A coherent frequency-domain THz spectrometer with a signal-to-noise ratio 60 dB at 1 THz

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ABSTRACT

A terahertz frequency domain spectrometer is implemented using two ErAs:GaAs photomixers in a highly compact configuration, utilizing all solid-state components and no moving parts. Digital signal processing electronics provide precise frequency control and yield ~200 MHz accuracy of the THz signal frequency. Continuous frequency sweeping is demonstrated with better than 1 GHz resolution from 200 GHz to 1.85 THz. The coherent detection sensitivity is shown to be in good agreement with previous theoretical predictions and yields a signal-to-noise ratio of 80 dB*Hz at 200 GHz and 60 dB*Hz at 1 THz through a path length in air of one foot.

Keywords: Terahertz, THz, Photo-mixing, Distributed Feedback Laser, ErAs:GaAs, Frequency Domain Spectrometer

1. INTRODUCTION

The sub-millimeter (submm) and terahertz (THz) regime of the electromagnetic spectrum has historically been employed in the characterization of molecular gasses, typically for applications involving compounds of atmospheric importance [1,2]. Recently, new interest has developed employing THz radiation for the characterization and/or detection of solid materials. Some compounds that have been characterized are: illicit drugs, biologically important compounds like sugars and hormones, and explosives [3,4,5]. Terahertz radiation is even being used in the field of art conservation as a method to determine the proper materials for restoration of paintings [6]. There are several key reasons for the interest in THz radiation for these applications. Many dielectric, non-metallic materials are transparent at THz frequencies thus making it potentially possible to measure or detect materials that are hidden behind fabrics, packaging materials, paper or, as in the case of art characterization, layers of paint. Non-polar liquids are also very transparent to THz radiation [7]. Further, THz radiation is non-ionizing and completely eye safe. It may be used in public areas without the risk of harm to humans, flora or fauna. Finally, these key features of THz radiation would be of little interest if it weren't for the many different compounds that have distinct and measurable characteristic signatures in the THz regime. While there are numerous ways to generate and detect THz radiation, most of them suffer from low scanning bandwidths or low signal to noise ratios. One of the more promising approaches for the production and detection of THz radiation which has high scanning bandwidths and good signal to noise ratios is through photo-mixing in ErAs:GaAs [8]. Photo-mixing may be split into two similar but significantly different techniques: time-domain and frequency-domain.

Time domain systems employ optical pulses from a mode locked laser to produce THz pulses through a demodulation process in a photo-conductive (i.e., "Auston") switch (PCS) [9-12]. The THz pulse is then passed through the sample of interest before being focused onto a second PCS (the detector) that is driven by a delayed optical pulse from the same mode locked laser. The delay of the optical detector pulse is varied and the detector PCS photocurrent measured as a function of delay to obtain the THz autocorrelation function. Normalization and Fourier transformation then produces the frequency-dependent transmission through the sample of interest. As in Fourier Transform spectroscopy, the spectral resolution is determined primarily by the travel of a moving delay line. A typical delay-line travel of 1 cm renders

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spectroscopic resolution of 1 cm^{-1} or 30 GHz. In addition, moving delay-lines are not amenable to ruggedized packaging for harsh environments.

In the frequency-domain technique, on the other hand, continuous-wave THz radiation is produced through photomixing of the combined output of two single-frequency diode lasers in a PCS. The wavelength of one (or both) of the lasers is tuned to vary the THz output frequency. In most spectroscopic applications of photomixing to date, the THz output beam from the PCS has been coupled to a sensitive broadband thermal detector (e.g., LHe bolometer or Golay cell), making the overall signal processing incoherent and phase insensitive. Coherent (homodyne) detection can be achieved at room temperature by mixing the same optical radiation from the diode lasers in a detector PCS onto which the THz signal is also incident [13-15]. This provides greater sensitivity and faster data acquisition then the incoherent technique, and preserves phase information. Some of the benefits of the coherent frequency-domain technique compared to the time-domain technique are: (1) no moving parts (i.e. no mechanical scanning delay line), (2) higher frequency resolution, and (3) the ability to selectively scan specific frequency regions of interest with adjustable resolution. Also, unlike time-domain systems, CW frequency-domain photo-mixing results in all of the THz power being concentrated at a single THz frequency, thus improving spectral density and signal-to-noise ratio at that frequency. However, previously it has been difficult to realize practical frequency-domain spectrometers due to the challenges associated with the construction and control of the dual lasers, namely mode-matching and co-collimation of the two laser beams [8] and precise control of their difference frequency.

2. METHODOLOGY

These challenges are addressed in the present work through careful attention to the diode laser packaging and the use of digital signal processing for accurate laser control. The key component of our coherent frequency domain THz spectrometer is a highly-integrated dual semiconductor laser module. This photonic module was designed specifically for this application and contains two distributed feedback (DFB) laser diode chips mounted on independent Peltier thermo-electric coolers (TECs) (Figure 1). The center wavelengths of the DFB lasers are nominally 783 nm at 25°C, but the wavelengths may be temperature-tuned over 2.5 nm (1.25 THz) resulting in a difference frequency of over 2.5 THz without mode-hops. The thermal mass on the controlled surface of the TECs is kept to a minimum which allows for rapid frequency tuning. The output from each laser is collimated with an aspheric lens on a precision lens-mount with sub-micron adjustment capability [16-18]. A 50/50 beamsplitter is used to co-collimate the beams into primary and secondary beams at right angles to each other. The lenses and the beamsplitter are carefully adjusted so that the beam overlap is maximized.

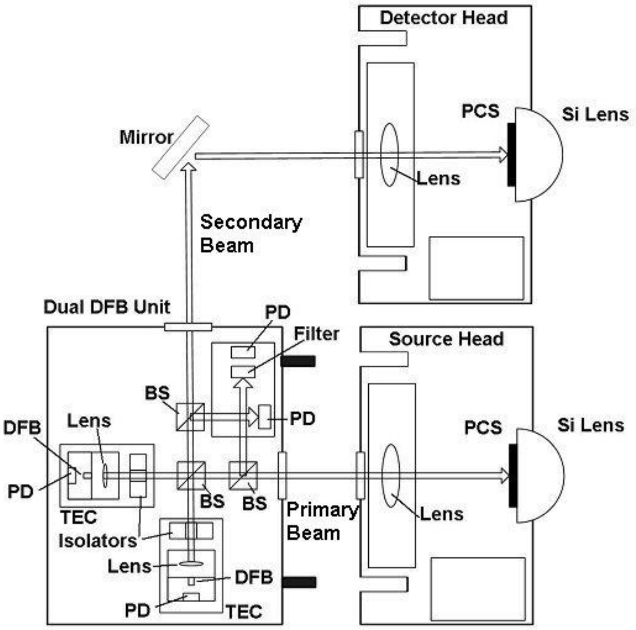

Figure 1. Integrated source and detector module drawing.

An important aspect of photomixing spectroscopy is frequency metrology. To measure the laser frequencies, 20% of the primary beam is coupled through an optical filter that has a predetermined wavelength profile and is then incident on a photodiode. The same amount of power is coupled out of the secondary beam and is incident on an unfiltered photodiode. The two DFB lasers are current-modulated at slightly different frequencies, which makes it possible to distinguish their individual power levels on the filtered and non-filtered photodiodes with a simple frequency-sensitive detection technique. After initial calibration, comparison of the relative amplitudes of the lasers on these two photodiodes indicates accurately their respective wavelengths to within ~100 MHz. After photomixing, this translates into a THz frequency accuracy of ~200 MHz. To measure the spectral purity of the system the lasers were offset in optical frequency by 10 GHz, as measured on a Burleigh WA-1500 wavemeter, and then focused onto a high-speed photodiode. The output was recorded on a RF spectrum analyzer and is displayed in Figure 2. The FWHM linewidth of the photomixing signal is under 20 MHz, limited by the instantaneous linewidths of the DFB lasers.

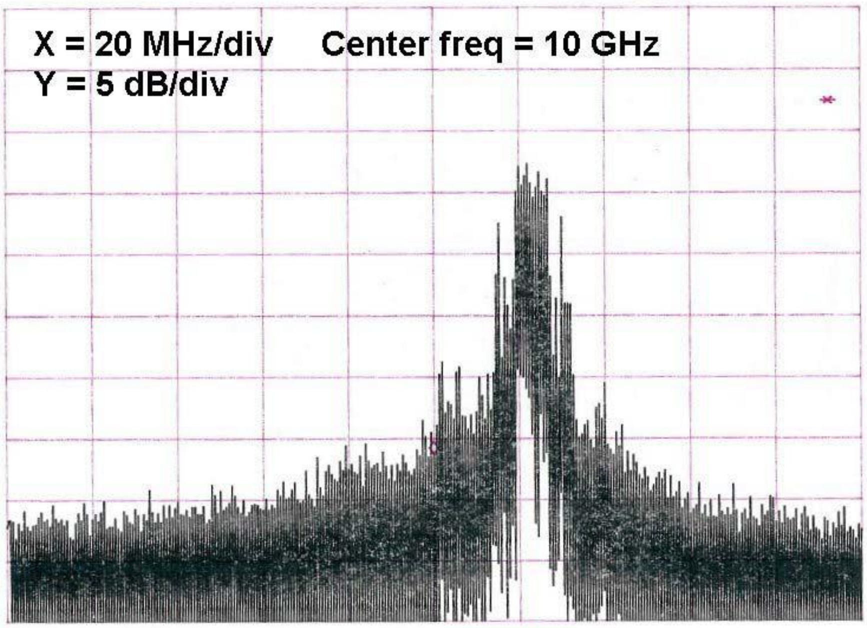

Figure 2. THz signal spectrum measured on RF spectrum analyzer.

Another important aspect is the quality of the PCS devices. In the present demonstration, we use ErAs:GaAs devices similar to those described in Ref. 8. The active region consists of ErAs nanoparticles embedded in a GaAs matrix. The electrical bias and THz photocurrents are coupled through interdigital electrodes fabricated on the top surface and located in the driving gap of a three-turn self-complementary square spiral antenna (Figure 3) [19]. The photomixers are qualified through their dark current (~1 microamp) and 780-nm external responsivity (~0.015 A/W) at 25 V bias.

After characterization of the lasers and PCS devices, the dual DFB photonic module was placed inside the THz head unit which houses control electronics, focusing optics, and the source PCS. The PCS is mounted on a hyper-hemispherical Si lens which is part of the THz head unit. The focusing optics are employed to focus the primary beam from the dual DFB photonic module onto the source PCS, the bias of which is electronically 'chopped' with a 25 KHz square wave at +/- 25V. This technique is only possible with coherent, phase sensitive detection and yields a 6 dB improvement in THz output power compared to conventional mechanical chopping of the input laser beam [20]. Further, the 25 KHz frequency is much higher than a mechanical chopper, which moves the detection frequency away from 1/f noise processes and permits significantly higher data acquisition bandwidths.

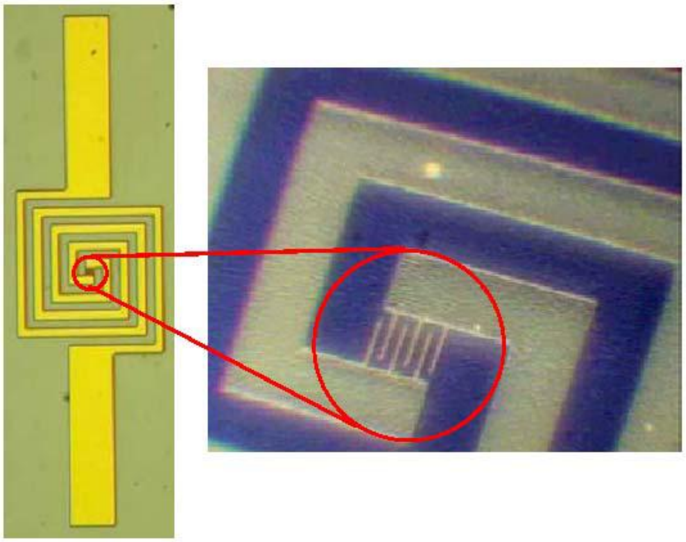

Figure 3. ErGa:GaAs three-turn self-complementary square spiral antenna with inter-digital electrodes

The secondary beam from the dual DFB photonic module is directed out of the side of the head unit and mirrors are used to align it with the detection ErAs:GaAs PCS which is mounted in a separate housing. The electronic output from the unbiased detector PCS is connected to a lock-in amplifier in transimpedance mode. Homodyne detection is then performed at the 25 kHz bias frequency. Two off-axis parabolic mirrors are employed to further focus and collimate the THz beam from the source PCS to the detection PCS. The system is shown in Figure 4 and consists of the aforementioned components, the control circuitry in a rack style enclosure, lock-in amplifier and a computer (not shown).

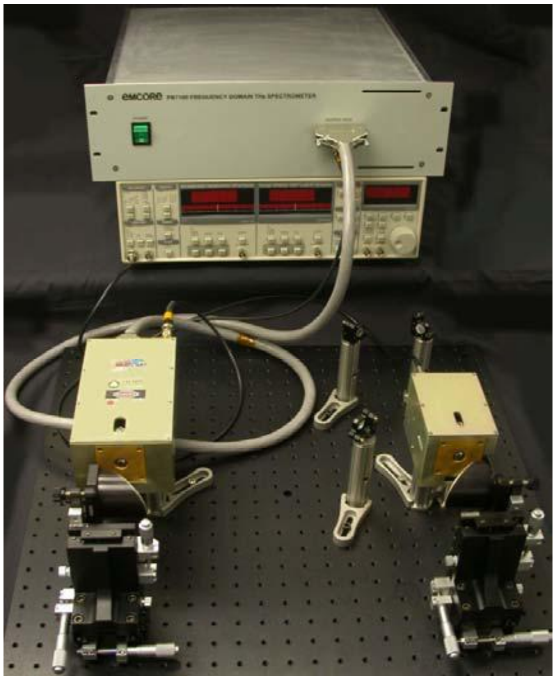

Figure 4. Photograph of the Highly Optically Integrated
Coherent Frequency-Domain THz Spectrometer.

3. DATA AND DISCUSSION

The output power spectrum of the THz source as measured on a Golay cell is shown in Figure 5. The bottom trace of Figure 5 is the Golay cell power measurement using a DC PCS bias voltage of 30V and a 14 Hz mechanical chopper in the laser beam path. The top trace is the +6 dB calculated result for the output power when using differential AC bias of +/- 30V at 25 KHz. This measurement indicates that the THz power is 10 to 20 μW at 100 GHz, and 2 μW at 1 THz. The Golay cell calibration was carried out at 104 GHz using a Gunn-diode oscillator, attenuators, and a separately-calibrated commercial waveguide (WR-10) thermal power head.

The signal-to-noise ratio of the spectrometer is illustrated in Figure 6 in which the top trace shows the detected power spectrum for a 1 foot path length in air with ~1 GHz frequency resolution and 1 s integration time on the lock-in amplifier. The bottom trace is the detected current when the THz beam is blocked, but the laser beams to both PCS devices are not. The signal is shown with (black) and without (gray) a 25-point smoothing function applied. The rapid variation in the unsmoothed signal amplitude vs frequency is expected, and is due to the phase-unbalanced interferometric configuration of the spectrometer. In future work, this signal will be processed to extract phase information from the interferogram. It is noted that the signal–to-noise ratio of ~80 dB*Hz obtained at 100 GHz is significantly higher than the experiment results, but is consistent with the theoretical predictions, of prior work [8]. The SNR improvement is attributed mostly to improved optical beam collimation and overlap in the integrated laser assembly, and improved optical and THz coupling of the present instrument, as suggested in Ref. 8. The dashed vertical lines mark the positions of the strongest water vapor absorptions.

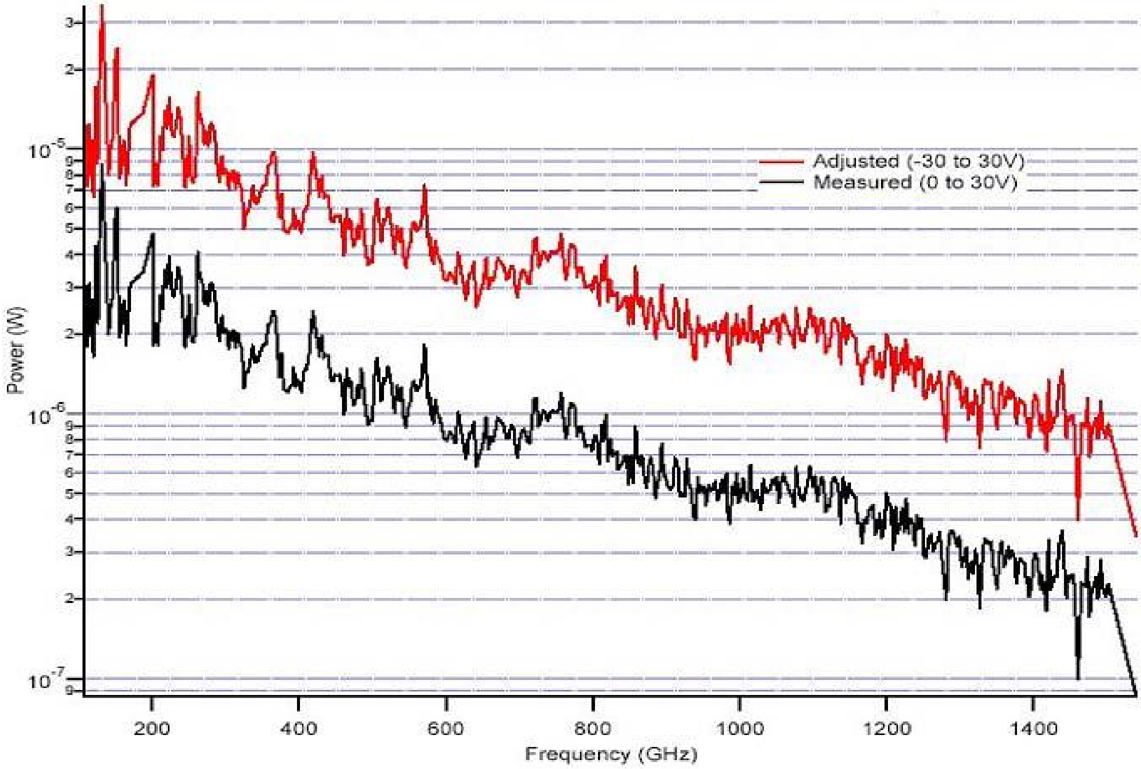

Figure 5. THz source power versus frequency, measured with calibrated Golay cell (lower) and calculated for actual system (upper).

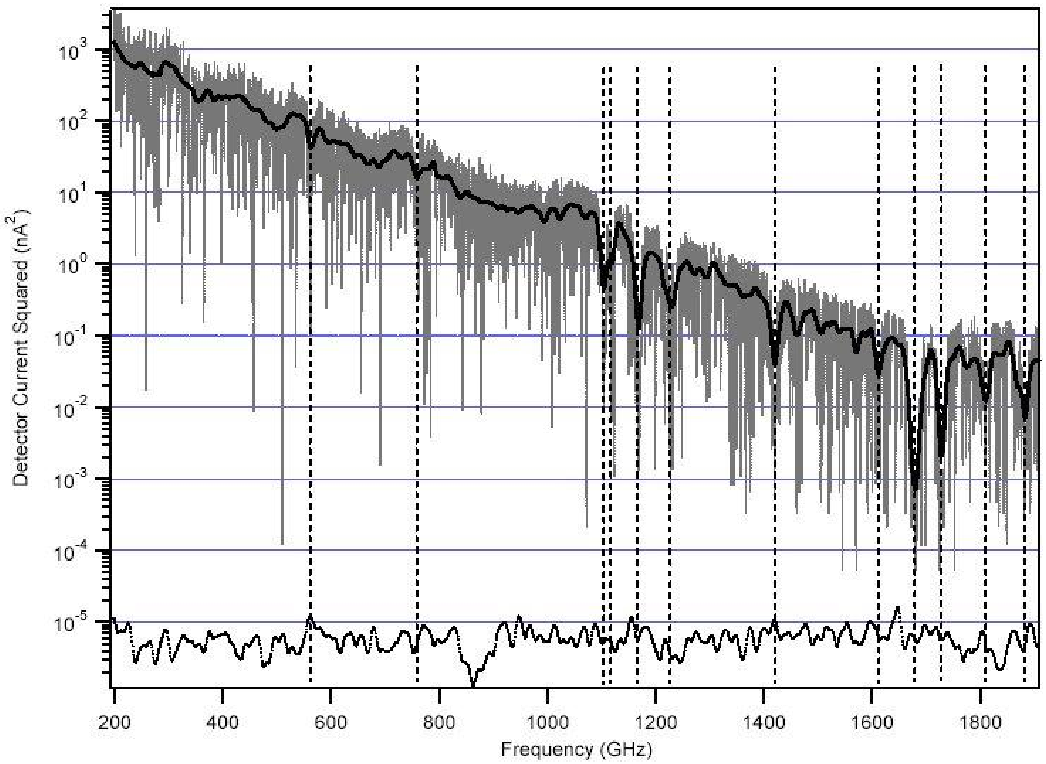

Figure 6. Spectrometer output vs. frequency. Upper: 1-foot path in air showing expected water vapor absorptions. Lower: noise floor of system with THz beam blocked. The dashed vertical lines indicate the frequencies of the stronger water vapor absorptions. The integration time was 1 s.

After system characterization the PB7100 was employed to characterize several different compounds. One of the first compounds measured was lactose monohydrate which is a solid with a very strong absorption at 535 GHz (Figure 7).

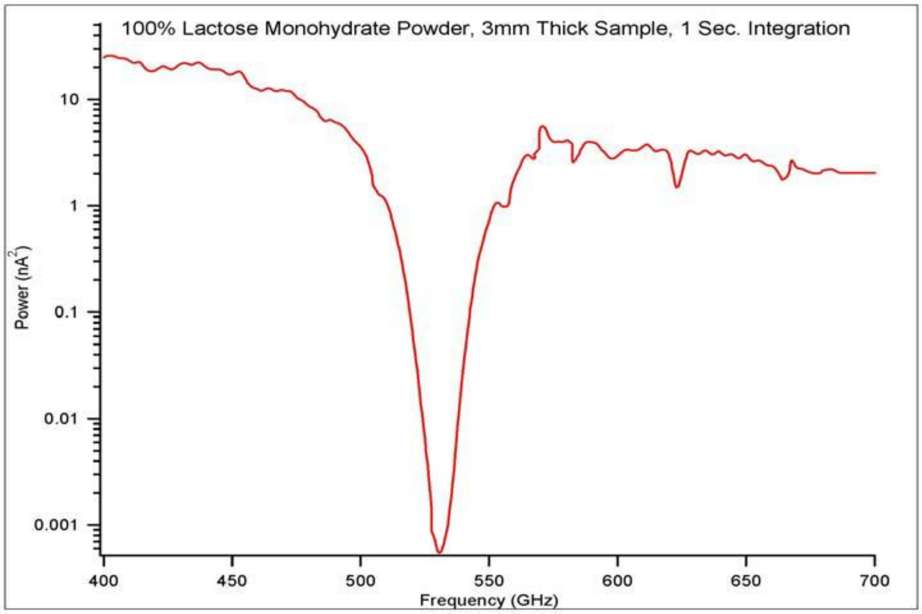

Figure 7. Lactose Monohydrate powder 3mm thick with a 1 sec. integration and 500 MHz resolution

The powder was prepared by placing it in the center of a large, metal, fender-washer and holding it in place with clear plastic adhesive tape on both sides. The data was collected with a 1 s integration time, a 500 MHz resolution and a 25 point running average was employed to remove the interference pattern. The five decade dynamic range of the PB7100 at these frequencies is clear. The measured full width half max of the absorption feature is difficult to determine on a logarithmic plot but is approximately 25 GHz which is similar to previously measured results [5].

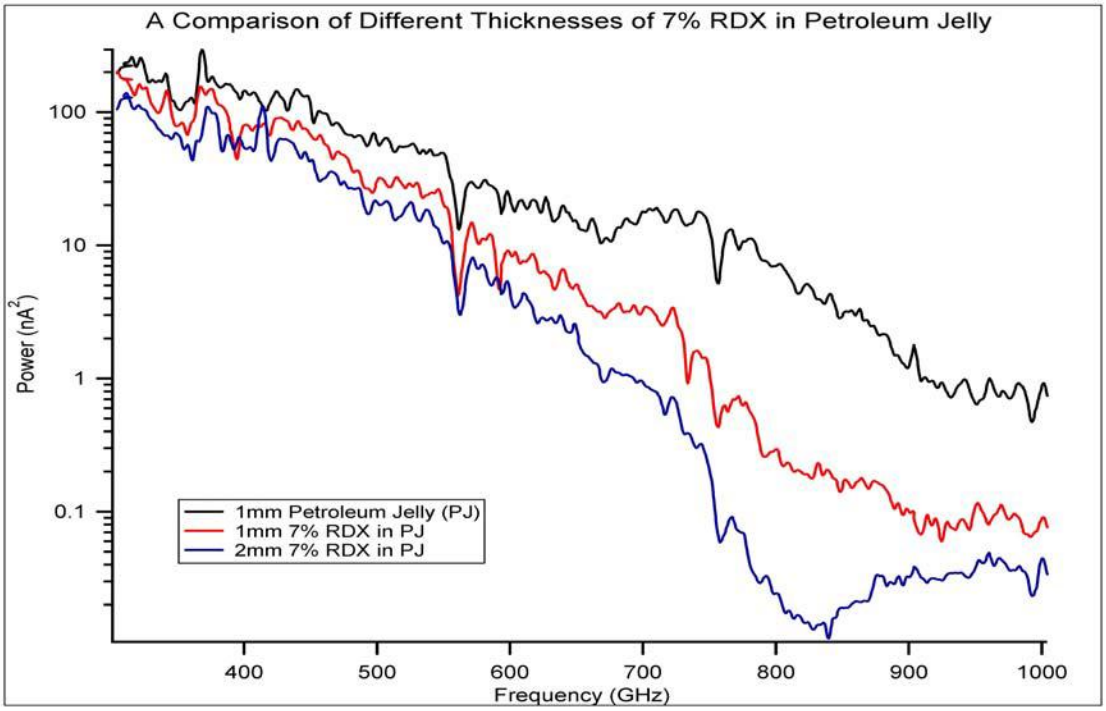

Figure 8. Different thicknesses of 7% RDX in petroleum Jelly as compared to pure petroleum jelly. A 1 s integration time was employed with a resolution of 1 GHz.

A key reason that there exists great interest in developing THz technology is for the potential application of explosives detection. RDX (cyclotrimethylenetrinitramine) is an extremely stable military grade explosive which has a very distinctive THz spectrum. It is available in a 7% mixture with petroleum jelly and is used as a canine training tool. This mixture was employed to map out the absorption of RDX as a function of the sample thickness. The spectrum illustrated in Figure 8 illustrates pure petroleum jelly as a control sample followed by a 1mm thick sample of the RDX mixture. Thickness was maintained and set by employing washers between the two polyethylene windows. While the characteristic 800GHz absorption that RDX displays may be seen in the 1 mm thick sample, it becomes much more dramatic with the 2mm thick sample.

Both the lactose monohydrate and the RDX are more readily available through standard shipping channels. However, it was the goal of this research to study pure samples of the following explosives: TNT (Tri-Nitro-Toluene), Dynamite, ANFO (Ammonium Nitrate Fuel Oil) and TATP (Tri-Acetone Tri-Peroxide). In order to study these significantly more dangerous compounds it was necessary to work with Normand J. Bergeron of the Bureau of A.T.F.E. in Nevada. We traveled to location where we set up two PB7100's: one vertical and the other horizontal (see photograph in Figure 9). This allowed the simultaneous measurement of both powders (vertical system) and solid materials (horizontal system).

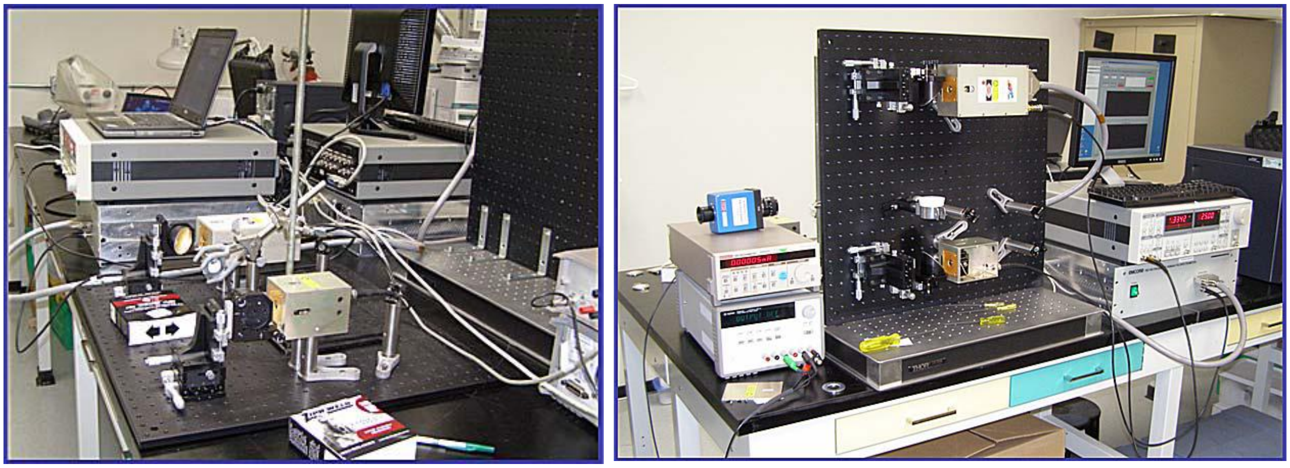

Figure 9. Pictures of the two PB7100s setup at A.T.F.E in Reno: one horizontally orientated and one vertically orientated.

A considerable amount of time was spent looking for THz signatures in the ANFO, the Dynamite and the TNT, but nothing significant was discovered in the frequency range of 200 GHz to 1.5THz. Measuring the pure form of the RDX resulted in data that wasn't significantly different than the RDX in petroleum jelly reported above. After studying these relatively stable compounds, TATP was measured. TATP is an unstable material at room temperature that exists in many different forms and is extremely sensitive to shock. A powder approximately 1 mm thick was measured with a 1 second time constant and a 500 MHz resolution. The results are illustrated in Figure 10. There is clearly a broad absorption at approximately 975 GHz as well as an asymmetric feature at 800 GHz. The narrower features in the valley of the 975 GHz absorption and above 1000 GHz are most likely due to reaching the noise level, but time constraints prevented further experimentation or an increased time constant to confirm.

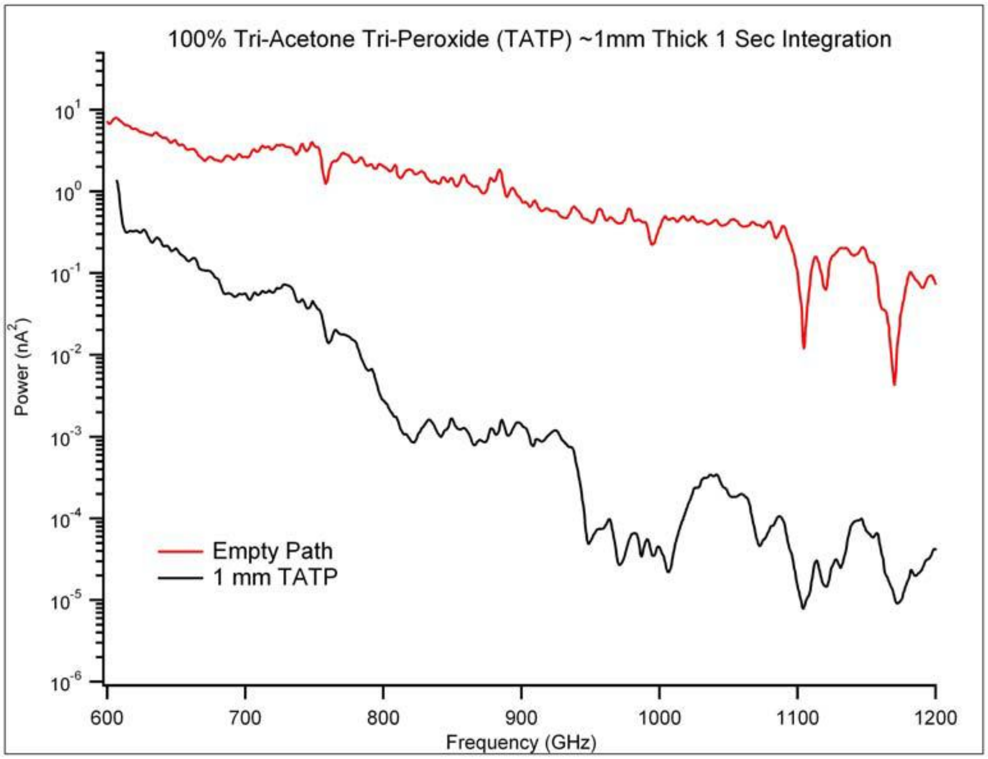

Figure 10. Room temperature, TATP powder approximately 1mm thick, a 1 s integration time, 500 MHz resolution.

4. SUMMARY

A compact frequency-domain terahertz coherent spectrometer with continuous mode-hop-free tuning was demonstrated from 200 GHz to 1.85 THz. The construction employs highly compact photonic integration techniques, electronic chopping, and room-temperature coherent detection. It is expected that the spectrometer will be useful for rapid identification of chemical, biological and explosive materials in solid-phase and gas-phase forms at standard atmospheric pressure. The highly integrated photonic assembly employing semiconductor diode lasers employs no moving parts and is inherently rugged. Also, the coherent (homodyne) detection technique provides excellent SNR in agreement with theory, with much faster data acquisition times and no cryogenic cooling as required by the LHe bolometers in more common (incoherent) THz photomixing spectrometers. After characterization, the spectrometer was employed to characterize lactose monohydrate, RDX, TNT, Dynamite, ANFO and TATP. Of these materials studied only the lactose monohydrate, RDX and TATP had measurable absorptions in the range of 200 GHz to 1.5 THz.

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