A COMPARISON OF UP-CONVERTED PM AND AM NOISE IN BIPOLAR JUNCTION TRANSISTOR AMPLIFIER CONFIGURATIONS[*]

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Abstract - In this paper we report on the sensitivities of phase modulation (PM) noise and amplitude modulation (AM) noise to baseband emitter current noise and collector-base voltage noise of different bipolar junction transistor (BJT) amplifier configurations. Experimental results and predicted sensitivities are compared for a common emitter (CE) amplifier, a common base (CB) amplifier and a common collector (CC) amplifier. Results show that the sensitivities vary with transistor, amplifier configuration and circuit parameters.

Keywords: amplifier noise, AM noise, PM noise.

1. INTRODUCTION

Amplifiers add 1/f phase modulation (PM) noise and amplitude modulation (AM) noise about the amplified carrier signal. This 1/f noise is the result of low frequency (baseband) 1/f noise in the dc currents, dc voltages and amplifier impedances which are up-converted to noise about the carrier signal [1]. In this paper we present experimental results of the PM and AM noise sensitivities to baseband current and voltage noise in different bipolar junction transistor (BJT) amplifier configurations. The experimental results are compared to the sensitivities predicted from theory. Detailed description of the theory and derivations of the equations used are given in [1,2], and will not be repeated here.

The AM and PM noise equations for different BJT amplifier configurations can be derived by applying the definitions of AM and PM noise to the linear gain of the amplifier [1]. When the phase shift of the amplifier is << 1, the resulting AM noise is given by

$$\frac{1}{2}S_a(f) \cong \frac{1}{2}\left\{\left[\frac{\Delta G_o}{G_o}\right]^2 + \left[\delta^2\Delta\delta^2\right]\right\}\frac{1}{BW} + \frac{kTFG}{2P_o}, \quad (1)$$

where G_o is the midband gain of the amplifier, δ is the phase angle, BW is the measurement bandwidth, k is Boltzmann's constant, T is the temperature in kelvins, G is the gain of the amplifier, F is the noise figure and P_o is the output power. The first term of Eq. (1) is the flicker AM noise added by the amplifier (when operating in the linear region); the second term is the thermal AM noise. The resulting PM noise is given by

$$\frac{1}{2}S_\phi(f) \cong \frac{1}{2}\Delta\delta^2\frac{1}{BW} + \frac{kTFG}{2P_o}. \quad (2)$$

2. AM AND PM NOISE SENSITIVITIES TO CURRENT AND VOLTAGE NOISE IN CE AMPLIFIER

The AM and PM noise due to baseband current noise in a linear common emitter (CE) amplifier with a resistive load are given by

$$\frac{1}{2}S_a(f) \cong \frac{1}{4}\left(\frac{r_e}{r_e + R_E + r_g/\beta}\right)^2\left(\frac{\Delta I_E}{I_E}\right)^2, \quad (3)$$

$$\frac{1}{2}S_\phi(f) \cong \frac{1}{4}\frac{\left(\omega C_{bc} r_g r_e R_L\right)^2}{(r_e + R_E + r_g/\beta)^4}\left(\frac{\Delta I_E}{I_E}\right)^2, \quad (4)$$

where r_e is the small signal emitter resistance, R_E is the unbypassed emitter resistance, r_g is the equivalent ac input resistance, R_L is the load resistance, $\omega = 2\pi\nu_o$, ν_o is the carrier frequency, C_{bc} is the collector-base junction capacitance, β is the current gain of the transistor, and ΔI_E represents the fluctuations in the dc emitter current.

Measurements of the AM and PM noise sensitivities to baseband current noise in this configuration were made at a carrier frequency of 5 MHz for two different transistors and for two different values of R_E. For the CE amplifier used $I_E \cong 25$ mA, $R_L \cong 94\ \Omega$, and $r_g \cong 45\ \Omega$. To make the measurements, current noise was injected at the emitter leg of the CE amplifier. Figure 1 shows a block diagram of the measurement system used. We measured the baseband emitter current noise and the resulting AM and PM noise, and from these measurements obtained the experimental sensitivities. Table 1 shows the experimental results

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along with the predictions according to Eqs. (3) and (4). Column A in Table 1 shows the measured AM noise sensitivities to current noise ($\gamma = \Delta I_E/I_E$) when using a 2N2222A transistor and a microwave transistor for $R_E = 0$. Column C shows results from similar measurements when using $R_E = 10\ \Omega$. As expected, the AM sensitivity to current noise is independent of Fourier frequency and of the transistor used and decreases as R_E increases. The theoretical values computed according to Eq. (3) are shown in columns B and D. There is good agreement between theoretical and experimental values.

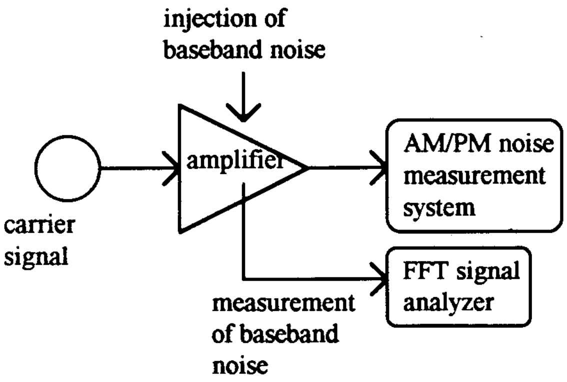

Figure 1. Block diagram of measurement system used.

Columns E and G show the PM noise sensitivities to baseband current noise for $R_E = 0$ and $R_E = 10\ \Omega$ when using a 2N2222A transistor and a microwave transistor. As expected the PM noise sensitivities are smaller when using the microwave transistor (due to the smaller C_{bc}), and decrease as R_E is increased. The theoretical predictions according to Eq. (4) are shown in columns F and H. An extra factor was included in the computation of the PM sensitivity for $R_E = 0$ since the total phase shift for this configuration was close to 1. [Equation (4) was derived assuming the total phase shift was less than 0.2 rad.] For the 2N2222A, the theoretical values are within 1-2 decibels of the experimental values.

Voltage noise was injected at the collector terminal of the amplifier in order to measure the AM and PM noise sensitivities to collector-base voltage noise (ΔV_{CB}). Table 2 shows the predicted and measured values of the sensitivities to ΔV_{CB} in a CE amplifier for $R_E = 0$ and $R_E = 10\ \Omega$ when using a 2N2222A and a microwave transistor. The theoretical sensitivities were computed using

$$\frac{1}{2} S_\phi(f) \cong \frac{1}{4}\left[\omega G_o r_g \frac{n C_{bc}}{V_{bi} + V_{CB}}\right]^2 \Delta V_{CB}^2, \tag{5}$$

$$\frac{1}{2} S_a(f) \cong \delta^2 \frac{1}{2} S_\phi(f), \tag{6}$$

where n is a parameter related to the doping profile of the base-collector junction ($n \approx 0.74$ for the 2N2222A and $n \approx 0.55$ for the microwave transistor), $V_{bi} \approx 0.7$ is the built-in potential of the base-collector junction, V_{CB} is the dc collector-base voltage, and G_o is the midband gain given by

$$G_o = \frac{R_L}{r_e + R_E + r_g/\beta}. \tag{7}$$

Columns A and C show the measured PM sensitivities to collector-base voltage noise for $R_E = 0$ and $R_E = 10\ \Omega$ when using two different transistors: a 2N2222A and a microwave transistor. As expected,

Table 1. Theoretical and experimental sensitivities of AM and PM noise to baseband current noise in a linear CE amplifier at a carrier frequency of 5 MHz for $\gamma = \Delta I_E/I_E \cong 1.9 \times 10^{-5}$, $I_E \cong 25$ mA, and $V_{CB} \cong 9$ V. The output power was approximately 6 dB relative to 1 mW (dBm). The unit dBc/Hz refers to dB below the carrier in a 1 Hz bandwidth.

2N2222A	A	B	C	D	E	F	G	H
Fourier frequency	AM sensitivities (dBc/Hz rel to $\gamma = 1$)				PM sensitivities (dBc/Hz rel to $\gamma = 1$)			
	$R_E = 0$		$R_E = 10\ \Omega$		$R_E = 0$		$R_E = 10\ \Omega$	
	Measured	Predicted	Measured	Predicted	Measured	Predicted	Measured	Predicted
100 Hz	-8.5	-9.3	-22.7	-26.5	-16.3	-16.8	-45.6	-46.9
50 Hz	-8.6	-9.3	-22.6	-26.5	-16.2	-16.8	-45.2	-46.9
20 Hz	-8.6	-9.3	-22.2	-26.5	-15.6	-16.8	-45.8	-46.9
10 Hz	-8.6	-9.3	-22.0	-26.5	-16.3	-16.8	-45.4	-46.9
microwave transistor								
100 Hz	-8.5	-9.3	-22.4	-26.5	-43.2	-34.4	<-48.6	-68.8
50 Hz	-8.5	-9.3	-22.7	-26.5	-42.6	-34.4	limited by	-68.8
20 Hz	-8.5	-9.3	-22.6	-26.5	-42.1	-34.4	system	-68.8
10 Hz	-8.5	-9.3	-22.2	-26.5	-42.4	-34.4	floor	-68.8

Table 2. Theoretical and experimental sensitivities of AM and PM noise to baseband collector-base voltage noise in a linear CE amplifier at a carrier frequency of 5 MHz for $\Delta V_{CB} = 2.8 \times 10^{-4}\ V_{rms}/\sqrt{Hz}$, $I_E \cong 25$ mA, and $V_{CB} \cong 8$ V. The output power was approximately 6 dBm.

2N2222A	A	B	C	D	E	F	G	H
	PM sensitivities (dBc/Hz rel to $\Delta V_{CB} = 1\ V_{rms}/\sqrt{Hz}$)				AM sensitivities (dBc/Hz rel to $\Delta V_{CB} = 1\ V_{rms}/\sqrt{Hz}$)			
Fourier frequency	$R_E = 0$		$R_E = 10\ \Omega$		$R_E = 0$		$R_E = 10\ \Omega$	
	Measured	Predicted	Measured	Predicted	Measured	Predicted	Measured	Predicted
100 Hz	-40.7	-40	-52.3	-52.9	-42.4	-44.1	-64	-68.6
50 Hz	-40.7	-40	-52.4	-52.9	-42.6	-44.1	-63.8	-68.6
20 Hz	-40.6	-40	-52.4	-52.9	-42.8	-44.1	limited by noise floor	-68.6
10 Hz	-40.6	-40	-52.4	-52.9	-43.1	-44.1		-68.6
microwave transistor								
100 Hz	-73.6	-60.8	<-77	-78	<-63	-86.2	<-69	-116.8
50 Hz	-74.3	-60.8	limited by system noise floor	-78	limited by system noise floor	-86.2	limited by system noise floor	-116.8
20 Hz	-73.2	-60.8		-78		-86.2		-116.8
10 Hz	limited by noise floor	-60.8		-78		-86.2		-116.8

the sensitivities are smaller when the microwave transistor is used, and the sensitivities decrease with increasing R_E. The theoretical predictions are given in columns B and D. For the case of the 2N2222A when $R_E = 0$ an extra factor was added to Eq. (5) since in this case δ (total phase shift) was close to 1 [2]. For the 2N2222A the agreement between predicted and experimental values is very good, while the agreement when using the microwave transistor is not as good. Nevertheless, the sensitivity when using the microwave transistor was smaller than the sensitivity when using the 2N2222A, as expected from theory.

Experimental AM sensitivities to voltage noise are given in columns E and G of Table 2. Except for the case of the 2N2222A and $R_E = 0$, the results were limited by the noise in the measurement system. Nevertheless, a lower sensitivity was observed when using the microwave transistor (when compared to the 2N2222A for $R_E = 0$), as expected from theory.

3. AM AND PM NOISE SENSITIVITIES TO CURRENT AND VOLTAGE NOISE IN CB AMPLIFIER

We also measured AM and PM noise sensitivities to baseband current and voltage noise on a linear common base (CB) amplifier. The CB amplifier used had the following parameters: 2N2222A transistor, $I_E \cong 25$ mA, $R_E \cong 200\ \Omega$, R_S (equivalent source impedance) $\cong 22.2\ \Omega$, and $R_L \cong 387\ \Omega$.

The experimental and predicted sensitivities to current noise for carrier frequencies of 5 MHz and 10 MHz are shown in Table 3. Column A of Table 3 shows the measured AM noise sensitivities to current noise at 5 MHz carrier frequency, while column D shows the measured sensitivities at 10 MHz. As expected, the sensitivities do not change with frequency. The predicted values, computed using

$$\frac{1}{2}S_a(f) \cong \frac{1}{4}\left(\frac{r_e}{r_e + R_s}\right)^2 \left(\frac{\Delta I_E}{I_E}\right)^2, \qquad (8)$$

are shown in columns B (5 MHz) and E (10 MHz). The measured and predicted values are within 3 dB. The measured PM noise sensitivities to current noise are shown in columns C (5 MHz) and F (10 MHz). These values do not change with frequency as expected from theory and are probably the result of AM to PM conversion in the mixer of the PM noise measurement system (which is usually between -15 and -25 dB) [3].

PM and AM noise due to ΔV_{CB} in a CB amplifier are given by

$$\frac{1}{2}S_\phi(f) \cong \frac{1}{4}\left(n\omega R_L \frac{C_{bc}}{(V_{bi} + V_{CB})}\right)^2 \Delta V_{CB}^2, \qquad (9)$$

$$\frac{1}{2}S_a(f) \cong \delta^2\left(\frac{1}{2}S_\phi(f)\right) \cong (\omega C_{bc} R_L)^2\left(\frac{1}{2}S_\phi(f)\right). \qquad (10)$$

The predicted and measured AM and PM noise sensitivities to voltage noise in the CB amplifier tested for carrier frequencies of 5 and 10 MHz are given in Table 4. Columns A ($\nu_o = 5$ MHz) and E ($\nu_o = 10$ MHz) show the measured PM sensitivities, and columns B ($\nu_o = 5$ MHz) and F ($\nu_o = 10$ MHz) show the predicted values. The measurements show an increase of 5 dB in the sensitivity when the carrier frequency was doubled. This is expected from theory which predicts that the PM noise (due to ΔV_{CB}) is proportional to ν_o^2, and thus it should increase 6 dB

Table 3. Sensitivities of AM and PM noise to baseband current noise in a linear CB amplifier for $I_E \cong 26$ mA and $V_{CB} \cong 7$ V. For these measurements the output power was adjusted to 9 dBm and $\gamma \cong 2.6 \times 10^{-4}$.

2N2222A	A	B	C	D	E	F
	5 MHz			10 MHz		
	AM sensitivities		PM sensitivities	AM sensitivities		PM sensitivities
Fourier	(dBc/Hz rel to $\gamma = 1$)			(dBc/Hz rel to $\gamma = 1$)		
frequency	Measured	Predicted	Measured	Measured	Predicted	Measured
100 Hz	-28.9	-32.5	-49.8	-30.0	-32.5	-50.3
50 Hz	-29.0	-32.5	-49.8	-29.8	-32.5	-50.0
20 Hz	-29.0	-32.5	-49.9	-29.6	-32.5	-49.9
10 Hz	-29.1	-32.5	-50.0	-29.7	-32.5	-49.2

Table 4. Sensitivities of AM and PM noise to ΔV_{CB} in a linear CB amplifier for $I_E \cong 26$ mA and $V_{CB} \cong 5.5$ V. For these measurements the output power was adjusted to approximately 4 dBm and $\Delta V_{CB} \cong 5 \times 10^{-4}$ $V_{rms}/\sqrt{Hz}$.

2N2222A	A	B	C	D	E	F	G	H
	5 MHz				10 MHz			
	PM sensitivities		AM sensitivities		PM sensitivities		AM sensitivities	
Fourier	(dBc/Hz rel to $\Delta V_{CB} = 1 V_{rms}/\sqrt{Hz}$)				(dBc/Hz rel to $\Delta V_{CB} = 1 V_{rms}/\sqrt{Hz}$)			
frequency	Measured	Predicted	Measured	Predicted	Measured	Predicted	Measured	Predicted
100 Hz	-50.6	-47.2	-59.6	-65.5	-45.6	-41.2	-50.0	-53.5
50 Hz	-50.5	-47.2	-59.8	-65.5	-45.6	-41.2	-50.0	-53.5
20 Hz	-50.6	-47.2	-59.8	-65.6	-45.7	-41.2	-50.0	-53.5
10 Hz	-50.5	-47.2	-59.4	-65.5	-45.8	-41.2	-50.1	-53.5

when the frequency is doubled. The predicted PM sensitivities, computed using Eq. (9) are within 4 dB of the measured values. The AM noise sensitivities to ΔV_{CB} are shown in columns C ($\nu_o = 5$ MHz) and G ($\nu_o = 10$ MHz). The sensitivity increased by 10 dB when the carrier frequency doubled. This agrees with theory which predicts an increase of 12 dB since $S_a(f) \propto \nu_o^4$. The predicted sensitivities (column D for $\nu_o = 5$ MHz; column H for $\nu_o = 10$ MHz), computed using Eq. (10) are within 4-6 dB of the measured values. At high output powers, the measured AM sensitivities showed some dependence on output power (with the sensitivity increasing as the output power increased).

4. AM AND PM NOISE SENSITIVITIES TO CURRENT AND VOLTAGE NOISE IN CC AMPLIFIER

Measurements of AM and PM noise sensitivities were also made on a linear common collector (CC) amplifier. In the CC amplifier tested the transistor used was a 2N2222A, $R_E \cong 69\ \Omega$, $r_g \cong 41\ \Omega$, $r_e \cong 1.2\ \Omega$, and $I_E \cong 23$ mA. The sensitivities of AM and PM noise to current noise are shown in Table 5. Columns A and D in Table 5 show the measured AM sensitivities to current noise at carrier frequencies of 5 MHz and 10 MHz, respectively. As expected, the measured sensitivities are independent of carrier frequency. The predicted values (columns B and E), computed using

$$\frac{1}{2}S_a(f) \cong \frac{1}{4}\left(\frac{r_e}{r_e + R_E + r_g/\beta}\right)^2 \left(\frac{\Delta I_E}{I_E}\right)^2, \qquad (11)$$

are within 5 dB of the measured sensitivities. This difference is probably due to errors in the values of r_e and R_E used for the computation (small errors in these parameters will cause significant errors in the predicted AM sensitivity). We noticed that at larger output powers [> 2 dB rel to 1 mW (dBm)] the AM sensitivity to current noise increased. This might be due the effect of the ac current i_e in the small signal emitter resistance r_e which was not taken into consideration in the calculations. The measured values of the PM noise sensitivities to current noise are shown in columns C ($\nu_o = 5$ MHz) and F ($\nu_o = 10$ MHz). These values do not show the expected dependence on carrier frequency ($S_\phi(f) \propto \nu_o^2$), and are probably the result of AM to PM conversion in the mixer of the PM noise measurement system.

Table 6 shows the measured and predicted sensitivities of AM and PM noise to ΔV_{CB}. The predicted values were computed using the equations

$$\frac{1}{2}S_\phi(f) \cong \frac{1}{4}\left(\frac{n\omega r_g[R_E + r_e]}{[r_e + R_E + r_g/\beta]}\frac{C_{bc}}{[V_{bi} + V_{CB}]}\right)^2 \Delta V_{CB}^2, \qquad (12)$$

$$\frac{1}{2}S_a(f) \cong \delta^2\left(\frac{1}{2}S_\phi(f)\right). \qquad (13)$$

The measured PM noise sensitivities to ΔV_{CB} are shown in column A ($\nu_o = 5$ MHz) and column E

(ν_o = 10 MHz). The predicted values, computed using Eq. (12), are shown in columns B and F. Even though there is a difference of 6 dB between the predicted and measured values, the measured sensitivities scale as ω^2, as predicted from theory. The AM sensitivities in this configuration are so small that the measurements were limited by the noise of the measurement system. Columns B and E show the measured AM sensitivities at carrier frequencies of 5 and 10 MHz respectively. The predicted values, shown in column D (ν_o = 5 MHz) and column H (ν_o = 10 MHz), are smaller than the measured sensitivities.

5. DISCUSSION AND CONCLUSION

We have presented results on measurements of AM and PM noise sensitivities to baseband current and voltage noise in three linear BJT amplifier configurations (CE, CB, and CC). As expected, the sensitivities are larger in configurations with larger gains and phase shifts (high gain CE amplifier). The measured sensitivities are generally in good agreement with the values predicted from theory. We showed experimentally that the AM sensitivity to current noise is independent of carrier frequency and independent of transistor used, while the AM sensitivity to voltage noise is a function of the carrier frequency ($S_a(f) \propto \nu_o^4$). The PM sensitivity to ΔV_{CB} increased with carrier frequency, approximately as ν_o^2. In addition, both the PM and AM sensitivities to ΔV_{CB} were smaller for transistors with smaller C_{bc}. Nevertheless the use of a transistor with small C_{bc} is not necessarily the optimum choice, since the intrinsic flicker noise of the transistor needs to be considered and it might be large for high frequency transistors. Also, the equations discussed here represent the magnitude of the up-conversion from low frequency 1/f noise to noise about the carrier. While these equations can be used to minimize the up-conversion factor, they do not provide insight on the magnitude of the low frequency 1/f noise of the amplifier. Some of the dc parameters of the amplifier and the type of transistor used play a role in the magnitude of the low frequency 1/f noise and should also be taken into consideration [2].

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Table 5. Sensitivities of AM and PM noise to baseband current noise in a linear CC amplifier for $I_E \cong 23$ mA and $V_{CB} \cong 9$ V. For these measurements the output power was adjusted to approximately 1 dBm and $\gamma \cong 4 \times 10^{-4}$.

2N2222A	A	B	C	D	E	F
	5 MHz			10 MHz		
	AM sensitivities		PM sensitivities	AM sensitivities		PM sensitivities
Fourier frequency	(dBc/Hz rel to γ = 1)			(dBc/Hz rel to γ = 1)		
	Measured	Predicted	Measured	Measured	Predicted	Measured
100 Hz	-36.3	-41.4	-69.9	-36.4	-41.4	-53.5
50 Hz	-36.4	-41.4	-69.7	-36.5	-41.4	-53.6
20 Hz	-36.4	-41.4	-69.5	-36.4	-41.4	-53.8
10 Hz	-36.4	-41.4	-69.6	-36.5	-41.4	-53.8

Table 6. Sensitivities of AM and PM noise to ΔV_{CB} in a linear CC amplifier for $I_E \cong 23$ mA and $V_{CB} \cong 6.8$ V. For these measurements the output power was adjusted to approximately 7 dBm and $\Delta V_{CB} \cong 7.7 \times 10^{-4}\ V_{rms}/\sqrt{Hz}$.

2N2222A	A	B	C	D	E	F	G	H
	5 MHz				10 MHz			
	PM sensitivities		AM sensitivities		PM sensitivities		AM sensitivities	
Fourier frequency	(dBc/Hz rel to $\Delta V_{CB} = 1 V_{rms}/\sqrt{Hz}$)				(dBc/Hz rel to $\Delta V_{CB} = 1 V_{rms}/\sqrt{Hz}$)			
	Measured	Predicted	Measured	Predicted	Measured	Predicted	Measured	Predicted
100 Hz	-75	-69.9	<-90.4	-108.5	-69.3	-63.9	<-88.6	-96.5
50 Hz	-74.8	-69.9	limited by	-108.5	-69.4	-63.9	limited by	-96.5
20 Hz	-74.9	-69.9	noise floor	-108.5	-69.5	-63.9	noise floor	-96.5
10 Hz	-74.8	-69.9		-108.5	-69.5	-63.9		-96.5