Integration of a Mobile Terahertz Spectroscopic System based on HEB Heterodyne Detection

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***Abstract*—We are developing a mobile heterodyne terahertz system based on hot electron bolometer (HEB) mixer receivers to both image and obtain spectra from biological samples. An HEB mixer provides unprecedented sensitivity and spectral resolution at terahertz frequencies. We have recently demonstrated a low-noise heterodyne passive imager operating at 0.85 THz [1]. A heterodyned HEB detector integrated with a low noise amplifier and quasi-optical beam handling based on polymer lenses are central to this radiometric system. The current design is optimized for the atmospheric windows centered at 650 GHz and 850 GHz, but can be extended to any terahertz frequency. A state-of-the-art mechanical cooler with a very small footprint, high temperature stability, and low mechanical vibrations is also under development for our HEB receiver technology. Here we report the integration of these different elements into one platform that will result in a flexible, mobile, and versatile diagnostic instrument capable of long-term, low-maintenance operation in biomedical applications. We intend to perform real-time tissue diagnosis using broadband terahertz spectroscopy that is guided by terahertz imaging with a spot size of 500 micrometers or less with this mobile platform.**

***Index Terms*—Heterodyne detection, hot electron bolometer (HEB) detectors, quasi-optical coupling, radiometry, terahertz imaging, terahertz spectroscopy.**

I. Introduction

Terahertz spectroscopy and imaging have great potential for healthcare and a wide range of remote sensing applications. Terahertz frequencies correspond to unique vibrational and rotational energy level transitions in molecules. Terahertz radiation also has a shorter wavelength than that of the microwave to millimeter wave range, easily providing sub-millimeter spatial resolution.

Terahertz radiation can identify complex gas molecules in plasma by their resonant rotational energy absorption from the field. These have a wide range of remote sensing applications from astronomy, to monitoring semiconductor fabrication, to homeland security. If the molecules reside in a partially ionized plasma then terahertz spectroscopy is better than its optical and microwave competitors in detection sensitivity.

We are also developing terahertz systems for non-destructive evaluation (NDE) of materials and chemical sensing in terms of scattering parameters and noise. Similar measurements can be made on solutions of thin cross-section. So terahertz sensing will be a natural complement to microfluidic and similar lab-on-chip systems.

By using hot electron bolometer (HEB) heterodyne detectors in terahertz spectrometers, we can come close to quantum-noise-limited sensitivity with spectral resolution that approaches a few kilohertz. This potential for high resolution spectra is particularly important in measuring minute changes in terahertz absorption that occur with conformational changes such as protein folding, or complex formation between biomolecules. Here we detail the integration of an HEB receiver with a quasi-optical system to handle local oscillator and radiometric signals along with a state-of-the-art mechanical cryogenic cooler in a mobile platform for terahertz imaging and spectroscopy.

II. HEB Heterodyne Detection

HEBs are surface superconducting devices with extremely small parasitic reactances, even at the highest terahertz frequencies. HEB devices are able to absorb radiation up to the visible range due to their very short momentum scattering times. The detection signal comes from a change in device resistance as the quasi-particles warm. HEB devices are fabricated from 3.5 to 4 nm thick NbN films that are sputtered onto silicon. Typical device size can range from 2 micrometers wide by 0.5 micrometers long down to sub-micrometer dimensions. We direct beams carrying the local oscillator (LO) signal and the radiometric signal from a sample to this HEB detector using quasi-optics. A twin slot antenna couples the radiation to the HEB device, and this mixer/antenna combination is centered at the second focus of a 4 mm diameter silicon ellipsoidal lens to maximize optical coupling. The twin-slot antenna surrounding the HEB has a highly symmetrical and linearly polarized radiation pattern providing nearly perfect power coupling to the incident Gaussian beam. This gold monolithic terahertz antenna is patterned on a silicon substrate by use of an electron-beam metallization step followed by a lift-off step. The impedance of the HEB is matched to this antenna by adjusting its aspect ratio. In this configuration, radiation from the antenna becomes a plane wave in the aperture plane outside the lens. The combination of the silicon lens and the twin-slot antenna results in a far-field beam with a full width at half power (FWHP) of about 3 degrees.

HEBs made of NbN films have a thermal time constant that is determined by both the rate at which phonons are emitted by

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the electrons and the escape rate of the phonons from the NbN film to the substrate. NbN HEBs are, therefore, known as phonon-cooled HEBs and can exhibit conversion gain bandwidths of about 4 GHz, while the receiver noise temperature bandwidth can be up to twice the gain bandwidth. An operating temperature range for the HEB devices of 4 K to about 6 K is an advantage over most other far-infrared (FIR) devices, which require cooling to sub-Kelvin temperatures.

In a typical receiver system, the front-end mixer is integrated with a low-noise amplifier (LNA). We have demonstrated a design for integrating the HEB device and a monolithic microwave integrated circuit (MMIC) LNA in the same block [1]. 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. This particular MMIC LNA has been characterized against standards developed at the National Institute of Standards and Technology (NIST) and, by use of a recently developed measurement technique [2], exhibits noise performance of below 5.5 K from 1 GHz to 11 GHz. To power the device and extract the intermediate frequency (IF) signal from it, we use a bias “tee” circuit that is built into the mixer block.

We have also demonstrated an integrated design for a small focal plane array (FPA) with two pixels that allows for dual-frequency and dual-polarization operation [3]. Fig. 1 shows a photograph of the two-pixel HEB/MMIC-LNA integrated mixer block. The pixels operate independently of each other. SMA coaxial 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 other components in the focal plane. The performance of this FPA demonstrates the suitability of HEBs as mixer elements in much larger FPAs in the future. FPAs with two or more pixels will increase image scan rate and simultaneous operation of neighboring pixels at different frequencies or polarizations. They can also operate in correlation receivers. 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 and speeds.

III. Quasi-Optical System Design

Our previous terahertz imaging system relied on off-axis paraboloid (OAP) mirrors for beam handing [1]. While this approach minimizes optical power loss, aberrations from these mirrors limit the minimum spot size and shape that can be achieved. A better approach, which retains the high efficiency of free space propagation, uses a quasi-optical imaging system [4] based on lenses. Our approach uses three dielectric lenses that are machined from high density polyethylene (HDPE) to create convex surfaces at a design wavelength of 635 gigahertz. This provides diffraction-limited spatial resolution as measured by the beam width on the sample.

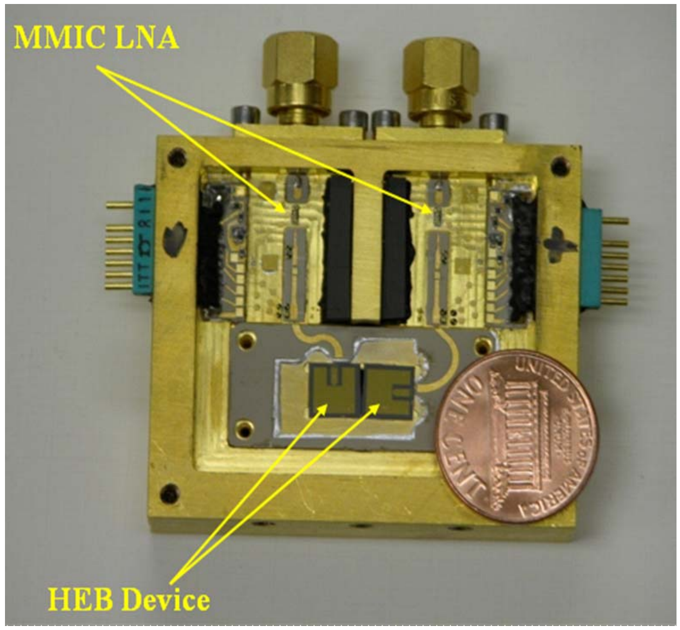

Fig. 1. Two-pixel integrated mixer block housing two HEB devices and two MMIC LNAs. This configuration maximizes SNR [3].

To relay the signal beam a distance of approximately 800 mm between sample surface and HEB receiver, lens structures were designed from the object (sample) plane, as follows: (1) an objective lens with its first surface focusing to a waist of ~1 wavelength at 25 mm and a second surface at infinite radius to generate a collimated beam, (2) a lens to collect this collimated beam that has both surfaces designed to focus at 100 mm, and (3) a much larger focusing lens with both surfaces machined to focus at 100 mm, designed to couple the beam into the 4 mm elliptical silicon lens, to which the HEB/antenna element is affixed. The radiometric signal beam is drawn over a photograph of our optical layout in Fig. 2. The collimated region allows compliance in beam path length for integration.

Lens positions were initially simulated using a custom graphical layout program that we developed and then tested by direct calorimetric measurements. To achieve this, the 635 and 850 gigahertz sources were placed at the HEB mixer position, reversing the light path to map the beam and measure beam waists at critical points. This was done by cutting the Gaussian beam with a razor blade assembly mounted to an XY stage driven by micro-stepping linear motors. Calorimetric measurements made as this beam was cut then resulted in data that approximated an error function curve.

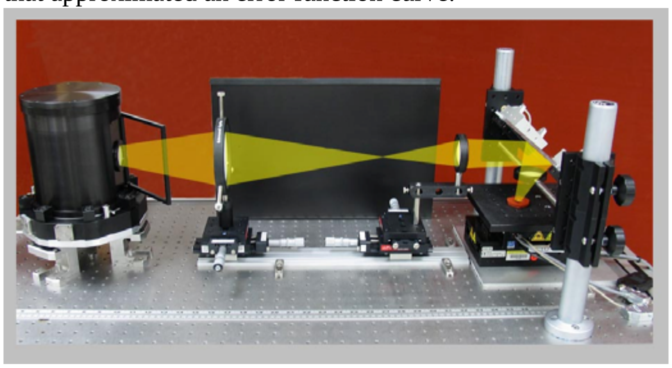

Fig. 2. Optical beam layout for radiometric signal on XY stage.

We differentiated and fit this curve to a Gaussian profile to determine beam width. Data from one of these fits is shown in Fig. 3. The minimum measured beam widths at the object plane for 635 GHz and 850 GHz were 600 micrometers and 500 micrometers, respectively. We also confirmed that using the 850 GHz source with the hyperbolic profile lenses, we designed for 635 GHz, increased focal distances by 3%.

IV. System Integration

A photograph of the mobile cart platform that we are assembling our new terahertz system on is shown in Fig. 4. With it we are engineering a robust platform for a terahertz system that ultimately will provide fixed-frequency imaging and chirped spectroscopy. It combines the HEB receiver, a custom mechanical cryocooler, a local oscillator source, quasi-optics for beam handling and a motion control/data acquisition system. The custom cooler is a 4K Stirling-type pulse tube design, developed through an ongoing collaboration with our colleagues in the NIST Chemical Sciences and Technology Laboratory [5]. Its operation at 30 Hz minimizes temperature

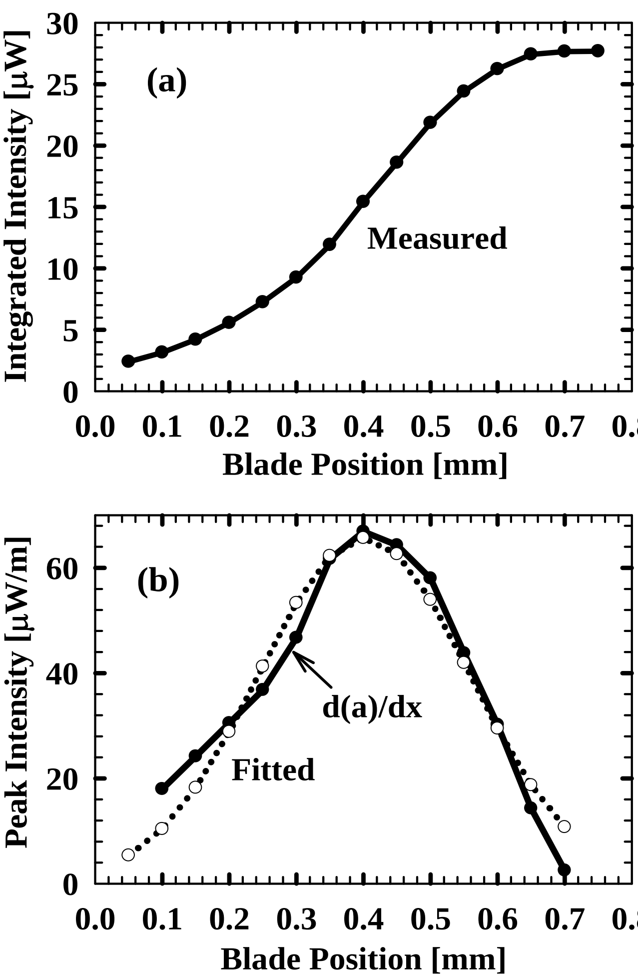

Fig. 3 An example of experimental beamwidth fitting. In (a), intensity is measured with a calorimeter as the beam is progressively opened past a razor edge that cuts/occludes it orthogonally. Note that while intensities are given units here, the absolute value depends on calorimeter placement and any collection optics used downstream of the cut. In (b) the first derivative of the data (averaging two points) is calculated from the data and a Gaussian peak is least squares fit to the result. Here the full width to e^{-2} of peak is 580 micrometers.

Fig. 4. Photograph of our terahertz imaging and spectroscopy system assembled on a mobile cart platform.

fluctuations and mechanical vibrations at the HEB mixer block, thus reducing noise and gain fluctuations. Moreover, configuring the cryogenic system in this way allows for many months of operation without supervision or maintenance. An automated motion controller drives XY sample translators and acquires data in real-time.

The practical choices of LO sources at terahertz frequencies include FIR lasers operating on a number of discrete spectral lines throughout the terahertz spectrum, and harmonic multiplier sources in the lower terahertz spectrum. We have chosen the harmonic multiplier architecture for our LO sources because of their compact size, ease of use, and availability for frequencies in the lower terahertz spectrum. We have deployed a number of commercially available harmonic multiplier sources [6] as the LO signal. Our 850 GHz source consists of a phase-locked dielectric resonance oscillator with an output signal at 11.8 GHz and a 72x multiplication chain. This source produces about 300 microwatts, which is sufficient for a small array of HEB mixers. A tunable range of about 10% was achieved with this multiplier source by replacing the low frequency signal that drives the multiplication chain with a microwave synthesizer having sub-hertz spectral resolution. Tunability is important because the next step will be to chirp this source for rapid spectral acquisition.

In order to combine the LO and radiometric signal along the final beam path into the mixer, we employ Mylar beam splitters, ranging in thickness from 6 to 25 micrometers, reflecting 28% to 1% of the incoming LO radiation, respectively. In future designs the material under measurement will be actively polarized with a source that also relies on harmonic multiplication.

V. Biomedical Applications

We are integrating hardware and sample handling methods in a mobile cart platform to perform terahertz imaging and spectroscopy aimed at sensing the large and increasing number of diseases that are being identified as problems caused by protein excesses in the cell [7]-[9]. For cancer, protein production goes on unchecked, but in many more cases there are problems with the way a protein self-folds or with the cell machinery that helps it fold. Protein conformational problems lead to aggregated complexes, as in the case of amyloidosis or proteins that can't be recognized by the normal proteolysis machinery of the cell that takes out the garbage. Many important diseases result from protein conformational problems, e.g. Alzheimer's, Huntington's, the prion diseases, cystic fibrosis, type 2 diabetes and Parkinson's disease.

Terahertz spectroscopy on biological substances is still novel, but results so far suggest that it is sensitive to protein folding [10]-[11] and protein surface hydration [11]-[13] in isolated biochemical samples. While some authors have been investigating the degree to which terahertz spectroscopy can report structure down to the level of singular bonds, the conditions that allow such specificity are too restrictive and require extensive modeling [14]. Also, frequency-domain spectra of random biopolymers dried into 100 micrometer thick test films are too averaged to show spectral shapes characteristic of the small biomolecule constituent [15].

Terahertz spectra of good resolution can be achieved only through techniques which control the signal attenuation due to water absorption and spectral broadening caused by the thermal averaging. Both of these aspects demand techniques that limit the thickness of samples to tens of micrometers. To perform terahertz imaging and spectroscopy that are selective for the tissue surface, we plan to combine optical focusing with active polarization of the sample surface for real-time diagnostics during surgery. By imaging with a spot of 500 micrometers or less at the tissue surface it should be possible to identify the extent of diseased tissue during surgical removal. For clinical diagnostics outside of the operating theater, tissue and cell biopsies may additionally be flash-frozen to distinguish such protein imbalances with much greater sensitivity. We are integrating the above capabilities that will allow the efficacy of a drug treatment to be monitored over time, for example. Therefore we envision a vital role for frequency-chirped terahertz spectroscopy in clinical diagnostics and real-time surgical monitoring of protein conformational diseases.

VI. Summary

Terahertz imaging and spectroscopy can play an important role in bioscience and materials sensing applications. Like any other spectroscopic method, it has challenges and limitations to overcome to advance beyond a curiosity. Some of these are technical, such as incorporation of the HEB mixer for detection; but development of appropriate sample handling and stimulus methods are just as important to an optimized platform. Our efforts have therefore shifted toward a more balanced approach that leverages the best available technology to serve the needs of biological applications. While there are many challenges ahead, we see the integration of a highly frequency selective and sensitive HEB receiver-based system combined with quasi-optical methods of beam handling on a mobile cart platform as a critical step toward making terahertz spectroscopy and imaging a relevant tool for real-time diagnostics in life sciences. We anticipate that the same consideration will lead to very similar platforms for materials NDE as well.

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