# SUPPRESSED CARRIER BASED PM AND AM NOISE MEASUREMENT TECHNIQUES[1]

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Abstract

The purpose of this paper is to discuss the advantages and disadvantages of using carrier suppression techniques to measure PM and AM noise in oscillators, amplifiers, and components. Carrier suppression was first introduced by Klaus H. Sann in 1968 to measure noise in amplifiers. The major advantages of these configurations over conventional measurements is that the noise contribution of the phase or amplitude detector is reduced by the degree of carrier suppression until the thermal noise limit is reached. This typically results in an improvement of 10-60 dB in the noise floor. The advantages over the three-cornered-hat cross-correlation technique is that the same or better results can be obtained in real time instead of having to wait for a large number of averages. The disadvantage is that this approach does not work as well as conventional approaches for measuring AM noise in sources. Three-cornered-hat techniques used with conventional mixer-based system or carrier suppressed systems are required to obtain an unbiased estimate of the PM noise in state-of-the-art sources. Suppressed carrier techniques can also be used to reduce the contribution of the phase detector in some specialized oscillator configurations.

## 1. Introduction

A carrier signal with a low amplitude modulation (AM) and phase modulation (PM) noise can be mathematically represented by [1].

$$V(t) = V_o\left(1 + \varepsilon(t)\cos(2\pi\nu_o t + \phi(t))\right), \qquad (1)$$

where the amplitude fluctuations about the nominal amplitude $V_o$ are contained in $\varepsilon(t)$, and the phase fluctuations about the average frequency $\nu$ are given by $\phi(t)$. Figure 1 shows a vector representation of a carrier signal with AM and PM noise. The IEEE-recommenced specification for single side band PM and AM noise is

$$L(f) = \frac{\delta\phi^2(f)}{BW}, \qquad (2)$$

$$\frac{1}{2}S_a(f) = \frac{1}{2}\left(\frac{\varepsilon(f)}{V_0}\right)^2. \qquad (3)$$

In 1968 Klaus H. Sann introduced a technique to enhance the PM and AM noise generated in a device under test (DUT) by carrier suppression [2]. Figure 1 shows the essence of his approach, which is inherently very broad band. The carrier signal in the DUT in the A arm of the bridge is partially canceled by the carrier signal in the B arm of the bridge when the two signals are combined $180^{\circ}$ out of phase in a hybrid.

To first order, the amplification or enhancement of the PM and AM noise generated by the amplifier or DUT is equal to the degree of carrier power suppression. This is illustrated in Fig. 3. Note that the noise about the carrier in Fig. 3a is not changed when carrier suppression is applied; only the carrier (and the noise originally associated with the carrier) is reduced. Since PM noise and AM noise are measured and defined relative to the carrier power, reducing the carrier has the effect of amplifying the PM and AM noise generated in the DUT. A key point here is that hybrids (and other reactive power summers) are very linear and have very low 1/f and thermal noise. The linearity is especially important for reducing the contribution of the source AM and PM noise to the measurement. In these discussions we assume that the PM noise is small enough that the small angle approximations can be made.

To read out the enhanced PM noise, the signal is compared to the original signal found in the second reference (C) arm of the bridge. This approach was originally used to measure the PM noise in high power linear and pulsed amplifiers [2].

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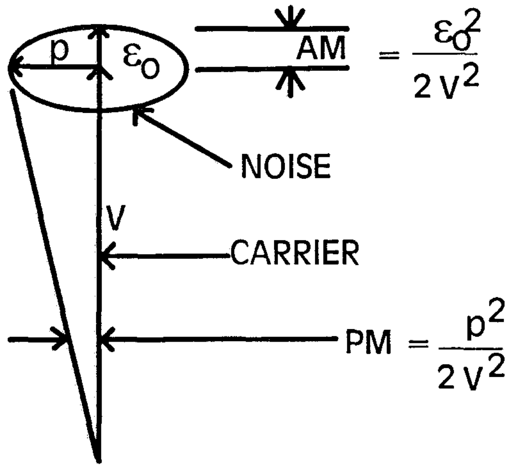


Figure 1. Vector representation of AM and PM noise on a carrier.

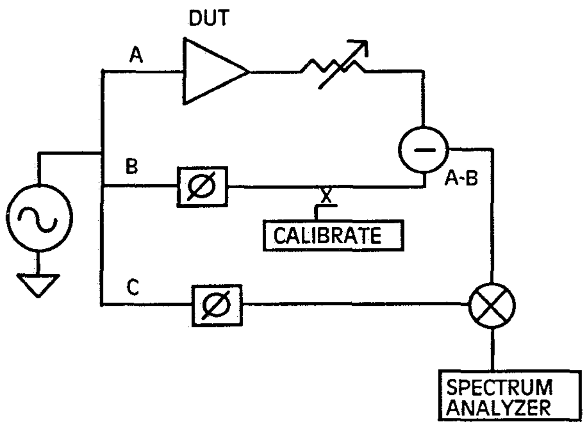


Figure 2. Block diagram of the bridge technique introduce by Sann [2] to amplify the PM and AM noise of an amplifier or other device under test (DUT) by suppressing the carrier signal.

The enhanced AM noise can be measured in a traditional AM detector without the need for the second reference arm as shown in Fig. 4. For simplicity, I will refer to any carrier suppression configuration of the type shown in Figs. 2, 4, or 5, which is used to amplify the PM or AM added by a DUT, as a Sann bridge.

The noise performance of the original Sann bridge [2] can be improved by using a linear, low noise amplifier after the $180^{o}$ hybrid as shown in Figs. 4 and 5. The amplifier allows us to use much larger values of carrier cancellation and still have enough signal to obtain good sensitivity and low noise from the PM (or the AM) detector. The noise generated in either the AM or PM detection process is thus suppressed by the degree of carrier suppression obtained in the bridge until the thermal limit is reached. In this regime, further amplification of the AM and PM noise of the DUT is matched by increased contribution of the thermal noise in the AM or PM detector. A reactive power combiner can be used as a replacement for the hybrid. The most serious requirement is that the bridge elements-power divider, phase shifter, adjustable attenuator, and power combiner-must have low noise because their noise will contribute directly to the enhanced signal, and therefore cannot be distinguished from AM and PM noise in the DUT. In many cases they will set the noise floor. This is illustrated in Section 3.3 below. See [3] for a detailed analysis of the noise performance of suppressed carried bridges.

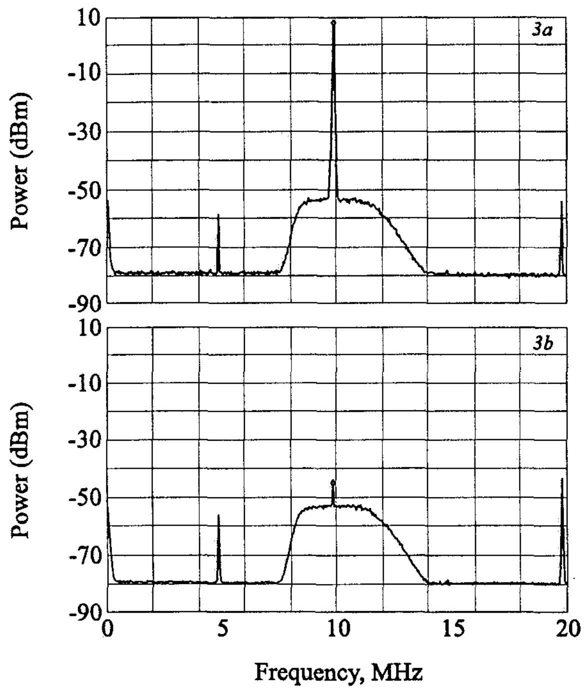


Figure 3a. Measured RF spectrum of the PM and AM noise added by a particular DUT at 10 MHz. The spurs at 5 MHz and 20 MHz are due to the source. Figure 3b. Measured RF spectrum of the PM and AM noise of the DUT of Fig 3a after carrier suppression has been applied.

## 2. Implementation and adjustment of the Sann bridge

The tuning of the bridge null requires fine adjustment of both the amplitude and phase of the two signals to obtain high carrier suppression. For example, balancing the power of the two signal to 0.086 dB yields a carrier power suppression of approximately 40 dB, if the angles are exactly $180^{o}$ out of phase. If the powers are balanced, the phase has to be within 0.01 rad to obtain 40 dB of carrier power suppression. To obtain 60 dB of carrier power suppression, the angle has to be within 0.001 rad and the power balanced within 0.0043 dB. Obtaining large carrier suppression requires very high stability in the bridge, the tuning of the source, and the DUT. Temperature variations of attenuation and/or phase will limit the practical values of carrier suppression. We find that carrier suppression of 40-60 dB can be maintained for hours to days, but that 80 dB is difficult to maintain without automatic control.

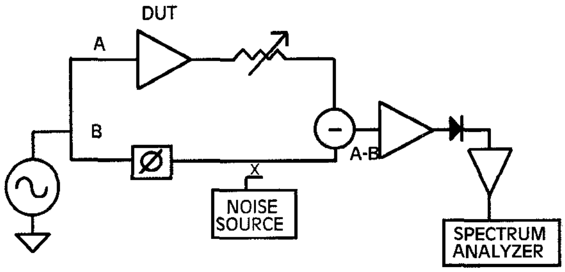


Figure 4. Block diagram of the Sann bridge applied to the measurement of AM noise in a device under test (DUT)[2].

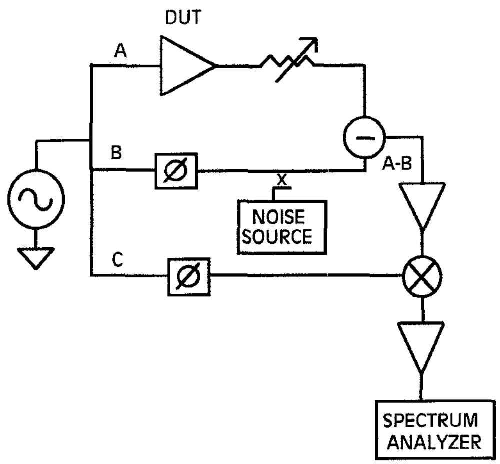


Figure 5. Block diagram of Sann bridge for low power amplifiers and other devices [2].

Because the bridge is so sensitive to small variations in amplitude and phase, it is very important that it be calibrated in the precise configuration that is used for the measurement The traditional method of using a substitution source to obtain a beat signal to calibrate the mixer and post amplifier gain is impractical because of the difficulty of achieving the same carrier suppression as during the measurement. Another problem is that the bridge becomes unbalanced over most of the cycle and can cause damage to the post amplifier. This problem could, of course, be addressed by using a limiter before the amplifier. Calibrating the bridge with a precision phase shifter only calibrates the gain at dc and cannot correct for frequency dependent effects. A PM Sann bridge can be calibrated over the full range of Fourier frequencies of interest by injecting a known amount of PM on either the A or the B leg of the bridge shown in Fig. 5 [2,4]. An AM Sann bridge can be calibrated over the full range of Fourier frequencies of interest by injecting a known amount of AM on either the A or the B leg of the bridge shown in Fig. 4 [2,4]. We find it convenient to use the NIST PM/AM noise standards to accomplish this task[4]. The calibration signal should be smaller than the carrier but larger than the noise. This condition becomes more difficult to achieve as the carrier suppression factor increases.

## 3. Comparison of the Sann bridge to other techniques for PM and AM measurements

The reduction of detector noise can lower the measurement noise in a wide variety of applications. In the following sections we compare the performance of a Sann bridge approach to traditional approaches for measuring PM and AM noise in various devices.

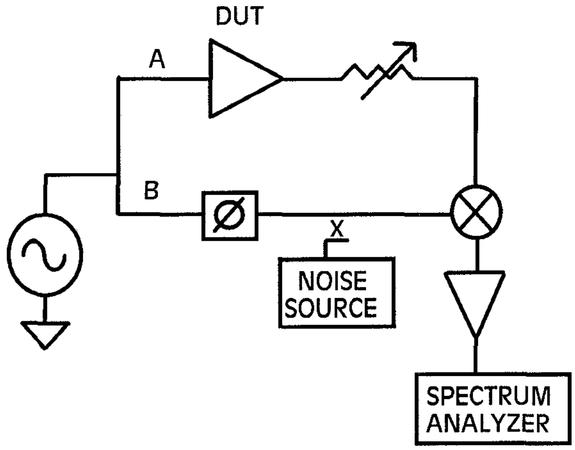


Figure 6. Convention phase bridge for measuring the PM noise added by an amplifier. The noise source is used to calibrate the gain versus Fourier frequency [2-6].

3.1 Measurement of PM noise added by a DUT using a Sann bridge: The noise floor or resolution of a Sann bridge for the measurement of PM noise in amplifiers and other components is improved, over the PM noise of the phase detector and base band amplifier as well as the PM noise of the source, by the carrier suppression factor until the thermal limit is reached. This factor, which is generally in the range from 10-60 dB, depends on the resolution for setting the bridge, the stability of the bridge components, the insertion loss of the device under test, and the power available from the driving source. When the carrier power is greatly suppressed, the contributions of the noise at the other harmonics and/or spurious frequencies will also be enhanced. In the case illustrated in Fig. 3b, the spurious signals at harmonics and sub harmonics of the signal are comparable to the carrier signal of interest. These spurs may interfere with the measurements of AM and PM noise. See [3] for a detailed analysis of the noise floor.

The conversion of the source AM noise to apparent PM noise should be much less than in traditional mixer-based systems because the carrier suppression (achieved using a hybrid or power combiner are much more nearly linear than mixers) amplifies the noise generated in the DUT before it is detected in the mixer. The suppression of AM to PM conversion could be as high as the carrier power suppression factor plus approximately 20 dB. It is likely, however, that typically measurements will be limited by the linearity of the DUT.

3.2 Measurement of PM noise added by a DUT using the conventional mixer-based phase bridge technique: Using the basic phase bridge shown in Fig. 6, we have attained noise floors close to the carrier for the measurement of PM noise in amplifiers that were as much as 130 dB below the PM noise of the source. These results were attained close to the carrier at X-band [5]. Using a two channel phase bridge with cross correlation, we have achieve as much as 150 dB suppression the source PM noise[5-7]. The maximum value for the suppression of source PM noise is limited by the decorrelation of the source noise by the phase shift between the two arms that is necessary to obtain a linear phase detector to $(2\pi f\tau_{delay})^2$, where $\tau_{delay}$ is the delay of the delay line. For the minimum delay of $90^0$ and a Fourier frequency offset f of 10% of the carrier, this carrier PM suppression factor is -16 dB. At 10 Hz offset from a X-band carrier the factor is -176 dB [6].

The conversion of source AM noise to apparent PM noise by the mixer is typically -15 to -40 dB [6]. The noise of the phase detector and base-band amplifier cannot be separated from a single measurement. Additional measurement can be used to estimate the noise floor of the system and thereby estimate the contribution to the measurement. Cross correlation can be used to reduce the contribution of the phase detectors by $N^{0.5}$, where N is the number of measurements averaged, however, the AM to PM conversion in the mixer is not reduced. The improvement with averaging is limited to approximately 10-30 dB due to the long averaging times required [6,7].

3.3 Measurement of AM noise added by a DUT using a Sann bridge: The noise floor for the measurement of AM noise in amplifiers and other components can be exceptionally good in a Sann bridge. The suppression of the AM noise of the source is very high, limited only by the linearity of the DUT and the hybrid or power combiner. The contribution of the AM detector and the base band amplifier is reduced by the degree of carrier power suppression, which can be of order 10 to 60 dB.

Table 1 shows the results of AM noise floor measurements at 10 MHz with and without the use of a Sann bridge. Column 2 shows the results using a simple diode detector at a power of about 11 dBm, while column 3 shows the results using a mixer as the AM detector. Column 4 shows the results using the diode detector with a Sann bridge, a carrier suppression factor of 42 dB, and rf amplification of approximately 37 dB after the bridge. Column 5 shows the results using the mixer as an AM detector with the same bridge. Although the two AM detectors differ by approximately 15 dB in their noise performance, the results with the Sann bridge are identical to within the uncertainty of the measurement. These results are available in real time and do not require ultra long averaging time required by cross correlation [5-7]. The noise floor realized in this measurement was not due to the noise in the AM detectors but the noise in the bridge components. The most likely culprit is the variable attenuator. Much lower AM noise floors have been demonstrated in [3] by paying careful attention to the noise in the bridge components.

Table 1. Comparison of AM noise floor with and without a Sann bridge with 42 dB of carrier suppression at 10 MHz.

| Fourier frequency f (Hz) | Diode AM Detector L(f) dBc/Hz | Mixer AM Detector L(f) dBc/Hz | Diode AM Detector Sann Bridge L(f) dBc/Hz | Mixer AM Detector Sann Bridge L(f) dBc/Hz |
|---|---|---|---|---|
| 10 | -130.1 | -145.3 | -160.4 | -160.8 |
| 100 | -141 | -156.5 | -170.6 | -170.7 |
| 1 k | -152.4 | -167.3 | -176.3 | -176.9 |
| 10 k | -152.4 | -170.0 | -177.7 | -178.5 |

3.4: Measurements of AM noise added by amplifiers and other components using the conventional AM detection techniques: The noise floor for the measurement of AM noise in amplifiers using a conventional detector or a mixer used as an AM detector is generally limited by the detector and the residual AM noise in the source. See Fig. 7. Cross correlation, shown in Fig. 8, can reduce the contribution of the AM detector, but there is not a good method to remove the contribution of the AM noise of the source [5]. The contribution due to PM noise in the source being converted to AM noise in the detector is usually negligible.

3.5 Measurement of PM noise in sources using a Sann bridge: Figure 9 shows one method of applying the techniques of carrier suppression to the measurement of PM noise in a pair of sources. The contribution of noise in the phase detector and the base band amplifier is reduced by the carrier power suppression factor. This method cannot provide the PM noise of each source without additional measurements. The system is easily calibrated by adding known PM to one leg of the bridge.

Conventional three-cornered-hat measurements, composed of sequentially measurements between the three possible pairs, can be used to reduce the contribution of the reference oscillators but still include some of the measurement system noise [6]. Cross correlation can be applied to a simultaneous three-cornered-hat measurement to obtain an unbiased measurement of a single oscillator and also reduce the contribution of the measurement system [6,7].

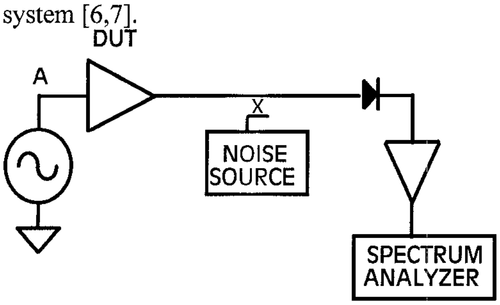


Figure. 7 Convention configuration for measuring the AM noise in an amplifier or other device.

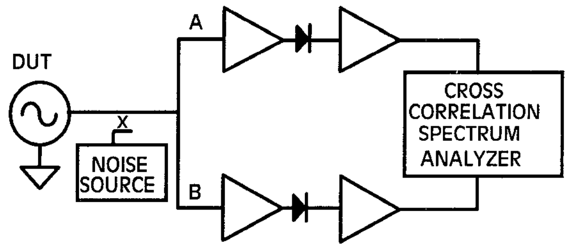


Figure 8. Two channel system with cross correlation for measuring AM noise in a source.

3.6 Measurement of PM noise in sources using the traditional two oscillator method: Figure 10 shows the traditional two oscillator method for measuring the PM noise in a pair of sources [6]. The noise floor for such measurements is set by the noise in the phase detector and the base band amplifier plus AM to PM conversion in the mixer. For many low noise measurements the AM to PM conversion in the mixer is the limiting factor [6]. This method cannot provide the PM noise of each source without additional measurements.

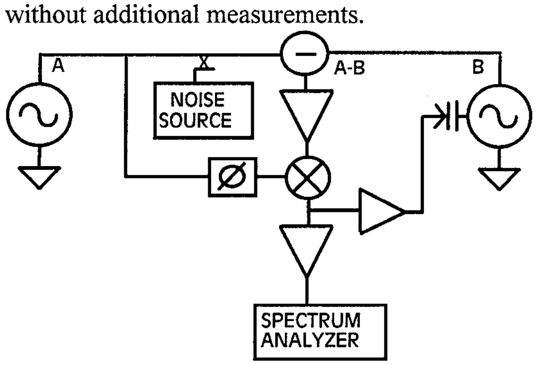


Figure 9. Block diagram for a two oscillator PM measurement using carrier suppression.

Conventional three-cornered-hat measurements, composed of sequentially measurements between the three possible pairs, can be used to reduce the contribution of the reference oscillators but still include some of the measurement system noise. Cross correlation can be applied to a simultaneous three-cornered-hat measurements to obtain an unbiased measurement of a single oscillator and also reduce the PM noise contribution of the measurement system. The PM noise of the two references and the contribution of the phase detectors is reduced by $N^{0.5}$, where N is the number of measurement averaged. This factor is limited to approximately 10-30 dB due to the long averaging times required [6,7] and the interference of ground loops.

3.7 Measurement of PM noise in sources using a delay line with carrier suppression : Figure 11 shows a delay line based PM noise measurement system with carrier suppression that was introduced by Fred Laabar [8]. He obtained an improvement in the noise floor of 35 dB using carrier suppression in the microwave region. Although the noise floor of such a discriminator varies as $1/f^2$ and is therefore poor near the carrier, it is often sufficient to characterize microwave sources.

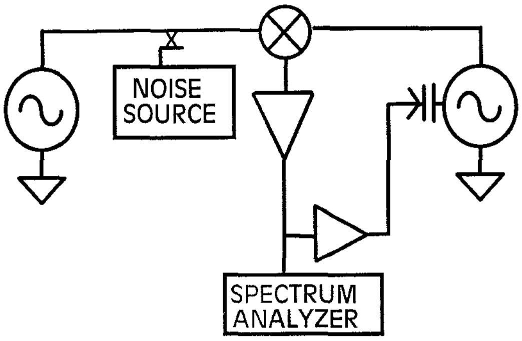


Figure 10. Block diagram of a traditional two oscillator measurement system with integral PM noise standard [6].

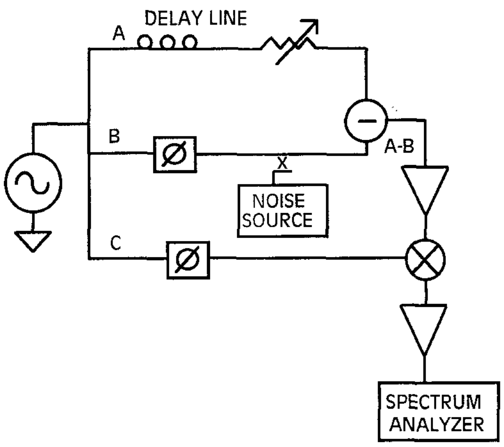


Figure 11. Block diagram of a delay line frequency discriminator using carrier suppression [8].

3.8 Measurement of PM noise in sources using a cavity frequency discriminator with carrier suppression: A cavity discriminator can be used to measure the PM noise in a source or as a frequency controlling element in an oscillator [6]. G. J. Dick used the technique schematically shown in Fig. 12 to control the frequency of a low noise microwave source. In his approach, carrier suppression was achieved by adjusting the input to near critical coupling. His work reintroduced the concept of carrier suppression technique to enhance the sensitivity and to lower the effective noise of the phase detector [3,9,10].

4. Other applications of the carrier suppression technique

The method of carrier suppression can be used to reduce the noise in an amplifier. Figure 13 shows a feed-back system where the PM noise introduced by the amplifier is detected using carrier suppression and the error signal applied to a variable phase shifter to remove the PM noise. In a practical system it is probably necessary to correct both PM and AM noise to obtain large reduction of the PM noise introduced by the amplifier.

A different method of reducing the PM and the AM noise of an amplifier is shown in Fig. 14. In this case both the PM and AM noise are reduced by the use of feed-forward. The suppressed carrier error signal contains the AM noise, PM noise, and inter modulation signals generated by the amplifier. This signal is amplified and added to the output with the appropriate gain so as to cancel out the noise added by the amplifier. This approach also improves the linearity and inter modulation performance of the amplifier. The cancellation of the 1/f AM and PM noise is not expected to be as stable as the feed back configuration, but it is simpler.

Amplifiers with improved PM and AM noise can be used to construct oscillators with close to carrier noise dominated by the resonator instead of the amplifier as is the usual case in the microwave region [9,10].

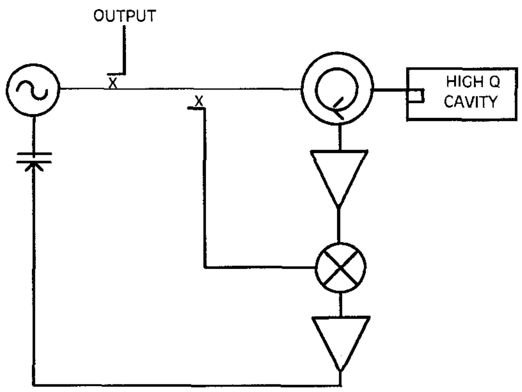


Figure 12. Block diagram of a cavity discriminator using suppressed carrier techniques [9].

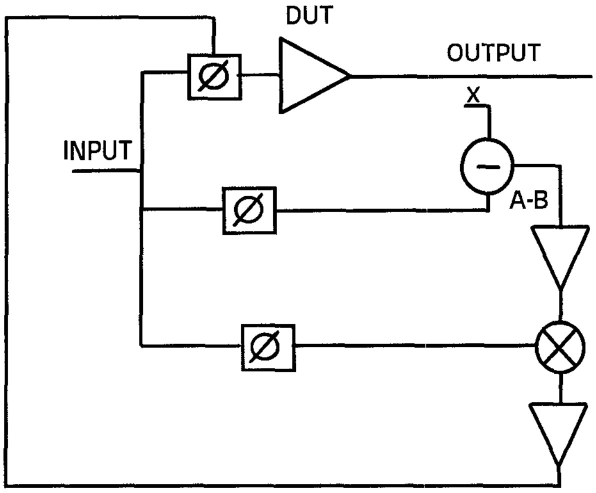


Figure 13. Block diagram showing one method for reducing the PM noise of an amplifier using suppressed carrier. See also [3].

## 5. Conclusions

Carrier suppression techniques can be used to reduce the 1/f and thermal noise in PM and AM detectors by 10-60 dB. This technique can therefore be used to improve the noise floor for measuring AM and PM noise introduced by components. The improvements are roughly 10-80 dB for AM measurements and roughly 10-60 dB for PM measurements. When low noise sources are used, carrier suppression techniques generally lead to lower noise floors for measuring AM and PM noise added by components and amplifiers than conventional techniques, even when cross correlation is used. Conventional techniques generally are not able to suppress the AM noise of the source in these measurements.

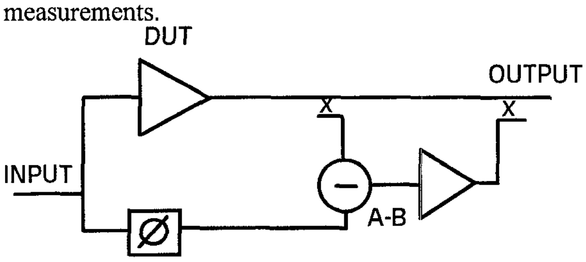


Figure 14. Block diagram of a feed-forward amplifier.

Carrier suppression techniques can be used to reduce the noise floor for two oscillator PM and AM measurements. The measurement yields the noise of the pair. If the noise of a single oscillator is desired, either the reference must be much better than the DUT, or some form of three-cornered-hat technique must be used. Three-cornered-hat measurements using cross correlation yield the best reduction of the noise from the two reference oscillators [5-7]. AM measurements of sources can be more easily done using cross correlation techniques [5-7].

Carrier suppression techniques can be used to reduce the noise floor for frequency discriminator measurements using either a cavity or a delay line. Improvements of 10-50 dB might be expected.

Carrier suppression techniques can be used to reduce AM and or PM noise in amplifiers. Feed-forward architectures reduce both AM and PM without the need for a servo. Feed-back designs are likely to be more stable over time and environmental factors and therefore probably will offer higher degree of improvement in the noise.

Carrier suppression techniques can be used to reduce the AM and PM noise in oscillators when the noise originates in the loop sustaining elements.

## 6. Acknowledgments:

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## 7. References

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