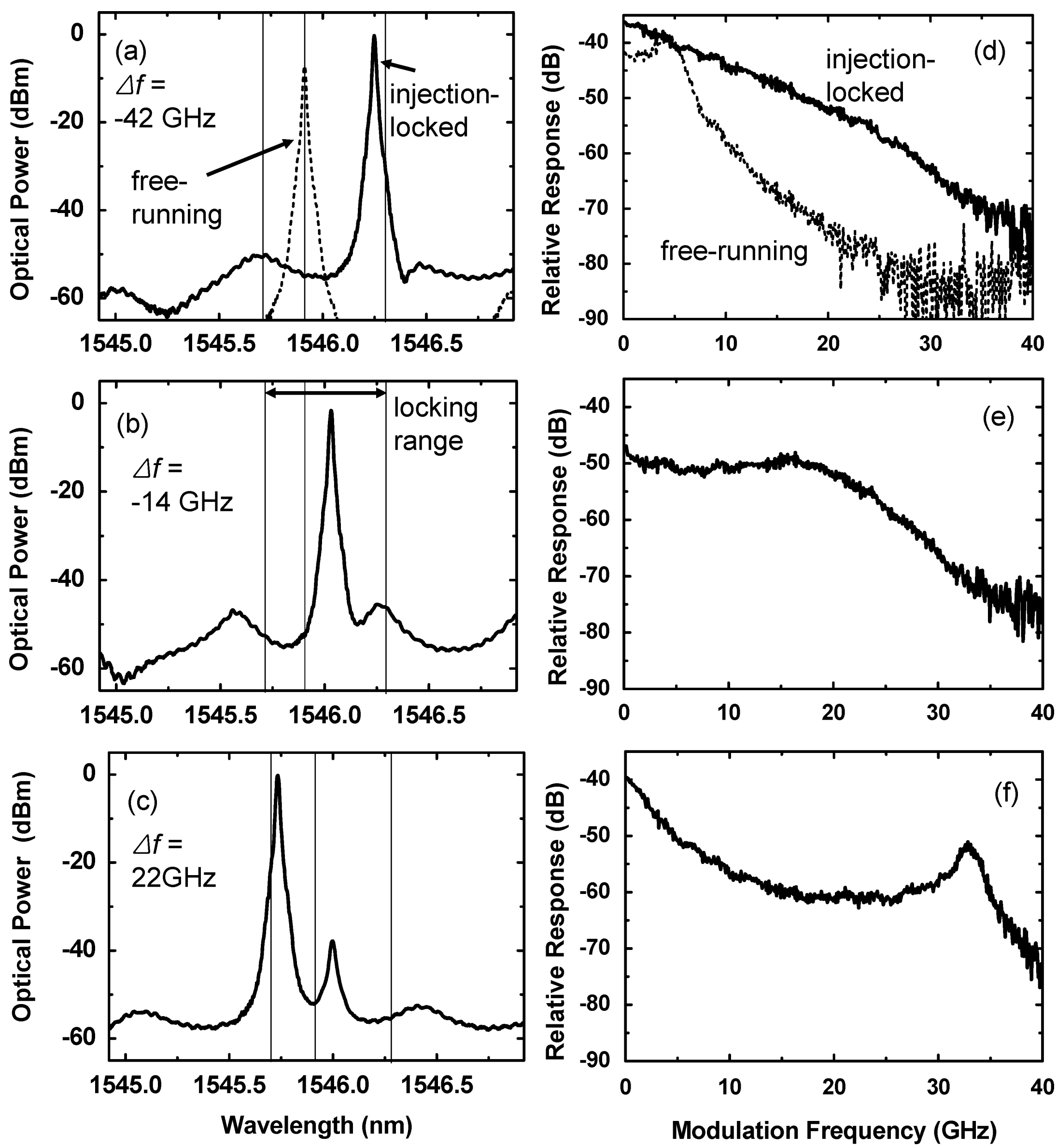

Fig. 2. (a)–(c) Experimentally measured optical spectra and (d)–(f) frequency responses of an ultrastrong optical injection-locked laser for various detuning conditions. The injection ratio is kept at 12 dB. Frequency detuning. (a) and (c) $\Delta f = -42$ GHz. (b) and (d) $\Delta f = -14$ GHz. (c) and (f) $\Delta f = 22$ GHz. For comparison, optical spectrum and frequency response of the free-running laser are depicted as dot lines in (a) and (c), respectively. Three vertical solid lines in the optical spectra represent positive detuning edge, free-running lasing wavelength, and negative detuning edge from left to right.

the cavity mode. Since the cavity mode is on the longer wavelength side, only the upper wavelength sideband is resonantly amplified. The asymmetric sidebands can be exploited to achieve single sideband modulation and reduce dispersion penalty in optical fibers [28]. The details will be reported elsewhere [29].

As shown by the experimental data presented here, the frequency response of the slave laser is dictated by the relative location of the residue cavity mode with respect to the injection-locked frequency. When the cavity mode is close to the master frequency, the resonance enhancement leads to increased modulation efficiency at low frequencies (Regime I). When the cavity mode is far away, it results in an enhanced resonance peak whose frequency is much higher than the relaxation oscillation frequency of the free-running laser (Regime III). At intermediate spacing, a broad modulation bandwidth is observed (Regime II).

IV. Theoretical Model

Several researchers have investigated the resonance frequency increase in directly modulated semiconductor lasers with strong optical injection locking, both experimentally and theoretically [5], [12], [19], [25], [30], [31]. To model the three distinctive frequency responses observed experimentally, the dynamics of injection-locked lasers are simulated by rate equations, which couple the temporal variations of the amplitude, the phase, and the carrier concentration of the slave laser [12], [23]

$$\frac{dA(t)}{dt} = \frac{1}{2} g \left[N(t) - N_{\text{th}} \right] A(t) + \kappa \, A_{\text{inj}} \cos \phi(t) \tag{1}$$

TABLE I
VALUES USED IN CALCULATIONS

Symbol	Quantity	Value
g	linear gain coefficient	5.667×10^{3} s^{-1}
N_{th}	threshold carrier number	2.088×10^{8}
κ	coupling coefficient	1.002×10^{11} s^{-1}
α	linewidth enhancement factor	3
γ_N	carrier decay rate	$1/(1 \times 10^{-9}$ s)
γ_P	photon decay rate	$1/(3 \times 10^{-12}$ s)

$$\frac{d\phi(t)}{dt} = \frac{\alpha}{2} g\left[N(t) - N_{\text{th}}\right] - \kappa\frac{A_{\text{inj}}}{A(t)}\sin\phi(t) - 2\pi\Delta f \quad (2)$$

$$\frac{dN(t)}{dt} = J - \gamma_N N(t) - \{\gamma_p + g\left[N(t) - N_{\text{th}}\right]\} A^2(t) \quad (3)$$

where $A(t)$ is the field amplitude defined as $A^2(t) = S(t)$, where $S(t)$ is the photon number; $\phi(t)$ is the phase difference between the temporal laser field of the slave laser and master laser; $N(t)$ is the carrier concentration; and J is the injection current. For all calculations in this section, J is set at $3J_{\text{th}}$. N_{th} is the threshold carrier concentration; g is the linear gain coefficient; γ_P is the photon decay rate; $\kappa(= 1/\tau_{\text{in}})$ is the coupling coefficient; τ_{in} is the cavity round-trip time of the slave laser; α is the linewidth enhancement factor of the slave laser; and γ_N is the carrier decay rate. N_{th} also defines the carrier number at the onset of lasing, and contains both transparency carrier number and photon loss rate $N_{\text{th}} \equiv N_{\text{tr}} + \gamma_P/g$. The values used for the calculation are listed in Table I. Regarding the injection condition, A_{inj} is the field amplitude injected into the slave laser and Δf is the lasing frequency difference (i.e., frequency detuning) between the master and the free-running slave lasers. The dynamics of the slave laser is governed by the injection-locking parameters, including frequency detuning Δf and injection power ratio $R = A_{\text{inj}}^2/A_{\text{free}}^2$, where A_{free} is the field amplitude of the free-running slave laser.

By applying the small-signal linear approximation and stability analysis to the aforementioned rate equations [12], [22], [23], the injection-locking range $\Delta\omega_L$ and locking stabilities can be derived as

$$-\sqrt{1+\alpha^2}\kappa\left(\frac{A_{\text{inj}}}{A_0}\right) < \Delta\omega_L < \kappa\left(\frac{A_{\text{inj}}}{A_0}\right) \quad (4)$$

where A_0 is the stationary amplitude of the slave laser under optical injection. The stable locking range is shown as a function of injection-locking parameters in Fig. 3. Equation (4) and Fig. 3 illustrate that a stronger optical injection broadens the stable injection-locking range.

Fig. 4 shows the calculated frequency responses of the injection-locked laser under various frequency detuning values while fixing the injection ratio R at 10 dB. The frequency responses are derived from the coupled rate equations using first-order linear approximation. The response is normalized by the free-running dc optical output power. The calculated frequency response at large negative detuning ($\Delta f = -60$ GHz) shows an increase in low frequency amplitude response. A broad

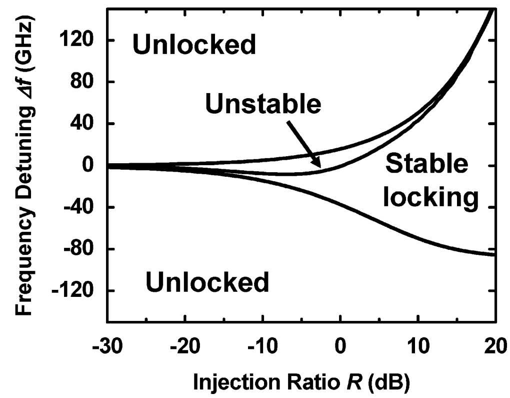

Fig. 3. Injection-locking stability as a function of injection ratio R and frequency detuning Δf. Stronger optical injection broadens the locking range.

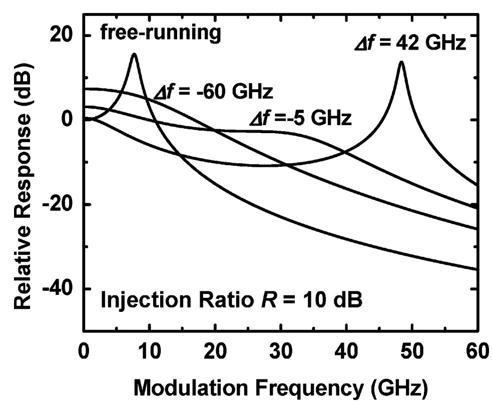

Fig. 4. Calculated frequency responses of ultrastrong ($R = 10$ dB) injection-locked lasers under various frequency detuning values.

3 dB bandwidth is attained when the frequency detuning Δf is set at -5 GHz, near the center of the locking range. A high resonance peak at 48.3 GHz is demonstrated at the detuning value Δf of 42 GHz. These distinctive modulation characteristics of ultrastrong optical injection-locked lasers agree very well with the measurement results.

By linearizing the coupled rate equations, we can derive an approximate formula for the enhanced resonance frequency ω_R [12], [22]

$$\omega_R^2 \approx \omega_{R0}^2 + \kappa^2\left(\frac{A_{\text{inj}}}{A_0}\right)^2 \sin^2\phi_0 \quad (5)$$

where ω_{R0} is the relaxation oscillation frequency of the free-running slave laser, and ϕ_0 is the steady-state phase difference between the injection-locked slave laser and the master laser. Here, we see that increasing the injection ratio enhances the resonance frequency. Fig. 5 shows the calculated frequency response curves where the resonance frequency increases with an increasing injection ratio.

V. BROAD 3 dB BANDWIDTH AND HIGH RESONANCE FREQUENCY WITH NARROWBAND RF GAIN

Fig. 6(a) and (b) are optical spectra of the ultrastrong injection-locked laser showing the tunability of the relative

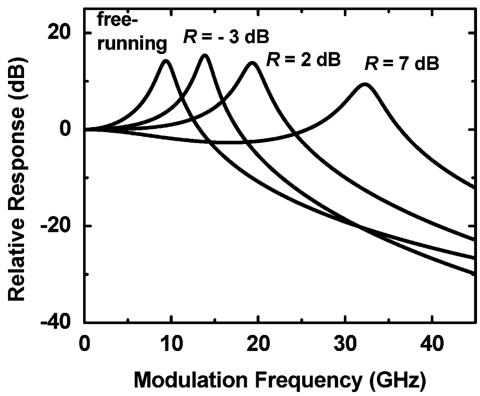

Fig. 5. Calculated frequency responses for various injection ratios. Frequency detuning Δf is set at the positive edge of the locking range.

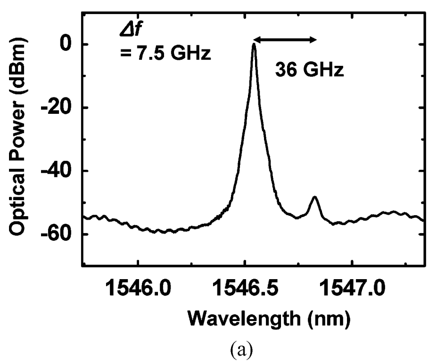

Fig. 6. Measured optical spectra showing the frequency tunability of cavity resonance at an injection ratio of $R = 16$ dB. (a) $\Delta f = 7.5$ GHz. (b) $\Delta f = 38$ GHz.

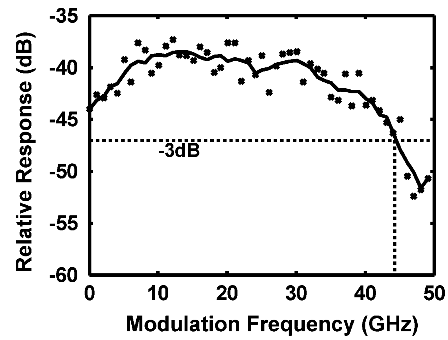

Fig. 7. Experimental results showing the highest 3 dB bandwidth. Injection ratio R is set at 18 dB.

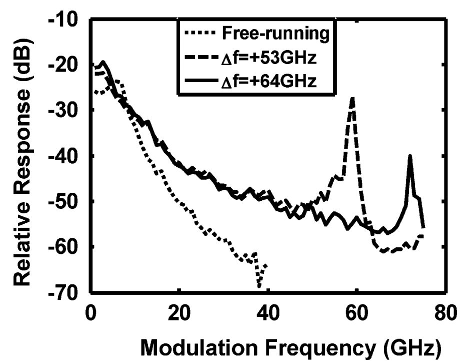

Fig. 8. Experimental results showing the highest resonance frequency.

spacing between the injection-locked wavelength and cavity mode. The injection ratio is fixed at 16 dB, and frequency detuning is varied from 7.5 GHz [Fig. 6(a)] to 38 GHz [Fig. 6(b)]. As the master laser frequency tunes toward the shorter wavelength (positive frequency detuning), the spacing between the injection-locked and cavity modes is increased from 36 GHz [Fig. 6(a)] to 71 GHz [Fig. 6(b)]. By adjusting the frequency detuning, tunable resonance frequency can be achieved.

With this understanding, we can optimize the frequency response of the slave laser to achieve the maximum 3 dB bandwidth or the highest enhanced resonance frequency. Fig. 7 shows a 3 dB bandwidth of 44 GHz, achieved with an injection ratio of 18 dB. This is more than five times increase as compared to the free-running bandwidth. The increased locking range also enables us to detune the master laser further ($\Delta f = +64$ GHz) and achieve higher resonance frequency. Fig. 8 shows the modulation response with a resonance peak at 72 GHz. To our knowledge, this is the highest resonance frequency achieved by optical injection locking. The frequency response was measured by a novel heterodyne technique [26]. Heterodyne techniques are useful for creating and detecting frequencies beyond those of their fundamental components. Here, we use a $4 \times$ RF multiplier to create frequencies in the 50–75 GHz (V-band) range. We use a novel heterodyne detection method to detect the optical modulation. Typically, heterodyne detection suffers from frequency and phase drift, necessitating complicated phase locking and frequency stability techniques. This method overcomes these limitations by relying on the slow nature of the optical phase fluctuations by searching for the peak quadrature point that gives maximum response. The upper limit to measurable frequency response is limited only by the source frequency.

VI. Conclusion

We have experimentally investigated the optical properties and electrical modulation characteristics of ultrastrong ($R \sim 10$ dB) injection-locked DFB lasers. The measured frequency responses exhibit three distinctive regimes, depending on the frequency detuning values.

In the large negative detuning regime, the optical spectrum shows a single-mode spectrum with a high SMSR. The frequency response shows enhanced modulation efficiency in low frequency. Broad 3 dB bandwidth has been demonstrated when the frequency detuning is located around the center of the locking range. The resonance enhancement at the intermediate frequency detuning compensates the *RC* roll-off of the slave laser. At positive detuning edge, the frequency response exhibits a pronounced resonance peak at high frequency (>30 GHz). The optical spectrum showed both the injection-locked frequency and cavity mode. The resonance frequency is equal to the difference between the locked and the cavity-mode frequencies.

These experimental results agree well with the calculation using coupled rate equations. By optimizing the injection-locking conditions, we have demonstrated a broad 3 dB bandwidth of 44 GHz and a high resonance frequency of 72 GHz. The distinctive modulation performances can be exploited in various high-speed applications such as analog fiber optic links, broadband digital communications, RF photonics, and optoelectronic oscillators.

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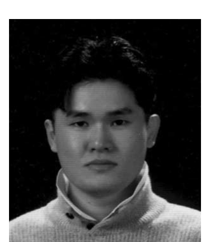

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