Terahertz frequency scattering and plasmonic probe studies

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Introduction

It is known that terahertz (THz) scattering can be used to determine the characteristic size, location and even texture of an object concealed in a matrix of other material. The accurate detection and interpretation of THz pulses from broadband sources is particularly important for the development of standoff security systems, for example. Such broadband sources are advantageous over their single frequency counterparts, in that they also provide the possibility of identifying organic and biological compounds for example, by their characteristic spectral fingerprints. A new and potentially important tomographic imaging method has been developed, using the loan-pool laser. The method is relatively simple and enables the position and size of hidden objects (metal and dielectric cylinders) to be determined. The geometry used is analogous to that used in X-ray CAT scanners, which indicates that signal-processing routines used for that modality might be adapted for THz tomography.

Purpose of the work undertaken

A femtosecond oscillator from the RAL loan pool was acquired to address the following: Investigate scattering characteristics of THz radiation in non-homogeneous materials at various angles; Evaluate the possibility of undertaking tomographic measurements, using pulsed THz radiation; Evaluate the possibility of using a fibre-fed plasmon probe in THz biological measurements. The experiments undertaken with the near infrared RAL loan pool laser proceeded well, but a lot of time had to be spent on realising the fibre-fed THz detector system into which the near infrared pulses were fed. This could not have been accomplished 'off line' as a number of critical alignments and steps requiring small, but time-consuming, technical developments were needed to optimise performance. In consequence, only undertaking tomographic measurements, by measuring scattered THz radiation, was addressed fully. The capabilities developed in the present work are highly relevant to such applications as: monitoring the progress (in location, time and chemical activity) of a reaction in a pharmaceutical process within a reactor vessel; monitoring the presence of impurities in a food mixture; or determining the nature and position of a foreign body within a fabricated plastic or composite structure.

Terahertz radiation and tomography

Terahertz radiation lies between the microwave and infrared regions of the electromagnetic spectrum and applications are emerging in many areas, especially security and surveillance. Various work has been undertaken in the general area of terahertz imaging, with most images thus far produced being either 2-dimensional or pseudo 3-dimensional; THz tomography schemes have been reviewed elsewhere [1]. In this work, we combined signal processing of THz pulses, which we have previously developed [2], with a standard computed tomography reconstruction method, namely the filtered back projection algorithm [3], but here, the ramp filter function is replaced by the THz pulse signal processing algorithm.

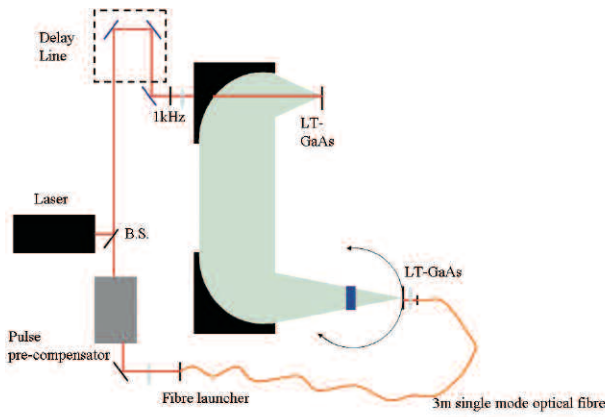

Figure 1. Schematic of terahertz scattering setup.

Construction of a fibre-fed THz detector system

A THz scattering spectrometer was constructed, which had the ability to record scattered waveforms over a 180° range, and this can be seen in figure 1. Briefly, pulses of near infrared radiation (75 fs, centre wavelength 800 nm) were split in two: 70% was used to generate the THz radiation using a photoconductive switch, fabricated on LT-GaAs, with the other 30% being used to detect the THz radiation. The gating beam was initially negatively chirped, using a mini group velocity dispersion compensator, before propagating along a length of single mode optical fibre. The combination of this group velocity dispersion, with the self phase modulation introduced by the optical fibre ensured that the pulses which emerged from the fibre still had a femtosecond profile and could be described as 'ultrashort.' These pulses were then focused onto the THz detector (photoconductive switch). Use of the optical fibre to gate the detector ensured that the optical beam was always correctly incident on the receiver when it was rotated to the various scattering angles, and therefore remained switched 'on'. Pulses of usable bandwidth 1.5 THz were produced by this system [4].

Experimental procedures

In order to test the capabilities of the arrangement, a number of test phantoms were constructed. Cylinders, of diameter 1.37 cm were fabricated from polystyrene: this material serves as a 'mechanical vacuum', having a refractive index of 1 at 1.0 THz. Metallic panel pins of diameter 1.5 mm and length 19 mm, were then inserted in various configurations into the polystyrene cylinders. Another phantom was also constructed, which had an off-centre hole of diameter 4 mm bored out from it. This could be filled with PTFE powder, of average particle size 100 µm, or a small amount of chemical (biotin).

The phantoms were placed at the centre of rotation of the detector, with the focus of the THz beam on the receiver. By setting the distance from the centre of rotation to the detector as 3.5 cm, the whole of the phantom width was illuminated by the THz beam. Since it is known that **E**–polarisation leads to more scattering, the THz radiation was polarised so that the **E** field was perpendicular to the optical bench (i.e. out of the plane of the paper). After recording a reference pulse, with no phantom in the beam, the THz pulses transmitted through the cylinders and scattered at various angles were recorded (between ± 10 and ± 90 degrees in ten degree steps)[4]. Figure 2 shows the orientation of some of the phantoms, relative to the incoming THz beam.

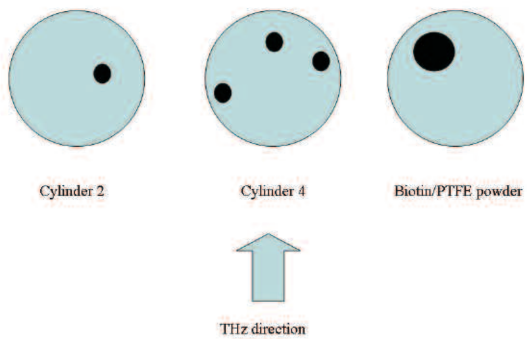

Figure 2. Phantom layout with respect to THz beam.

Back projection

To form the images below a variant of the filtered back projection method was used. Filtered back projection is a common algorithm used in tomography to solve the Fourier Slice Theorem and allows the reconstruction of images from experimentally obtained projection data.

After reconstruction, using the signal processing algorithm[2], the scattered pulses show delays that depend on both the coordinates of the scatterer and the detector angle. For each pixel in the field of view, and for each detector angle, the expected time delay can be calculated and the corresponding value of the reconstructed scattered signal selected. The back projected image is then formed by summing over the range of detector angles.

Results

Figure 3 is the back projected image obtained by signal processing and then back projecting the scattered signals from cylinder 2, containing a single (off-centred) metal

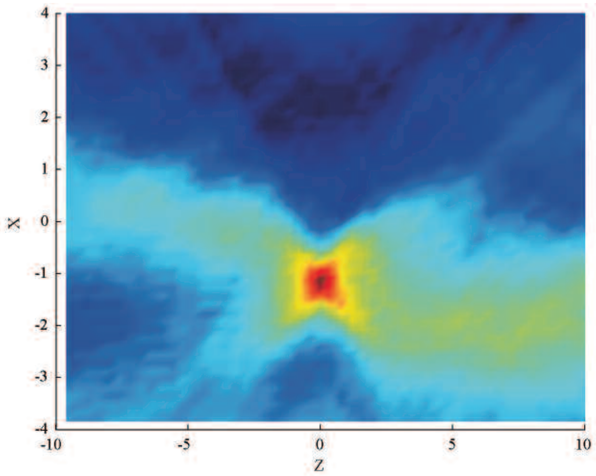

Figure 3. Reconstructed image of cylinder 2.

pin. Since scattered pulses collected over an angular range of ±90° were used, the longitudinal and transverse resolutions are identical (0.3 mm in this case, since the reconstructed source pulse had a full width of 1 ps.)

As more pins were added to the phantoms, the scattered signals became weaker. Consequently, contrast enhancement techniques were applied to the back projected images and figure 4 shows this for cylinder 4. In this image, the separation of the pins are measured to be 4.8, 6.4 and 9.5 mm, which are in very good agreement with the separations taken physically from the phantom, namely 4.7, 6.6 and 9 mm.

Figure 5 shows the back projected image obtained from scattering measurements from a polystyrene cylinder filled with PTFE powder. A clearly defined off-centred image can be seen having diameter of a few mm. The position and size of the image correspond well with those expected. The limited bandwidth of the system unfortunately prevented spectral identification of the PTFE: the first absorption of PTFE in the THz region is at around 6 THz. A similar measurement on a cylinder filled with the chemical biotin, which has resonances in the range of the spectrometer,

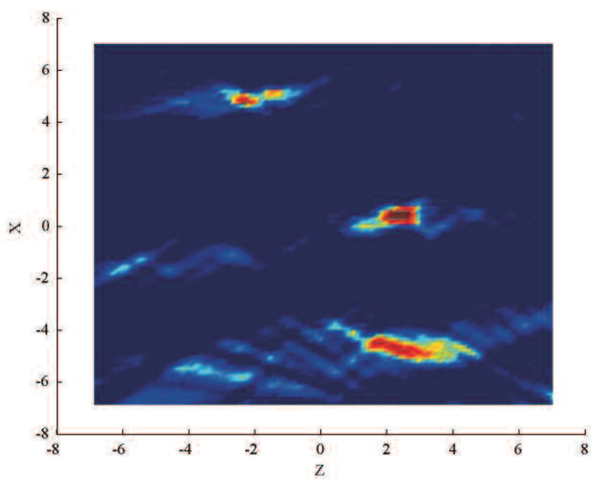

Figure 4. Contrast enhanced image of cylinder 4.

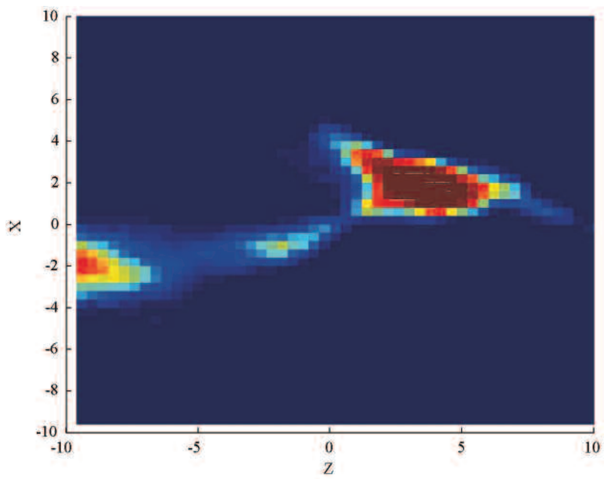

Figure 5. Contrast enhanced image of cylinder filled with PTFE.

failed to accurately locate the powder since too much of the weakly powered beam was absorbed by the sample.

Conclusion

A broadband THz scattering spectrometer was constructed, pumped using the RAL loan-pool laser. This was used to reveal the presence, and determine the dimensions, of metallic cylinders and dielectrics hidden within a plastic container. The system used a fixed source, rotating detector geometry, which is analogous to that routinely used in X-ray CAT scanning, but which has not heretofore been reported at THz frequencies. Scattered signals detected using a coherent scheme, fed with femtosecond pulses from an optical fibre, were reconstructed using a previously reported algorithm and then back projected to form an image of the object under investigation.

This work, undertaken using the loan pool laser, has proven to be extremely useful and has shown that, in principle, it is possible to undertake THz tomography using scattered radiation with a pulsed, broadband source.

Acknowledgements

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