Bias-Dependent Noise Up-Conversion Factor in HBT Oscillators

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Abstract—**This paper reports on the low-frequency noise up-conversion process in HBT transistors and their contributions to the close-in carrier phase noise of the HBT based oscillators. The experimental results of an HBT oscillator at 5.6 GHz demonstrate that the low-frequency noise up-conversion factor is primarily function of the transistor's phase variation to its quiescent point. Thus, in addition to the transistor's noise parameters of f_c and N_F, the phase sensitivity to the bias point provides another important transistor parameter in design of low phase noise oscillators. This concept can also be extended to oscillators based on other devices, such as BJT's, MESFET's and HEMT's.**

I. Introduction

IN MANY communications and surveillance systems, the low phase noise of local oscillators is critical to the overall system performance. It is known that the close-in-to-carrier phase noise in oscillators is determined through up-conversion of the low-frequency (LF) noise in the devices [1]–[3]. Therefore, HBT's with their low LF noise in conjunction with high Q dielectric resonators have been used to reduce the phase noise in oscillators [4], [5].

However, it is not well known that the oscillators' phase noise could potentially be further reduced by adjusting the noise up-conversion factor in which the transistor converts its LF noise to the residual phase noise at microwave frequencies. Thus, it is of utmost importance to predict and minimize the LF noise up-conversion factor in the design of low phase noise oscillators.

This letter predicts the up-converted residual phase noise of HBT in an oscillator using the phase and amplitude variation of the small-signal S-parameters to the transistor's bias condition. In particular, phase noise of a 5.6-GHz HBT oscillator was 15 dB reduced by simply operating at the bias point where a small transistor phase sensitivity is observed to the transistor bias current.

II. Theory

Microwave oscillators are presented as a gain stage and a positive feedback network, as shown in Fig. 1. The phase noise of most oscillators is dominated by the residual phase noise in the amplifier gain stages [6]. Since the microwave gain and phase shift of an amplifier are bias dependent, they can be expressed as $G(I_i, V_j)$ and $\Phi(I_i, V_j)$, where I_i and V_j are independent variables of the bias current and voltage in the gain stage. The LF noise forces are expressed as noise current of $\langle i_i^2 \rangle$ and noise voltage of $\langle v_j^2 \rangle$ sources at the bias ports. These noise sources modulate the amplifier gain and phase and then appear as an up-converted noise at the oscillator's microwave signal [7]. More specifically, the phase and amplitude noise are expressed in terms of the phase and amplitude bias sensitivities as

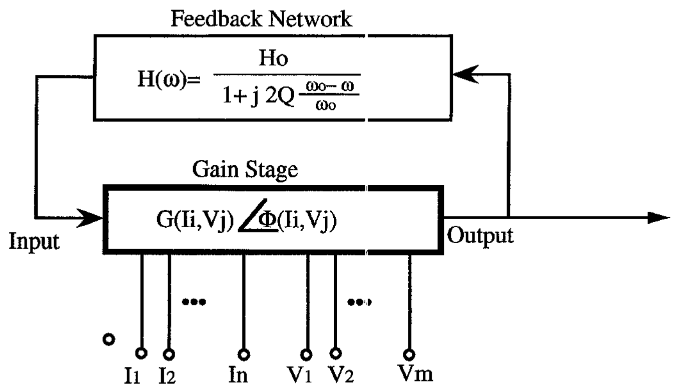

Fig. 1. Conceptual block diagram of a microwave oscillator. n and m are the total number of the independent bias currents and voltages in the gain stage.

$$\mathcal{L}_{r\phi}(\Omega) = \frac{1}{2}\left(\sum_{i=1}^{n}\left(\frac{\partial \Phi}{\partial I_i}\right)^2 \langle i_i^2(\Omega)\rangle + \sum_{j=1}^{m}\left(\frac{\partial \Phi}{\partial V_j}\right)^2 \langle v_j^2(\Omega)\rangle\right) \tag{1}$$

$$\mathcal{L}_{r\mathrm{AM}}(\Omega) = \frac{1}{2}\frac{1}{G^2}\left(\sum_{i=1}^{n}\left(\frac{\partial G}{\partial I_i}\right)^2 \langle i_i^2(\Omega)\rangle + \sum_{j=1}^{m}\left(\frac{\partial G}{\partial V_j}\right)^2 \langle v_j^2(\Omega)\rangle\right) \tag{2}$$

In the above equations, the $\mathcal{L}_{r\phi}(\Omega)$ and $\mathcal{L}_{r\mathrm{AM}}(\Omega)$ are the single-side-band noise power spectrum density of the residual phase and amplitude noise; Ω is the angular offset frequency. Furthermore, for simplicity, uncorrelated noise sources are considered, and in addition, G and Φ are assumed to be independent of Ω, however bias dependent.

In oscillators, the up-converted amplitude (AM) noise $\mathcal{L}_{r\mathrm{AM}}(\Omega)$ also contributes to the total residual phase noise and is simply presented by AM-to-PM conversion figure of merit. This process is explained as the AM noise is fed back to the gain stage through the feedback network and hence modulates the amplifier phase via nonlinearity of the device. This phase

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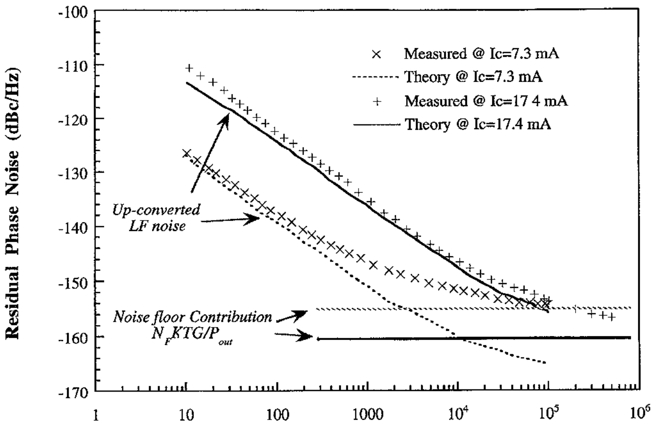

Fig. 2. The residual phase noise of the HBT in the oscillator as a function of offset frequency. The measured data are retrieved based on Leeson's Equation: $\mathcal{L}_{\mathrm{res}\phi}(\Omega) = (\frac{2Q\Omega}{2\pi f_0})^2 \mathcal{L}_{\mathrm{osc}\phi}(\Omega)$. The up-converted noise are calculated based on the measured LF current noise. At $I_c = 7.4$ mA, the transistor has a compressed gain of 10 dB, an output power of -1 dBm, and a noise figure of 7 dB. At I_c =17.4 mA, the transistor has a compressed gain of 10 dB, an output power of 5 dBm, and a noise figure of 9 dB.

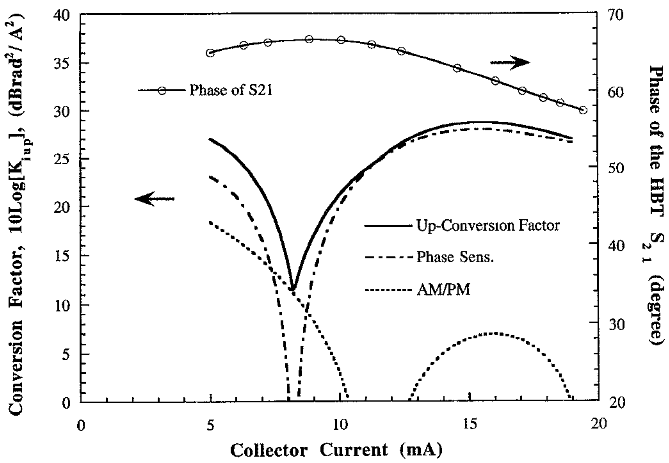

Fig. 3. Noise up-conversion factor and the phase of S_{21} for the HBT transistor. In the figure, "Phase sens." denotes the contribution from phase variation to bias current; "AM/PM" denotes the contribution from AM-to-PM conversion. The gain sensitivity varies from -0.1 dB/mA to 0.5 dB/mA at different bias points. The AM-to-PM conversion factor is about 0.3°/dB at different bias with a gain compression of about 2 dB.

noise contribution can be considered to be coherent and in phase with $\mathcal{L}_{r\phi}(\Omega)$.

Knowing the up-converted residual phase noise and the noise floor at the oscillation frequency of f_0, the oscillator phase noise, $\mathcal{L}_{\mathrm{osc}\phi}$, can be approximately expressed in terms of the Q factor of feedback network as [8]

$$\begin{aligned} \mathcal{L}_{\mathrm{osc}\phi}(\Omega) \approx & \left(\frac{2\pi f_0}{2Q\Omega}\right)^2 \Bigg(\sum_{i=1}^{n} K_{i\mathrm{up}i}\langle i_i^2(\Omega)\rangle \\ & + \sum_{j=1}^{m} K_{v\mathrm{up}j}\langle v_j^2(\Omega)\rangle \frac{GN_FKT}{P_{\mathrm{out}}}\Bigg) \\ & + \mathcal{L}_{r\phi}(\Omega) + \frac{GN_FKT}{P_{\mathrm{out}}} \\ K_{i\mathrm{up}i} = & \frac{1}{2}\left(\frac{\partial\Phi}{\partial I_i} + \frac{1}{G}\frac{\pi K_{\mathrm{AM/PM}}}{9\ln(10)}\frac{\partial G}{\partial I_i}\right)^2; \\ K_{v\mathrm{up}j} = & \frac{1}{2}\left(\frac{\partial\Phi}{\partial V_j} + \frac{1}{G}\frac{\pi K_{\mathrm{AM/PM}}}{9\ln(10)}\frac{\partial G}{\partial V_j}\right)^2 \end{aligned} \quad (3)$$

In (3), $K_{i\mathrm{up}}$ and $K_{v\mathrm{up}}$, in units of (rad/A)^2 and (rad/V)^2 respectively, are referred to as noise up-conversion factors, in which the LF noise is up-converted to the residual phase noise of the gain stage. N_F, G and P_{out} are the noise figure, compression gain, and the output power of the gain stage at f_0; K is Boltzmann constant, and T is the temperature in °K. $K_{\mathrm{AM/PM}}$ is the AM-to-PM conversion factor in the unit of degree/dB, leading to the AM noise contribution to the phase noise at close-in to carrier offset frequency [9]. Influence of these various bias-dependent sensitivities on phase noise is demonstrated in the experiments to be discussed next.

III. Experimental Results and Discussions

An HBT-based oscillator was fabricated at 5.6 GHz using an unmatched common-emitter AlGaAs/GaAs HBT as a gain stage. The positive feedback is provided by a 50-Ω coaxial delay line with a time delay of 9 nS (with the equivalent Q factor of about 150 [6]). To avoid strong nonlinearity of the transistor as the operating points were altered, attenuation in steps of 1 dB was introduced in the feedback loop to adjust the gain compression by 1 to 2 dB. It is stipulated that the noise contribution as result of the 1–2 dB incremental change in the feedback loop loss is insignificant to the overall noise floor of the transistor.

The oscillator phase noise was characterized using the injection locking theory. A clean reference signal was employed to injection lock the oscillator. The true phase noise of the free-running oscillator is then retrieved by comparing the locked oscillator phase noise against the reference signal using a homodyne mixer approach [10]. Based on the measured oscillator phase noise, the residual phase noise of the HBT is retrieved [8] and presented in Fig. 2 as a function of offset frequency for two different operation points. At an operation point of $I_c = 17.4$ mA (class A), a larger phase noise is observed than that at $I_c = 7.3$ mA (class AB). As clearly seen in Fig. 2, the corner frequency, f_c, at class AB operation point is reduced by about two orders of magnitude compared to class A operation. However, a lower output power at $I_c =$ 7.3 mA would result in a 6-dB-higher noise to carrier ratio than that at $I_c = 17.4$ mA, hence resulting in a higher phase noise only at a far-away offset carrier frequency (i.e. $\Omega >$ 10 KHz). Therefore, to estimate the transistor's residual phase noise using the expression of $\mathcal{L}_{\mathrm{res}\phi}(\Omega) = \frac{N_FGKT}{P_{\mathrm{out}}}(1 + \frac{2\pi f_c}{\Omega})$ [11], one has to be aware that f_c is actually a function of both LF noise up-conversion factor and noise floor, which are both device operation point dependent.

The LF phase noise up-conversion factor of the HBT, as presented in (3), is employed to explain the observed bias-dependent phase noise behavior. To predict the residual phase noise, the up-conversion factor of LF noise in the collector current, $K_{i\mathrm{up}}$, is calculated and shown in Fig. 3 for a single

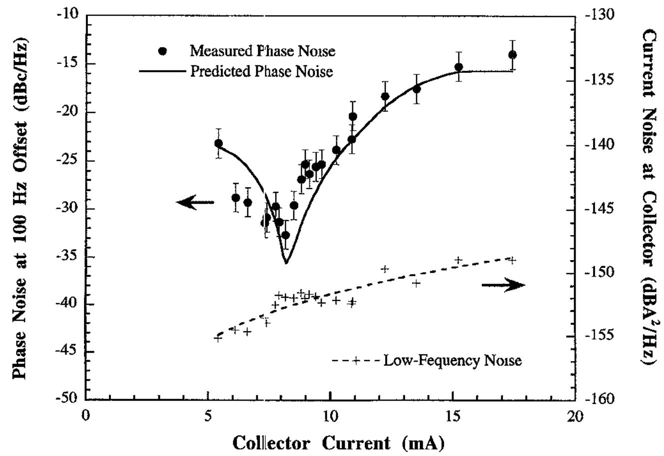

Fig. 4. Low- frequency current noise at 100 Hz and the oscillator's phase noise at offset of 100 Hz. The predicted results are calculated based on the curve fitted LF noise. An error bar of about 3 dB is also presented.

HBT gain stage. The slope sensitivities of phase and amplitude to collector current were obtained from the bias-dependent small-signal S_{21} of the HBT transistor. Because of the small $K_{AM/PM}$, the noise up-conversion factor K_{iup} is dominated by the phase sensitivity in terms of the bias variation. The AM/PM noise would only dominates at bias point where a higher gain sensitivity than the phase sensitivity is experienced in terms of the bias variation.

The measured LF noise current at collector, depicted in Fig. 4, is approximately proportional to the bias current raised to the power of 1.6 [12]. Using this LF noise and K_{iup}, the residual phase noise can be predicted. Measured and predicted phase noise of the oscillator at 100-Hz offset carrier frequency are within the experimental errors, shown in Fig. 4 as a function of collector current. The phase noise minimum is primarily due to the zero phase sensitivity to the collector current for a particular bias point, as depicted in Fig. 4. However, the AM-to-PM noise contribution would still establish the minimum up-conversion factor.

IV. Conclusion

The experimental results indicate that the residual phase noise of HBT transistor depends on the bias dependent LF noise up-conversion factor of the device. This bias-dependent phase sensitivity is an important design criteria, in addition to the device selection and matching network, in achieving low phase noise oscillator.

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