LASER INDUCED PHASE NOISE IN OPTICALLY INJECTION LOCKED OSCILLATOR

Xiangdong Zhang, Tsang-Der Ni, Afshin S. Daryoush

Center for Microwave/Lightwave Engineering
E.C.E. Dept., Drexel University, Philadelphia, PA.

ABSTRACT

The spectral purity of a microwave reference signal, distributed by fiber optic link to subharmonically injection lock oscillator can be degraded by laser large-signal noise. This paper present analysis predicting the conversion of the laser intrinsic noise to the FM noise of the frequency reference. The Langevin noise conversion model was validated through measurement of the phase noise of the subharmonically injection locked 5GHz oscillator.

INTRODUCTION

The frequency and phase coherency of phased array antennas can be provided by the fiber-optic distribution of a reference frequency to subharmonically injection lock local oscillators [1]. Since the close-to-carrier phase noise in such a system is very important in signal processing, the study of the phase noise behavior of fiber optic links is critical for establishing a high quality antenna system. The intrinsic noise of a laser diode under large-signal modulation would contribute to the FM noise of the frequency reference, however, this conversion has not been quantified.

This paper presents the noise conversion process leading to the increase of FM noise in the frequency reference. The analysis is based on the noise of laser diode under large-signal modulation. The noise-free large-signal response of the laser diode is analyzed first by using the nonlinear model of Daryoush [2]. Then the noise signal response, considered as a perturbation of the noise-free situation, is calculated with *conversion matrices* which have been developed by large-signal analysis. The theoretical results show that the noise spectrum density of the reference signal is increased under a certain modulation of laser diode, and that this increase in the noise level of the reference degrades the FM noise of the subharmonically injection locked oscillator. The phase noise measurement of a free-space optical link with the second subharmonic injection locked local oscillator verifies the above analysis.

FM NOISE DEGRADATION ANALYSIS

The intrinsic noise in a semiconductor laser, namely the quantum fluctuations of the photon and electron population, can be expressed by the single-mode rate equation added with Langevin noise source terms $f_P(t)$ and $f_N(t)$ [3]:

$$\frac{dN}{dt} = \frac{i(t)}{qVol} - \frac{N}{\tau_s} - \alpha\,(N - N_{om})\,(1-\varepsilon P)\,P + f_N(t) \qquad (1a)$$

$$\frac{dP}{dt} = \Gamma\,\alpha\,(N - N_{om})\,(1-\varepsilon P)\,P - \frac{P}{\tau_{ph}} + \beta\frac{N}{\tau_s} + f_P(t) \qquad (1b)$$

where N and P are the population of electron and photon, the pump rate is $i(t)/qVol$, τ_{ph} and τ_s are lifetime of photon and electron, $\beta N/\tau_s$ is the spontaneous emission coupled into the lasing mode, α is the optical gain coefficient, N_{om} is the carrier density for transparency, and ε is the gain compression factor. Following the treatment of Yariv [3], the spectral power density of Langevin noise sources $f_P(t)$ and $f_N(t)$ and the cross spectral density are given for a laser dc bias of I_o and output photon density of P_o by:

$$<F_N^2(f)> = \frac{I_o}{qVol} + 2\alpha N_{om}P_o \qquad (2a)$$

$$<F_P^2(f)> = 2\frac{P_o}{\tau_{ph}} + 2\Gamma\alpha N_{om}P_o \qquad (2b)$$

$$<F_P(f)F_N(f)> = -\frac{P_o}{\tau_{ph}} + 2\Gamma\alpha N_{om}P_o \qquad (2c)$$

The electron and photon densities of Eq.1 can be decomposed as sum of large-signal responses $N_L(t)$, $P_L(t)$, and noise responses n(t) and p(t) :

$$N(t) = N_L(t) + n(t)$$
$$P(t) = P_L(t) + p(t) \qquad (3)$$

Considering the noise portion being much smaller than the noise-free large-signal response, we can use perturbation method and linearize Eq.1 around the operating points of $N_L(t)$, and $P_L(t)$ as:

$$\frac{dn(t)}{dt} = -F_N'(N_L, P_L)\,n(t) - F_P'(N_L, P_L)\,p(t) - \frac{n(t)}{\tau_s} + f_N(t)$$
$$\frac{dp(t)}{dt} = \Gamma\left[F_N'(N_L, P_L)n(t) + F_P'(N_L, P_L)p(t)\right] - \frac{p(t)}{\tau_{ph}} + \beta\frac{n(t)}{\tau_s} + f_P(t) \qquad (4)$$

Function F(N, P) is the stimulated emission contribution to the rate equation and $F_N'(N_L, P_L)$ and $F_P'(N_L, P_L)$ are its derivative with respect to N and P, respectively. The noise-free response in photon density P(t) at large modulation index can be expressed as [2]

$$P(t) = C\,e^{a\cos(\omega t + \theta)} \qquad (5)$$

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where C is the time averaged power density, and "*a*" is a function of laser current modulation index and can be solved for using the Harmonic Balance method. Based on this acceptable solution for P(t), $F_N'(N_L, P_L)$ and $F_P'(N_L, P_L)$ are calculated. Fourier transformation of Eq. 4 would lead to the upper $(\omega+\Omega)$ and lower $(\omega-\Omega)$ noise modulation side-bands of photon density, and can be represented in the matrix formation as:

$$\bar{p} = \frac{\left(\frac{1}{\tau_s} + H + [F_N']\right)\bar{f}_N + \Gamma\left([F_N'] + \frac{\beta}{\tau_s}\right)\bar{f}_P}{\left(\frac{1}{\tau_s} + H + [F_N']\right)\left(\frac{1}{\tau_p} + H - \Gamma[F_P']\right) + \Gamma\left([F_N'] + \frac{\beta}{\tau_s}\right)[F_P']} \qquad (6)$$

where

$$H = \begin{bmatrix} -(j\omega-\Omega) & 0 \\ 0 & j\omega+\Omega \end{bmatrix}; \bar{p} = \begin{pmatrix} p_l^* \\ p_u \end{pmatrix}; \bar{f}_N = \begin{pmatrix} f_{Nl}^* \\ f_{Nu} \end{pmatrix}; \bar{f}_P = \begin{pmatrix} f_{Pl}^* \\ f_{Pu} \end{pmatrix}$$

$$[F_P'] = \begin{pmatrix} F_{P0}' & F_{P2}'^* \\ F_{P2}' & F_{P0}' \end{pmatrix}; [F_N'] = \begin{pmatrix} F_{N0}' & F_{N2}'^* \\ F_{N2}' & F_{N0}' \end{pmatrix}$$

The vectors $\bar{f}_N$ and $\bar{f}_P$ are the Langevin noise terms.

The complex matrices $[F_P']$ and $[F_N']$ are the so called *conversion matrices*, and the terms F_{N0}', F_{N2}', F_{P0}', and F_{P2}' are the dc and the second harmonic term of $F_N'(N_L, P_L)$ and $F_P'(N_L, P_L)$ in frequency domain, respectively. It should be noted that amplitude and phase of $F_N'(N_L, P_L)$ and $F_P'(N_L, P_L)$ are dependent on the laser current modulation index through parameter "*a*". By using the following expression [4],

$$\begin{pmatrix} p_{AM} \\ p_{FM} \end{pmatrix} = \begin{pmatrix} 1 & 1 \\ -1 & 1 \end{pmatrix} \begin{pmatrix} p_l^* \\ p_u \end{pmatrix} \qquad (7)$$

the noise contribution from $\bar{p}$ to the AM and FM noise of the reference signal can be calculated.

Clearly, under large signal modulation, the off-diagonal elements in $[F_P']$ and $[F_N']$ will effectively convert noise signals from the upper side-band to lower side-band and vice versa. Therefore, a current modulation index can be found for a given modulating frequency where these two conversion processes would be in phase and enhance each other. Under this condition, the noise response would be increased significantly. This was experimentally studied and is presented next.

FM NOISE DEGRADATION: SIMULATION AND EXPERIMENTS

The validity of the noise modeling was investigated through a commercial AlGaAs injection laser (Ortel SL300H) as an indicator of general behavior.

Simulation:
To predict the noise contribution of laser to the FM noise degradation of the frequency reference, laser diode parameters are needed to be incorporated to Eq. 6 [2]. A laser diode, which was fully characterized and reported earlier, was used as subject of the simulation study.

Fig. 1 depicts how FM noises of frequency reference at 10KHz is changing as a function of modulating frequency for various current modulation index of laser diodes. For higher modulation indices, the peak in FM noise degradation shifts to a lower frequency. The RIN level of the laser is also shown for comparison. Fig. 2 shows the predicted result of the laser's noise contribution to the FM noise of a 2.5 GHz frequency reference signal as a function of current modulation indices. The FM noise decreases monotonically as a function of modulation index except for a peak at modulation index of 0.4. This decrease in the noise level can be explained due to the rapid increase in signal power, while the total noise power contribution is fixed. At modulation index of 0.4, on the other hand, the laser noise peaks and contributes to the FM noise degradation.

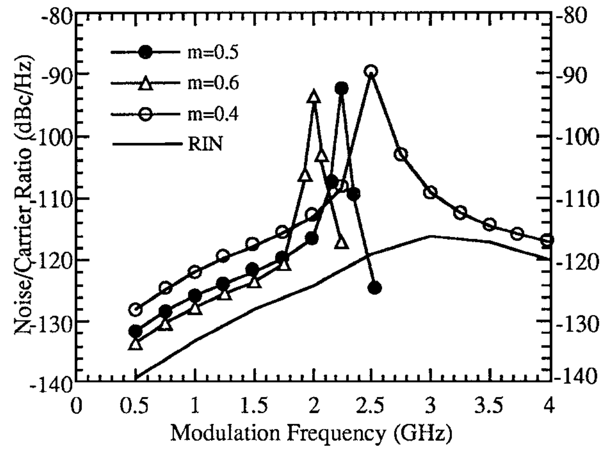

Fig. 1 Frequency dependance of FM noise of the frequency reference for modulation indices of m=0.4, 0.5, and 0.6. Frequency dependance of laser RIN is also shown.

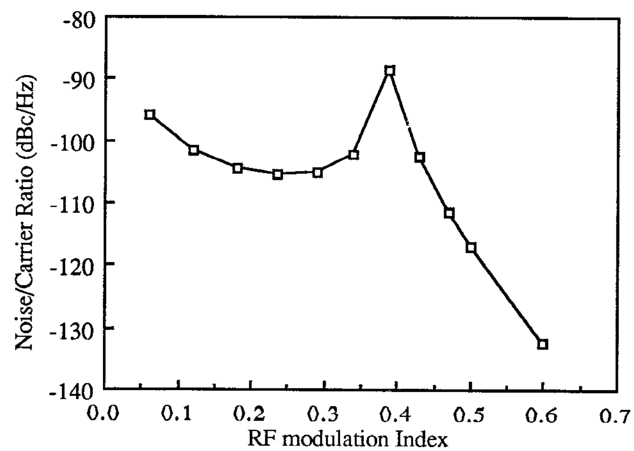

Fig. 2 Laser noise contribution to the FM noise of the frequency reference at 2.5GHz as a function of modulation index.

Experiments:
The experiments were performed at frequency of 2.5GHz where the highest FM noise degradation level was predicted. The experimental setup as shown in Fig. 3 was used to quantify the FM noise degradation induced by the laser noise as compared to the generator. In path A, the laser is directly

modulated by a synthesized 2.5 GHz signal from HP8340B. The modulated light is focused on a high speed photodetector. In the free space path, an optical isolator was inserted to prevent any light feedback causing change in the laser dynamics due to the coherent feedback. The detected signal is subharmonically injected to a 5GHz oscillator, where forced oscillation at second harmonic of of 2.5 GHz is achieved. The spectra of the injection locked signal is then measured by the spectrum analyzer. Path B is used to electrically injection lock the local oscillator to compare the injection locked oscillator FM noise degradation because of the laser diode.

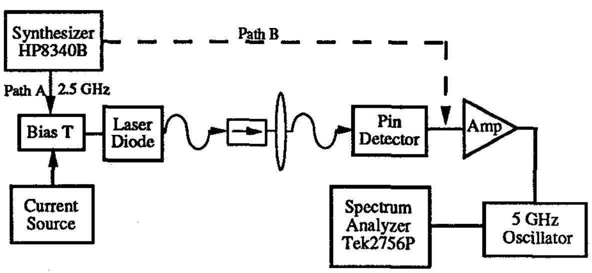

Fig. 3 Experimental setup to study FM noise degradation of the subharmonically injection locked 5GHz oscillator as result of laser diode noise.

To identify the noise contribution from the laser diode, the signal from the optical detector was measured at modulation indices of 0.1 to 0.6. As shown in Fig. 4, the overall noise power level of the reference signal at 2.5 GHz is dominated by AM noise (RIN noise) for small modulation indices. However, for modulation index of m=0.47, the overall noise is now influenced significantly by the FM noise. Further increase in the current modulation index will reduce the phase noise contribution and eventually the overall noise power level reduces to the standard RIN dominated noise power level.

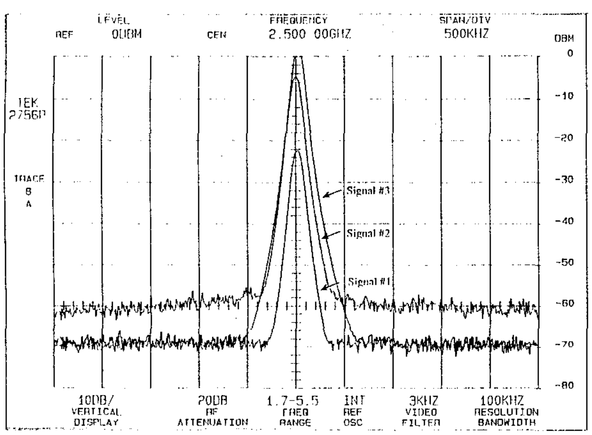

Fig. 4 Noise level of the frequency reference signal measured at optical detector. Signal #1 is the noise level under small-signal modulation (m=0.1); Signal #2 is the noise level under modulation index of m=0.47; Signal #3 the noise level under large-signal modulation (m=0.6).(Vertical scale of 10dB/div, horizontal scale of 500KHz/div, reference level of 0dBm, and resolution filter of 100KHz)

To quantify the noise contribution from the laser diode to a close-in to carrier of the injection locked local oscillator, a reference signal at 2.5GHz is injected directly into the amplifier, locking the oscillator (i.e. path B). Fig. 5 shows the comparison of the FM noise at 5KHz offset carrier frequency of the oscillator injected by signals from path A (through an optical link) and path B (through electrical link) with the same injection locking range. The FM noise of locked oscillator varies with injection power, as shown in Fig. 6. For an injected power level corresponding to the modulation index of m=0.47, the FM noise of the optical link degrades greatly as predicted and depicted in Fig. 2.

To verify the laser induced FM noise in other lasers, two laser diodes(GTE InGaAsP HFDL-15/L and Ortel AlGaAs SL1000H) were also used to perform a similar measurement. Results achieved similar to what was observed for the SL300H laser diode.

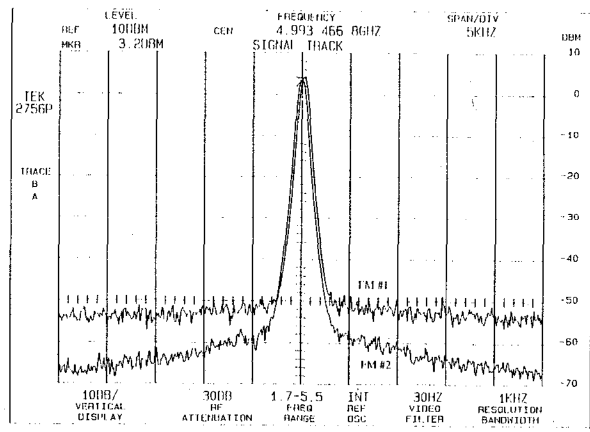

Fig. 5 Comparison of FM noise level of injection locked through paths A and B. FM#1 is the FM noise of the free space optical link where the local oscillator is injected by the same signal as Signal#2 (cf. Fig.4); FM#2 is the FM noise where the local oscillator is injected by the signal from the generator with the same power as signal #2.

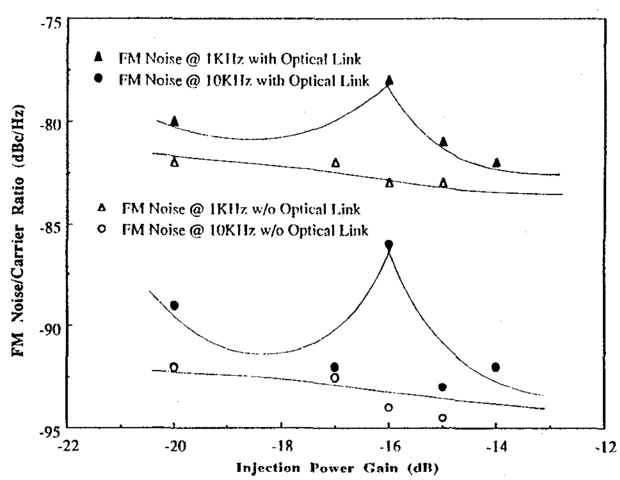

Fig. 6 Variation of the FM noise level of the injection locked oscillator with the injected power gain for two path A and B.

DISCUSSION

The above FM noise degradation process can be explained as that: 1) at the small modulation index, the laser response is linear and those off-diagonal elements in *conversion matrices* in Eq.6 are close to zero so that there is no noise conversion between the upper and the lower side-band and the laser's noise contribution is the RIN noise dominated; 2) while the modulation signal increases, the noise conversion between side-bands becomes stronger and are in phase at certain modulation level causing FM noise degradation of the frequency reference; 3) since the two noise conversions will get out of phase at higher modulation index, noise level reduced. The exact distribution of FM noise and AM noise has not been quantified, but through subharmonic injection locking, it has been demonstrated that this noise is primarily dominated by the FM noise.

Since in optically controlled phased array antenna, phase noise quality of the frequency reference is important, any laser induced FM noise degradation would in turn affect the spectral purity of the indirect optically injection locked oscillator. This FM noise level of the oscillator has been already related to the FM noise of the injected signal level for both fundamental [5] and subharmonic [6] injection locking process.

CONCLUSION

The laser diode noise behavior, under the large signal modulation, has been analyzed and verified indicating that large signal modulation can increase the laser's noise. Therefore, the large output noise from laser will degrade the FM noise of the frequency reference FO link. Based on the theoretical analysis, a careful selection of the modulation frequency and the laser current modulation index could prevent FM noise degradation.

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