TERAHERTZ RADIOMETER DESIGN FOR TRACEABLE NOISE-TEMPERATURE MEASUREMENTS*

Eyal Gerecht, Dazhen Gu, James Randa, David Walker, and Robert Billinger

National Institute of Standards and Technology
Boulder, CO 80305, U.S.A

Abstract

We report on the design of a radiometer for traceable noise-temperature measurements at terahertz frequencies, including noise measurements on cryogenic IF components, development and test of quasi-optical adapter technology, development of black body standards, and overall system design.

Introduction

Imaging at terahertz frequencies (defined roughly as 300 GHz – 3 THz) has great potential for both healthcare and homeland security applications. Terahertz frequencies correspond to energy level transitions of important molecules in biology and astrophysics. Terahertz radiation (T-rays) can penetrate clothing and, to some extent, can also penetrate biological materials, and because of its shorter wavelengths it offers higher spatial resolution than microwaves or millimeter waves. However, the development of terahertz heterodyne detection systems for imaging and spectroscopy is impeded or even prevented by the inability to characterize the noise properties, and consequently the sensitivity of such systems or even of components for such systems at terahertz frequencies. Without this characterization capability, it is impossible to separate signal from background noise for systems with low-level signals, such as imaging systems or spectroscopic systems, or characterize the basic performance of such systems—or, for that matter, for any system that detects or processes weak terahertz signals.

The problem of noise characterization is particularly challenging in the terahertz frequency range, which lies between the microwave/millimeter-wave range and the infrared range. Both microwave and infrared ranges have well-developed methods and technology for measuring noise and sensitivity, but neither set of noise-measurement tools can be extended directly to terahertz frequencies. Consequently, not only noise-measurement techniques but also the required technology and instrumentation are lacking at terahertz frequencies. In addition, in the terahertz range there is a transition in the dominant source of noise in electronic systems. At microwave and millimeter-wave frequencies, thermal noise is dominant, whereas at optical frequencies quantum noise, due to vacuum fluctuations, dominates. In the terahertz range, however, both quantum and thermal noise are important and must be dealt with.

We describe the design of a terahertz radiometer for traceable noise-temperature measurements. The terahertz radiometer includes the front-end near quantum-noise limited heterodyne detector, the quasi-optical design, the IF chain, and the integration of the system. Figure 1 shows a diagram for a terahertz noise-temperature measurement system.

Front-End Heterodyne Detector

The sensitivity of heterodyne ('mixer') receivers is usually expressed in terms of their double sideband (DSB) receiver noise temperature. The quantum-noise limit for a DSB system noise temperature is $hf/2k_B$. The DSB receiver noise temperatures of the best receivers from 300 GHz to 3 THz are presently close to $10 \times hf/2k_B$. Hot electron bolometric (HEB) mixers are near quantum–noise limited heterodyne detectors operating over the entire terahertz spectrum [1]. HEB devices rely on the ability to absorb the terahertz radiation up to the visible range due to the very short momentum scattering times; and on the ability to change their resistance as the quasi-particles heat as a function of the incoming energy. These two properties are independent of the RF/LO frequency. HEB devices are "surface" devices. Therefore, their parasitic reactances are extremely

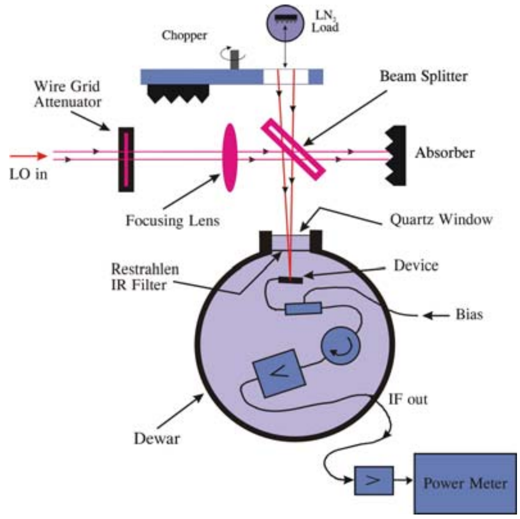

Figure 1: Diagram of noise-temperature measurement system.

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small, even at the highest terahertz frequencies. The HEB devices are fabricated from an NbN film that has been sputtered on a silicon substrate. The film thickness is typically 3.5 to 4 nm. A typical device size is 4 μm (width) x 1 μm (length). The devices are fabricated at the terminals of a terahertz antenna. The HEB device can be matched to the antenna by changing its aspect ratios, and using the fact that its impedance at terahertz frequencies (well above the superconducting bandgap frequency) is real, with a value equal to its normal resistance just above the critical temperature. NbN HEBs have a thermal time-constant that is determined by the rate at which phonons are emitted by the electrons, and also by the escape rate of the phonons from the NbN film to the substrate. The resulting conversion gain bandwidth is about 3 to 3.5 GHz for our devices, while the receiver noise temperature bandwidth is about twice the gain bandwidth. An operating temperature for the HEB devices of 4 K to about 7 K is an advantage compared to most other far infrared (FIR) devices, which require cooling to sub-kelvin temperatures.

Quasi-Optical Design

The majority of HEB receivers now use quasi-optical coupling to the incoming radiation field by use of a combination of a dielectric lens and an integrated antenna. Some HEB receivers in the range of up to about 2 THz are likely to be waveguide-coupled in the next few years. HEB receivers at the highest terahertz frequencies are likely to continue to use quasi-optical power coupling.

We have employed two types of antennas: twin-slot antennas, which have about 30 % bandwidth, and log-periodic antennas, which can be designed to have several octaves of bandwidth, depending on the number of teeth. The antenna structures are fabricated from an e-beam-evaporated Ti/Au film by use of a lift-off step. We currently use UV lithographical techniques. The antenna is, in turn, coupled through an elliptical lens 4 mm in diameter.

IF Chain

An integral component of a terahertz radiometer is the IF Low-Noise Amplifier (LNA). Since it is desirable to keep the noise contribution from the IF amplifier to the system noise temperature small compared to the intrinsic noise of the HEB mixer, a need for ultra low-noise amplifiers drove the development of a new family of cryogenic IF amplifiers. Advances in modeling and fabrication technologies have yielded Microwave Monolithic Integrated Circuit (MMIC) Low Noise Amplifiers (LNAs) made of InP High Electron Mobility Transistors (HEMTs) with remarkable noise performance and low dc power consumption. We have developed a method for measuring the effective input noise temperature of a cryogenic (liquid-helium temperature) amplifier under matched conditions [2]. The method corrects for transmission-line effects and requires only one internal cryogenic noise source to determine the gain and noise temperature of the LNA. This method (and a careful uncertainty analysis) enabled us to measure the effective amplifier input noise temperature of below 5.5 K at frequencies from 1 to 11 GHz with an uncertainty as low as ± 0.3 K.

Terahertz Radiometer System

The terahertz radiometer consists of the front-end heterodyne detector integrated with the state-of-the-art MMIC LNA on the same mixer block. The block is then mounted in a mechanical cryocooler system that allows access within minutes for any modification of the cold setup. The terahertz local oscillator (LO) consists of a commercial harmonic multiplier source that can provide tens of microwatts of power. Both the LO and the terahertz signals are combined with the use of a thin Mylar beam splitter. Losses and reflections from each of the radiometer components are characterized in order to calibrate the system.

A critical part of the radiometer system is the design of a blackbody source for noise measurements in the terahertz frequency region. The challenge is to produce and characterize the absorbing coating materials for the blackbody cavity walls. The design of the cavity is determined, in large part, by the reflectance of the coating material, and whether it is specular or diffusive in nature. A number of materials surveyed in the open literature are promising candidates for blackbody materials at terahertz frequencies.

Summary

We report on the design and implementation of a radiometer system for traceable noise-temperature measurements in the terahertz frequency regime. The use of near quantum noise-limited heterodyne detectors allows for the development of a new tool for characterizing noise in a frequency regime that lacks such capability. Such a tool will be crucial in establishing new standards already available at other frequencies.

References

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