F2-C: THz Imager and Science of Broadband THz Wave Photonics

Abstract— In the year 5 research and development phase we continued working on a THz imager (THz shoe scanner) as well as the fundamental science of THz wave air photonics. We report on our progress on both aspects of the project. Our notable achievements are: 1) We tested the imaging capability of a THz wave imaging system by making images of different types of shoes, and our results show that a THz wave imager is a very good fit for security applications; 2) we demonstrated THz REEF detection in the counter-propagation configuration, and found it to be more useful for real-world applications [1,2].

I. PARTICIPANTS

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II. PROJECT OVERVIEW AND SIGNIFICANCE

Development of a real-time, compact, and cost-effective THz-wave device for imaging of explosive threats in public areas such as airports is among the top priorities of the DHS-ALERT program. Compared to other imagers at different wavelength ranges such as X-ray, infrared, and microwave imagers, the THz imager has some unique features such as low photon energy of the radiation source (non-ionizing radiation and hence no health concerns), sufficient spatial image resolution (higher than microwave imaging), and spectroscopic capability for potential explosive detection applications in security checkpoints at airports.

In the past year (Year 5), we came up with a new design of a THz imaging system with fast scanning rates for real-world applications (Figure 1). Our THz shoe scanner addresses the shortcomings of most existing imaging systems. As shown in the figure, the THz imaging system incorporates a continuous wave (CW) system and a time-domain spectroscopic system (TDS). The CW system will obtain imaging data related to the internal structure of the shoe, while the TDS will be used to sample suspicious points looking for signatures
of explosives. The scanner system will scan a single shoe area, which we estimate to be about 15” (380 mm) long and 6” (150 mm) wide. The time to acquire an image will be between 2 seconds (at 5 mm2 pixel size) and 20 seconds (at 1 mm2 pixel size). In Year 4 of the ALERT program, we focused on the design and testing of the fast scanning CW imaging system, the key component of the system, as shown in Fig. 1. In Year 5, we ran more detailed tests of different design scenarios and tested imaging capabilities of a CW THz system (shoe scanner) for imaging of different types of shoes.

In addition to the shoe scanning work, we are continuing to refine our understanding of the underlying science of THz-wave photonics using air and other gases as THz-wave emitters and sensors to advance the technology of detecting concealed items at standoff distances. Air-plasma THz wave generation is intriguing for its ability to generate high peak THz electric fields, currently reaching strengths over 2.0 MV/cm. For comparison, the peak THz field generated by the synchrotron at Brookhaven National Laboratory is ~ 750 KV/cm. THz air photonics provides a feasible approach for standoff detection. We demonstrated the feasibility of standoff THz-wave generation at a distance of 116 m in 2009. We also demonstrated true standoff THz-wave generation at a distance of 30 m. In order to realize the ultimate goal for remote sensing and identification of explosives, both THz wave generation and detection at standoff distances are necessary. During the past two years, detailed investigation of the physics behind THz air photonics revealed that interaction between intense THz waves and laser-induced air plasma not only results in second-harmonic generation, which has been utilized for the detection of broadband THz waves with laser-induced gas plasma, but also enhances the fluorescence emission in the plasma. We call this technique THz-radiation-enhanced emission of fluorescence (THz-REEF). By monitoring the change in fluorescence caused by THz radiation, THz-REEF can be used for THz-wave sensing. To make THz air photonics more practical for standoff detection, we have recently demonstrated an alternative innovative approach for coherent THz-wave detection utilizing THz-enhanced-acoustics (TEA). More recently, in collaboration with the Laser Plasma Laboratory at University of Central Florida, we demonstrated broadband THz detection (THz-REEF) in counter-propagating scheme using intensified CCD (iCCD) camera, which more closely replicates real-world stand-off THz sensing scenarios. Spatially-resolved variations in the plasma was recorded for the first time using an iCCD camera, allowing the temporal waveform of the THz field to be measured in the counter-propagating geometry without the need for a probe delay sweep. This new THz wave detection scenario is one more step closer to the DHS applications for remote THz wave sensing.

![Figure 1: A THz shoe scanner that combines both fast scanning CW imaging system for real-time THz imaging of a shoe and a THz time-domain spectroscopy system (TDS) for spectroscopic information of the shoe and its context.](image)

### III. RESEARCH AND EDUCATION ACTIVITY

#### A. State-of-the-Art and Technical Approach

**New design of a fast scanning CW THz imager incorporated with two galvanometers and gunn diode THz wave emitter (The design has been reported last year)**

Instead of using conventional 2D translation stages for raster scanning of the target, in the new design we use two galvanometers for 2D scanning, which reduces the scanning time from 0.5 frames per minute to 1 frame per second. In this design, a new geometry is used to collect the reflected or scattered THz radiation from the target. The THz radiation source with our initial design is a Gunn diode THz wave emitter. In future
tests, other THz wave sources may be used for the feasibility verification. Moreover, recent experimental test indicates that, in order to get high scanning resolution CW THz sources with high beam quality that can be focused to form a smaller spot are required. Since the beam quality of the THz radiation from Gunn diodes limits the resolution of THz imager to more than 5 mm we proposed to use some photonic crystal structures/ waveguides to generate high-brightness THz waves, with high beam quality, using compact laser sources working at visible or near-infrared region.

**Fast image acquisition using line- or ring-shape scanning**

In order to increase the scanning rate for real-time imaging, we designed line- and ring-shaped scanners. Fig. 2 shows the scanning patterns with visible optical beams using line- and circular scanners. Figs. 2 (a) and (b) show the line- and ring-shape scanners, respectively, using He-Ne laser as the visible radiation for demonstration purpose.

![Figure 2: Imaging with different scanning patterns (red). (a) Line shape scanner; (b) Ring shape scanner (red)](image)

**B. Major Contributions**

**Imaging of a variety of shoes and other objects with a THz shoe scanner**

Using a 0.3-THz radiation source with high beam quality and reflection geometry, we have recently been able to image different types of shoes and some other objects using a THz shoe scanner. The resolution is better than 2 mm. Figures 3-5 on the following pages show the testing results using the CW THz source working at 0.3 THz (wavelength is 3 mm), in comparison with those corresponding optical images.

**Publications and Patents (see section VII)**

We have published 8 papers (including one submitted to Physical Review Letters) on Physical Review Letters, Applied Physics Letters, Optics Letters, IEEE Transactions on Terahertz Science and Technology, and Chemical Physical Letters etc during year 5 research and development supported by ALERT program.

**Education and outreach**

Starting in 2009, our group has developed strong ties with Prof. Willie Rockward at Morehouse College. We are currently assisting him in starting a THz research program at this minority-serving institution. Furthermore, in year 4 we have had two undergraduate students from the University of Rochester participate in the design and testing of the THz shoe scanner. The students (Gavin Perrella and Garrett West) gave a presentation on their design work for the THz shoe scanner at the Institute of Optics.

Benjamin Clough, an ALERT Center of Excellence doctoral student at RPI, has developed a novel method for decoding terahertz information hidden in invisible plasma acoustic bursts. For this work he was awarded the 2011 Lemelson-MIT Rensselaer Student Prize, one of four Lemelson-MIT Student Prize winners nationwide.
Figure 3: Image of a pair of man's leather shoes using a THz shoe scanner with a THz source working at 0.3 THz. (a) Optical image of leather shoes (top view); (b) THz image of the shoes shown in (a) using CW THz radiation (top view). The resolution is higher than 2 mm; (c) Optical image of leather shoes (bottom view); (d) THz image of the shoes (bottom view); (e) Optical image of leather shoes (side view); (f) THz image of the shoes (side view).

Figure 4: Image of a pair of shoes with a stainless steel ruler and a small knife inside using a THz shoe scanner with a THz source working at 0.3 THz. (a) Optical image of the shoes from top view; (b) CW THz image of the shoes shown in (a); (c) Optical image of the shoes from bottom view; (d) CW THz image of the shoes (bottom view). We can clearly see the stainless steel ruler and the small knife from the THz images (both top view and bottom view). However, the rule and knife cannot be seen from the optical images.
IV. FUTURE PLANS

In the future, we will continue to work on the development of the THz shoe scanner device for real-time imaging of explosives threats. The following are our plans in the following years.

1. Develop a compact CW THz sources using THz wave photonic devices with high beam quality using CW or quasi-CW compact laser as the excitation. The purpose is to use replace the Gunn diode THz source which has very low beam quality.

2. Improve the spatial resolution of the THz shoe scanner from ~1 cm to less than 4 mm by using the above THz source with higher frequency and better THz beam quality.

3. Improve the imaging data acquisition speed.

4. We will use a new opto-mechanical design for the focusing of the THz beam that incorporates a faster galvanometer scanner to further increase the scanning rate.

5. Increase the sensitivity and signal-to-noise ratio (SNR) from ~10 dB to more than 30 dB by using heterodyne detection of THz waves.

6. Prototype the design of the integrated THz shoe scanner with the proposed new CW THz source. The design itself needs more funding support.

7. Continue research on the science of broadband THz-wave photonics.

8. We will continue to improve the THz wave emission efficiency from laser-induced gas plasma and look into the possibility for using the THz radiation from the air-plasma as a THz radiation source of a THz imager (or shoe scanner). We will also continue research on coherent control of polarization of THz radiation from a laser-induced gas plasma, either by applying a helical electrical field along the plasma region or by using a phase compensator incorporated with a THz prism which can be used to convert a linearly polarized THz beam to a circular polarized beam.

We continue to team up with Dr. Rockward and engage in undergraduate student education and training. We will also work with Prof. Julie Bentley at the University of Rochester to train undergraduate students on THz optical design and testing of different scanner schemes. We will also continue to help other research and education groups establish and improve the THz technology lab at different institutes by helping them address...
their technological needs, and advising them on future experiments.

V. RELEVANCE AND TRANSITION

In Years 1-4, we focused on the science of THz-wave air photonics, which is the foundation for the application of this technology to homeland security needs. In Years 4-5, we put a major focus on the THz imager (THz shoe scanner) for real-time THz wave imaging of explosive threats, which will potentially become a commercial product for homeland security customers. The fundamental research on THz-wave air photonics could provide alternative THz-wave sources, new detection techniques, and guidelines in designing new THz-wave imaging or identification devices. In addition, our recent work with an NEC THz camera resulted in images of the THz beam generated from laser-induced gas plasma, which was not previously possible. This new camera shows great potential for the development of new THz-wave imaging techniques with intense plasma THz radiation sources.

VI. LEVERAGING OF RESOURCES

Other funded projects that support our research and development of THz science and technology in the Center for Terahertz Research include:

1. DTRA project: This project partially supports the research on THz-wave air photonics and THz-wave nonlinear spectroscopy;
2. NSF project: Supports student training on THz science and technology.

VII. PROJECT DOCUMENTATION AND DELIVERABLES

A. Peer Reviewed Archival Publications


B. **Peer Reviewed Conference Proceedings**


2. Khan Lim, Magali Durand, Xuan Sun, Fabrizio Buccheri, Matthew Weidman, Bruno Bousquet, Matthieu Baudelet, Xi-Cheng Zhang, and Martin Richardson, “Broadband THz detection in the counter-propagating configuration using THz-enhanced plasma fluorescence”, Nonlinear THz Technology (CM4J), 2012.

C. **Other Presentations**

a. **Seminars**


4. Jing Zhang, Albert Redo-Sanchez, and X.-C. Zhang, “THz Polarization-Dependent Imaging of Nuclear Graphite”, FTu3A8, Frontier in Optics (FiO) 2012, Rochester, New York, USA.

5. X.-C. Zhang, “THz wave air photonics, covering the gap and beyond”, National Chiao Tung University, Tsinchu, Taiwan, March 25, 2013.


8. X.-C. Zhang, “Next rays? T-ray!” Tin Ka Pin lecture, National Chiao Tung University, Tsinchu, Taiwan, March 27, 2013.


b. **Workshops**


c. **Short Courses**


d. **Other (poster presentations)**

2. Preliminary Imaging Tests at THz Frequencies, Craig. W. McMurtry, Judith L. Pipher, Mark V. Bocko, Zeljko Ignjatovic, Jianming Dai, Xi-Cheng Zhang, University Technology Showcase. CEIS(Center for Emerging and Innovative Sciences), Tuesday March 26, 2013.

3. F. Buccheri, B. Shulkin, J. James, T. Tongue, X.-C. Zhang, "THz-ABCD: a spectrometer covering the THz gap", University Technology Showcase. CEIS(Center for Emerging and Innovative Sciences), Tuesday March 26, 2013.

4. Jing Zhang, Brian Schulkin, J, James, Thomas Tongue and X.-C. Zhang, "THz Shoe Scanner", University Technology Showcase. CEIS(Center for Emerging and Innovative Sciences), Tuesday March 26, 2013.


VIII. REFERENCES

