COMPARISON OF THE PHASE NOISE PERFORMANCE OF HEMT AND HBT BASED OSCILLATORS

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Abstract — This paper presents a comparative study on the phase noise contribution of HBT and HEMT oscillators. For a quantitative comparison, HBT and HEMT oscillators were constructed at 5.6 GHz using the same circuit topology. Experimental results show that the low-frequency (LF) noise (i.e. 1/f noise) in HBT is relatively lower than that in HEMT; however, the lowest phase noise can be achieved in the HEMT oscillator due to its low LF noise up-conversion to the phase noise. A proposed theoretical model explains the difference in noise up-conversion performance of HEMT and HBT. The experimental investigation emphasizes the importance of LF noise level and its up-conversion factor in the design of microwave oscillators.

INTRODUCTION

THE close-in to carrier phase noise in oscillators is primarily due to the up-conversion of the low-frequency (LF) noise in the active devices [1-3]. HBTs with their low LF noise in conjunction with high Q dielectric resonators have been used to reduce the phase noise in oscillators [4, 5]. On the other hand, HEMT is another type of device structure often used in microwave and millimeter-wave oscillators [6,7], of which the LF noise has been identified to be lower than that in MESFET devices [8]. Therefore, it is necessary to have a comparison between the phase noise performance of HBT and HEMT devices in order to select the most appropriate device and operating point in oscillator design.

This study focuses on the understanding and the prediction of the different phase noise factors dominating in this two different types of devices, rather than reporting the champion performance of each device structure. The measured phase noise performance of an AlGaAs/GaAs HBT and an AlGaAs/InGaAs/GaAs pseudomorphic HEMT are explained using a theoretical phase noise model of the oscillator. The model is developed based on the noise up-conversion factor in which the transistor converts its LF noise to the residual phase noise at the microwave frequencies [9].

Using this model, the single-side-band phase noise of the oscillator at near-carrier offset frequencies, $£_{osc\phi}$, is approximately expressed using the feedback network's Q factor as [10] :

$$£_{osc\phi}(\Omega) \approx \left(\frac{2\pi f_o}{2Q\,\Omega}\right)^2 \left(K_{up}\left\langle e^{\,2}_{LF}(\Omega)\right\rangle + \frac{GN_FKT}{P_{out}}\right) \qquad (1)$$

Ω is angular offset frequency; N_F, G and P_{out} are noise figure, compression gain, and output power of the active device at f_o, the oscillating frequency; K is Boltzmann's constant, and T is the temperature in °K. $\langle e_{LF}^2 \rangle$ represents the LF noise power spectrum density of the device for a given DC bias. For simplicity, only one independent LF noise source is assumed in the device. $K_{up}\langle e_{LF}^2\rangle$ is the up-converted residual phase noise. K_{up} is referred to as noise up-conversion factor, which can be characterized in terms of the device's phase and gain sensitivities to its bias variable, E, in which $\langle e_{LF}^2\rangle$ exists:

$$K_{up} = \frac{1}{2}\left(\frac{\partial\Phi}{\partial E} + \frac{1}{G}\,\frac{\pi K_{AM/PM}}{9\ln(10)}\,\frac{\partial G}{\partial E}\right)^2 \qquad (2)$$

G and Φ are the transmission gain and phase of the device. $\partial\Phi/\partial E$ and $\partial G/\partial E$ are the phase and gain sensitivities to E and present the noise up-conversion via phase and amplitude modulation respectively. $K_{AM/PM}$ 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 [11]. The accurate values of $\partial\Phi/\partial E$ and $\partial G/\partial E$ are difficult to predict analytically because of the device nonlinearity under large-signal operation. However, they can be approximated using the small-signal performance by assuming that a significant change in the phase and gain

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sensitivities is not experienced under large-signal operation.

Based on the above theory, the phase noise performance of the two types of devices are explained based on their bias-dependent small-signal S-parameters and the LF noise performance in this paper. The up-converted residual phase noise of the two devices were obtained from oscillators at 5.6 GHz using a similar circuit topology.

DEVICE CHARACTERIZATION AND COMPARISON

HEMT and HBT devices used in this study are research devices fabricated at Army Research Laboratory and Research Triangle Institute, respectively. The f_{max} of the HBT is about 70 GHz with emitter area of $2.4\times10.4\mu m^2$. The I_{cc} of this HBT is about 20 mA. The f_{max} of the HEMT is about 120 GHz with its gate dimensions of $0.1\mu m\times100\ \mu m$. The I_{dss} of the HEMT is about 25mA. In order to predict the up-conversion factors of LF noise of the devices, the S_{21} (forward transmission functions) of both devices at 5.6 GHz were characterized at different bias currents. The collector-emitter voltage and drain-source voltage are kept at 2V in the measurement.

As reported early [9], the phase slope of HBT demonstrates a sharp turning point with respect to the bias current, which could be due to the competition between the junction and the intrinsic base charging capacitances. A gain roll-off above 12 mA was also observed which is caused by increase in junction temperature and the current saturation.

The measured S_{21} of HEMT shows an inflection region of both phase and amplitude around the zero gate bias voltage, which is traced to the carrier conduction competition between the two-dimensional electron gas in GaAs and the AlGaAs parasitic channel [12]. In the HEMT, above certain gate voltage, the contribution to transconductance and capacitance due to the two-dimensional electron gas starts to decrease, however the contribution from the AlGaAs cap layer becomes more and more significant at the same time. Therefore, an inflection region of the total transconductance and capacitance is resulted. Knowing the bias-dependent phase and gain performance, one can then estimate the noise up-conversion factors in HEMT and HBT using Eq. 2.

The calculated up-conversion factor of the HEMT is shown in Fig. 1 as a function of its drain current normalized to I_{dss} (I_{dss}=25 mA). K_{up} is defined as the factor in which the LF noise in drain current is converted into the residual phase noise, with a unit of $(rad/A)^2$. Clearly, a very low K_{up} in the HEMT at currents between 20 to 30 mA (I_d/I_{dss}=0.8 to 1.0) is obtained because both phase and amplitude sensitivities to current reach to minimum value simultaneously due to the unique property of HEMT device. For the HBT [9], even though a sharp minima at current of 8 mA (I_c/I_{cc}=0.25) also exists in the phase sensitivity of the HBT, the bottom line of K_{up} is dominated by the contribution from a high amplitude sensitivity. Hence forth, relatively high noise up-conversion factors in the HBT are resulted over all the bias currents as compared to the HEMT.

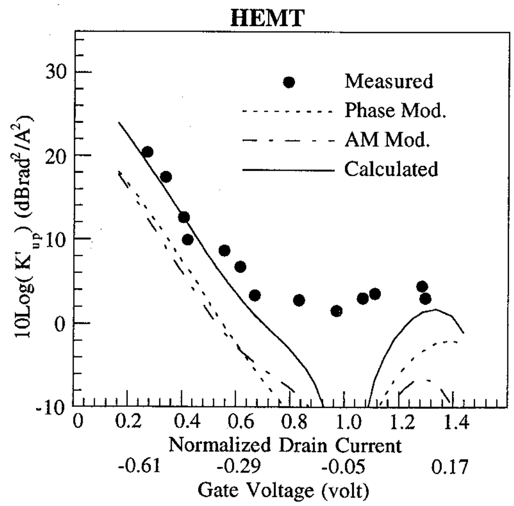

Fig. 1. Noise up-conversion factors of HEMT within the feedback bandwidth. In the figure, "Phase Mod." denotes the contribution from phase variation to bias current; "AM Mod." denotes the contribution from AM noise modulation via AM-to-PM conversion. The AM-to-PM conversion factor for HEMT is about 0.2 °/dB and 0.3 °/dB respectively with gain compression around 1.5 to 2 dB.

OSCILLATOR PHASE NOISE MEASUREMENT AND COMPARISON

To verify above theoretical comparison, HBT and HEMT based oscillators were fabricated at 5.6 GHz by using the same positive feedback network, as shown in Fig. 2. The feedback network is provided by a 50 Ω coaxial delay line with a time delay of 9 nS (with the equivalent Q factor of about 150 [13]). 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. Unmatched common-emitter HBT and common-source HEMT were used as the gain stage to provide oscillation.

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 [14]. Both transistors were biased by dry battery cells to minimize the noise contribution from electronic power supplies.

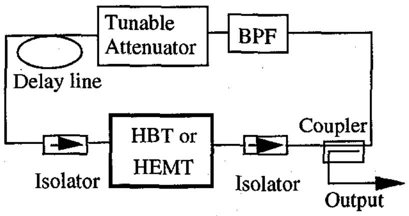

Fig. 2. Block diagram of the oscillator circuit used to characterize HBT and HEMT phase noise performance.

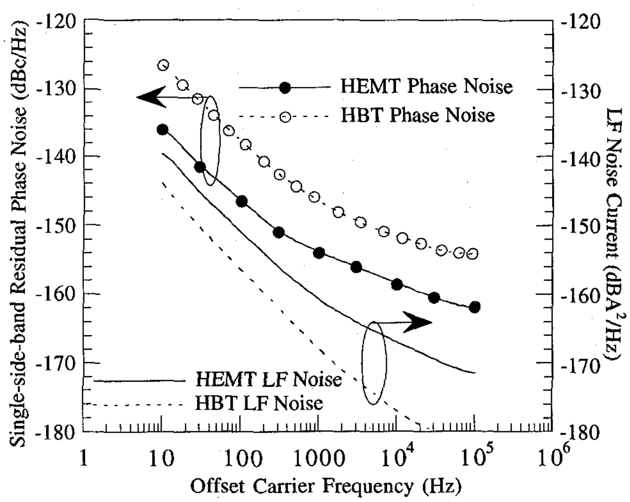

Fig. 3. The residual phase noise of the HEMT and HBT as a function of offset carrier frequency, Ω. The normalized drain current of HEMT is 1.04 (26 mA), and the collector current is 0.25 (8 mA).

The residual phase noise as a function of offset carrier frequency of HEMT and HBT are depicted in Fig. 3, which are retrieved from the oscillator phase noise by using Leeson's model [10]. The bias current of HEMT and HBT are selected at the points corresponding to the minimum up-conversions factor. The LF noise in the drain and collector current of HEMT and HBT are also displayed in Fig. 3. Above 1 KHz the LF noise to frequency relation in HEMT changes from 1/f to about $1/f^{0.6}$ [15], which results in a much higher corner frequency in HEMT than in HBT for LF noise. On the other hand, the phase noise of HEMT is about 10 dB lower than HBT over all measured offset frequencies because of the different up-conversion factors. The deviation in the phase noise slope from the LF noise slope at high offset frequencies is due to the contribution from noise floor at microwave frequency in both devices. The signal-to-noise level in the HEMT is relatively high because of its low noise figure of 1.5 dB and high output power of 8 dBm. On the contrary, the high noise figure of 7dB and low output power of 0 dBm in the HBT result in a low signal-to-noise level.

In Fig. 4, the single-side-band phase noise of HBT and HEMT oscillator at 100 Hz offset frequency from carrier are compared as a function of their bias currents. The normalized collector current of HBT (I_c/I_{cc}) and the normalized drain current of HEMT (I_d/I_{dss}) are used as a common variable for the noise performance comparison. The measured LF noise power in HBT's I_c and in HEMT's I_d at 100 Hz are also depicted in Fig. 4 for comparison. The LF noise power in HEMT and HBT are proportional to the bias current at power of 1.0 and 1.6 [16], respectively. Clearly, the phase noise of HEMT oscillator is much lower than that of HBT, especially at currents above 0.6 (Id=10 mA, Ic=12 mA) although the LF noise of HEMT is a few dB higher than that of HBT. This fact verifies the theoretical prediction that the noise up-conversion factor of the HEMT is much lower than HBT, which is predicted in Fig. 1.

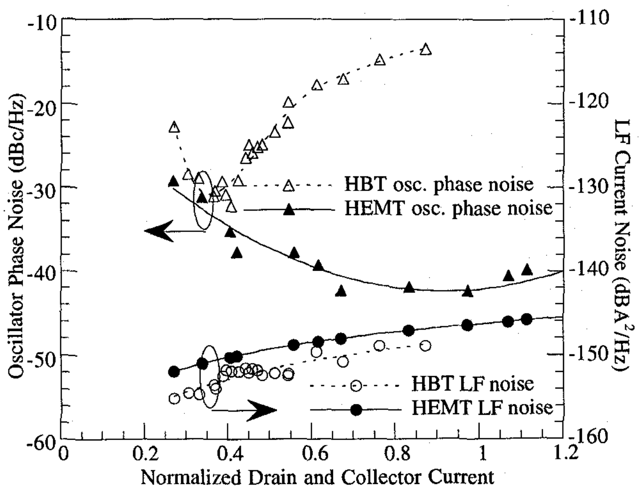

Fig. 4. The measured phase noise of HEMT and HBT based oscillators at 100 Hz offset carrier frequency, and the corresponding LF current noise of HEMT and HBT at 100 Hz. (The β of HBT is 30, and the transconductance of HEMT is 13 m ℧).

Using the measured phase noise of the oscillator and LF noise of the device , the actual noise up-conversion factors of the unmatched HEMT are retrieved and compared with the predicted value in Fig. 1. Good agreements between the measured and the estimated results are obtained under most bias conditions. Since the contribution from the high order nonlinearity of the device is not included in the small-signal linear approximation, there is a big discrepancy in the calculated conversion factor around the bias points with the lowest conversion factor. Therefore, either a large-signal transmission function measurement or a numerical simulation based on the nonlinear device model has to be used [17] to accurately calculate the conversion factors at this operating point.

CONCLUSIONS

The phase noise performance in both HEMT and HBT are compared and explained by using the bias dependent small-signal forward transmission coefficient. Measurement results verify that the error of this linear approach is reasonably small, and it is very useful in predicting the oscillators phase noise.

Since LF noise and noise up-conversion factor in the same type of device can be influenced by other parameters such as device's material (Si vs. GaAs) and physical size (large vs. small emitter area) [18], there is no simple preference of one type device over another in terms of phase noise performance. However, above comparisons clearly demonstrate that, in general, a lower noise up-conversion factor can be achieved in HEMT than in HBT because of the inherent linear behavior of HEMT over certain bias conditions; on the other hand, LF noise level in HBT can be generally much lower than that in FET devices [19]. Therefore, for a stable oscillator design, it is of utmost significance to consider both the LF noise and the noise up-conversion mechanisms of the candidate devices to achieve the lowest up-converted residual phase noise. Furthermore, use of the most suitable circuit topology combined with optimum device at low LF noise conversion bias point will result in a stable source at MW and MMW frequencies.

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