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Investigation of HBT Oscillator Noise Through 1/f Noise and Noise Upconversion Studies†

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ABSTRACT

It is shown that the $\mathcal{L}$(f) characteristics of a HBT DRO can be approximated using the HBT's low frequency noise spectra and the oscillator's upconversion factor, K'_{FM}. Experimental studies have been used for this purpose and the measured $\mathcal{L}$(f) ranged -89dBc/Hz to -101dBc/Hz at a 10kHz offset frequency (-124dBc/Hz best performance at 100kHz). It was shown that the upconversion of the low frequency noise is the primary cause of $\mathcal{L}$(f) in the oscillator and its frequency dependence is directly impacted by the low frequency noise spectrum rather than K'_{FM} itself. $d\mathcal{L}(f)/df$ deviates from the -30dB/decade rate, expected for upconversion of ideal 1/f noise, due to traps in the device.

INTRODUCTION

Heterojunction Bipolar Transistors (HBT's) have shown excellent performance in microwave circuits [1], [2]. The very good phase noise characteristics that can be obtained by HBT's in the microwave regime makes them very attractive for fundamental source applications. In order for circuits, using these devices, to achieve their ultimate performance, a systematic study of the factors which impact the oscillator noise is required. To date a systematic study of the parameters which contribute to these characteristics has not been carried out. This paper presents the results of the first systematic study of the parameters which impact the phase noise of HBT oscillators including the low frequency noise (1/f noise), the upconversion coefficient (K'_{FM}), and the low frequency base termination. The low frequency noise is an inherent device property which, through upconversion, degrades the spectral purity of the oscillator. The measured low frequency output noise is a function of frequency, bias, temperature, termination, device material, and processing technology. On the otherhand, K'_{FM} is a characteristic of the oscillator circuit and device which indicates how sensitive the oscillator is to phase modulation by an external signal.

HBT and Oscillator Description

A Npn, GaAs/AlGaAs HBT is used in these experiments. The device has 5 emitter fingers ($2\mu m \times 20\mu m$) and a total emitter area of $200\mu m^2$. The devices were fabricated from MOCVD grown material using a self-aligned process which served to minimize parasitic resistances [3]. Their f_T and f_{max} are 20 GHz and 40 GHz, respectively. The oscillator studied in this work is a Dielectric Resonator Oscillator (DRO) using feedback between the collector and the base [1]. The oscillation frequency is 11.02GHz. The complete schematic is shown in figure 1. A single voltage source supplied collector and base bias. The base current is controlled via a 10KΩ wirewound potentiometer (external to the fixture), which also controls the low frequency base termination.

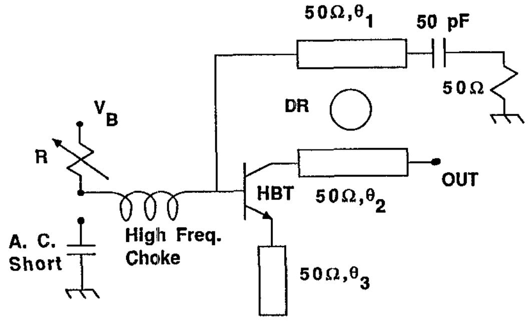

Figure 1: Schematic Diagram of the Oscillator used in this Work.

PHASE NOISE RESULTS

$\mathcal{L}$(f), of the DRO, was measured from 10Hz to 100kHz using an HP3048A phase noise measurement sys-

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tem. Both the bias conditions and the low frequency base termination, $R_{b,t}$, were varied. The results for $\mathcal{L}$(f) are summarized in Table 1 at a 10kHz offset. V_{CE} was either 3V or 5V, and I_C was varied from the minimum required to sustain oscillation to 50mA. $R_{b,t}$ was set to either the bias resistance, R, needed for a given I_C, or 0Ω (a.c. short) using a shunt capacitor (external to the test fixture) from the base to ground. The best result, at a 10kHz offset, is -101dBc/Hz for V_{CE}=5V, I_C=50mA, and $R_{b,t}$=0Ω. This decreased to -124dBc/Hz, at a 100kHz offset. Figure 2 is a plot of $\mathcal{L}$(f) versus frequency for V_{CE}=5V, I_C=50mA, and two different base termination conditions. This figure clearly shows the impact of the base termination on $\mathcal{L}$(f). The noise was reduced by about 4dB to 7dB over the entire measurement band when the base was a.c. short circuited at baseband frequencies.

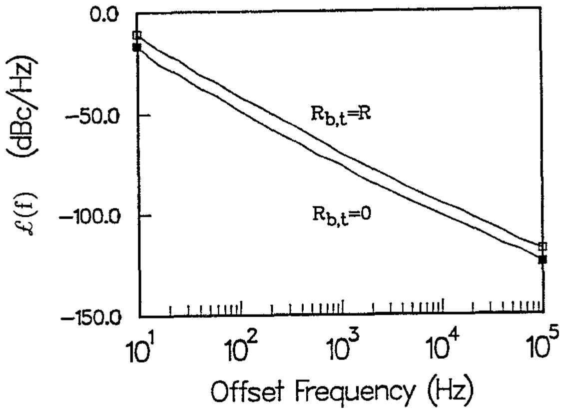

Figure 2: Comparison of the phase noise, $\mathcal{L}$(f), for V_{CE}=5V and I_C=50mA for different base terminations

V_{CE}	I_C	$\mathcal{L}$(10kHz)(dBc/Hz)	
(V)	(mA)	$R_{b,t} = R$	$R_{b,t} = 0$
3	40	-91	-93
3	50	-93	-97
5	20	-91	-94
5	30	-89	-96
5	40	-92	-99
5	50	-95	-101

Table 1: $\mathcal{L}$(10kHz) of the DRO for various bias conditions and base terminations. $R_{b,t} = R$ is the case when the base is terminated into the bias resistor. $R_{b,t} = 0$ is the case where the base is terminated into a shunt capacitor.

Table 1 clearly shows the trends obtained. $\mathcal{L}$(10kHz) decreases as I_C is increased. For instance, $\mathcal{L}$(10kHz) decreased from 94dBc/Hz to 101dBc/Hz as I_C was increased from 20mA to 50mA with V_{CE}=5V and $R_{b,t}$=0Ω. In addition, $\mathcal{L}$(f) also decreases with the use of a short circuit base termination. The decrease varied from 2dB to 7dB depending on the bias condition. Moreover, there is also a tendency for $\mathcal{L}$(f) to decrease as V_{CE} is increased. For instance, for I_C=50mA and $R_{b,t}$ = 0Ω, $\mathcal{L}$(f) decreased by about 4dB as V_{CE} was increased from 3V to 5V.

The slope of $\mathcal{L}$(f) versus frequency does not follow an ideal $1/f^3$ relation as would be expected if $\mathcal{L}$(f) was entirely due to upconversion of ideal $1/f$ noise. Figure 3 is a plot of the slope of $\mathcal{L}$(f) as a function of frequency (d$\mathcal{L}$(f)/df). Between 10Hz and 100Hz the slope -30dB/decade. However, this changes to about -22dB/decade from 10kHz to 100kHz. In general, at high frequencies, it was found that the slope varied between -20dB/decade and -25dB/decade. This change in slope clearly shows that the $\mathcal{L}$(f) is not simply upconversion of an ideal 1/f low frequency noise spectrum.

In order to begin to understand these results, both the low frequency noise behavior of the HBT, and the K'_{FM} of the oscillator have been characterized.

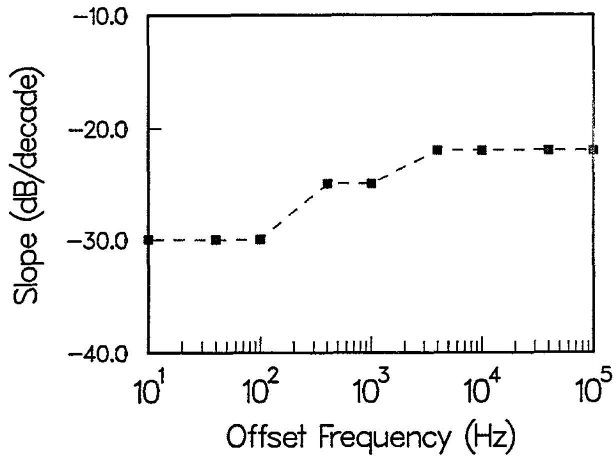

Figure 3: Slope of oscillator phase noise, $\mathcal{L}$(f), showing the deviation from -30dB/decade.

HBT LOW FREQUENCY NOISE CHARACTERISTICS

HBT low frequency noise can have many origins, including: recombination, diffusion, trap, burst, and partition [4]. Measurement of the noise spectra as a function of bias, frequency, and temperature will provide information describing the origin(s) of the noise. It is desirable to use short circuit noise currents to aid in identifying origins of the noise as opposed other noise models, such as that used in noise figure calculations, because the noise is not referred to only one port. i_1 is the short circuit base noise current, with the collector terminal simultaneously short circuited. Its spectra is designated by $S_{I_B}(f)$ (A^2/Hz). i_2 is the short circuit collector noise current, with the base terminal simultaneously short circuited. Its spectra is designated by $S_{I_C}(f)$ (A^2/Hz). Figure 4 is a plot of $S_{I_C}(f)$ for V_{CE}=5V and I_C=20 and 40mA for the device used in the oscillator. The noise clearly increases with I_C in the region which is approximately $1/f$ in nature. This is not

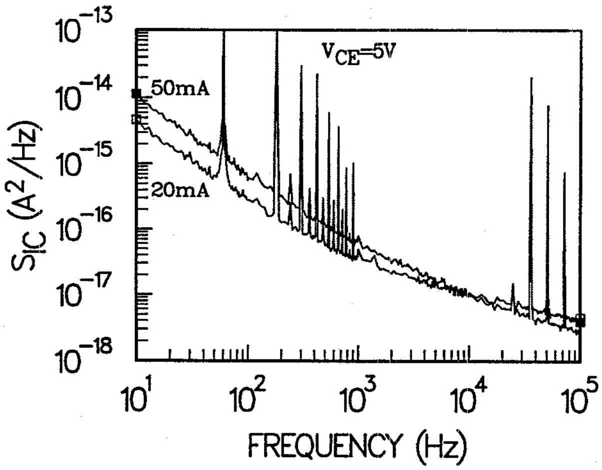

Figure 4: Low frequency short circuit collector noise spectra, $S_{I_C}(f)$ as a function of bias and frequency for the HBT used in the oscillator.

the case in the regions where the spectra begin to level out since this region is dominated by a different noise mechanism, as described below. The bias dependence of the noise spectra has been characterized by measuring $S_{I_C}(f)$ for various I_C, and it is found to follow $S_{I_C}(10Hz) \propto I_C^{1.7}$. This bias dependence suggests that both diffusion and recombination noise contribute to $S_{I_C}(10Hz)$. In general, the dependence of $S_{I_C}(f)$ on V_{CE} is weak, unless substantial heating is observed in which case the noise will then also increase with increasing V_{CE}.

The frequency dependence of $S_{I_C}(f)$ is clearly not 1/f over the entire measurement band. Npn GaAs/AlGaAs HBT's often do not display perfect 1/f noise spectra. It is known that a substantial noise bulge is seen in the 1/f noise spectra [5] in the vicinity of 10kHz due to trapping. This is often associated with the n-type doping of the AlGaAs in the emitter and was present in the spectrum of the transistor tested here. As shown in figure 4, from 10Hz to 100Hz the noise is essentially 1/f in nature. At higher frequencies this tends to reduce dramatically. This is due to traps which introduce a Lorentz component to the spectrum. This component will change the frequency dependence of the low frequency noise. In fact, if the Lorentz component is large enough, it will cause the spectrum to flatten out over some part of the measurement band.

To determine the impact of the base termination on the measured output noise, $S_{I_C}(f)$ was measured for the base termination used in the oscillator. The results for the oscillator bias condition V_{CE}=5V and I_C=20mA show a clear increase of the $S_{I_C}(f)$ for the non-zero $R_{b,t}$ case. At 10Hz the noise increased by 3.8dB, while at 100kHz it increased by 5.4dB. This effect is easily understood by recalling the noise equivalent circuit of the HBT. For the short circuit base condition, i_1 has no effect on the output noise current. This is due to i_1 being shunted out of the device. However, when the base termination is non-zero, some fraction of i_1 flows into the base where it is then amplified and contributes to the total output noise current.

UPCONVERSION FACTOR, K'_{FM}

K'_{FM} is an upconversion factor that quantifies the sensitivity of the oscillator to an input signal applied to the base of the transistor. Its units are Hz/V. K'_{FM} can be determined experimentally by using a carrier suppression technique. The amplitude of a baseband signal, applied to the base, is increased until the carrier is nulled. In general:

$$K'_{FM} = \frac{f_m \beta}{A_m} \tag{1}$$

where f_m is the frequency of the modulating signal which has an amplitude, A_m. β is the modulation index. In the carrier suppresion technique, β equals 2.408.

K'_{FM} was measured for this oscillator as a function of bias and frequency. The results are shown in figure 5. Measurements of K'_{FM} at 5kHz and 50kHz showed

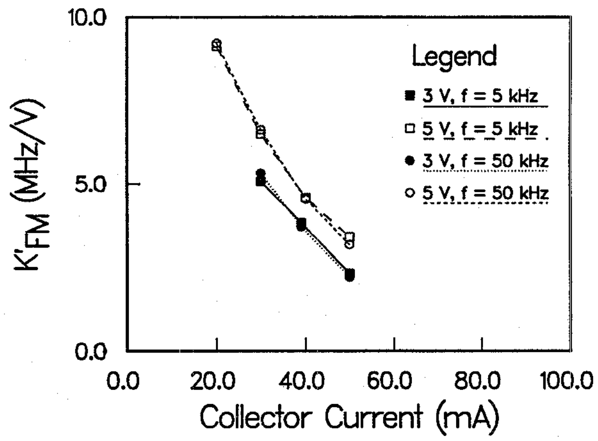

Figure 5: The upconversion coefficient, K'_{FM}, as a function of bias and frequency.

that it was frequency independent. Similar results have been obtained for measurements made on MESFET's and HEMT's [6]. The bias dependent results showed that K'_{FM} decreases from 9.2MHz/V to 3.2MHz/V with increasing I_C (20mA to 50mA, V_{CE}=5V). This is believed to be due to the nonlinearities becoming less significant as the DC bias point is moved farther from cutoff. K'_{FM} decreased from 3.2MHz/V to 2.2MHz/V with V_{CE} varying from 5V to 3V.

Using the experimentally determined value of K'_{FM} and $S_{I_C}(f)$ the $\mathcal{L}$(f) can be calculated using [6]:

$$\mathcal{L}(f) = 10 \log \frac{S_v(f) K'^2_{FM}}{2f^2} \tag{2}$$

where: $S_v(f)$ is the equivalent input noise voltage of the HBT for a given base termination. $S_v(f)$ can be determined from $S_{I_C}(f)$ and the voltage gain of the HBT in the test configuration. Figure 6 contains measured and calculated $\mathcal{L}$(f) for V_{CE}=5V and I_C=20mA for the short circuited base termination condition. The agreement here is very good, typically less than 3dB difference. The same is true for the case where the base is terminated into the bias resistor. Since K'_{FM} is frequency independent, the results indicate that the frequency dependence of the oscillator noise, $\mathcal{L}$(f), is directly related to the low frequency noise characteristics of the HBT; the oscillator circuit and device charateristics reflected by K'_{FM} do not seem to affect the frequency dependence of the phase noise. K'_{FM} is on the otherhand a measure of the low frequency noise upconversion determined by the circuit and device characteristics. As discussed already, the noise upconversion will be lower at high I_C's (see figure 5), but the HBT noise itself will increase (see figure 4). The results of Table 1 suggest that the net result of this is a noise reduction or equivalently, upconversion plays a more predominant role as far as the I_C dependence of oscillator noise is concerned.

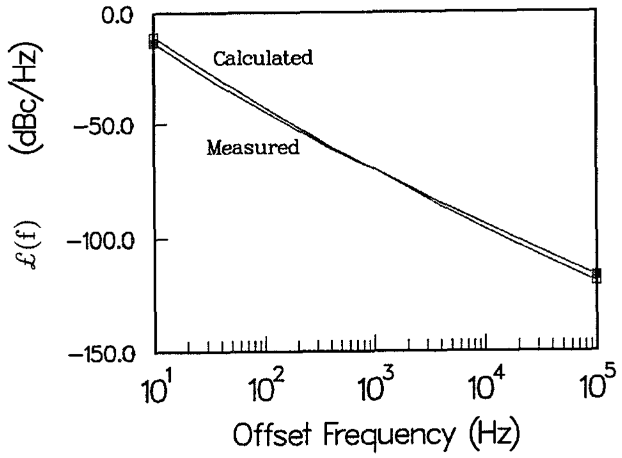

Figure 6: Comparison of Calculated and measured $\mathcal{L}$(f) for $V_{CE} = 5V$ and $I_C = 20mA$. These results are for the short circuited base termination.

When the I_C is increased to 50mA the fit between theoretical and experimental results (not shown in the figure) degrades. The error can be as great as 9dB. However, the trends are still correct. The disagreement indicates that other mechanisms, such as PM-PM conversion (not accounted for by equation (2)) must be considered.

CONCLUSIONS

The $\mathcal{L}$(f) of a HBT DRO has been measured as a function of bias and low frequency base termination. Best $\mathcal{L}$(f) obtained was -124dBc/Hz at a 100kHz offset at V_{CE}=5V, I_C=50mA, and a short circuit base termination. The phase noise decreased by as much as 7dB (at a 10kHz offset frequency) by increasing I_C, from 20mA to 50mA, due to a reduction K'_{FM}. $\mathcal{L}$(f) also decreased by as much as 7dB (at a 10kHz offset) with the use of a short circuit base termination due to shunting the input noise of the transistor. The low frequency collector noise spectra, $S_{I_C}(f)$, was measured as a function of I_C and base termination. $S_{I_C}(f)$ increased with I_C, over most of the measurement band, which is opposite to that observed for $\mathcal{L}$(f). In addition, $S_{I_C}(f)$ increased with $R_{b,t}$ which is consistent with what is observed for $\mathcal{L}$(f). $S_{I_C}(f)$, of the HBT, did not follow an ideal 1/f dependence under any condition due to traps. The measured K'_{FM} of the oscillator is constant with offset frequency and decreases with I_C. This decrease in K'_{FM} with bias is consistent with what is observed in $\mathcal{L}$(f). It is possible to approximate $\mathcal{L}$(f) using K'_{FM} and the transistor noise. Agreement to within 3dB between measured and calculated $\mathcal{L}$(f) has been obtained in most test cases. However, under some conditions other mechanisms (possibly PM-PM conversion) play a significant role. $d\mathcal{L}(f)/df$ is found to increase with increasing offset frequency, in a manner corresponding to the frequency dependence of the low frequency noise of the HBT.

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