

# Development of Focal Plane Arrays with Hot Electron Bolometer Heterodyne Detectors for 3 to 10 THz<sup>1,2</sup>

Sigfrid Yngvesson, Eyal Gerecht, John Nicholson, Fernando Rodriguez-Morales, Dazhen Gu, Xin Zhao

Department of Electrical and Computer Engineering  
University of Massachusetts  
Amherst, MA 01003  
413-545-0771  
yngvesson@ecs.umass.edu

Jerry Waldman, Thomas Goyette,  
Submillimeter Wave Technology Laboratory  
University of Massachusetts, Lowell  
175 Cabot Street, Lowell, MA 01854

Erik Kollberg

Department of Microelectronics  
Chalmers University of Technology  
S-412 96 Gothenburg, Sweden

**Abstract** – Broadband tunable, hot electron bolometer (HEB) heterodyne detectors with receiver noise temperatures of the order of  $10 \times hf/k$  in the frequency range 3 THz to 10 THz are required for future space systems. The HEB detectors have to be configured in focal plane arrays (FPA) with many elements (hundreds). We discuss the feasibility of such FPAs, especially the expected performance of HEB detectors at high terahertz frequencies, the role of quantum noise, and quasi-optical configurations. We show that a fly's eye configuration with separate silicon lenses is preferable, and that MMIC IF amplifiers can be directly integrated with the HEB detectors. We also discuss suitable integrated antenna elements for the FPA and LO injection schemes.

## TABLE OF CONTENTS

1. INTRODUCTION.....	1
2. REVIEW OF THE STATE-OF-THE-ART.....	2
3. PRESENT HEB TECHNOLOGY.....	3
4. THE ROLE OF QUANTUM NOISE IN TERAHERTZ RECEIVERS.....	5
5. FOCAL PLANE ARRAYS WITH HEB DETECTORS.....	6
6. CONCLUSIONS.....	8
ACKNOWLEDGMENT.....	8
REFERENCES.....	9
BIOGRAPHIES.....	10

## 1. INTRODUCTION

Space astronomy in the far infrared/submillimeter region has recently been revitalized by the ongoing development of a number of projects. In the next few years, three new significant FIR/submm space observatories will become active: SIRTf (now launched), SOFIA (airborne, operations starting in 2005), and Herschel (launch 2007). Previous observatories in this frequency region were much more modest in size and scope (the airborne Kuiper, IRAS, ISO). The new emphasis on expansion of space activities in the submm/FIR region owes much to the realization that a new generation of instruments in the FIR region would have the potential to solve important astronomical problems related to the origin of galaxies, star formation, etc. in a unique way. It is anticipated that these research activities will lead to even larger projects in this frequency range in the next decade or so. The most recent NAS Decadal survey recommended that "A rational coordinated program for space optical and infrared astronomy would build on the experience gained with NGST to construct a JWST-scale filled-aperture far-IR telescope SAFIR" [1]. The participants in the Second Workshop on New Concepts for Far-Infrared/Submillimeter Space Astronomy, which was held on 7–8 March 2002, issued a Community Plan for Far-Infrared/Submillimeter Space Astronomy which also emphasized the importance of the development of new technologies in the FIR region, and the anticipated benefits in terms of astronomical goals [2].

The group represented in this paper has been active in the development of hot electron bolometer (HEB) heterodyne detectors for the lower terahertz frequency region (1 to 2.5 THz). The drastic improvement of heterodyne detector sensitivity demonstrated by HEB detectors (by more than an order-of-magnitude), which has occurred in the last ten years, is one of the most important factors that have spurred the rebirth of activity in this region of the spectrum. Another factor is the

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very low local oscillator (LO) power required by the detectors. HEB receivers have now been employed on three groundbased sites [3,4]. We have recently installed an HEB receiver on the AST/RO submm telescope at the Amundsen/Scott US South Pole Station [3]. HEB receivers will also be on board SOFIA and Herschel [5,6]. At this point it is appropriate to ask the question: what type of heterodyne detectors will be required for the next generation of space instruments, anticipated to be operating over the entire submm/FIR range of 1 to 10 THz. Presently there are no heterodyne detectors operating in space in the higher terahertz range, and only one preliminary laboratory experiment with an HEB detector has been performed up to 5.3 THz [5]. We will describe our efforts so far related to actively exploring these questions. The SAFIR project is the best example of a future NASA mission activity which would require this type of technology development. There are also other projects which could use this technology, such as remote sensing of the upper atmosphere in the FIR. The Single Aperture Far-Infrared (SAFIR) observatory is envisioned as a 10 meter class FIR observatory that would begin full-scale development late in this decade and is planned for launch in 2015-2017 [7]. It will "enable the study of galaxy formation and the earliest stages of star formation by revealing regions too enshrouded by dust to be studied by JWST, and too warm to be studied effectively by ALMA" [1]. Although much of the observing time with SAFIR will be devoted to direct detector arrays, it is predicted that from 1/4 to 1/3 of that time may be available for heterodyne work [8]. There are a number of strong spectral lines in the FIR region of a typical galaxy. Prominent among these are CII at 158  $\mu\text{m}$ , NII at 205 and 122  $\mu\text{m}$ , as well as OI at 63  $\mu\text{m}$  and OIII at 88  $\mu\text{m}$ . There are also numerous lines due to  $\text{H}_2\text{O}$  and CO. ISO observed these and other spectral lines, but with a grating spectrometer that could not resolve them. Full resolution of galactic spectral lines corresponds to a velocity interval of about  $1 \text{ km s}^{-1}$ , which in the FIR translates to a frequency resolution ( $\Delta\nu/\nu$ ) of  $3 \times 10^{-5}$ . Grating spectrometers of such high resolution would become impractically large, and are thus not used. Fabry-Perot inter-

ferometers can probably be built with the required resolution, but lose sensitivity due to having to scan in frequency, whereas heterodyne detectors can record all frequency channels simultaneously. Therefore, **SAFIR specifications identify "Quantum-Noise Limited Heterodyne Spectrometers" as one of four critical detector technologies which will be needed before the goals of the SAFIR instrument may be realized** [8,9]. Heterodyne detectors are intrinsically less sensitive than an ideal direct detector, by virtue of having to also detect the phase of the incoming radiation, and the related restrictions imposed by Heisenberg's uncertainty relation. Nevertheless, for high resolution spectrometers, they are still the best choice. We will discuss quantum noise issues in some detail in a later section. SAFIR requirements anticipate **a sensitivity of the heterodyne detectors of a few times the quantum noise limit**, and we discuss the feasibility of achieving this. **Another important requirement is that the heterodyne detectors be tunable over a very broad band** [10]. We discuss later how HEB heterodyne detectors can meet this requirement. **NASA also stresses the need for developing miniaturized and highly integrated arrays of sensors.** In the context of heterodyne focal plane arrays, this translates mainly into (1) designing an optimum quasi-optical system for coupling a telescope to a focal plane array (FPA), and (2) finding solutions to integration of the intermediate frequency (IF) amplifiers, and associated transmission lines and bias lines.

We have been working on solving all of the above problems, and will present our results and future plans in this paper.

## 2. REVIEW OF THE STATE-OF-THE-ART

The sensitivity of heterodyne ('mixer') receivers is usually expressed in terms of their double sideband (DSB) receiver noise temperature. The state-of-the art for different types of receivers over a broad terahertz frequency range is shown in Figure 1. The quantum-noise limit for the DSB system noise temperature is  $hf/2k$ . The distinction between system noise tempera-

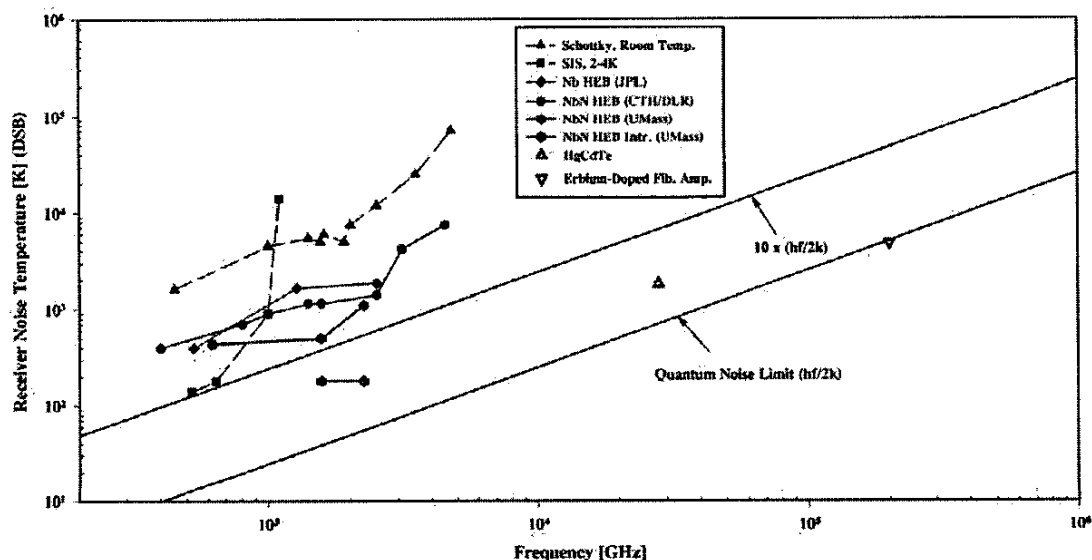


Figure 1. Double sideband receiver noise temperature for different heterodyne receivers over a wide frequency range.

ture and receiver noise temperature is that the former includes the noise from the input source (ideally the vacuum fluctuations), whereas the latter includes the noise generated in the receiver only. This distinction between different types of definitions for the noise temperature is not always clearly stated. For example, the “quantum noise limit” is often loosely given as  $hf/k$  even in a diagram for the DSB receiver noise temperature. The quantum limit for the *single sideband system noise temperature* is  $hf/k$ , whereas the quantum limit for the *DSB receiver noise temperature* is 0 K [11]. The DSB receiver noise temperatures of the best receivers from 100 GHz to 2.5 THz are presently close to the  $10 \times hf/2k$  line. The next generation of SIS receivers will have DSB noise temperatures from 200 GHz to 700 GHz of about  $8 \times hf/2k$  [10]. SIS mixers have the best sensitivity up to about 1 THz, but are limited in frequency by the bandgap frequency of the superconductor used in the junction. The oldest technology, Schottky-barrier diodes (SBD), yields noise temperatures at terahertz frequencies at least an order-of-magnitude higher than that of hot electron bolometer (HEB) devices. SBD receivers require three to four orders of magnitude higher LO power than that of HEB receivers (hundreds of nanowatts to a few microwatts). LO power at terahertz frequencies is very difficult to produce. Our UMass group was first to demonstrate HEB DSB receiver noise temperatures close to  $15 \times hf/2k$  from 1 THz to 2.5 THz [12], to be followed shortly after by the group at Chalmers University of Technology, Sweden [13]. Other recent results are given in references [14,15]. All of the above data were obtained with NbN phonon-cooled (see below) devices. Nb diffusion-cooled devices initially obtained noise temperatures in the same general range, but have not been developed further in the last few years. Very few measurements have been performed on HEB receivers above 2.5 THz; the only published data was measured by the DLR/MSPU collaboration [5]. No heterodyne detectors have been developed so far between about 5 THz and 28 THz. At 28 THz, there is an established heterodyne technology using  $Hg_{1-x}Cd_xTe$  devices with  $CO_2$  lasers as LO sources (see Figure 1). Note that these detectors are within a factor of three from the quantum noise limit. Erbium doped fiber amplifiers, a work-horse component in fiber communication systems at 200 THz, are another technology which represents coherent detection and exhibits noise temperatures at the quantum noise limit (also shown in Figure 1). Clearly, the challenge is to demonstrate quantum-noise limited detectors in the intermediate frequency range of 3 THz to 10 THz.

### 3. PRESENT HEB TECHNOLOGY

The important features of the NbN HEB technology can be summarized as follows:

1. HEBs are “surface” devices. Therefore, parasitic reactances are extremely small, even at the highest terahertz frequencies. A typical device size is  $4 \mu m$  (width)  $\times$   $1 \mu m$  (length). A device integrated with a broadband log-periodic antenna is shown in Figure 2. The device can be matched to the antenna by changing its aspect ratio, 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.

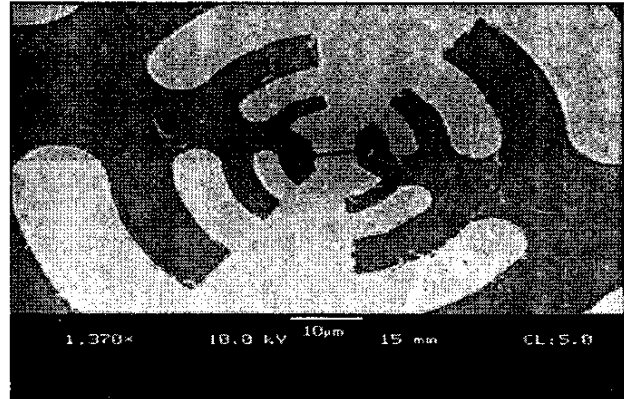


Figure 2. SEM picture of an NbN HEB device integrated with a broadband log-periodic antenna.

2. HEBs rely on a) being able to absorb the terahertz radiation up to the visible range due to the very short momentum scattering times; and on b) being able 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.
3. NbN HEBs have a thermal time-constant which 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 4.2 K to about 10 K is an advantage compared to most other FIR devices, which require cooling to sub-K temperatures.

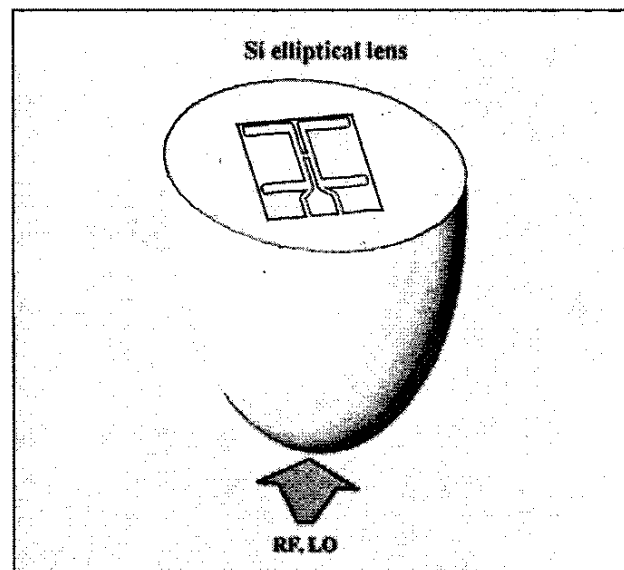


Figure 3. Quasi-optical coupling to the HEB device using a twin-slot antenna.

4. The majority of HEB receivers now use quasi-optical coupling to the incoming radiation field using a combination of a dielectric lens and an integrated antenna. Some HEB receivers in the range of up to about 2.5 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 (see Figure 2). The device is fabricated from an NbN film, which has been sputtered on a silicon substrate. The film thickness is typically 3.5 to 4 nm. The antennas are produced in an e-beam-evaporated Ti/Au film by lift-off. We currently use UV lithographical techniques. The antenna is in turn coupled through an elliptical lens (4 mm in diameter) as illustrated in Figure 3.

5. We use a CO<sub>2</sub>-laser pumped gas laser LO, see Figure 4. This system can provide up to 100 mW on the strongest lines, and several tens of mW on a typical line. Although this is much more than the minimum power required, it makes experiments convenient to set up and perform. We employ a mylar beam splitter which reflects only about 1 % of the power in order to separate the LO and the signal frequencies. We have operated this laser up to close to 5 THz (60  $\mu$ m). Many lines are available over the frequency range of 1 THz to 5 THz. In the future we will extend the operation of our laser system to 10 THz.
6. To couple the DC signal to the device and extract the IF signal from the device, we use a bias "tee" circuit which is built into the mixer block, as shown in Figure 5. We have also developed a broadband MMIC IF amplifier in collaboration with Dr. S. Weinreb of CalTech/JPL, see Figure 6. The measured noise temperature of this amplifier varies from about 5 K at 1 GHz to 10 K at 8 GHz. This noise temperature performance is sufficiently low so as

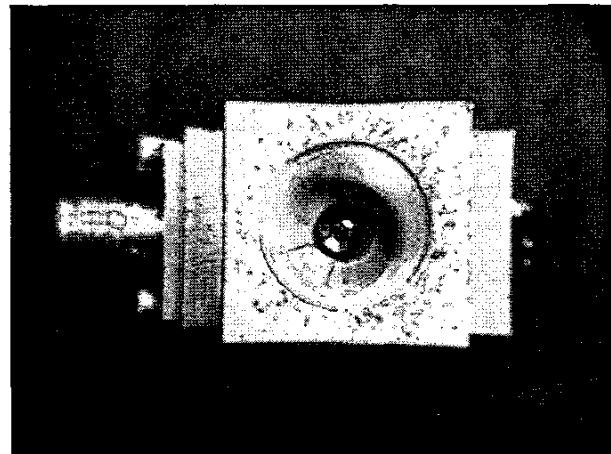
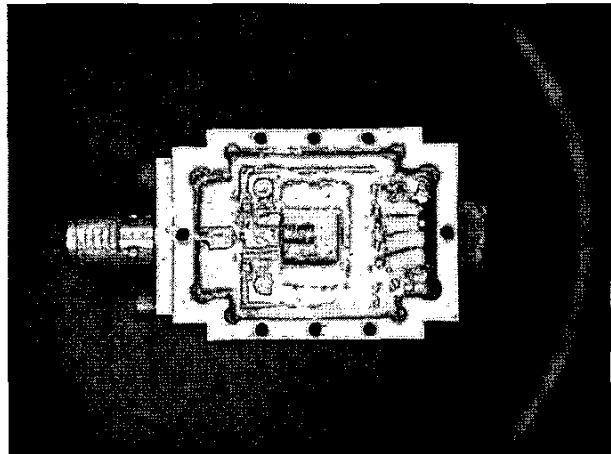


Figure 5. Pictures of the mixer block. The HEB is at the center. The IF output is through the SMA connector to the left, and bias connections are to the right. The silicon lens is on the opposite side, as shown in the lower photo.

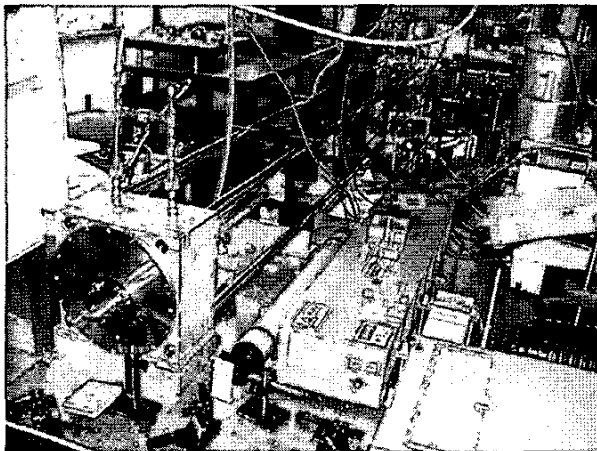


Figure 4. Optical setup used for measurements of HEB devices. The CO<sub>2</sub> laser is in the blue box in the center foreground, and the FIR laser is located to the left. The liquid helium dewar is in the background to the right.

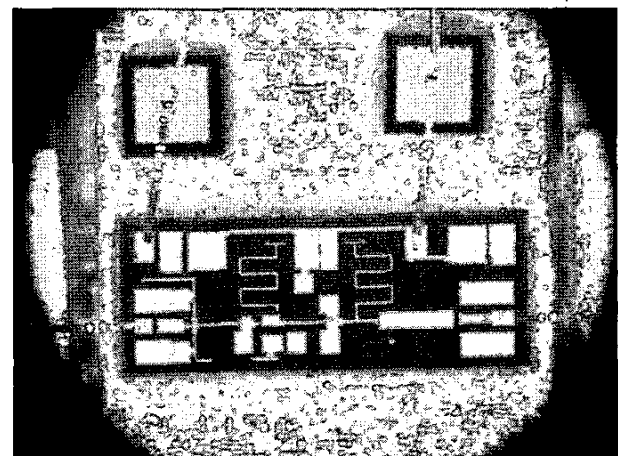


Figure 6. MMIC amplifier chip to be integrated with an HEB device.

not to influence the total HEB receiver noise temperature by more than a few percent. The amplifier gain is presently 20 dB and will be increased to 30 dB in the next version currently being fabricated. The size of the chip is about 1 mm x 2 mm. We have performed comparative experiments with this amplifier (i) without isolators between it and the HEB device, and (ii) using a series of octave band isolators (the widest ones available). The receiver noise temperature bandwidth (the IF frequency at which the HEB receiver noise temperature has doubled in comparison to the extrapolated value at zero IF) was measured to be 5.5 GHz [16] with the isolators. Remarkably, the amplifier was stable (no oscillation) when used without isolators. The mixer receiver noise temperature was very similar in the two experiments at the lowest frequencies, and rose more rapidly above about 3 GHz. **This shows that it should be feasible to eliminate the isolators in an array HEB receiver. Note that the isolators are much larger than any other components, and thus can not be used in multi-element FPAs.**

#### 4. THE ROLE OF QUANTUM NOISE IN TERAHERTZ RECEIVERS

The question of quantum noise is obviously fundamental to the utility of HEB heterodyne detectors for performing observations at the higher terahertz frequencies. Previous work on the quantum noise limit for the noise temperature of coherent detectors has clearly established that the minimum system output noise power for a linear amplifier, referred to the input, is  $hfB$ , where  $B$  is the bandwidth over which the noise is measured. The corresponding system noise temperature is  $hf/k$  [17]. Likewise, the minimum system noise output power for an ideal DSB SIS receiver is also  $hfB$  [11]. The minimum output noise in the SIS mixer case is due entirely to the quantum noise from the input source ( $hfB/2$  from each sideband). Reference [18] primarily discusses the quantum noise limit in SIS receivers, but also appears to show that the minimum output noise power for *any ideal DSB receiver* is the same,  $hfB$ . There is clearly a need to analyze the quantum noise limit specifically for HEB receivers, and the first paper on this topic was presented by Kollberg and Yngvesson in 2002 [19]. An extension of this work will also soon be submitted for publication [20]. We will discuss the quantum noise limit for HEB receivers based on this theory. One basic assumption is that (consistent with all of the above references) the DSB receiver noise temperature of any ideal 'broadband' receiver is 0 K. The term 'broadband mixer' refers to one which has equal conversion loss in both sidebands, which is expected to be true for a typical terahertz mixer due to the large ratio between RF and IF frequencies. We use the term 'Ideal Broad Band Mixer' (IBBM) receiver for this ideal receiver. The quantum noise limit of such ideal receivers is also clearly discussed in [21] and [22]. Based on this concept, one can derive the DSB receiver noise temperature for an HEB receiver to be:

$$T_{RX}^{DSB} = (L_{300} - 1) \frac{P_{Planck}(300K)}{kB} + \frac{hf}{2k} \left( L_{300} L_4 \frac{R_B}{R_A} - 1 \right) + \frac{L_{300} L_4}{2G_{MXR}} (T_{CL}^{out} + T_{IF, Amp}) \quad (1)$$

The approach is still basically the same as in [19], except for the above-mentioned assumption that the ideal HEB receiver (from a quantum noise point of view) is equivalent to an IBBM. The further assumptions that go into this equation need to be discussed:

1. We assume that there are optical losses between the input source and the receiver, both at 300 K and at 4 K (inside the dewar). The thermal noise of these is given by the standard Planck function. Only the thermal noise at 300 K is significant at terahertz frequencies. This is the first term in Eq. (1).
2. The second term represents extra quantum noise from the HEB mixer itself, due to the fact that it is not ideal. A similar increase in quantum noise is well-known from optical heterodyne detectors, which may have "quantum efficiency" less than one. The non-ideal nature of the HEB arises from the fact that only a portion of the device is active in performing frequency conversion, according to the most recent "hot-spot" models for HEB operation [23]. Note that if  $R_A$  (the resistance of the active portion of the HEB) is equal to  $R_B$  (the total bolometer resistance at terahertz frequencies) and there is also no optical loss, this term vanishes, as expected.
3. The third term represents the "classical" noise of the HEB detector ( $T_{CL}^{out} \sim 50$  K) as described in standard HEB theoretical papers so far. It is produced directly at the IF (and therefore is not influenced by quantum noise since  $f_{IF} \ll f_{LO, RF}$ ), and is primarily due to temperature fluctuations in the bolometer.  $G_{MXR}$  is the intrinsic conversion gain of the mixer, typically about -10 dB.  $G_{MXR}$  is considerably lower than what is predicted for a uniform bolometer due to the division of the bolometer into active and passive sections. We also add the noise temperature of the IF amplifier chain. Both contributions to the third term are independent of the LO frequency, thus the HEB receiver noise temperature should also be independent, provided that the optical input losses do not depend on frequency. Measured noise temperatures do increase with frequency and there is a need to analyze if this increase is due to increased optical loss, quantum noise, or a combination of both. The quantum noise will have a clear effect only in the higher terahertz frequency range.

Figure 7 shows noise temperatures measured by researchers at (i) Chalmers University, and (ii) the DLR/MSPU group, compared with a prediction based on Eq. (1). We also show a line corresponding to  $20 hf/2k$  for comparison. The DLR data show much steeper frequency dependence than the CUT data. It is possible that the optical losses in the DLR setup increase with frequency much faster than in the experiment performed by CUT (or perhaps the antenna efficiency decreases). The blue curve is predicted from Eq. (1), assuming  $R_B/R_A = 3$ . This curve matches the measured CUT points, but these of course only extend to 2.5 THz, at which frequency quantum noise effects are not so prominent. There seems to be no reason why one cannot extrapolate the CUT data in attempting to estimate the future performance of HEB mixers up to 10 THz, however. The frequency dependence of the DSB receiver noise temperature for HEB detectors above 2.5 THz would then be predicted

to be close to  $20 \times hf/2k$ . This frequency dependence is in reasonable agreement with our present (limited) understanding of quantum noise in HEB mixers. In a space instrument using HEB detectors, the system sensitivity will be determined by the *system noise temperature*. This can be obtained by adding the noise temperature of the source to the receiver noise temperature in Eq. (1):

$$T_{system}^{DSB} = T_{RX}^{DSB} + \frac{hf}{k} + T_{Planck}^{background} \quad (2)$$

The second term is the *equivalent* quantum noise temperature *induced* by the vacuum fluctuations at the input of the receiver, and the third term is the thermal noise from the astronomical background that the receiver "sees". The third term is often called the photon noise background, or simply "the background". At the frequencies we consider, the photon background is usually negligible compared with the first two terms. In contrast, *direct detectors* do not have the second term, and can have a noise equivalent power which is comparable to or less than the background.

In conclusion, the predicted sensitivity ( $10 \times hf/k$ ) of future HEB heterodyne detectors is in the range desired for detectors under development for deployment with space instruments such as SAFIR [8,9].

## 5. FOCAL PLANE ARRAYS WITH HEB DETECTORS

Plans for future FIR space instruments specify a need for focal plane arrays (FPAs) with thousands of elements [7,8,9]. Similar FPAs exist in the visible and Near IR range, but will be a novelty in the FIR. FPAs increase the mapping speed compared with a single detector telescope by a factor essentially equal to the number of elements in the array. Large aperture telescopes such as SAFIR will be able to resolve a galactic cluster at the furthest reaches of the universe. There are no precedents for *heterodyne* FPAs with anywhere near this number of elements, although equivalent FPAs with up to about 30 elements exist at 100 GHz [24]. Can they be built in the terahertz region? To explore this, we are presently building a three element prototype array for 1.6 THz, shown in Figure 8. The main guidelines for the design are discussed below:

### Quasi-Optical Considerations

There are well-known limitations for the smallest beam spacings which can be obtained in an FPA [25]. These can be discussed in terms of the geometric spacing ( $\Delta x$ ) of adjacent elements in the array. If each element in the array illuminates a telescope at an f-number of  $f/D$ , then ideal sampling of the focal plane image at the Nyquist rate requires that  $\Delta x = 0.5 \times$

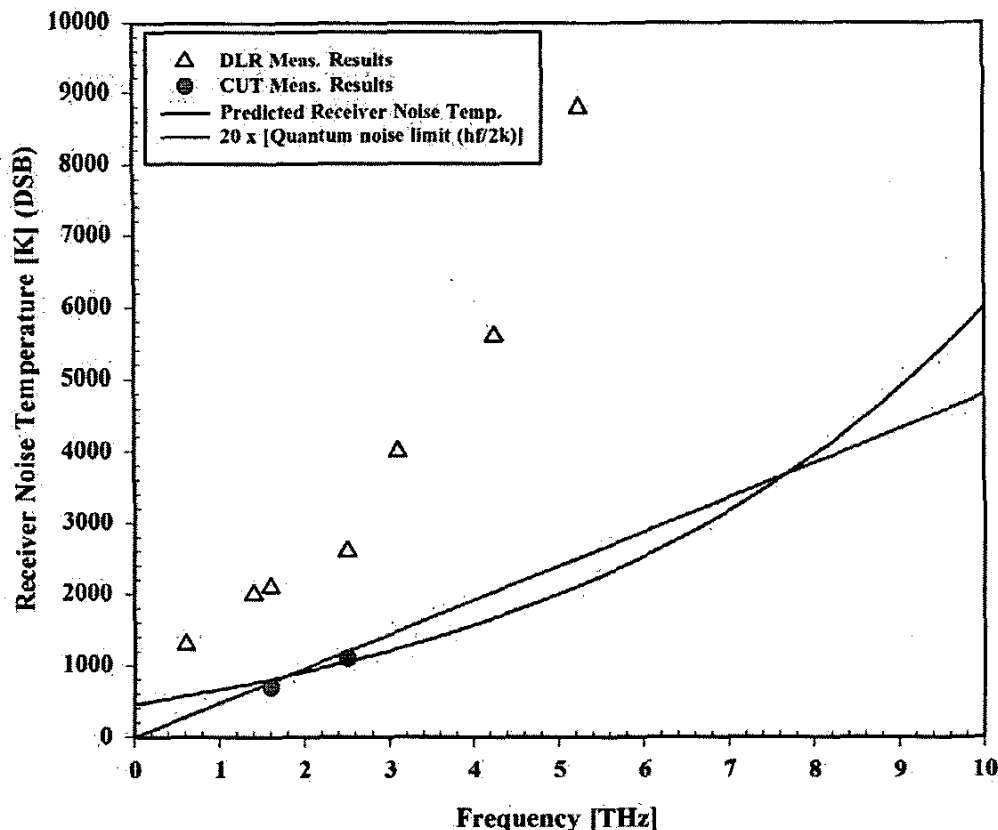


Figure 7. Measured and predicted DSB receiver noise temperatures for HEB receivers up to 10 THz.

$(f\lambda/D)$  [26,27]. There is no type of feed element that is capable of being spaced this close while still illuminating the telescope efficiently. The best that has been achieved in practice is  $\Delta x = 1 \times (f\lambda/D)$ . Corrugated horns, for example, which are especially efficient feed antennas, must be spaced at about  $2 \times (f\lambda/D)$  [27]. The displacement (N) of the telescope beam on the sky, measured in Full Width Half Maximum Power (FWHM) beamwidths is also related to  $\Delta x$  by  $N \approx \Delta x / 1.2\lambda(f/D)$  [26]. An array element spacing of about  $1.2 \times (f\lambda/D)$ , thus, corresponds to a spacing of adjacent beams on the sky of one FWHM beamwidth.

There are two different methods for coupling dielectric lenses to an antenna array:

- (i) a single-lens configuration; and
- (ii) a multi-lens configuration.

If we first consider the single-lens case, the individual elements placed near the focus of the lens will radiate a beam which has an f-number of roughly 1.0, i.e. a 56 degree FWHM beamwidth. Filipovic et al [28] analyzed this case and derived the minimum spacing possible. To obtain a rough estimate, we assume a spacing corresponding to one beamwidth, and find  $\Delta x \approx \lambda / \sqrt{\epsilon_r}$ , or  $30 \mu\text{m}$  for  $\lambda_0 = 100 \mu\text{m}$ . This leads to impossibly tight constraints on any wiring that has to be connected to the devices and antennas, and it is obviously impossible to place the IF amplifiers close to the antennas.

The multi-lens configuration, on the other hand, is much more flexible. The relatively small (radius  $R = (40-130) \times \lambda_0$  in the frequency range considered here) elliptical lens that we have developed, lends itself well for use in this "fly's eye" type of array, see Figure 8. Both the LO and the incoming signal are injected through a quasi-optical diplexer. The optics is thus unchanged from our single-element approach. The beamwidth from each lens is approximately given by  $1.2 \times \lambda / (2R)$ , and the lenses can be placed at a spacing equal to their diameter ( $2R$ ), i.e.  $\Delta x = 2R$ . The beam-scan (N) will be about one FWHM beamwidth. The angular resolution (angular spacing between adjacent pixels) will thus be about equal to the diffraction-limited beamwidth of the telescope, which is typical of the best resolution obtainable for FPA receivers as discussed above.

While the array architecture with silicon lenses will be the approach we will plan to use to demonstrate our new technology, we are also exploring the feasibility of etching grooved Fresnel lenses in the surface of the device silicon substrate by deep RIE. A problem to solve with this approach is that this type of lens (which is being used in today's optoelectronic technology) works best for large f-numbers, whereas the illumination produced by integrated antenna elements has an f-# close to 1. The lenses also need to have about an octave of bandwidth.

#### Antenna Elements

The SAFIR requirements speak of heterodyne detectors that are *as widely tunable as possible*. Quasi-optical coupling allows the use of very broadband antenna elements, actually several octaves (log-periodic self-complementary toothed ele-

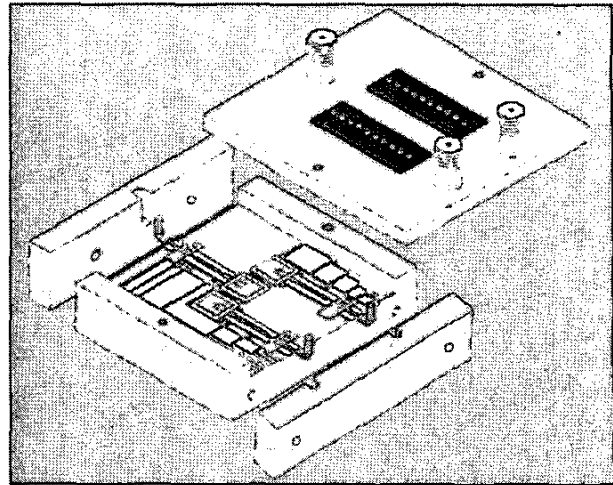


Figure 8 a. View from the device/circuit board side of the 1 x 3 element array concept.

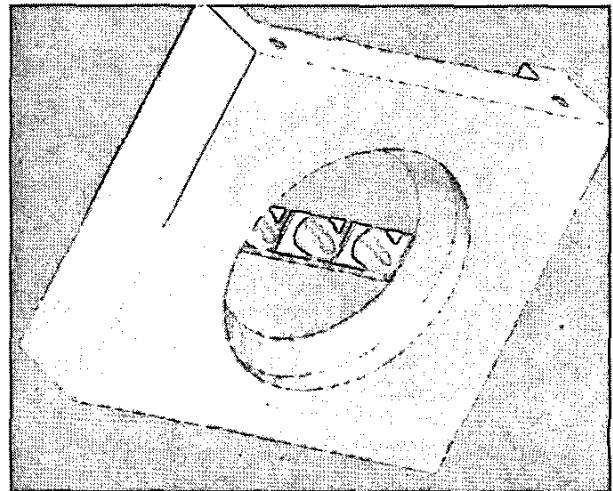


Figure 8 b. View from the lens side of the 1 x 3 element array concept

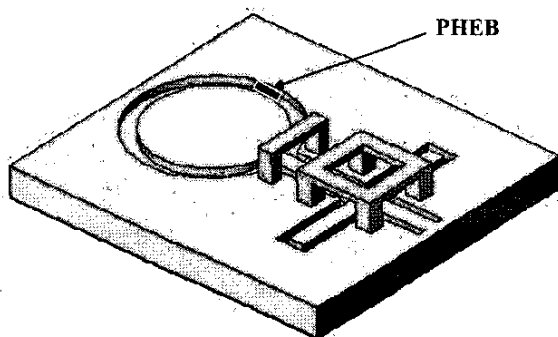
ments, see Figure 2; logarithmic spiral elements are also commonly used). While the beamwidth of the antenna elements may be quite independent of frequency, the beamwidth (and f-#) of the lens/antenna combination (Figure 3) is determined by the lens diameter since the lens acts as an aperture antenna. The f-# presented to the telescope will thus vary and change the illumination of the latter. These effects will effectively determine the bandwidth over which a quasi-optically coupled HEB detector may be used. An octave of bandwidth appears to be a reasonable estimate of what can be accomplished.

There is very little guidance to be obtained from previous work, since very few antennas have been developed for such high frequencies. DLR used a log-periodic spiral antenna up to 5.3 THz for their measurements. Logarithmic spiral antennas up to 30 THz were designed and measured [29]. It was found that although 50 % efficiency was obtained at 30 THz for coupling to a thermal source, large changes occurred in radiation patterns and polarization properties, presumably due to kinetic inductance effects in the antenna conductive material. No fur-

ther systematic study of these phenomena in integrated antennas has been performed since that time. The different antenna elements do not have the same size, but are still very small compared with a unit cell in the FPA. Since they all produce a radiation pattern which matches that required for the lenses, their different sizes are not an important consideration. The log-periodic toothed antenna and the spiral antenna have the advantage of not requiring a separate filter structure to stop the terahertz radiation from leaking out. The twin-slot antenna (Figure 3) on the other hand requires very precise definition of the CPW center structure and the filter, and would be difficult to fabricate at 2.5 to 10 THz. It is also difficult to design for high frequencies [30]. We are developing the slot-ring antenna, as shown in Figure 9. This element has a simpler shape and would be easier to fabricate, but does require a filter. The filter also almost certainly would only work well if air-bridges (which prevent mode conversion) are inserted as shown in the Figure. An additional advantage of this antenna is the elimination of the requirement for a diplexer for pumping the LO into the devices. This can be achieved by using different polarization for the LO beam and the signal beam and coupling both directly to the slot-ring antenna. The fabrication of air bridges has never before been attempted at terahertz frequencies, as far as we know. An alternative might be to use a microstrip feed line on a separate dielectric, as is common in SIS mixer designs. A final possible antenna element is to use a small array of bow-tie antennas, as demonstrated at 15 THz in [31].

#### LO Injection

Injection methods for the LO also need to be discussed, since this issue impacts the choice of antenna element. In laboratory experiments with a gas laser LO source, a very thin mylar beam splitter, which reflects a small percentage of the LO, is sufficient. There is essentially zero loss to the signal in this case. To optimize LO use in the array system, one needs to employ a more efficient method, however. Thicker mylar beam splitters with appropriate choice of polarization would allow a larger percentage (but not 100 %) of the LO to be injected, with some loss to the signal as well. Basically, with any LO injection scheme, an acceptable compromise has to be found between the loss to the LO and the loss to the signal. One method, which has been employed with SIS mixer arrays, is to inject the LO through an interferometer. The loss to the LO may typically be about 3 dB, which would be an acceptable value. It is



**Figure 9.** Slot-ring antenna element for terahertz applications, including airbridges.

very difficult to design this injection system for many beams, however, and we prefer some other method. Injection through a wire grid is very low loss; the LO and signal then are injected in orthogonal polarizations. This is possible for the slot ring antenna, for example, and we demonstrated this up to 35 GHz with Schottky diodes [32]. The HEB element would be placed in a 45 degree position (refer to Figure 9) and ideally both beams can be injected with no loss. As noted above, it is not clear if it is feasible to fabricate slot ring antennas at the high terahertz frequencies if air bridges are necessary. The spiral antenna is sensitive to circular polarization. Since the LO signal would typically have linear polarization, half of its power would be lost. If a wire grid were used for LO injection in an actual system with spiral antenna elements, the orthogonal signal and LO beams would each experience a 3 dB loss, which may be acceptable. The log-periodic antenna is close to linearly polarized, and the direction of the linear polarization varies periodically by  $\pm 22.5^\circ$  as the frequency is changed. We measured this effect at terahertz frequencies in [33]. This antenna could be oriented at an intermediate angle and allow LO and signal injection in orthogonal polarizations, again with a relatively small loss. Clearly, LO injection issues need to be studied in depth to find the optimum compromise. The choice of the actual LO source in future space systems is not discussed in detail in this paper. However, quantum cascade lasers appear promising [34].

#### Array Integration

Testing the array configuration shown in Figure 8 will provide experience with HEB devices in an integrated configuration. This type of architecture will place MMIC IF amplifiers on a circuit board very close to the device chips for the first time. This layout is not possible for two-dimensional arrays with many elements. The array concept can scale to larger arrays by employing separate parallel boards for the IF amplifiers and the bias circuitry. Suitable connection methods will be developed for connecting vertically between these boards. Similar configurations are being designed for direct detector arrays, and should be feasible for heterodyne arrays as well.

## 6. CONCLUSIONS

The development of HEB heterodyne detectors and associated array architectures is very promising for employment in future space systems in the 3 to 10 THz range. Such systems are predicted to have receiver noise temperatures close to  $10 \times hf/k$ , and should be tunable over about an octave. We have demonstrated that HEB detectors are directly integratable with broadband MMIC IF amplifiers, and are presently constructing a prototype three-element FPA. Our fly's eye array concept is scalable to much larger arrays. A crucial question which remains to be solved is that of an LO source with small volume, weight, and power consumption, and the optimum method for injecting the LO into the FPA.

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## REFERENCES

- [1] "Astronomy and Astrophysics in the New Millennium," National Academy Press, Washington, DC (2001).
- [2] "Community Plan for Far-Infrared/Submillimeter Space Astronomy", available at <http://mips.as.arizona.edu/MIPS/fircase3.pdf> (Febr. 2000).
- [3] "Deployment of TREND – A Low Noise Receiver User Instrument at 1.25 THz to 1.5 THz for AST/RO at the South Pole," E. Gerecht et al, 14<sup>th</sup> Intern. Symp. Space THz Technology, Tuscon, AZ, (April 2003).
- [4] "First Light with an 800 GHz Phonon-Cooled HEB Mixer Receiver," J. Kawamura et al., p. 35-43, 9<sup>th</sup> ISSTT, (1998). Also see: "CO(9-8) in Orion," S. Radford, . 14<sup>th</sup> Intern. Symp. Space THz Technology, Tuscon, AZ, (April 2003).
- [5] A.D. Semenov et al., "Design and Performance of the Lattice Cooled Hot-Electron Terahertz Mixer," J.Appl.Phys. vol. **88**, p.6758, 2000.
- [6] "1.4 to 1.7 THz NbN Hot Electron Bolometer Mixer for the Herschel Space Observatory," S. Cherednichenko, H. Merkel, Th. Ottoson, A. Adam, E. Kollberg, D. Lodkov, B. Voronov, G. Gol'tsman, H. Richter and H.-W. Huebers, Proceedings of the Symposium on Astronomical Telescopes and Instrumentation, SPIE. Hilton Waikaloa Village Hotel, Hawaii, August 22-28, 2002.
- [7] "SAFIR – The Single Aperture Far Infrared Observatory," H. Yorke, IEEE Aerospace Conference, (March 2003).
- [8] "SAFIR Science: Single Aperture Far Infrared Observatory : P.M. Harvey, G.H. Rieke, D.F. Lester, & D.J. Benford, Proc. SPIE #4850, pp. 1120-1131 (2002).
- [9] "Cryogenic Detectors for Infrared Astronomy: The Single Aperture Far-Infrared (SAFIR) Observatory," D.J. Benford and S.H. Moseley, to be published in NIMPA (from 10th International Workshop on Low Temperature Detectors; Genoa, Italy) - July 2003.
- [10] "Heterodyne Receiver Requirements for the Single Aperture Far-Infrared (SAFIR) Observatory," D.J. Benford and J.W. Kooi, 14<sup>th</sup> Intern. Symp. Space THz Technology, Tuscon, AZ, (April 2003).
- [11] "Receiver Noise Temperature, the Quantum Noise Limit, and the Role of the Zero-Point Fluctuations," A.R. Kerr, M. J. Feldman, and S. -K. Pan, in Proc. 8<sup>th</sup> Int. Nat. Symp. Space Terahertz Technology, March 25-27, 1997, pp. 101-111. Available: URL: <http://colobus.aoc.nrao.edu/memos> as MMA Memo 161.
- [12] "NbN Hot Electron Bolometric Mixers - A New Technology For Low Noise THz Receivers," E. Gerecht, C. F. Musante, Y. Zhuang, and K. S. Yngvesson, T. Goyette, J. Dickinson, J. Waldman, P. A. Yagoubov, G. N. Gol'tsman, B. M. Voronov, and E. M. Gershenzon, IEEE Trans. Microw.Theory Techniques . **MTT-47**, 2519-2527, (Dec. 1999).
- [13] "NbN hot electron bolometric mixers for terahertz frequencies", M. Kroug, S.Cherednichenko, H. Merkel, E. Kollberg, B. Voronov, G. Gol'tsman, H.-W. Hubers, H.Richter, IEEE Trans on Appl. Supercond. Vol.**11**, no.1, pp.962-965, (March 2001).
- [14] "Noise Performance of NbN Hot Electron Bolometer Mixers at 2.5 THz and its Dependence on the Contact Resistance," J.J. Baselmans et al., 14<sup>th</sup> Intern. Symp. Space THz Technology, Tuscon, AZ, (April 2003).
- [15] "1.6 THz HEB mixer for far infrared space telescope (Herschel)", S. Cherednichenko, M. Kroug, N. Wadefalk, P. Khosropanah, A. Adam, H. Merkel, E. Kollberg, D.Loudkov, B. Voronov, G. Gol'tsman, H.-W. Huebers, H. Richter, to be published in Physica C (2003).
- [16] "Impedance and Bandwidth Characterization of NbN HEB Mixers," F. Rodriguez-Morales and S. Yngvesson, 14<sup>th</sup> Intern. Symp. Space THz Technology, Tuscon, AZ, (April 2003).
- [17] "Quantum limits on noise in linear amplifiers," C.M. Caves, Physical Review D **26**, 1817-1839 (1982).
- [18] "Quantum Noise in Heterodyne Detection," M.J. Wengler and D.P. Woody, IEEE J. Qu. Electronics, QE-23, 613-622 (1987).
- [19] "Quantum Noise Contribution to the Receiver Noise Temperature of HEB THz Heterodyne Receivers," E.L. Kollberg and K.S. Yngvesson, 13<sup>th</sup> ISSTT, pp. 73-84 (2002).
- [20] "The Role of Quantum Noise in HEB THz Heterodyne Receivers," E.L. Kollberg and K.S. Yngvesson, to be submitted to IEEE Trans. Microw.Theory Techniques (2003).
- [21] "Principles of Quantum Electronics," D. Marcuse, New York, Academic Press (1980).
- [22] "Electromagnetic Noise and Quantum Optical Measurements," H.A. Haus, Berlin, Springer Verlag (2000).
- [23] "NbTiN and NbN Hot Electron Bolometers, a Comparison", P. Khosropanah, H. Merkel, S. Cherednichenko, V. Drakinskiy, J. Baubert, 14<sup>th</sup> Intern. Symp. Space THz Technology, Tuscon, AZ, (April 2003).
- [24] "Focal Plane Imaging Systems for Millimeter Wavelengths," P.F. Goldsmith, C.-T. Hsieh, G.R. Huguenin, J. Kapitzky, and E.L. Moore, "IEEE Trans. Microw. Theory Techniques, **MTT-41**, 1993.
- [25] "Near Millimeter Imaging with Integrated Planar Receptors: General Requirements and Constraints," K.S. Yngvesson in Infrared and Millimeter Waves (K. J. Button, Ed.), Academic Press, Orlando, FL., Vol. **10**, Chap. 2, p.91 (1983).
- [26] "Integrated-Circuit Antennas," D.B. Rutledge, D.P. Neikirk, and D.P. Kasilingam, in Infrared and Millimeter Waves, (K. J. But ton, Ed.), Academic Press, Orlando, FL., Vol. **10**, Chap. 1, p.1 (1983).

- [27] "Realizable Feed-Element Patterns and Optimum Aperture Efficiency in Multi-Beam Antenna Systems," K.S. Yngvesson, J.F. Johansson, Y. Rahmat-Samii, and Y.S. Kim, *IEEE Trans. Antennas and Propagat.*, **AP-36**, 1637, 1988.
- [28] "Off-axis Imaging Properties of Substrate Lens Antennas," D.F. Filipovic and G.M. Rebeiz, *Proc. 5th Intern. Symp. Space THz Technology*, May 1994.
- [29] "Lithographic Spiral Antennas at Short Wavelengths", Grossman, E.N.; Sauvageau, J.E.; McDonald, D.G., *Appl. Phys. Lett.* **59**(25): 3225-3227, (1991).
- [30] "Broadband Fourier Transform Spectrometer (FTS) Measurements of Spiral and Double-Slot Planar Antennas at THz Frequencies", D. Loudkov, P. Khosropanah, S. Cherednichenko, A. Adam, H. Merkel, Kollberg, G. Gol'tsman, 13<sup>th</sup> ISSTI, Harvard Univ., Cambridge, MA(2002).
- [31] "Improved Performance of a Superconducting Optical Detector with Planar Antennas," M. Leung et al., *IEEE Trans. Applied Supercond.*, **3**, 2163 (1993).
- [32] "Modeling of a Monolithic Slot Ring Quasi-Optical Mixer," Masarweh, S.K., Sherer, T.N., Yngvesson, K.S., Gingras, R.L., Drubin, C., Cardasmenos, A.G., and Wolverson, J., *IEEE Trans. Microw. Theory Techniques*, **MTT-42**, 1602. (1992).
- [33] "Terahertz Receiver With NbN HEB Device (TREND) - A Low-Noise Receiver User Instrument for AST/RO at The South Pole", K.S. Yngvesson, C.F. Musante, M. Ji, F. Rodriguez, and Y. Zhuang, E. Gerecht, M. Coulombe, J. Dickinson, T. Goyette, and J. Waldman, C. K. Walker, A. Stark and A. Lane, 12<sup>th</sup> Intern. Symp. Space THz Technology, San Diego, CA (2001).
- [34] "High-Performance Continuous-Wave Operation of Superlattice Terahertz Quantum-Cascade Lasers," R. Köhler, A. Tredicucci et al., *Appl. Phys. Lett.*, **82**, 1518 (2003).

## BIOGRAPHIES

**K. Sigfrid Yngvesson** (M'62-SM'92-F'98) was born in



Lidköping, Sweden in 1936. He received the degrees of Civilingenjör, Tekn.lic. and Tekn. Dr. in Electrical Engineering from Chalmers University of Technology, Gothenburg, Sweden, in 1958, 1965, and 1968, respectively, majoring in physical electronics. He was a post-doctoral fellow in the Department of Physics, the University of California,

Berkeley, during two two-year periods in the 1960s. Yngvesson has been teaching in the Department of Electrical and Computer Engineering, the University of Massachusetts/Amherst since 1970 where he became a full professor in 1978. He has worked on quantum electronic low-noise receivers for radio astronomy, and on integrated arrays of antenna elements and active devices with applications to imaging and power combining. His present main research interests are in

the areas of quasi-optical terahertz low-noise devices and applications, in particular hot electron bolometric mixers. He is the author of *Microwave Semiconductor Devices*, a text and reference book (Kluwer Academic, 1991).

**Eyal Gerecht** (S'88-M'98) received the B.S.E.E. degree in



Electrical Engineering with a minor in Solid State Physics (Magna Cum Laude) from the University of Houston, Houston, TX in 1990 and the M.S.E.C.E and Ph.D. degrees in Electrical and Computer Engineering from the University of Massachusetts at Amherst in 1994 and 1998, respectively.

In 1998, he joined the Department of Physics and Astronomy at the University of Massachusetts at Amherst as a Senior Postdoctoral Research Associate. Since 2000, he has been a physicist in the Electromagnetic Division at the National Institute of Standards and Technology, Boulder, CO, developing a number of terahertz related technologies. His interests also include the development of receivers for millimeter and submillimeter applications.

Dr. Gerecht is a member of Tau Beta Pi and Eta Kappa Nu.

**John J. Nicholson** received the B.S. Degree in marine biology



from Southeastern Massachusetts University of North Dartmouth (presently University of Massachusetts) in 1976, and the Associate degrees in industrial technology/electronics and engineering science in 1984 and 1989, respectively.

From 1987 to 1996, he was with Millitech Corporation working on millimeter wave and sub-millimeter wave

whisker contacted multipliers before becoming a semiconductor process engineer. He continued this work at Millivision, LLC and became lab manager of the semiconductor fabrication facility. Mr. Nicholson joined the *TREND* group as a Research Engineer for the University of Massachusetts Department of Electrical and Computer Engineering in May 2001 where he is also lab instructor for the semiconductor fabrication course.

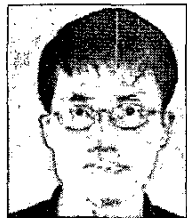
**Fernando Rodriguez-Morales** received the B.S. degree in



electronics from Universidad Autonoma Metropolitana, Mexico, in 1999. From 2000 to 2001 he was with the Department of Physics and Astronomy, University of Massachusetts at Amherst, where he collaborated in the development of single electron transistor (SET) technologies as well as bolometric array detectors. In 2003 he received the M.S.E.C.E degree

in electrical and computer engineering from University of Massachusetts at Amherst, where he is currently pursuing a Ph.D. degree in the same field. His research interests include the development of highly integrated HEB focal plane arrays for terahertz frequencies, microwave circuit design, and computer graphics.

**Dazhen Gu** received the B.S. degree in Physics from Nanjing University, Nanjing, China, in 1999, and is currently working toward the Ph.D. degree in Electrical Engineering at the University of Massachusetts Amherst. From 1999 to 2001, he was a research assistant in Superconductor Electronics Laboratory of Nanjing University, where he worked on the three-terminal device employed High T<sub>c</sub> Superconductor,



Ferro-electric and Ferro-magnetic materials. Since 2001, he has been involved in the design and fabrication of NbN hot electron bolometric mixer for terahertz receivers. From November 2003, he is temporarily a guest researcher at the National Institute of Standards and Technology, Boulder, CO. His research interest includes nano-fabrication, quantum electronics and RF circuit design.

**Xin Zhao** received the B.S. degree in physics from University of Science and Technology of China in 2000. Since 2001, he is pursuing a Master degree in the Electrical and Computer Engineering department in University of Massachusetts at Amherst. He is currently a research assistant in the terahertz group. His work is focused on the antenna design, calculation and measurement in terahertz frequency range.

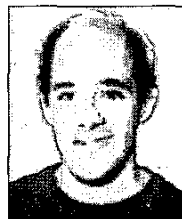


**Jerry Waldman** received the B.A. degree in physics from Columbia University, New York, NY, and the Ph.D. degree in physics from the Massachusetts Institute of Technology, Cambridge, MA, in 1960, and 1970, respectively. He joined the faculty of the University of Massachusetts in 1970, where he is presently Professor of Physics. Following a two-year leave-of-absence at MIT Lincoln Laboratory, he helped cre-



ate the Submillimeter Technology Laboratory (STL). During the past decade STL has developed submillimeter wave radar components and systems for scale-model measurements.

**Thomas Goyette** received his Ph.D. in Physics from Duke University in 1990. Dr. Goyette has done research in molecular spectroscopy, millimeter and sub-millimeter wavelength sources, and low temperature experiments and detectors. He is now performing research on new far-infrared sources and devices, optically pumped lasers, low noise detectors, and laboratory radar systems.



**Erik Ludvig Kollberg** is a professor at the School of Electrical and Computer Engineering at Chalmers University of Technology in Sweden since 1980. His research has comprised low-noise millimeter wave Schottky diode mixers, varactor diode multipliers, superconducting quasi-particle (SIS) mixers, quantum well devices, submillimeter wave hot electron mixers and three terminal devices such as FETs and HBTs. He is the inventor of the heterostructure barrier varactor diode. In the fields mentioned above about 250 scientific papers have been published. He received the Microwave Prize given at the 12th European Microwave Conference in Helsinki, Finland, the Gustaf Dahlen gold medal 1986, and was elected Fellow of IEEE 1990. He was invited as a guest professor to Ecole Normal Supérieure, Paris, France, and as a Distinguished Fairchild Scholar at the California Institute of Technology in 1990. He was given honorary Ph.D. at the Technical University of Helsinki, Finland, in 2000. He is a member of the Royal Swedish Academy of Science and the Royal Swedish Academy of Engineering Sciences.

