Terahertz Imaging with Antenna Coupled Detectors

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Abstract— **Practical cost effective implementations of imaging systems operating at terahertz frequencies are currently not available. Specifically, imaging at terahertz frequencies still requires advances in technologies such as detectors and sources and imaging techniques to make applications that use these frequencies a reality. This paper discusses work which is advancing knowledge in the terahertz area through development of antenna coupled detectors with an emphasis on their properties in an imaging system.**

I. INTRODUCTION

Today, imaging systems at millimeter and microwave wavelengths have been deployed for a range of applications most of which exploit the wavelength's ability to image through barriers. For example, ground probing radar systems are used in buried void and obstruction detection, X-band mine wall imaging can monitor wall movements through dusty environments [1], automotive radar systems at 35 and 77 GHz are finding wide uptake in adaptive cruise control and collision avoidance for bad weather, and active mm-wave systems at 25-30 GHz are currently being trialed in airports for detection of weapons concealed under clothing [2]. As technology at higher frequencies matures, imaging at these frequencies will become a reality across a broad range of applications. Imaging systems will need to exploit characteristics such as the transmission through materials along with unique interactions that occur at these frequencies. Within CSIRO a team of researchers are exploring imaging issues at these frequencies.

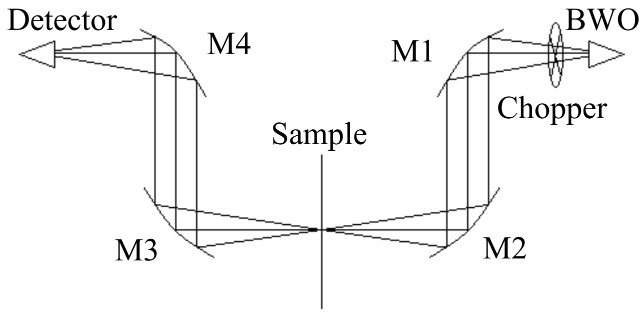
Due to a lack of technology at sub-terahertz frequencies the team is:

- developing the technology needed for imaging,
- constructing imaging techniques suitable at these frequencies,
- and exploring applications.

This paper overviews some of these activities.

II. I IMAGING SYSTEM

To explore applications of terahertz imaging an imaging system was constructed from commercially available components with the aim of rapidly developing an imaging capability. The imaging system [3] design is shown in Fig 1. The system comprises of a Backward Wave Oscillator (BWO) source from Elva-1 and a Schottky diode detector from Virginia Diodes, both operate across a 500-700 GHz bandwidth. The beam from the BWO was chopped by an optical chopper at a frequency of approximately 1 kHz. The diverging beam was then collimated by mirror M1 and focused to a spot by mirror M2. Mirrors M3 and M4 then collimate and focus the energy passing through the sample into the detector. The output signal from the detector was then detected by a lock-in amplifier coherent with the chopping frequency. The sample is then raster scanned through the focused beam to generate images.



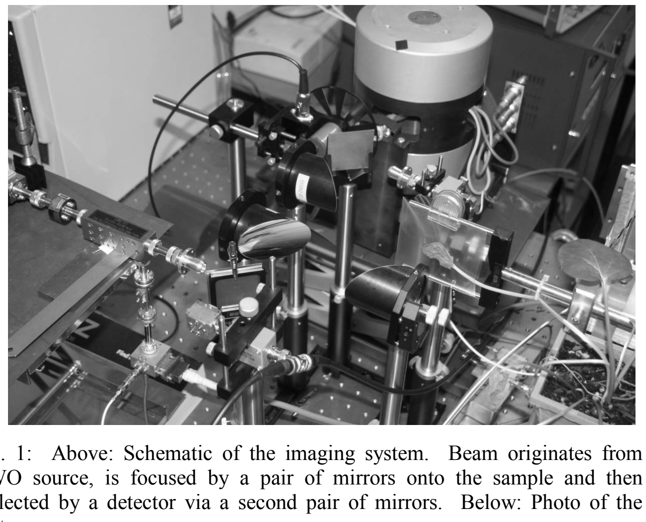


Fig. 1: Above: Schematic of the imaging system. Beam originates from BWO source, is focused by a pair of mirrors onto the sample and then collected by a detector via a second pair of mirrors. Below: Photo of the system.

The quasi-optical design was chosen to minimise the spot size and match the BWO radiation pattern. Therefore mirrors M2 and M3 have a short focal length to maximise the subtended angle at the focal spot, and mirrors M1 and M4 have longer focal lengths to match the radiation patterns of the diagonal horn [4] coupled Schottky diode and the BWO which comprises of an open ended (~WR-10) waveguide output with a similar beam width as the diagnonal horn.

III. HARDWARE DEVELOPMENT

Conventional electronics cannot respond at terahertz frequencies due the limited ability of charge carriers to respond at fast enough rates. Alternative devices need to be employed that respond at these frequencies. One such technology developed at CSIRO is based on superconducting junctions integrated into an antenna design (Fig 2) which is optimally matched into the imaging system. The device is integrated into a ring-slot antenna on a MgO substrate which is mounted on a lens and coupled into the imaging system. The beamwidth of the antenna is selected to optimally match into the quasi-optical imaging system.

The superconducting Josephson junction devices have the potential to operate at high temperatures (77K) and therefore the cooling requirements are less stringent than equivalent cooling systems operating at low temperatures (4K). The ring-slot antenna is resonant at 600 GHz, and has a directive and highly Gaussian pattern into the substrate. A co-planar waveguide is used for DC probing of the superconducting device. An RF choke was implemented to isolate the DC probing structure from the terahertz antenna.

The MgO substrate has a permittivity of ~10. MgO is used because it is the lowest permittivity material whose crystalline lattice matches that of the crystalline YBCO superconducting device. A high resistivity silicon lens is attached to the rear face of the MgO substrate. Because the substrate is electrically thick (0.5mm thick with 0.5mm free space wavelength) trapped modes occur in the substrate. The hemispherical lens eliminates these modes. High resistivity silicon material is used for the lens to ensure low loss inside the material and minimal reflection between the MgO substrate and silicon material which have similar values for permitivity. The silicon-air interface will still produce significant reflection and an anti-reflection coating has not been implemented at this point to rectify the problem.

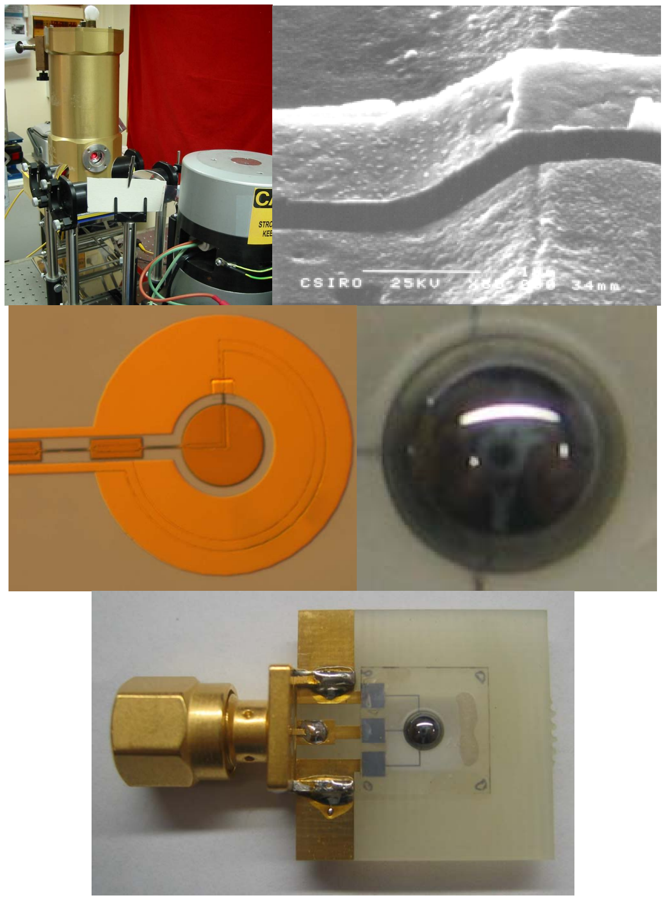


Fig. 2: Detector integrated into imaging system. Top left: Imaging system using a superconducting detector in a cryo-cooler. Top right: Superconducting junction device. Middle left: ring-slot antenna. Middle right: silicon substrate lens. Bottom: detector.

IV. IMAGING TECHNIQUES

Imaging algorithms have been applied at these frequencies. These include super-resolution methods [5] based on knowledge of the system point spread function and focus-free imaging with amplitude only measurements [6, 7]. Focus free imaging can be achieved by measuring the amplitude and phase of a field and backprojecting to the region where the image needs to be formed. The difficulty of this technique at terahertz frequencies is that coherent detection is far harder than amplitude only detection. This is especially true when considering future arrays built from these detectors. Arrays utilising coherent detection typically require a local oscillator signal for the mixers. Distributing the local oscillator to all elements in the array in a manner that maintains phase stability is a significant problem. Direct detectors; however have no need for local oscillators, but do not provide phase information of the received signal. Here a phase retrieval technique has been utilised to solve this problem. Fig. 3 demonstrates the capability of amplitude only measurements to be used in a focus-free imaging system. By measuring the field amplitude on two planes, the field's phase is reconstructed. Reconstruction occurs by minimisation of a cost function which depends on the ability of the estimated

field to generate the measured amplitude distribution and additional known constraints such as the extent of the target being imaged. The final target image is generated by back projection. These techniques have been applied at 200 GHz where the fields phase has been measured to verify algorithms accuracy and at 600 GHz where only amplitude information is available.

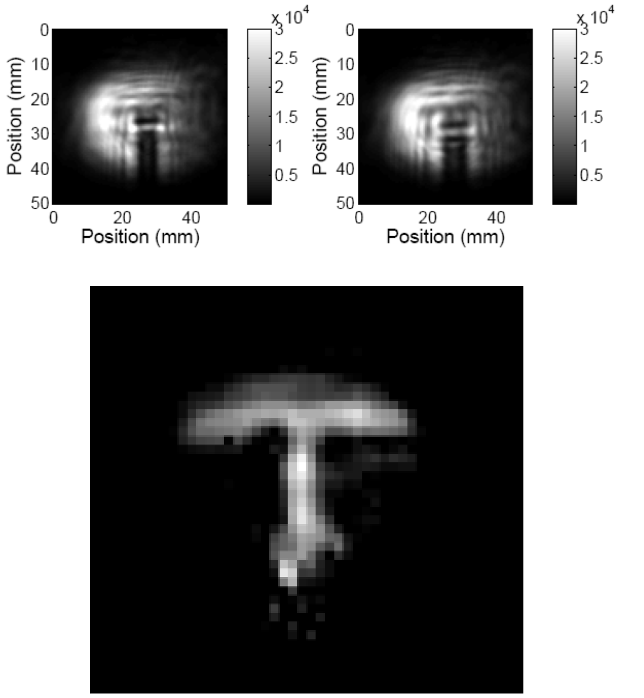


Fig. 3: Top: left and right: images of the field amplitude on two planes. Bottom: image resulting from back projection to the plane in which a thumb tack target is located.

V. Application Exploration

Any application needing terahertz should exploit its unique characteristics such as large bandwidths, penetration through materials, high resolution, sensitivity to water or other characteristics. For example similar to x-ray systems terahertz can image through a range of packaging and clothing materials; however, compared to x-ray systems, terahertz systems are people safe and cheaper.

Fig. 4 shows some examples of transmission images of common materials with terahertz images overlaid.

Fig. 4: Top: transmission images of floppy disk. Bottom: chocolate bar with concealed razor blade.

The images in Fig. 4 demonstrate a number of things. First of all terahertz has the ability to penetrate through a range of materials such as plastics and paper, furthermore terahertz is sensitive to concealed structures such as blades, and even raised lettering as is the case in a chocolate bar. Although x-ray systems are capable of generating similar images, terahertz is non-ionising and hence safe for people. The region over which the samples are imaged at terahertz is approximately 5cm x 5cm and the resolution of the system can be inferred from the images at approximately 1mm. The diffraction limited resolution of the system optics is 0.8mm at 600 GHz and the images appear to demonstrate features approximately 1mm in size, indicating the suitability of the antennas in the system. The images were acquired using Virginia Diodes detectors with a beam width equivalent to the antennas mentioned in Section II.

VI. Conclusions

Terahertz imaging offers an intriguing new class of applications for imaging; however, a lack of technology is holding the area back. This team has built a terahertz imaging system and has demonstrated imaging through plastic

materials and packaging. The ultimate aim is to build a compact scanning imaging system for a variety of applications.

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