Directions in TeraHertz Technology

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Abstract–**The term 'T-rays' was coined in the early 1990's by Bell Labs to describe the spectrum in the TeraHertz range (1 THz= 10^{12} Hz). The THz region of the spectrum lies on the border of where electronics and optics meet, between the mm-wave and infrared bands. Infrared sources become very dim as we approach the THz region and high speed devices struggle to reach these frequencies. Consequently, practical 0.1 THz to 20 THz sources were difficult to obtain until recent developments in laser, quantum well and compound semiconductor technology in the 1990's. Historically, we know that each time a new band in the electromagnetic spectrum opens up, a whole new industry develops and revolves around that band.**

I. Introduction

This paper reviews the techniques used for THz emission and detection. Application areas and use of compound semiconductor devices are highlighted. Results are shown from the Australian THz program [1], in collaboration with RPI, New York, where T-ray images are achieved using 100 fs pulsed THz waveforms with an average source power of 1 W and a signal bandwidth approaching 3 THz. Developments to improve pulse duration from 100 fs to 10-20 fs will be described which will allow greater bandwidths and increase the peak power by approximately five times. Impulse techniques have several advantages over single frequency methods including interfering background signal elimination and simultaneous acquisition of many frequencies.

The hot application for T-rays is in the area of non-invasive detection and diagnostics. The key feature is that water, many polar liquids (eg. solvents), organic substances and most gases have very strong absorption lines in the THz range. This is due to these molecules having their characteristic rotational and stretching resonances in the TeraHertz region [2, 3]. T-ray detection usually employs a coherent technique, which implies that as both amplitude and phase can be determined, different substances can be identified from details of the distorted pulse 'signature' after it has been passed through or reflected off a sample. T-rays are thus of critical importance in the spectroscopy of condensed matter systems, trace gas analysis etc. A range of important applications, from quality control of plastics to drug detection, become possible with greater detection sensitivity than previously possible.

On the other hand, non-polar, dry, non metallic materials such as plastics, paper and cardboard are transparent to T-rays. This suggests the possibility that T-rays can be used in the quality control of food through a sealed non-metallic package or wrapper. The ability of T-rays to 'see through' things, suggests that it could replace X-rays for some applications. X-rays are an ionizing radiation (hence cancerous),

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invasive. This property also makes T-rays useful for IC inspection through the plastic packing. This paper will include results that demonstrate images non invasively obtained through paper packaging at submillimeter resolution.

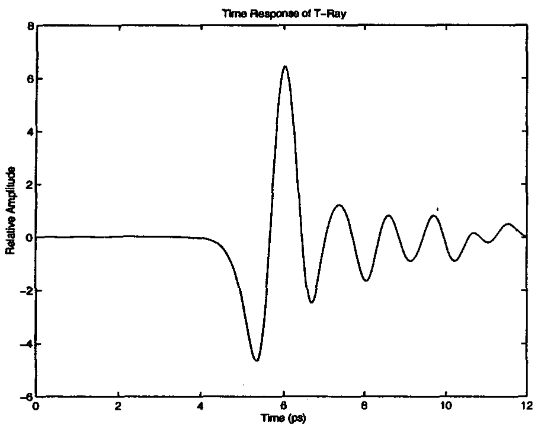

Figure 1: Time domain detected broadband pulse after transmission of terahertz pulse through a fresh leaf. Pulse incident on the leaf had 100 fs duration, 86 MHz repetition rate, 1 W average power and about 110 kW peak power.

Another application for T-rays is in biomedical imaging. As it is a coherent technique, both image and spectroscopic diagnostic information can be simultaneously obtained. Another key point here is that visible imaging is limited by Rayleigh scattering proportional to λ^{-4}, which attenuates and smears the image. On the other hand, microwave imaging operates at longer wavelengths, such that Rayleigh scattering is negligible, but is then limited to resolutions of the order of 1 cm. THz lies between these two extremes and thus offers the ideal trade-off for, say, the imaging of soft tissue [4].

The downside to T-rays is also the upside, depending on your viewpoint. The strong absorption by polar molecules makes T-ray spectroscopy very sensitive to those substances. However, it also means the its penetration through the earth's atmosphere and soft tissue is poor. Hence for soft tissue, the main application would be in the diagnostics of skin cancers and other disorders – this surface regime is precisely where X-rays have their poorest performance – hence the niche for T-rays. Poor penetration through the earth's atmosphere is both a curse and a blessing. It means that although this band is useless for terrestrial communications, the hot application becomes in creating wide bandwidth intersatellite communication channels that are secure from terrestrial eavesdropping. Accordingly THz is one of DARPA's core technology areas where the goal is to develop 0.3 THz to 10 THz solid-state sources and detectors for wide bandwidth intersatellite communications. Michigan, for example, have successfully demonstrated i-InAlAs /i-InGaAs/n+InGaAs grown on SI InP at the low end of this THz band.

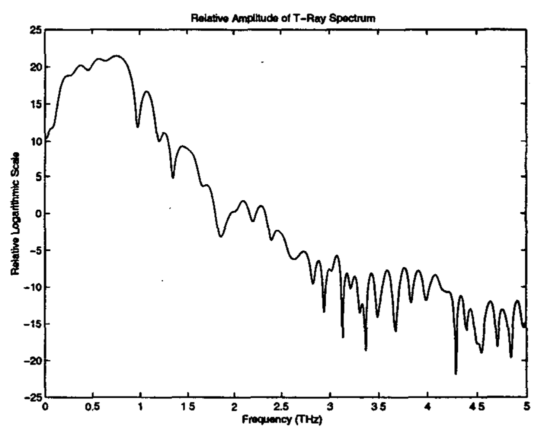

Figure 2: Frequency spectrum for same case as in the previous figure, illustrating performance approaching 3 THz.

II. Techniques

T-ray imaging is based on optoelectronic TeraHertz time-domain spectroscopy (TDS). The idea of T-ray imaging is to combine spectroadvanced signal processing, so that each pixel of the image contains spectroscopic information about the object. A typical T-ray imaging system usually consists of the following main elements: (a) a femtosecond optical pulse source (b) an optically gated transmitter of THz transients with broad spectral bandwidth (c) an imaging system consisting of lenses and/or mirrors (d) an object under investigation (e) a time-gated detector (f) a scanned mirror that introduces an optical path delay between the femtosecond gating pulses on the THz transmitter and detector (g) a computer to process the time domain data (h) a display to view the image.

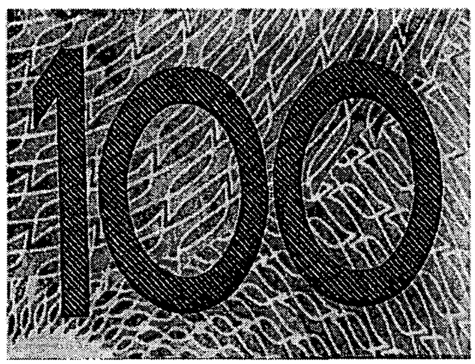

Figure 3: A feature from $100 Australian banknote (plastic) – the original. The horizontal dimension is about 40mm.

This pump/probe type configuration uses the scanned mirror to vary the optical path between the pump and probe pulses – this enables the extraction of phase as well as amplitude information. After data acquisition of the THz waveforms on a computer, both with the object in place and the object removed (reference), a numerical FFT is typically performed to enable deconvolution of the unwanted system response and then to extract both amplitude and phase information. The emitter is usually either a photoconductive antenna device on a GaAs substrate or simply an LT-GaAs crystal to perform an identical antenna structure (of the order of 50 μm in size) or can be a ZnTe crystal. The EO crystal acts as a THz-to-optical transducer, because it has a birefringent property whereby its angle of polarization to optical light is modulated by the intensity of the THz beam. By using a polarizer and analyzer an image can be formed either by using a scanned single photodetector or a CCD camera.

Table 1 illustrates the trade-off between bandwidth and noise equivalent power (NEP) - where ZnTe has been chosen for best noise performance.

II. Results

Using the χ^2 nonlinearity of GaAs, optical rectification using LT-GaAs produced the THz emissions. The LT-GaAs wafer was gated by a 1 W optical fs laser with 86 MHz repetition rate and 100 fs pulse duration. ZnTe was used for the EO sampling detection method.

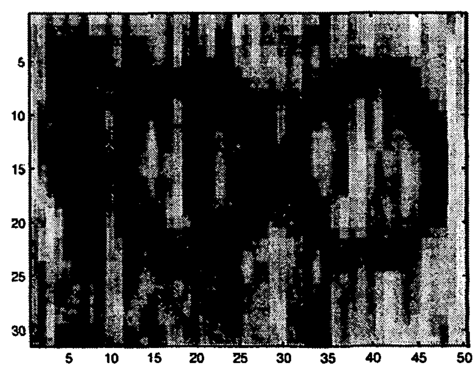

Figure 4: T-ray image of the same feature shown in the previous figure, of a $100 note. Image obtained with lock-in amplifier time constant= 10 ms.

Fig. 1 shows a typical pulse shape after it has been transmitted through the DUT. In this case the DUT was an oak leaf. Fig. 2 shows the resulting frequency spectrum indicating a bandwidth approaching 3 THz. In Fig. 3 we see the an Australian $100 banknote. Then in Fig. 4 we see the T-ray image with a lock-in amplifier integration time of 10 ms. In Fig. 5 the $100 is concealed in an envelope and yet is clearly seen as a T-ray image. This has implications for the use of T-rays in security or perhaps in diagnostics of food through a paper wrapper. The ability to form T-ray images of banknotes may well find use in high accuracy automated counting of notes or in detecting forgeries. Work is on going to now repeat these tests with a MIRA-SEED laser, with external optical compression, that can achieve as low as 13 fs pulse widths. This will both increase bandwidth and increase peak power performance.

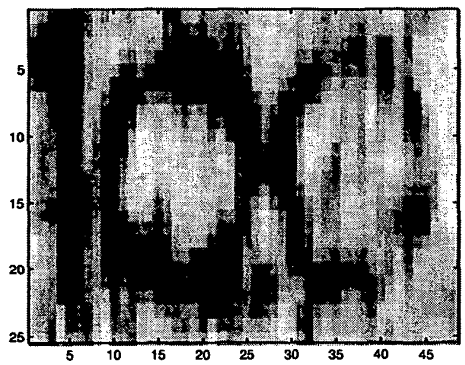

Figure 5: T-tay image when $100 note is hidden inside an envelope. Image obtained with lock-in amplifier time constant= 10 ms.

V. Conclusion

Use of GaAs and ZnTe devices have been reviewed in the emission and detection of THz bandwidth femtosecond pulses. Non invasive imaging of an Australian banknote concealed in an envelope has been reported to illustrate 'X-ray' like transmission capability through thin layers without disadvantage of ionizing effects. 100 fs pulses at 1 W average power were achieved and work to improve this to 10-20 fs will be completed shortly. The Australian T-ray group will investigate future biomedical applications of this

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References

[1] S.P. Mickan, D. Abbott, J. Munch, X-C. Zhang and T. van Doorn, "Analysis of system trade-offs for terahertz imaging" *Proc. SPIE Electronics and Structures for MEMS*, **vol. 3891**, pp. 226-237, 1999.

[2] D.M. Mittleman, "T-ray imaging," *IEEE J. Selected Topics Quantum Elec.*, **vol. 2**, no. 3, pp. 679-692, 1996.

[3] M.C. Nuss "Chemistry is right for T-ray imaging," *IEEE Circuits and Devices*, **vol. 12**, pp. 25-30, 1996.

[4] D.D. Arnone, "Applications for terahertz technology to medical imaging," *Proc. SPIE Euro Opto*, **vol. 3828**, pp. 209-219, 1999.

	ZnTe	GaAs	InP	GaP
Bandwidth (THz)	5.3	8.1	9.1	11.0
E_π at $d = 1$ mm (kV/cm)	89	161	153	252
Field Sens. (mV/cm$\sqrt{\text{Hz}}$)	3.2	5.8	5.5	9.1
NEP (10^{-16} W$\sqrt{\text{Hz}}$)	0.27	0.89	0.8	2.2

Table 1: Trade-off between noise equivalent power (NEP) and other key performance parameters for the EO detection method.