Thermal Noise Metrology with Time-Based Synthesis

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***Abstract*—We present a new measurement technique for quantifying noise temperature based on temperature and time. A single-pole, double-throw (SPDT) ultra-fast switch combines signals from outputs of two synchronized electromechanical (EM) switches. The input ports of EM switches are terminated by one unknown noise source, one known cold noise source, and two known noise references at ambient temperature. The magnitude of the combined noise signal can be adjusted by the duty cycle of the transistor-transistor logic (TTL) pulse that controls the fast switch. The measurement approaches the balanced mode by regulating the TTL duty cycle in order to minimize the difference between the combined noise signal and the ambient noise reference. In comparison to conventional total-power radiometers, this new instrumentation is more efficient and potentially provides a wider dynamic range.**

***Index Terms*—Balanced radiometer, feed-back loop, noise synthesis, switch, thermal noise.**

I. Introduction

Thermal electromagnetic noise originates from ergodic random processes and is one of the most important microwave parameters. Because of its ubiquitous presence in nature, thermal noise has become the subject of many practical applications. These include precision calibration of receivers, microwave sounding and imaging in earth science, non-invasive temperature measurement for industrial and medical applications, personnel and substance screening in security surveillance, and radiation detection of interstellar medium in radio astronomy.

Thermal noise measurements often present challenges due to the low signal strength. Radiometers have been developed to accurately measure the power of thermal noise signals. Filtering and amplification are almost always needed to bring the level of signal in a frequency band of interest up to the dynamic range of radiometers. However, the considerable amount of noise and gain instability introduced by components in a radiometer necessitate frequent calibration. Total-power radiometers are one of the most popular configurations for metrology applications. Other types of radiometers are also used, such as switched radiometers (Dicke type) and noise-injection radiometers among others. In this report, we present a new instrumentation using null balance between synthetic noise signal and references. Such a configuration, although bearing similarities with noise-injection radiometers, holds some specific traits and merits.

II. Background

A noise-injection radiometer is developed to address the temporal gain and noise-temperature (NT) fluctuation at the expense of radiometric resolution. It was first introduced by Goggins [1] and later Hardy demonstrated an S-band radiometer by improving the injection with modulated pulses [2]. The injected noise power level is constantly adjusted by gating the noise signal from a known source with pulses of variable width, until the injected noise, in combination with the noise signal under test, equals the power level of a reference noise signal; hence the radiometer approaches a null balance. It can be shown that the averaged noise injection power has a linear dependence on the pulse frequency or equivalently the pulse width, as long as the square-law detection holds in the radiometer backend. As a result, noise-temperature measurements essentially reduce to time measurements [2].

The instrumentation depicted above is successfully used in a variety of remote-sensing applications. However, there exists an underlying complication that impedes its utility in the metrology field. PIN diodes, and in fact any solid-state (SS) switches in a broader scope, are driven by pulse waveforms for fast switching. The leading edge voltage spike at both the rise and fall of the pulse waveform produces a spurious signal, called video leakage. This additional noise bleeds into the RF output ports of the switch when it is in active switching regardless of any RF signal present at the input ports of the switch. The video-leakage effects can be safely neglected when dealing with large signals. However, the extra noise introduced by pulse waveforms has to be accounted for, when the signal at the input ports of the switch is also small at thermal noise level.

Characterization of added noise by a SS switch deserves independent investigation in its own right. In principle, a SPDT SS switch is a 3-port device and its equivalent noise can be calibrated with traditional noise-temperature measurement methods. However, the calibration may be practically infeasible due to the dependence of added noise on many variables, such as the supply voltage, the TTL control voltage, and more importantly the switching frequency and the duty cycle.

III. Measurement Principle of New Technique

A block diagram of the proposed radiometer is shown in Fig. 1. Two EM switches are placed in the frontend and they operate synchronously at slow time periods of tens to hundreds of milliseconds. The switching speed of the EM switches is mainly limited by their own operating mechanism and the response time of the square-law detector in the radiometer backend. One of the EM switches (S1) is terminated by a device under test (DUT) with NT of T_x and an ambient noise reference with NT of T_a. The other switch (S2) is terminated by a cryogenic noise standard with NT of T_c and another

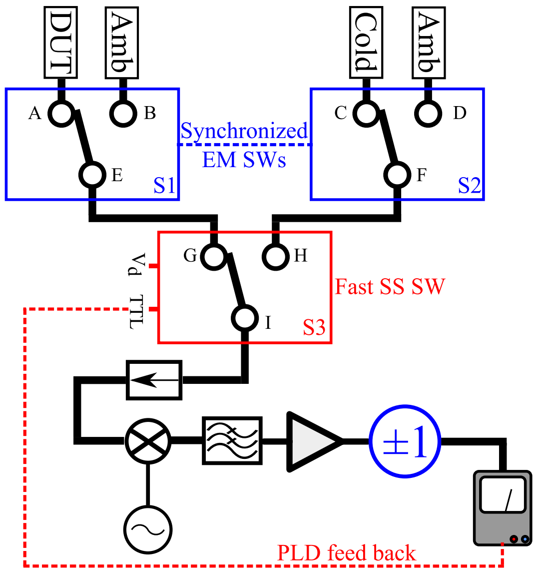

Fig. 1. Block diagram of a radiometer with a feed-back loop to adjust the magnitude of the synthesized noise signal balancing with ambient noise references. The component in the red box is a SS switch at a rapid switching speed and the ones in the blue boxes are two synchronized EM switches at much slower switching speed.

ambient reference with the same NT of T_a as the one on S1. The output of S1 and S2 are connected individually to the two input ports of a SS switch (S3). S3 operates at a very fast speed, which generates a synthesis of noise signals from port G and H measurable by the backend detector. When S1 toggles to port A and S2 toggles to port C, the NT at port I is related to the weighted average of T_x and T_c plus the added noise from S3 (ΔT_{S3}). When S1 toggles to port B and S2 toggles to port D, the NT at port I is roughly the sum of T_a and ΔT_{S3}. The NTs of synthesized noise signals at these two states can be expressed with approximation as

$$T_{\text{AC}} = \alpha T_x + (1-\alpha)T_c + \Delta T_{\text{S3}}, \tag{1a}$$

$$T_{\text{BD}} = T_a + \Delta T_{\text{S3}}, \tag{1b}$$

where α is the duty cycle of the pulse that drives S3.

The rest of the radiometer backend is fairly standard, consisting of isolators, down converters, filters, amplifiers, and a detector. The detector is also synchronized with the EM switches by either digital or analog methods. The resultant detection amounts to the difference between T_{AC} and T_{BD} and is fed back to adjust the TTL duty cycle of S3. The excessive noise (ΔT_{S3}) introduced by the SS switch always contributes equally to the synthesized signals and consequently the need for calibration of ΔT_{S3} is eliminated. Once a null balance is reached, we can easily infer T_x from (1a) and (1b) without knowing ΔT_{S3}.

The formulation in (1), especially (1a), does not include the mismatch and loss corrections. To account for these items, scattering (S-) parameter measurements of components and transmission paths are required. In practical implementation all the radiometric components are expected to be thermally stabilized at T_a, so that (1b) still holds true. After corrections are made to (1a), T_x can be determined from:

$$T_x = \frac{\left[\begin{array}{r} \alpha T_a(M^{\text{I}}_{\text{BEGI}} - M^{\text{I}}_{\text{AEGI}} + M^{\text{A}}_{\text{AEGI}}\eta_{\text{AEGI}}) \\ +(1-\alpha)(T_a - T_c)M^{\text{C}}_{\text{CFHI}}\eta_{\text{CFHI}} \\ +(1-\alpha)T_a(M^{\text{I}}_{\text{DFHI}} - M^{\text{I}}_{\text{CFHI}}) \end{array}\right]}{\alpha M^{\text{A}}_{\text{AEGI}}\eta_{\text{AEGI}}}, \tag{2}$$

where $M^{\diamond}_{\star*\circ\text{I}}$ refers to the mismatch factor at the reference point '$\diamond$' when the signal path '$\star * \circ$I' between the frontend ports and port I is established under pertinent switching conditions, and $\eta_{\star*\circ\text{I}}$ is the efficiency of the signal path '$\star*\circ$I'.

IV. Discussion and Conclusion

We proposed a greatly improved variant of a null-balanced, noise-injection radiometer suitable for metrology applications. A few noteworthy items are highlighted as follows:

1) With a specialized arrangement of components and proper synchronization, the added noise introduced by electronic switches, such as PIN diode switches and SS switches, are correctly addressed for the first time. This represents a major step forward for implementing noise-synthesis (or injection) techniques in microwave thermal-noise metrology. Its applications to other fields can evidently improve measurement accuracy.
2) The linearity requirement of backend detectors is relieved because of null-balance operations. This not only reduces cost by choosing economical components for instrumentation but also eliminates the measurement uncertainty due to detector nonlinearity and broadens the detection dynamic range.
3) In comparison to total-power radiometers used in most metrology labs, this new instrument can improve the measurement efficiency by at least 33% since the number of switching states is reduced from 3 to 2.
4) Time and frequency represent the most precise measurands available to metrologists. As long as the pulse duration is kept much longer than the switching time (~30 ns), the overall NT measurement uncertainty would still be dominated by S-parameter measurements.
5) Synchronization and feed-back functions can be realized by analog electronics to achieve fully automation at high speed. However, a digital implementation with simplified software developments may be adequate for validating a prototype system.

In summary, we presented a new instrumentation concept for thermal-noise metrology traceable to temperature and time. The radiometer consists of two synchronized EM switches and one SS switch. The arranged switch operation produces a synthesis of adjustable noise signals to match a known reference. This new approach allows cancellation of added noise from the SS switch and enables precision NT measurements.

References

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