A Prototype Terrestrial Terahertz Imaging System

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***Abstract*—Interest in alternative imaging, with an emphasis on medical and security applications, is increasing. The terahertz spectrum is beginning to be explored for these applications. A prototype scanning imaging system is described here. This system currently operates at 1.6 THz and uses a HEB as a heterodyne detection element. Object scanning is accomplished by using an oscillating mirror running at 8 Hz with a scanning angle of 30°. Theoretical calculations for this system yield a thermal resolution of better than 0.5 K with an integration time of 1 ms. This calculation is based on a system noise temperature of 1000 K at the image and neglects the effects of system gain fluctuations. At this time, the system's RMS thermal noise level is 1 K with an integration time of 1 second. A major component of the system is IF gain stabilization through active LO power control. Currently, the LO power control is under development. Completion of this subsystem is likely to greatly enhance thermal resolution. Further improvements--specifically, faster scan rates optimized to the stabilized IF output--can then be pursued.**

***Index Terms*—HEB, hot electron bolometer, THz, terahertz, imaging.**

I. INTRODUCTION

For the purposes of the prototype imaging system described here, terahertz (THz) video imaging is defined, minimally, as scanning a 1 m x 2 m object with 20 mm resolution at a rate of 10 frames per second. Under these criteria, hot electron bolometer (HEB) heterodyne systems have advantages over other systems. For example, in terahertz time domain spectroscopy (THz-TDS), video imaging is currently not possible due to limitations of delay line speed and difficulties in forming arrays. With these limitations, THz-TDS systems produce an image in a time on the order of minutes [1].

A 640 GHz imaging system was recently demonstrated that used Schottky diode mixers [2]. Schottky diode mixers require a LO power on the order of 1 mW, which makes this system impractical for the multi-pixel arrays needed to achieve video rate imaging. Conversely, the LO requirement of an HEB mixer is on the order of 1 μW, which is well-suited for the arrays needed in a video rate system. Schottky direct detectors have to contend with large 1/f noise [3]. Room-temperature niobium (Nb) direct detectors have an RMS noise-equivalent input temperature fluctuation level (NEΔT) of about 100K [4] with an integration time of 100 ms. Current HEB technology yields an NEΔT of 0.5 K with an integration time of 1 ms. These values assume that the contributions from gain fluctuations are small. The system proposed here actively compensates for these fluctuations on two levels.

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II. REFERENCED LINE SCANNING IMAGER

A. Overview

The Referenced Line Scanning Imager (RLSI) under development at University of Massachusetts—Amherst (UMASS) combines techniques from many disciplines into a unique arrangement. The system is diagramed in Fig. 1. A multifaceted rotating mirror, producing one scan per facet, scans the object. Between the facets are reference loads used for real-time calibration. The thermal radiation from the object is combined with the LO, produced by a gas laser, and is mixed at the HEB array. The HEBs are constant voltage biased, and the current is stabilized with the LO. The signal from the reference load controls the back-end gain.

B. Rotating Mirror and Optics Configuration

The specifications for the system given in the introduction require that we detect radiation from 100 (vertical) x 50 (horizontal) pixels. The HEB array is oriented horizontally, and the rotation of the mirror scans the object vertically, producing signals corresponding to 100 pixels from each array element in each scan. The number of array elements determines the number of vertical scans required. We propose a linear array of 25 elements. We would first scan the 25 horizontal pixels in the left half of the object, and then the 25 pixels in the right half. Thus, two scans will cover the entire image. To achieve the alternating left/right scans, alternating facets of the rotating mirror are at offset angles in the horizontal plane. A 30-degree field width requires a 15-degree mirror angle articulation. Therefore, a mirror with 24 facets at alternating angles could be employed. The scanning action is rotational rather than reciprocating, making very high scan rates achievable. This leaves open the possibility of multiple scans per frame. The system uses as a reference a square wave with a period of T_{ref} equal to the frame rate (100 ms) divided by the number of vertical pixels (100). The mirror rotation is locked to this reference. Between each facet is a black body reference load. The signal from the reference is used to normalize the pixels and stabilize the back-end gain.

There are also focusing elements (offset paraboloidal mirrors) between the object and the HEB (not shown). In a future system capable of imaging at greater distances (say 25 meters) the rotating mirror would be positioned near the focus of a Cassegrain reflector system with sufficiently large main reflector diameter to produce the required resolution of 20 mm on the object.

C. HEB Bias

The HEB mixer uses a constant voltage bias. The bias current is sensed and sent to a proportional integral derivative (PID) control. The error signal from the PID

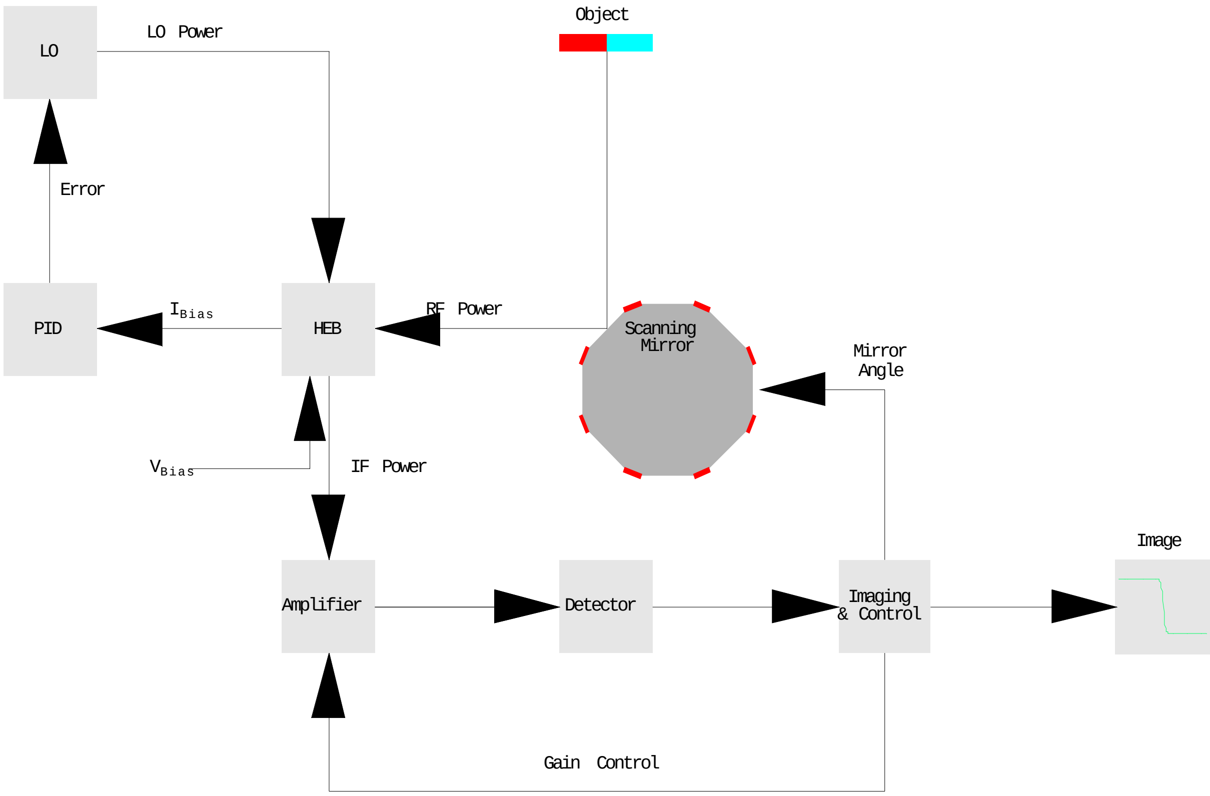

Figure 1. Block diagram of the proposed Reference Line Scanning Imager

control trims the LO power. An acousto-optical modulator in the FIR pump beam controls the LO power. The PID time constant is 1 ms, which effectively stabilizes the bias point during scanning.

D. Demodulation

All pixel levels are simultaneously demodulated from the raw signal of the detector. Each pixel is demodulated as follows. From the T_{ref} signal a pulse is produced with positive width equal to T_{ref}. This pulse has a phase shift appropriate for the pixel. A product is formed between the raw signal and the pulse. The difference between this product and the level from the reference load is the pixel level. The signal from the reference load is leveled by a feedback loop with the back-end amplifier gain. The image size is 100 pixels x 50 pixels, containing a total of 5,000 pixels. With a 25-element array, an integration time of 0.5 ms is afforded. This integration can be an average of multiple scans or a single scan. Current HEB technology can achieve a noise temperature of 1,000 K with a bandwidth of 4 GHz. By the radiometer formula, an RMS input noise level of 0.7 K is expected. With an average image temperature of 300 K, this is a signal-to-noise ratio of better than 400:1. This is an improvement by a factor of four over a much slower photomixing technique used by Siebert, *et al.* [4]. Their 3,072 pixel image forms in about 11 minutes with a signal-to-noise ratio of 100:1.

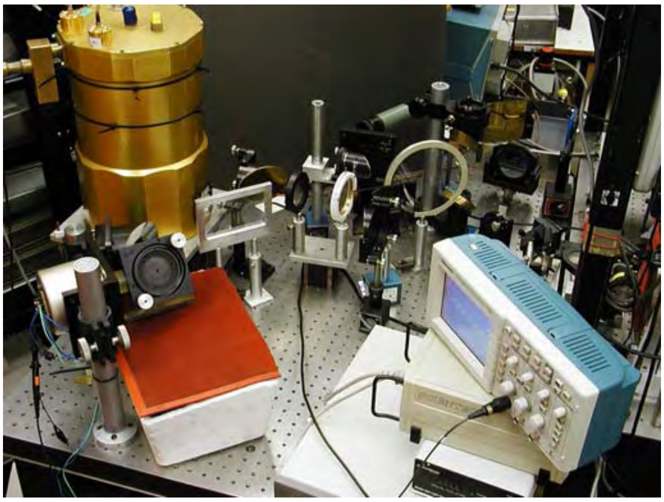

Figure 2. Photograph of current prototype imager.

III. Current Prototype

A. Description

The currently operating prototype is a test bed for many of the systems in the RLSI. The optical design is pictured in Fig. 2 and can be explained with reference to Fig. 3. In this single element system a line of the image is scanned

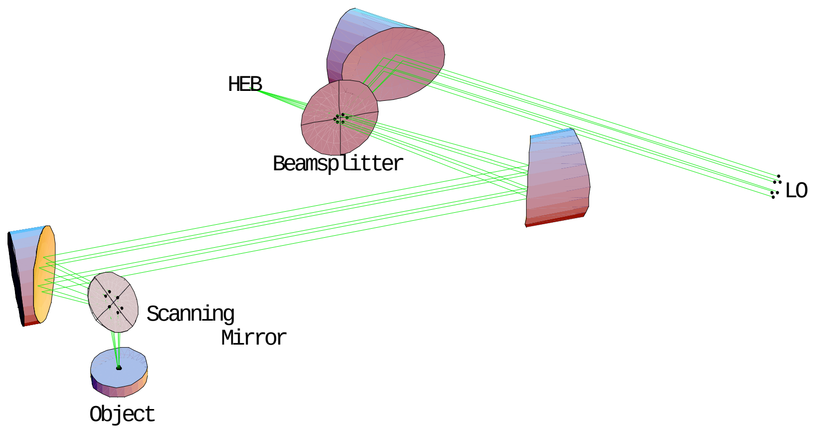

Fig. 3 Optical diagram for the prototype imager.

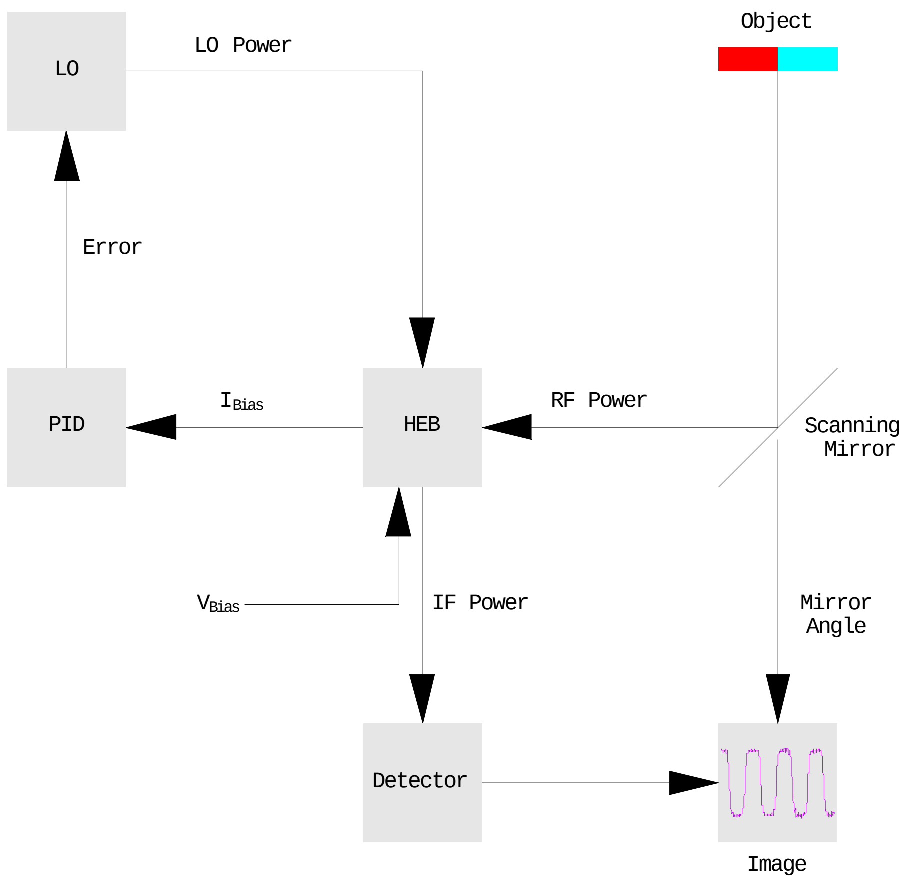

Figure 4. Block diagram showing signal processing for the prototype imager.

with an *oscillating* mirror running at 8 Hz. The mirror is driven with a triangle wave, which also triggers the sweep of the digitizer (Tektronix Digitizing Oscilloscope type 11403A), where the image of the line scan is formed. The scan angle is 30 degrees. The imaged area is a 50 mm line approximately 100 mm from the oscillating mirror. Signal processing is diagrammed in Fig. 4 and described as follows. The amplified IF signal from the HEB covers a bandwidth of 0.5 GHz to 4 GHz, and is rectified with a standard microwave detector. This signal is low-pass filtered to the pixel acquisition time and then applied to the vertical input of the digitizer. The digitizer then averages over a set number of sweeps. The HEB current lock is currently being tested.

B. Results

The measured noise temperature of the HEB used in this system was 3,500 K at the image. We employ an HEB integrated in a mixer block, with an MMIC IF amplifier similar to the elements we used in the focal plane array described in [6]. At the time the images presented here were recorded, the HEB current lock had yet to be integrated. Nevertheless, the results from this simplified system are encouraging. In Fig. 5, an integration time of 1 s is used to image a transition from an absorbers at 280 K to one at 77 K.

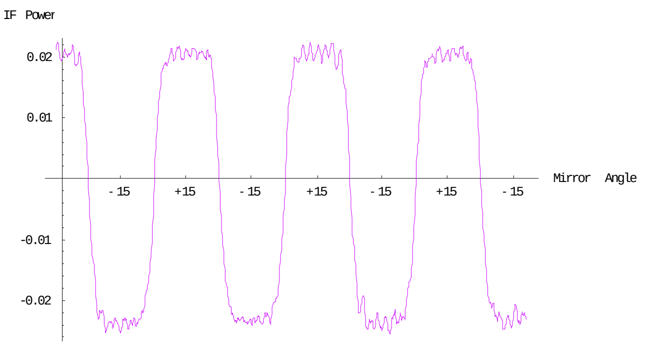

Figure 5. Test recording from the prototype imager with a split object at 280 K and 77 K, respectively.

The image records a peak-to-peak level of 43 mV for a ΔT of 200 K. From this, a responsivity of 0.2 mV K^{-1} is inferred. Using the same experimental setup to record an image of a steel bar in thermal equilibrium with a 280 K background, the image in Fig. 6 was recorded.

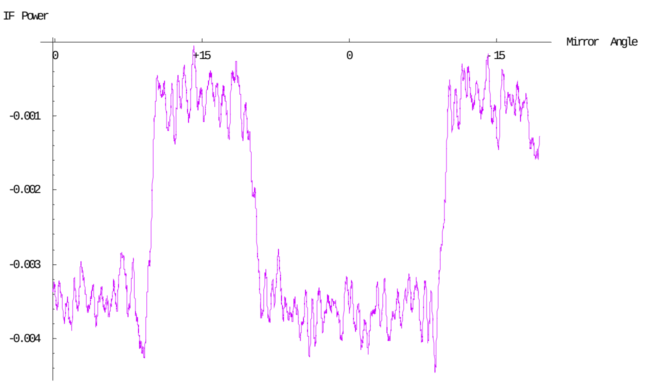

Figure 6. Image of a steel bar over a 280 K background. The lowest signal is due to the steel bar.

The peak-to-peak level in the latter image is 3 mV, which translates to a ΔT of approximately 15 K. The steel bar was measured by a conventional thermometer to be in thermal equilibrium with the 280 K background absorber it rested on. The peak-to-peak noise in this image is less than 1 mV or 0.3 mV RMS. Therefore, the fluctuation level at the system input is equivalent to a thermal signal of less than 1.5 K RMS. This value is far greater than what would be expected from the radiometry formula (0.06 K). A portion of the noise level in the recorded signal may still be due to pick-up of 60 Hz and other interfering signals. We also expect that we are seeing the result of system gain fluctuations that we are now beginning to combat with the HEB current lock. Preliminary tests of the current lock show a dramatic reduction in the measured Allan variance of the detected IF power. We define the normalized Allan deviation as follows. Sampling the IF power, the vector, $\{P_1, \ldots, P_N\}$, is formed with sample time Δt. The mean of X equals:

$$<X> = <\{X_1, \ldots, X_N\}> = \frac{1}{N}\sum_{i=1}^{N}[X]_i$$

When the least integer function is defined as [.], then

$$m = [\frac{N}{j}]$$

We also define

$$\delta_j = \{<\{P_1, \ldots, P_j\}>, <\{P_{j+1}, \ldots, P_{2j}\}>, \ldots, <\{P_{j(m-1)+1}, \ldots, P_m\}>\}$$

and we can now express the standard Allan variance as:

$$\sigma_j^2 = \frac{1}{2m}\sum_{k=1}^{m-1}([\delta_j]_k - [\delta_j]_{k+1})^2$$

Finally, we define the dimensionless normalized Allan deviation:

$$\sigma_j = \frac{\sqrt{\sigma_j^2}}{<P>}$$

When we use a bandwidth of 250 MHz, the normalized Allan deviation (with an integration time of 0.1 s) is reduced from 1.3 10^{-3} (with the current lock off) to 6.8 10^{-5} (with the lock on).

III. Future Progress

The integration of the HEB current lock is presently underway. With this completed, we expect the noise to be greatly reduced.

Replacing the oscillating mirror with the rotating mirror is the next advancement. This arrangement will allow the system to be tested at video scan rates. Amplifier back-end gain leveling can also be enabled once the rotating mirror is operational.

Array development is progressing concurrently. A three-element array has already been tested [6], and we believe that a 10-element linear array is within reach. With all these components in place, the full capability of the RLSI system can be ascertained.

We are collaborating with the National Institute of Standards and Technology (NIST) in Boulder, CO in a related project where a 700 GHz HEB imaging system is also being built. This work is described in [7].

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