RELATIONSHIP OF AM TO PM NOISE IN SELECTED MICROWAVE AMPLIFIERS, RF OSCILLATORS, AND MICROWAVE OSCILLATORS*

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ABSTRACT

A study of AM and PM noise in microwave amplifiers, rf oscillators, and microwave oscillators was done to provide a basis for developing models for the origin of AM noise. We find that the 1/f and f^0 components of PM and AM noise in amplifiers and oscillators are often of equal magnitude, and that they probably have common sources, namely, a 1/f modulation of the gain element and thermal noise.

INTRODUCTION

To our knowledge there has been little quantitative work analyzing the relationship between amplitude modulation (AM) and phase modulation (PM) noise in amplifiers and oscillators. Most of the literature assumes that the AM noise is much smaller than the PM noise. We have therefore undertaken a detailed study of PM and AM noise in several microwave amplifiers, rf oscillators, and X-band oscillators to provide a basis for developing models for the origin of AM noise and its relationship, if any, to the PM noise.

To measure the noise in these devices we generally used two channel measurement systems with cross correlation spectrum analysis to reduce the noise contribution of the measurement process.[1] Based on this data we then suggest general noise models for these devices that include both AM and PM noise. The noise model for amplifiers is, to our knowledge, the first to show that the PM and AM noise added by an amplifier originates from two common sources. Specifically we show that for most of the amplifiers tested the 1/f (flicker) noise, which has always been assumed to be PM noise,[2] also produces AM noise of approximately equal amplitude. Thermal noise, the second source, also produces an equal amount of AM and PM noise. Our model for oscillators is also the first one to include both PM and AM noise. As in the amplifier case, we find that there is often 1/f and f^0 components of AM and PM noise of nearly equal amplitude. The AM noise and PM noise generally differ only at frequencies close to the carrier, where the PM noise varies as $1/f^3$ (flicker FM noise). In general the PM noise roughly follows the Leeson model.[3]

PM AND AM NOISE IN X-BAND AMPLIFIERS

A two channel measurement system with cross correlation spectrum analysis was used to measure the PM and AM noise of the amplifiers. The details of the measurement process have been discussed previously.[4] The results for PM noise in amplifier A are shown in Figure 1. This amplifier shows a 1/f behavior from approximately 1 Hz to 1 MHz from the carrier. Around 10 MHz from the carrier the PM noise is basically white at -173 dBc/Hz. The PM noise in this amplifier follows very closely Parker's PM noise model for linear amplifiers,[5] in which the spectral density of phase fluctuations, $S_\phi(f)$, is given by the expression

$$S_\phi(f) = \alpha_E \frac{1}{f} + \frac{2kTFG(f)}{P_o}, \qquad (1)$$

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where α_E is the flicker noise coefficient, k is Boltzmann's constant, T is the temperature in kelvins, F is the noise figure of the amplifier, G(f) is the gain of the amplifier, and P_o is the output power of the carrier signal from the amplifier.

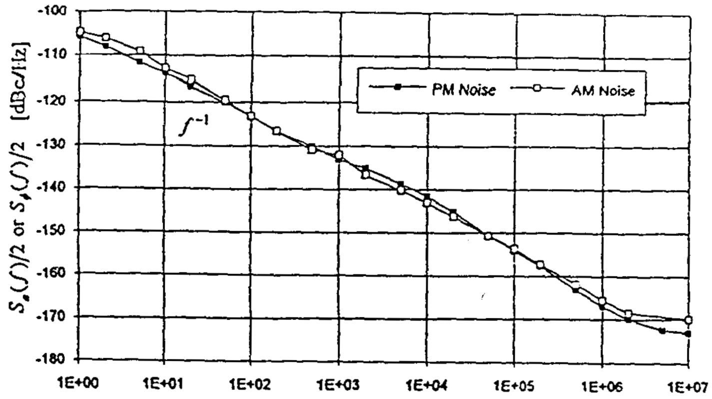

Figure 1. Single sideband AM noise $[S_a(f)/2]$ and PM noise $[S_\phi(f)/2]$ in amplifier A at 10.6 GHz.

The AM noise added by amplifier A, also shown in Figure 1, shows the same 1/f and white noise components as the PM noise. This suggests that the PM and AM noise of an amplifier originate from two common sources added to the signal. The 1/f component scales proportionally to the signal and the thermal component is independent of the signal. The AM noise for a linear amplifier is thus similar to the PM noise model given by Equation (1), that is,

$$S_a(f) = S_\phi(f) = \alpha_E \frac{1}{f} + \frac{2kTFG(f)}{P_o}. \tag{2}$$

The noise added by the rest of the amplifiers tested showed a similar behavior. Excess noise above the intrinsic flicker component, possibly caused by noise from the bias supplies in the amplifier, was observed in some samples.[4]

AM AND PM NOISE IN OSCILLATORS

PM and AM noise investigations in 5 MHz, 100 MHz and 10.6 GHz oscillators were made using two channel and three-corner-hat measurement techniques previously described.[4,6] Results from PM noise measurements in a 5 MHz oscillator, Figure 2, show three different power-law noise processes: flicker FM ($1/f^3$), flicker PM (1/f), and white PM (f^0). In general the PM noise follows the Leeson/Parker[3,5] PM noise model for oscillators given by

$$S_\phi(f) = \alpha_R {\nu_o}^4 (\frac{1}{f^3}) + \alpha_E {f_\tau}^2 (\frac{1}{f^3}) + \alpha_E (\frac{1}{f}) + \frac{2kTG(f)}{P_o}, \tag{3}$$

where the first term, characterized by α_R and the carrier frequency ν_o, is due to phase fluctuations in the resonator, the second and third terms are from the amplifier and the fourth term is the thermal noise of the amplifier.[5] The second term is usually negligible in quartz oscillators but may dominate in X-band oscillators. In some cases, depending on the noise and bandwidth of the resonator, there can be additional terms.[4,5]

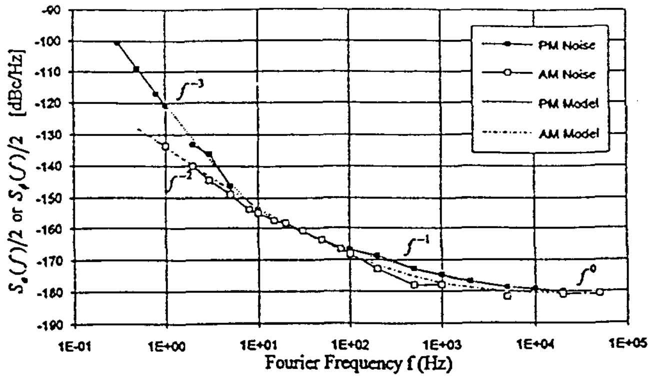

Figure 2. Single sideband AM noise $[S_a(f)/2]$ and PM noise $[S_\phi(f)/2]$ of a 5 MHz oscillator.

The AM noise in the 5 MHz oscillator, also shown in Figure 2, closely follows the PM noise from 10 Hz to 50 kHz. Thus, the flicker PM and the white noise processes seen in the PM noise are also part of the AM noise. At frequencies below 10 Hz, the AM noise exhibits a $1/f^2$ component not present in the PM noise. We believe this is caused by amplitude fluctuations in the amplitude control loop of the oscillator. As mentioned earlier the $1/f^3$ process observed in the PM noise is due to phase fluctuations in the resonator and thus is not expected in the AM noise. The AM noise of this oscillator can then be described by

$$S_a(f) = \beta(\frac{1}{f^2}) + \alpha_E(\frac{1}{f}) + \frac{2kTG(f)}{P_o}. \tag{4}$$

Figure 3 illustrates the PM and AM noise measured in a 100 MHz oscillator. The same noise processes observed in the PM noise of the 5 MHz oscillator (flicker FM, flicker PM and white PM) are present in this oscillator. In this specific case, the $1/f^3$ noise process was present in the 1 Hz - 500 Hz frequency range, while the 1/f was only observed from ≈ 1 kHz - 3 kHz. The AM noise is somewhat different since it only shows flicker PM and white PM noise. Although the AM noise is 1/f from 1 to 300 Hz, the level appears about 10 dB higher than we would predict based on the AM and PM noise at 3 kHz. The white FM noise observed in the 5 MHz oscillator is not present in this analysis range.

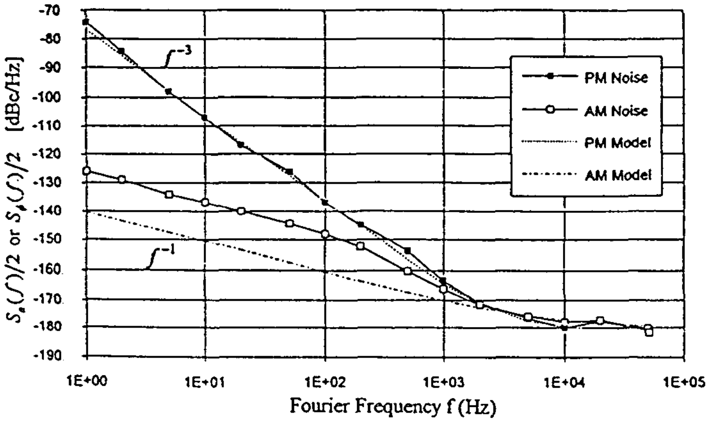

Figure 3. Single sideband AM noise $[S_a(f)/2]$ and PM noise $[S_\phi(f)/2]$ of a 100 MHz oscillator.

The PM noise in X-band oscillators showed similar characteristics to 5 MHz and 100 MHz oscillators. In general, all the X-band oscillators showed a $1/f^3$ component up to 1 MHz from the carrier. Figure 4 illustrates the PM noise in one of the 10.6 GHz oscillators tested. In this case the thermal noise is reached at approximately 100 MHz from the carrier. The AM noise, also shown in the figure, follows a 1/f behavior from 1 Hz to 500 Hz. Though excess noise is observed between 1 kHz and 1 MHz, it can be argued that the intrinsic AM noise behavior of the oscillator (excluding the excess noise) is 1/f until the thermal noise is reached. At high frequencies the two curves, AM and PM, converge to the thermal noise level.

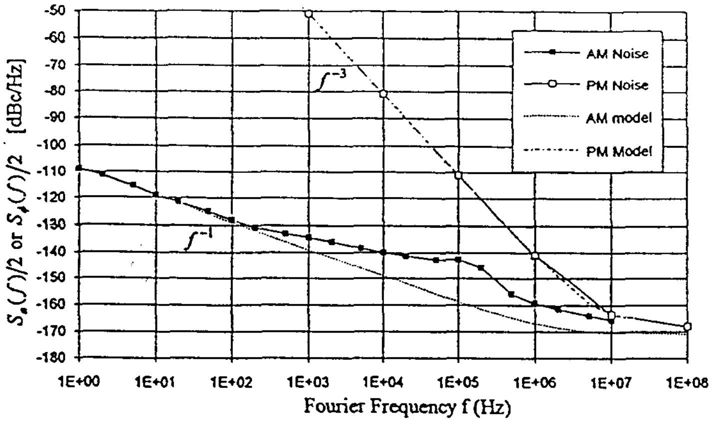

Figure 4. Single sideband AM noise $[S_a(f)/2]$ and PM noise $[S_\phi(f)/2]$ of a 10.6 GHz oscillator.

C●NCLUSI●N

The noise measurements in the amplifiers and oscillators tested indicate a strong relationship between AM and PM noise. In both amplifiers and oscillators, the AM and PM noise showed a flicker noise component (1/f) and a white noise (f^0) component of similar magnitude. These findings suggest that the AM and PM noise in amplifiers and oscillators have two common sources: a 1/f noise modulation of the gain element and a thermal noise component. In oscillators, the PM noise had an additional $1/f^3$ component close to the carrier caused by frequency fluctuations in the resonator.[5] In some cases the AM noise had a $1/f^2$ component probably due to amplitude fluctuations in the oscillator's amplitude control loop.

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REFERENCES

1. W.F. Walls, Proc. 46th Ann. Frequency Control Symp., pp. 257-261 (1992).
2. D.Halford, A.E.Wainwright & J.A.Borno, Proc. 22nd Ann. Frequency Control Symp., pp. 340-341 (1968).
3. D.B. Leeson, Proc. IEEE, Vol. #54, No. 1, pp. 329-330 (1966).
4. F.G. Ascarrunz, E.S. Ferre and F.L. Walls, Proc. 47th Ann. Frequency Control Symp. (1993), to be published.
5 T.E. Parker, Proc. 41st Ann. Frequency Control Symp., pp. 99-110 (1987).
6. L.M. Nelson, C.W. Nelson and F.L. Walls, Proc. 47th Ann. Frequency Control Symp. (1993), to be published.