Characterisation of Terahertz Beam Profile and Propagation through Complex Quasi-Optic Systems

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Abstract: We report on a simple technique, readily applicable to existing Terahertz Time Domain Spectroscopy (THz-TDS) systems, that allows the spatial distribution of the terahertz beam to be resolved in both the temporal and frequency domains. It requires minimal equipment and no adjustment of the pump/probe path lengths of the electro-optic detection system. While THz TDS has become widely used, in many cases a considerable amount of unknowns exist regarding the THz beam profile and its evolution as it propagates through the system. Misalignment and poor beam shape can lead to results with reduced amplitude of detected frequency components, frequency shifted components, and narrowed spectra. [1] Characterization of the beam profile allows for better alignment of the optics, increased efficiency and improved measurement accuracy. We present the results of this technique and compare them with a model of Gaussian beam optics.

Keywords: Terahertz, Quasi-optical, Beam profile, Coherent, Time-domain Spectroscopy

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1. INTRODUCTION

Terahertz Time Domain spectroscopy (THz-TDS) due to the broadband nature of the radiation and the strong molecular absorption lines present in this frequency band, has found many applications in the identification of chemical compounds across a wide variety of sectors including: pharmaceuticals, medical imaging, defence and security. In order to improve the efficiency and accuracy of THz-TDS systems used to perform these measurements, a full characterisation of the propagation of terahertz pulses is necessary. This requires that both the temporal and spatial variations of the electrical field be recorded [2].

In practice, the temporal evolution of THz pulses has been studied in detail both theoretically and experimentally; while studies into the spatial distribution of the E-field have been lacking [2] as result of a number of factors. First, THz-TDS systems generally record measurements in the focal plane of the system, where the spatial distribution is small and the wavefront is assumed to be planar [3]. Second, the measurement of the spatial distribution is inconvenient and time consuming.

Several methods have been developed to spatially resolve THz pulses: Jepsen and others have used a single spot detector scanned transversely through the beam [4-6], Zhang and co-workers have recorded the electrical field in two dimensions with an Electro-Optic crystal coupled to a CCD camera [7-9] and Bitzer et al. have used a gimbals mounted mirror to scan a THz beam across a standard THz-TDS detector [2]. These methods tend to suffer from several problems: constant re-alignment of the laser in the first case [2], small dynamic range and poor signal to noise characteristics of CCDs [2], and significant space to operate. These set-ups are especially designed to spatially resolve the electromagnetic field with a single element under test, and are not readily adaptable for use with pre-existing multi-element systems.

We report on a simple technique, readily applicable to pre-existing THz-TDS systems, that allows the spatial distribution of the terahertz beam to be resolved in both the temporal and frequency domains, with no adjustment to the setup necessary.

2. EXPERIMENT

The system under test has a typical THz-TDS configuration. The activating laser is a mode-locked Ti:Sapphire laser, having a peak wavelength of 800 *nm*, a repetition rate of 77 *MHz*, a pulse length of 20 *fs* and an average power of 450 *mW*. The output of the Ti:Sapphire is split into pump and probe beams. The terahertz source is a biased GaAs photoconductive emitter. The THz beam is directed through the path by a set of four off-axis parabolic mirrors: within this system there are two measurement locations. The first, between mirrors M2 - M3, contains a focus, used for imaging samples; the second, between mirrors M3 - M4, where the beam should be collimated, is used for spectroscopy (see Fig. 1). The THz radiation is detected electro-optically using a ZnTe crystal.

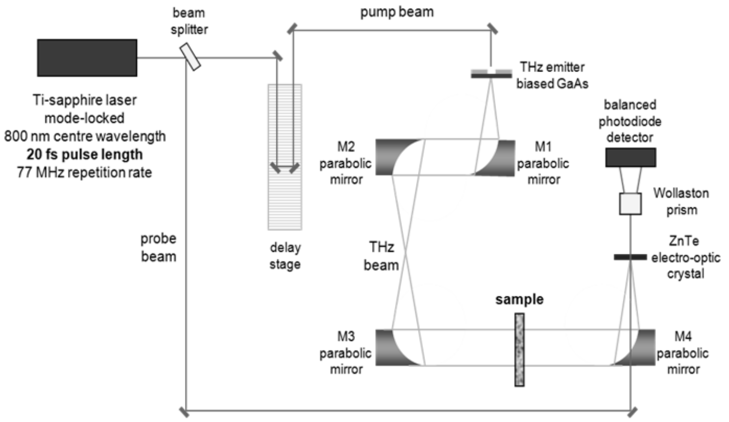

Fig. 1 Schematic of THz - TDS system

To image the terahertz beam profile, a large beam stop with a small aperture mounted on an X-Y translation stage was placed in the beam path. As the aperture samples the beam spatially at whichever point it is placed, a complete coherent image of the beam profile can be built up through raster scanning the aperture across the beam path. The selection of the aperture size is of considerable importance, such that a balance can be found between spatial resolution and signal to noise ratios, for the extremely broadband and spatially divergent THz pulses.

To determine the minimum aperture that would allow acceptable discrimination of the signal from noise, an adjustable iris was placed in the centre of the beam between mirrors M3 and M4. The diameter of the iris was reduced in 0.5 *mm* steps from 5.0 to 1.5 *mm*, and a spectrum recorded for each (see Fig. 2). Due to the stability of the pump laser, a value one order of magnitude greater than the noise floor (5 x 10^{-8} in Fig. 2) could be safely selected as the minimum detectable signal. This corresponds to an iris diameter of 2 *mm*.

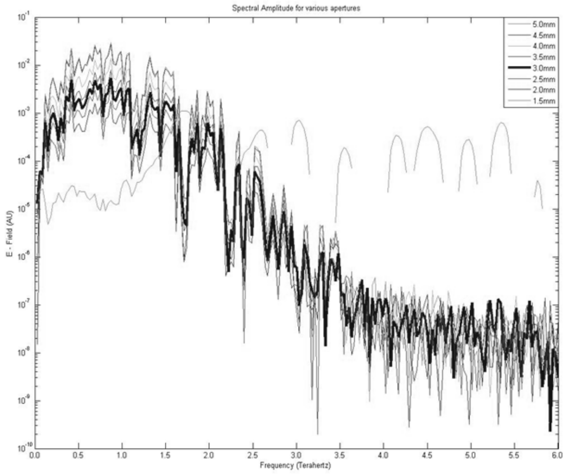

Fig. 2 Spectral amplitude of THz Pulses

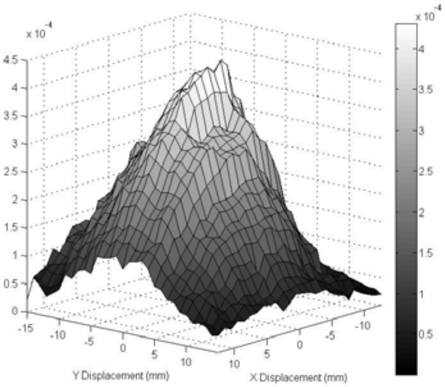

Fig. 3 Spatial distribution of E- field 220mm from M3

Aperture sizes were determined so that the first minimum of the circular diffraction pattern would fall on the edge of the M4 (which has a radius of 37.5 *mm*), using the simple diffraction equation for a single slit [9]. Hence for the two extremes of the pulse wavelength 300 *um* and 100*um*, the minimum apertures that would satisfy this condition were 5.17 *mm* and 1.72 *mm* respectively. An intermediate diameter of 3 *mm* was selected, as it would allow good signal discrimination and spatial resolution, because the longer wavelengths carry more of the pulse intensity

The X-Y translation stage on which the aperture was mounted had an effective range of 24 *mm* in both axes; by sampling the beam every 1.5*mm*, an image of 16x16 "pixels" was produced. The imaged area was extended though interleaving a series of images, which combined to cover a square area of 39x39 *mm* represented by an array of 26x26 "pixels". The beam was sampled at 6 locations: 3 between mirrors M2-M3 including the focus, and 3 between mirrors M3 – M4. The spatial distribution of the E-field 220*mm* from M3, recorded as the maximum of the time domain peak, is shown in Fig. 3.

3. RESULTS

The optical components are aligned using the infrared pump laser beam, based on the assumption that beam propagation is similar for near IR and THz radiation, and follow the basic theoretical model for the propagation of Gaussian laser beams as described by Kogelnik & Li [10]. To test the validity of this assumption and the accuracy of the imaging method we will consider the beam intensity as represented by the maximum of the time domain peak, and compare it with the model (see Table 1).

The rate of divergence of the THz beam is $0.066°$, i.e. more than 2.5 times greater than that predicted by Kogelnik & Li's formalism [10], which gives for the two extreme wavelengths of the broadband THz pulse $0.025°$ for $300\ \mu m$ and $0.0015°$ for $100\ \mu m$.

The observed deviations of the results from theory may be due to several factors. First, the beam is not truly Gaussian in nature, this can be observed by comparing the measured beam profiles with model Gaussian profiles, so this treatment can only be an approximation. Second, the source is extremely broadband, the contribution of various wavelengths to the peak of the pulse changes in a continuous fashion as the plane of detection moves through the focus. Third, the distance between mirror M2 and the focus is close to the Rayleigh length of the beam [8], so small experimental errors in the measurement of distances from the mirror can contribute to large angular deviations.

Tab.1 Beam diameters, measured using the time domain peak, and theoretical predictions.

Position	Distance (mm)	Measured Diameter (mm)	Theoretical Diameter (mm) for λ= 300 μm	Theoretical Diameter (mm) for λ= 100 μm
From centre M2	122	4.68 ± 1.25	3.85	2.2
	150	1.57 ± 0.68	3.78	2.18
	160	2.43 ± 0.69	3.79	2.18
From centre M3	80	9.55±3.0	5.60	2.94
	150	11.17±3.0	6.08	3.38
	220	13.0±3.0	6.69	3.75

4. CONCLUSION

We have developed and demonstrated a novel method of characterising coherently the spatial beam profile of a pre-existing THz-TDS system. The techniques and equipment necessary to implement this method are readily accessible to the majority of terahertz experimentalists. The advantage of this method over others documented in the literature is that there is no adjustment to any of the system optics. Hence the pump/probe optical path lengths remain constant and phase delays may be conveniently observed. Using this method we have spatially resolved the beam path of a functioning THz TDS system in a coherent fashion. These results have allowed us to confirm the accuracy of using a near-IR beam to align terahertz optics, and validated the use of generic Gaussian optics to calculate the position of beam waists, although not the spot sizes.

5. ACKNOWLEDGEMENTS

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