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Terahertz Time-Domain Spectroscopy for Explosive Trace Detection

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Abstract *– This paper presents Terahertz time-domain spectroscopy for stand-off detection of explosive traces. Despite several well-developed explosive detection techniques available, the detection of a small amount of explosive traces is still challenging. Terahertz spectroscopy demonstrates potential for explosive detection through unique absorption spectra pattern of various kinds of explosive materials. Terahertz waves show good penetration through many dielectric materials that are visually opaque. These characteristics promise the effectiveness of Terahertz radiation in the detection of concealed explosives.*

Keywords *– Terahertz time-domain spectroscopy, Explosive trace detection, Absorption spectrum*

I. INTRODUCTION

Popular explosive detection techniques include X-ray imaging, nuclear detection, and infrared imaging. Despite the successes in detecting bulk explosives and related compounds, each method has its own limitations in detecting explosive traces. X-rays have been used to search for explosives and other contrabands in luggage and cargo containers, but with no spectroscopic fingerprints of explosives. Nuclear detection uses a neutron source to detect nitrogen-rich explosives. Neutrons are captured by nitrogen nuclei and emit γ-rays with a specific energy when penetrate explosives. However, X-rays and nuclear detection methods produce harmful ionizing radiation and have limitations in sensitivity. The thermal infrared energy emitted by explosives can be easily detected with relatively inexpensive infrared cameras. However, infrared imaging lacks specificity for explosives.

The Terahertz (THz) region of the electromagnetic spectrum (0.1–10 THz) offers an innovative sensing technique that provides information unavailable in other conventional methods [1][1]. THz radiation is more selective than X-ray, and sensitive to explosives. THz waves show good penetration through nonpolar dielectric materials that are opaque to visible or mid-infrared light. This characteristic enables THz technologies to inspect the insides of packaging materials, such as paper, textile, plastic, and wood. Low photon energies (one million times weaker than an X-ray photon) of THz waves will not cause harmful ionization, which are safe for both operators and targets. The advent of Terahertz time-domain spectroscopy (THz-TDS) [2] enables the investigation of the wavelength dependence of complex refractive index in dielectric materials. The application of near-infrared laser pulses with a duration of less than 100 fs (femtosecond; 10^{-15} sec) to a semiconductor optical switching device generates a Terahertz light pulse flashing for only a short period of time in the order of picosecond (10^{-12} sec). THz-TDS directly measures the change in the electric field intensity of the pulses over time when the generated pulses are transmitted through or reflected by the sample.

THz spectroscopy of explosives and other related compounds have been investigated with THz-TDS for potential homeland defense and security applications. Early studies validated THz spectral features of common explosives [3][4][5][6]. This paper presents a stand-off detection of low-density explosive traces using THz-TDS. Three typical explosive types are examined: PETN, RDX, and TNT. PETN is a powerful explosive sensitive to shock or friction with 140% more power than TNT. RDX is a white crystalline solid usually used in mixtures with other explosives, oils, or waxes. RDX has a high degree of stability in storage and is the main ingredient in plastic-bonded explosives such as C-4. TNT is a popular explosive unaffected by ordinary shocks and must be set off by a detonator, which is favored for munitions and construction. THz absorption spectra demonstrate the potential of THz-TDS for the detection of low-density explosive traces as well as bulk explosives.

II. THZ TIME-DOMAIN SPECTROSCOPY

A. Experiment Setup

A THz-TDS system is developed to observe spectral characteristics of explosive trace samples. The THz-TDS setup consists of a laser excitation source for activation, scanning delay stage, THz wave transmitter and a photo detector. Figure 1 shows optical layout of the THz-TDS system used in this experiment. The laser source is a compact mode-locked fiber laser (IRMA femtolite 780) that emits laser pulses with center wavelength of 780 nm, pulse duration of 100 fs, and a maximum power of 25 mW. The laser light is split into a pump and a probe beam to actuate the THz emitter and detector. The pump beam is delayed by a mechanical translation stage and then focused on a THz emitter. A motorized delay stage (Newport ESP-300) adjusts the mirror position to change the optical path length and therefore the amount of time for the pump beam to reach the THz emitter. A biased photoconductive GaAs antenna generates THz pulses when excited by pump laser beam. The emitted THz beam is collimated and focused on the sample by a pair of off-axis parabolic mirrors. The focused beam size on the sample is approximately 2 mm. Using another pair of parabolic mirrors, THz beam is collimated and focused onto a ZnTe crystal. The THz detector measures the electric field intensity of the THz light pulse in the instant when the probe light flashes. The polarization changes of the probe beam modulated by THz field are probed with photodiodes and input into a lock-in amplifier. A LabVIEW program with GPIB communications is used to control the scanning of the translation stage, and the signal acquisition of lock-in amplifier to measure the THz waveforms.

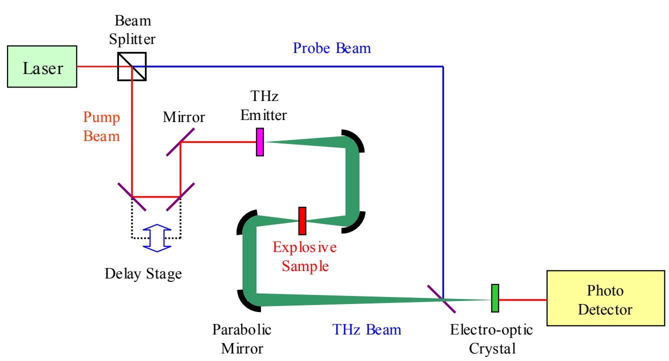

Figure 1: Optical layout of a THz time-domain spectroscopy system for explosive trace detection

B. THz-TDS Signal Acquisition

THz-TDS is tested as a potential sensing modality for explosives trace detection. Trace samples of typical explosives of PETN, RDX, and TNT are obtained. The samples for THz-TDS measurements were prepared by applying a small amount of solutions on polyethylene film substrates. Though visibly opaque, polyethylene is almost transparent in the THz band. The THz spectrum with a useful bandwidth of 0-3.0 THz is obtained by applying a Fourier transform on the THz waveform. Figure 2 shows THz waveforms and the corresponding Fourier spectra of free air at room temperature and the humidity of 59%. A strong water vapor absorption in ambient air at 1.1 – 1.2 THz is clearly visible in the THz spectrum.

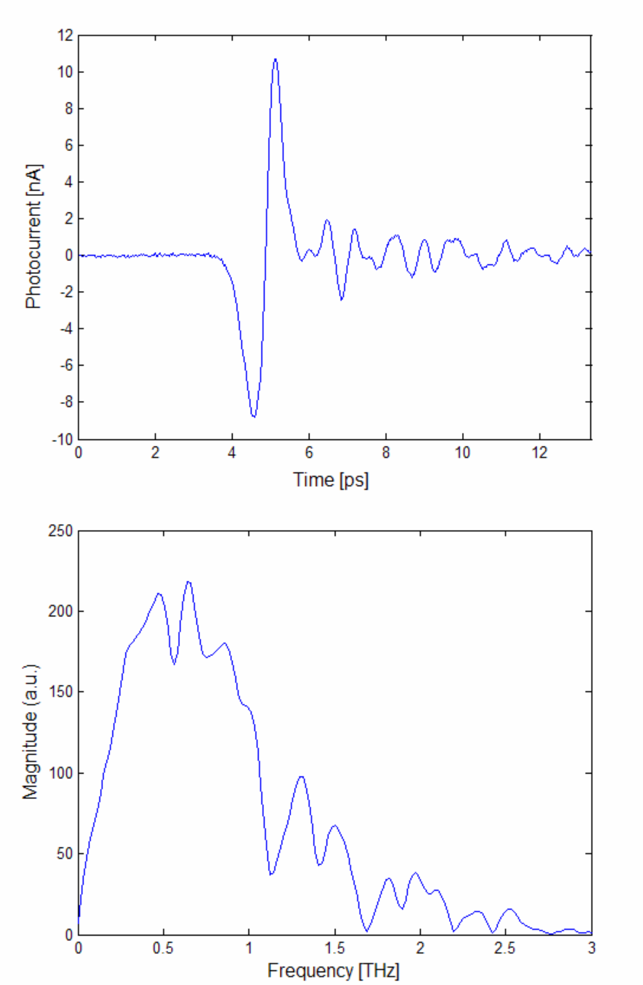

Figure 2: Time waveform and Fourier magnitude spectra of the free background air at room temperature and humidity

III. SPECTRAL SIGNATURE FOR EXPLOSIVE TRACE DETECTION

Terahertz absorption spectra are tested for two types of explosive samples: solid surrogate explosives and low-density explosive traces. Solid samples of Dinitrotoluen (DNT) and dinitrobutane (DNB) are used as surrogate explosive samples. The samples are prepared in the form of circular pellet of 1 inch diameter and thicknesses of 2.98 mm (DNT) and 1.52 mm (DNB). Figure 3 shows THz waveforms of air background, DNT, and DNB pellets. The signals are delayed and attenuated after they penetrate the solid samples. The bottom graph shows absorption spectra of DNT and DNB with an offset to visualize the two spectra. The two surrogate explosive samples can be characterized by the peaks at different locations in the absorption spectra.

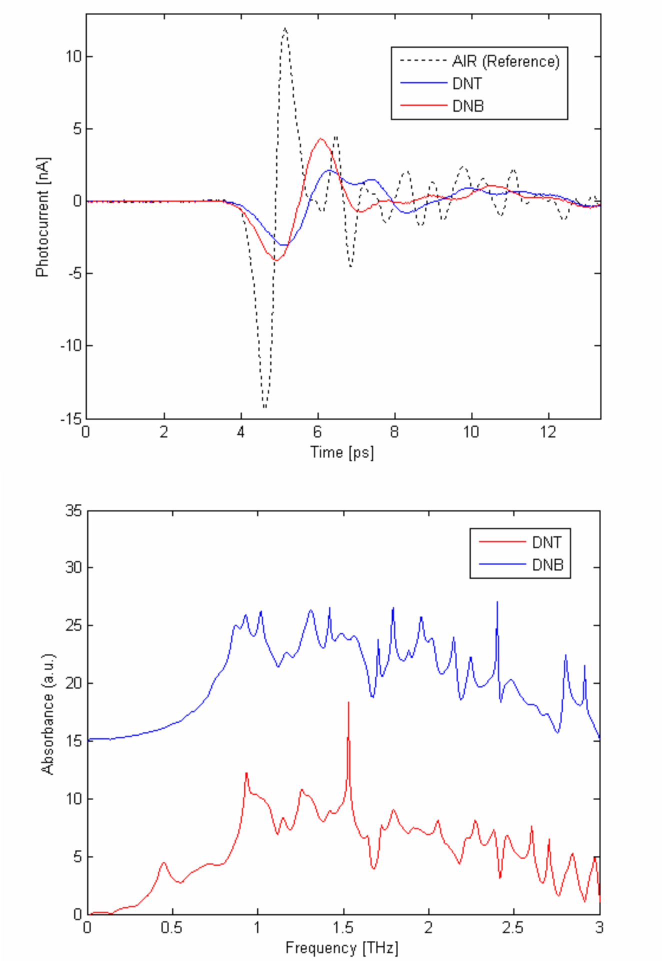

Figure 3: Time waveform and Fourier magnitude spectra of the free background air at room temperature and humidity

While solid surrogate explosive samples clearly demonstrate the existence of unique spectral peaks that can be used to characterize the materials, the detection of explosive traces are quite challenging especially for low-density samples. The explosive trace samples were prepared by painting low-density explosive solution on polyethylene film substrate. Solution concentrations are 0.08 g/mL (PETN), 0.09 g/mL (RDX), and 0.06 g/mL (2,4-TNT), which correspond to estimated mass of analyte deposited of 0.0008 g, 0.0009 g, and 0.0016 g. The analytes are not evenly distributed on the substrate due to its addition as solvent. A ring effect is observed so the outer edges are more dense than the inner portion.

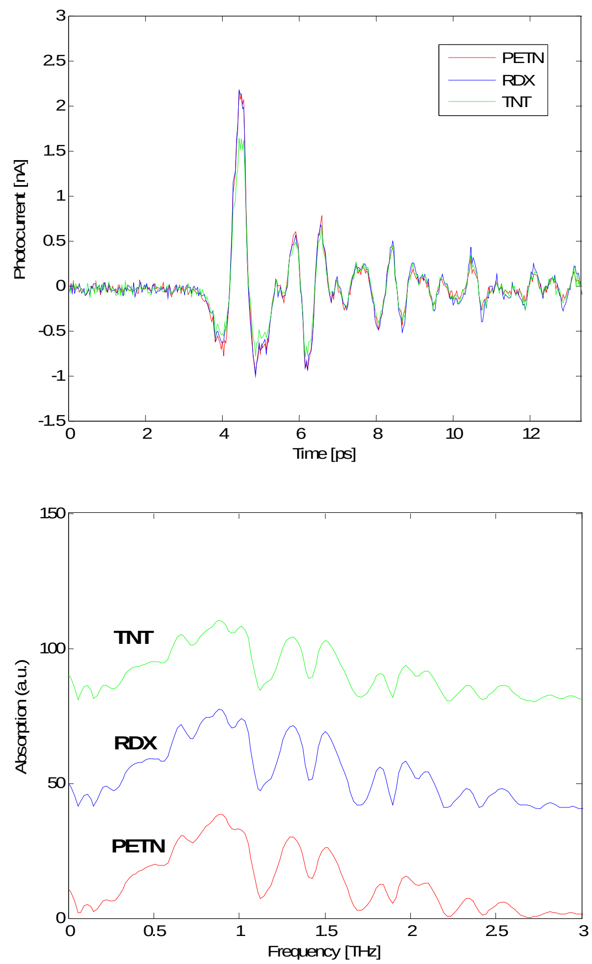

Figure 4: THz absorption spectra of the trace of selected explosive samples DNMB, PETN, RDX, and TNT in the 0 – 3.0 THz range obtained with THz-TDS. The spectra were vertically offset for display purposes.

Figure 4 shows the difference signal between the background air and the explosive trace samples. The absorption spectra were obtained from transmission measurements of the samples. The experiments were conducted at room temperature and humidity of 59%. The spectral signatures in the range of 0.1-3.0 THz are significant for inspecting hidden explosives since THz waves in this range show high penetration through commonly used nonpolar dielectric materials, which are opaque for visible and infrared light or exhibit low contrast to X-rays. This makes THz spectroscopy a unique technique for sensing hidden explosives behind various dielectric materials. Particularly, the spectral characteristics in the range below 1.5 THz are desired for the standoff explosives detection due to the relative low atmospheric attenuation in this range.

IV. CONCLUSION

This paper presents a Terahertz time-domain spectroscopy technique for the detection of low-density explosive traces. The THz technology has advantages in detecting hidden explosives in that explosives show unique THz fingerprints in the range of 0.1-3.0 THz. The absorption peaks in the THz band are generally many times lower than those in the mid-infrared range, resulting in a relatively low sensitivity for THz sensing. However, this is shadowed by the fact that THz waves have much higher penetration for many nonpolar dielectric materials than visible or infrared waves, which is critical to sense hidden explosives behind covers or inside packages. Signal processing technique is required to enhance the absorption peaks in the range of 0.3-1.0 THz in order to detect low-density explosive traces.

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