A High Signal-to-Noise Ratio, Coherent, Frequency-Domain THz Spectrometer Employed to Characterize Explosive Compounds

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***Abstract*—A compact terahertz frequency domain spectrometer realized through photo-mixing of two distributed feedback (DFB) diode lasers in ErAs:GaAs is shown to have a signal-to-noise ratio of 80 dB*Hz at 200 GHz and 60 dB*Hz at 1 THz. Continuous frequency sweeping is demonstrated with better than 1 GHz resolution from 200 GHz to 1.85 THz. The system is employed for the characterization of several explosives.**

I. INTRODUCTION AND BACKGROUND

There has been significant research into characterizing materials in the terahertz (THz) frequency range of the electromagnetic spectrum (100 GHz – 10,000 GHz). Interest in this portion of the electro-magnetic spectrum has developed for several reasons: THz radiation is eye safe and non-ionizing, so may be used around people; many explosive compounds have been shown to have strong and unique absorption features in the solid phase at THz frequencies; THz radiation can penetrate obscuring dielectric materials such as clothing, paper, cardboard and plastic; THz beams can, in principle, be used in a stand-off fashion to interrogate objects at short distances; and the short wavelengths allow high resolution imaging. Of particular interest to the authors was to develop an adaptable system that would be capable of hopping between frequency regions of interest, would have a resolution of 1 GHz or better, room temperature operation, and a clear and reasonable path to size reduction. While many different techniques for the production and detection of THz radiation exist, it was felt that only one technique had the potential to achieve these goals: photo-mixing with semiconductor lasers.

THz radiation may be produced and detected through a process of photo-mixing in an ErAs:GaAs photo-conductive switch (PCS) through one of two similar but significantly different techniques: time-domain or 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) [1-3]. 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 a resolution of 1 cm^{-1} or 30 GHz.

In the frequency-domain technique continuous-wave THz radiation is produced through photo-mixing 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 photo-mixing 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 second PCS (the detector) onto which the THz signal is also incident [4-6]. This provides greater sensitivity and faster data acquisition than the incoherent technique [7], 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, (3) the ability to selectively scan specific frequency regions of interest with adjustable resolution (i.e. frequency hopping), (4) the potential to highly integrate the inexpensive semi-conductor laser chips into an extremely small form factor package and (5) low current requirements that may allow battery operation. 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 beams [7] as well as precise control of their difference frequency.

II. SYSTEM DESCRIPTION

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 the frequency domain THz spectrometer is a highly-integrated dual semiconductor laser module that has been discussed in detail in prior work [8], but for completeness is briefly described here. This photonic module contains two distributed feedback (DFB) laser diode chips mounted on independent Peltier thermo-electric coolers (TECs), as well as a frequency metrology filter assembly. The wavelengths of the DFB lasers are nominally 783 nm at 25 °C, but may be

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temperature-tuned over 2.5 nm (1.25 THz) resulting in a difference frequency of over 2.0 THz.

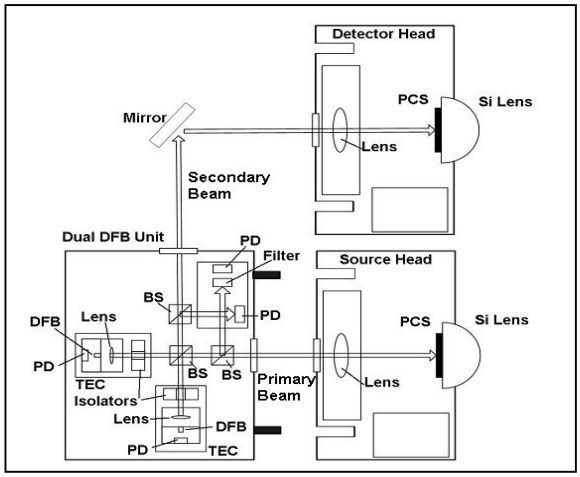

Figure 1: Block diagram illustrating components and layout of THz source unit containing lasers and frequency metrology filter assembly and the THz detector unit.

The output from each laser is collimated with an aspheric lens on a precision lens-mount with sub-micron adjustment capability [9-11]. A 50/50 beamsplitter is used to co-collimate the beams into primary and secondary beams at right angles to each other. Two 10% beamsplitters are then employed to direct a portion of each beam onto two photodiodes, one of which has an optical filter with a predetermined wavelength profile in the beam. The two DFB lasers are current-modulated at slightly different frequencies, which makes it possible to distinguish the individual power levels on the filtered and unfiltered photodiodes. The ratio from the filtered and unfiltered photodiode outputs is then calibrated and used for wavelength determination. The entire optical assembly, termed "Dual DFB Unit" in Figure 1, is contained within a hermetic 2" x 2" x 0.5" package [8].

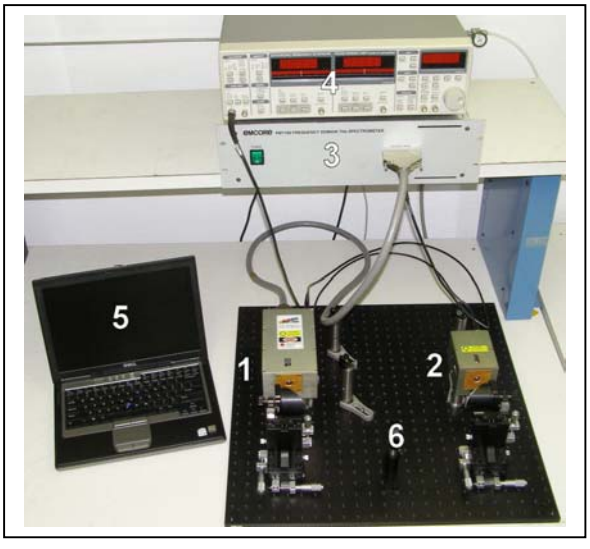

Figure 2 : an image of the entire system including: the THz source head (1), the THz detector head (2), the control electronics (3), the lock-in amplifier (4), the control and data acquisition computer (5) and a sample holder for solid samples (6).

The primary and secondary laser beams are focused onto a source PCS, in the THz source head, and a detector PCS, in the THz detector head (Figure 2). These heads are separated by approximately 1 foot and off-axis parabolic mirrors provide THz collimation (source) and focusing (detector). The sample under test is placed in the collimated beam between the two mirrors. Both the source and detector PCS devices are fabricated from ErAs:GaAs [12] with active regions that consist 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 [13]. A 75 KHz square wave at +/- 20V is applied to the source PCS while the detector PCS is unbiased and connected to a SR810 Lock-in amplifier. Both devices are mounted on Si hemispheres that partially collimate (focus) the THz radiation before (after) striking the off-axis mirrors.

III. RESULTS

After the system was built and characterized, the signal-to-noise ratio was measured (Figure 3). The top trace shows the detected power spectrum for a 1- foot path length in air with a 1 GHz frequency resolution and 1 s integration time. The bottom trace is the power spectrum with the THz beam is blocked. The signal is shown with (black) and without (gray) a 25-point smoothing function applied.

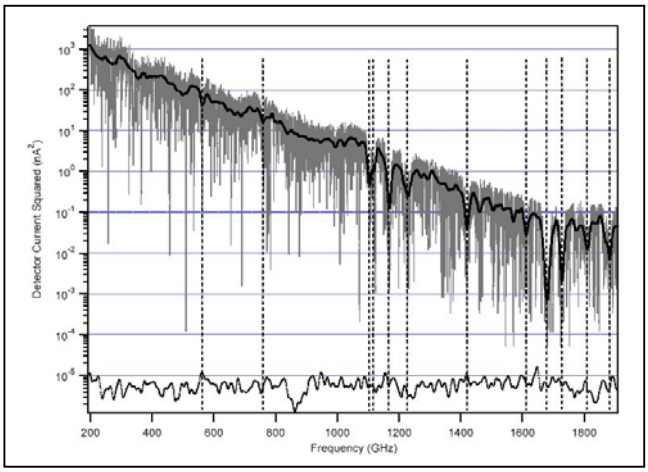

Figure 3 : Spectra of 1-foot path in air showing expected water vapor absorptions (top) and the noise floor of system with THz beam blocked (bottom). A 1 s integration time and 500 Mhz resolution was employed.

The rapid variation in the unsmoothed signal power versus frequency is expected, and is due an interferometric effect caused by the significantly different lengths of the laser-to-photo-mixer arms of the spectrometer. Smoothing removes this interferometric effect but also discards the phase information contained within. The signal–to-noise ratio of ~80 dB*Hz obtained at 200 GHz is consistent with the theoretical prediction of prior work [7]. The SNR improvement over prior work 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. [4]. The dashed vertical lines mark the

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positions of the strongest water vapor absorptions. The system clearly resolves the pressure broadened rotational transitions in water. The system was then employed to measure a sample of 7% RDX dissolved in petroleum jelly which had been sandwiched between two polyethylene windows in a simple holder (Figure 4). The plot illustrates no sample (top), 1 mm thick sample (middle) and a 2 mm thick sample (bottom). A very broad feature centered at 828 GHz, which is slightly higher than previously reported [14], was measured in the 2 mm sample.

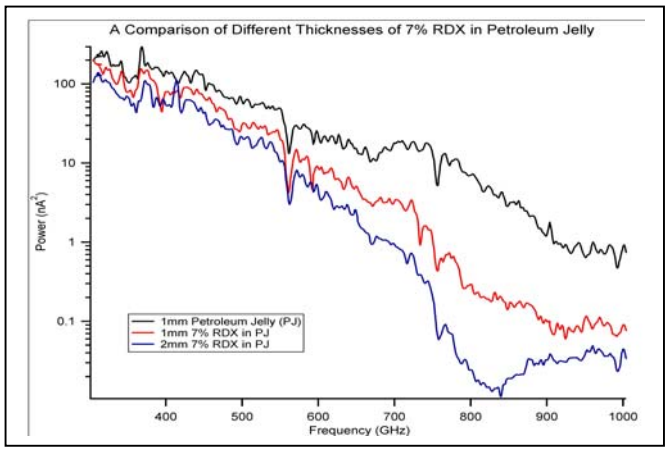

Figure 4 : Spectra of different thicknesses of 7% RDX in petroleum jelly as compared to pure petroleum jelly (top). A 1 s integration time was employed with a resolution of 1 GHz.

One of the challenges in measuring the THz characteristics of explosives is manufacturing, storing and handling the dangerous materials. For this reason, two of the described THz spectrometers were shipped to the Washoe County Crime Laboratory in Reno, Nevada. Here the authors had access to pure forms of several different explosives as well as the assistance of an explosive expert. Of particular interest was performing measurements on the highly volatile explosive tri-acetone tri-peroxide (TATP).

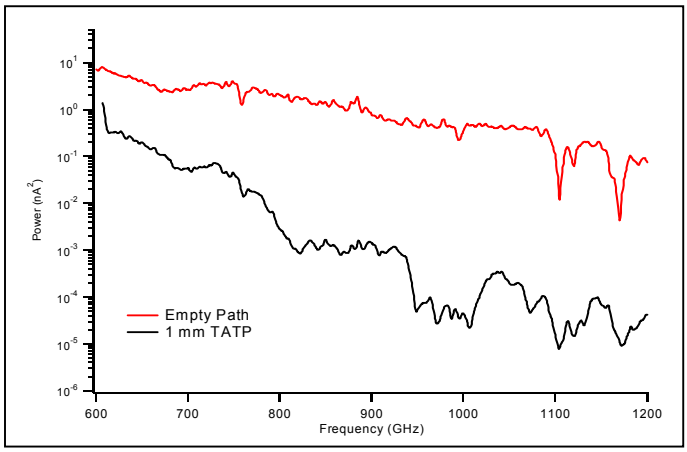

Figure 5 : Spectra of an approximately 1 mm thick sample of TATP (bottom) compared to the empty path (top). A 1 s integration time was employed with a resolution of 1 GHz.

The data recorded for thin granular TATP approximately 1 mm thick is displayed in Figure 5. The sample was very lossy across the entire frequency band. The mechanism of the loss was not explored, but is likely due to scattering. Two significant spectral features were recorded, one at 820 GHz and a second at 986 GHz. The features above 1100 GHz are of questionable significance due to their proximity to the noise floor. Measurements on pulverized pellets of ammonium nitrate and fuel oil (ANFO) and dynamite were also performed, but no discernable signatures were found in the frequency range of 200 GHz to 1.5 THz. Measurements performed on pure RDX resulted in a spectrum that was similar to that shown in Figure 4.

IV. SUMMARY

A compact frequency-domain terahertz coherent spectrometer with an SNR of 60 dB*Hz at 1 THz was employed to measure the absorption features of various explosive compounds between the frequency range of 200 GHz to 1.5 THz. Future work includes improvements to system architecture as well as repeating the experiments on an environmentally controlled sample of TATP.

REFERENCES

[1] J. Zhang, Y. Hong, S. Braunstein, and K. Shore, "Terahertz pulse generation and detection with LT-GaAs photoconductive antenna," IEE Proc.: Optoelectron **151**, 98 (2004).

[2] D. M. Mittleman, "Imaging and Sensing with Terahertz Radiation," AIP Conf. Proc. **760**, 25 (2005).

[3] Y.-C. Shen, P. F. Taday, D. A. Newnham, M. C. Kemp, and M. Pepper, "3D chemical mapping using terahertze pulsed imaging," Proc. SPIE **5727**, 24 (2005).

[4] I. S. Gregory, C. Baker, W. R. Tribe, I. V. Bradley, M. J. Evans, E. H. Linfield, A. G. Davies, and M. Missous, "Optimization of photomixers and antennas for continuous wave terahertz emission," IEEE J. Quantum Electron. **41**, 717 (2005).

[5] S. Verghese, K. A. McIntosh, and E. K. Duerr, "Generation and detection of THz waves with photomixers," Proc. SPIE **3828**, 118 (1999).

[6] S. Verghese, K. A. McIntosh, S. Calawa, W.F. Dinatale, E. K. Duerr, and K. A. Molvar, "Generation and detection of coherent terahertz waves using two photomixers," Appl. Phys. Lett. **73**, 3824 (1998).

[7] J. E. Bjarnason and E.R. Brown, "Sensitivity measurement and analysis of an ErAs:GaAs coherent photomixer transceiver," Appl. Phys. Lett., Vol. 87, 134105 (2005)

[8] J.R. Demers and R.T. Logan Jr, "A coherent frequency-domain THz spectrometer with a signal to noise ratio of 60 dB at 1 THz," Proc. SPIE Defense and Security, Orlando (2008).

[9] K.K. Wong, R.T. Logan Jr., "Advanced Photonic Hybrid Sub-Systems for Military and Space Applications," Proc. of European Optical Society, Paris (2006).

[10] J. R. Demers, et al, "Sub-micron adjustable mount for supporting a component and method," US Patent No. 7,075,028.

[11] J. R. Demers, et al, "Sub-micron adjustable mount for supporting a component and method," US Patent No. 7,126,078.

[12] J. E. Bjarnason, T. L. J. Chan, A. W. M. Lee, E. R. Brown, D. C. Driscoll, M. Hanson, A. C. Gossard, and R. E. Muller, "ErAs:GaAs photomixer with two-decade tunability and 12 μW peak output power," Appl. Phys. Lett. , vol. 85 (no 18), p. 3983 (2004).

[13] E.R. Brown, A.W.M. Lee, B.S. Navi, and J.E. Bjarnason, "Characterization of a Planar Self-Complementary Square-Spiral Antenna in the THz Region," Microwave and Optical Tech Lett, Vol. 48, No. 3, pp. 524-529 (2006).

[14] F. Huang, B Schulkin, H. Altan, J. F. Federici, D. Gary. R. Barat, D. Zimdars, M. Chen, and D. B. Tanner, "Terahertz study of 1,3,5-trinitro-s-triazine by time-domain and Fourier transform infrared spectroscopy," Appl. Phys. Lett., Vol 85, 5536 (2004).

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