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INVESTIGATIONS OF AM AND PM NOISE IN X-BAND DEVICES*

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Abstract

In this paper we report on measurements of phase modulation (PM) and amplitude modulation (AM) noise in a variety of amplifiers, dielectric resonator oscillator (DRO) sources and mixers at 10.6 GHz. There is little information on AM noise and only limited information on PM noise in microwave devices. Two channel measurement systems and cross-correlation analysis were used in these noise measurements. In amplifiers there are at least two random noise processes that generate equal levels of PM and AM noise when the amplifier is in the linear operating range. The noise processes correspond to a flicker noise process and a white noise process. In the DRO sources we show that these noise mechanisms are present in the active components and determine the AM and PM characteristics of the oscillator. We suggest a noise model for oscillators incorporating Leeson's PM noise model and a model for AM noise in which the active components have 2 common random noise processes. We report AM noise levels of 140 dB below the PM levels at 1 Hz and typical noise floors of -169 dBc/Hz at 10 MHz. We have no evidence for AM to PM conversion in these sources. We report on noise residuals in mixers from three different companies. Typical 1 Hz intercepts vary from -110 to -127 dBc/Hz. Noise floors are typically ~ -173 dBc/Hz. Cross-correlation techniques can be used to lower this value to below -190 dBc/Hz.

I. Introduction

In this paper we report on the measurement of amplitude modulation (AM) and phase modulation (PM) noise in a variety of X-band double balanced mixers, amplifiers and DRO oscillators. There is little information of AM and PM noise in these devices, and this information is critical for the design of many microwave systems and measurements. These measurements are meant to be a beginning for characterizing microwave components and developing noise models. The measurement techniques outlined here permit us to measure the residual noise in virtually any present X-band device. Clearly there are thousands of models available on the market, some of which probably have lower noises than the models tested. Since only 1 or 2 samples were tested, we cannot be certain that these results are typical of these models nor should the inclusion of a model in this study imply that it is the best for this use. The models chosen for this study were those that happened to be available in the laboratory.

To measure the noise in these devices we generally used a two channel measurement system with cross-correlation or, more accurately cross-spectrum analysis to reduce the noise contribution of the measurement process [1-3]. On the basis of these data we then suggest general noise models for these devices that include both AM and PM noise. Specific samples often deviate from the models, but they still give us a better insight into the total noise process within the device. The noise model for X-band double balanced mixers is similar to that of rf mixers [4,5]. The noise models for amplifiers are, 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 noise, which has always been assumed to be only PM noise [6,7], also produces AM noise of approximately equal amplitude. Our models for oscillator noise are among the first to include both PM and AM noise. As in the amplifier case, we find that there is often a 1/f component of AM and PM noise of nearly equal amplitude. Close to the carrier the $1/f^3$ PM noise dominates as is generally accepted [2,4,8]. There has been speculation that PM to AM conversion with the oscillator would cause the AM noise close to the carrier to vary as $1/f^3$. We have not been able to observe this conversion in the oscillators tested. We present a model that suggests a relationship between the PM noise and AM noise in oscillators. The PM noise roughly follows Leeson's Model.

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II. PM and AM Noise in X-Band Amplifiers

This section discusses PM and AM noise measurements and characterization of commercial GaAs FET amplifiers designed for 10-11 GHz frequency range. All measurements were made with the amplifiers operating in the linear region.

A. PM Noise:

The two channel measurement system shown in Fig. 1 was used to measure the PM noise added by various amplifiers [1,3]. In this configuration the oscillator signal is split into two channels, and the amplifier under test is placed in one of the channels. Each channel is split again and fed into two phase noise detectors, composed of a phase shifter and a double-balanced mixer. The phase shifters are adjusted so that there is a 90^o phase difference between the input signals (the signals are in quadrature). At this point the output of each mixer is proportional to the phase fluctuations between the input signals to the mixer. The signal is then low pass filtered, amplified, and fed into a two-channel cross-correlation FFT signal analyzer. Calibration of mixer sensitivity and amplifier gain can be performed by adding a known level of wideband Gaussian noise and measuring the power spectral density in the FFT [9].

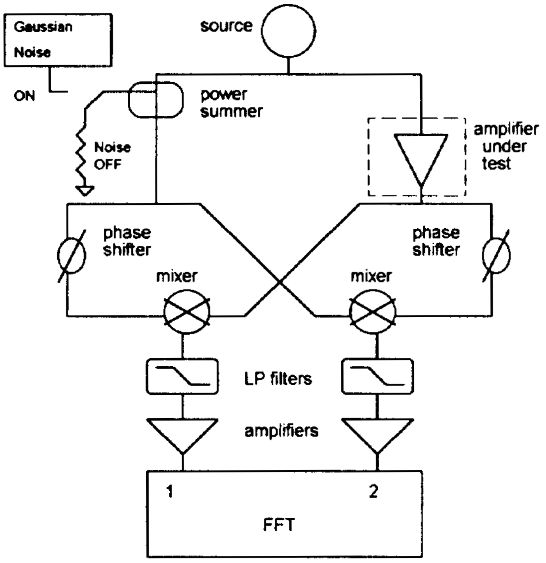

Figure 1. PM Noise Measurement System for Amplifiers

The calibrated gain of each channel ($k_dG(f)$) is obtained from the equation

$$PSD(V_n)_{noise\,ON} = PMCAL(k_dG(f))^2, \qquad (1)$$

where PMCAL is the calibrated PM noise added to the system, k_d is the mixer sensitivity to phase fluctuations, and G(f) is the gain of the output amplifier. Three different spectral density functions are obtained from the FFT signal analyzer: the power spectral density of channel 1 (PSD(V_{n1})), the power spectral density of channel 2 (PSD(V_{n2}) and the power spectral density of the cross-spectrum of the two channels PSD(V_{n1} X V_{n2}) (where X denotes cross-spectrum). PSD(V_{n1}) includes the PM noise of the amplifier under test in addition to the noise added by the mixer and amplifier in channel 1. Similarly, PSD(V_{n2}) includes the PM noise of the amplifier under test in addition to the noise added by the mixer and amplifier in channel 2. PSD(V_{n1} X V_{n2}) includes only the coherent noise between the two channels, that is, the PM noise of the amplifier. The uncorrelated noise added by each channel is averaged away as $N^{-1/2}$, where N is the number of averages taken by the FFT. Eqs. (2), (3), and (4) summarize these relations:

$$PSD(V_{n1}) = (k_dG(f))^2[PM_{amp} + System_1] \quad (2)$$

$$PSD(V_{n2}) = (k_dG(f))^2[PM_{amp} + System_2] \quad (3)$$

$$PSD(V_{n1}XV_{n2}) = (k_dG(f))^2 PM_{amp}. \qquad (4)$$

The noise floor of the system, given by PSD(V_{n1} X V_{n2}) when the amplifier under test is taken out of the system, is shown in Fig. 2. The figure also illustrates the PM noise of two X-band amplifiers. The PM noise of these amplifiers is at least 15 dB higher than the noise floor of the system throughout most of the frequency range (from 10 Hz to 10 MHz). The PM noise of various amplifiers is illustrated in Figs. 3 and 4. Amplifier 1, shown in Fig. 3, has a 1/f (flicker) PM noise component from approximately 1 Hz to 1 MHz from the carrier. Around 10 MHz from the carrier, the PM noise is white at -173 dBc/Hz. This white noise originates from the thermal PM noise of an amplifier [4,5] given by the expression

$$S_{\phi,thermal}(f) = \frac{2kTFG(f)}{P_o}, \qquad (5)$$

where k is Boltzmann's constant, T the temperature in degrees kelvin, F the noise figure of the amplifier, G(f) the gain of the amplifier, and P_o the output power of the amplifier. For this amplifier the noise figure is ~3 dB, the gain 16 dB, and the output power 18 dBm; therefore,

$$S_{f,\mathrm{thermal}} = -173.9\ \mathrm{dBc/Hz} + 3\ \mathrm{dB} + 16\ \mathrm{dB} - 18\ \mathrm{dB}$$

$$S_{f,\mathrm{thermal}} = -172.9\ \mathrm{dBc/Hz}.$$

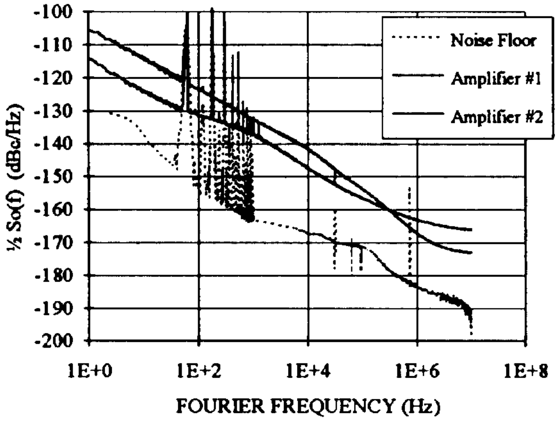

Figure 2. Noise floor of PM Measurement System.

This calculated value is almost equal to the thermal noise obtained from the PM curve in Fig. 3. Hence, amplifier 1 follows very closely Parker's PM noise model for amplifiers [4,5], in which the spectral density of phase fluctuations, $S_\phi(f)$, is given by

$$S_\phi(f) = \alpha_E \frac{1}{f} + \frac{2kTFG(f)}{P_o}. \qquad (6)$$

The first term is flicker PM noise, characterized by the flicker noise coefficient α_E, and the second term is one half the thermal (or Johnson) noise of the amplifier. α_E depends on both the gain element and the circuit configuration [6]. Fig. 4 shows the PM noise of amplifier 2. Although excess noise is observed at certain frequencies, throughout most of the frequency range the PM noise exhibits a 1/f dependence. At 10 MHz the PM noise reaches the white noise level. It is likely that the intrinsic noise of this amplifier (excluding the excess noise) follows the model presented by Eq. (6). The excess noise above the intrinsic flicker component may be caused by noise from the bias supplies in the amplifier.

B. AM Noise

The AM noise added by the amplifiers was measured using the two-channel measurement system schematically shown in Fig. 5 [1-3]. In this configuration, a carrier signal (split into two) is fed into two similar channels for AM noise detection. Each channel contains an AM noise detector, a low pass filter and an amplifier. The AM noise detector consists of a power splitter, a phase shifter and a double-balanced mixer. The phase shifter is set so that the input signals to the mixer are in phase ($\Delta\phi=2\pi n$). At this point the output voltage of the mixer is proportional to the amplitude fluctuations of the input signals. The PM noise suppression obtained in this system was very high, exceeding 140 dB at 1 Hz. The AM system includes the option of adding Gaussian noise to one of the channels, as discussed earlier in the PM noise section. Since added noise contributes equally to both AM and PM, the calibration method for the AM measurement system is similar to the calibration method for the PM measurement system discussed previously. The amplifier under test is added to one of the channels, ahead of the AM detector. The

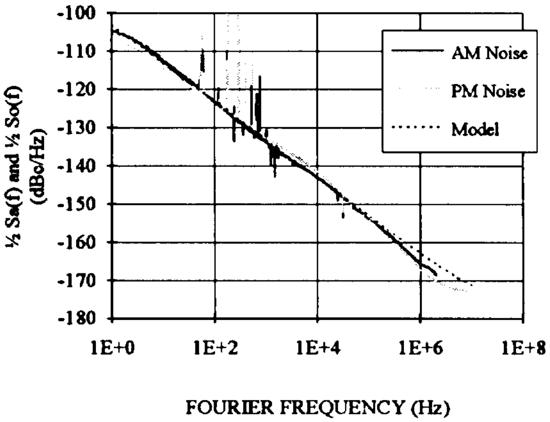

Figure 3. AM and PM Noise in Amplifier #1.

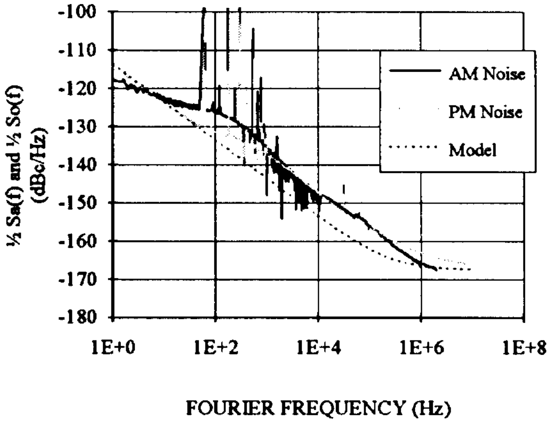

Figure 4. AM and PM Noise in Amplifier #2.

PSD of this channel, measured by the FFT, includes AM noise from the source, AM noise added by the amplifier under test, and noise from the AM detector

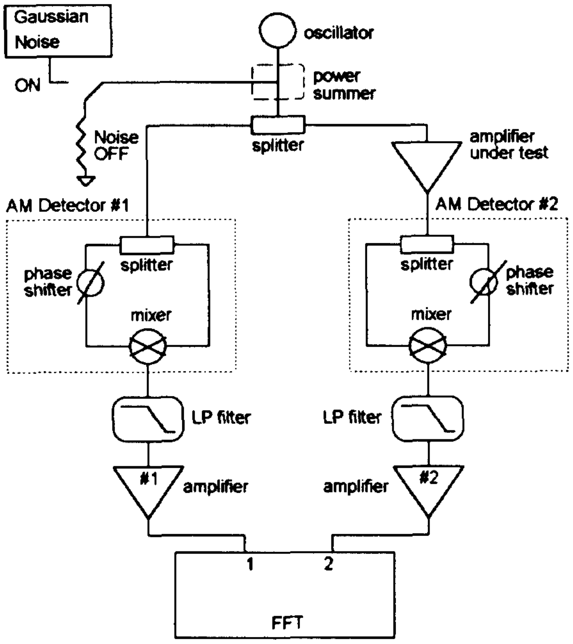

Figure 5. AM Noise Measurement System for Amplifiers.

and IF amplifier (Eq. (8)). The PSD of the other channel (when the Gaussian noise is OFF) includes AM noise from the source, and noise added by the AM detector and IF amplifier (Eq. (7)). The cross-spectrum of the two channels consists of the noise coherent or common to the two channels, that is, the source noise. The uncorrelated noise added by detectors and IF amplifiers is averaged away as $N^{-1/2}$, where N is the number of averages in the FFT signal analyzer. $PSD(V_{n1})$ - $PSD(V_{n2})$, the difference between spectral densities of the two channels, includes AM noise from the amplifier plus noise from channel 1 minus noise from channel 2 (Eq. (9)). Since the noise added by the channels is subtracted, $PSD(V_{n1})$ - $PSD(V_{n2})$ is a good measure of the AM noise added by the amplifier under test. Eqs. (7-10) summarize these relations.

$$PSD(V_{n1}) = (k_d G(f))^2 [AM_{Source} + System_1], \quad (7)$$

$$PSD(V_{n2}) = (k_d G(f))^2 [AM_{Source} + AM_{Amp} + System_2], \quad (8)$$

$$PSD(V_{n1}) - PSD(V_{n2}) = (k_d G(f))^2 [AM_{Amp} + System_1 - System_2], \quad (9)$$

$$PSD(V_{n1} X V_{n2}) = (k_d G(f))^2 AM_{Source}. \quad (10)$$

The noise floor of the measurement system is obtained from $PSD(V_{n1})$ -$PSD(V_{n2})$ when the amplifier under test is not in the system. Results from this measurement are illustrated in Fig. 6. Also included in the figure are AM noise results of two sample amplifiers. The noise floor of the system is at least 15 dB lower than the AM noise of the sample amplifiers from 10 Hz to 10 MHz.

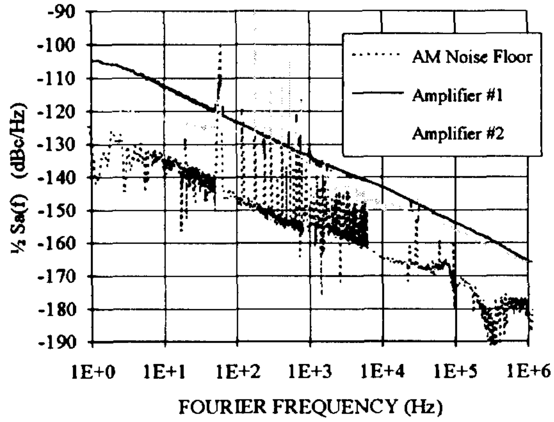

Figure 6. Noise Floor of AM Measurement System.

AM noise for amplifiers 1 and 2 is compared with their PM noise in Figs. 3 and 4. In both amplifiers the AM noise is comparable in value to the PM noise. In amplifier 1 the AM noise shows the same 1/f and white noise components as the PM noise. In amplifier 2, the AM noise closely follows the PM noise at most frequencies and shows the excess noise observed in the PM noise. These results suggest that the PM and AM noise of an amplifier originate from two common sources added to the signal, a 1/f modulation of the gain element and thermal noise. The 1/f component scales proportionally with the signal and the thermal component is independent of the signal level. Thus, the AM noise of a linear amplifier is the same as the PM noise given in Eq. (6); that is,

$$S_a(f) = S_\phi(f) = \alpha_E \frac{1}{f} + \frac{2kTFG(f)}{P_o}. \quad (7)$$

III. PM and AM noise in DRO Oscillators

In this section we apply the model for PM and AM noise presented in the previous section to the case where the amplifier is used as a feedback element in an oscillator. We compare the model to measurement data on commercial DRO sources operating at 10.6 GHz.

A. AM and PM Model for DRO Oscillators:

The noise characteristics of dielectric resonator oscillators (DRO) are necessarily dependent on the noise characteristics of the components that make up the oscillator. As a minimum an oscillator consists of a passive resonator and an active feedback element or amplifier. Some oscillators also contain a buffer or power amplifying stage. In the following discussion we will consider the case of an oscillator without the buffer or amplifying stage.

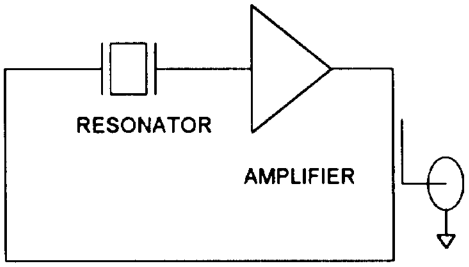

Figure 7. Oscillator Model

The open loop noise characteristics of resonators are not well understood, and a discussion of the subject is beyond the scope of this paper. However, measurements indicate that both the frequency and phase fluctuations across a resonator follow a 1/f power law. The frequency and phase fluctuations are given by Eq. (8) where α_R characterizes the resonator noise and Q_L is the resonator loaded quality factor:

$$S'_\phi(f) = (4Q_L)^2 S_y(f) = \left[\frac{\alpha_R}{f}\right]. \qquad (8)$$

The open loop noise characteristics of an amplifier as described in Section II B, suggest that two random processes produce equal amounts of AM and PM noise when the device is in a linear operating range. Since an amplifier is an integral part of an oscillator we expect these processes to be generating AM and PM noise in the oscillator. The open loop expression for the AM and PM noise in the amplifier is given by Eq. (7).

When the loop is closed, the conditions for oscillation are that the phase around the loop be an integer of 2π and that the gain be equal to the losses around the loop (G=1). Leeson derived the equation for the phase noise of the oscillator when the restriction on the phase is imposed [8]. The closed loop PM noise is given by

$$\begin{aligned} S_\phi(f) = {} & \left(\frac{\upsilon_o}{2Q_L}\right)^2 \frac{1}{f^2}\left[\frac{\alpha_{A1}}{f} + \frac{2kTF_1G_1}{P_1}\right] \\ & + \left[\frac{\alpha_{A1}}{f} + \frac{2kTF_1G_1}{P_1}\right] \\ & + \left(\frac{\upsilon_0}{2Q_L}\right)^2 \frac{1}{f^2}\left[\frac{\alpha_R}{f}\right] \end{aligned}, \qquad (9)$$

where ν_0 is the carrier frequency, Q_L the loaded quality factor of the resonator and f is the offset frequency from the carrier. P is the power output of the amplifier and G is the gain of the amplifier. Inside the bandwidth of the resonator, the frequency of oscillation must vary so that the phase changes around the loop are an integral multiple of 2π [8]. Therefore the flicker phase noise of the amplifier and resonator determine the flicker frequency noise of the oscillator. Likewise the thermal noise floor of the amplifier determines the white frequency noise of the oscillator and its thermal noise floor as well.

The AM noise of the oscillator is generated by the amplifier. There is no evidence for the generation of AM inside the oscillating loop or an AM component generated by the resonator. Therefore the AM noise in the oscillator is given by Eq. (10) if the amplifier is operating linearly. In most DROs this is not the case. The open loop gain of the amplifier is usually much greater than one. This excess gain is designed into the oscillator to ensure oscillation over temperature variations or imperfections in the gain elements. The steady state gain of one is achieved by limiting in the amplifier after a particular power level is reached or by an active form of gain control. When limiting occurrs we can approximate the AM noise at the output by Eq. (11).

$$S_A(f) = \left[\frac{\alpha_E}{f} + \frac{2kTF_1G_1}{P_1}\right] \qquad (10)$$

$$S_A(f) = \frac{1}{C}\left[\frac{\alpha_E}{f} + \frac{2kTF_1G_1}{P_1}\right], \qquad (11)$$

where C is the gain compression in the amplifier. Some investigators have reported a degradation of the PM noise performance in amplifiers that are operating non linearly [4]. In this case Eq. (9) does not hold. We also expect a degradation of the PM noise in oscillators with feedback amplifiers operating non-linearly. Since both the AM and PM noise components of the amplifier come from the same source, the AM and PM noise of the oscillator is characterized by α_E, the flicker noise parameter and the thermal or Johnson noise. The noise in the dielectric resonator is probably smaller than the noise contributed by the amplifier in the DRO [10]. We can conclude that the AM and PM noise of the oscillator is solely determined by the noise processes in the amplifier and the loaded Q of the resonator. Resonators with high Q and high loop power will have low flicker frequency noise and low thermal noise floors.

B. Noise Measurements on DRO Oscillators:

We used two different methods to measure the PM noise in the DRO sources. For Fourier frequencies of 1 Hz to 100 kHz, we used the cavity discriminator method (for a detailed explanation see [11]). For Fourier frequencies of 10 kHz to 100 MHz we used the two oscillator measurement method. For the two oscillator measurements we used a very low noise reference at 10.6 GHz and the NIST automated phase noise measurement system [11]. The noise floor of the system is -172 dBc/Hz at 20 MHz for an input power of +16 dBm. The AM noise measurements were done using the two channel cross-correlation system shown in Fig. 5 without the amplifier. Dual balanced mixers were used as AM detectors by setting the phase of the input signals to zero degrees [4]. The noise floor of the AM measurement system was -190 dBc/Hz at 10 MHz for an input power of +16 dBm. We measured the AM and PM noise in 5 DRO's that were readily available in the laboratory. The operating frequency of these oscillators is 10.6 GHz and the output power varies between +13 dBm and +24 dBm. For modeling, we used a loaded Q of 1000 as specified by the manufacturer for one brand of DROs. The AM and PM noise measured for DRO 1 is illustrated in Fig. (8). We can indirectly estimate α_E for the amplifier and the thermal noise parameter of the oscillator from the AM or PM noise measurement. The dashed lines indicate the AM and PM noise predicted by the model if we use the AM noise data to estimate α_E and the thermal noise floor. The measured noise data from oscillator 1 does not match our model very well. Notice that the PM noise floor is about 6 dB higher than the AM noise floor. It is likely that the amplifier is operating under 6 dB of compression. If we assume 6 dB compression and recalculate our model we obtain a very good fit (Fig. 9). If we use the PM noise data we can get an estimate of

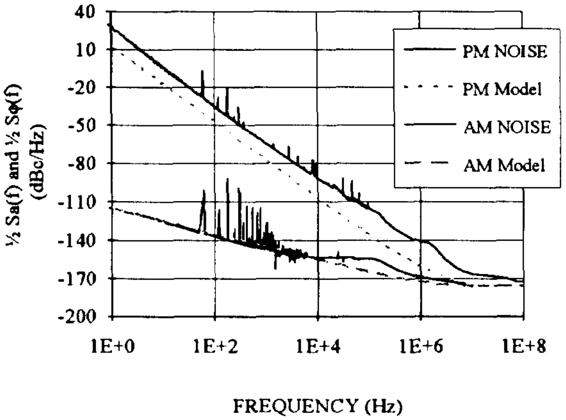

Figure 8. AM and PM Noise in DRO 1.

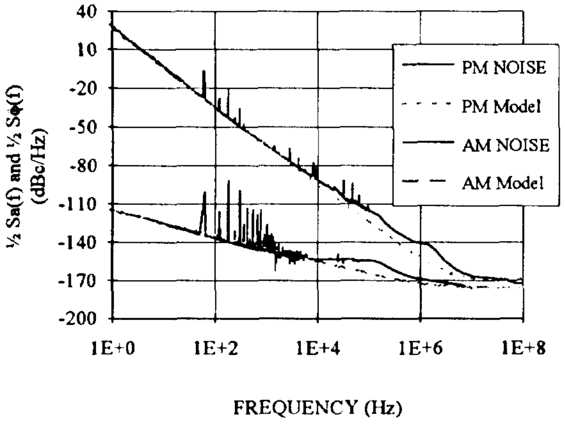

Figure 9. AM and PM Noise in DRO 1.

α_E and the thermal noise. However we can predict the AM noise performance of the oscillator only for the linear case unless the magnitude of compression occurring in the amplifier is known. There is an additional noise source that the model does not account for. Both the AM and PM noise of the DRO 1 (Fig. 9) deviate from the model at Fourier frequencies of 10 kHz to 1 MHz. We believe that this noise is caused by excess noise in the FET bias circuitry. It contributes to both the AM and PM noise in the source.

In DRO 2, Fig. (10) we see the same noise characteristics seen in the previous source. The extraneous noise affects both the AM and PM noise, and the amplifier is self limiting or compressing. The difference between the AM thermal noise floor and the PM noise floor indicate at least 8 dB of compression in the amplifier. Adjusting the model for this amount of compression results in a good fit of the model to the data Fig. (10).

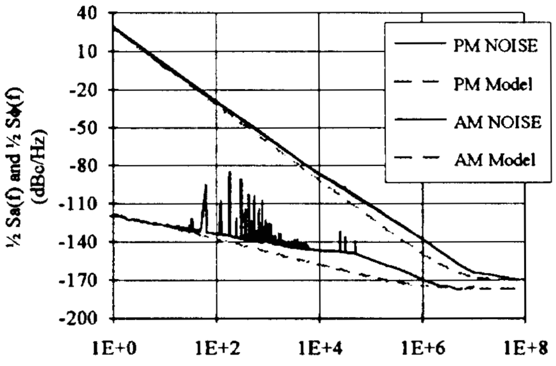

Figure 10. AM and PM Noise in DRO 2.

The same processes that generate AM noise in oscillators also determine the characteristics of the PM noise. We did not observe any PM to AM conversion in any of the oscillators even though the PM noise at 1 Hz from the carrier was over 140 dB higher than the AM noise. To reach a better understanding of these noise processes, we need to start characterizing both the AM and PM noise in these devices. In the past, the AM noise has been considered negligible; while this is true in oscillators at frequencies close to the carrier, the AM noise characteristics are still an important piece of the puzzle. Other noise processes can degrade the AM and PM noise characteristics in oscillators and amplifiers. Minimizing these noise processes can lead to better oscillators.

IV. Residual Noise in Mixers

In this section we discuss the residual noise in mixers. Mixers are a basic building block for many systems. The characterization of noise residuals in mixers is important, especially in measurement system applications where the residual noise in mixers can be the noise floor of the system.

Both PM and AM noise residual measurements were done on two pairs of mixers. In general the residual noises in mixers have two components. There is a 1/f component at low Fourier frequencies and a thermal noise floor. The levels of these noise processes are dependent on a variety of environmental factors, the drive powers, vswr, and the isolation in the mixer [12]. We were not able to draw any conclusive model but we can show some of the limiting factors of the noise performance. The PM residual measurements were done using a DRO at 10.6 GHz with known AM and PM characteristics. The signal was split in a reactive power splitter and one signal was phase shifted to obtain a 90^{0} phase difference between the two mixer inputs. The input powers on the LO and RF ports were + 13 dBm. The same hardware setup was used in the AM residual measurements except that the phase between the mixer input ports was set at a multiple of 2 π. The powers at the mixer inputs were +10 dBm. Dual channel measurements were done on two pairs of mixers to try to separate the mixer residuals from other system noise. A comparison of the PM residuals in four different mixers is shown in Fig. 11. The 1/f component of the residual varies as much as 8 dB in these four different mixers. We think that part of this 1/f noise is due to AM to PM conversion occurring in the mixer. The AM noise levels of our source follow a 1/f power law with a 1 Hz intercept at -115 dBc/Hz. The noise floor of our IF amplifier is about -173 dBc/Hz. As shown in the Figs. 11,12 the noise floor of the mixers could possibly be lower than -173 dBc/Hz, but we cannot measure it with the present scheme. A two channel measurement system with real time cross-spectrum analysis capability is useful in separating

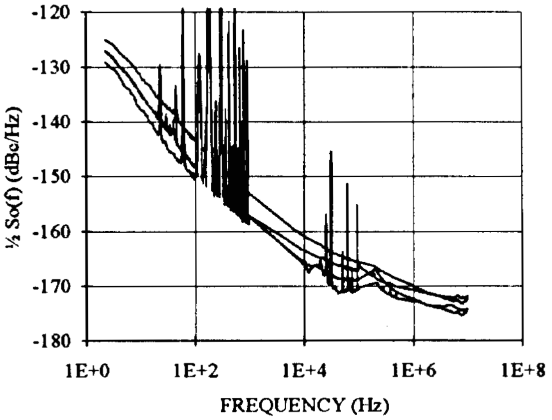

Figure 11. PM Noise Residuals in Various Mixers

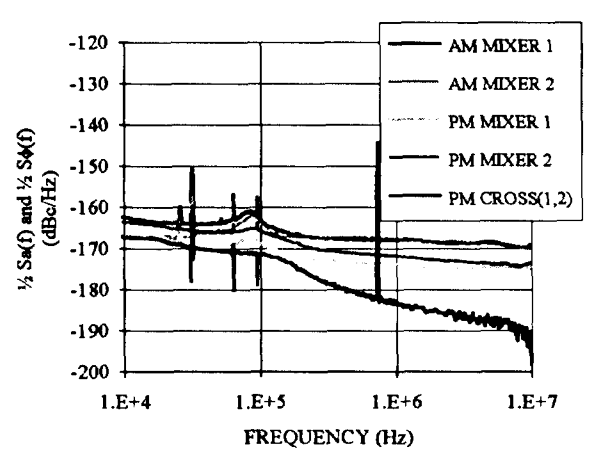

Figure 12. AM and PM Residual Noise in Mixer 12-18B

system noise from the residual noise measurement. The power spectral density of the cross-spectrum will contain only the coherent noise terms. The uncorrelated noise such as the noise generated in the mixers and the IF amplifiers will average down as $N^{-1/2}$, where N is the number of averages. Fig. 12 shows the PSD of the two mixers and the PSD of the cross-spectrum. The number of averages was 10 000, so the expected uncorrelated noise suppression is 20 dB. The cross-spectrum measurement indicates that for most of the frequency range the residual noise is not coherent in the two channels and probably is due to noise contributions by the mixers and the IF amplifiers. The AM residuals in the mixer can be obtained from two channel measurements. The power spectral density of channel 1 (Eq. (7)) minus the power spectral density of the cross-spectrum (Eq. (10)) will result in the residual noise in the mixer and the noise in the amplifier Fig. 12. There are limitations to how well you can determine residual noise from mixers. The limitations for PM single channel measurements are the noise floor of the IF amplifier following the mixer and the level of the AM noise in the source. Typically we have found the suppression of AM in mixers to be about 15-22 dB. The AM levels in the source do not average away as $N^{-1/2}$ in two channel cross-spectrum measurements since it is coherent between the two channels. The AM residual noise in a mixer cannot be measured without using a two channel measurement system because there is no way to sort out the noise contributions of the IF amplifier or the AM noise of the source. For both system calibration and actual AM or PM measurements it may be critical to measure both the AM and PM noise in the sources to be able to accurately interpret the measurement data.

V. Conclusion

There is a thermal noise source and a flicker noise source that generate equal levels of AM and PM noise in a linear amplifier. The thermal noise has been well characterized but the flicker noise source is still not understood. In summary, the PSD of the output voltage of an amplifier can be expressed by the following equation, where $\delta(\nu_0)$ is the carrier.

$$S_V(f) = \frac{V_o^2}{2}\left[\delta(\nu_o) + \frac{2\alpha_E}{f} + \frac{4kTFG(f)}{P_0}\right] \quad (8)$$

The thermal noise contribution of the amplifier, $4kTFG(f)/P_0$, contributes equally to both AM and PM noise. The wideband AM and PM noise in amplifiers are typically dependent on the signal level because they originate from the thermal noise and therefore scale as $1/V_0^2$. This noise model for amplifiers can be used to interpret the noise in oscillators. We propose a noise model for oscillators where the AM and PM noise due to the electronics is generated by the same noise processes, a thermal noise process and a flicker noise process. The PM noise in oscillators is also dependent on the noise and loaded Q of the resonator. The AM noise does not seem to be affected by the characteristics of the resonator and we did not observe any PM to AM conversion.

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