A RELATIVELY INEXPENSIVE RADIOMETER

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Abstract

A relatively inexpensive radiometer, intended to serve the needs of a calibration laboratory with a moderate workload, was designed at NIST. It utilizes heterodyning for broad frequency coverage, and a precision waveguide-below-cutoff attenuator to achieve a null-balancing mode of operation. The overall accuracy (with a primary cryogenic standard attached) is about 2%.

Introduction

Thermal noise metrology is based on the well-known approximation $P = kBT$, where $k$ is Boltzman's constant, $B$ is the bandwidth over which the generated noise power $P$ is measured, and $T$ is the temperature of the source of thermal noise. Primary noise standards, designed around this formula, generate an accurately known amount of noise power. A source under test, assumed to generate noise whose characteristics are indistinguishable from thermal, is then, via a 'radiometer', compared against those standards. Inevitably, though, elements of the measuring circuit generate noise, some of which - depending on the properties of those elements - adds to the power generated by the source under test. This fact - namely, that there are no passive elements in noise work, coupled with the extremely broadband nature of the signal - distinguishes the radiometers from other self-calibrating (i.e. having a standard attached!) low-level power measurement systems.

Requirements

The radiometer under discussion is intended to serve the needs of a calibration laboratory with a moderate workload. The design philosophy was, therefore, to have a system with a high degree of accuracy and precision, while cost-containment considerations resulted in it being relatively slow, and having to rely on the reflection coefficient measurements being performed by a separate vector network analyzer.

The noise temperature of a device under test (DUT) is assumed to be between 77 K and 10,000 K, although lower and higher temperatures can be measured with some degradation in accuracy. The radiometer sensitivity of ±8 K out of 10,000 K is considered adequate in this application. The overall accuracy of this system was intended to be comparable to that of similar systems operated at the National Institute of Standards and Technology (NIST); with a NIST primary cryogenic standard attached, it is about 200 K out of 10,000 K.

The frequency coverage of this instrument was planned to be very wide. At the 'low end' the isolators become impractical below 250 MHz, but at the 'high end' there are no specific restrictions, besides the general availability of components.

Overview

The radiometer is a simply cascaded, i.e. a 'total-power', instrument, utilizing a calibrated, precision waveguide-below-cutoff attenuator to achieve a null-balancing operating mode. Frequency downconversion is employed as close as possible to the radiometer input port, so that various RF 'front ends' can be economically integrated. The radiometer presently operates in four frequency bands, between 1.0 and 12.0 GHz, with a female precision type N connector at the input.

There are two noise standards associated with the radiometer. One of the standards is maintained at ambient temperature. This choice results in a significant simplification in both the standard's and the radiometer's design. The other standard needs to be operated at a temperature different - preferably greatly different - from the ambient temperature. The radiometer presently works with a primary cryogenic standard (at nominal 77 K), previously developed at NIST [1].

The noise temperature (in kelvin) of the DUT is determined by

$$T_{DUT} = T_{AMB} + \frac{M_{STD}Y_{STD} - Y_{DUT}}{M_{DUT}Y_{DOUT} - 1} \left( T_{STD} - T_{AMB} \right)$$

where

- $T_{AMB}$ is the ambient temperature [K],
- $T_{STD}$ is the temperature of the non-ambient standard [K],
- $M_{STD}$ corrects for input mismatches and asymmetry,
- and $Y_{DOUT}, Y_{STD}$ are the measured 'Y factors'.

Description

The radiometer consists of several RF 'front ends' and a common IF section. Switches used to connect various parts of the RF section of the radiometer are omitted in the block diagram, which shows the simplified realization of just one band.

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Ideally, one wishes a highly directive isolator to be the very first component at the radiometer input in order to isolate the radiometer from the effects of its changing input environment (in the form of various standards etc.). Bowing to the reality of connector wear, a decision was made to have instead a 3-way switch in front of the isolator, and thus create separate, dedicated ports for the two standards and the DUT. Since it is possible to 'model out' the effects of the switch, and its repeatability proved acceptable, this addition improved the convenience and speed, without significantly penalizing the accuracy, of the measurements.

Following the isolator is a high gain (e.g. 40 dB) amplifier, serving to bandlimit the (theoretically infinitely wide!) incoming signal. A typical coaxial filter is unsatisfactory in this role, because its properties vary unpredictably in its far out-of-band region. The amplifier is passive - and consequently behaves as poorly - far outside its own band, but the signal level there is also 40 dB lower than within the band. It is imperative to limit the bandwidth of the signal because the next element, a mixer, being non-linear, forms strong in-band intermodulation products of the local oscillator (LO) frequency and the out-of-band noise, if such is present. The specifications for the amplifier are not severe: an octave (or less) of bandwidth, good linearity, and a reasonably low noise figure.

The mixer is double balanced in order to maximally attenuate the second intermodulation product that can fall into an octave-wide band. Any LO leakage through the mixer degrades the sensitivity of the radiometer, but does not cause errors, since it is 'nullled out' during the measurement. As long as the noise signal is carefully bandlimited, the spurious frequencies of the LO present no problems either. A reasonable amount of LO phase noise is inconsequential in broadband measurements.

The IF section of the system operates at 30 MHz, dictated by the availability of a commercial, continuously variable, high precision waveguide-below-cutoff attenuator. It is used to adjust the noise power of the two standards and the DUT to precisely the same level. The differences in the attenuator settings (in dB) form the two 'Y factors' in the radiometer equation. The attenuator is series tuned, with a narrow bandwidth that is also the limiting bandwidth of the system. Since the dynamic range during a typical measurement does not exceed 10 dB, the attenuator is easily operated in its linear region (insertion loss >40 dB), but away from the very high attenuation values where its leakage becomes significant.

The IF chain provides most of the radiometer's gain. Since amplifiers behind the attenuator need not be particularly linear, most amplification occurs there, although some gain is necessary in front of the attenuator, due to its EMI susceptibility.

The power (now at the same level for all three noise sources) is detected by a simple square law diode detector. The overall system gain is chosen to optimize the detector sensitivity. The DC output of the detector is 'nullled' by a voltage from a constant DC source, and the balanced 'null' is recorded on a strip chart recorder.

The radiometer, the standards and the auxiliary equipment all fit into a standard equipment rack. The radiometer itself is housed in a metallic box for EMI control. The bottom of that box is a rigid brass plate with milled-out channels for water circulation. The plate has an array of regularly spaced threaded holes that serve as anchor points for simple clamping bars, which then secure the radiometer components. This arrangement provides excellent temperature control, mechanical support and flexibility with component placement.

References