Experimental Study on Close-In to Microwave Carrier Phase Noise of Laser Diode with External Feedback

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Abstract—**The residual phase noise at close-in to carrier offset frequency is studied for optical links using a laser diode with an external optical feedback. Since the measured FM noise degradation of the modulating signal was found to be insignificantly higher than the expected 20 log (n) in dB, the residual phase noise of the laser diode was measured to quantify the expected carrier signal FM noise floor level. The measured residual phase noise of a InGaAsP laser diode at 1 KHz offset carrier signal of 5.08 GHz is measured to be −100 and −90 dBc/Hz for with and without a 3-cm-long free-space external cavity, respectively. The close-in to carrier phase noise results of this laser at the external cavity resonance frequency of ≈5 GHz is explained for the first time in terms of laser diode nonlinearity and FM noise theory of injection locked microwave oscillators. A good match between the predicted and measured results was observed.**

I. INTRODUCTION

DIRECTLY MODULATED fiber-optic links are envisioned to be used for distribution of signals to MMIC-based T/R modules in active phased array antennas. However, at high microwave frequencies, the laser diode-limited bandwidth, nonlinearity, and high relative intensity noise (RIN) results in a high insertion loss and low dynamic range. These performance limitations can be overcome by modifying the laser diodes' simple structures.

A method based on a laser diode with the external cavity has been demonstrated [1]–[3], achieving an efficient modulation at frequencies beyond the laser's bandwidth. The enhanced frequency response is observed at a frequency associated with the feedback resonance and is coined "resonant modulation." However, in a previous study [4], we have demonstrated this concept using a subharmonic modulation frequency. For example, a 35-dB fourth harmonic enhancement was obtained when the external cavity's resonant frequency matched up with the fourth harmonic frequency. A similar resonance peak is observed in the RIN for this modified laser; however, the RIN levels at off-resonance frequencies are reduced by ≈25 dB compared to the without-feedback case [5].

Using this simple modification to a laser structure, a fiber-optic link could be implemented to feed the T/R module of phased array antenna [6]. In this system, the external cavity resonant frequency is matched up to the nth harmonic of the modulating signal, which is detected and used as a frequency reference to injection lock local oscillators. The IF information signal is also transmitted via the same laser diode, which is up-converted to a high quality RF signal by the injection locked local oscillators in the T/R module. Ni *et al.* [5] have reported a high dynamic range for the laser diode with external cavity. Since the modified laser's RIN power is peaked primarily at the external cavity resonance frequency, the AM and FM noise of the microwave reference signal may be influenced. Therefore, it is critical to understand ramification of this new resonance peak on the frequency reference signal fidelity used for injection locking of the local oscillators in the T/R level data mixing architecture of phased array antennas [6].

To distinguish the microwave carrier phase noise from the other laser noise terms, the small-signal modulated optical signal is presented as

$$P_{\mathrm{opt}}\{1+\boldsymbol{m}\cos(\omega_m \boldsymbol{t}+\delta\phi_m(\boldsymbol{t}))+\boldsymbol{n}_{\mathrm{RIN}}(\boldsymbol{t})\}\\ \cos(\omega_{\mathrm{opt}}t+\phi_{\mathrm{opt}}(t)+\delta\phi_{\mathrm{opt}}(t))$$

where P_{opt} is the averaged optical power, $\boldsymbol{m}$ is the optical modulation index at modulating microwave carrier, ω_m. The focus of present work is $\delta\phi_m$, the residual phase noise added to the microwave carrier from the laser diode noise source. $\boldsymbol{n}_{\mathrm{RIN}}$ is the relative intensity noise; ω_{opt} is the optical frequency; ϕ_{opt} is the optical phase signal due to side modes and modulation; and $\delta\phi_{\mathrm{opt}}$ is the phase noise of the optical signal. Since most proposed fiber-optic links for antenna remoting use intensity detection, only the noise signals in optical intensity affect the microwave carrier signal, namely, $\delta\phi_m$ and $\boldsymbol{n}_{\mathrm{RIN}}$.

Even though at this resonant frequency the AM noise of carrier signal is degraded due to the peak of $\boldsymbol{n}_{\mathrm{RIN}}$, the final AM noise contribution to the injection locked local oscillators is insignificant as result of the high AM compression of the injection locking process [6]. Nevertheless, the resonant $\boldsymbol{n}_{\mathrm{RIN}}$ could contribute to the FM noise of the reference signal through nonlinear AM/PM conversion [7].

This question emphasizes the essence of this paper: How will the phase noise of the modulating microwave signal be affected by the optical feedback? Published noise models [3],

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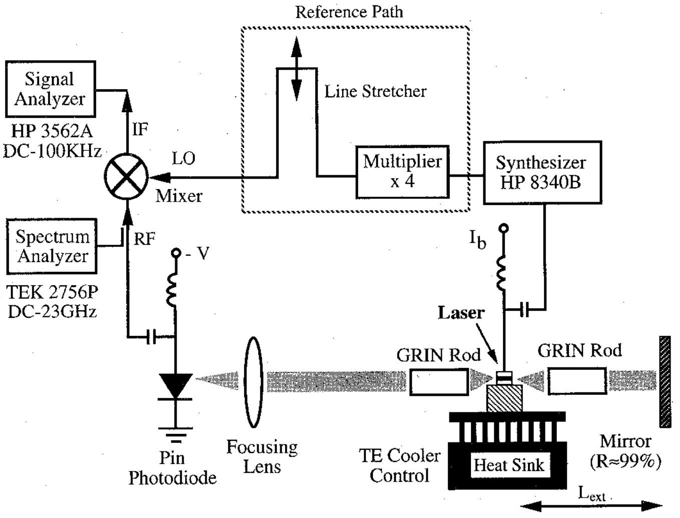

Fig. 1. Experimental setup for measuring the close-in to carrier phase noise of laser diode with the external feedback.

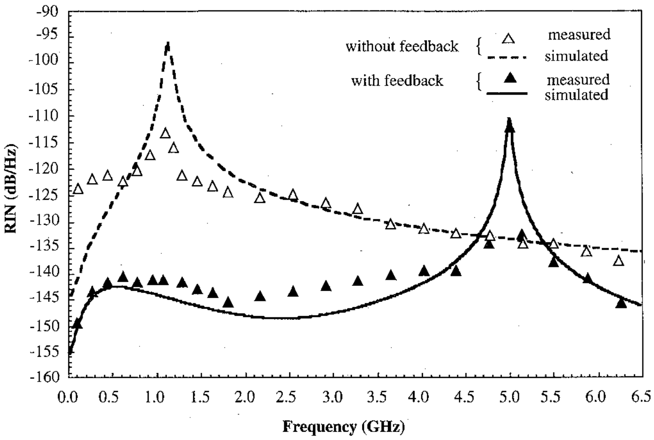

Fig. 2. The measured and simulated RIN response of semiconductor laser with and without external optical feedback at bias of 105 mA and threshold level of 90 mA. The simulation is based on the model provided in [6].

[8], which predict signal-to-noise ratio and RIN at far-away offset carrier frequencies ($\Omega \geq 1$ MHz) around the "resonant modulation" frequency, do not address FM noise of microwave signal at near-carrier offset frequencies ($\Omega << 1$ MHz). This modeling limitation is due to the absence of the low frequency (LF) noise nonlinear conversion to phase noise (i.e., AM/PM conversion), resulting in the $1/f$ noise behavior. This paper presents an experimental evaluation of the residual phase noise of the laser diode and a theoretical explanation based on the nonlinear AM/PM conversion in laser diodes. The experimental setup is introduced in Section II; the phase noise measurements at $\Omega \leq 1$ MHz is presented in Section III. A theory based on the laser AM/PM noise conversion in the microwave carrier signal is introduced in Section IV to qualitatively explain the measured phase noise level of laser without and with the external feedback.

II. EXPERIMENTAL SETUP AND PROCEDURES

The experimental setup for measurements of RIN and FM noise of the laser diode at the carrier frequency of 5 GHz is shown in Fig. 1. An optical module was constructed to study laser diode performance in presence of the external optical feedback. This optical module incorporates a set of collimating lenses (GRIN lens) for an InGaAsP laser diode manufactured by David Sarnoff Research Laboratory (DH 752-1) without any anti-reflection coating. A 3-cm external optical cavity is constructed using a GRIN lens and a high reflectivity flat mirror with flatness of $\lambda/20$ (Melles-Griot 02MLQ). By placing this external cavity at the back facet of the laser diode, light is fed back to laser at the resonance frequency rate of about 5 GHz. A coupling factor of 1% is predicted based on the change in the laser threshold current. The laser light from the front facet is focused on a high-speed photodetector (GTE HFPD-15). The photodetector and its focusing lens are tilted slightly to prevent optical feedback to the laser's front facet. In fact, by monitoring the RIN noise, there was no other significant round-trip feedback observed other than that from the external cavity. All the optic lenses are anti reflection coated at 1300 nm.

The laser diode is directly modulated by a 1.27 GHz signal; the modulated light is detected by the photodetector and its associated RIN noise spectra is measured by a spectrum analyzer. The FM noise close-in to the microwave carrier are monitored by a homodyne phase noise detection system. The synthesizer output is also multiplied by 4 and is used as the reference signal. The phase information of the generated fourth harmonic of the modulating signal out from the laser after optical detection is compared against the reference signal in a double balanced mixer. A line stretcher is used to provide a quadrature phase relation between RF and LO signals of the mixer to cancel the synthesizer AM noise contribution to the total measured noise spectra.

III. NOISE MEASUREMENT RESULTS

A. RIN Measurement

The laser was biased at 105 mA, where the relaxation oscillation frequency of 1.2 GHz was measured. The laser RIN results, observed on the spectrum analyzer, are shown in Fig. 2. As optical feedback is applied, RIN is increased at the frequency corresponding to the round-trip time delay of the external cavity because of the new natural resonant frequency. However, this RIN is suppressed about 20–30 dB outside the resonant frequency of 5.08 GHz. Notice that the RIN is also significantly reduced at very low frequency (1–100 KHz), as shown in Fig. 3. The LF noise of the laser current source was also measured to identify its negligible contribution to the overall laser noise. The 15 dB reduction in the laser RIN at $\Omega \approx 100$ KHz is expected, since this laser without feedback operates as a multimode laser and becomes single mode due to the external optical feedback, reducing the mode-partition noise [9]. A $1/f$ flicker noise slope can be qualitatively observed at lower frequencies. However, the true $1/f$ noise of the laser diode at $\Omega \leq 1$ KHz is difficult to assess since the sub- and super-harmonics of 60 Hz are dominant in the present experimental setup.

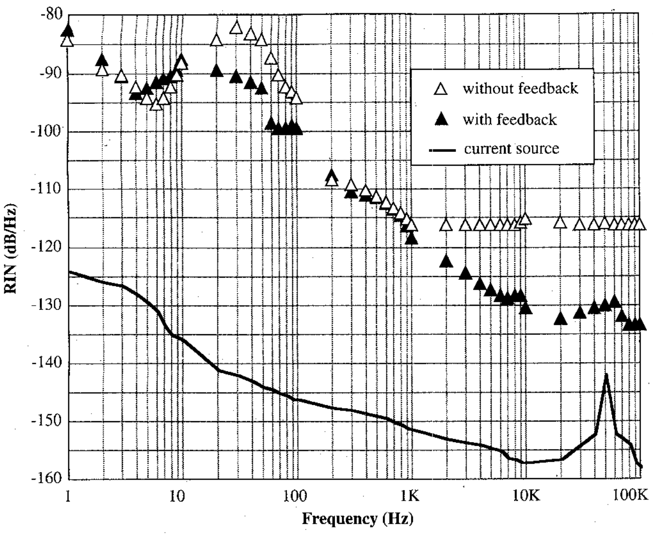

Fig. 3. Measured low frequency RIN response of the laser with and without external cavity. The relative AM noise of the laser current source is also displayed as a baseline.

B. Microwave Carrier Phase Noise Measurements

Numerous measurements were conducted to assess the FM noise degradation of the frequency reference in the laser with and without external cavity. These measurements were conducted at the carrier frequency of 5.08 GHz. The measured degradation was the standard multiplication by four effect ($20\log(4) = 12$ dB) indicating that the laser RIN converted to the microwave FM noise is lower than the synthesizer noise spectra. Therefore, we have proceeded to measure the residual FM noise level to identify the laser diode's contribution to the FM noise floor of the microwave carrier.

The single side-band (SSB) residual phase noise of the microwave carrier signal is measured using the setup shown in Fig. 1. The measurement system phase noise level (i.e., without the laser and detector) is depicted as the baseline in Fig. 4. This measured SSB system noise level is lower than the noise floor of signal analyzer. The phase noise measurement repeatability of the whole system is about ±3 dB.

The laser is modulated at 1.27 GHz by an input power level of 0 dBm (corresponding to a current modulation index of $m \approx 0.9$). The measured residual phase noise of the fourth harmonic signal at 5.08 GHz for the laser with and without external optical feedback is shown in Fig. 4. The offset carrier frequency is from 1 Hz–100 KHz. As seen in this figure, the phase noise are very close for both with and without feedback cases at offset carrier frequencies less than 1 KHz, which is primarily dominated by the 60 Hz sub- and super-harmonics of the ac power-line. A crossover of residual phase noise at about few hertz is observed for the laser with and without feedback. It is speculated that this increase level of the residual phase noise is due to the light scintillation in the external optical cavity. At offset carrier frequency larger than 1 KHz, the difference in the phase noise levels are distinct for these two cases. In fact, the phase noise level of the feedback case is reduced by 20 dB to a level of −100 to −110 dBc/Hz at far-away offset carrier frequency. This relative high residual phase noise level is the result of high RIN level at the bias current only about 1.05 times of threshold current, and the laser RIN in turn is converted to the residual phase noise of the microwave carrier.

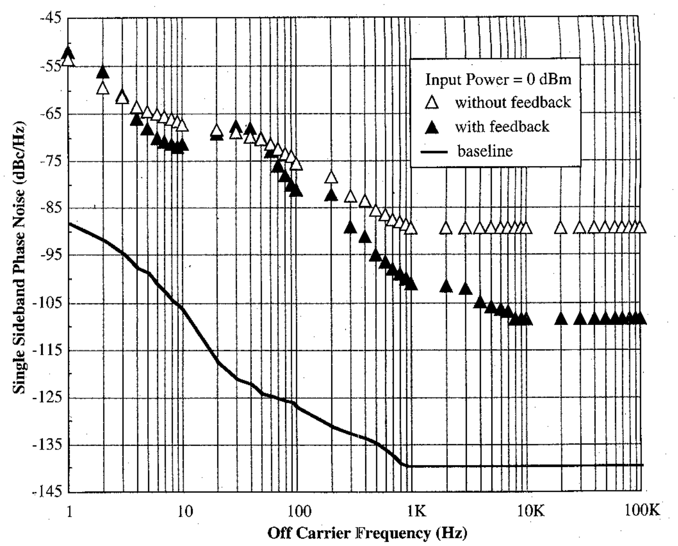

Fig. 4. The measured residual phase noise at the fourth harmonic (5.08 GHz) for the laser with and without optical feedback. The modulation frequency is 1.27 GHz, and the input power level is 0 dBm.

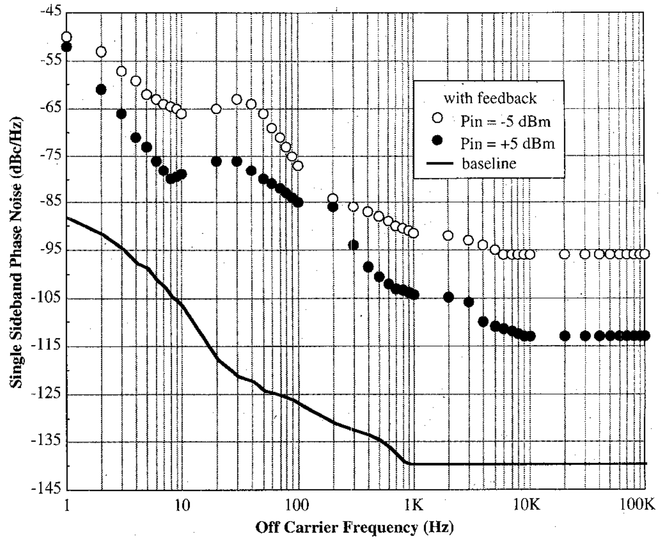

Fig. 5. The measured residual phase noise at the fourth harmonic (5.08 GHz) for the laser with external optical feedback. The modulation frequency is 1.27 GHz, and the input power levels are −5 and +5 dBm.

The residual phase noise was also measured under different RF input power levels. As shown in Fig. 5, a lower SSB phase noise at offset carrier frequency of 1 KHz and above is achieved at +5 dBm as compared to the −5 dBm input power level. Once again the 60 Hz sub- and super-harmonics dominate at offset carrier frequency of 200 Hz and below.

IV. Discussion

The measured results of RIN noise and the residual FM noise of the laser diode under feedback are quite interesting. A rigorous model of the close-in to carrier phase noise requires development of the nonlinear conversion matrix of the laser with the external cavity [7], which is difficult without having an accurate large-signal model for the lasers in presence of the external optical feedback. Unfortunately, the accuracy of the reported large-signal models for the lasers with optical feedback for modulation indices ≥40% are low [1], [10], and our attempts to make any meaningful results out of them for a large modulation index of $m \geq 0.9$ have been unsuccessful. Recent noise modeling attempts have predicted a Gaussian shape FM noise characteristics, which is dependent on the optical modulation index [8]; however, this model would not predict a well known $1/f$ noise contribution at close-in to carrier, which dominates over the Gaussian shape noise at close-in offset carrier frequencies in any oscillation system (electrical and optical). Therefore, a nonlinear analytical explanation based on the concept of forced oscillation [11] is developed to qualitatively justify the observed close-in carrier phase noise of microwave signal. Details of this modeling is described below.

A. Residual Phase Noise Model

The laser diodes SSB phase noise of the nth harmonic of the modulating signal, $\mathcal{L}_{\text{out}}$, has contributions from three noise terms: 1) the input reference signal phase noise, $\mathcal{L}_{\text{in}}$; 2) the low frequency noise of laser diode up-converted to the carrier frequency , $\mathcal{L}_{\text{up}}$; and 3) the RIN noise at the offset microwave carrier, $\mathcal{L}_{\text{RIN}}$. This behavior is quite analogous to microwave systems [12]. Therefore at angular offset carrier frequency of $\Omega, \mathcal{L}_{\text{out}}$ can be approximately expressed as [13]

$$\mathcal{L}_{\text{out},n\omega}(\Omega) = n^2\mathcal{L}_{\text{in},\omega}(\Omega) + n^2\mathcal{L}_{\text{up},\omega}(\Omega) + \mathcal{L}_{\text{RIN},n\omega}(\Omega). \quad (1)$$

The factor of n is the harmonic order of the modulation signal, and in our case is 4. The subscript ω indicates the modulation frequency. The last two terms are the residual phase noise contribution of laser diode and is discussed next.

The phase noise at far away from offset frequency is dominated by the RIN contribution at the operating frequency; this is analogous to the thermal noise floor of the amplifier's active device far away from carrier [14]. This portion of noise contribution can be predicted based on the analysis of laser RIN model [7], [15]. However, the residual phase noise in the low offset carrier frequency region is primarily dominated by the laser's very low frequency (LF) noise, which exists in photon and carrier densities and up-converts to the side-band noise of the carrier frequency through laser's nonlinearity. The measured residual phase noise, shown in Fig. 4, indicates that this noise spectral density is very much similar to the measured LF RIN noise in optical power density; hence, it validates our intuition that the up-conversion phenomena is the dominant process [16]. The LF laser noise can be characterized by measurement of LF RIN of laser diode (see Fig. 3), although the physical nature of such LF noise has not been well understood.

The up-converted noise process is presented by using the large-signal analysis of laser diode at microwave frequency. The large-signal modulated laser optical power intensity, P_L, is related to the current modulation index, m, and the laser's physical parameters [5], [17]

$$P_L(t) = Ce^{a\cos(\omega t+\theta)} = P_o \sum_{n=0}^{\infty} \frac{I_n(a)}{I_o(a)} \cos(n\omega t + n\theta) \quad (2)$$

$$\theta = \tan^{-1}\left[\frac{\omega\tau_p\left(1 + \dfrac{1}{\alpha P_o \tau_s}\right)}{\dfrac{\omega^2\tau_p}{\alpha P_o} - \dfrac{I_1(a)}{2aI_o(a)}}\right] \quad (3)$$

$$m = a\sqrt{\left[\frac{\omega^2\tau_p}{\alpha P_o} - \frac{I_1(a)}{2aI_o(a)}\right]^2 + \omega^2\tau_p^2\left[\frac{1}{\alpha P_o\tau_s} + 1\right]^2}. \quad (4)$$

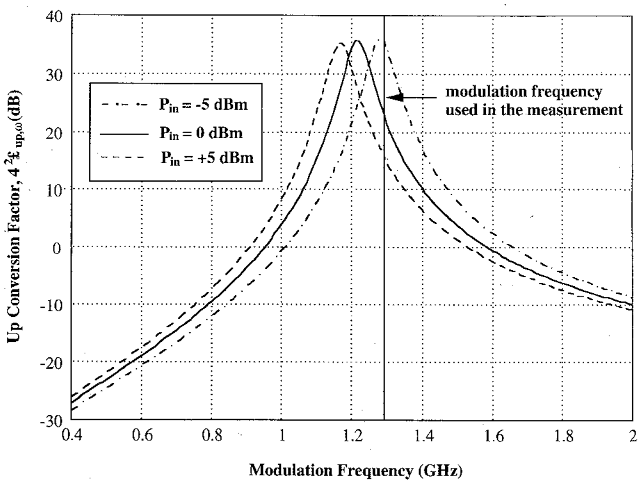

Fig. 6. Up-conversion factor for the laser without feedback at the fourth harmonic frequency ($n = 4$) as a function of modulation frequency at three input power levels of −5, 0, +5 dBm.

In above equations, α is optical gain coefficient, τ_p and τ_s are the photon and carrier lifetime, respectively, ω is the angular modulation frequency, P_o denotes the time-averaged optical power density, and $I_n(a)$ is the modified Bessel function of the first kind and order n with argument a.

Since the phase shift θ introduced to the microwave envelope of the optical signal is a function of P_o, the LF fluctuation of the time-averaged optical power density, $\langle\Delta p^2\rangle$, will then be converted into the fluctuation of the phase noise of modulating microwave signal, $\langle\Delta\theta^2\rangle$. Considering that Δp is a small perturbation signal to P_o, the spectral power density of the up-converted phase noise of the modulated signal is therefore related to the LF RIN of the laser diode by linearizing (3)

$$\mathcal{L}_{\text{up},\omega}(\Omega) = \frac{1}{2}\langle\Delta\theta^2(\Omega)\rangle = \frac{1}{2}\left(\frac{\partial\theta(\omega)}{\partial P_o}\right)^2 P_o^2 \,\text{RIN}(\Omega). \quad (5)$$

The up-conversion factor of LF RIN to phase noise is $C_{\text{up},\omega} = 1/2(\partial\theta(\omega)/\partial P_o)^2 P_o^2$, which is a function of modulation frequency and averaged optical power level. A similar approach was used by Lau *et al.* [16] to explain the up-converted mode-partition noise. Fig. 6 shows the up-conversion factor as a function of the modulation frequency at different input power level. Clearly high up-conversion factor is obtained around the relaxation frequency because of the strong nonlinearity of the

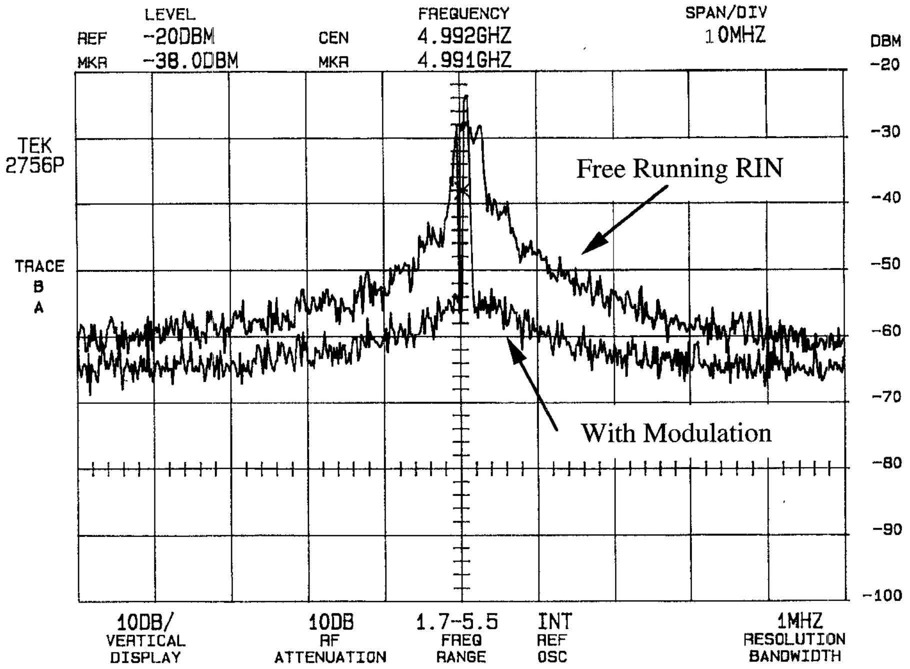

Fig. 7. The power spectrum of the laser diode output light intensity under the conditions with and without injection of the subharmonic modulated signal.

laser diode. Since modulating frequency in the experiments is selected to be at 1.27 GHz, which is close to the large-signal relaxation oscillation frequency, and hence, resulting in a high harmonic content. The up-conversion factor is about 24 dB at RF power of 0 dBm. This conversion factor approximately matches up with the measured 27 dB for without feedback case, calculated by comparison of the noise levels shown in Figs. 3 and 4.

B. Residual Phase Noise Modeling of the Lasers with Optical Feedback

As clearly shown in Fig. 2, the RIN of the laser with optical feedback has a resonant peak corresponding to the inverse of the round-trip time delay of the external cavity. Because of the higher RIN at the resonant frequency, one may anticipate a higher RIN contribution to the phase of modulating microwave signal via AM/PM noise conversion. But it was observed otherwise! As an explanation, we advocate the oscillation condition as the source of the increase in RIN at this particular frequency and the reduction in the close-in to carrier is expressed in terms of concept of subharmonic injection locking [11]. The oscillation is fairly broad, corresponding to a low Q factor, which is stabilized using the subharmonic injection signal from the microwave source. Henceforth, a clean carrier signal is achieved because of the forced oscillation phenomena at frequency of 5.08 GHz.

This intuitive reasoning was proven by monitoring the spectra of the laser output at ≈5 GHz in the presence of a modulation signal. A typical power spectra of forced oscillation at outside of the injection locking range was observed [18], where single sided side-band signals are generated around the oscillation signal. When the modulation frequency is close enough to the fourth subharmonic of the oscillation frequency, injection locking takes place and the FM noise of the signal is significantly reduced, as shown in Fig. 7. A similar intuition was expressed by Lau *et al.* [8], however their analysis has followed more standard approach of super modes in mode-locking argument. An injection locking range of 41 MHz at a subharmonic factor of 4 was measured for the oscillation signal. The primary difference between the conventional electrically injection locked oscillators and our case is that the microwave oscillation is generated in the optical domain and is injection locked by the subharmonically modulated light. The oscillation frequency, Q factor, and the power can be calculated from the modified rate equation for external optical feedback. (Although classical mode-locking theory can be also used to explain the above harmonic enhancement and noise reduction [8], [19], the microwave injection locking theory is implemented here for the completeness of FM noise modeling.)

Following the above justification, one can consider that the oscillation signal in the optical cavity is injection locked by the harmonic of the modulation signal, which is generated due to the laser nonlinear multiplicative behavior. Furthermore, since the laser nonlinearity will not be influenced much by the optical feedback at the frequency, which is far away from the resonant frequency [3], previous large-signal analysis

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$$\mathcal{L}_{\text{out},n\omega}(\Omega) = \frac{[n^2\mathcal{L}_{\text{in},\omega}(\Omega) + n^2\mathcal{L}_{\text{up},\omega}(\Omega)]\Delta\omega_{\text{Lock}}^2 + \Omega^2\mathcal{L}_{\text{osc},n\omega}(\Omega)}{\Omega^2 + \Delta\omega_{\text{Lock}}^2}. \tag{6}$$

for modulation signal at the subharmonic of the resonant frequency is valid for the laser in presence of optical feedback. Using the subharmonic injection locking theory in regular microwave oscillator, the phase noise of the locked oscillation signal in light intensity at $n\omega$ can be expressed [11] as (6), shown at the bottom of the previous page.

The first term in the numerator represents the contribution from the modulation signal, which is degraded by up-converted laser LF noise $\mathcal{L}_{\text{up},\omega}$. The locking range is a function of the oscillating optical power density, P_{osc}, and the harmonic signal in photon density, $P_oI_n(a)/I_o(a)$, which is generated by laser's nonlinearity

$$\Delta\omega_{\text{Lock}} = \frac{n\omega}{2Q}\frac{P_oI_n(a)}{I_o(a)P_{\text{osc}}}. \tag{7}$$

On the other hand, adopting the phase noise expression of a microwave oscillator, the phase noise of the free-running laser with coherent feedback (an oscillation without any external force) is written as [14], [20]

$$\mathcal{L}_{\text{osc},n\omega}(\Omega) = \left\{\left(\frac{n\omega}{2Q}\right)^2\frac{1}{\Omega^2}+1\right\}\{\mathcal{L}_{\text{up},n\omega}(\Omega) + \mathcal{L}_{\text{RIN},n\omega}(\Omega)\}. \tag{8}$$

In (8), the RIN contribution can be neglected for close-in offset frequency since it is much lower than the up-conversion noise because of high oscillation power. Substituting (8) and (7) into (6) and recognizing $\Omega \ll \Delta\omega_{\text{Lock}}$, one obtains an approximation for the residual phase noise in the enhanced harmonic signal $\mathcal{L}_{r,n\omega}$

$$\mathcal{L}_{r,n\omega}(\Omega) = \mathcal{L}_{\text{out},n\omega}(\Omega) - n^2\mathcal{L}_{\text{in},\omega}(\Omega) \approx n^2C_{\text{up},\omega}\,\text{RIN}\,(\Omega) + C_{\text{up},n\omega}\left(\frac{I_oP_{\text{osc}}}{P_oI_n}\right)^2\text{RIN}\,(\Omega). \tag{9}$$

The first term of the residual phase noise in (9) is as result of the up-converted RIN, whereas the second term is controlled by the injection power level and is dominated by the ratio of $I_o(a)/I_n(a)$. Since the nonlinearity of the laser is approximately the same for both with and without optical feedback cases, the up-converted noise can be approximated using the results in (5). Clearly, the LF noise of laser diode up-converted to the harmonic of the modulating signal dominates over any other processes.

To justify use of this theory, comparison were conducted between the theoretically predicted and the experimentally measured results. The time averaged optical power P_o and the oscillation optical power density P_{osc} were required for the calculations. P_o was calculated directly from the dc photo-generated current in the photodetector. To calculate P_{osc}, the spectrum analyzer measured power level at 5.08 GHz was converted into detected RF current in the photodetector using a 50-Ω load impedance. When the laser was modulated by a -5 dBm signal at 1.27 GHz (i.e., $m = 0.5$), the optical power ratio of $\{I_4(a)P_o/I_o(a)\}/P_{\text{osc}}$ is about -18 dB, which implies a relatively large injection locking force. Hence, the oscillation noise contribution to the total residual phase noise is negligible and the up-converted laser noise in the modulation signal is dominant. The noise up-conversion factor in the fourth harmonic of the modulated signal is dominated by the term $4^2C_{\text{up},\omega}$, which is 35 dB. The measured results in Fig. 5 indicate a conversion factor of 38 dB, which quantitatively matches the calculated up-conversion factor of 35 dB. With an input power at 5 dBm (i.e. $m = 1.5$), the up-conversion noise factor of 16 dB was calculated versus the measured result of 20 dB. These small difference lies within the measurement repeatability error margin of ±3 dB.

V. CONCLUSION

This study shows that in optical links using a laser diode with an external optical feedback, the reference signal remains stable and the high RIN level at the resonant frequency will not degrade the frequency reference stability. Experimental as well as the theoretical results show that low residual phase noise can be achieved in the laser with optical feedback due to low mode-partition noise and low LF RIN contribution. Noise can be further reduced by an increase in the modulation index. Furthermore, the residual phase noise in the laser with and without feedback at close-in offset carrier frequency of microwave signal is dominated by the up-converted low frequency noise in the laser diode.

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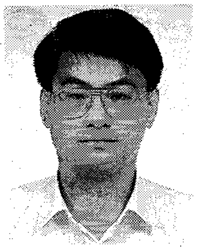

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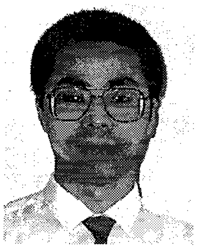

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