Advanced Imaging and Spectroscopy of Biological and Chemical Agents at Terahertz Frequencies*

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Abstract

We are developing hot electron bolometer (HEB) mixer receivers for heterodyne detection at terahertz frequencies. HEB detectors provide unprecedented sensitivity and spectral resolution at terahertz frequencies. Terahertz imagers based on HEB technology have sufficient sensitivity to operate in a passive imaging mode, thus eliminating the need for active illumination. HEB mixers have, therefore, become the detectors of choice for applications requiring low noise temperatures at frequencies from 0.5 THz to 10 THz. Previously, we have developed receivers and focal plane arrays operating near the quantum noise limit for astrophysical applications. We have demonstrated a low-noise heterodyne focal plane array (FPA) operating at 0.85 THz. HEB technology is becoming the basis for advanced terahertz imaging and spectroscopic technologies for the study of biological and chemical agents over the entire terahertz spectrum. We also demonstrated a fully automated passive imaging system based on our HEB technology. Our high spectral resolution terahertz imager has a noise equivalent temperature difference (NEΔT) value of better than 0.5 K and a spatial resolution of a few millimeters.

Introduction

Imaging and spectroscopy at terahertz frequencies have great potential for healthcare, plasma diagnostics, and homeland security applications. Terahertz frequencies correspond to energy level transitions of important molecules in biology and astrophysics. Because of its shorter wavelength, terahertz radiation also offers higher spatial resolution than microwaves or millimeter waves.

Hot electron bolometric (HEB) mixer receivers for terahertz frequencies have been under development for astronomical applications during the past two decades [1]. HEBs are "surface" superconducting devices with extremely small parasitic reactances. The devices are fabricated from an NbN film that has been sputtered onto a silicon substrate. The film thickness is typically 3.5 to 4 nm. A typical device size is 2 μm (width) x 0.5 μm (length). The terahertz radiation couples to the device via a quasi-optical system consisting of an elliptical lens and a monolithic terahertz antenna.

The *TREND* spectroscopic instrument, which was deployed successfully at the South Pole in 2003 [2], is based on HEB technology. Ultra-sensitive and fast spectrometers based on HEB technology promise to provide a diagnostic tool for biological and chemical agents both in the laboratory and in the field.

Terahertz Imagers and Spectrometers

A general scheme for a terahertz imager or spectrometer is shown in Fig. 1. Heterodyne detection techniques require a local oscillator (LO) source and an intermediate frequency (IF) amplification chain. The main components of an imaging or spectroscopic system are the front-end detecting receiver, the optics focusing components, and the data acquisition system.

In order to produce a two-dimensional raster, the heterodyne receiver collects radiation from the scanned object through optical components in both the elevation and azimuth directions. This signal beam is chopped against a room-temperature black-body source. The IF output signal from the heterodyne detector is amplified by a cryogenic low-noise amplifier (LNA) cascaded with a back-end IF chain of tunable gain and bandwidth, operating at room- temperature. This signal is then fed to a lock-in amplifier referenced by the chopping frequency. A dedicated data acquisition (DAQ) system collects the lock-in amplifier's output signal as a function of position with respect to the target.

Terahertz HEB imagers are designed with frequencies centered at known atmospheric windows that have lower signal degradation (the 850 GHz window is one example). Large FPAs, employing tens of HEB elements, promise to provide video rate imaging with superior sensitivities.

We have recently demonstrated a passive two-dimensional imager based on HEB technology operating at 850 GHz [3]. The total sensitivity of our imager, in terms of noise equivalent temperature difference (NEΔT), is better than 0.5 K and the spatial resolution is only a few millimeters. Fig. 2 shows an 850 GHz image of two room-temperature objects suspended

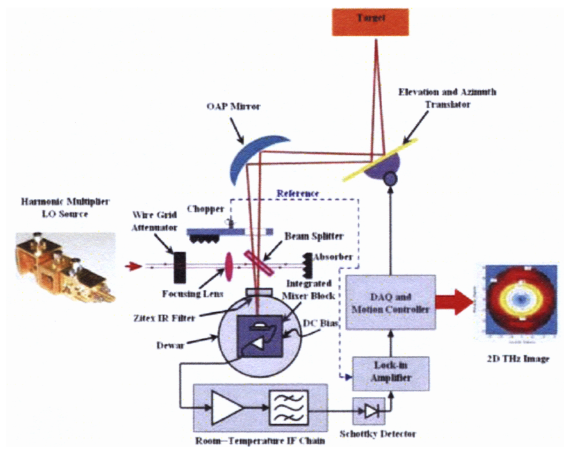

Fig. 1: A schematic of a two-dimensional heterodyne imaging and spectroscopic system.

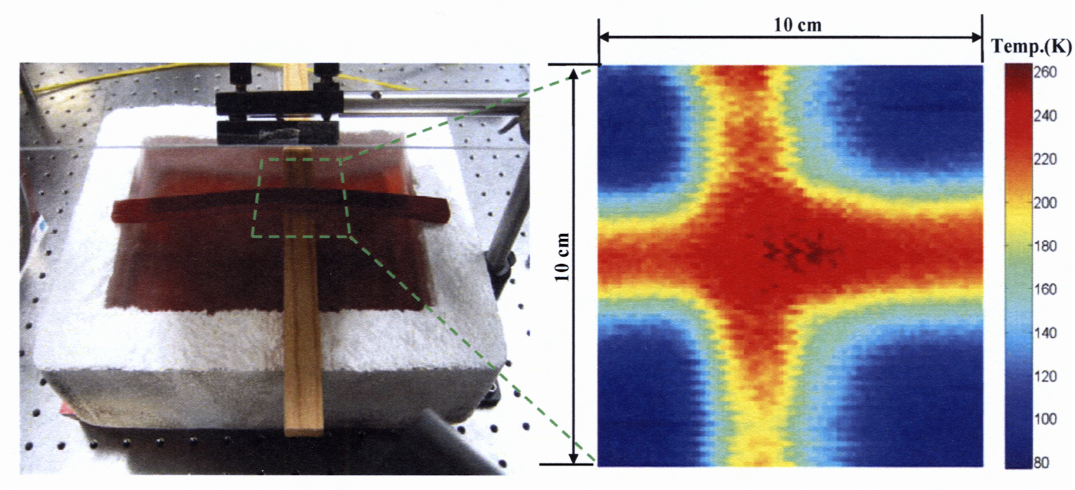

Fig. 2: A photograph (left) and an 850 GHz image (right). Red corresponds to warm temperatures and blue corresponds to cold temperatures (~200 K difference).

over an absorber immersed in liquid nitrogen. The emissivity and reflectivity of each material determine its temperature, to be detected by the HEB receiver.

HEB Focal Plane Array Receiver

In order to demonstrate the performance of the HEB-based imager, a single-element HEB mixer detector was used to image the structure shown in Fig. 2. In a typical receiver system, the mixer and the low-noise amplifier (LNA) are assembled in separate blocks and connected by coaxial cables. An isolator is often included between the mixer and the LNA in order to minimize the standing wave between them. Although this configuration has been widely adopted in astrophysical receiver systems, it does not meet the requirement for a compact multi-pixel focal plane array (FPA). Furthermore, the use of isolators limits the IF bandwidth to no more than an octave. In order to eliminate the use of isolators, we have accomplished a design for integrating the HEB device and a monolithic microwave integrated circuit (MMIC) LNA in the same block [4]. A multi-section microstrip matching network is employed to achieve broadband coupling between the HEB and the MMIC LNA. The HEB device is located in close proximity to the MMIC chip, which is mounted in a narrow rectangular cavity for the purpose of eliminating possible amplifier oscillations.

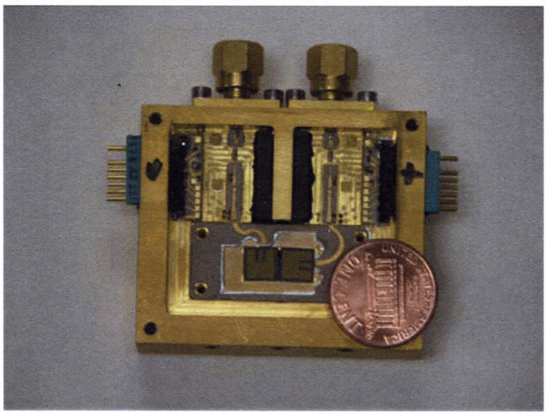

Fig. 3: Photograph of the two-element HEB focal plane array mixer block centered at 0.85 THz.

We have extended the integrated receiver design described above into a two-pixel FPA block shown in Fig. 3. The two pixels are separate and operate independently of each other. SMA coax lines and connectors allow us to extract the two IF outputs from the sides of the block, and two connectors provide all DC bias lines for the HEB devices and the MMIC LNAs. The optical configuration of the pixels in the array is of the "fly's eye" type, which allows ample space for the other components in the focal plane. The performance of this FPA demonstrates the suitability of HEBs as mixer elements in a much larger FPA imager in the future.

FPAs with two or more pixels have a number of advantages over a single-pixel array. First, an object can be scanned faster using multiple pixels (image time is inversely proportional to the number of pixels in the array). Second, different pixels in the array can be operating at different frequencies simultaneously (taking advantage of the high spectral resolution associated with heterodyne detectors). Third, signals with different polarizations can be detected simultaneously using different antenna structures for different pixels in the array. In summary, this general architecture is well suited for construction of FPAs with a large number of pixels to produce terahertz imagers and spectrometers with superior sensitivities.

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