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Development of radiometer operating between 50 MHz and 26.5 GHz using gain-stabilized LNA

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Abstract: A radiometer operating between 50 MHz and 26.5 GHz and consisting of microwave channels all with a low-noise amplifier (LNA) was established. Microwave switches were used to select an appropriate channel according to measurement frequency. The effect of variations both in input and output reflection coefficients on LNA gain was investigated. To keep the change in the gain of the LNA at minimum, the LNA output was terminated with a load whose impedance was equal to that of matched load. This technique gives the opportunity of full-band noise measurements of noise sources with one total power radiometer. The performance of the overall radiometer was tested. The difference in excess noise ratio (ENR) between the experimental results and actual values was found between –0.32 dB and 0.30 dB with an expanded uncertainty between 0.13 dB and 0.34 dB (k = 2). The results illustrate the validity of the full-band radiometer for determining ENR.

Key words: Excess noise ratio, impedance matching, low-noise amplifier, noise temperature, radiometer

1. Introduction

Noise sources are used as the standard in measurements such as remote sensing, electronic component characterization, and noise figure characterization of receiving systems and amplifiers [1,2]. For traceability of noise temperature, the characterization of the noise sources is performed using radiometers like total power radiometers [3]. The noise temperature equation for the total power radiometer in [4] is valid in the case of stable radiometer gain during measurements. The low-noise amplifier (LNA) is the most important component that determines the radiometer gain stability, since it is the amplifier in which microwave noise is amplified and filtered as a first step in the radiometer [5,6]. Additionally, it is where the microwave noise is doped by a substantial noise. Since LNAs are manufactured as narrow-band components, the total power radiometers are established having just one frequency band [7]. However, it is not enough to characterize a noise source operating in more than one frequency band. We proposed a new full-band radiometer consisted of channels for each frequency band depending on the frequency of microwave components. Thus, the narrow-band microwave elements were integrated into a full-band radiometer structure. Thereby, wide band noise sources could be characterized by only one radiometer.

In this study, LNA gains with respect to input and output reflection coefficients were analyzed theoretically. The deviation in the gain was also experimentally investigated by changing the output reflection coefficient between 0 and 0.8. The use of a microwave switch having matched load at each channel was proposed to keep

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the reflection coefficients at the same value when in use and not in the use of the related microwave components. To verify the overall radiometer, the measurements were carried out by two solid-state noise sources. With the radiometer developed in the frequency range of 50 MHz to 26.5 GHz, the excess noise ratio (ENR) value of a noise source could be measured at a time.

2. Design of full-band radiometer and the results

There are two types of radiometers used in calibration of noise sources, the Dicke radiometer [5,8] and the total power radiometer [9]. In order to perform microwave noise temperature measurements at the National Metrology Institute (UME) of Turkey, a total power radiometer with good sensitivity and drift performance was used. The noise power values obtained at the output of the radiometer as P_a, P_s, and P_x when ambient, standard, and unknown noise sources are connected, respectively, are used to calculate the corresponding noise temperature of an unknown noise source by the well-known relationship $P_n = kT_nB$ where n is a, s, or x. The actual noise temperature of an unknown noise source is calculated by [4]:

$$T_x = T_a + (T_s - T_a)\left[(Y_x - 1)\ M_s\,\eta_s/((Y_s - 1)\ M_x\,\eta_x)\right], \tag{1}$$

where T_a, T_s, Y_x, Y_s, M_x, M_s, η_x, and η_s are the ambient noise temperature (K), the standard noise temperature (K), the ratio of output powers (unknown Y-factor) when unknown and ambient noise sources are alternately connected to the radiometer input, the ratio of output powers (standard Y-factor) when standard and ambient noise sources are alternately connected to the radiometer input, the mismatch factor between the unknown noise source and the radiometer input, the mismatch factor between the standard noise source and the radiometer input, the efficiencies of microwave switch paths connected to the unknown noise source, and the efficiencies of microwave switch paths connected to the standard noise source, respectively. Since Eq. (1) loses its validity when the gain of the radiometer is not stable, the stabilization of LNAs becomes crucial. The establishment of a full-band radiometer is extremely difficult due to the difficulty in obtaining stability of each LNA especially just after selection by a classical switch. In the case of change of the frequency band of the measurement, the load impedance of the newly selected channel alters from open circuit to the equivalent impedance of the rest of the microwave elements. In contrast, impedances of the previously used channel alter from the equivalent impedance to open circuit. The gain of the LNA is expressed in terms of the s-parameters as:

$$G_T = \left(1 - |\Gamma_g|^2\right)|S_{21}|^2\left(1 - |\Gamma_l|^2\right)\Big/|(1 - S_{11}\Gamma_g)(1 - S_{22}\Gamma_l) - S_{12}S_{21}\Gamma_g\Gamma_l|^2, \tag{2}$$

where Γ_g, Γ_l, and S_{xy} $(x,\ y = 1,\ 2)$ are the source reflection coefficient, the load reflection coefficient, and s-parameters of the LNA, respectively. The s-parameters of the LNA (Miteq, AFS33-18002650) at 20 GHz, which are S_{11} = 0.1751 + i0.16306, S_{12} = 0.00060 + i0.00178, S_{21} = 93.195 – i59.214, and S_{22} = 0.1347 – i0.1121, and source and load reflection coefficients with values changing from –1 to +1, were used in Eq. (2). The obtained gain of LNA with respect to both variable source and load impedance is given in Figure 1. It approaches zero when the reflection coefficients go to +1 (for open load) and –1 (for short load). On the contrary, the gain has maximum value when the reflection coefficients are zero. Moreover, the gain responses given to the change in the reflection coefficients become sharper as approaching the limits. Variable port reflections change, as well as the LNA gain, the noise figure value produced by the LNA as given in [10].

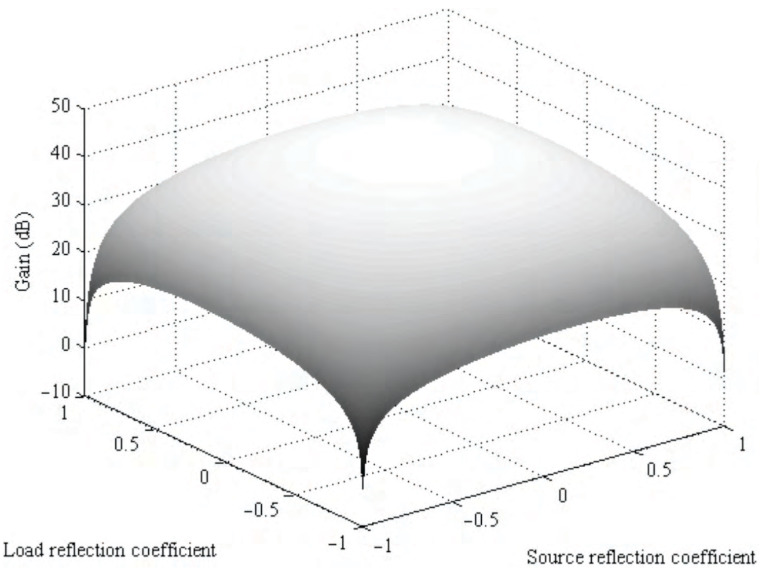

Figure 1. Variation in LNA gain.

The measurement setup given in Figure 2 was established to verify the theoretical results. The vector network analyzer (VNA; HP 8510C) was calibrated using the short, open, load, and through (SOLT) calibration procedure before the measurements [11]. When the manual tuner with Focus Microwaves MMT-2604 was connected directly between the VNA ports, reflection coefficients of the manual tuner at 20 GHz were measured depending on its positions. Then the LNA input and output ports were connected to the VNA port 1 and the tuner input, respectively. LNA gains for different specified tuner positions were measured and the LNA gains were calculated considering that VNA port 1 reflection coefficient $|\Gamma_g|$ (VNA used as a source) had constant value of 0.0037 and that $|\Gamma_g|$ (tuner used as a load) was being changed between 0 and 0.85. The measured and the calculated values are shown in Figure 2. There is a difference between the curves changing in value from –0.9 to 1.7 dB. The reason for this difference is that the tuner positions for both the measurement of reflection coefficients and the LNA gain were not exactly the same. The change in the gain decreases as the absolute reflection coefficient increases and it is higher than 10 dB for the maximum reflection coefficient of 0.82.

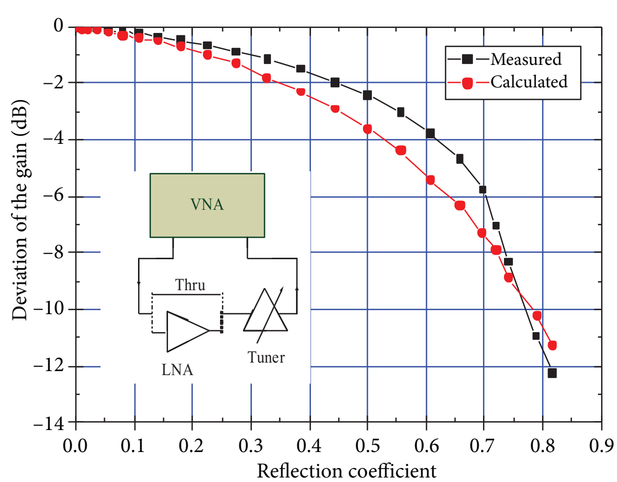

Figure 2. Measurement setup and deviation of the LNA gain versus load reflection coefficient.

Whether currently in use or not, load impedance of LNA in the channel should be approximately equal to the equivalent impedance of the rest of microwave elements, but this is not possible for a standard switching system. A Dow-Key 571K-420803 model match-loaded microwave switch was used to keep the LNA load reflection coefficient value close to zero when the LNA is not in use. Thus, holding the working conditions similar, the LNA had been made to have stable gain all the time.

In order to perform the full-band noise temperature measurements, all frequency points must be swept without a break. The way of making microwave elements with different frequency ranges operate together in the same system is to bring them together by a switching system. A total power radiometer operating between 50 MHz and 26.5 GHz, whose block diagram is given in Figure 3, has been developed using this approach. There are six channels operating at 50, 100, 200, 300, 400, and 500 MHz frequency points and seven channels operating between 500 MHz and 1 GHz, 1 and 2 GHz, 2 and 4 GHz, 4 and 8 GHz, 8 and 12 GHz, 12 and 18 GHz, and 18 and 26.5 GHz frequency bands in the radiometer. According to the measurement frequency, channels are selected using $S2-S8$ switches, of which $S3-S6$ (Dow-Key 571K-420803) are match-loaded. Switches S1, S2, and S3 or S1, S2, and S4 are positioned to apply output of the noise source to the selected channel input compatible with measured noise signal frequency. Then the noise signal passes through the isolators. For below 500 MHz, A-info isolators were used with model number JXWBGL-T-XX-XX-15. The code XX-XX shows the frequency range of the isolator; for example, a 200 MHz isolator model number is JXWBGL-T-198-202-15. Raditeq isolators for 0.5–1 GHz, 1–2 GHz, 2–4 GHz, and 18–26.5 GHz bands; Ditom D3IXXXX-2 model isolators for 4–8 GHz and 12–18 GHz bands; and Quest SR0812T13 model isolators for the 8–12 GHz band were used. The output of the isolators is applied to the LNA input. Miteq AFS3, AFS4, and AFS6 series LNAs were used. For low frequency Mini Circuits ZFM-150 and for high frequency Marki Microwave M40026LJ mixers were used to down-convert the noise signal frequency at microwave to IF. Positioning switch S7 (Dow-Key 401K-4208), the local oscillator (LO) output is applied to the input of the mixer compatible with the frequency. The noise signal, down-converted to an intermediate frequency at the output of the mixer, passes through the filter (Anatech Electronics M6353) and the amplifiers (HD19462) after being selected by switch S8 (Dow-Key 401K-4208) and then this signal, which corresponds to input noise signal, is measured by an Agilent E4413 power sensor and E 4417A power meter.

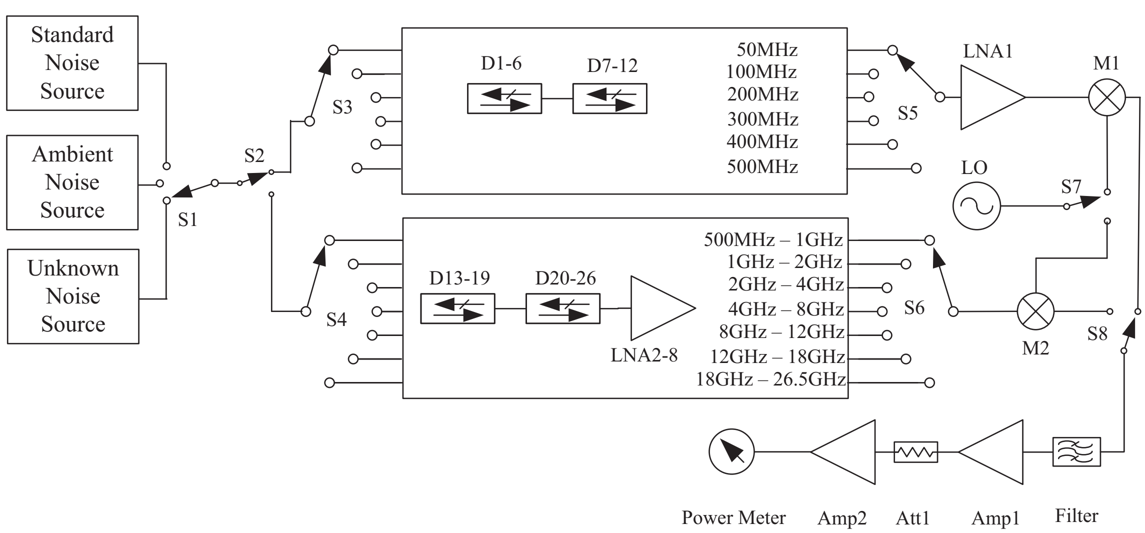

Figure 3. Block diagram of established full-band total power radiometer.

Microwave noise measurements between 50 MHz and 26.5 GHz were performed using two NC346C model noise sources with 15 dB ENR, certified by the National Physical Laboratory of the United Kingdom, and an ambient noise source. Two noise sources were used as standard and unknown and the rest was used as ambient. Substitution of measurement results and the radiometer parameters into Eq. (1) leads to calculation of noise temperature of unknown noise. The mismatch factors M_s and M_x were calculated according to equation $M_{s,x} = \left[\left(1 - |\Gamma_{s,x}|^2\right)\left(1 - |\Gamma_{ss,sx}|^2\right)\right] \big/ |1 - \Gamma_{ss,sx}\Gamma_I|^2$, where Γ_s and Γ_x are the reflection coefficient of the standard and unknown noise sources respectively, Γ_{ss} and Γ_{sx} are the reflection coefficient of the S1 switch input connected to the standard and unknown noise sources respectively, and Γ_I is the reflection coefficient at the S2 input of the radiometer. The efficiencies of the switch channels η_s and η_x were defined with the equation $\eta_{s,x} = \left[\left(1 - |\Gamma_I|^2\right)|S_{21_{s,x}}|^2\right] \big/ \left[\left(1 - |\Gamma_{ss,sx}|^2\right)|1 - S_{22_{s,x}}\Gamma_I|^2\right]$, where S_{21_s}, S_{21_x}, S_{22_s}, and S_{22_x} are S-parameters of ports connected to the standard and unknown noise sources and that of common port. Both the mismatch factors and the switch efficiencies are given in Figure 4. It is seen from the figure that the mismatch factors and the channel efficiencies for switches connected to standard and unknown noise sources are coherent with each other.

Source ENR values were calculated by ENR (dB) = 10 log$((T_x - T_0)/T_0)$ after noise temperature of T_x had been calculated (T_0 = 290 K). Calculated and actual ENR values of the unknown noise source are given in Figure 5. To analyze the radiometer performance, the calculated ENR values were compared with the actual values. The differences between them vary from −0.32 dB to 0.30 dB. The results were evaluated, and the agreement between them was satisfactory when the expanded uncertainty ranges of the measured and actual values coincided with each other [3,12]. Since the differences were in the interval of overall expanded uncertainty of the measured and actual values, the measurements can be accepted as satisfactory. Expanded uncertainties of the measurement lie between 0.13 dB and 0.34 dB. The results show that the ENR values obtained at 3, 5, 9, 13, and 19 GHz at which the measurements were performed just after the channel selection are also compatible with the actual values within 0.12 dB.

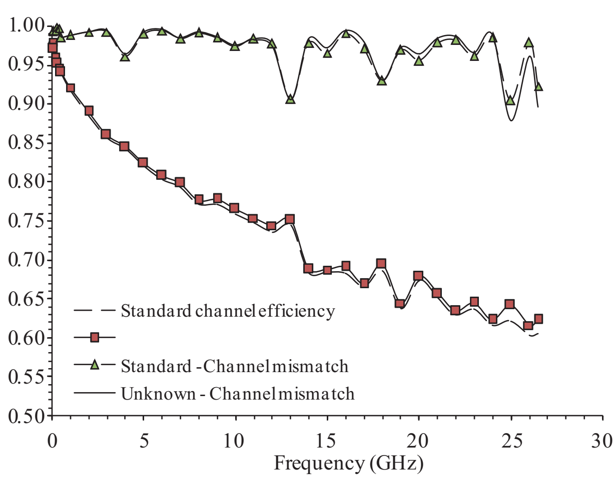

Figure 4. Switch efficiencies and mismatch factors of measurement channels and noise standards.

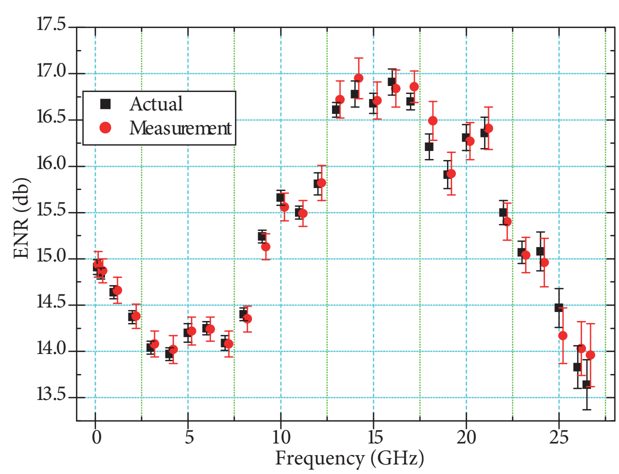

Figure 5. ENR measurement result.

3. Conclusion

In this study, theoretical source and load impedance dependency on LNA gain was analyzed and load impedance dependency was experimentally investigated. The full-band radiometer instead of wide-band radiometer operating between 50 MHz and 26.5 GHz was established using loaded-microwave switches. The results of the noise source measurement performed with the radiometer were compared with the actual ENR values of the noise source and good agreement was obtained. To determine the effect of LNA stability, especially the results of the measurement performed shortly after channel selection were analyzed. The maximum difference was found as 0.12 dB. We can conclude that the measurement results and the actual values for full-band agree with each other within the expanded uncertainty value. In this way, a noise source can be characterized through its full-band using only one radiometer system. This provides an efficient measurement on the account of reduction in errors coming from the connector repeatability and the operator.

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