Proceedings of the 2003 IEEE International Frequency Control Symposium and PDA Exhibition
Jointly with the 17th European Frequency and Time Forum

Noise Figure vs. PM Noise Measurements: A Study at Microwave Frequencies[1]

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Abstract - **This paper addresses two issues: (i) it compares the usefulness of phase-modulation (PM) noise measurements vs. noise figure (NF) measurements in characterizing the merit of an amplifier, and (ii) it reconciles a general misunderstanding in using –174 dBc/Hz (relative to carrier input power of 0 dBm) as thermal noise level. The residual broadband (white PM) noise is used as the basis for estimating the noise figure (NF) of an amplifier. We have observed experimentally that many amplifiers show an increase in the broadband noise of 1 to 5 dB as the signal level through the amplifier increases. This effect is linked to input power through the amplifier's nonlinear intermodulation distortion. Consequently, this effect is reduced as linearity is increased. It is important to note that NF is sometimes used as a selection criteria for an amplifier but yields no information about potentially important close-to-carrier 1/*f* noise of an amplifier, whereas PM and amplitude modulation (AM) noise measurements do. We have verified theoretically and experimentally that the single-sideband PM (and AM) noise floor due to thermal noise is –177 dBc/Hz, relative to a carrier input power of 0 dBm.**

I. INTRODUCTION

This paper addresses the appropriateness of "Noise figure" (NF) measurements in amplifiers in the presence of a carrier signal. NF is a common amplifier specification that is used to calculate the noise at Fourier frequencies f that are far from a carrier frequency v_0. In the presence of a carrier signal, the noise level near the carrier is no longer constant but often increases as f decreases. This increase usually changes at a rate of at least $1/f$, "flicker" behavior, which often significantly dominates over the white-noise level given by the NF, which in practice is measured in the absence of an actual signal through the amplifier. Furthermore, the flicker- noise level depends on the amplifier's linearity and input power. Because of this signal-induced rise in amplifier noise, many systems do not achieve the performance predicted by using the no-signal NF characterization.

The inherent near-DC noise of an amplifier, which is usually flicker noise, is up-converted and projected partially as PM noise and partially as AM noise onto the signal being amplified [1, 2]. It is this behaviour that significantly limits the performance of an amplifier used to amplify and/or distribute low-noise, spectrally pure oscillating signals designed as reference clocks for rf and digital systems. Most notably, timing jitter is often used to assess the limit of system performance, and an amplifier's merit under these circumstances is always better characterized by a PM noise measurements than by a NF measurement.

In the present paper we have derived an expression for NF in terms of single-sideband PM noise, which is given

$$\mathcal{L}(f) = N_{Th} + NF - P_{in} ,$$

where N_{Th} is the room temperature thermal noise and is equal to –177 dBm, P_{in} is the signal power in dBm and $\mathcal{L}(f)$ is the PM noise in dBc/Hz. This is the wideband PM noise floor of an amplifier. This result differs from that found in early literature [3, 4]. Though $\mathcal{L}(f)$ is represented as function of f, it has no frequency dependence, because the function is due to thermal noise.

We have extensively and carefully measured the phase noise $\mathcal{L}(f)$ of different low-noise amplifiers at 10 GHz under different conditions of input signal. We have observed that the NF derived from a measurement of PM noise is often 1 to 5 dB higher than that obtained with 0 input signal. We have also observed that some amplifiers with low NF do not have lower $1/f$ noise than those having a higher NF. We conclude that PM noise measurements are substantially more useful in characterizing an amplifier's noise than measurements of no-signal NF.

II. DERIVATION OF NOISE FIGURE FROM PM NOISE MEASUREMENT

To compute the NF based on PM measurements, let us start from the basic definition of the RF power spectrum of an oscillator's signal, given by

$$S_{RF}(f) = \frac{\mathrm{PSD}V_N(v_0 - f) + \mathrm{PSD}V_N(v_0 + f)}{V_0^2} \qquad (1)$$

where V_0 is the rms voltage level of the carrier, $\mathrm{PSD}V_N(v_0 \pm f) \equiv V_N^2\,(v_0 \pm f)$ is the power spectral density of the voltage noise at frequency $v_0 \pm f$, v_0 is the carrier frequency, and f is the Fourier frequency. Since the random RF noise is distributed equally between amplitude modulation (AM) and phase modulation (PM) noise, the PSD of just the PM noise, denoted as $S_\phi(f)$ in units of rad^2/Hz is half of $S_{RF}(f)$. Using the definition $\mathcal{L}(f)_{rad} \equiv ½\, S_\phi(f)$ [5, 6], one obtains

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$$L(\mathrm{f})_{rad} = \frac{\mathrm{PSD}V_N(\nu_0 - f) + \mathrm{PSD}V_N(\nu_0 + f)}{(4)V_0^2} \quad (2)$$

Referring to Fig.1, the expected voltage noise V_n of the oscillator's source resistance of 50 Ω is $\sqrt{4kTR\Delta f}$, where Boltzmann's constant k = 1.38 x 10^{-23} J/K, T is in Kelvins, R is resistance in ohms, and Δf is the bandwidth. The voltage noise appearing across the load resistance at the input of the amplifier under test is one-half of this source noise, or $\sqrt{kTR\Delta f}$ as shown in figure 1.

With Δf =1 Hz, the voltage noise is $\sqrt{kTR}$. Thus, V_N^2 = kTR can be regarded as the power spectral density PSDV_n(F).

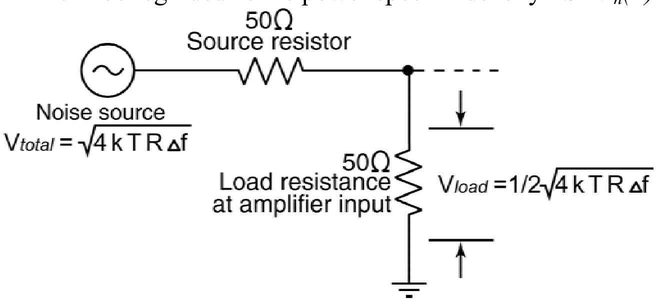

Fig 1. Equivalent input circuit showing the thermal noise generator with a source resistance of 50 Ω terminated with the amplifier's input (load) resistance, which is also 50 Ω. Note that the thermal noise voltage is divided in half at the amplifier's input (maximum power transfer theorem).

Substituting kTR into the expression for L(f) above yields

$$L(f)_{rad} = \frac{(2)\mathrm{kTR}}{(4)V_0^2} \quad (3)$$

$L(f)_{\mathrm{rad}}$ expressed in units of dBc/Hz is obtained here by computing 10log $L(f)_{\mathrm{rad}}$. For V_0 = 1 V_{RMS}, $L(f)$ = -190 dBc/Hz. Since one volt (rms) applied to 50 Ω corresponds to a power level of +13 dBm, $L(f)$ = -177 dBc/Hz, referenced to 0 dBm.

Using 0 dBm as the reference level, the room-temperature thermal-noise power relative to the signal power is simply -177 dBm – (P_{in}), where P_{in} is the signal power in dBm. The noise figure (NF) is the ratio (in dB units) of excess noise to thermal-noise power and the final formula (in terms of PM noise) is

$$L(f) = -177 + \mathrm{NF} - (P_{in}) \quad (4)$$

This is the wideband PM noise floor of an amplifier.

III. MEASUREMENT SYSTEM

To ensure that the noise contribution of the measurement system is much lower than the PM noise of an amplifier under test, a two-channel cross-correlation system for PM noise measurement is used [7, 8]. A block diagram is shown in figure 2. The two-channel system is comprised of two separate phase-noise measurements that operate simultaneously. Each is comprised of a power splitter, a phase shifter, and a mixer. The phase shifters establish true phase quadrature between two signals at the mixer inputs. The output (after amplification) of each mixer is fed to a two-channel cross-correlation fast Fourier transform (FFT) spectrum analyzer. The advantage of this technique is that only the coherent noise present in both channels averages to a finite value. The time average of the incoherent noise [7, 8] approaches zero as $N^{-1/2}$, where N is the number of averages. The measurement system has a PM noise floor of approximately L(10 Hz)= -140 dBc/Hz at a carrier frequency of 10 GHz. This noise level is much lower than the PM noise of the amplifiers under test that are the subject of this writing.

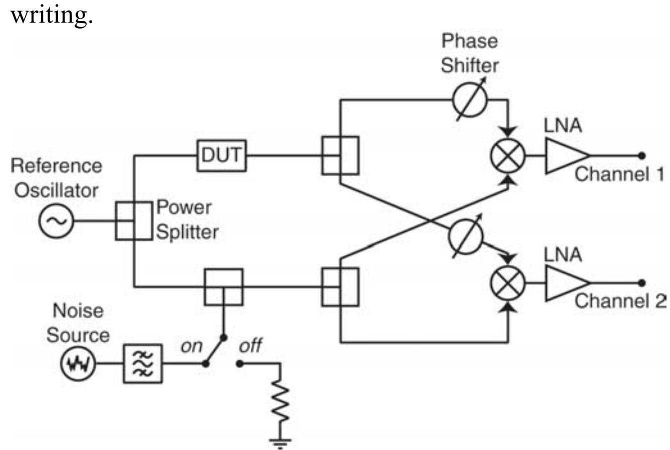

Fig 2. Block diagram of PM noise-measurement system for amplifiers. LNA is "low noise amplifier" and DUT is "device under test."

IV. EXPERIMENTAL RESULTS

We have measured the PM noise at 10 GHz of different amplifiers under different input conditions. Figure 3(a) shows the PM noise of a GaAs HEMFET amplifier as a function of Fourier frequency for different input power levels. For this particular amplifier, the broadband noise is higher for low input power, whereas 1/*f* noise is lower for low input power. It is apparent from figure 3(a) that white PM noise is not flat, there is a rise in the noise level close to *f* = 10 MHz. This is due to noise contribution of the FFT analyzer. It order to estimate NF from the experimental graph, a horizontal line has been drawn (shown in figure 3(a)) for each input power level and is considered as thermal noise level, $L(f)$. The NF of the amplifier is calculated from 177+P_{in}+$L(f)$, and its dependence on P_{in} is shown in figure 3(b). When the carrier power is low there is good agreement between NF measured with no carrier and NF measured with carrier. But, as the carrier power is increased there are discrepancies between two results. The calculated NF is higher by 2 dB when the amplifier is under 1 dB compression. This effect is due to nonlinear intermodulation processes inside the amplifier [1, 2]. Furthermore, figure 3(b) also shows the NF obtained using $174+P_{in}+L(f)$, yielding a negative NF, which is physically impossible. These observations confirm the derivation in section II that the thermal noise level is –177 dBc/Hz, rather than –174 dBc/Hz (referenced to 0 dBm).

Similar results are shown in figures 4(a) and 4(b) for a different GaAs FET amplifier having a NF of 1.5 dB. The results show that this amplifier shows an increase of the broadband PM noise of 1 to 3 dB as the signal level increases. In other words, the equivalent NF computed from *L* (*f*) is a function of input carrier power.

If this effect is due to nonlinear intermodulation processes, then it should be reduced in the case of a highly linear, low-distortion amplifier. We will test this hypothesis by measuring a feed-forward-type linear amplifier whose approach is shown in figure 5. The feed-forward configuration implements the technique of carrier suppression, which to a large extent reduces the effect of third order intermodulation [9, 10]. We have measured the PM noise of a commercially available feed-forward amplifier at 10 MHz. The results are shown in figure 6(a) and 6(b). Note that the 1/f noise of this amplifier is very low, due to the high linearity of the amplifier. The broadband noise is also relatively low in comparison to other commercially available amplifiers [10]. Figure 6(b) shows that there is very good agreement between NF with no carrier and NF with carrier, as long as carrier suppression is in effect in the amplifier. Furthermore, the observations with this linear amplifier once again confirm that the thermal noise level is –177 dBc/Hz referenced to 0 dBm.

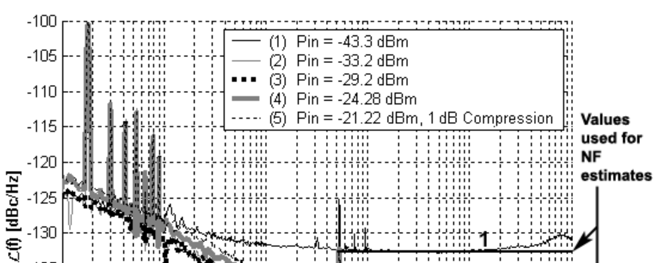

Fig 3(a). PM noise of GaAs HEMFET amplifier at different input power levels. Gain= 32.5 dB, NF= 1 dB, frequency= 10 GHz.

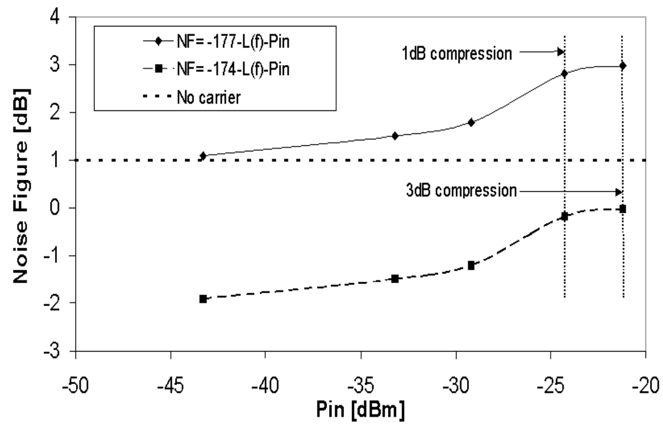

Fig 3(b). Variation of NF with input power for the amplifier in figure 3(a).

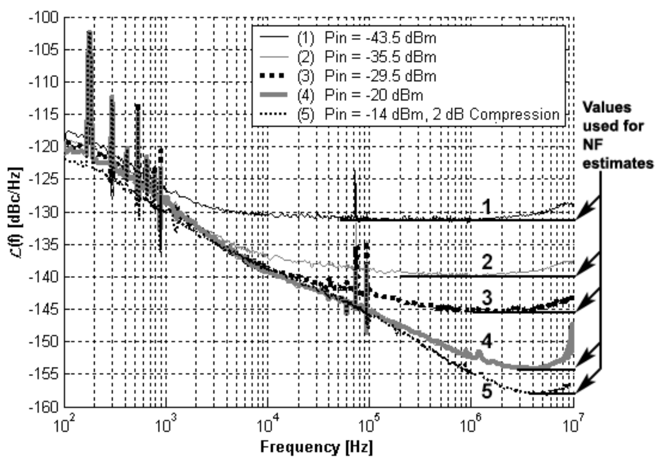

Fig 4(a). PM noise of GaAs FET amplifier at different input power levels. Gain= 35 dB, NF= 1.5 dB, frequency= 10 GHz.

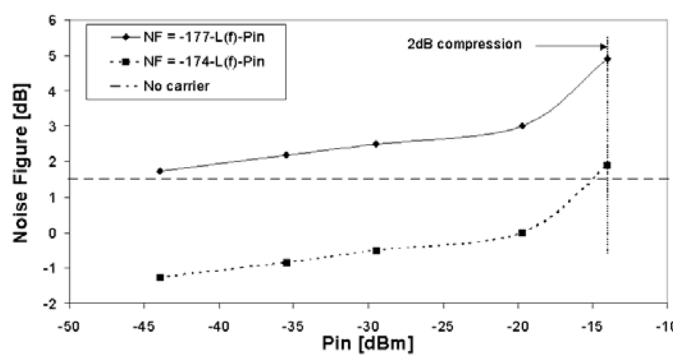

Fig 4(b). Variation of NF with input power for the amplifier in figure 4(a).

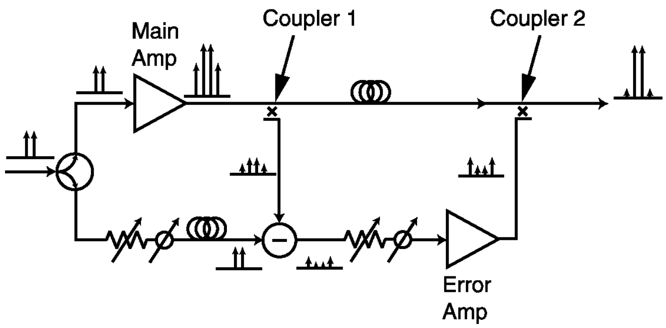

Fig 5. Block diagram of a feed-forward linear amplifier. Two-tone intermodulation byproducts are shown in the power spectra at various points in the diagram.

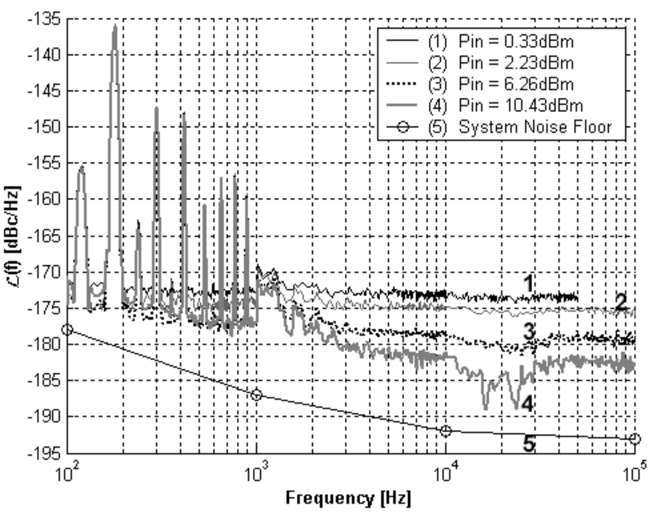

Fig 6(a). PM noise of a high-linearity feed-forward amplifier at different input power levels at 10 MHz. Gain= 12.5 dB, NF= 4 dB.

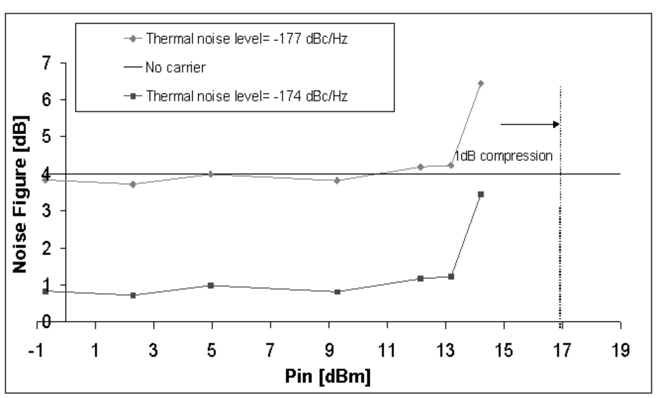

Fig 6(b). Variation of NF with input power for the amplifier in figure 6(a).

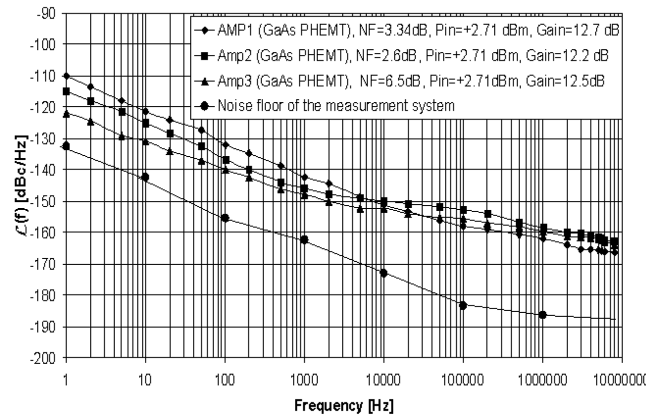

Fig 7. Variation of flicker noise of different amplifiers with Fourier frequency at 10 GHz.

Above results show that PM noise measurement is more accurate than NF measurement in estimating the NF of an amplifier. Another advantage of PM noise measurement is that it yields information about the flicker, $1/f$ noise of an amplifier whereas NF measurements do not, because NF is meaningful at Fourier frequencies f where phase noise is white. In order to support this fact we measured the PM noise of different amplifiers. Figure 7 shows the flicker noise of three different amplifiers under the same input conditions but having different NF's. All three are GaAs FET amplifiers. In these examples, note that the amplifier with highest NF of 6.5 dB has the lowest 1/f noise, almost 7 to 10 dB lower than the others. Contrary to popular belief, it is impossible to predict the 1/f PM noise level of an amplifier based on its NF.

V. CONCLUSIONS

We have extensively and carefully measured the phase noise $L(f)$ of different low-noise amplifiers at 10 GHz under different input signal conditions. It has been observed that the NF of an amplifier is a function of both carrier power and nonlinear intermodulation distortion. As the linearity of an amplifier increases NF is less dependent on carrier power. We find that the NF obtained from a PM noise measurement is often higher by 1 to 5 dB than NF obtained in a conventional manner. We conclude that PM noise measurements are substantially more useful in characterizing an amplifier rather than attempting to guess PM noise from NF measurements. It has also been shown theoretically as well experimentally that in the presence of a carrier, thermal noise level is –177 dBc/Hz referenced to 0 dBm.

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