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WR-10 Band Noise Measurement

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13. ABSTRACT *(Maximum 200 words)*

A WR-10 band (75 to 110 GHz) noise measurement system was developed to evaluate a solid state noise source in this band. The system was characterized with a gas discharge tube that provided a stable output Excess Noise Ratio (ENR) of 14.2 dB + 0.5 dB throughout the band. To ensure the accuracy of the system characterization, the results were correlated with the results of noise temperature measurements, obtained from a load maintained at ambient and liquid nitrogen temperatures. The principles of noise measurement, method and limitations of each technique, and results of receiver characterization are discussed. The results of the receiver characterization are applied to the evaluation of solid-state noise sources. The resulting double sideband (DSB) ENR of the noise sources are presented and discussed. The accuracy of this DSB evaluation was compared to a single sideband (SSB) measurement using the "Three Point Measurement" method.

Two WR-10 band noise sources were evaluated with the noise measurement system developed at NRL. The device performance was specified as an ENR of 15 dB + 1 dB and full waveguide coverage. The actual performance results indicate that ENR values in excess of 15 dB are available, but the devices lacked a flat output over the band.

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CONTENTS

WR-10 BAND NOISE MEASUREMENT

1. INTRODUCTION

Millimeter wave systems being developed can provide many features that are not available at lower frequencies, such as smoke penetration, directivity, and frequency selective transmission. Consequently, investigations of millimeter wave systems have explored the use of frequencies in the WR-10 band (75-110 GHz) for military applications [1]. Since the measurement of system noise is essential to the characterization of receiver sensitivity and performance, our study examined the methodology of noise measurements in the WR-10 band.

This report describes the theory, technique, and results obtained from a developmental WR-10 band noise measurement system. The system under development uses the Y-factor technique with frequency down-conversion. Although the Y-factor technique with frequency down-conversion is widely and successfully used to measure noise at lower frequencies, calibration uncertainties in the signal source, standard noise source, and measurement instruments make it difficult to do at the WR-10 band.

A frequency locked-loop signal source was developed at the Naval Research Laboratory (NRL) to act as a highly accurate local oscillator (LO) driver for a state-of-the-art single-ended mixer. The resulting signal source was tested to determine how well it could step across the WR-10 band and lock within ±10 Hz to a desired frequency. The noise figure of the system was characterized during a month long evaluation to determine its stability. With the noise figure established, the system was used to evaluate solid-state noise sources developed through NRL contracts. A technique called Three Point Measurement (TPM) was developed and applied to determine the single sideband (SSB) excess noise ratio (ENR) of a solid-state noise source and establish the validity of less rigorous measurement techniques (e.g., double sideband (DSB)). Accuracy of SSB ENR obtained by the TPM technique is verified by comparing calculated and measured values. The criteria, technique, and results for both the SSB and DSB are presented.

2. NOISE MEASUREMENT THEORY

2.1 Noise Figure of Electronic Devices

Electronic devices contribute noise to signals propagating through a circuit. Noise results from thermal and quantum instabilities occurring in the physical structure of matter. A figure of merit called noise factor F is used to describe this phenomenon [2]. The logarithmic expression of noise factor, noise figure F_{dB}, is often used in engineering calculations of noise. F describes the noise contribution that an electronic device makes to the total noise level carried on the signal. F is expressed as a quotient of the signal's noise content (signal-to-noise ratio) compared at the input and output ports of the device. This relationship is expressed as

$$F = \frac{S_{in}/N_{in}}{S_o/N_o} \quad (1)$$

where S_{in} is input signal power (W),
N_{in} is input noise power (W),
S_o is output signal power (W), and
N_o is output noise power (W).

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Since noise is associated with thermal instabilities in matter, the noise factor of an electronic device varies with ambient temperature. This characteristic results in a need to define a standard noise factor F_S. Conventionally, the standard noise factor of an electronic device characterizes the device noise production at an ambient temperature of $T_o = 290°$ K [3, p. 41]. That is,

$$F_S = \left. \frac{S_{in}/N_{in}}{S_o/N_o} \right|_{T = T_o = 270° K} . \tag{2}$$

Consider a two-port linear device with an available power gain of G. The output signal power is equal to the input signal power multiplied by the gain as described by

$$S_o = G \cdot S_{in} . \tag{3}$$

On the other hand, the output noise power has two components: the input noise multiplied by the gain and the noise added N_{ad} by the electronic device. Output noise power is mathematically and graphically described as

$$N_o = N_{ad} + G \cdot N_{in} . \tag{4}$$

Substituting Eq. (3) and Eq. (4) into Eq. (1), the noise factor then becomes

$$F = \frac{S_{in}(N_{ad} + GN_{in})}{GS_{in}N_{in}} \tag{5}$$

or

$$F = \frac{N_{ad} + GN_{in}}{GN_{in}} . \tag{6}$$

Since N_{ad} is always a positive quantity, the noise factor of an electronic device is always greater than unity, or the noise figure, $F_{dB} = 10 \log (F)$, of an electronic device is always greater than zero.

Equation (6) shows that the noise factor of a Device Under Test (DUT) is a function of the input noise as well as the gain and the added noise. However, the equation is impractical since it is difficult to measure the noise entering a device. To avoid this difficulty, the concept of thermal noise is introduced.

Consider the case of a resistance R_1 at a temperature of T ° K. This resistance is a thermal noise generator. The noise generated by R_1 is nearly Gaussian and white in nature [3, p. 33]. If the resistance R_1 is connected to a matched load resistance R_2, then, according to the Rayleigh-Jeans approximation to Planck's law of thermal radiation [3, p. 441], the noise power P_n delivered by the generator R_1 to the resistance R_2 is

$$P_n = k \cdot T \cdot B \text{ Watts}, \tag{7}$$

where k is Boltzman's constant (1.381×10^{-23} W-s/° K),
T is temperature of source resistance (° K), and
B is bandwidth of noise being considered (Hz).

Equation (7) shows that the amount of noise power in a bandwidth is a linear function of the absolute temperature of the source impedance.

Consider now that the DUT's input noise is equivalent to the thermal noise generated by a resistance R at a room temperature T_o. That is,

$$N_{in} = k \cdot T_o \cdot B \text{ Watts}. \tag{8}$$

Substituting Eq. (8) into Eq. (6) yields

$$F = \frac{N_{ad} + k \cdot B \cdot G \cdot T_o}{k \cdot B \cdot G \cdot T_o} . \tag{9}$$

Equation (9) can be used to determine the noise factor. The Signal Generator technique applies Eq. (9) directly to noise measurement. The numerator is obtained by measuring the DUT's output noise power with a source resistance at the temperature T_o attached to its input. On the other hand, evaluating the denominator is difficult since it involves determining the gain bandwidth product of the DUT [4]. This difficulty limits the usefulness of the Signal Generator technique in noise measurement.

To overcome the difficulty presented in the Signal Generator technique, Eq. (7) is manipulated further. The following manipulation of Eq. (9) becomes the basis for the commonly used Y-factor technique for noise measurement.

According to Eqs. (4) and (7), the total output noise power N of DUT is

$$N_o = N_{ad} + k \cdot B \cdot G \cdot T . \tag{10}$$

Assuming that the gain G is a constant over the temperature range of interest, then Eq. (10) has the form of a straight line with a slope of kBG as described in Fig. 1. The slope of the straight line in Fig.1 can be determined if coordinates of two different points on the line are known. Coordinates of two different points on the line can be obtained by applying a source impedance to the DUT input at two different temperatures and measuring the output noise powers of the DUT at these two temperatures. Suppose that the two temperatures are T_h and T_c and their respective output noise powers are N_h and N_c as described in Fig. 1. According to Eq. (10), the relationships between these temperatures and their respective output noise powers are

$$N_h = N_{ad} + k \cdot B \cdot G \cdot T_h \tag{11}$$

and

$$N_c = N_{ad} + k \cdot B \cdot G \cdot T_c . \tag{12}$$

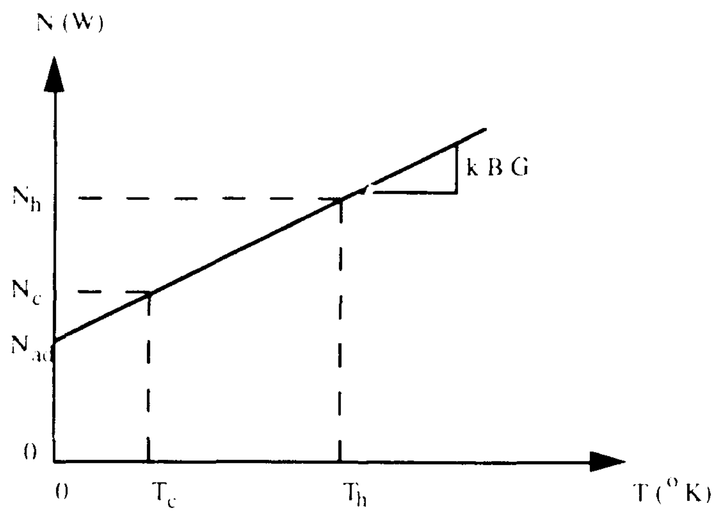

Fig. 1 — Thermal noise power vs temperature of source impedance

The slope of the line is the power's rate of change with respect to temperature of the source impedance. That is,

$$\text{Slope} = \frac{\Delta N}{\Delta T} \tag{13}$$

which is the same as

$$\text{Slope} = \frac{N_h - N_c}{T_h - T_c}. \tag{14}$$

N_{ad} can be solved from either Eq. (11) or Eq. (12). If Eq. (12) is chosen, then

$$N_{ad} = N_c - k\ B\ G\ T_c. \tag{15}$$

By substituting the slope from Eq. (14) for kBG in Eq. (15), we get

$$N_{ad} = N_c - \frac{(N_h - N_c) \cdot T_c}{T_h - T_c} \tag{16}$$

or

$$N_{ad} = \frac{(T_i - Y \cdot T_c) \cdot N_c}{T_i - T_c}, \tag{17}$$

where Y is the ratio of N_h to N_c ($Y = N_h / N_c$); hence the method is called the Y-factor method.

Substitute N_{ad} of Eq. (17) into Eq. (9), and after algebraic manipulations, the noise factor becomes

$$F = \frac{\left[(T_i/T_o) - 1\right] - Y \cdot \left[(T_c/T_o) - 1\right]}{Y - 1}. \tag{18}$$

Expressed in terms of noise figure, Eq. (18) becomes

$$F_{dB} = 10\ \log\left[\left(\frac{T_h}{T_o} - 1\right) - Y \cdot \left(\frac{T_c}{T_o} - 1\right)\right] - 10\ \log(Y - 1). \tag{19}$$

To simplify the procedure, either T_h or T_c can be set to room temperature T_o. If T_h is equal to T_o, then Eq. (19) becomes

$$F_{dB} = 10\ \log\left[Y \cdot \left(1 - \frac{T_c}{T_o}\right)\right] - 10\ \log(Y - 1). \tag{20}$$

On the other hand, if T_c is equal to T_o, then

$$F_{dB} = 10\ \log\left(\frac{T_h}{T_o} - 1\right) - 10\ \log(Y - 1). \tag{21}$$

The first term on the right-hand side of Eq. (21) is equivalent to the ENR, in dB, of a noise source that has output power in ON and OFF states equal to thermal noise power generated by a source resistor at temperatures T_h and T_o, respectively [5]. If a noise figure measurement is performed with a noise source whose ENR is known, then the noise figure of the DUT can be expressed in terms of the noise source's ENR and Y-factor as shown in

$$F_{dB} = ENR - 10\ \log(Y - 1) \tag{22}$$

where ENR is the excess noise ratio of the noise source used in the measurement (dB),
Y is N_h/N_c; or N_{on}/N_{off},
N_c is output noise power of DUT when the noise source is in cold (or OFF) state (W), and
N_h is output noise power of DUT when the noise source is in hot (or ON) state (W).

2.2 Excess Noise Ratio of an Unknown Noise Source

Once the noise figure of the measurement system is known, the ENR of a noise source can be determined by applying the noise source to the measurement system. The Y-factor is measured and substituted in Eq. (22) to determine the ENR. That is,

$$ENR = F_{dB} + 10 \log (Y - 1) . \tag{23}$$

3. NOISE MEASUREMENT TECHNIQUE

Frequency down-conversion is an approach used to make noise measurement at high frequencies by using current technology.

3.1 Frequency Down-conversion

At WR-10 band, the frequency down-conversion can be accomplished by using a millimeter wave mixer as shown in Fig. 2.

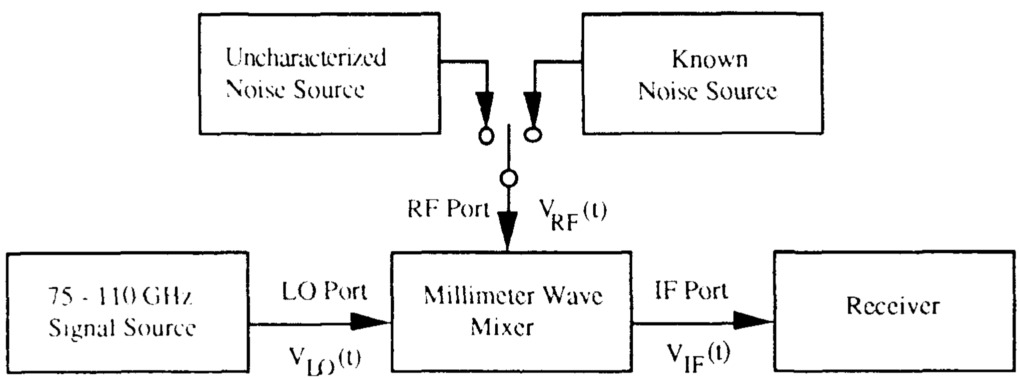

Fig. 2– Block diagram of measurement system

3.1.1 Double Sideband Conversion

Suppose that the input noise and LO signal in Fig. 2 are defined as

$$V_{RF}(t) = n(t) \cdot A\cos[\omega_{RF}t] \tag{24}$$

and

$$V_{LO}(t) = B\cos[\omega_{LO}t] . \tag{25}$$

Then, according to the frequency conversion theory (Appendix A), the down-conversion Intermediate Frequency (IF) signal is

$$V_{IF}(t) = Cn(t)\cos[\omega_{IF}t] , \tag{26}$$

where

$$\omega_{IF} = \omega_{RF} - \omega_{LO} \quad \text{and} \quad C = \frac{A \cdot B}{2} . \tag{27}$$

That is, the RF signals at the two frequencies as described in Eqs. (28) and (29) are down-converted to the same IF. For upper sideband:

$$\omega_{RF} = \omega_{LO} + \omega_{IF}, \tag{28}$$

and for lower sideband:

$$\omega_{RF} = \omega_{LO} - \omega_{IF}. \tag{29}$$

Noise at the frequency of interest can be down-converted to the available IF by tuning the LO frequency according to the relationship in Eq. (27).

Thus, the IF signal $V_{IF}(t)$ in Fig. 2 is a result of the conversion of the upper RF signal (upper sideband) and the lower RF signal (lower sideband) to the same IF. Hence, a measurement implied by the block diagram in Fig. 2 is a double sideband measurement. This DSB characterization complies with the noise calibration procedure developed by the National Institute of Standards and Technology (NIST) [6].

3.1.2 Single Sideband Conversion

SSB characteristics of a noise source can be determined by inserting a filter at the RF port of the mixer so that one of the sidebands of the RF signal is rejected. This method is extensively and successfully used in noise measurement at low frequencies. However, it is difficult to accomplish in the WR-10 band because of the limitation of current technology for the band (Appendix A).

Another method to characterize SSB ENR of a noise source is the TPM method. This method actually relies on DSB measurement implied by the block diagram in Fig. 2. The characterization is done by measuring the noise source power in groups of three LO frequencies and two IFs so that the results yield a system of three linear equations with three unknowns. The three unknowns, i.e., frequency down-converted versions of the noise source power at three RF frequencies, can be solved by this linear system. This method requires that the system have "identical" performance at the three LO frequencies and two IFs. Otherwise, there will be more than three unknowns in the three equations (Appendix A).

3.2 Receiver

The receiver section includes an amplifier, a bandpass filter, and a spectrum analyzer. The amplifier is needed to amplify the IF signal above input threshold of the spectrum analyzer so that it can be detected. The frequency down-conversion loss and the amplification of input noise make detected noise power no longer the true power of the input noise. However, these processes do not affect the noise measurement since Y-factor is a relative value between the ON and OFF powers of the noise source. That is, Y-factor is the ratio of the detected power when the noise source is ON to the detected power when the noise source is OFF. Thus, if the gain factor is the same in both the ON and OFF states, then it will be cancelled out in the ratio. The bandpass filter eliminates the presence of mixer harmonics that would alter the result of power measurements. Consequently, the measurement is only of the in-band noise passing through the system.

3.3 The Measurement System

3.3.1 System Description

Figure 3 is the system block diagram that describes the apparatus used to characterize the noise sources. This system expresses the current state of the technology in components. The system is controlled by a computer that communicates with the rest of the system via the IEEE-488 bus. The system uses a Ka-band yttrium-iron garnet (YIG) oscillator to provide the baseband RF for the frequency-stabilized LO. The YIG is tuned to a frequency through the host computer that establishes the frequency by adjusting the current supplied to the YIG. This provides coarse tuning. Fine tuning is established by referencing the down-converted RF signal to a 10 MHz reference signal. A microwave-synthesized signal generator operating at 8.6-13.3 GHz is used as the LO to perform frequency down-conversion of the sampled baseband signal. The down-converted signal is divided and mixed with the divided reference signal. The resulting IF signal is filtered to remove harmonics. The error signal is then converted to a small drive current for fine tuning.

The RF signal passing through the main line of the coupler passes to an amplifier and is then multiplied to produce a signal in the WR-10 band. The signal is then attenuated as necessary with a variable attenuator.

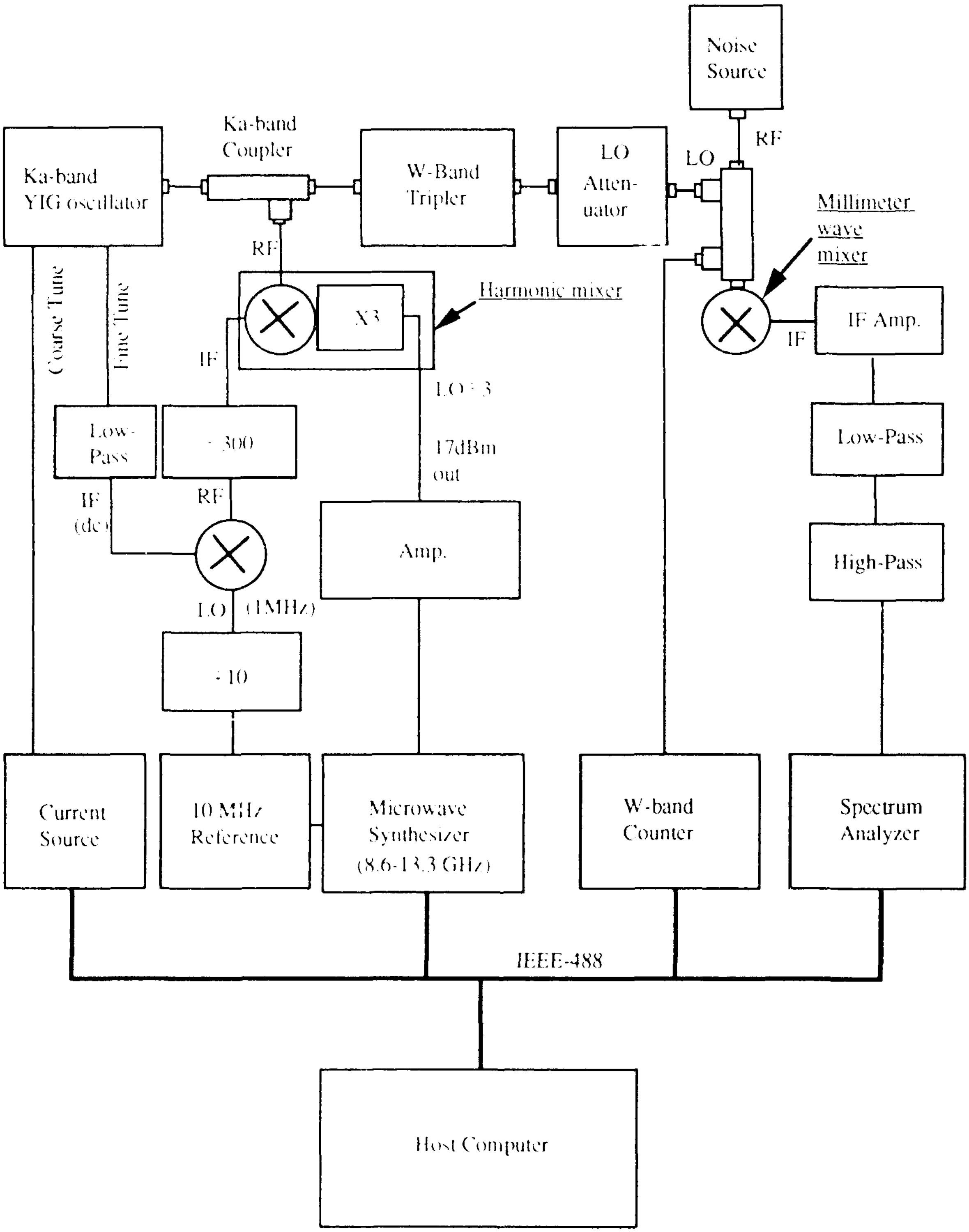

Fig. 3 — Component diagram of WR-10 noise measurement system

The resulting signal acts as the LO that is mixed with the noise source. The LO and noise signal are coupled and pass into the RF port of a single-sided WR-10 band mixer. The resulting IF signal is amplified and filtered to remove out-of-band harmonics. The power is measured with the spectrum analyzer. The frequency counter in the system is used solely to monitor the stability of the WR-10 band LO signal and is not essential to the operation of the system. The stability of the system is based on the use of a synthesized signal that is stable to ±1 Hz. The frequency stability resulting at WR-band is ±9 Hz, which is primarily a result of multiplications used within the system.

3.3.2 *Description and List of Required Components*

To achieve the desired results, the individual components used in the measurement system must have the following minimal characteristics:

Standard Noise Sources: Both Hot/Cold and wideband gas discharge tube noise sources are needed. The requirements for these standard sources are that their noise production parameters must be well known and stable.

Signal Source (LO): The output frequency of this source should be stable enough to provide accuracy to the measurement. The mixer's LO specifications should be used to determine the signal source power requirements. This is a critical constraint because lower LO power will cause excessive losses and increase the noise figure of the mixer.

Mixer: The millimeter wave mixer is used to down-convert noise to the frequency range that can be monitored using current technology. The mixer should have the lowest loss/noise available. Higher loss/noise characteristics require higher LO power inputs caused by the increase in conversion losses.

Receiver: The receiver section contains an IF amplifier, a bandpass filter, and a spectrum analyzer. The IF signal is amplified above the input threshold of the receiver. The filter network rejects harmonics produced by the mixer. Noise power is detected by the spectrum analyzer. The receiver should be linear in the range of measurements, otherwise errors are introduced into results.

Table 1 provides a full list of components used in the measurement system.

Table 1 — Noise Measurement System Components

Qnty	Description	Manufacturer	Part Number
1	Unknown noise source	Noise Com Inc.	NC 65910
1	Unknown noise source	Marconi	DA9708
1	Liquid Nitrogen load	Alpha Industries, Inc.	575W
1	Termination	Hewlett Packard	W910-C
1	Gas discharge tube	CP Clare Corp.	TN-165
1	Ka-band YIG oscillator	Avantek	AV-26240
1	Synthesizer	Hewlett-Packard	8340B
1	W-band tripler	Hewlett-Packard	85100W
1	W-band attenuator	Hughes	45726H-1000
1	Ka-band coupler	Aerowave	28-3000/10
1	Microwave harmonic mixer	Hughes	47441H-2002
1	Microwave amplifier	Avantek	SFT84-2408
1	Directional coupler	Hughes	4546H-1310
1	Single-ended mixer	Millitech	MXW-10T-002
1	IF amplifier	MitEq.	AU-3A-0150
1	Filter 10 MHz high pass	K&L	5LH31-10/500
1	Filter 500 MHz low pass	Mini Circuit	SPL 550
1	Spectrum Analyzer	Hewlett-Packard	8566B
1	Desktop computer w/IEEE-488	Hewlett-Packard	9121
As needed	Power supplies	various	

3.4 Noise Figure Measurement

Four methods of noise figure measurement were considered. They are: Hot/Cold sources, discrete frequency noise tubes, gas discharge tubes, and IF substitution. All of these methods are based on the Y-factor technique but rely on different standard noise sources and are procedurally different.

3.4.1 *Hot/Cold Loads*

This method relies on being able to accurately acquire the temperatures of the standard noise source in both the OFF (T_c) and ON (T_h) states. The Hot/Cold source approach requires two loads (waveguide terminations). One is immersed in a high-temperature bath and is referred to as a hot source. The other is immersed in a low-temperature bath and is referred to as a cold source. Usually, boiling water and liquid nitrogen (N_2) are used for hot and cold sources because of their accurately known critical temperatures and availability. The method achieves high accuracy because it uses accurately known temperatures. However, this method is time consuming, because all measurements must be made under manual control.

The Y-factor is determined by the following procedure: apply the hot source output to the RF port of the mixer, adjust LO to the desired frequency, measure the output noise power, and record this value as N_h. Switch the RF port of the mixer to cold source, measure the corresponding output noise power and record it as N_c. If the measured powers are in watts, then the Y-factor can be obtained directly by Eq. (30). If these measured values are in decibels, then the Y-factor can be calculated by Eqs. (31) and (32).

$$Y = N_h / N_c \tag{30}$$

$$Y_{dB} = N_h - N_c \tag{31}$$

$$Y = 10^{Y_{dB}/10} \tag{32}$$

Once the Y-factor at a frequency is known, the noise figure of the measurement system at that frequency can be determined by solving Eq. (19) for F_{dB}. That is,

$$F_{dB} = 10 \log \left[\left(\frac{T_h}{T_o} - 1 \right) - Y \cdot \left(\frac{T_c}{T_o} - 1 \right) \right] - 10 \log (Y - 1) . \tag{33}$$

The noise figure of the measurement system in the entire WR-10 band is obtained by stepping the LO frequency across the band and repeating the above procedure.

Switching between hot and cold source in the above procedure is very time consuming. It can be eliminated by the following procedure: apply the hot source to the RF port of the mixer, step the LO signal to the desired frequencies, and record the noise output powers. Repeat the procedure for the cold source. Apply the data to Eqs. (32) and (19) to obtain the noise figure for the measurement system at each frequency.

3.4.2 *Discrete Frequency Noise Source*

A discrete frequency noise tube can be used to characterize the measurement system at the frequency at which the tube is calibrated. To make the noise figure measurement, the output noise must be measured with the noise tube ON (N_h) and again with the noise tube OFF (N_c). Depending on the measurement units, mW or dBm, either Eq. (30) or Eq. (31) is used with Eq. (32) to calculate the linear value of the Y-factor as described in the Hot/Cold source method. Once the linear value of the Y-factor is known, the noise figure is determined by solving Eq. (22) for F_{dB}. That is,

$$F_{dB} = ENR - 10 \log (Y - 1) \tag{34}$$

where ENR is the Excess Noise Ratio of the noise source tube provided by the manufacturer.

Because a discrete frequency noise tube covers only one frequency, full WR-10 band (or a limited frequency band) coverage would require several of these sources. Although some discrete frequency sources are available, not all frequencies are covered. It would be extremely expensive to develop sources to cover all frequencies individually.

3.4.3 Wideband Gas Discharge Tube

The gas discharge tube method uses an electronic tube filled with a rarefied gas under pressure. A gas discharge tube produces a relatively stable ENR. The ENR of a gas discharge tube depends on the type of gas used; it ranges from 15 dB for mercury or argon and up to 22 dB for helium. With a gas discharge tube output flange connected to the RF port of the mixer and the LO frequency set, output noise power is measured with the gas discharge tube ON (N_h) and again with the gas discharge tube OFF (N_c). The tube is turned ON and OFF by turning its power supply ON and OFF. The two measured values are then used to calculate the Y-factor and noise figure of the system as described in the discrete gas discharge tube method. The procedure is repeated by stepping the LO frequency across the band to obtain the noise figure at each measured frequency in this band.

3.4.4 IF Substitution

The difference between this method and the others is that the Y-factor in this method is determined by means of a precision attenuator inserted in the line carrying the IF signal. To determine Y-factor at a frequency, apply a noise source in the OFF state to the mixer RF port, set the LO to the desired frequency, then adjust the attenuator so that the IF signal is detectable on the power detector. Next, turn the noise source ON and adjust the attenuator until the same power level is reached on the power detector. The difference in the attenuation level of the precision attenuator is the decibel value of the Y-factor. Equation (32) is used to solve for the linear value of the Y-factor. The noise figure is determined by solving Eq. (19) if a Hot/Cold source is used or Eq. (22) if a gas discharge tube is used. The procedure is repeated at the desired frequencies in the band.

The IF substitution method has an advantage over the Hot/Cold source method in that it requires fewer calculations. However, it is even more time consuming because the precision attenuator has to be adjusted at every frequency. Also, the precision attenuator must be linear, otherwise error is introduced into the results.

Both Hot/Cold and wideband gas discharge sources were chosen to characterize the noise measurement system. The Hot/Cold noise source was chosen because it yields the most accurate results. The wideband gas discharge tube was chosen because it provides a flat and relatively large output ENR. Results obtained from the two standards were compared to each other to ensure the accuracy of the characterization. Note that since the noise figure of a device varies with ambient temperature T_0, T_0 was stabilized as much as possible throughout measurements to achieve accuracy.

3.5 ENR Measurement

To comply with the NIST noise calibration procedure, the noise sources are characterized by DSB measurement. SSB characteristics of the noise sources also are determined by the TPM method. The accuracy of the DSB ENR related to the SSB characteristic of the source can then be established.

3.5.1 DSB ENR

In DSB measurement, it is important to choose the correct IF for the best results, particularly if the response of the noise source with frequency has significant variations.

The LO frequency is stepped across the frequency band, and the noise is measured in the ON and OFF state for each frequency increment. The Y-factor is calculated from these data. The ENR of the noise source is determined from Eq. (23) for each frequency. The result is a DSB characterization of a noise source in a specified frequency band.

3.5.2 SSB ENR

The TPM method is chosen to determine the SSB ENR of the noise source. The LO power at frequencies throughout the band of interest should be measured, because the power level is referenced in the method (Appendix A).

The TPM deviates from the DSB technique by the requirements for noise measurement in groups of three LO frequencies at two IFs. Three linear equations result. From the three linear equation system, the SSB noise power is obtained for N_h and N_c. The Y-factor is calculated and the ENR of the noise source is determined from Eq. (23).

4. MEASUREMENTS AND RESULTS

4.1 Noise Measurement System

The noise figure of the measurement system was established by using two different measurement standards (gas discharge tube and Hot/Cold load) and comparing the results.

4.1.1 System Noise Figure with Gas Discharge Tube

Following the procedure of Appendix B, the system noise figure was measured five times at two different IFs to study the stability and consistency of the system performance. The gas discharge tube used in the measurements was the CP Clare TN-165 (Serial #3J030). The gas tube was calibrated at 93 GHz and the ENR was established as 14.2 ± 0.5 dB.

Figures 4(a) and (b) show the system noise figures at two IFs. The scale was chosen to accommodate their comparison in later sections.

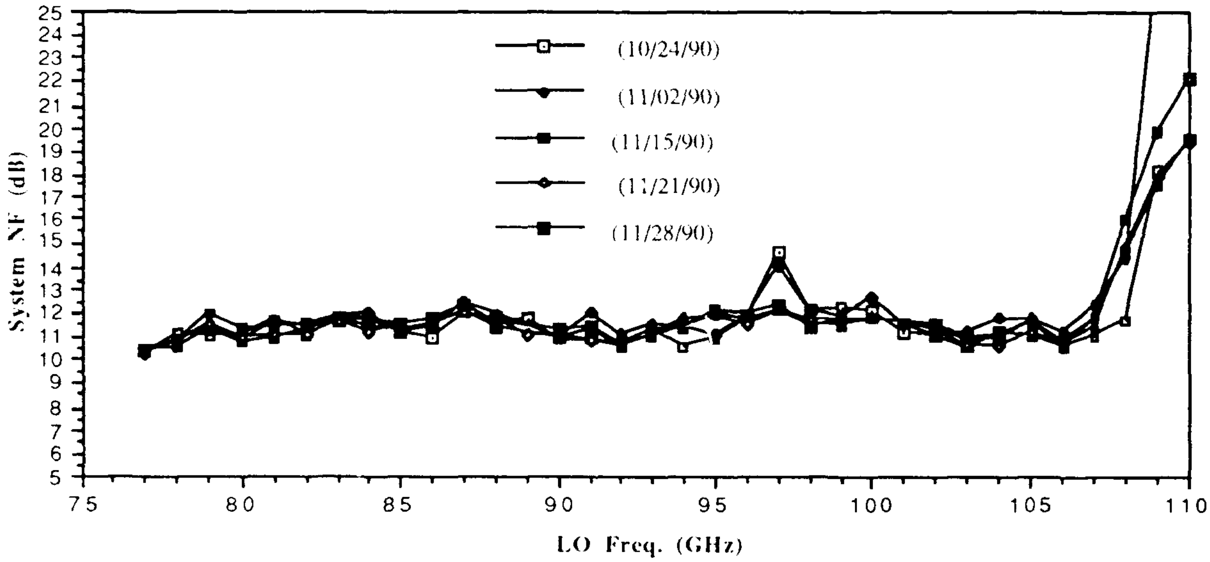

Fig. 4(a) System noise figure with gas discharge tube at f_{IF} = 200 MHz

Comparing Fig. 4(a) to Fig. 4(b), we see that the system noise figure at f_{IF} = 200 MHz is less stable than that at f_{IF} = 400 MHz. In the interval from 77 GHz to 107 GHz, the largest difference between the noise figures at f_{IF} = 200 MHz is about 2 dB (at 97 GHz), while at other test points they differ from each other by about 1 dB. On the other hand, the system noise figures at f_{IF} = 400 MHz are very stable and they agree with each other to within 1 dB. The instability of the system noise figure with f_{IF} = 200 MHz was experimentally determined as a characteristic of the single-ended mixer. The fluctuation above 107 GHz was related to the available LO power. The LO powers at these frequencies were determined to be insufficient to drive the mixer. As a result, the mixer was underdriven and operating under unstable conditions. Measurement errors were another source of the deviation. For Y-factor measurement, this can be as much as ±0.25 dB. With the amount of the measurement error, the deviation in the system noise figure becomes ±0.35 dB, using an ENR of 14.2 dB and a typical Y-factor of 5 dB.

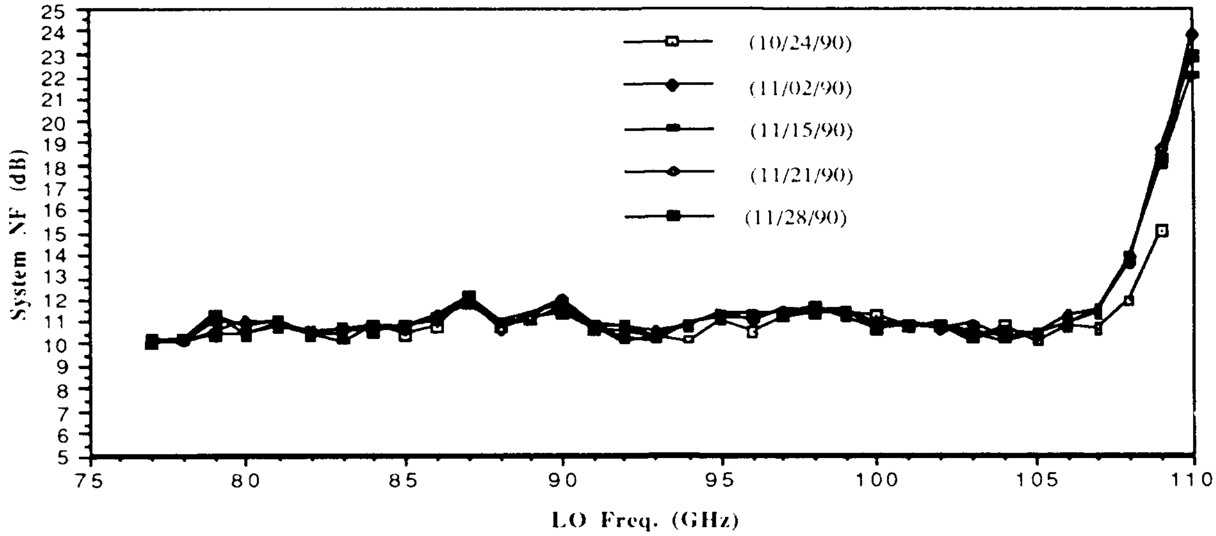

Fig. 4(b) System noise figure with gas discharge tube at f_{IF} = 400 MHz

4.1.2 *System Noise Figure with Hot/Cold Load*

Figure 5 displays the system noise figures obtained from Hot/Cold load measurements. An Alpha Industries cold load 575W/387 (Serial #44) was used. At each IF, an average system noise figure obtained through the gas tube measurement procedure is also presented for verification.

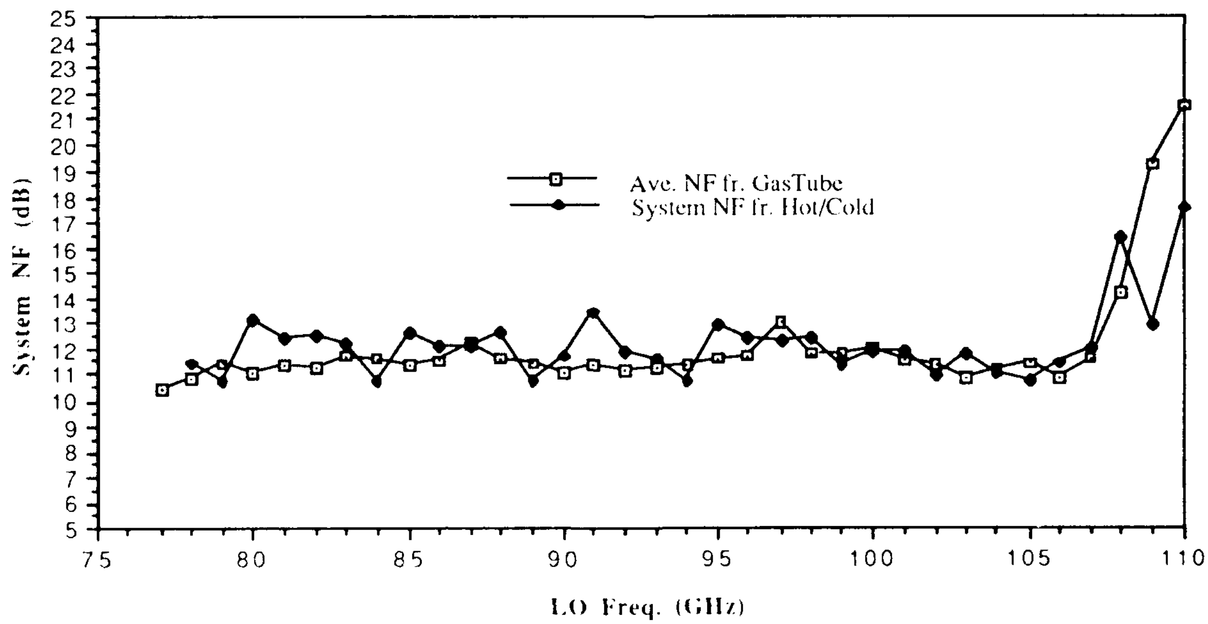

Fig. 5(a) System noise figure at f_{IF} = 200 MHz

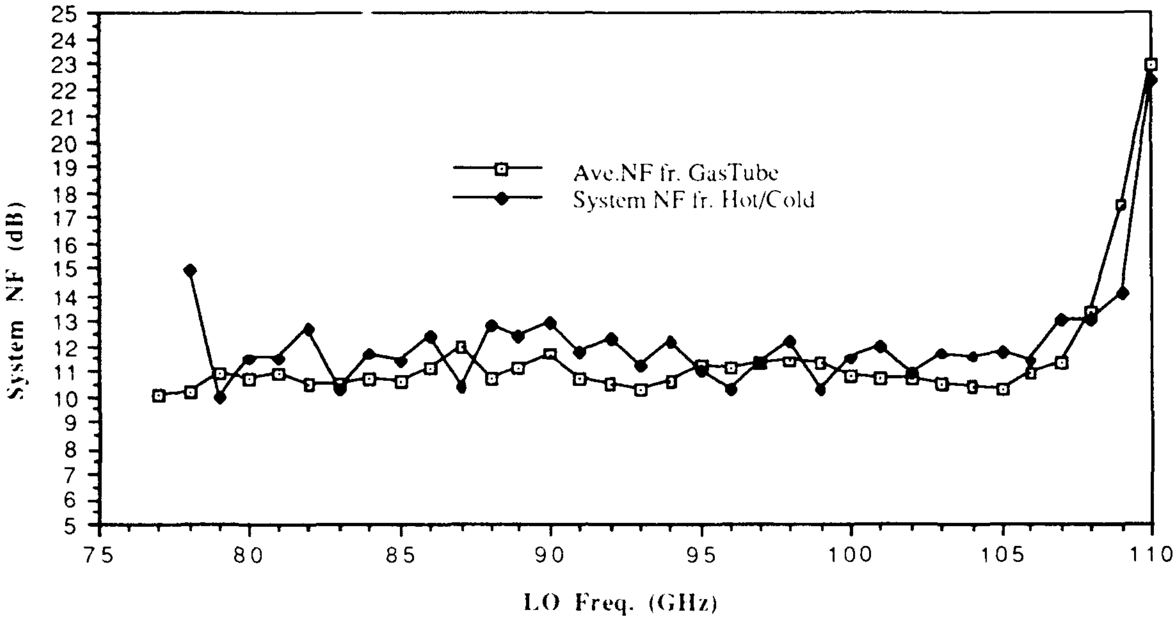

Fig. 5(b) System noise figure at f_{IF} = 400 MHz

In Figs. 5(a) and 5(b), the system noise figures obtained from the two standards agree to within the measurement uncertainty (±1 dB) except at the two ends where the mixer was underdriven. These two regions, however, are small compared to the rest of the band. From the graphs in Figs. 5(a) and 5(b), we can conclude that the operating bandwidth of the system is from 79 GHz to 107 GHz. Since the Hot/Cold load is used as the standard, the resulting noise figure obtained from measurements made with this source is used to establish the system noise figure. The ENR of solid state noise source is determined using this system noise figure in all calculations.

4.2 DSB ENR of Solid-state Noise Source

4.2.1 DSB ENR of Marconi Noise Source

Figures 6(a) and 6(b) present the measured DSB ENR of Marconi noise source DA-9708 (Serial #001) at f_{IF} = 200 MHz and f_{IF} = 400 MHz, respectively. The two graphs also provide data by Marconi for comparison.

From Figs. 6(a) and 6(b), we find that the DSB ENR of f_{IF} = 200 MHz is less stable than that of f_{IF} = 400 MHz. We expected this result because the system performance at f_{IF} = 200 MHz is less stable than that at f_{IF} = 400 MHz. As in the case of system noise figure measurement, measurement errors contribute to the differences in the data. The values of the five measurements at f_{IF} = 400 MHz agree at most frequencies to within the ± 0.25 dB margin of error established for the experiment. Instabilities in the measurement system add to the measurement error for the f_{IF} = 200 MHz. Nevertheless, the five measurements at the two IFs agree to within ±0.5 dB. Since the system was more stable at f_{IF} = 400 MHz, the measured ENR using this IF was chosen to calculate the excess noise produced by the noise source.

The differences between the measurement results and the Marconi data can be explained from the fact that Marconi may use a different IF in measurement and use a different measurement system. These factors will yield slightly different results in the DSB ENR measurements, as discussed in Appendix A.

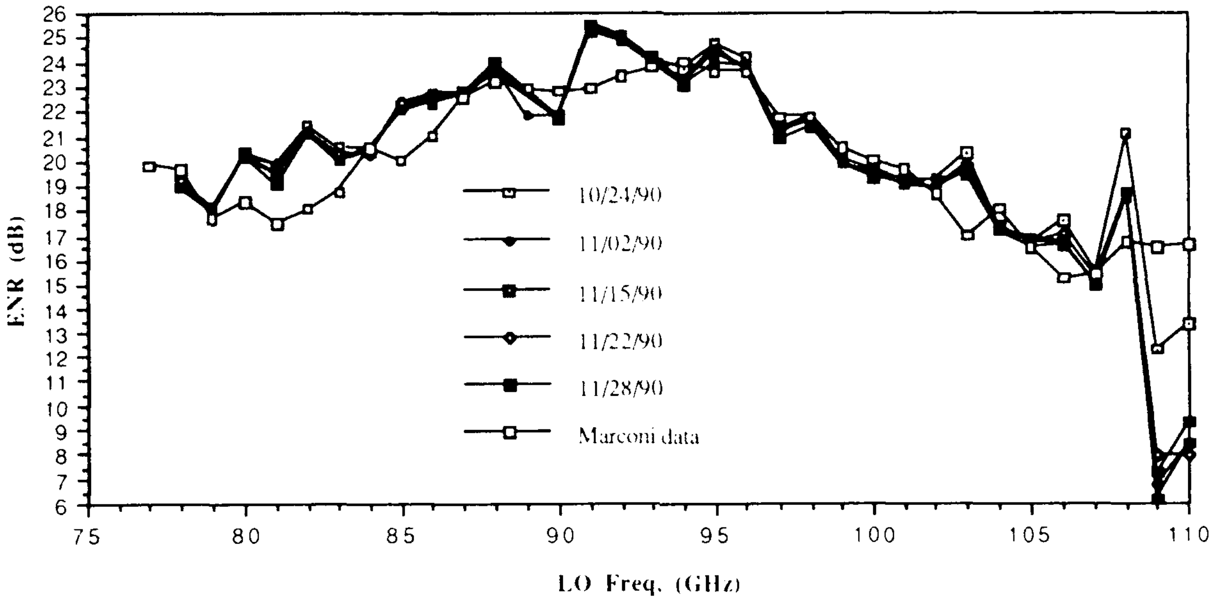

Fig. 6(a) Marconi noise source DSB ENR at f_{IF} = 200 MHz

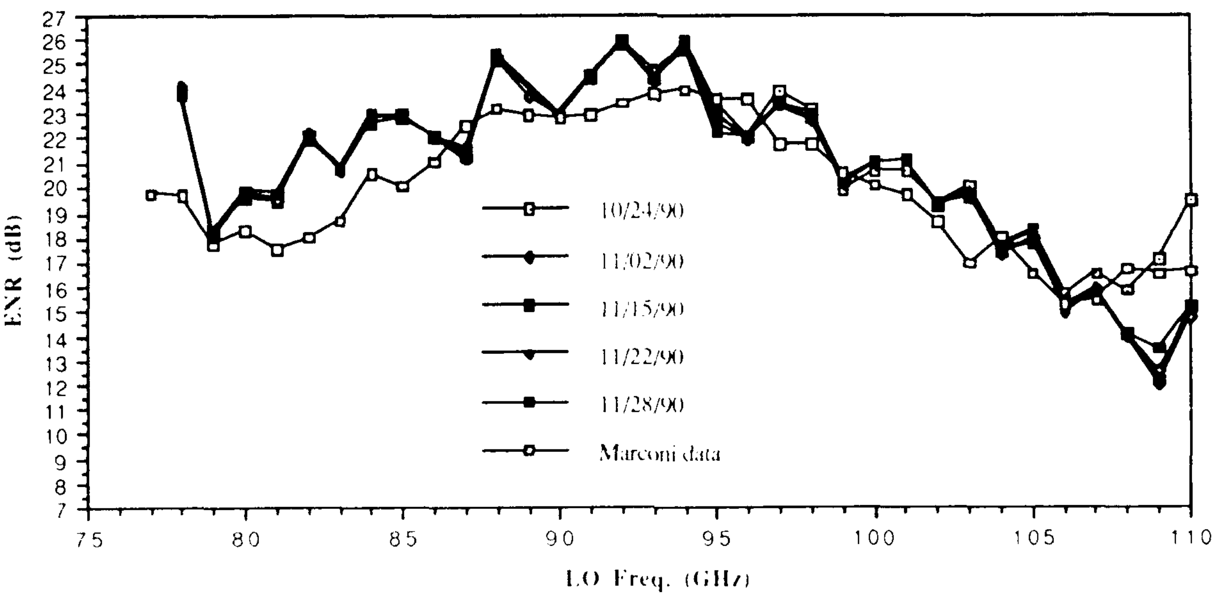

Fig. 6(b) Marconi noise source DSB ENR at f_{IF} = 400 MHz

4.2.2 DSB ENR of Noise Com Noise Source

Figures 7(a) and 7(b) are graphs of the Noise Com noise source NC-65915 (Serial # 3074) DSB ENR. The data provided by the manufacturer, at eleven points, is also presented for comparison.

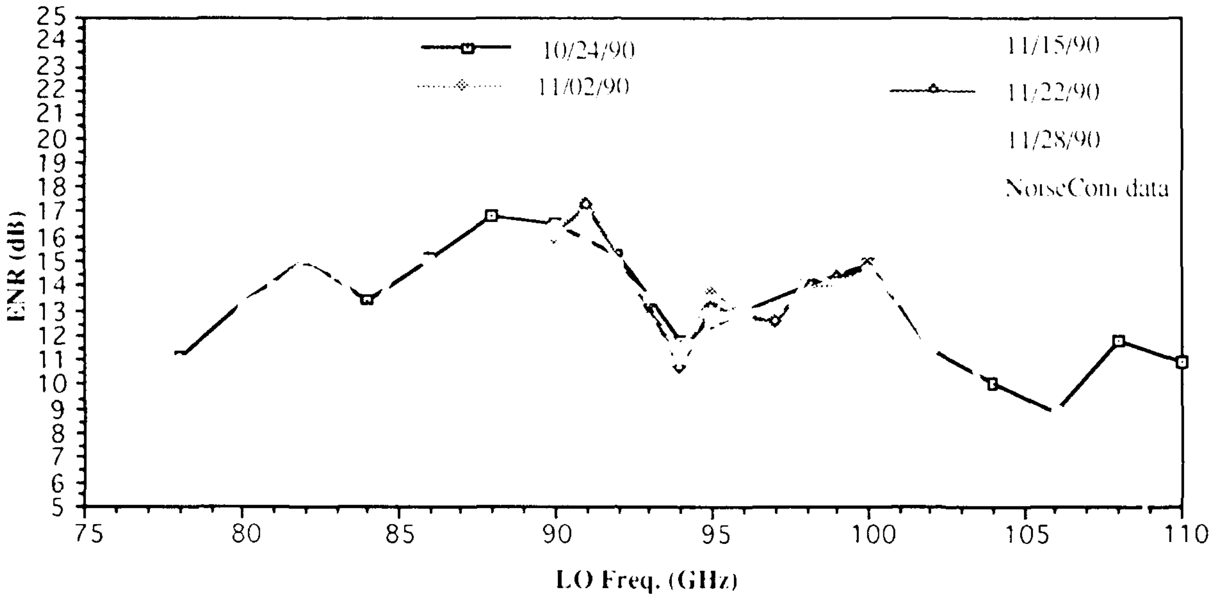

Fig. 7(a) Noise Com noise source at f_{IF} = 200 MHz

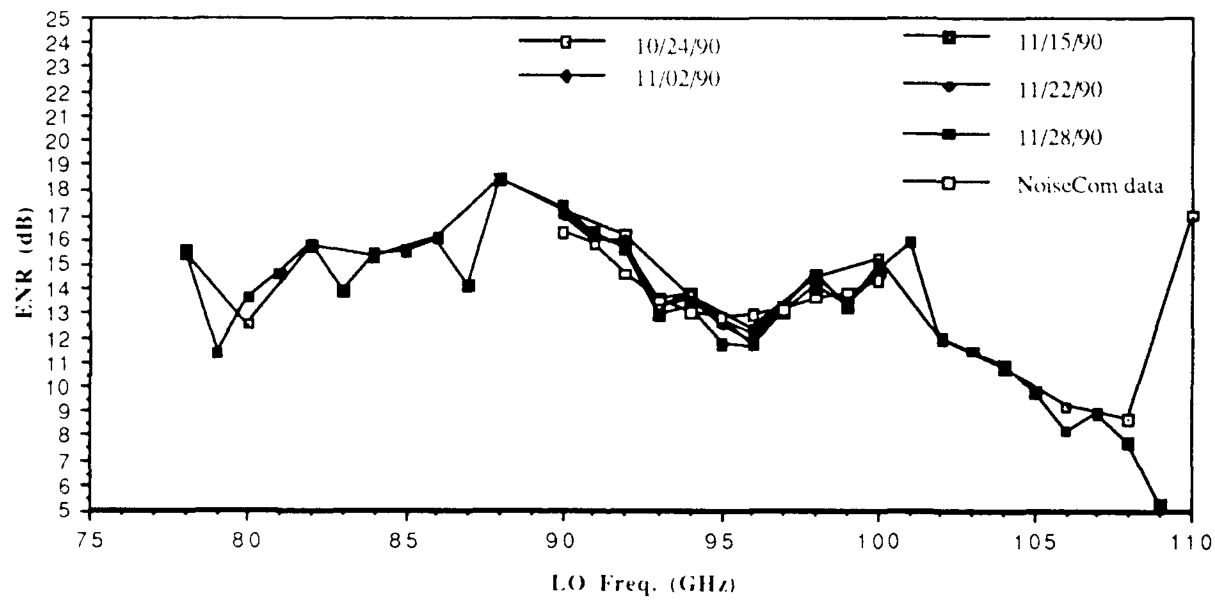

Fig. 7(b) Noise Com noise source at f_{IF} = 400 MHz

As indicated in Figs. 7(a) and 7(b), similar results were obtained at the two IFs as in the case of the Marconi noise source. However, both the stability and power of the output ENR of the Noise Com noise source are less than that of the Marconi noise source.

4.3 SSB ENR Determination

4.3.1 Measurement Apparatus and Results

The SSB ENR of the solid-state noise source was determined by following the TPM procedure in Appendix A. Experimentally, the Millitech double-balanced mixer (model number MXP-10) and Watkins-Johnson signal sources (WJ-785P, WJ-860P, WJ-950P, and WJ-050P) were chosen to satisfy the condition of "identical" performance at three LO frequencies and two IFs in a measured group. The double-balanced mixer was chosen because its IF response is flatter than that of the single-ended mixer. A characteristic of this mixer is that it requires a large LO power (13 dBm typical). Watkins-Johnson signal sources were chosen to drive the mixer because their output powers are larger than that of the frequency locked-loop LO source developed at NRL. However, the Watkins-Johnson sources still do not have enough power to drive the mixer in the upper end of the band. The system noise figure was measured by using the CP Clare gas discharge tube TN-165 (Serial #3J030). The noise source characterized was the Marconi solid-state noise source DA-9708 (Serial #001).

Figures 8 and 9 present the system noise figure and the Marconi noise source SSB ENR. Note that the measurement was done at two IFs (200 and 400 MHz) as explained in Appendix A.

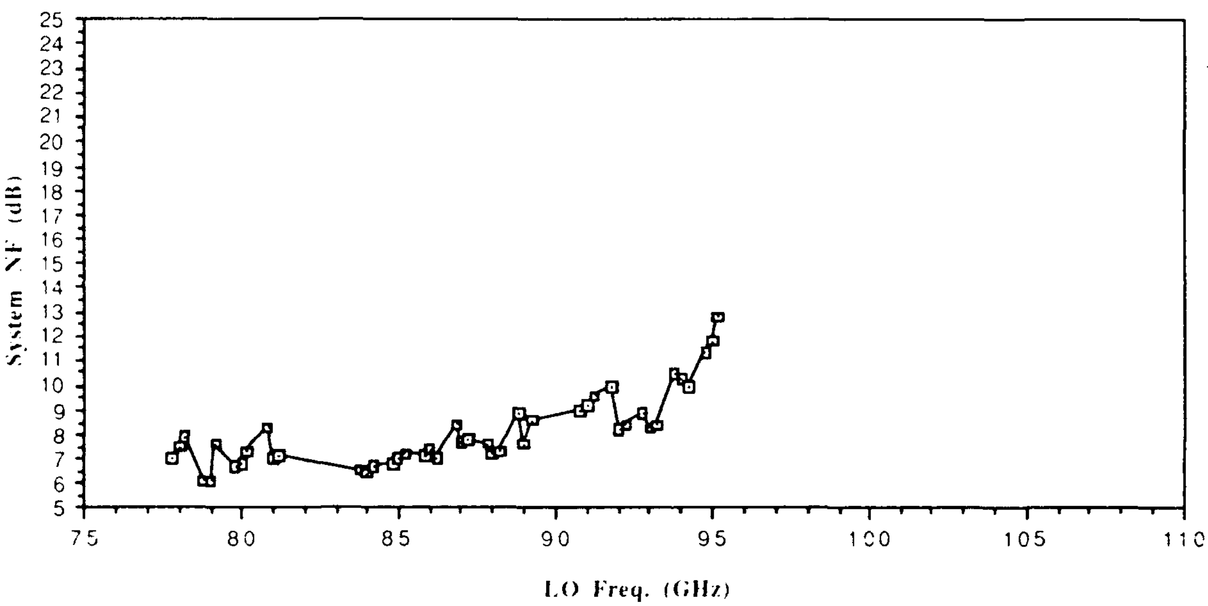

Fig. 8 — Noise figure of measurement system using double balanced mixer and Watkins Johnson sources as LO

4.3.2 Analysis

In Fig. 8, notice that the system noise figure rises sharply at about 95 GHz. This is because the power level of the LO source was not sufficient to drive the mixer at the upper end of the band. The identical performance condition for the TPM was not perfectly satisfied; i.e., the system noise figures at three LO frequencies in a group differ from each other. This variation produces inaccuracy in the measurement. These inaccuracies are discussed later in this section.

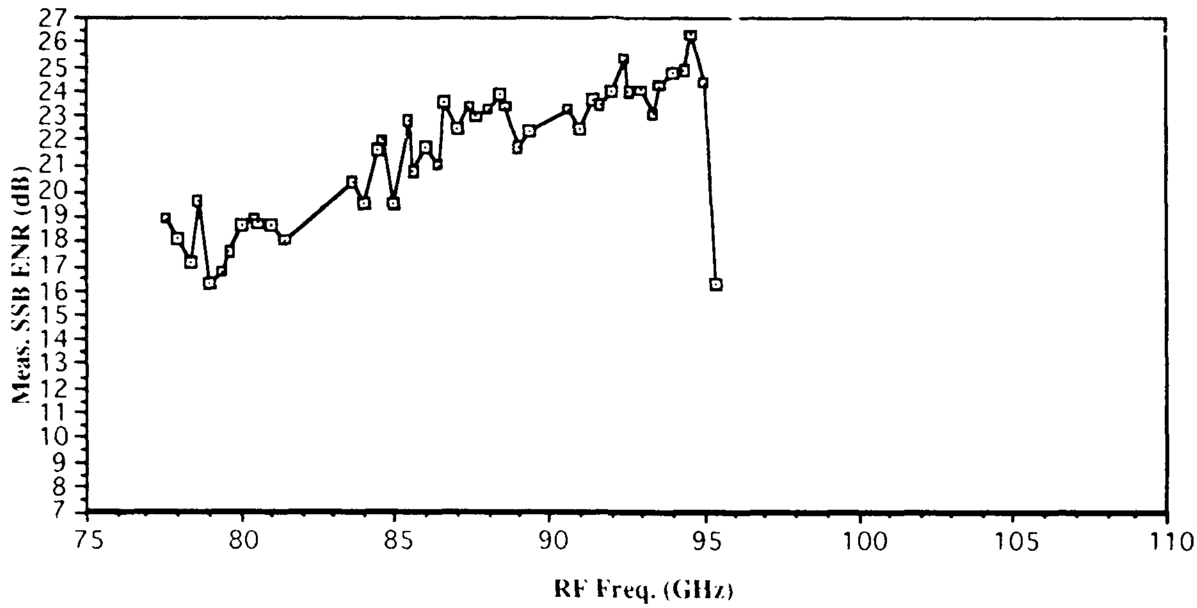

Fig. 9 — Measured SSB ENR of Marconi noise source

Figure 9 shows the SSB ENR of the Marconi noise source. Notice that the SSB ENR at 95.4 GHz differs from that at 95 GHz by more than 4 dB. This abrupt transition of the output ENR seems unlikely to be a characteristic of the solid-state noise source. The explanation lies in the fact that the last data point is in a cut-off region of the response curve of the mixer, resulting from the LO underdriving the mixer. As a result, the data for 95.4 GHz is invalid. In fact, data in the whole group (at 94.6 GHz, 95 GHz, and 95.4 GHz) can be omitted since they were obtained from the same equation system. The accuracy of the measured SSB ENR, however, should be verified by another measurement. The DSB ENR of the noise source can be either calculated from the measured SSB ENR or measured directly, as in Section 4.2. The two values are then compared. Note that the ENR is a characteristic of a noise source; it is independent of the measurement system. Therefore, if the measured DSB ENR obtained by using another system agrees with the calculated values, we can conclude that the SSB ENR obtained from the TPM is accurate.

In the process of solving the linear equation system, the ON and OFF levels for each RF frequency were determined. From these ON and OFF levels, the DSB ENR of the noise source is calculated. Table 2 shows the calculated DSB ENR from the data of SSB ENR at 79.6 GHz, 80 GHz and 80.4 GHz.

Table 2 — Calculated DSB ENR

Measured SSB ENR			Calculated DSB ENR		
RF Freq.(GHz)	ON level (mW)	OFF level (mW)	LO Freq.(GHz)	IF Freq. (MHz)	Cal. DSB ENR (dB)
79.6	27652	2205	79.8	200	18.08
80.0	34007	2159	80.0	400	18.19
80.4	30558	1821	80.2	200	18.72

This means that if the LO frequency is tuned to 79.8 GHz and the IF of the receiver is 200 MHz, then the calculated DSB ENR results from the down conversion of noise powers at 79.6 GHz and 80 GHz to the 200 MHz IF, e.g.,

$$ENR_{DSB\ at\ LO=79.8GHz} = NF_{at\ LO=79.8GHz} + 10\log[((27652+34007)/(2205+2159)) - 1]$$

$$= 6.90 + 10\log[((27652+34007)/(2205+2159)) - 1]$$

$$= 18.8 \text{ dB}$$

However, if the LO frequency is tuned to 80 GHz and IF is 400 MHz, then the calculated DSB ENR results from the down-conversion of noise powers at 79.6 GHz and 80.4 GHz to the 400 MHz IF. The calculated DSB ENR with f_{LO} = 80.2 GHz and f_{IF} = 200 MHz is obtained in this same manner.

In the DSB measurement setup, the down-conversion mixer is a Millitech single-ended mixer (MXW-10) and the LO is the frequency locked-loop source that was developed at NRL. Figures 10 and 11 display the system noise figure and the measured DSB ENR of the Marconi noise source.

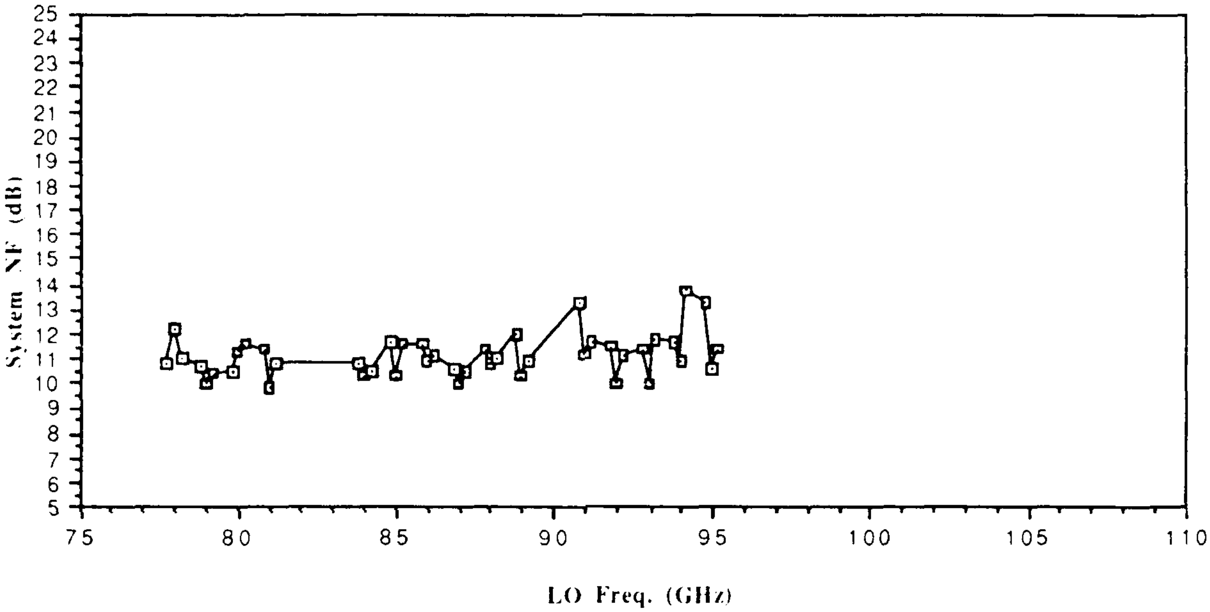

Fig. 10 System noise figure with single ended mixer and frequency locked-loop as LO

In comparing Fig. 10 to Fig. 8, note that the system noise figure of the setup with the single-ended mixer for direct DSB measurement is about 4 dB larger than that of the setup with the double-balanced mixer for TPM. However, as stated previously, the ENR of a noise source should not depend on the measurement system, and agreement between the calculated and measured DSB ENR is expected.

Figure 11 displays the expected result. Despite using two different setups with two different noise figures, the calculated and measured DSB ENR of the Marconi noise source closely agree to each other. As explained earlier, the first and last three calculated data points can be omitted because they were obtained in an area of unstable operation. Other data points agree to within ± 0.5 dB; in fact, many of them agree to within ± 0.25 dB. The differences between the two sets of data are explained from the fact that the calculated data was obtained by the TPM method and the identical performance condition was not satisfied at all measurement frequencies. Other factors such as measurement error and component differences contribute to the noted deviations. However, within an allowance of ± 0.5 dB, the two curves agree. Therefore, with the allowance, we conclude that the SSB ENR obtained from the TPM method is accurate.

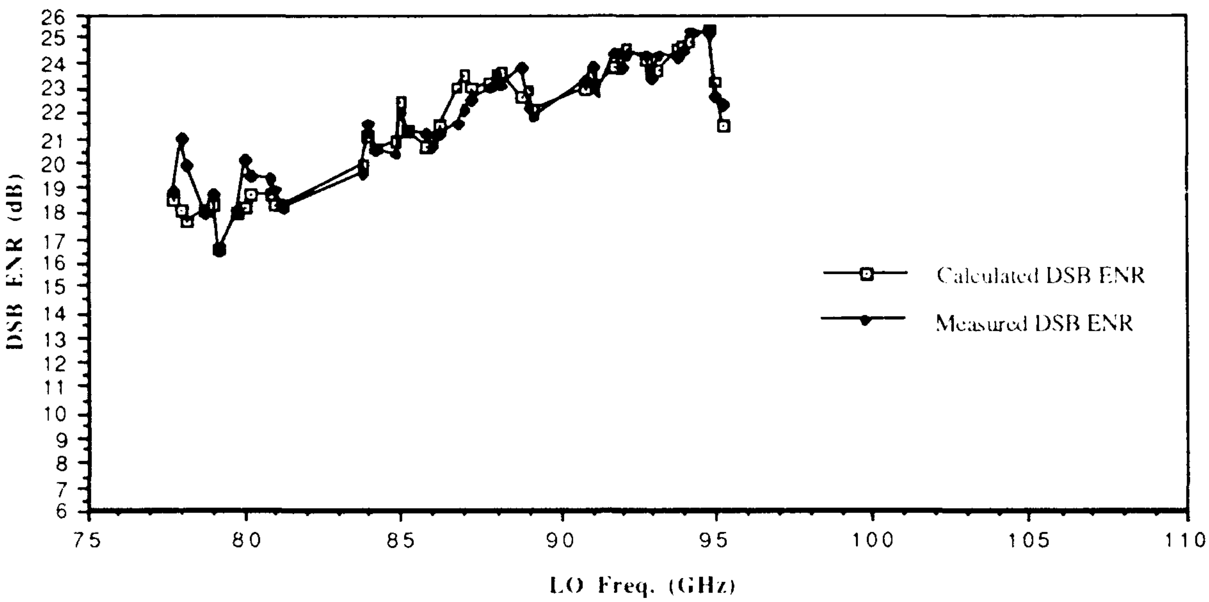

Fig. 11 Calculated and measured DSB ENR of Marconi noise source

5. SUMMARY AND CONCLUSION

A WR-10 noise measurement system was developed based on the Y-factor technique with frequency down-conversion. The frequency down-conversion is accomplished by using a millimeter wave single-ended mixer. A signal source with a capability to step across the WR-10 band and lock to the desired frequency to within ±10 Hz was developed to serve as a highly accurate LO driver for the single-ended mixer.

The system noise figure was characterized with standard noise sources: a wideband gas discharge tube and Hot/Cold load. With an allowance of ±1 dB for experimental error, the system noise figures obtained from the two standards are strongly correlated. This establishes the consistency of the system. The repeatability of the system performance was verified by five measurements at two IFs with the gas discharge tube. The results show that the system has the desired repeatability at IF = 400 MHz. The only unsatisfactory feature of the system is that the operating bandwidth does not cover the entire WR-10 band, although it covers a large portion of the band; i.e., 79 - 108 GHz. This is because the LO output power at the two ends of the band was very small and the mixer was under-driven. Advances in millimeter wave technology have made it practical to replace the existing baseband source with a source that produces similar output power but improves the system bandwidth. Future work will incorporate the newer YIG source that operates from 25-37 GHz.

Solid-state noise sources developed under the millimeter wave program were evaluated with the WR-10 measurement system. The noise sources were evaluated based on their DSB characteristics to comply with the NIST noise calibration procedure. The Three Point Measurement was developed and applied to evaluate the SSB ENR of noise sources. The solid-state noise source DSB ENR evaluation showed that the Marconi noise source produced a repeatable output ENR, ±0.5 dB, in excess of 15 dB. On the other hand, the Noise Com noise source produced a less stable and lower output ENR. The Noise Com noise source also has a narrower bandwidth. These properties make the Noise Com noise source unacceptable. The SSB ENR of the Marconi noise source was also evaluated by the TPM method. The accuracy of the TPM was verified by comparing the calculated DSB ENR (calculated from the measured SSB ENR) to the directly measured DSB ENR. Agreement was within ±0.5 dB.

In conclusion, WR-10 noise measurements were accomplished by the system developed in this study. The results of this study indicate that research for higher output power baseband source should be continued to improve the system bandwidth. In addition, considering the constraints on oscillator output power, advances may result from research into improving the conversion efficiency of mixers and multipliers, or from amplifier improvements. Also, the development of a fundamental WR-10 signal source could be used to improve the operational characteristics of the system. The measurement system will be integrated in a field measurement test set. A preliminary study shows that VXI (VME eXtended Instrument) is a desirable approach because it provides the portable and automatic properties necessary for an operational environment. Further study on the feasibility of using the VXI instrument to accomplish the goal is recommended.

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5. "Noise Source Technical Reference Brochure," (brochure), CP Clare Corporation, Chicago, IL, 1979, p. 2.

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Appendix A

FREQUENCY DOWN-CONVERSION

At WR-10 band, frequency down-conversion can be accomplished by using a millimeter wave mixer as shown in Fig. A1.

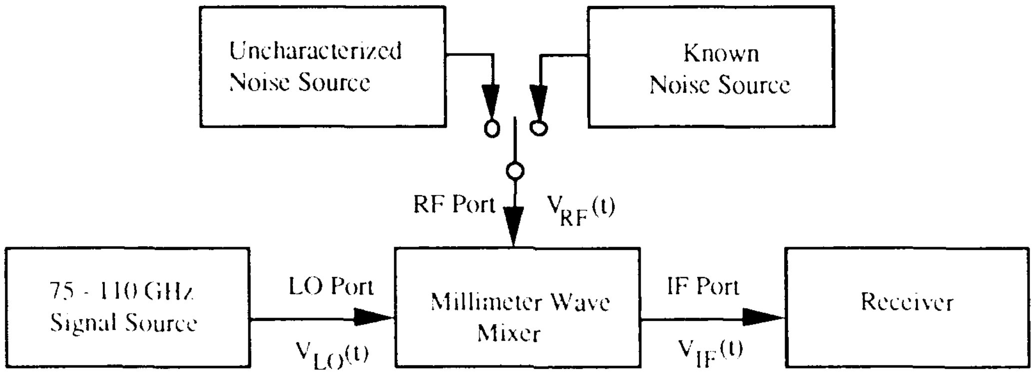

Fig. A1 Block diagram of measurement system

A1. DOUBLE SIDEBAND MEASUREMENT

Basically, a mixer is realized in practice by a square-law device as shown in Fig. A2. The time domain transfer characteristic of this device is

$$i_0(t) = A \cdot v_i(t) + B \cdot [v_i(t)]^2 \tag{A1}$$

where A and B are constants of proportionality and

$$v_i(t) = v_1(t) + v_2(t) \,. \tag{A2}$$

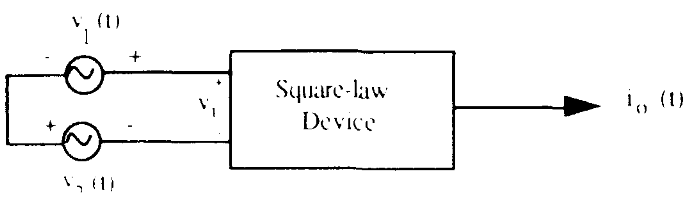

Fig. A2 Mixer as a square law device

If $v_1(t)$ and $v_2(t)$ are defined as

$$v_1(t) = V_1(t)\cdot\cos[\omega_1 t] \tag{A3}$$

and

$$v_2(t) = V_2(t)\cdot\cos[\omega_2 t], \tag{A4}$$

then, after substitution, Eq. (A1) becomes

$$i_o(t) = A(V_1\cos[\omega_1 t] + V_2\cos[\omega_2 t]) + BV_1^2\cos[\omega_1 t]^2 + BV_2^2\cos[\omega_2 t]^2 + 2\cdot BV_1V_2\cos[\omega_1 t]\cos[\omega_2 t]. \tag{A5}$$

Usually, the first four terms in Eq. (A5) are not of interest in signal processing and they are removed by filtering. The last term in Eq. (A5) is called the product term and it produces the desired frequency conversions. Using a trigonometric identity, the product term becomes

$$2B\cdot V_1V_2\cos[\omega_1 t]\cos[\omega_2 t] = B\cdot V_1V_2\cos([(\omega_1-\omega_2)t] + B\cdot V_1V_2\cos[(\omega_1+\omega_2)t]). \tag{A6}$$

Complete analysis of a mixer can be found in communication texts.* For our purpose, frequency conversion may be analyzed by considering the mixer as a signal multiplier, as shown in Fig. A3. In this model, the multiplier produces the product term as described in Eq. (A6) and the bandpass filter rejects the unwanted signal produced by the mixer; i.e., the last term in Eq. (A6).

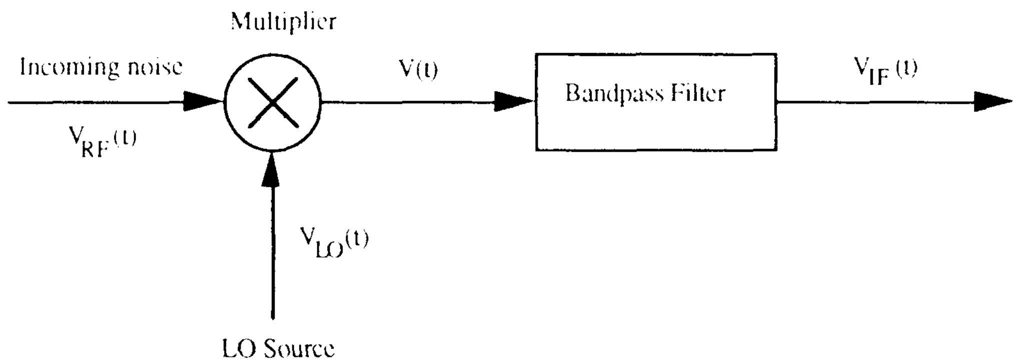

Fig. A3 Simple model of a mixer as a multiplier

Suppose that the incoming noise $V_{RF}(t)$ in Fig. A3 has the form

$$V_{RF}(t) = n(t)\cos[(\omega_{RF})t], \tag{A7}$$

where $n(t)$ is the noise signal and ω_{RF} is an arbitrary angular frequency. Also, suppose that the output signal of the LO source $V_{LO}(t)$ is

$$V_{LO}(t) = A\cos(\omega_{LO}t), \tag{A8}$$

where A is amplitude of the LO output. By the use of the trigonometric identity, the output of the multiplier V(t) is

* For example, see R. A. Williams, *Communications Systems Analysis and Design* (Prentice Hall, Englewood Cliffs, NJ 1987).

$$V(t) = n(t)\cos[(\omega_{RF})t] \cdot A\cos(\omega_{LO}t) \tag{A9}$$

$$V(t) = 0.5n(t) \cdot A\cos[(\omega_{LO} - \omega_{RF})t] + 0.5n(t) \cdot A\cos[(\omega_{LO} + \omega_{RF})t]. \tag{A10}$$

On the right-hand side of Eq. (A10), the first term is the frequency down-conversion and the second term is the frequency up-conversion of the original incoming noise. The original incoming signal is now distributed at two frequencies: $(\omega_{LO} - \omega_{RF})$ and $(\omega_{LO} + \omega_{RF})$. These frequencies are referred to as intermediate frequencies ω_{IF}, i.e., for frequency down-conversion

$$\omega_{IF} = \omega_{LO} - \omega_{RF}. \tag{A11}$$

Equation (A11) shows that the incoming noise distributed below the LO frequency, at w_{IF} apart, has been down-converted to the frequency w_{IF}. The lower sideband characteristic implied in Eq. (A11) becomes clearer if we rearrange the equation as

$$\omega_{RF} = \omega_{LO} - \omega_{IF}. \tag{A12}$$

Applying the same trigonometric identity to Eq. (A9), we show the upper sideband of the incoming noise is also down-converted to the same IF, i.e.,

$$V(t) = 0.5n(t) \cdot A\cos[(\omega_{RF} - \omega_{LO})t] + 0.5n(t) \cdot A\cos[(\omega_{RF} + \omega_{LO})t]. \tag{A13}$$

The IF is shown in Eq. (A13) as

$$\omega_{IF} = \omega_{RF} - \omega_{LO}. \tag{A14}$$

The bandpass filter in Fig. A3 is to pass the signal centered at the intermediate frequency to the IF port of the mixer. Thus, by combining Eqs. (A11) and (A14), the resulting down-converted IF signal $V_{IF}(t)$ is

$$V_{IF} = C \cdot n(t) \cdot \cos[\omega_{IF}t], \tag{A15}$$

where

$$\omega_{IF} = |\omega_{RF} - \omega_{LO}|. \tag{A16}$$

Note that absolute value notation is used in Eq. (A16).

Constant C in Eq. (A15) is a characteristic of the mixer in use. However, a mixer is not specified by this constant; instead it is specified by a quantity called "conversion loss." Conversion loss is the ratio of the output signal power to the input signal power, i.e., the ratio of the power of $V_{IF}(t)$ to the power of n(t). If expressed in dB, conversion loss is the amount of power, in dBm, that the incoming signal has lost in the frequency down-conversion process. The specified conversion loss of a mixer holds true only if the LO power is sufficient to drive the mixer into the saturated operational mode. The required LO power to drive a mixer is a critical constraint because lower power will cause the mixer to be underdriven and operated in a roll-off area of its response curve, which is an unstable area of operation.

From Eq. (A16), noise on both sides of the LO frequency, noise at $(\omega_{LO} - \omega_{IF})$ and $(\omega_{LO} + \omega_{IF})$, are down-converted to the same IF. The DSB conversion becomes clearer by using a graphical spectrum analysis method.

Suppose that power spectrum of the incoming noise at two frequencies $(\omega_{LO} - \omega_{IF})$ and $(\omega_{LO} + \omega_{IF})$ are A and B, as indicated in Fig. A4. If the LO frequency is tuned to ω_{LO}, then, according to Eq. (A11), A is frequency down-converted to ω_{IF} with magnitude A', according to Eq. (A14); B is also frequency down-converted to ω_{IF} with a magnitude B'. The resulting spectrum C in Fig. A5 is the sum of A' and B'. Power of C depends on powers and relative phase between A' and B'. Since phase of a noise signal is totally random, we may consider that noise represented by A' and B' are in phase. Thus C, the power of the resulting IF signal $V_{IF}(t)$, is the sum of A' and B'.

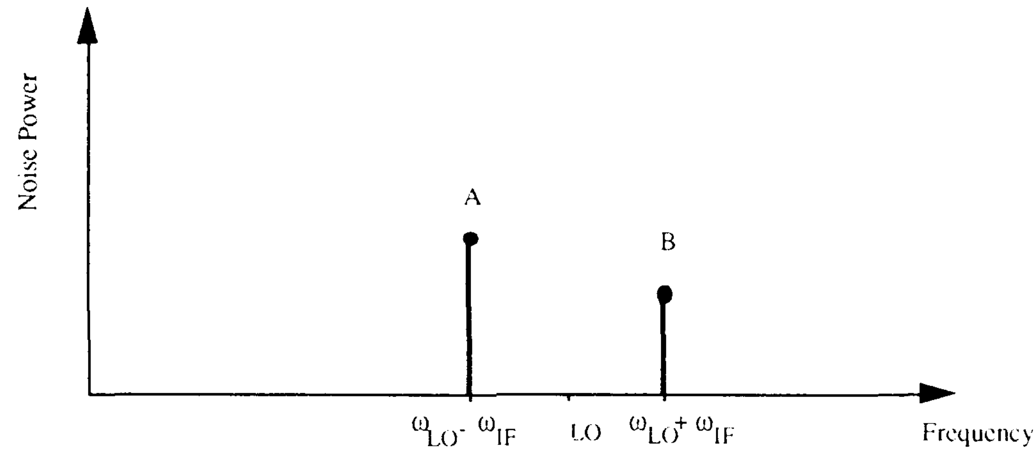

Fig. A4 Power of a noise source at $(\omega_{LO}-\omega_{IF})$ and $(\omega_{LO}+\omega_{IF})$

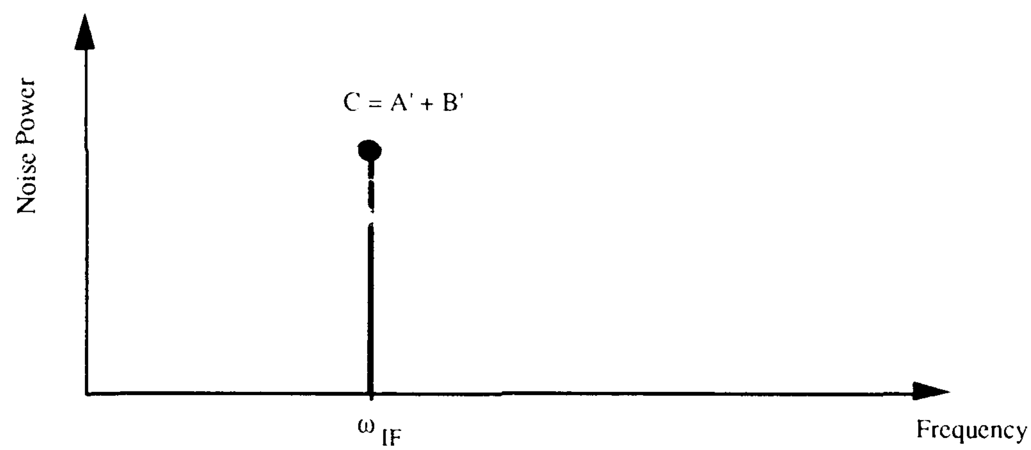

Fig. A5 Resulting power of wideband noise at $(\omega_{LO}-\omega_{IF})$ and $(\omega_{LO}+\omega_{IF})$ after being frequency down-converted to ω_{IF}

Because noise sources to be characterized by the system developed under this study are wideband noise sources a noise measurement using the frequency down-conversion scheme, as shown in Fig. A1, is a DSB measurement.

In a DSB measurement, system noise figure or noise source ENR are calculated based on the measured average powers of the two sidebands. Suppose that power spectrum of a noise source at two frequencies $(\omega_{LO}-\omega_{IF})$ and $(\omega_{LO}+\omega_{IF})$ are A and B as shown in Fig. A4. If the noise source is ON, LO tuned to ω_{LO} and IF is ω_{IF}, the resulting measured noise power C_{on} is

$$C_{on} = A' + B', \tag{A17}$$

where A' and B' are the frequency down-converted versions of A and B, respectively.

When the noise source is in the OFF state, it acts as an impedance at a temperature, and generates thermal noise. Because thermal noise has a flat power spectrum, the resulting measured power with the noise source OFF is the sum of two equal power levels. That is, if X is the level of the thermal noise generated by the noise source and C_{off} is the resulting measured power, then

$$C_{off} = X' + X' = 2X', \tag{A18}$$

where X' is the frequency down-converted version of X.

The Y-factor at this LO frequency is

$$Y = C_{on}/C_{off}, \tag{A19}$$

or

$$Y = \frac{1}{X'} \cdot \frac{A' + B}{2}, \tag{A20}$$

which is the Y-factor based on the average value of noise powers at two frequencies $(\omega_{LO}-\omega_{IF})$ and $(\omega_{LO}+\omega_{IF})$.

The DSB measurement discussed in this section complies with the NIST noise calibration procedure. However, it is important to choose the correct IF so that the results closely reflect the noise source's SSB characteristic. Filtering must be performed to measure the SSB noise power.

A2. SINGLE SIDEBAND MEASUREMENT

The preselector and TPM methods are used to measure SSB. The former is extensively applied in noise measurement at lower frequencies, while the latter is computationally intensive.

A2.1 SSB Measurement by Preselector Method

In this method, a filter is inserted between the noise source and the RF port of the mixer to preselect the desired sideband. If a bandpass filter with a bandwidth of ω_B, as shown in Fig. A6, is inserted, then only the noise signal in this bandwidth enters the RF port of the mixer, i.e., only noise signal "B" enters the mixer RF port for frequency down-conversion.

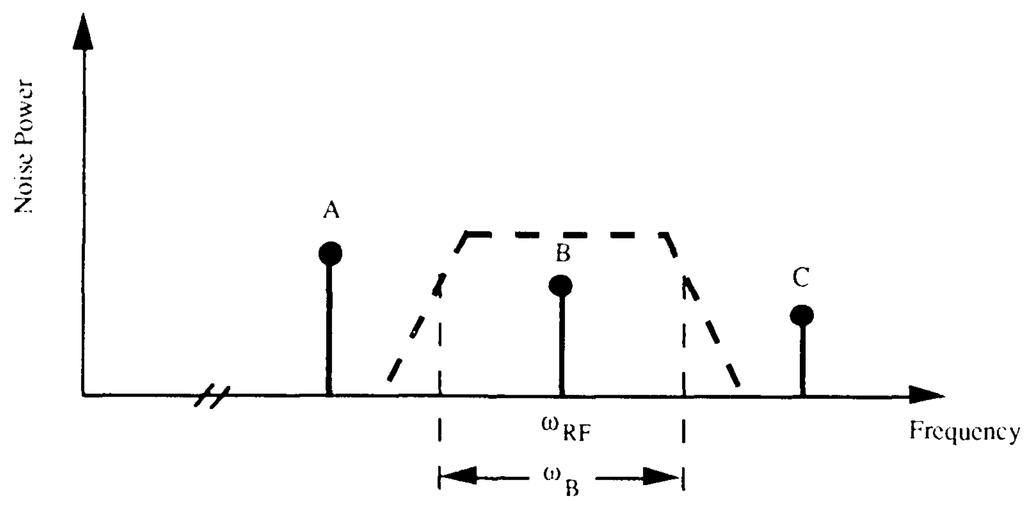

Fig. A6 Effect of bandpass filtering on noise signal

From Eq. (A16), to convert noise at a frequency of ω_{RF} to an IF of ω_{IF}, the LO frequency ω_{LO} can be tuned to either side of ω_{RF}, i.e.,

$$\omega_{LO} = \omega_{RF} - \omega_{IF} \quad \text{or} \quad \omega_{LO} = \omega_{RF} + \omega_{IF} . \tag{A21}$$

There is a precaution in this method; the bandwidth of the bandpass filter must be less than twice the IF, i.e.,

$$\omega_B < 2 \cdot \omega_{IF} . \tag{A22}$$

If $\omega_B \geq 2\ \omega_{IF}$ then when the LO frequency ω_{LO} is tuned to the center frequency of the bandpass filter, filtered noise on both sides of w_{LO} will appear in the IF signal and the result is a DSB measurement.

If the condition in Eq. (A21) is satisfied, then for each LO frequency, only one sideband of the RF signal is down-converted to the IF. The other sideband is rejected by the filtering resulting in an SSB measurement.

Bandpass filters for the WR-10 band are available with optional bandwidths from 1% to 15% of center frequency. If the inserted filter has a center frequency at 81 GHz with a bandwidth of 15%, then the noise signal in the 75 GHz to 88 GHz frequency range is passed to the filter's output and enters the RF port of the mixer. If the millimeter wave mixer has an IF of 14 GHz, then the 75 GHz to 88 GHz noise signal can be frequency down-converted by varying LO frequency accordingly to Eq. (A16), i.e., 89 GHz to 102 GHz. At least three filters are required to convert the entire WR-10 band. Since a single tunable filter is not available at WR-10 band, the preselector method is less desirable in the design of an automatic noise measurement system.

A2.2 SSB Measurement by the Three Point Measurement Method

In this method, the noise signal is not preselected and each measurement is actually a DSB measurement. Noise powers are measured in a group of three LO frequencies and two IFs to obtain a system of three linear equations with three unknowns. Suppose that power spectrum of the noise signal at three frequencies (ω_{RF} - $2\omega_{IF}$), ω_{RF}, and (ω_{RF} + $2\omega_{IF}$) are A, B, an ' C as described in Fig. A7. The measurements at three LO frequencies and two IFs are done as follows.

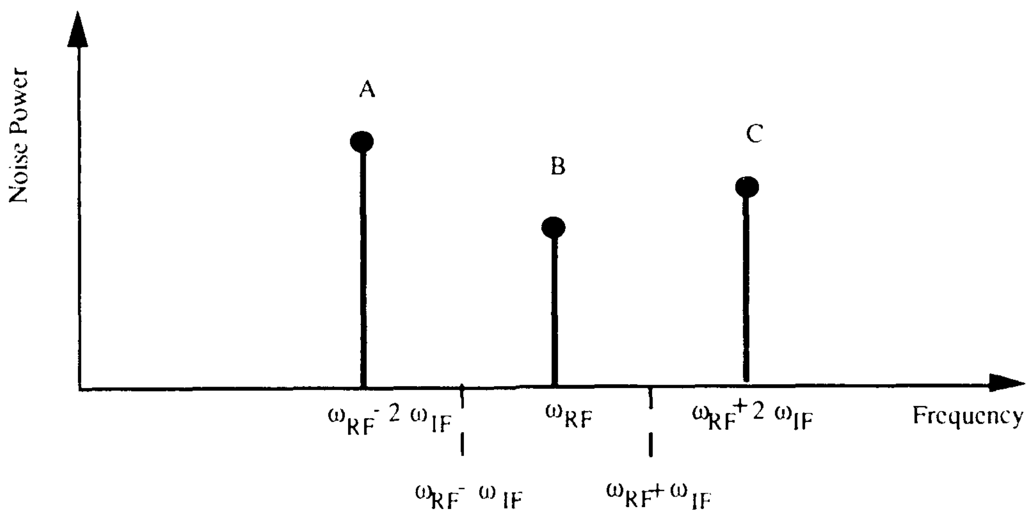

Fig. A7 Power spectrum of noise at three different frequencies with $2\omega_{IF}$ separation

First, tune the LO frequency to $\omega_{LO} = \omega_{RF} - \omega_{IF}$. According to frequency down-conversion theory, the resulting power is the sum of A' and B'; A' and B' are the frequency down-converted versions of A and B, respectively. That is, if the measured power is denoted as P_1, then

$$P_1 = A' + B'. \tag{A23}$$

The LO frequency is then tuned to $\omega_{LO} = \omega_{RF} + \omega_{IF}$. As above, the resulting measured power is the sum of B' and C'. If the measured power is denoted as P_2, then

$$P_2 = B' + C'. \tag{A24}$$

Finally, the LO frequency is tuned to $\omega_{LO} = \omega_{RF}$ to measure the sum of A' and C'. An extra step must be done here to obtain the desired result. Since A and C are $2\omega_{IF}$ apart from ω_{RF}, the IF of the receiver needs to adjust to $\omega'_{IF} = 2\omega_{IF}$ so that A and C are down-converted to this new IF. If the resulting measured power is denoted as P_3, then

$$P_3 = A' + C'. \tag{A25}$$

Using Eqs. (A22), (A23), and (A24), the three unknowns A', B', and C' can be solved by Gaussian elimination, yielding

$$A' = \frac{P_1 - P_2 + P_3}{2}, \tag{A26}$$

$$B' = \frac{P_1 + P_2 - P_3}{2}, \tag{A27}$$

and

$$C' = \frac{P_2 + P_3 - P_1}{2}. \tag{A28}$$

The same procedure is repeated in both states (ON and OFF) of the noise source to obtain ON and OFF levels at the three frequencies. Once ON and OFF levels are determined, Y-factors and SSB ENR are calculated.

In the evaluation of solid-state noise sources, however, the TPM method is difficult to accomplish. It requires the millimeter wave mixer and the receiver to have "identical" performance characteristics (i.e., the same operating point) within the group of three LO frequencies and two IFs. If this requirement is not satisfied, then the two A's in Eqs. (A22) and (A24) are two different variables. This is also true for the two B's in Eqs. (A22) and (A23), and the two C's in Eqs. (A23) and (A24). These six unknowns can not be solved by the three linear equation system. The two critical constraints to satisfy the "identical" performance requirement are LO power level and flatness of IF response of the system.

LO power: Since it is an integration of diodes, the mixer can operate in either a saturated or a roll-off area. The operation of the mixer is determined by its driver—the LO source power. Once it is driven into a saturated operating region, the mixer response no longer depends on the LO power. On the other hand, the roll-off area is the operation area in which the mixer response depends on the LO power. Thus, if LO powers at three frequencies in a group are all equal or above the required level to drive the mixer into saturation, then there is no difference in the mixer performance. Hence, the "identical" performance at three LO frequencies is satisfied. However, if LO powers are below the required minimum level, then the mixer is underdriven and operates in the roll-off area. As a consequence, if it is driven by different LO powers, the same input will produce different outputs. This is the situation where we have three equations with six unknowns, as described above. If this is the working condition, one way to satisfy the "identical" performance requirement is to level the LO powers. That is, make the mixer operate at the same operation point in its roll-off area. To accomplish the leveling, an adjustable attenuator is inserted between the LO source output and the LO input port of the mixer. The attenuator is tuned according to relative values between the three LO powers in a group to level them. The LO power at desired frequencies should be measured before noise measurement.

System IF characteristic: Using two different IFs in measurement leads to the requirement that the system must have the same response at these two IFs. If the system responses at the two IFs are different, then the same input will produce different output powers at the two IFs. The problem results in having more unknowns than available equations. That is, A' and C' in Eq. (A24) are different from A' in Eq. (A22) and C' in Eq. (A23). The system IF response is determined by the mixer and components in the receiver section, i.e., IF amplifier, IF filter, and power detector. Nothing in the system design will change the characteristics of these components, however, the component can be experimentally chosen to obtain the best results.

Appendix B

MEASUREMENT AND CALCULATION PROCEDURES

This appendix presents procedures for using a Hot/Cold load and gas discharge tube to measure the noise figure of the measurement system. Procedures to characterize DSB and SSB ENR of unknown noise sources are also provided.

B1. SYSTEM NOISE FIGURE WITH HOT/COLD SOURCES

B1.1 Prevention of Temperature Gradient

Since the temperature gradient from Hot/Cold sources to measurement system tends to lower the desired accuracy, the system needs to be thermally isolated from the Hot/Cold sources. To establish the thermal isolation, a thermal radiator is inserted between the Hot/Cold sources and the measurement system. The thermal radiator includes a straight waveguide, thermal sink, thermal compound, copper tubes, nylon tubes, and water reservoirs. These parts are connected as depicted in Fig. B1. Thermal sink compound is applied between copper tubes and thermal sinks, and between thermal sinks and waveguide to provide good thermal contacts between these parts. Water flow is established. Heat from the sources dissipates through the thermal contacts and is carried away by the flowing water. Hence, the thermal radiator prevents a thermal gradient from the sources to the measurement system.

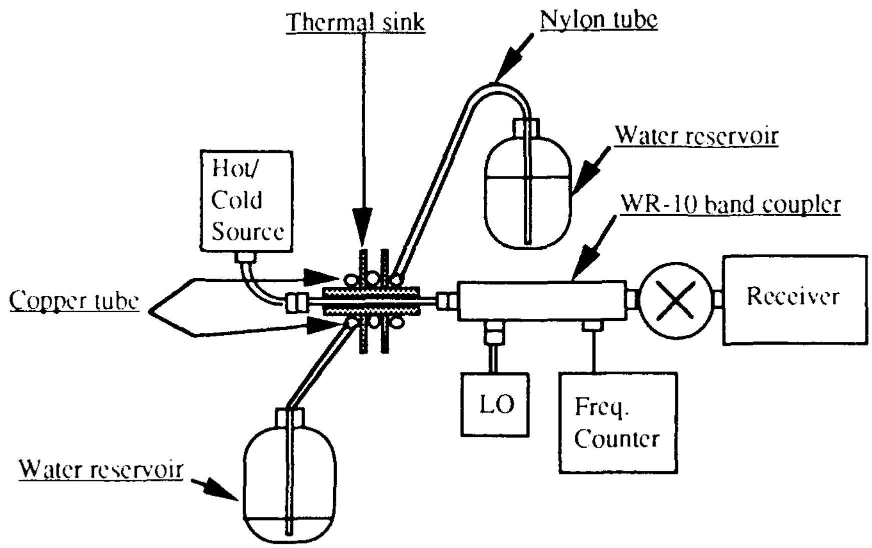

Fig. B1 -Thermal radiator to prevent thermal gradient from Hot/Cold load to receiver system

B1.2 Measurement of Noise Output Level of Hot Source

1. Set up the system as shown in Fig. B2.

2. Connect the output flange of the Alpha cold load 575W to the RF port of the mixer as illustrated in Fig. B2.

3. Connect the instruments to appropriate power supplies.

4. Turn the power supplies to ON.

5. Wait for 15 minutes.

6. Measure room temperature and record it as T_o ° K.

7. From the host computer keyboard, execute the program for the measurement (see Note 1) and set the LO frequency to 75 GHz.

8. Set the spectrum analyzer to ZERO SPAN and center frequency to the desired value. Since the system IF bandwidth is 0 - 500 MHz, the IFs are chosen as 200 and 400 MHz so that the TPM method can be carried out.

9. Use the spectrum analyzer marker to measure the noise level in dBm and record this value as Nh for the frequency being considered.

10. Press the WRITE/CLEAR button on the spectrum analyzer.

11. From the host computer keyboard, increase the LO frequency by 1 GHz.

12. Measure room temperature. If the room temperature is different from T_o in step 6, make an adjustment so that it is the same as in step 6.

13. Repeat steps 9 through 12 until the LO frequency has reached 110 GHz.

Note 1: Steps 8, 10, and 11 are automatically done by the host computer. A program was developed for the host computer, HP-9121, to perform these steps and other calculations, as explained later in the calculation section. This program also controls the frequency-locked-loop of the LO source by adjusting the coarse tune current of the Ka-band YIG oscillator.

B1.3 Measurement of Noise Output Level of Cold Source

1. After finishing the measurements for the hot source, pour liquid nitrogen into the cold load dewar flask so that the WR-10 termination is immersed in the liquid nitrogen.

2. Repeat steps 8 through 13 in Section B1.2 with the measured noise output level recorded as N_c.

To prevent the accumulation of liquefied oxygen or solidified water vapor inside the waveguide, which will cause degradation of emissivity, the load must be evacuated prior to charging with liquid nitrogen *. The evacuation is maintained throughout the measurement by a running vacuum pump.

* Millimeter Waveguide Component Catalog, Alpha Industries Inc., 1984, p 89.

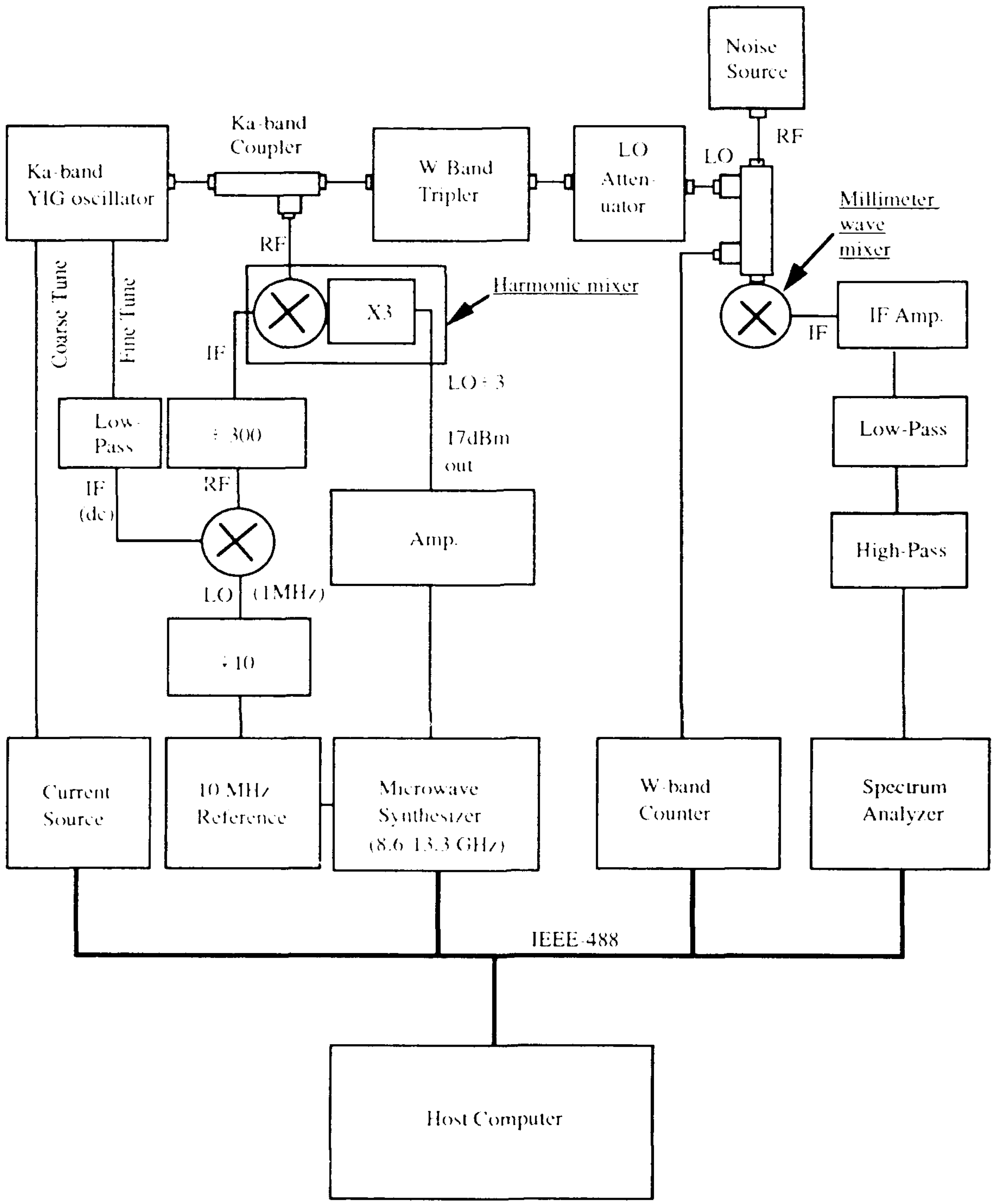

Fig. B2 — Component diagram of WR-10 noise measurement system

B1.4 Calculation

1. For each frequency in the measurement, calculate the Y-factor in dB by solving the equation

$$Y_{dB} = N_h - N_c. \qquad (B1)$$

Record these values as Y_{dB}.

2. Convert the dB values of Y-factor to linear by using the following equation

$$Y = 10^{Y_{dB}/10} \qquad \text{(B2)}$$

Record the values as Y.

3. Calculate the cold load effective noise temperature by solving the following equation, as indicated by Menon et al. *

$$T_c = T'_c + (T_0 - T'_c)\left[\frac{L_1}{8.686} + \frac{L_2}{4.343}\right], \qquad \text{(B3)}$$

where T_c is effective noise temperature of the load (^{0} K),
T'_c is liquid nitrogen temperature (77.2^0 K),
T_0 is ambient temperature (^{0} K),
L_1 is loss in waveguide with uniform temperature T_0 (0.2 dB), and
L_2 is loss in waveguide with linear temperature gradient from T'_c to T_0 (0.2 dB).

L_1 and L_2 are characteristics of the cold load and are provided by the manufacturer.

4. For each frequency in the measurement, calculate the noise figure F_{dB} of the measurement system by solving the following

$$F_{dB} = 10 \log \left[Y \cdot \left(1 - \frac{T_c}{T_0}\right)\right] - 10 \log (Y - 1), \qquad \text{(B4)}$$

where T_c is effective noise temperature of cold load (^{0} K),
T_0 is ambient temperature (^{0} K), and
Y is Y-factor in linear value.

Record the calculated values.

5. From the calculated values, construct a graph of noise figure F_{dB} vs frequency for the measurement system.

Note 2: The above calculations are done by the program developed for the measurement, as mentioned in **Note 1**.

B2. SYSTEM NOISE FIGURE WITH GAS DISCHARGE TUBE

B2.1 Measurement

1. Set up the system as shown in Fig. B2.
2. Connect the output flange of the noise tube to the RF port of the mixer.
3. Connect the instruments to appropriate power supplies.
4. Turn the power supplies ON.
5. Switch the gas tube's power supply to OPERATE and press the START button. Turn the CURRENT ADJUST knob so that the meter of the power supply reads 75 mA. Switch the power supply to STBY.

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* R. C. Menon, N. P. Albaugh, and J. W. Dozier, "Cooled Load as Calibration Noise Standards for the Millimeter Wavelength Range," *Proc. IEEE* **54**, 1966, 1501-1503.

6. Wait 15 minutes.

7. Measure room temperature and record it as T_0 ° K.

8. From the keyboard of the host computer, execute the program for the measurement and set the LO frequency to 75 MHz.

9. Set the spectrum analyzer to ZERO SPAN and the center frequency to the desired IF.

10. Use the spectrum analyzer marker to measure the noise power in dBm and record this value as N_c.

11. Switch the tube's power supply to OPERATE and press the START button. The power supply's indicator should indicate 75 mA; if not, adjust it by turning the CURRENT ADJUST knob.

12. Use the spectrum analyzer marker to measure the noise power in dBm and record this value as N_h.

13. Switch the tube's power supply to STBY.

14. From the computer keyboard, increase the LO frequency by 1 GHz.

15. Repeat steps 10 through 14 until the LO frequency has reached 110 GHz.

B2.2 Calculation

1. Repeat steps 1 and 2 in Section B1.4.

2. The system noise figure is calculated by solving the following equation

$$F_{dB} = ENR + 10 \log (Y-1), \tag{B5}$$

where ENR is the Excess Noise Ratio of the gas tube provided by the manufacturer (14.2 dB).

3. Repeat the procedure for the desired frequencies.

B3. ENR OF SOLID-STATE NOISE SOURCE

B3.1 DSB ENR

B3.1.1 Measurement

1. Set up the system as shown in Fig. B2.

2. Connect the uncharacterized noise source to the RF port of the millimeter wave mixer.

3. Repeat steps 3, 4, and 5 in Section B1.2.

4. Adjust the room temperature, if necessary, so that it is the same (or at least close to) as recorded in step 6 of Section B1.2.

5. Turn ON and OFF the power supply of the noise source at a suitable frequency so that ON and OFF power levels clearly appear on spectrum analyzer.

6. Repeat steps 7 and 8 of Section B1.2.

7. Use the spectrum analyzer marker to measure the difference between the ON and OFF levels. Record this value as Y_{dB} for the frequency being considered.

8. Press the WRITE/CLEAR button on the spectrum analyzer.

9. From the keyboard of the computer, increase the LO frequency by 1 GHz.

10. Repeat steps 7 through 9 until the LO frequency has reached 110 GHz.

B3.1.2 Calculation

1. Convert the dB values of the Y-factor to linear values as follows

$$Y = 10^{Y_{dB}/10} \tag{B6}$$

Record the calculated values as Y.

2. Calculate the ENR of the uncharacterized noise source by solving the following equation

$$ENR = F_{dB} + 10 \log (Y - 1), \tag{B7}$$

where F_{dB} is the noise figure of the measurement system that was obtained in Section B1.4. Record the calculated values.

3. From the calculated values of ENR, construct a graph of ENR vs frequency in the WR-10 band for the noise source.

The unknown noise source is now characterized.

B3.2 SSB ENR: Three Point Measurement

B3.2.1 Measurement

Since the two available IFs for the TPM are 200 and 400 MHz, three LO frequencies in a group are 200 MHz apart, e.g., 77.8, 78.0, and 78.2 GHz.

1. Repeat steps 1 through 5 in Section B3.1.1.

2. From the computer keyboard, tune LO to the first frequency in the group; i.e., 77.8 GHz.

3. From the LO power table, determine whether or not all of the LO powers at the three frequencies in the group are sufficient to drive the mixer into saturation. If not, level the LO powers at the minimum value. The leveling is accomplished by tuning the WR-10 attenuator; see Fig. B2.

4. Repeat step 5 in Section B3.1.1.

5. Set the spectrum analyzer to ZERO SPAN and the center frequency to 200 MHz.

6. Use the spectrum analyzer marker to measure the ON and OFF levels of the noise source and record them as P_{1on} and P_{1off}, respectively.

7. From the computer keyboard, tune LO to the second frequency in the group, i.e., 78.0 GHz.

8. Repeat steps 3 and 4 in this section.

9. Repeat step 5 in this section with a center frequency of 400 MHz.

10. Use the spectrum analyzer marker to measure the ON and OFF levels of the noise source and record them as P_{2on} and P_{2off}, respectively.

11. From the computer keyboard, tune LO to the third frequency in the group, i.e., 78.2 GHz.

12. Repeat steps 3 and 4 in this section.

13. Repeat step 5 with a center frequency of 200 MHz.

14. Use the spectrum analyzer marker to measure the ON and OFF levels of the noise source and record them as P_{3on} and P_{3off}, respectively.

15. Repeat steps 2 through 14 for desired frequency groups.

B3.2.2 Calculation

1. ON and OFF levels of three frequencies in a group are obtained by solving the three unknown three equation linear system as described in Section A2.2 of Appendix A.

2. Once ON and OFF levels at each frequency are determined, Y-factor and SSB ENR of the noise source are calculated as described in Section B3.1.2.

The noise source SSB ENR is now characterized.