Two-Dimensional Terahertz Imaging System Using Hot Electron Bolometer Technology*

Dazhen Gu, Eyal Gerecht, Fernando Rodriguez-Morales, and Sigfrid Yngvesson

***Abstract*—We present first results with a two-dimensional (2D) scanning terahertz passive heterodyne imaging system, currently under development. The imager is based on a phonon-cooled quasi-optically coupled hot electron bolometric (HEB) mixer integrated with an InP MMIC IF low-noise amplifier (LNA). A harmonic multiplier with an output power of about 250 μW is employed as the local oscillator (LO) source, resulting in a very compact setup. Terahertz images are obtained by scanning the target with a flat mirror mounted on a computer-controlled elevation/azimuth translator. The receiver is designed to operate at 850 GHz, but can in principle operate at any terahertz frequency. We produced full 2D imagery of different objects. The demonstrated overall sensitivity of the imager in terms of a figure of merit NEΔT is better than 0.5 K. We are working on extending the system into a multi-pixel array configuration for faster scanning rates and improved spatial resolution.**

***Index Terms*— Hot electron bolometer, quasi-optical systems, terahertz imaging, terahertz receivers, twin-slot antennas.**

I. INTRODUCTION

TERAHERTZ radiation (T-rays) can penetrate cloth, dust, and smoke better than infrared and visible light. The shorter wavelengths of T-rays allow for higher spatial resolution compared with that of microwaves or millimeter waves. This has opened the field to applications such as remote sensing and detection of concealed weapons and illicit drugs. Furthermore, the partial ability of terahertz radiation to penetrate biological materials offers excellent opportunities for imaging and spectroscopy appealed to healthcare.

In order to realize a passive terahertz imaging system with high sensitivity and a real video acquisition rate, we need to use multi-pixel arrays in which each detection element provides sensitivities near the quantum noise limit. Receivers based on hot electron bolometric (HEB) mixers have demonstrated near quantum-limited noise performance [1]. Moreover, the local oscillator (LO) power requirement of HEB mixers is about four orders of magnitude lower than that of Schottky barrier diode (SBD) mixers. Maintaining a low LO power consumption is a major challenge in the development of multi-pixel focal plane arrays (FPAs) at terahertz frequencies. This is due to the difficulties encountered in producing high power at terahertz frequencies.

The feasibility of the passive detection technique presented here relies on the fact that all objects, whose temperatures are above absolute zero (0 K), emit terahertz radiation. Their actual emission is related to the black-body radiation by a wavelength dependent emissivity, which is specific to the material in question. In other words, all objects behave like grey-body emitters with respect to the ideal black-body. By using ultra sensitive HEB detectors, an imaging system can potentially distinguish between different materials in thermal equilibrium. We chose 850 GHz as the operating frequency for our system, as it is one of the atmospheric windows for terahertz radiation and it gives relatively high spatial resolution for this application.

In this paper, we present progress in the development of a two-dimensional passive imaging system operating at 850 GHz. The system is based on an integrated HEB/MMIC heterodyne receiver [2] with a solid state multiplier source used as the LO. We describe our design considerations, discuss recent experimental results, and present the challenges involved in future development of the next-generation terahertz imagers.

II. DESCRIPTION OF THE IMAGING SYSTEM

Fig. 1 shows a schematic of the terahertz passive imager we are developing. The scanning of the signal beam produced by the target is accomplished by use of a flat mirror mounted on a custom-designed translation unit. The receiver collects radiation from the scanned object in both the elevation and azimuth directions. This signal beam is chopped at 23 Hz against a room temperature black-body source. The LO and the signal beams are coupled to the HEB mixer through optical components, such as off-axis parabolic mirrors and a thin mylar beam-splitter. The intermediate frequency (IF) output signal is amplified using a cryogenic low-noise amplifier (LNA) cascaded with a back-end IF chain of tunable gain and bandwidth, operating at room temperature. The IF bandwidth of the receiver is limited by means of a band pass filter, which is, in turn, connected to a standard microwave detector to produce a rectified voltage signal. This signal is then fed to a lock-in amplifier referenced by the chopping frequency. A dedicated

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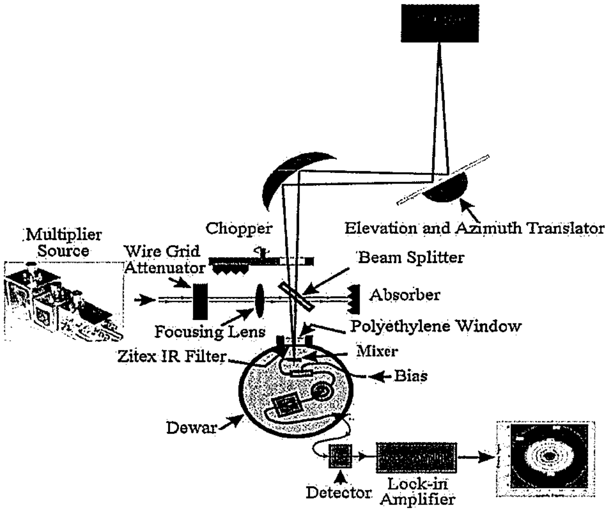


Fig. 1. A schematic of a two-dimensional terahertz passive imaging system.

data acquisition (DAQ) system collects the lock-in amplifier's output signal as a function of position with respect to the target.

A. *Quasi-optical coupling*

In order to effectively couple the incoming radiations onto the HEB mixer, we have designed a quasi-optical system consisting of a silicon lens and a monolithic antenna centered at 850 GHz, shown in Fig. 2. The twin-slot antenna is patterned on a silicon substrate by using electron-beam metallization followed by a lift-off step. The HEB device, made of an ultra thin NbN film, with dimensions of 2 μm wide by 0.5 μm long, is fabricated between the terminals of the twin-slot antenna.

The twin-slot antenna has a highly symmetrical and linearly polarized radiation pattern and provides nearly perfect power coupling to the incident Gaussian beam [3]. The radiation pattern can be calculated by using the first excited modes and the electromagnetic field distribution inside the slots. The far-field pattern is then derived as:

$$E_\theta(\theta,\varphi)\sim M(\theta,\varphi)\cdot\sin\varphi \qquad (1)$$

$$E_\varphi(\theta,\varphi)\sim M(\theta,\varphi)\cdot\cos\theta\cdot\cos\varphi, \qquad (2)$$

where

$$M(\theta,\varphi)=\frac{\left[\cos\left(\frac{L}{2}k_d\sin\theta\cos\varphi\right)-\cos\left(\frac{L}{2}k_m\right)\right]\cos\left(\frac{k_d}{2}S\sin\theta\sin\varphi\right)}{k_m^2-k_d^2\sin^2\theta\cos^2\varphi}$$

and L and S are the length and separation of the twin slots, respectively, $k_d=2\pi/\lambda_d$ is the wave-number at the dielectric side, and $k_m=2\pi/\lambda_m$ is the effective wave-number at the vacuum/dielectric interface. The simulated radiation pattern is shown in Fig. 3. Evidently, most of the radiation propagates into the dielectric side.

The silicon lens is a rotational ellipsoid that functions as an aperture antenna, and hence reshapes the far-field radiation pattern. By using a ray-tracing technique, one can show that the radiation from the twin slot antenna, placed at the second focus of the lens, becomes a plane wave in the aperture plane outside the lens. By considering the combination of the silicon lens and the twin-slot antenna, one can show that the far-field beam has a full-width half-power (FWHP) width of about 3 degrees.

B. *LO source*

The available choices of LO sources at terahertz frequencies include far-infrared (FIR) lasers, quantum cascade lasers (QCLs) in the higher terahertz spectrum, and harmonic multiplier sources in the lower terahertz spectrum. We have chosen a harmonic multiplier source as the LO because of its compact size and ease of use.

A commercially available 850 GHz harmonic multiplier source [4] is employed as the LO signal. A phase-locked oscillator generates an output signal at 11.8 GHz. This signal is used to drive a multiplier chain, which is composed of one amplifier, two triplers, and three doublers. The entire chain produces a total of $2^3\times3^2=72$ times frequency multiplication, resulting in an output signal of $11.8\times72\approx850$ GHz. The terahertz signal injection is then achieved by using a WR 1.2 diagonal horn module assembled at the end of the multiplier chain. This particular harmonic multiplier source can produce an output power of up to about 250 μW.

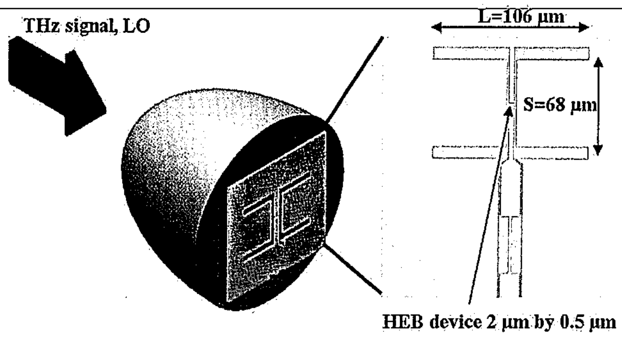


Fig. 2. Illustration of a quasi-optical system and a twin-slot antenna photograph.

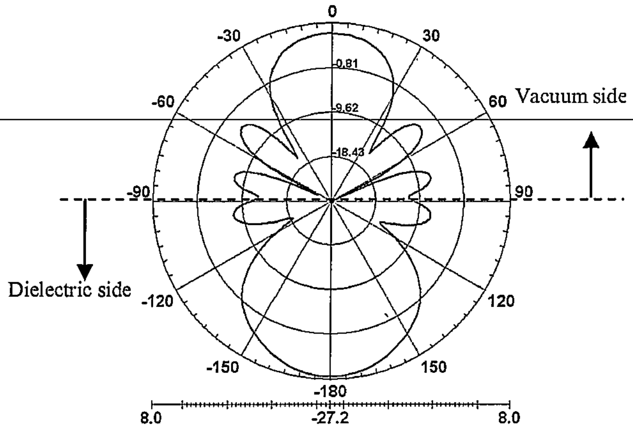


Fig. 3. Simulated radiation pattern of the 850 GHz twin-slot antenna on a silicon substrate.

C. *Integrated receiver block*

In a typical receiver system, the mixer and the 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 [5] [6], it does not meet the requirement for a compact multi-pixel 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 the MMIC LNA in the same block. 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 purpose of eliminating possible amplifier oscillations [2]. This particular MMIC LNA has been characterized against standards developed at the National Institute of Standards and Technology (NIST) and with a recently developed measurement technique [7], exhibits noise performance of below 5.5 K from 1 GHz to 11 GHz and a minimum of 2.3 K at 7 GHz. Fig. 4 is a photograph of the HEB/MMIC integrated mixer block.

D. *Beam scan and data acquisition*

A scanning scheme was designed to record the image of the target by means of a line-by-line sweep, often called a raster scan. Each line of the scan is divided into a number of pixels. The number of pixels and the distance between pixels can be adjusted according to the desired resolution and the size of the target.

The total wait period at each pixel is based on the lock-in integration time constant. In order to achieve fast scanning and stability of the signal, the wait period is made ten times longer than the lock-in time constant.

An automated motion controller, which also functions as a DAQ system, is used to drive the translator and collect the data in real-time. The motion controller provides a 0.001 degree angular resolution and can gather data with 14 bit accuracy (±600 μV on a ±10 V scale) at rates up to 10 kHz. The motion controller has a built-in Pentium processor and is capable of communicating with a user PC via Ethernet protocol.

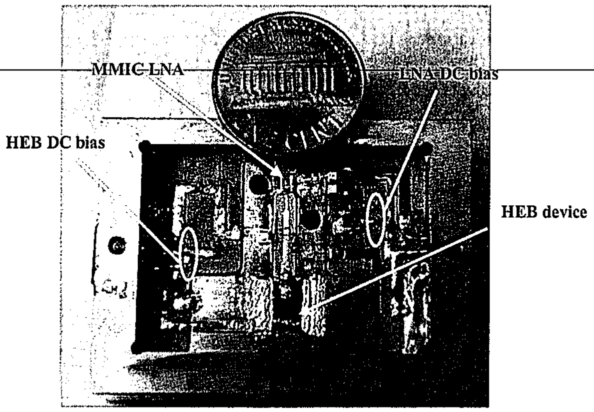


Fig. 4. An integrated mixer block housing an HEB device and an MMIC LNA.

III. RESULTS AND DISCUSSION

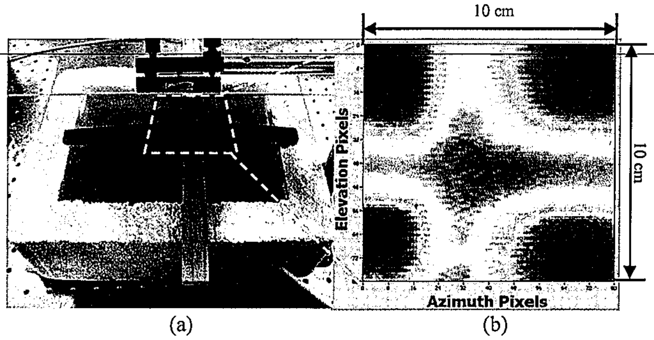
Our terahertz system was used to take images of various objects. Fig. 5 shows an example of two room temperature objects forming a cross suspended over an absorber immersed in liquid nitrogen. The temperature difference (of about 200 K) can be clearly distinguished by the color contrast.

The HEB receiver in our imaging system has a noise temperature of 2200 K. This is not the most sensitive HEB mixer we have produced [1]. The integration time constant on the lock-in amplifier was 300 ms, which integrates 7 periods of the chopping frequency (23 Hz). The IF bandpass filter, with a center frequency of 2.35 GHz and a bandwidth of 2.3 GHz, ensures the best overall performance in terms of low noise and widest bandwidth. We can enhance the spatial resolution of the image by minimizing the beam waist on the target. In our case, we had a beam waist of about 3.6 mm. The DAQ system allows for ten periods of the lock-in amplifier time constant (3 s) at each pixel, resulting in about 90 minutes total to complete a scan of a 40 by 40 pixel image.

For our imager, the RMS fluctuation in the measured radiation temperature can be obtained according to the radiometer formula,

$$\Delta T_{RMS} = \frac{2T_{sys}}{\sqrt{B\cdot\tau}} = \frac{2\times(2200+300)}{\sqrt{2.3\times10^{9}\times0.3}} \approx 0.2\ \text{K}, \tag{3}$$

where T_{sys} is the system noise temperature, B is the receiver bandwidth, and τ is the integration time. ΔT_{RMS} is the figure of merit to evaluate the thermal resolution of passive imaging systems. This figure of merit is also known as NEΔT. In our case, the imaging system can theoretically resolve a temperature difference as small as 0.2 K. The system temperature can be decreased to 1000 K with optimum HEB detectors, while the bandwidth may be increased to at least 3 GHz, resulting in NEΔT=37 mK, normalized to a 1 s integration time. The best published results for a direct detector passive imaging system translates to NEΔT = 700 mK [8]. Presently, heterodyne systems are more sensitive by a factor of 20. Laboratory results



(a) (b)

Fig. 5. (a) Photograph and (b) a 850 GHz image of two room temperature objects suspended over an absorber immersed in liquid nitrogen. Red corresponds to warm temperatures and blue corresponds to cold temperatures (about 200 K difference).

for a direct detector [9] indicate improved sensitivity but this direct detector is a long way from system realization.

A target made of a resistor coil in front of a room temperature absorber was used to measure the thermal resolution of our imaging system (Fig. 6). The temperature difference between the resistor coil and the absorber can be adjusted by changing the voltage across the resistor. Images at 850 GHz were taken for two different temperature differences: 35 K and 3 K. The hot spot corresponding to the warm coil for the 35 K temperature difference is clearly observed from Fig. 6b. For the 3 K case (Fig. 6c), the image became somewhat blurred. By using image post-processing based on a de-speckle algorithm, the image can be enhanced (see Fig. 6d). From the 3 K case we can estimate an actual NEΔT = 0.5 K for the present system.

IV. SUMMARY AND FUTURE PLANS

We have developed a two-dimensional passive terahertz imaging system operating at 850 GHz based on HEB technology. Preliminary results give evidence of a high thermal resolution (about 0.5 K). The detection speed can be increased by employing a faster chopper. The next step for increasing system speed will be to use an FPA. A prototype FPA containing three elements based on HEB mixers and MMIC LNAs has already been demonstrated [10].

Fig. 7 shows a conceptual architecture for future large FPAs using multiple HEB detectors. The lenses and the HEB devices will be arranged in a fly's eye configuration. Such a configuration can produce an angular resolution slightly larger than one diffraction-limited beamwidth. IF amplifiers and DC circuitry will be assembled on separate boards, connected to the HEB devices through kapton ribbon transmission lines. We expect that this new architecture, combined with MEMS micro-cryocooler technology, currently under development, will potentially be able to produce an extremely compact system for mobile terahertz imagers with video-rate speeds. Potential applications for these receivers range from medical diagnostics to security surveillance.

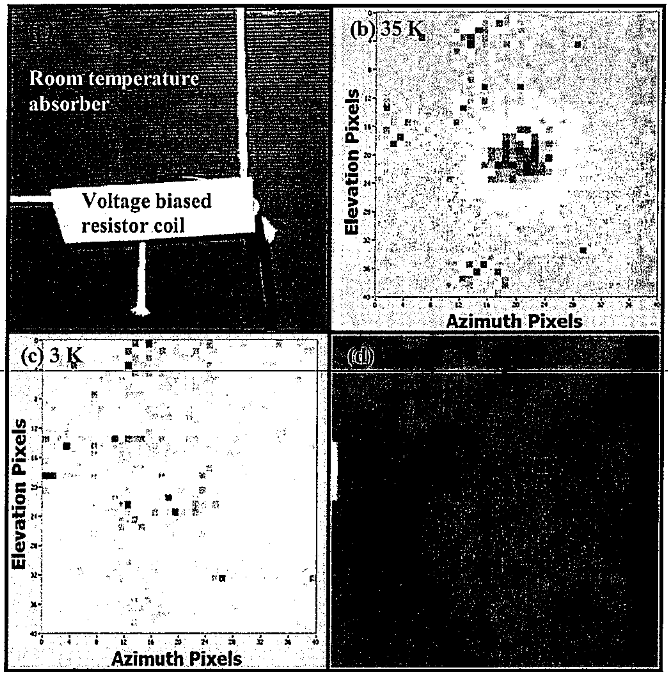


Fig. 6. (a) photograph of the resistor coil and the absorber; (b) image of 35 K difference; (c) image of 3 K difference; (d) the same 3 K difference image after post-processing.

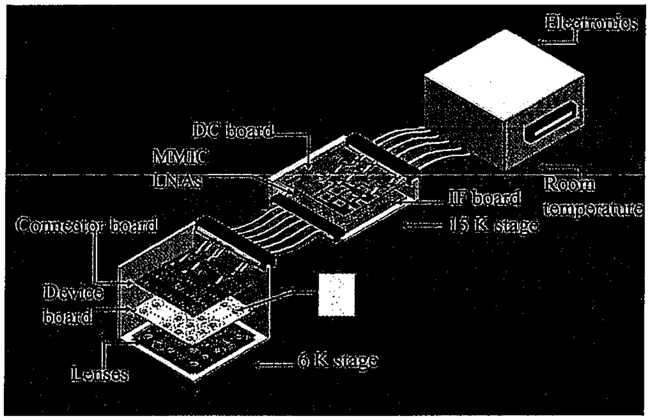


Fig. 7. A conceptual architecture for a terahertz FPA with multi pixels using HEB/MMIC technology.

ACKNOWLEDGMENT

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