Analysis of system trade-offs for terahertz imaging

Samuel Mickan*[a], Derek Abbott*[a], Jesper Munch[b], X.-C. Zhang[c] and Tim van Doorn[d]

[a]Centre for Biomedical Engineering, The University of Adelaide 5005, Australia
[b]Applied Physics, The University of Adelaide 5005, Australia
[c]Department of Physics, Rensselaer Polytechnic, NY, U.S.A.
[d]Royal Adelaide Hospital 5000, Australia

ABSTRACT

The rapidly developing field of terahertz (or T-ray) imaging promises to provide a non-invasive method of identifying the composition of various objects. Biomedical diagnostics, semiconductor device diagnostics, trace gas analysis and moisture analysis for agriculture are among the growing number of important T-ray applications. We present results using an electro-optical sampling method and and discuss how this can be simplified by using a micro antenna array realised by MEMs technology. The challenges and advantages of both approaches are compared.

In our set-up, sub-picosecond pulses of terahertz radiation are produced via optical rectification, using an LT gallium arsenide wafer. A coherent method is used, whereby both amplitude and phase of the THz beam are detected, providing an exact signature of the material under observation.[1] From the analysis of the amplitude and phase it is possible to tomographically reconstruct a terahertz-domain image of an object.[2] Current terahertz systems, however, remain too slow for many real-time applications and the need for high speed image processing is evident.[3–5] Previous systems have relied on simple signal processing algorithms, based on Fourier transformations, for de-convolving the system response and extracting phase/amplitude information. We discuss enhanced processing based on wavelet transforms. Wavelet techniques for signal analysis provide near optimal thresholding for signal recovery and are computationally inexpensive for pulsed waveforms.[6] The improved signal characterisation and speed of wavelet analysis over Fourier methods is demonstrated on sample T-ray data.

Keywords: terahertz, T-ray imaging, optoelectronics, wavelets

1. INTRODUCTION

This paper discusses the features of terahertz radiation, or *T-rays*, outlining the methods of generation and detection, and presents a number of possible applications. Terahertz radiation has unique and unexplored properties. As terahertz technology rapidly develops, new implementations and applications of these properties are rapidly evolving.

The terahertz frequency band has remained less utilised than the adjacent field of mid-infrared (MIR) lasers and technology, and remains less developed than the field of gigahertz radiation, or millimeter waves. The rarity of terahertz radiation technologies can be largely explained by the lack of good radiative sources, and recent research has been driven by the development of new terahertz sources. The photoconductive dipole antenna (PDA), which relies on ultra high speed photocurrent oscillations, is a popular and reliable source, and other methods, utilising nonlinear optical effects or quantum devices, are gaining in power and reliability. The photoconductive dipole antenna is also used as a terahertz detection device for time-gated spectroscopy. Far infrared radiation is emitted by all bodies at room temperature, so T-rays are typically detected by time gating an ultra fast pulse or by using a cold bolometer. Nonlinear optical and photocurrent emitters generate ultra short pulses of radiation, which can be detected using a *pump-probe* configuration,[7] whereas continuous wave sources (FIR lasers and quantum devices) rely on thermal detection. The development of new terahertz sources runs parallel to research into new detectors and detector configurations.

Since practical terahertz sources became available, a number of potential terahertz systems have been realised for applications such as spectroscopy, tomography, microscopy and FIR imaging. An example of terahertz pulse spectroscopy is ***terahertz time-domain spectroscopy*** (THz-TDS).[8,9] THz-TDS can use a photoconductive dipole antenna to generate an ultrafast FIR pulse, which is then passed through a sample and subsequently detected with another PDA. The incident T-ray pulse contains a broad bandwidth of Fourier components, running from the upper

*Email: spm@ieee.org, dabbott@eleceng.adelaide.edu.au

gigahertz to low terahertz frequencies, and because only certain spectral lines are absorbed by any given sample, it is possible to define a material by the Fourier components it absorbs. This is principle of any spectroscopy, but the terahertz region is populated by rotational and vibrational spectral lines that are unique for each molecule. Two-dimensional images of terahertz waves have been observed by various groups[5,10–12] and are a natural extension of spectroscopic analysis. Depth information can be extracted tomographically, just as in radar, and the thickness of layers is revealed by measuring the time delay of returning pulses from successive layers. One of the real limits of T-rays in imaging is its resolution, which is 0.3 mm for a frequency of 1 THz. This can be improved by operating at higher frequencies or by working in the optical near field.[2] The other main problem with imaging is producing meaningful results in a realistic time frame. This problem is being solved through better detection schemes and signal processing.

New signal processing and detection schemes offer to speed up acquisition and analysis of terahertz data. There is typically huge amount of noise in a THz signal because the radiation is strongly attenuated by common polar substances like water. When a sample contains even a small amount of water it is very difficult to detect the emitted terahertz radiation. The major source of noise in pulsed terahertz systems is the femtosecond laser, which exhibits characteristic 1/f noise. This problem can be overcome through using a lock-in amplifier, which is expensive and slow. Another problem is speed of acquisition, because scanning a sample is very slow. Scanning can be avoided by using a detector array, but this is accompanied by a corresponding sharing of the signal energy. Once a sufficient signal-to-noise ratio (SNR) is achieved, engineering solutions are required to open up the bottlenecks of signal amplification, digitisation, transmission and processing. T-ray data processing can be complicated by taking in account the full spectroscopic information contained in an image. Each image pixel can be the source of a spectroscopic Fourier spectrum, from which the material imaged by that pixel can be identified. Although this could be extremely useful information, it would require a huge processing burden that only efficient algorithms will be able to shoulder.

2. PROPERTIES OF FAR INFRARED RADIATION

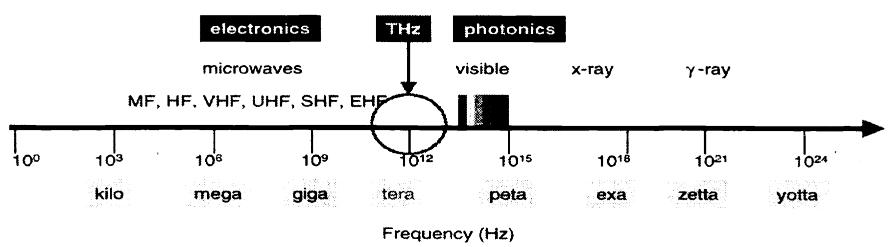

Figure 1. T-rays on the electromagnetic spectrum lie between gigahertz radio frequencies and MIR light.

The properties of T-rays are dominated by their spatial resolving power and the strong interactions between terahertz radiation and common matter, like polar liquids and gases. As seen in Fig. 1, terahertz usually encompasses the wavelengths running from about 15 μm to 0.6 mm, which in turn specify T-rays' spatial resolution. As discussed in Sect. 3, available emitters contain primarily longer wavelength waves, thus limiting terahertz resolution to around half a millimeter. This resolution is insufficiently accurate to displace all current methods of imaging in biomedicine, biology and chemistry, so research is looking into shorter wavelength T-rays. The wavelength of the radiation also determines the photon energy and thus the molecular transitions that interact with the light. The terahertz regime is populated by the rotational and vibrational energy states of polar molecules, either in liquid or gas form. Water is a prime example of a molecule that interacts strongly with T-rays. Water molecules absorb terahertz very strongly, on the one hand limiting penetration of the radiation in moist substances, and on the other making it readily detectable even in very low concentrations. In terms of applications, terahertz radiation will penetrate substances such as fats, cardboard, cloth and plastic with little attenuation, and it can be used for detecting low concentrations of polar gases, conceivably for pollution control. Apart from detection, materials can also be differentiated spectroscopically using T-rays. The identification of a group of rotational or vibrational line in the molecular spectrum lead to unique classification of the molecular substance itself.

Most molecules have dense and distinctive absorption spectra in the far infrared, which has led to much interest in terahertz spectroscopy.[13–17] Spectroscopy has been largely based on pulses of terahertz radiation, mainly due to the availability of appropriate emitters, and because a pulse contains a broad Fourier spectrum, many spectral lines can be discerned simultaneously. In principle it is possible to calculate the absorption spectrum of a transmitted or reflected pulse and thus determine which molecules are present in the beam path. Practically, attenuation is often too severe for a signal to be transmitted, meaning only thin samples or surface molecules can be analysed, and the wavelengths available provide only around 0.5 mm resolution. To understand the current limitations of T-rays, it is necessary to consider which detectors and emitters are available.

3. TERAHERTZ EMITTERS AND DETECTORS

The terahertz regime has been populated for many years by clumsy, weak emitters and inefficient detectors. Gradually improvements are being made, in some cases driven by the enabling technology of femtosecond lasers.

3.1. Emitters and detectors

A number of methods are used to generate terahertz radiation, from lasers to nonlinear effects, which produce radiation of different wavelength ranges, either pulsed or continuous wave (cw), with varying degrees of success. The most desirable emitter would of course be a solid-state lasing material, with tunable wavelength and high power, so a number of attempts have been made to create T-ray lasers. The first problem is finding a suitable radiative transition, because rotational and vibrational energy levels of large molecules are difficult to use in a laser.[18] Terahertz lasers have also been built with a p-Germanium oscillator, but these are similarly unsatisfactory since they offer no cw operation and operate only at 2° K.[19] Current research focuses on photomixing,[20,21] and on transitions in semiconductor materials, using quantum wells,[22–26] quantum dots,[27] superlattices[28] and unipolar lasers.[29] Lastly, the free-electron laser is capable of emitting in the far infrared, but current requirements for T-rays do not justify the inconvenience and expense of a FEL except for experimental use.

Detecting terahertz signals is difficult because blackbody radiation in the far infrared is strong at room temperatures. This difficulty can be overcome by using a helium cooled bolometer, which is de-sensitised to ambient temperature and registers the heating effect of a terahertz beam. The bolometer is, however, an incoherent detection scheme, so only the amplitude of any signal is registered. Using a pump-probe configuration, on the other hand, allows for a far greater sensitivity and full coherent signal acquisition, but the pump-probe technique is limited to pulsed T-ray systems. Pulsed systems include those using photoconductive antennas, optical rectification emitters and electro-optic detectors. A pump-probe setup is shown in Fig. 2, demonstrating how separated fractions of a pulse can be delayed relative to each other in time. The detector only operates when gated by the probe pulse, so it has a time resolution limited only by the width of the ultrafast pulse and the cut-off speed of the detector.

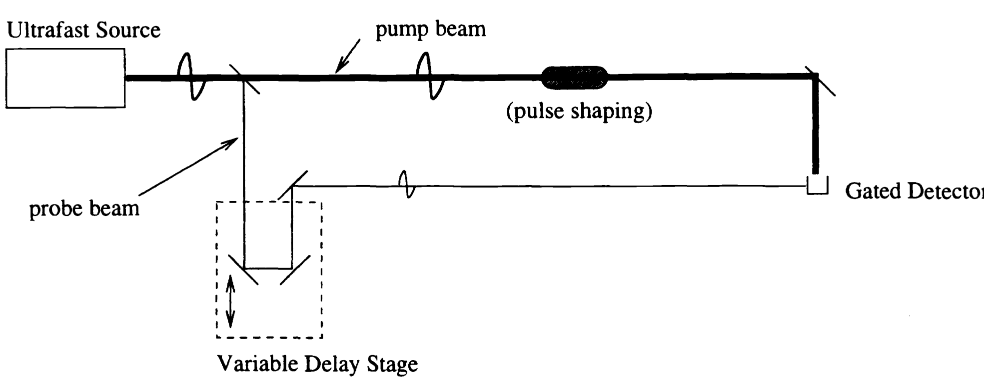

Figure 2. Pump-probe detection - gated detection with an ultrafast pulse.

The photoconductive dipole antenna (PDA) was first described by Auston *et al.* in the early 1980s and rapidly grew in popularity among high speed laser research groups around the world.[30] The PDA is typically a dipole antenna drawn on a semiconductor substrate, which radiates when a laser pulse enables a photocurrent pulse to flow across the biased semiconductor gap.[31] Although simple to construct, a PDA requires an ultrafast laser to turn it on, and femtosecond lasers are still not cheap*. On the other hand, femtosecond gating enables the use of PDA detectors in the high resolution pump-probe configuration. The PDA is a pulsed device, activated by ultrashort laser pulses and emitting terahertz pulses of comparable durations. PDA emitters can have high powers, although they are limited by the maximum surface current flow. The energy radiated from a PDA depends not on the energy of the laser pulse, but on the bias, which powers the current cascade. The main problem with PDAs is their bandwidth limitation. The bandwidth of PDA detection has a high frequency limit determined by the speed of the photocurrent response.[32] As mentioned in Sect. 2 the resolution of T-rays is poor at low terahertz frequencies, and PDAs emit over a spectral range from about 100 GHz to 1 THz, peaking at about 500 GHz.[33] For pulsed terahertz applications, the PDA is powerful and sensitive, but lacks a fine wavelength for resolution.

The other primary pulsed T-ray technique is the so-called *free-space electro-optic sampling* (FSEOS) method, a technique based on emission by optical rectification and detection by electro-optic sampling. Optical rectification is a process first observed in the 1960s that describes how a pulse at optical frequencies can be down-shifted by degenerate difference frequency generation inside a nonlinear crystal.[34–37] In FSEOS, an ultrafast pulse with 800 nm centre wavelength is directed into a nonlinear crystal, which subsequently emits a pulse with terahertz centre frequency. In contrast to PDA emission, the power of the terahertz pulse is derived entirely from the incident laser pulse, so FSEOS typically has lower power. For example, the most efficient dipole configuration emits an average of 3 μW of terahertz under 20 mW of excitation,[38] whereas, for example, only 30 nW might be generated from 175 mW of excitation with optical rectification.[39] The advantage of FSEOS lies in its bandwidth, which limited not by the speed of the photocurrent pulse as in a PDA, but by the nonlinear characteristics of the emitter crystal.[31] Terahertz pulses with spectra extending from 7 to 15 μm have been generated.[39] The higher frequencies of emitted terahertz in FSEOS are detected using electro-optic sampling, a technique reliant on the electro-optic, or Pockels effect.[40] Electro-optic sampling operates by writing the terahertz waveform into the polarisation of an electro-optic crystal and then reading it off with a second femtosecond pulse, that is, the probe pulse in a typical pump-probe configuration. The electro-optic effect is extremely fast but very weak compared to photoconductive sampling, so an electro-optic crystal can be used to detect up to 37 terahertz,[41] but the signal becomes increasingly disguised by background laser noise.[32] FSEOS benefits from the temporal resolution and coherent detection of the pump-probe method, and its lack of power is balanced by its improved resolution.

3.2. Detection Schemes

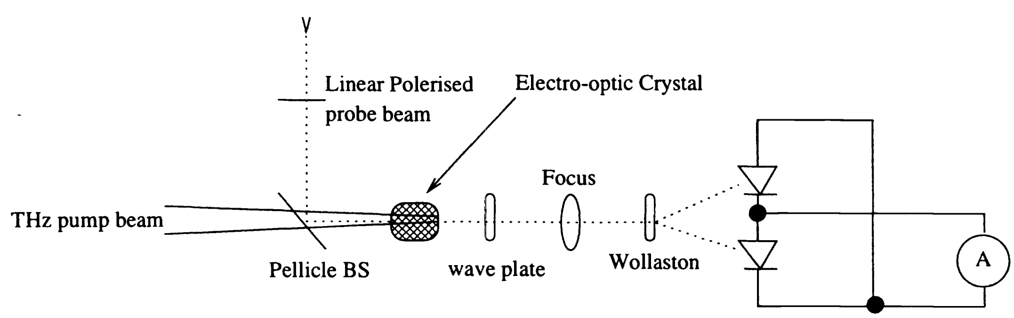

Figure 3. THZ pump - fs probe system with crossed polarisers and balanced photodiode detectors..

Coupled with devices required to transduce terahertz radiation to some form of electrical or optical signal, there are a number of methods used to optimise detection of terahertz waveforms. These are concerned more with the field of electronics than optics and form the bridge between free space waves and their digital representations on computer. Three techniques in common use are balanced photodiode detection, lock-in amplification and digital data capture.

Balanced photodiode detection is a simple implementation of photodiodes that cancels out the noise of the laser, which is independent of the polarisation of the light.[42] Balanced photodiodes are used with a pair of crossed polarisers to convert the polarisation modulation of an electro-optic detector crystal into a current modulation. Figure 3 shows a probe pulse being modulated by the crossed polarisers, and then having its two polarisations split

*A cheap femtosecond laser can be purchased for about $25,000 U.S. from FemtoLasers (www.femtolasers.com).

onto the photodiodes. The diodes are configured in parallel so that any polarisation-common intensity fluctuations, such as those due to laser noise, are cancelled out.

The speed of terahertz data analysis in any system will depend on the signal-to-noise ratio available and on the hardware for signal capture, digitisation, transmission and analysis. More information can be produced by scanning the pump-probe delay faster, but the SNR must be sufficiently high and the photodetectors sufficiently fast. Using a lock-in amplifier increases the SNR dramatically, but in turn slows down the flow of information.[43] Finally, high-speed signal processing algorithms will ensure that data can be displayed and understood in realistic time frame.

4. SPECTROSCOPY, RANGING, TOMOGRAPHY AND MICROSCOPY

Far infrared radiation is rarely present at really high powers and is thus considered primarily for observation rather than physical manipulation. Observation with T-rays has involved spectroscopy, range finding, tomography and microscopy. Terahertz spectroscopy is valuable for distinguishing molecules and studying intermolecular interactions, while tomography relates more to imaging through various layered materials. Microscopy with T-rays is realised by only working in the near-field terahertz radiation pattern, thus overcoming the far-field wavelength limitation on resolution.

4.1. Spectroscopy

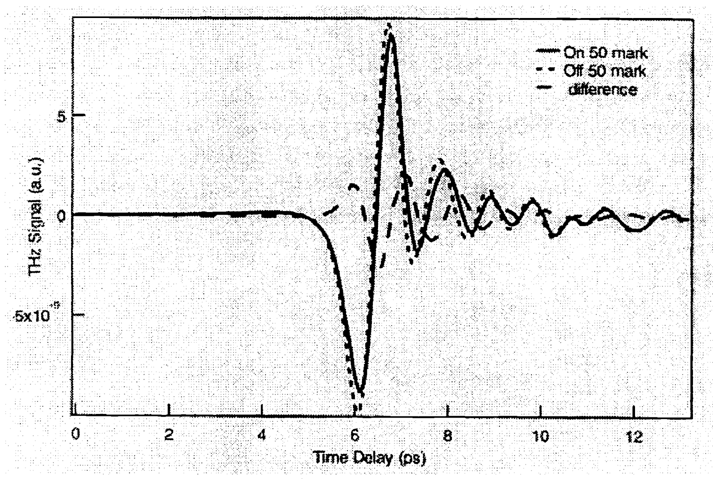

Figure 4. Two terahertz pulse waveforms after transmission through an Australian $50 plastic note. The solid line is through the lettering ($50) and the dotted line is through the surrounding plastic. The dashed line shows the difference between the two waveforms.

As in any spectroscopic system, T-ray spectroscopy is based on the idea of shining radiation through or bouncing it off a material, and then observing how the radiation spectrum has changed. The most common terahertz spectroscopy system is terahertz time-domain spectroscopy.[13] THz-TDS relies on T-ray pulses. In its most simplistic form, the Fourier spectrum of a free-space terahertz pulse is first characterised, then compared to the spectrum of a pulse that has passed through some sample. The far infrared absorption peaks are then available and can be used to classify the molecular rotational and vibrational modes present in the sample. THz-TDS has been used to measure the refractive index of dielectrics,[44] thin films,[17] semiconductors,[45] liquids and superconductors. It has also featured in studying the dielectric properties of polar liquids,[46] in recognising gases and gas mixtures,[47] in observing the rotational absorption spectra of hot water vapour in flames,[48] and in classifying of FIR material parameters.[15] Spectroscopy in the far infrared is particularly interesting because one can study the dynamics of chemical reactions, which is very important in understanding how chemical and biological systems operate and interact.[49]

THz-TDS in particular is advantageous because a wide spectral range can be probed with the one pulse, so there is no need for frequency sweeping as in a cw system. Another pulsed system, FSEOS, has a similarly broad bandwidth but typically is able to operate over shorter wavelengths. This may be important for discerning particular spectral lines at frequencies higher than 1 THz. Pulse spectroscopy has the advantage of broad bandwidth, but this means that the pulse energy is spread across many wavelength and might be a waste if only particular spectral lines are interesting.

An important variation on transmission spectroscopy is reflection spectroscopy. Both techniques are very similar, yet there are two important differences to note. The first relates to penetration depth, basically because T-rays are easily blocked by large amounts of material, especially if it contains water. Chicken skin, for example, has been shown to completely block terahertz pulses if it is much more than 3 mm thick,[50] due to the high attenuation of terahertz in water. The second important point of reflection spectroscopy is consideration of the phase. Unlike the transmission geometry, the path length will change depending on the placement of the sample, so phase information has to be referenced to a known surface or carefully measured distance.

4.2. Ranging and Tomography

Two obvious modalities for pulsed radiation are inherited from the radar field, being ranging and tomography, both of which rely on a reflective geometry. The basic elements of ranging involve measuring the time of flight of the terahertz pulses and thus calculating the distance and shape of objects. More importantly, the radar profiles of large objects can be characterised using scale models using T-rays.[51] Tomography is a similar application, looking at the flight time of pulse reflections from subsequent boundaries inside an object. Thus the internal structure of, for example, a floppy disc can be observed non-invasively.[2] In a second step, tomography could be combined with spectroscopic analysis to reveal the structure and composition of certain objects. This will be an interesting research area, but requires intensive signal processing to deal with large amounts of data efficiently.

4.3. Microscopy

Near-field terahertz microscopy first developed from a desire for better resolution, and can be used to nicely demonstrate some important properties of light and ultrafast phenomena.[52] Near-field microscopy has enabled imaging at spatial resolutions better than the diffraction limit, down to a quarter wavelength.[53] For terahertz, this corresponds to a resolution of about 50 micrometers. The near field is created with a tapered near-field tip, similar to those of scanning optical microscopes. The tip is held in contact with the sample and images can be generated by scanning in two dimensions. Near-field microscopy provides a method for imaging in the far-infrared without the resolution limitations arising from longer wavelengths.

5. IMAGING

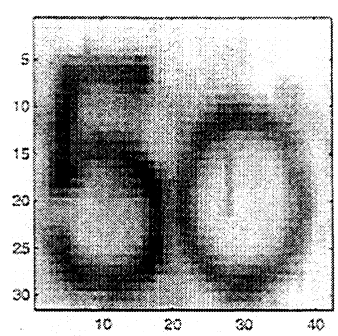

Figure 5. An image of an Australian $50 note imaged with scanning imaging (FSEOS) at the delay corresponding to maximum terahertz amplitude. The numerals stand out because the particular ink used in printing has different FIR absorption to the surrounding plastic, thus the '50' would still show if the money were stored in an envelope.

Imaging in the far infrared was a natural extension of spectroscopic analysis and initially involved building up a two-dimensional image from an array of spectroscopic measurements.[10] Terahertz imaging has been performed using both PDAs and FSEOS by a number of groups and has also been implemented with a CCD camera, which obviates scanning the sample through each pixel.[1,5,54] The aim is to speed up acquisition of a T-ray image, so real-time processes can be observed. Many applications for T-ray imaging have been suggested and some implemented, including quality control of packaged goods, inspection of artwork and tissue burn reflectometry.[55] The future of terahertz imaging lies with cheap, robust systems that produce images of the far infrared swiftly and intelligently.

5.1. Scanning Imaging

The original terahertz imaging was scanning imaging, where an array of spectroscopic elements is built up to create an image.[10] Figure 5 shows an image generated by scanning imaging - each pixel corresponds to a different waveform, two of which are shown in Fig. 4. A typical apparatus requires three motorised stages; two are for moving the sample in two dimensions through the terahertz beam and the third operates the pump-probe detection scheme. In fact, if full spectroscopic information is taken at each pixel, the delay stage must scan through for each pixel, and that takes a long time. An alternative is to choose a delay that corresponds to a pulse peak and take an image of the terahertz amplitude transmitted at that delay. However, this method discards a lot of information about the distortion of the pulse and is prone to errors, because it is insensitive to large phase shifts and jitter. Clearly, an ideal terahertz image would contain not only amplitude attenuation information, but also a complete spectroscopic analysis in the FIR, thus enabling different materials to be classified across the sample. Unfortunately this requires burdensome signal processing and is very slow, but not intractable and is a target area for our research.

5.2. Parallel Processing - Imaging Arrays

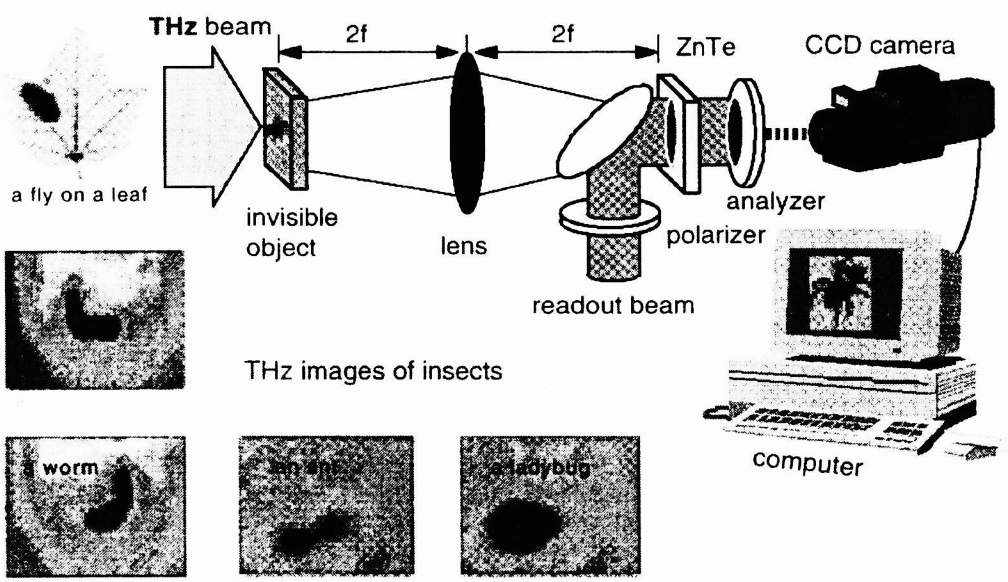

Figure 6. A system for terahertz imaging with FSEOS and a CCD camera. The images shown are of insects imaged with the T-rays (Figure courtesy of X.-C. Zhang).

The slowness of two-dimensional scanning imaging can be avoided by using an imaging array, rather than moving to process each pixel individually. With electro-optic sampling, it is easy to replace the balanced photodiodes with a CCD camera and image the entire plane of terahertz radiation.[5] There is, however, a trade-off between the signal-to-noise ratio and the size of the area being imaged, since the energy of the pulse is being spread over an array of detectors. The other main disadvantage of CCD imaging is the loss of the lock-in amplifier, which normally provides cancellation of the 1/f laser noise; a lock-in CCD is not presently available. Figure 6 shows a system for T-ray imaging with a CCD camera, accompanied by some two-dimensional FIR images of insects.

A similar concept of array imaging could be applied to PDAs by fabricating a two-dimensional array of PDA receivers. This would suffer from the bandwidth limitation of PDA systems and the energy distribution of any array imaging, but might be more useful than a CCD in electro-optic because of the higher sensitivity of PDA detectors.

Although one-dimensional PDA arrays have been fabricated for beam steering, two-dimensional imaging arrays for terahertz have not been reported.[56]

5.3. Wavelet Image Processing

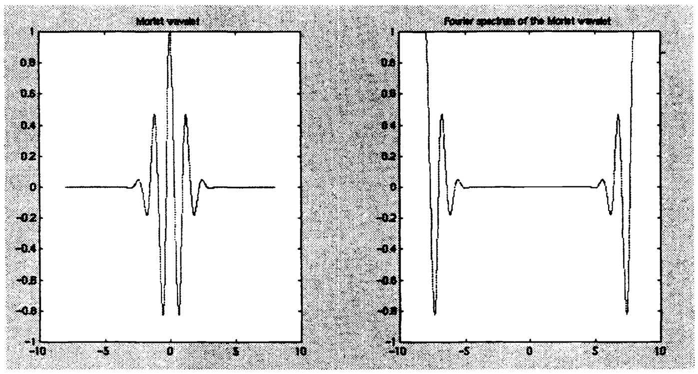

Figure 7. Plot of a Morlet wavelet function (on the left) and of its Fourier spectrum. It exhibits localisation in both time and frequency.

It is clear that development of a robust and speedy terahertz imaging system requires efficient signal analysis and information processing algorithms. Apart from detection and system interfaces, it is vital to take incoming terahertz waveforms or images, enhance salient signal features and present the information for storage and understanding. At this point most operational T-ray imaging systems are pulse driven, so the idea of processing based on wavelets appears practical.[4] Wavelet analysis extends the concept of Fourier decomposition to a more complicated time and scale decomposition. In wavelet analysis, a signal is decomposed into an array of pulse-shaped *wavelets*, so that the time domain and spectral domain of a signal can be studied simultaneously, much like the short-time Fourier transform.[57] The basic premise of wavelet analysis is to construct the signal from the scaled wavelets instead of from infinite sinusoidal functions, as used in Fourier analysis. Figure 7 depicts a common wavelet function, the Morlet wavelet, and shows the localisation of the wavelet in time and frequency. When applied to pulsed systems, like pulsed T-ray imaging, the wavelet function fits far more closely to the shape of the actual signal than any sinusoid would, and thus correlation coefficients are higher than for Fourier transforms. Higher coefficients mean better noise thresholding and better signal detection. In fact, it has been shown that wavelets have near optimal noise reduction properties for a wide range of signals.[58]

Image processing must not only be effective, it must also be fast. One of the primary features of the *discrete wavelet transform* (DWT) algorithm is its speed. Compared to the Fast Fourier Transform, which has complexity of order $O(NlogN)$, the DWT is far quicker with complexity order $O(N)$.[6] This can make a phenomenal difference to the time required to de-noise and analyse signal data. The central trade-off in wavelet analysis comes between performance and speed. Although the DWT is fast, better and more flexible performance can be achieved by introducing some redundancy, and using an *over-complete wavelet transform* (OCWT). The OCWT provides better noise robustness, allows for non-uniform sampling and allows adjustment of its bandwidth.[59] The trade-off with the OCWT is performance against speed - algorithms to implement the OCWT drop to speeds corresponding to a complexity of order $O(N)$.

5.4. Imaging Applications

Finding applications for terahertz imaging systems remains an important investigative pursuit as the field continues to mature. Mittleman has provided a recent review of terahertz pulse imaging and mentions applications such as inspection of packages and art, as well as tissue burn tomography and high-resolution near-field imaging.[55] Terahertz imaging is applicable to biomedical diagnostics, semiconductor device diagnostics, trace gas analysis and moisture analysis for agriculture.[14] T-rays can also be used to explore the internal structure of plastics, image components in a flame[1] and view packaged objects.[60] Medical imaging is a fertile field for terahertz imaging because, unlike x-rays, they are not harmful to tissue. An example of medical imaging is shown in Fig. 8, where a FIR image of a breast cancer phantom clearly shows where simulated cancers are. Although terahertz do not penetrate far into the body, it would be possible to project terahertz endoscopically, as in optical coherence tomography.[61] T-rays are even being considered for intersatellite communications, supported by $12 million of DARPA research funding.[62]

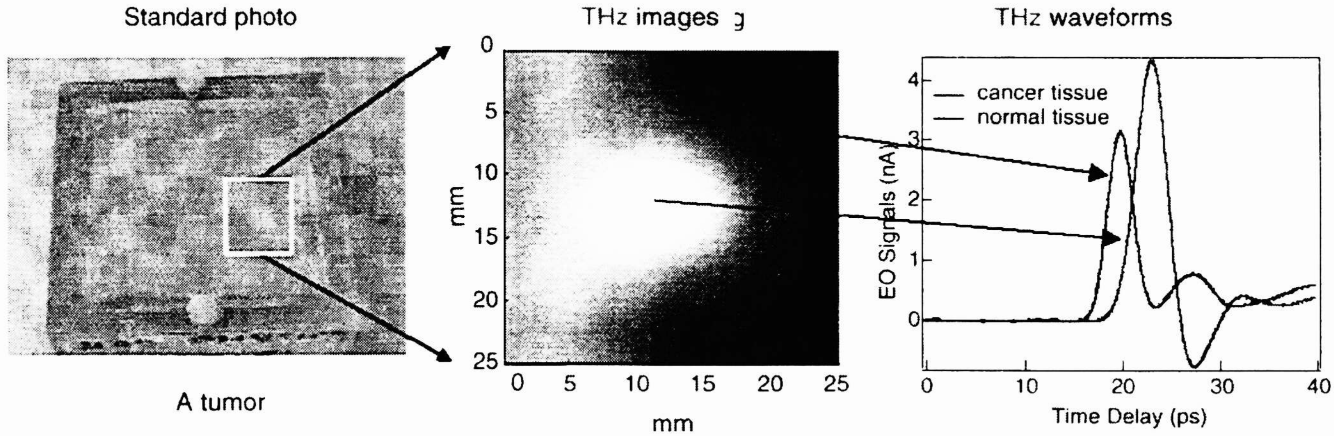

Figure 8. T-ray image of a breast phantom (wax) with fibres embedded to simulate cancerous growths (Figure courtesy of X.-C. Zhang).

6. CONCLUSIONS AND FUTURE DIRECTIONS

The field of terahertz imaging is rapidly maturing to a point where practical T-ray systems are realisable. Based on femtosecond lasers, terahertz pulse imaging offers scope for wide-ranging analysis in the FIR, once some system issues have been resolved and signal processing is optimised. For the first time we demonstrate results based on T-ray imaging of Australian plastic banknotes. This may find application in the identification of currency.

ACKNOWLEDGMENTS

We would like to gratefully acknowledge the support of X.-C. Zhang's group at Rensselaer Polytechnic and I. Brener's group at Lucent Technologies

REFERENCES

1. D. M. Mittleman, R. H. Jacobson, and M. C. Nuss, "T-ray imaging," *IEEE Journal of Selected Topics in Quantum Electronics* **2**(3), pp. 679–692, 1996.
2. D. M. Mittleman, S. Hunsche, L. Boivin, and M. C. Nuss, "T-ray tomography," *Optics Letters* **22**(12), pp. 904–906, 1997.
3. S. Hunsche, D. M. Mittleman, M. Koch, and M. C. Nuss, "New dimensions in T-ray imaging," *IEICE Transactions on Electronics* **E81-C**(2), pp. 269–276, 1998.
4. D. M. Mittleman, R. Neelamani, R. G. Baraniuk, and M. C. Nuss, "Applications of terahertz imaging," in *Nonlinear Optics '98: Materials, Fundamentals and Applications Topical Meeting*, pp. 294–296, IEEE, 1998.
5. Q. Wu, T. D. Hewitt, and X.-C. Zhang, "Two-dimensional electro-optic imaging of terahertz beams," *Applied Physics Letters* **69**(8), pp. 1026–1028, 1996.
6. C. S. Burrus, R. A. Gopinath, and H. Gou, *Introduction to Wavelets and Wavelet Transforms: A Primer*, Prentice-Hall, Englandwood Cliffs, NJ, U.S.A., 1998.
7. J. A. Valdmanis, G. Mourou, and C. W. Gabel, "Picosecond electro-optic sampling system," *Applied Physics Letters* **41**(3), pp. 211–212, 1982.
8. P. R. Smith, D. H. Auston, and M. C. Nuss, "Subpicosecond photoconducting dipole antennas," *IEEE Journal of Quantum Electronics* **24**(2), pp. 255–260, 1988.

9. M. V. Exter and D. Grischkowsky, "Characterization of an optoelectronic terahertz beam system," *IEEE Transactions on Microwave Theory and Techniques* **38**(11), pp. 1684–1691, 1990.
10. B. B. Hu and M. C. Nuss, "Imaging with terahertz waves," *Optics Letters* **20**(16), pp. 1716–1718, 1995.
11. M. Knott, "See-through teeth," *New Scientist* **162**(2192), p. 22, 1999.
12. M. Koch, "THz imaging: Fundamentals and biological applications," in *Conference on Terahertz Spectroscopy and Applications*, SPIE, (Munich, Germany), 1999.
13. M. V. Exter, C. Fattinger, and D. Grischkowsky, "Terahertz time-domain spectroscopy of water vapour," *Optics Letters* **14**(20), pp. 1128–1130, 1989.
14. M. C. Nuss, "Chemistry is right for T-rays," *IEEE Circuits and Devices* **12**(2), pp. 25–30, 1996.
15. L. Duvillaret, F. Garet, and J.-L. Coutaz, "A reliable method for extraction of material parameters in terahertz time-domain spectroscopy," *IEEE Journal of Selected Topics in Quantum Electronics* **2**(3), pp. 739–746, 1996.
16. G. Gallot and D. Grischkowsky, "THz time-domain spectroscopy (THz-TDS) with electro-optic sampling," in *Conference on Lasers and Electro-Optics '99*, pp. 492–493, OSA, Optical Socety of America, (Baltimore, MD, U.S.A.), 1999.
17. M. Li, G. C. Cho, T.-M. Lu, X.-C. Zhang, S.-Q. Wang, and J. T. Kennedy, "Time-domain dielectric constant measurement of thin film in GHz-THz frequency range near Brewster angle," *Applied Physics Letters* **74**(15), pp. 2113–2115, 1999.
18. B. Lax, "Applications of far infrared lasers," in *Tunable Lasers and Applications*, A. Mooradian, T. Jaeger, and P. Stokseth, eds., vol. 3 of *Springer Series in Optical Sciences*, pp. 340–347, Springer-Verlag, Berlin, 1976.
19. T. Klaassen, N. Hovenier, T. Wenckebach, A. Murajov, S. Pavlov, and V. N. Shastin, "Pulsed and mode-locked p-Ge THz laser: Wavelength dependent properties," in *Conference on Terahertz Spectroscopy and Applications*, SPIE, (Munich, Germany), 1999.
20. 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," *Applied Physics Letters* **73**(26), pp. 3824–3826, 1998.
21. P. Gu, M. Tani, M. Hyoho, K. Sakai, and T. Hidaka, "Generation of cw-terahertz radiation using a two-longitudinal-mode laser diode," *Japanese Journal of Applied Physics* **37**(8B), pp. L976–L978, 1998.
22. P. C. M. Planken, M. C. Nuss, I. Brener, and K. W. Goossen, "Terahertz emission in single quantum wells after coherent optical exciation of light hole and heavy hole excitons," *Physical Review Letters* **69**(26), pp. 3800–3803, 1992.
23. A. J. Sengers and L. Tsang, "Valence-band mixing and continuum excitons in the excitonic model for coherent terahertz radiation form quantum wells," *Journal of the Optical Society of America B: Optical Physics* **14**(5), pp. 1057–1065, 1997.
24. M. S. C. Luo, S. L. Chuang, P. C. M. Planken, I. Brener, H. G. Roskos, and M. C. Nuss, "Generation of terahertz electromagnetic pulses from quantun-well structures," *IEEE Journal of Quantum Electronics* **30**(6), pp. 1478–1488, 1994.
25. C. Chansungsan, "Coherent terahertz radiative dymanics of excitons from ultrafast optical excitation of single semiconductor quantum wells," *Journal of the Optical Society of America B: Optical Physics* **13**(12), pp. 2792–2800, 1996.
26. A. N. Korotkov, D. V. Averin, and K. K. Likharev, "Tasers: Possible dc pumped terahertz lasers using interwell transitions in semiconductor heterostructures," *Applied Physics Letters* **65**(15), pp. 1865–1967, 1994.
27. V. A. Kovarsckiĭ, "Squeezed states of long-lived terahertz vibrations in quantum dots," *JETP Letters* **65**(2), pp. 215–, 1997.
28. C. Waschke, H. G. Roskos, R. Schwedler, K. Leo, H. Kurz, and K. Köhler, "Coherent submillimeter-wave emission from Bloch oscillations in a semiconductor superlattice," *Physical Review Letters* **70**(21), pp. 3319–3322, 1993.
29. C. Y. L. C. et al, "Modulation bandwidth optimization for unipolar intersubband semiconductor lasers," *IEE Proceedings Optoelectronics* **144**(1), pp. 44–47, 1997.
30. D. H. Auston, K. P. Cheung, and P. R. Smith, "Picosecond photoconducting Hertzian dipoles," *Applied Physics Letters* **45**(3), pp. 284–286, 1984.
31. D. H. Auston, "Ultrafast optoelectronics," in *Ultrashort Laser Pulses and Applications*, W. Kaiser, ed., vol. 60 of *Topics in Applied Physics*, ch. 5, pp. 183–233, Springer-Verlag, Berlin, Germany, 1988.

32. Y. Cai, I. Brener, J. Lopata, J. Wynn, L. Pfeiffer, J. B. Stark, Q. Wu, X.-C. Zhang, and J. Federici, "Coherent terahertz radiation detection: Direct comparison between free-space electro-optic sampling and antenna detection," *Applied Physics Letters* **73**(4), pp. 444–446, 1998.
33. P. U. Jepsen, R. H. Jacobsen, and S. R. Keiding, "Generation and detection of terahertz pulses from biased semiconductor antennas," *Journal of the Optical Society of America B: Optical Physics* **13**(11), pp. 2424–2436, 1996.
34. M. Bass, P. A. Franken, J. F. Ward, and G. Weinreich, "Optical rectification," *Physical Review Letters* **9**(11), pp. 446–448, 1962.
35. K. H. Yang, P. L. Richards, and Y. R. Shen, "Generation of far-infrared radiation by picosecond light pulses in $LiNbO_3$," *Applied Physics Letters* **19**(9), pp. 320–323, 1971.
36. D. H. Auston, K. P. Cheung, J. A. Valdmanis, and D. A. Kleinman, "Cherenkov radiation from femtosecond optical pulses in electro-optic media," *Physical Review Letters* **53**(16), pp. 1555–1558, 1984.
37. A. Rice, Y. Jin, X. F. Ma, X.-C. Zhang, D. Bliss, J. Larkin, and M. Alexander, "Terahertz optical rectification from ¡110¿ zinc-blende crystals," *Applied Physics Letters* **64**(11), pp. 1324–1326, 1994.
38. Y. Cai, I. Brener, J. Lopata, J. Wynn, L. Pfeiffer, and J. Federici, "Design ans performance of singular electric field terahertz photoconducting antennas," *Applied Physics Letters* **71**(15), pp. 2076–2078, 1997.
39. A. Bonvalet, M. Joffre, J. L. Martin, and A. Migus, "Generation of ulttrabroadband femtosecond pulses in the mid-infrared by optical rectification of 15 fs light pulses at 100 mhz repetition rate," *Applied Physics Letters* **67**(20), pp. 2907–2909, 1995.
40. Q. Wu and X.-C. Zhang, "Design and characterization of traveling-wave electrooptic terahertz sensors," *IEEE Journal of Selected Topics in Quantum Electronics* **2**(3), pp. 693–700, 1996.
41. Q. Wu and X.-C. Zhang, "Free-space electro-optics sampling of mid-infrared pulses," *Applied Physics Letters* **71**(10), pp. 1285–1286, 1997.
42. Q. Wu, M. Litz, and X.-C. Zhang, "Broadband detection capability of ZnTe electo-optic field detectors," *Applied Physics Letters* **68**(21), pp. 2924–2926, 1996.
43. M. L. Meade, *Lock-in amplifiers: principles and applications*, vol. 1 of *Numerical Measurement Series*, Peter Peregrinus, London, 1983.
44. D. Grischkowsky, S. Keiding, M. V. Exter, and C. Fattinger, "Far-infrared time-domain spectroscopy with terahertz beams of dielectrics and semiconductors," *Journal of the Optical Society of America B: Optical Physics* **7**(10), pp. 2006–2015, 1990.
45. D. M. Mittleman, J. Cunningham, M. C. Nuss, and M. Geva, "Noncontact semiconductor wafer characterization with the terahertz Hall effect," *Applied Physics Letters* **71**(1), pp. 16–18, 1997.
46. J. T. Kindt and C. A. Schmuttenmaer, "Far-infrared dielectric properties of polar liquids probed by femtosecond terahertz pulse spectroscopy," *Journal of Physical Chemistry* **100**, pp. 10373–10379, 1996.
47. R. H. Jacobsen, D. M. Mittleman, and M. C. Nuss, "Chemical recognition of gases and gas mixtures with terahertz waves," *Optics Letters* **21**(24), pp. 2011–2013, 1996.
48. R. A. Cheville and D. Grischkowsky, "Observation of pure rotational absorption spectra in the μ_2 band of hot H_2O in flames," *Optics Letters* **23**(7), pp. 531–533, 1998.
49. B. N. Flanders, D. C. Arnett, and N. F. Scherer, "Optical pump-terahertz probe spectroscopy utilizing a cavity-dumped oscillator-driven terahertz spectrometer," *IEEE Journal of Selected Topics in Quantum Electronics* **4**(2), pp. 353–359, 1998.
50. D. Arnone, "Applications of terahertz technology to medical imaging," in *Conference on Terahertz Spectroscopy and Applications*, SPIE, (Munich, Germany), 1999.
51. R. A. Cheville, R. W. McGowan, and D. Grischkowsky, "Late-time target response measured with terahertz impulse ranging," *IEEE Transactions on Antennas and Propogation* **45**(10), pp. 1518–1524, 1997.
52. K. Wynne, J. C. Carey, J. Zawadzka, and D. A. Jaroszynski, "Superluminal propogation of terahertz pulses in sub-wavelength structures," in *Conference on Lasers and Electro-Optics '99*, p. 397, OSA, (Baltimore, MD, U.S.A.), 1999.
53. S. Hunsche, M. Koch, I. Brener, and M. C. Nuss, "THz near-field imaging," *Optics Communications* **150**, pp. 22–26, 1998.
54. X.-C. Zhang, "Ultrafast electro-optic field sensor and its image applications," in *OSA TOPS on Ultrafast Electronics and Optoelectronics*, M. Nuss and J. Bowers, eds., vol. 13, OSA, 1997.

55. D. M. Mittleman, M. Gupta, R. Neelamani, R. G. Baraniuk, J. V. Rudd, and M. Koch, "Recent advances in terahertz imaging," *Applied Physics B: Lasers and Optics* **68**, pp. 1085–1094, 1999.
56. N. M. Froberg, "Terahertz radiation from a photoconducting antenna array," *IEEE Journal of Quantum Electronics* **28**(10), pp. 2291–2301, 1992.
57. A. Graps, "An introduction to wavelets," *IEEE Computational Science and Engineering* **2**(2), pp. 50–61, 1995.
58. D. L. Donoho, "De-noising by soft thresholding," *IEEE Transactions on Information Theory* **41**(3), pp. 613–627, 1995.
59. A. Teolis, *Computational signal processing with wavelets*, Birkhauser, Boston, Massachusetts, 1998.
60. M. May, "T-rays spell sharper, safer images," *New Scientist* **154**(2083), p. 22, 1997.
61. J. A. Izatt, A. M. Rollins, R. Ung-arunyawee, A. Chak, R. C. Wong, K. Kobayashi, and M. V. Sivak, "Real-time endoscopic optical coherence tomography in human patients," in *Conference on Lasers and Electro-Optics '99*, pp. 336–337, OSA, (Baltimore, MD, U.S.A.), 1999.
62. D. A. R. P. Agency, "Electronics technology office: Solicitations: Baa 99-15." Internet (World Wide Web), 1998. http://www.darpa.mil/ETO/Solicitations/BAA99-15/S/Section1.html.