CHARACTERIZATION OF ROOM TEMPERATURE TERAHERTZ DIRECT DETECTORS

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Engineering

By

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ABSTRACT

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Characterization of Room Temperature Terahertz Direct Detectors.

Room temperature direct detectors operating in the so-called Terahertz (THz) region of the electromagnetic spectrum, and representing the most common detection technologies currently available, were characterized at 104, 280 GHz or 600 GHz within their intended range of operating frequencies. These detectors included commercial Schottky-diode rectifiers (Virginia Diodes and Spacek Labs), commercial pyroelectric detectors (Spectrum Detector), and a commercial Golay cell (QMCI). The characterization included antenna patterns, responsivity, electrical noise, noise equivalent temperature difference (NEΔT), and noise equivalent power (NEP). Since all the characterization measurements were made the same way, quantitative comparisons can be made between the performances of the individual detectors and conclusions are drawn about their relative merits for particular applications. The noise characteristics of the amplifiers used in the experiments were also measured and taken into account in the characterization of the detectors.
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INTRODUCTION

1.1 Motivation

In recent years, many in the physics and engineering fields have become interested in the region of the electromagnetic spectrum lying between the microwave and infrared as shown in Fig. 1 and commonly known as the Terahertz (THz) or the millimeter-wave (MMW) / sub-millimeter (SMM)-wave regions. While there is no standard definition of its bounds, a common definition is the frequencies between 300 GHz and 3 THz or wavelengths of 1 mm to 100 μm [1]. The interest stems from the unique properties of the radiation in this region, usually in connection with its interaction with various forms of matter. Like microwaves, it transmits rather well through most dielectrics and can be propagated through free space or through waveguides at lower frequencies. On the other hand, its shorter wavelength means it can be manipulated using optical components like mirrors or lenses, similar to infrared radiation. One of the most ubiquitous features of the THz region is the presence of numerous water vapor absorption lines which has been the source of both many opportunities and many limitations for potential applications in the field. Water, however, is not the only substance with resonances in the THz region. Many substances have resonances in the THz region associated with their molecular bonds creating many phenomena of interest to spectroscopists. Of interest to those pursuing medical applications is the fact that, not only is THz radiation have strongly absorbed by water, the photons are low enough energy to be considered non ionizing and therefore innocuous compared to many medical applications using higher energy radiation such as x-rays.
Because of all its interesting properties, ideas for applications of THz radiation abound and many groups are working toward the realization and ultimate commercialization of these applications. The difficulty is that the development of instrumentation for work in this region of the spectrum is well behind the development of the ideas. A good example, and the subject of this Thesis, is radiation detectors. Over the past several decades, many different detectors for infrared (IR), microwave, millimeter-wave (MMW) or sub-millimeter (SMM), and terahertz (THz) radiation have been invented, developed, and commercialized. In the infrared and microwave regions, these detectors are well characterized and readily available. Microwave detectors are used in everything from military radar to cell phones and they are mass produced as integrated circuits. Infrared detectors aren't quite so common but are commercially available for many uses such as radiometers and cameras. There are also IR metrological standards allowing for accurate calibration of the devices. However, in the THz and MMW/SMM-wave region, this is not the case. Every year more papers are written about new detectors and naturally every author thinks that their detector is an improvement. All kinds of numbers are cited to prove which detector is better, but it is hard to actually compare and contrast detectors since each detector was tested differently by each laboratory and no metrological standards exist as of yet. This makes it very difficult to do more than estimate important parameters like source power. Even the commercially available detectors are difficult to evaluate for the same reasons as well as the fact that some (not all) come with rather vague, unexplained calibration data and performance specifications. This means that for any useful work to be done with a given detector, it must first be calibrated by the user relative to other equipment and techniques.
To address this problem, this Thesis presents a collection of room temperature direct detectors representing some of the most common and useful types of THz detectors were all tested in the same way on the same equipment. The decision to limit the testing to room temperature detectors was made based on the belief that room temperature detectors are the ones most likely to make it through the research and development pipeline and into the commercial world. The rationale for characterizing only direct detectors was also based on their commercial viability and applicability to developing focal-plane arrays, as well as a desire to make the problem more tractable. Heterodyne detection systems are much more sensitive than direct detectors and use frequency mixing and down-conversion so that the actual detection can occur at intermediate frequencies much lower than THz. But they require a local-oscillator which increases the complexity and cost of such an approach.
OVERVIEW OF DETECTION TECHNOLOGIES

2.1 Thermal detectors

Two of the three detection technologies explored in this study belong to the class of detectors known as thermal detectors. The basic idea behind all such detectors is that the incident radiation causes a temperature change in some detection element, equivalent to a thermometer, which can then be measured electronically. While this sounds like a relatively simple concept, its realization can range from relatively simple in the case of the pyroelectric detectors discussed below to complex and intricate like the Golay cell.
2.1.1 Golay Cell

The Golay cell, invented by Marcel Golay in the 1940s as an infrared detector, is sometimes known as a pneumatic detector because the radiation absorbing element heats a small amount of gas that expands as the temperature increases. This gas is contained in a small chamber that has an absorbing film on the front to efficiently transfer the thermal energy from the radiation to the gas and a flexible mirror on the back that moves as the gas expands and contracts [2]. In order to detect the change in volume of the chamber, an optical system consisting, in essence, of a light source, a line screen, a lens, and a photocell arranged in such a way that changes in the position of the mirror change the amount of light that is incident on the photocell and thus change the output voltage of the photocell. Like most other thermal detectors, the incident radiation must be modulated because of the AC readout circuit of the photocell [3]. Fig. 2 shows a simplified schematic of a Golay cell and Fig. 3 shows a more detailed diagram from the original design.
Fig. 2. A schematic diagram of a Golay cell taken from [2].
Since the Golay cell is broadband and operates by absorbing the incident radiation, it is very sensitive to thermal IR that peaks near 10 μm at room temperature. In order to detect THz, a window is usually used to block IR and pass THz. These windows can be made out of a variety of materials but they are frequently made out of high density polyethylene (HDPE) [4].

Of course, the complexity of the Golay cell naturally creates many sources for error and non-uniformity in the manufacturing process, so anecdotal evidence exists that newer Golay cells are inferior to ones produced in the “good old days”. More easily
substantiated is the fact that they are fragile and their performance can be quickly
destroyed by one careless action. The easiest destructive action is exposure to too much
radiation, which creates excess thermal expansion and destroys the membrane on the
pneumatic chamber. Adding to the complexity is the fact that damage may or may not be
immediately obvious as the author knows from experience. The damaged Golay cell may
continue to give a signal when exposed to radiation but that signal can vary dramatically
or display other erratic behavior. This will be discussed further later.

2.1.2 Pyroelectric detectors

Pyroelectric detectors are also thermal detectors but they rely on a completely different
physical phenomenon. Figure 4 shows a schematic of how a typical pyroelectric detector
works. The detector is based on a crystal in which each unit cell has a built-in dipole
moment pointing along a particular axis of the crystal. This creates a net electric
polarization along with surface charge densities on opposite ends of the crystal that are
normally cancelled by internal charges. The polarization, however, is temperature
dependent so a change in the temperature of the crystal will create a transient
macroscopic polarization and surface charge while the internal bound charges are moving
to a new equilibrium. If the crystal is cut precisely across the axis of polarization and
inserted into a circuit, a polarization current will flow when this transient surface charge
is created. One practical effect of this type of detection mechanism is that the detector is
inherently incapable of responding to a steady radiation source because the response
depends on a change in temperature, so the source power must be modulated. [5, 6]
Fig. 4. Schematic diagram of a typical pyroelectric detector. Figure from [5].

A plot of the electric polarization of the crystal (P) vs. temperature (T) shows that
the polarization curves downward with increasing temperature reaching zero at a point
known as the Curie temperature. The slope of this graph at any given temperature,
p=dP/dT, is known as the pyroelectric coefficient. The magnitude of the current created
by a particular change in temperature is

\[ I = pA \frac{dT}{dt} \]  

(1)

where \( \Delta T \) is the change in temperature of the crystal and A is the area of the pyroelectric
crystal. [6] In practice, the current generated is too small to be of much use by itself so
some sort of amplification circuit must be included as part of the detector circuitry. This
circuitry is of two kinds depending on whether the pyroelectric crystal and the electrodes
attached to it are coupled to a current amplifier or a voltage amplifier. Fig. 5 shows
exemplary circuits for both [5].
Fig. 5. Exemplary detection circuits for a pyroelectric detector coupled to (a) voltage and (b) current amplifiers. Figure from [5].

2.2 Schottky diode rectifiers

A Schottky diode is based on a metal-semiconductor junction. These diodes act as rectifiers like ordinary p-n junctions but there are some important differences that allow them to be used for detection at mm-wave and sub-THz frequencies. The key difference is that Schottky diodes are “unipolar”, meaning that their electrical behavior depends on only one carrier type, usually electrons. With n-type semiconductors, the electrons experience a potential-energy barrier created by differences in the work function between the metal and semiconductor. Without external electrical bias, there is an equilibrium between the electrons flowing from the semiconductor to the metal and vice versa. However, under forward bias, the proportion of electrons flowing from the semiconductor to the metal becomes greater, generating a net current. Under reverse bias, the electrons have difficulty flowing back the other way because of the potential barrier. This creates a rectifying effect. Unlike p-n junctions which require significant
time (typically nanoseconds) for carriers to recombine, Schottky diodes can rectify at much higher frequencies (approaching THz) because there is no recombination required, only transit time across a depletion layer on the semiconductor side. When unbiased Schottky diodes are used as detectors for mm-wave and sub-THz radiation, the oscillating electric field of the incoming radiation, usually coupled through some kind of antenna, is rectified because of the difference in forward and reverse current flow in response to electric fields. This in turn generates a dc current component proportional to the power of the signal. [7, 8]

**DETECTOR CHARACTERISTICS AND METHOD OF MEASUREMENT**

There are many different ways of quantifying the performance of a given detector but all of them ask the same basic questions: how small a signal can one detect and what is the quantitative relationship between the detector response and the input radiative power? For this study, detector responsivity, noise equivalent power (NEP), and noise equivalent temperature difference (NEΔT) were used for the thermal and Schottky detectors.

**3.1 Definition of Characteristics of Interest: Responsivity, NEP, and NEΔT**

Responsivity answers the question about the quantitative relationship between detector response and input power and is basically just the change in signal output per unit change in input power. For these detectors, the output signal is measured in volts
(making this a "voltage responsivity") and the input signal is measured in Watts so responsivity has units of V/W. [9]

NEP is often described as the minimum amount of power that can be detected by the detector in question [10] and can be more formally defined as "the power from the signal source required to give a voltage output equal to the root mean square noise voltage output" [9]. Technically, it has units of Watts as one would expect from the word "power" in its name. However, this number depends on the post-detection bandwidth, so it is often normalized to 1 Hz to make it independent of this bandwidth. Thus it is usually cited with units of W/√Hz.

NEΔT is very similar to NEP except that, instead of being a minimum detectable source power, it is a minimum change in source temperature assuming the source is a thermal radiator (e.g., blackbody). In this case, a change in the source temperature produces a linear change in the intensity of the radiation emitted according to the Planck theory of thermal radiation in the Rayleigh-Jeans limit. Such a change in the radiation coming into the detector should produce a change in the output signal and the point at which this change vanishes into the noise floor is the NEΔT. This quantity is useful for all direct detectors responding to thermal radiation in “passive” sensors, i.e. systems that detect the radiation emitted by a warm object without providing their own radiative illumination.

Unfortunately, these quantities are not always easy to measure directly, particularly the responsivity. At first glance, it seems simple. Just point a source of known power at the detector and measure the response. But is all the radiation coming
out of the source really getting to the detector or is some lost to the room? That makes
the experiment a little more challenging to say the least. In the end, some slightly less
direct measurements and a few calculations are required as efficiently coupling the source
radiation to the detector can be challenging.

3.2 Measurement Techniques

In order to obtain NEP, NEΔT, and responsivity for a given detector, three
measurements must be made: RMS noise voltage, detector output vs. blackbody source
temperature, and detector output as a function of incident angle of radiation or antenna
pattern. Using these three measurements, and a few assumptions about the sources
involved, the quantities in question can be easily calculated.

3.2.1 Noise Voltage

The noise voltage measurements made in this study were done with a lock-in
amplifier (LIA) which has certain digital signal processing features that make noise
measurements almost automatic but add a couple of steps to the calculations. The LIA
computes the noise using the mean average deviation (MAD) method. According to the
manufacturer’s LIA manual, this is simply “a moving average of the absolute value of the
deviations” [12]. If the noise is white Gaussian, then the I and Q components are equal
and can be combined into a total noise voltage by

\[ v_{\text{MAD}} = \sqrt{v_I^2 + v_Q^2} \]  \hspace{1cm} (2)

The conversion from MAD to RMS can then be made by multiplying by a factor of
A handy feature of doing it this way is that the LIA takes into account the bandwidth of the measurement, normalizing it to a one hertz bandwidth, and gives its results in units of \( \text{V/}\sqrt{\text{Hz}} \). This feature was not technically necessary for these measurements since a 1 s time constant was used which generates a 1 Hz bandwidth anyway, but it is still very useful for occasions where a different time constant is desired for other reasons. In this work, the measurement setup including placing the detector behind a piece of blank metal to block all incoming radiation and make sure that the output is all associated with detector and electronic noise. In the case of the Schottky detectors, a low-noise preamplifier was inserted between the detector and the LIA because the output of the detectors was so weak. In the case of the pyroelectric detectors, the device package (TO-5 can) has a built-in transimpedance amplifier.

The assumption of Gaussian noise was tested by plotting the histogram of the noise measurement over time. An example of this for a Schottky rectifier is shown in Fig. 6. The distribution is roughly Gaussian (the Gaussian fit has \( R^2 = 0.7725 \)) indicating that the assumption of Gaussian noise for the noise calculations was valid.
Fig. 6 Histogram of detector voltage noise with a Gaussian fit for the VDI WR1.5ZBD Schottky rectifier. $R^2 = 0.7725$.

If it is desired to separate out the noise of the detector itself from the noise of the LIA or any preamplifiers, another set of measurements must be made to determine the noise characteristics of the amplifier as a function of frequency and input impedance. For this work, this step was only really necessary for the Schottky diode detectors since the thermal detectors generate enough of a signal that no preamplifiers are needed. If the current and voltage noise of the amplifier are uncoupled and the noise is white Gaussian noise, then the total noise of the amplifier can be modeled as

$$v_{\text{total}} = v_n + i_n R_s$$  \hspace{1cm} (3)

where $v_n$ is the voltage noise, $i_n$ is the current noise, and $R_s$ is the input impedance. The conditions for this are usually at least a good approximation for most amplifiers. The total noise is measured at a range of frequencies for a particular $R_s$ and then another
A measurement is made at the same set of frequencies with a different $R_s$ and so on for impedances from short to a kΩ. Creating a series of plots of $v_{\text{total}}$ vs. $R_s$ for a range of frequencies gives a set of lines with slopes equal to $i_n$ and intercepts equal to $v_n$. The voltage noise and the current noise can then be found by doing a simple linear fit of the lines. This process is shown in Fig. 7 for the SRS 552 preamplifier. The resistance of the detector diode can be determined by doing a simple I-V curve. At that point, the noise from the detector alone can be separated from the amplifier noise in the total measured noise according to the following equation

$$v_{\text{diode}} = \sqrt{v_{\text{measured}}^2 - v_n^2 - (i_nR_d)^2}$$

(4)

where $v_{\text{measured}}$ is the measured noise voltage of the detector amplifier combination and $R_d$ is the resistance of the detector.

**Fig. 7** The noise measurements for the SRS 552 preamplifier.
### 3.2.2 Temperature Response

To measure detector output vs. source temperature, a blackbody source was placed in front of the detector. As the temperature of the blackbody is varied, the change in the detector signal can be monitored to produce a graph of detector output vs. blackbody temperature. The graph of the data shows a roughly linear relationship between the change in temperature and the change in output for a good detector and the slope of this can be found using a simple linear fit. This slope is the detector's temperature response in units of V/K. To get NEΔT, one simply divides the noise voltage by the temperature response. Of all the measurements, this one is the most simple and direct.

The complicated part of measuring the temperature response is coming up with a blackbody source. A true blackbody has an emissivity of 1.0 but these do not yet exist at THz frequencies, so a surrogate is needed. A good blackbody approximation has an emissivity very close to 1.0 that is nearly constant over the frequency range of interest. For the THz region, hot water in a low-density polyethylene (LDPE) bottle fits this description. To estimate its emissivity, we apply the double-Debye model for the dielectric function of water

\[
\varepsilon = \varepsilon_{\infty} + \frac{\varepsilon_0 - \varepsilon_1}{1 + j\frac{v_1}{v}} + \frac{\varepsilon_1 - \varepsilon_{\infty}}{1 + j\frac{v_2}{v}}
\]

where \( v_1 = 17.4 \text{ GHz}, v_2 = 693.1 \text{ GHz}, \varepsilon_0 = 79.7, \varepsilon_1 = 5.35, \) and \( \varepsilon_{\infty} = 3.37, \) [13] and given a dielectric constant of \( \varepsilon = 2.3 + 0.0j \) for LDPE, the total reflectivity of the bottle of water can be calculated using Fresnel’s equations and then the emissivity approximated by \( \varepsilon \approx \)
1 - R\textsubscript{tot} (Kirchoff’s law of radiation) where R\textsubscript{tot} is the frequency-dependent reflectivity.

The results of this calculation are shown in Fig. 8 and one can see that the emissivity of this "grey body" is a rather good approximation for a blackbody at THz frequencies.

![Emissivity vs. Frequency of Hot Water in a LDPE Bottle](image)

Fig. 8. Emissivity of a LDPE bottle filled with hot water for THz frequencies.

3.2.3 Antenna Pattern

The antenna pattern measurement does triple duty. Not only does it represent the detectors “field-of-view”, it also provides the rest of the information required to calculate the responsivity and the NEP. To make this measurement, the detector in question must be mounted on a gimbal or other rotational device directly in front of a radiation source of known output power in such a way that, when the detector is tilted, it remains aligned
with the center of the source beam. The magnitude of the detector response as a function of angle is measured over a 2-pi-steradian solid angle and the data recorded. At that point, all the information is available to calculate NEP and responsivity using the following process.

### 3.3 Calculations

If \( F(\theta, \phi) \) is the antenna pattern of a particular receiver horn or antenna expressed as signal as a function of incident elevational (theta) and azimuthal (phi) angles, then the directivity of that feedhorn is given by

\[
D = \frac{4\pi}{\iint F(\theta, \phi) \, d\Omega}
\]

(6)

In cases of azimuthal symmetry, this integral expression can be approximated as

\[
D \approx \frac{2}{1 - \cos\left(\frac{\theta}{2}\right)}
\]

(7)

where \( \beta \) is the angle of the full width half maximum (FWHM) of the main lobe of the antenna pattern. This, of course, does not technically hold true for the rectifiers used in this work because of the sidelobes in the antenna patterns whereas it works beautifully for the thermal detectors because their antenna patterns are defined by geometrical “field-of-view” so lack diffraction-induced sidelobes (to first order). However, for the feedhorns used on the rectifiers in this work, this is not as accurate because any sidelobes present are down only 10-20 dB below the main lobe. Nevertheless, Eq. (7) is a good basis for approximation. Using this directivity, the effective aperture of the detector horn can be calculated as follows where \( \lambda \) is the wavelength of the source and \( D_{\alpha} \) is the directivity of
the detector feedhorn.

\[
A_{\text{eff}} \approx \frac{\lambda^2 D_{\text{rx}}}{4\pi} \quad (8)
\]

The intensity of the source radiation hitting the detector, \(I_{\text{tx}}\), is a function of the source power, \(P_{\text{tx}}\), the source feedhorn’s directivity, \(D_{\text{tx}}\), and the distance between the two horns, \(r\), which should all be previously known quantities. \(I_{\text{tx}}\) is given by

\[
I_{\text{tx}} = \frac{P_{\text{tx}} D_{\text{tx}}}{4\pi r^2} \quad (9)
\]

Combining this with the effective aperture yields the total power that is actually incident on the detector, \(P_{\text{rx}}\).

\[
P_{\text{rx}} = A_{\text{eff}} I_{\text{tx}} \quad (10)
\]

This overcomes the main difficulty with a responsivity measurement that was mentioned above and the calculation then becomes very straightforward. The voltage responsivity of the detector, \(R_v\), is determined by dividing the average maximum signal voltage, \(v_{\text{signal}}\), by the incident power which gives \(R_v\) in V/W.

\[
R_v = \frac{v_{\text{signal}}}{P_{\text{rx}}} \quad (11)
\]

The maximum signal voltage is found by locating the maximum reading in the center of the main lobe of the antenna pattern and should correspond to a perfectly aligned detector with no rotation relative to the source.

The NEP can then be calculated as the ratio of the rms noise voltage from the detector to the responsivity.

\[
\text{NEP'} = \frac{v_{\text{noise}}}{R_v} \quad (12)
\]
4.1 Detectors

The Golay cell used in these experiments was an old model manufactured by Tydex with a diamond window. Current models by the same manufacturer are rated for a responsivity of $10^5$ V/W and NEP of $10^{-10}$ W/√Hz at 20 Hz modulation frequencies. This particular detector was hand selected by the distributor for its reliability and precision and it had given many years of good data in various experiments before its unfortunate demise in the course of this work [14].

Representing pyroelectric detectors in this study was a collection of three LiTaO$_3$ pyroelectric detectors manufactured by Spectrum Detector some years ago. Spectrum Detector was recently bought by Gentec EO but similar detectors are still being manufactured under different model numbers [15]. The detecting element is a 5 mm square LiTaO$_3$ crystal with a chrome plating on top as an absorber. Each detector has a built-in transimpedence amplifier and is packaged in a standard TO5 can. With the detector, a test box produced by the same manufacturer containing all the readout and bias circuitry was used. It has an 8.73 mm diameter circular aperture over the detector. Since pyroelectric detectors are particularly sensitive to IR, the aperture was covered with three layers of 4-mil-thick black polyethylene to block most of the IR from the environment so that only the THz characteristics of the detectors would be measured.

Another pyroelectric detector was also tested but this one was supplied by QMCI, Ltd. Instead of being made of LiTaO$_3$, it was made of Triglycine Sulfate which is a good pyroelectric material at room temperature. It came in a box with all the necessary
built-in transimpedence amplifier and circuitry so that the user only needs to add a power supply. The aperture is a round opening and it has a 500cm-l metal mesh filter over it [16].

The three Schottky rectifiers characterized in this study were all commercial detectors designed for use at frequencies from 100 GHz to 600 GHz. All of them operate at zero bias. For the 100 GHz frequencies, a W-band Schottky detector from Spacek Labs, model DW-2P, was used. The manufacturer’s test results sent with the detector at the time of purchase showed a responsivity of 1890 mV/mW at 100 GHz when characterized using a -20 dBm input [17]. The other two Schottky detectors were both manufactured by Virginia Diodes Inc. (VDI). The first one was labeled as model WR1.5ZBD and is designed to operate at frequencies between 500 and 750 GHz. The responsivity as measured by VDI has a typical value across the detectors operating range of about 750 V/W. VDI list its typical NEP as 1×10^{-10} W/√Hz. The second VDI Schottky detector was model WR2.2ZBD and is listed with a typical responsivity of 1250 V/W and a typical NEP of 5×10^{-11} W/√Hz. This particular detector was designed to operate between 330 and 500 GHz but a source at those frequencies was not available for characterizing the detector. After some exploratory testing, the best overlap between the sources and the WR2.2ZBD detector was determined to be at 286 GHz. The final results obtained at that frequency were comparable to the manufacturer’s test results at higher frequencies. These results will be discussed in more detail later but they do indicate that this detector can function reasonably well at frequencies slightly below its design band [18].
4.2 Sources

All the measurements on all the detectors were made using a source appropriate for the individual detector (i.e. a 600 GHz source for the WR1.5ZBD Schottky but a 100 GHz source for the Spacek Schottky). This required three different sources in addition to the hot water grey body used for the temperature response measurements.

The 100 GHz source was a varactor tuned Gunn oscillator from Spacek Labs, model GW-100V. According to the manufacturer’s data sheet, operating the oscillator at 10-V bias produced an output signal at 100 GHz of about 16 mW [17]. A 12dB attenuator was used to bring this power down to 1 mW because the Schottky detector operating at 100 GHz was saturating. To direct the beam, a 23-dB-gain conical feedhorn was placed on the output.

The second source operated at 286 GHz and was a combination of a YIG oscillator operating at 7.95 GHz and a ×36 multiplier chain. The source was electronically modulated using a PIN switch (as opposed to a mechanical chopper for the other sources) and the output power at 286 GHz was approximately 0.1 mW. The feedhorn on the output was pyramidal and rated at 26-dB-gain by the manufacturer.
The third source was also a YIG and multiplier chain but, in this one, the YIG operated at 12.5 GHz and a multiplier chain manufactured by VDI was used to multiply the frequency by a factor of 48 to give an output of 600 GHz. The output power at this frequency was approximately 0.5 mW according to the manufacturer’s specifications and it also had a 26-dB-gain pyramidal feedhorn on the output [18].

The output of all these sources was modulated at a frequency determined by the type of detector being used at the time: 10 Hz for thermal detectors and 200 Hz for the
Schottky detectors. Except for the 280 GHz source which had electronic modulation, the modulation was done with an optical chopper positioned directly in front of the source's output horn which accounts for our inability to modulate at higher frequencies. This modulation was done because a LIA was used for all the measurements.

RESULTS

5.1 Thermal Detectors

5.1.1 Golay Cell

The noise measurement results for the Golay cell with a diamond window are shown below in Fig. 10. These measurements were taken with the Golay cell connected directly to the LIA and the graph shows the actual LIA reading of just the I component (also known as the x component) of the noise using its MAD method of computation. When converted to rms, the first trial gave an average of 0.0182 mV/√Hz and the second an average of 0.0185 mV/√Hz for an average of 0.0184 mV/√Hz.
Fig. 10. Noise of the Golay cell over time showing the x component MAD noise as measured by the LIA.

The temperature response of the Golay cell for one trial is shown in Fig. 11. The graph shows the detector voltage reading as a function of the hot water source temperature with a linear fit of the data. This plot does not look like the ideal linear response one would expect (or even the closer approximation to linear that was produced by the other detectors) because the Golay cell is very nonlinear. Higher water temperatures mean higher power levels incident on the detector and eventually mechanical forces involved in the expansion of the pneumatic chamber start to counteract the expansion from the radiation leading to a saturation effect. There may also have been some thermal losses to the environment. Making the best of it however, the average
The slope of these tests is 0.70 mV/K which, when combined with the noise measurements shown above, gives a NEΔT of 0.0262 K/√Hz.

![Graph showing temperature response of the Golay cell with a linear fit of the data.](image)

**Fig. 11.** Temperature response of the Golay cell with a linear fit of the data.

Unfortunately, the Golay cell being used for these tests was damaged in some unknown way before any antenna pattern measurements could be made on it. It would still give a response to an input signal but this response would vary significantly over the course of minutes from very large to practically nothing. In addition, the response of the Golay cell was significantly noisier than it was before. This limits the comparison of the Golay cell to the other detectors to NEΔT.
5.1.2 Pyroelectric Detectors

The noise measurements for the pyroelectric detectors measured and converted to rms in the same way as the measurements for the Golay cell yielded an average rms noise reading of 0.810 mV/√Hz. The individual results for each pyroelectric detector are listed in Table 1. Two of the detectors both had noise readings around 0.5 mV/√Hz and the third was 1.5 mV/√Hz but all ended up having very similar NEΔT results. These noise readings were, like those for the Golay cell, made without any preamplifier between the detector and the LIA; but the pyroelectric detectors contain a built-in transimpedance amplifier (TIA). Since there was no way to separately measure its effect, the TIA noise is convolved with the pyroelectric-detector noise in these results.

The temperature response of the LiTaO$_3$ pyroelectric detectors was less problematic but more interesting than that of the Golay cell. Figure 12 shows the temperature response of one of the detectors. From this graph, it looks like a very good detector - good signal to noise ratio, large slope, and a large enough voltage response to make a preamplifier unnecessary. It was suspected, however, that this was too good to be true because it would mean that the detector had a NEΔT of about 0.3 K/√Hz which would be rather incredible in the THz region. Since pyroelectric detectors are also extremely good IR detectors, another set of tests was done to determine whether or not this stellar performance was due to the IR being emitted by the hot water in spite of the black polyethylene filter. The temperature response of each of the pyroelectric detectors was measured again with several different low pass filters in front of the detector aperture...
and the NEΔT calculated based on each of the new temperature responses. The filters were all metal mesh designs 1 inch in diameter provided by Ken Wood of QMCI, Ltd. As expected, the NEΔT of all the pyroelectric detectors increased dramatically as the filter cutoff wavelength was increased. This is shown graphically in Fig. 13. Since only THz frequencies were of interest for this study, only the data taken with the lowest frequency, highest wavelength cutoff, corresponding to 33 cm\(^{-1}\) or 1 THz, was used in the comparison of detectors. The low frequency temperature response and NEΔT for all the pyroelectric detectors are shown in Table 1.

The slight nonlinearity in the temperature response for these detectors is not fully understood at this point because other projects using these detectors have found their temperature responses to be very linear. The best explanation that could be found was that some other thermal effect was affecting either the temperature of the detectors themselves or the measurement apparatus. It could be as simple as the thermometer in the water not being at equilibrium yet or as obscure as the crystal not having enough time to heat properly because the modulation frequency was too high but nothing conclusive has been found.
Fig. 12. The temperature response of a LiTaO$_3$ pyroelectric detector with a linear fit
Fig. 13. The NEΔT of three different LiTaO$_3$ pyroelectric detectors by the same manufacturer as a function of filter cutoff.
Table 1. Characterization results for the LiTaO$_3$ pyroelectric detectors.

<table>
<thead>
<tr>
<th>Detector</th>
<th>LiTaO$_3$ 1</th>
<th>LiTaO$_3$ 2</th>
<th>LiTaO$_3$ 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source frequency</td>
<td>600 GHz</td>
<td>600 GHz</td>
<td>600 GHz</td>
</tr>
<tr>
<td>Modulation frequency</td>
<td>10 Hz</td>
<td>10 Hz</td>
<td>10 Hz</td>
</tr>
<tr>
<td>Noise, $v_{\text{noise}}$</td>
<td>0.469 mV/√Hz</td>
<td>0.438 mV/√Hz</td>
<td>1.495 mV/√Hz</td>
</tr>
<tr>
<td>Temperature response (&lt;33 cm$^{-1}$)</td>
<td>25.6 nV/K</td>
<td>27.8 nV/K</td>
<td>93.4 nV/K</td>
</tr>
<tr>
<td>Maximum signal, $v_{\text{signal}}$</td>
<td>40.0 mV</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Effective aperture, $A_{\text{eff}}$</td>
<td>2.62 mm$^2$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NEAT</td>
<td>18.3 K/√Hz</td>
<td>15.8 K/√Hz</td>
<td>16.0 K/√Hz</td>
</tr>
<tr>
<td>Responsivity</td>
<td>6400 V/W</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NEP</td>
<td>73.2 nW/√Hz</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 14 shows a representative plot of the "antenna" patterns for the LiTaO$_3$ pyroelectric detectors. It is almost perfectly round with no sidelobes as would be expected because the detectors simply have a round aperture (defined by the TO5 can) above the detecting element that defines the antenna pattern via a geometric “field-of-view”. This result is really more of a validation than a groundbreaking result because it is so expected, but it is interesting that this intensity pattern can be easily modeled to a fairly high degree of accuracy using only geometric optics. The real interest of this plot is what it can tell us about the detector. This plot was made at 600 GHz and the maximum detector response was about 40 mV. This was used as $v_{\text{signal}}$ which is listed in Table 1. The FWHM of the pattern used for calculating the effective aperture was
determined by finding the half power points on opposite sides of the pattern and noting the angle between them. This was then used to calculate the responsivity and NEP which are also listed in Table 1. In general, this set of pyroelectric detectors had an NE\Delta T on the order of 20 K/√Hz, a responsivity of about 6×10^3 V/W, and a NEP of <10^2 nW/√Hz.

Fig. 14. The antenna pattern of a LiTaO3 pyroelectric detector that was used to determine responsivity and NEP.

The Triglycine Sulfate pyroelectric detector from QMCI gave much different results than the LiTaO3 detectors. All the measurement parameter were the same but the measured voltage noise was 4.68 nV/√Hz which is several orders of magnitude down from the noise of the other pyroelectric detectors. This sounded promising but the
temperature response was also reduced. The temperature response was measured and the NEΔT calculated for all of the different filter cutoffs in the same way as the other pyroelectric detectors and the results listed in Table 2.

Table 2.

<table>
<thead>
<tr>
<th>Filter cutoff (cm⁻¹)</th>
<th>Temperature Response (V/K)</th>
<th>NEDT (K/√Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>1.4577E-06</td>
<td>3.21</td>
</tr>
<tr>
<td>300</td>
<td>4.4363E-07</td>
<td>10.55</td>
</tr>
<tr>
<td>100</td>
<td>3.1442E-08</td>
<td>148.90</td>
</tr>
<tr>
<td>33</td>
<td>3.4128E-09</td>
<td>1371.85</td>
</tr>
</tbody>
</table>

The first thing to notice about these numbers is that, for frequencies anywhere in the THz range (<3 THz), the NEDT of this detector is so high that it is practically useless. At higher frequencies, this detector does do better but it has a similar NEDT at 300 cm⁻¹ as the other pyroelectrics do at 33 cm⁻¹. The general trend makes this detector look promising for the IR but not for THz. This result was unexpected so the possibility of detector degradation has been considered. The Triglycine Sulfate crystal is very susceptible to humidity and that is a factor in the environment that is very difficult to control, particularly in Ohio during the summer.

Unfortunately, the NEP and responsivity for this detector were not able to be calculated because the antenna pattern measurement was not possible. The highest frequency source available for testing was the 600 GHz source which was used for the other pyroelectric detectors. However, a quick glance at Table 2 shows that the QMCI pyroelectric can detect very little below 1 THz so all attempted antenna pattern measurements revealed nothing more than noise. It is hoped that, with further
development and less humidity sensitivity, this kind of pyroelectric detector will fare better in future comparisons to LiTaO$_3$ pyroelectrics.

### 5.2 Schottky Rectifiers

The noise measurements and other characterizations for the Schottky rectifiers were made using a modulation frequency of 200 Hz and a voltage preamplifier between the detector and the LIA. This preamplifier was necessary because, while the response of a Schottky diode is higher than the response of a pyroelectric detecting element, the Schottky detectors do not have any built in amplification. The results that are listed in Table 3 for these detectors have had the effects of the amplifier subtracted out as described earlier.
Table 3. Characterization results for the Schottky rectifiers.

<table>
<thead>
<tr>
<th>Detector</th>
<th>Spacek DW-2P</th>
<th>VDI WR2.2ZBD</th>
<th>VDI WR1.5ZBD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating frequency</td>
<td>100 GHz</td>
<td>286 GHz</td>
<td>600 GHz</td>
</tr>
<tr>
<td>Modulation frequency</td>
<td>200 Hz</td>
<td>200 Hz</td>
<td>200 Hz</td>
</tr>
<tr>
<td>Width of Detector</td>
<td>35 GHz</td>
<td>175 GHz</td>
<td>250 GHz</td>
</tr>
<tr>
<td>Operating Range</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Noise, $v_{\text{noise}}$</td>
<td>38.968 nV/√Hz</td>
<td>22.497 nV/√Hz</td>
<td>6.371 nV/√Hz</td>
</tr>
<tr>
<td>Temperature response</td>
<td>3.613 nV/K</td>
<td>2.531 nV/K</td>
<td>1.113 nV/K</td>
</tr>
<tr>
<td>Maximum signal, $v_{\text{signal}}$</td>
<td>19.9 mV</td>
<td>0.270 mV</td>
<td>0.198 mV</td>
</tr>
<tr>
<td>Effective aperture, $A_{\text{eff}}$</td>
<td>70.95 mm²</td>
<td>8.74 mm²</td>
<td>7.23 mm²</td>
</tr>
<tr>
<td>NEΔT</td>
<td>10.786 K/√Hz</td>
<td>8.889 K/√Hz</td>
<td>5.723 K/√Hz</td>
</tr>
<tr>
<td>Responsivity</td>
<td>2600 V/W</td>
<td>1300 V/W</td>
<td>203 V/W</td>
</tr>
<tr>
<td>NEP</td>
<td>15.210 pW/√Hz</td>
<td>17.514 pW/√Hz</td>
<td>62.581 pW/√Hz</td>
</tr>
</tbody>
</table>

Graphs of the temperature response of each detector with a linear fit are shown in Figures 15-17. At first glance, it is apparent that the slope and signal to noise ratio are both significantly reduced for the lower frequency detectors and this might seem to reflect negatively on their quality. However, it must be remembered that the radiation from the hot water source is much stronger for the high-frequency detectors because of their greater bandwidth, so the difference is one of signal strength rather than detector quality. Each of the Schottky detectors is ostensibly spatially unimodal. In the Rayleigh-
Jeans limit, each spatial mode contributes $k_B T \Delta v$ of power, where $k_B$ is Boltzmann’s constant, $T$ is the source temperature and $\Delta v$ is the spectral bandwidth. These detectors are essentially integrating all the power from the blackbody across their frequency range so it is the spectral bandwidth difference that creates the difference in incident power.

The NE$\Delta T$ values calculated from the slopes in these plots are listed in Table 3 and it can be seen that all the detectors display NE$\Delta T$ values within the same order of magnitude.

Fig. 15. The temperature response of the Spacek Schottky rectifier with a linear fit of the data.
Fig. 16. The temperature response of the WR2.2ZBD Schottky rectifier with a linear fit of the data.
Fig. 17. The temperature response of the WR1.5ZBD Schottky rectifier with a linear fit of the data.

The antenna patterns for each of the Schottky detectors are shown in Figures 18-20. Because all these detectors had pyramidal feedhorns rather than a simple circular aperture, these patterns all have sidelobes visible. These sidelobes are all at least 15 dB lower than the main lobe and 20 dB down in the case of the WR2.2ZBD. For the WR1.5ZBD, the sidelobes are particularly visible and multiple sets can be observed. The maximum detector response from each pattern as well as all the responsivity and NEP values calculated for each detector are listed in Table 3.
Fig. 18. The antenna pattern of the Spacek Schottky rectifier that was used to determine responsivity and NEP. It also shows faint sidelobes characteristic of the pyramidal feedhorn.
Fig. 19. The antenna pattern of the WR2.2ZBD Schottky rectifier that was used to determine responsivity and NEP. There are two faint spots visible that may be sidelobes but they are nearly 20 dB down from the main lobe.
Fig. 20. The antenna pattern of the WR1.5ZBD Schottky rectifier that was used to determine responsivity and NEP. This plot shows numerous sidelobes, all at least 15 dB down from the main lobe.

So how does one make sense of all the numbers listed in Table 3? To begin with, comparing these numbers with those provided by the detectors' manufacturers shows that the measured NEΔT, responsivity, and NEP for the Schottky detectors are of the same order of magnitude and, in most cases, slightly better. The one case where this is not true is the WR1.5ZBD. The NEDT that was measured for this detector would lead one to believe that the responsivity would be higher than what was measured and the NEP lower. Even the manufacturer’s specifications give a responsivity that is a factor of three higher. To see if there was any degradation, the Torrey-Whitmer electrical responsivity and NEP of the WR1.5ZBD were calculated from the I-V curve of the diode.
Unfortunately, this resulted in an electrical responsivity of 4.6 kV/W and an electrical NEP of 1.4 pW/√Hz which does not indicate any kind of degradation so the low responsivity measurement is still unexplained. It is also possible that there was some inaccuracy in determining the precise power output of the 600 GHz source. This had to be estimated from earlier measurements with another detector in another lab. It is should be obvious that characterizing a source with a detector and then characterizing the same detector with the same source is not only illogical but problematic.

In summary, the general characteristics of the Schottky detectors were an NEΔT on the order of $10^1$ K/√Hz, a responsivity within an order of magnitude of $10^3$ V/W, and a NEP of $<10^2$ pW/√Hz.

### 5.3 Comparison

In general, the characterization results for all the detectors confirm what most researchers know about choosing detectors for particular projects. Thermal detectors, developed in the infrared and then extended down into the THz and sub-THz regions are the clear choice for higher frequency applications. Figure 13 from the discussion of pyroelectric detectors is a rather dramatic illustration of the fact that they get better and better the higher the frequency due to increased spectral bandwidth and hence increased blackbody radiation for thermal applications. Of course, the Schottky detectors are designed to operate at the lower frequencies so applications at the lower end of the sub-THz range would be better served by one of them. A comparison of the values listed in Table 3 shows that the responsivity of the Schottky detectors drops off and the NEP increases as the frequency is increased.
Comparing the performance of the Schottky detector and the pyroelectric detector at 600 GHz from Tables 1 and 3, it is also apparent that the responsivity and NEP of the Schottky detector are orders of magnitude lower. That presents a bit of a tradeoff. Better responsivity in the pyroelectric detector comes with a higher NEP. Some of this can be remedied by adding an amplifier to the Schottky detector to make it more comparable to the pyroelectric detector with its built-in amplifier. Since the Schottky’s responsivity is only one order of magnitude lower than the pyroelectric's and its NEP is three orders of magnitude lower, it is possible, with the right choice of amplifier, to get excellent performance out of a good Schottky detector. At that point, however, there are still many other reasons to consider a pyroelectric detector (assuming that their slow response time is not an issue) including cost, ease of use, and durability but these are more subjective factors in the decision.

CONCLUSION

6.1 Conclusions

Since THz detectors are not typically mass produced and each detector can vary from the next based on manufacturer, age, and other factors, these specific characterization results are probably most useful as a reference for characterizations performed on other individual detectors and as a general guideline for the choice of detector for a particular application.

In this work, the NEΔT, responsivity, and NEP of three Schottky detectors and three pyroelectric detectors were measured. The pyroelectric detectors were found to have the highest responsivity on the order of 6400 V/W whereas the Schottky detectors
had a lower $\Delta T$ of $10 \text{ K/}\sqrt{\text{Hz}}$ and a lower NEP less than $100 \text{ pW/}\sqrt{\text{Hz}}$.

To aid in summarizing the conclusions of this work, some diagrams are presented below. Figure 21 shows how the $\Delta T$ of a pyroelectric, when limited to frequencies below 1 THz, is much higher than that of the Schottky detectors although it does cover the entire frequency range. When its optical bandwidth is expanded into the infrared, its $\Delta T$ drops very low making it appear much more attractive, but it must be remembered that atmospheric absorption creates a very effective 1 THz low pass filter for most practical applications so the higher $\Delta T$ is the one that will be most applicable in most thermal imaging situations.

![Graphical representation of the NE$\Delta T$ of various detectors.](image)

Fig. 21. Graphical representation of the NE$\Delta T$ of various detectors.
A comparison of the NEP of both kinds of detector reveals a difference dramatic enough to require a log plot. In CW, non-thermal, applications, having a low NEP is of great importance and in this particular metric the Schottkies are better by three orders of magnitude. So why would research be invested in pyroelectric thermal imaging arrays and other similar systems? The answer lies in the next figure.

Fig. 22  Graphical representation of the NEP of Schottky and pyroelectric detectors

Figure 23 shows the relative cost of the different detectors tested here. Notice that this is a log plot so the difference in price is rather vast. Part of this is due to the complexity of manufacturing but, whatever the cause, pyroelectrics will continue to be used as long as they are so much cheaper than other detector technologies. If, at some point in the future, Schottky detectors become comparable in price, the pyroelectric will probably become much less popular.
Fig. 23  Graphical representation of relative detector cost.
REFERENCES


