Multichannel Continuous-Wave Terahertz Imaging

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***Abstract* - We demonstrate an all-optoelectronic, continuous-wave (cw) terahertz spectroscopy and imaging system based on temperature-tunable diode lasers. Time-domain waveforms are acquired for each pixel, and the use of multiple frequencies enables spectroscopic image display modes. We discuss the separation of the amplitude and phase parameters, and compare the accessible information with that obtained using pulsed terahertz systems.**

Applications using terahertz (THz) frequencies in the electromagnetic spectrum have attracted considerable interest in recent years, accompanied by the ongoing development of THz sources, detectors and optical systems [1]. Both imaging and spectroscopy can contribute to areas including medical diagnosis and surgical aids [2], security screening [3,4], quantitative analysis and non-destructive testing. Particularly prominent are systems that rely on the production of single-cycle pulses, using a femtosecond laser to excite photoconductive antennas. This enables the use of a coherent, phase sensitive detection scheme [5], which allows the THz electric field to be measured in the time domain. Such systems allow image and spectroscopy data to be obtained simultaneously, to yield a multitude of information at each image pixel, and through barriers – a property unique to THz technology.

Femtosecond lasers are, however, relatively costly and bulky, which might restrict their suitability for some potential applications. In contrast, compact and inexpensive diode lasers can be used for the generation of continuous-wave THz (cw-THz) radiation by photomixing in a photoconductor [6]. The beat frequency between the detuned lasers is adjusted to the required THz frequency, and quasi-monochromatic cw-THz radiation is emitted. Coherent detection is possible in the reverse scheme [7]: when the THz radiation and laser beat modulation arrive at a photoconductive receiver, a dc current is detected, with a magnitude that varies with their relative phase. Shifting the optical beat using an oscillating time delay line constructs an interferogram, containing amplitude and phase information about the THz electric field as with the pulsed case.

In recent work, we have demonstrated all-optoelectronic photomixing systems based upon both external cavity [8], and free-running diode lasers [9], which have shown that the requisite signal-to-noise ratio is possible with such lasers, and a dynamic range of up to 60 dB was achieved. However, these systems operated in a monochromatic mode, and consequently delivered little spectral information. Many previous demonstrations of such cw systems for imaging took their contrast simply from arbitrary changes in the amplitude of the reflected or transmitted THz wave [8,9], yielding information about the absorbance or reflectance of the sample as a function of lateral position. However, it is often desirable to image samples that do not display sufficient contrast in these modes. As an example, we discuss the medical application of cancer detection.

Previous work has focused upon the pulsed terahertz study of basal cell carcinoma, both *in vivo* and *ex vivo* [2], and has suggested that contrasts exist at relatively low THz frequencies (< 1 THz) that *may* enable the cancer to be diagnosed and the extent to be assessed. To exemplify preliminary images obtained using a cw-THz system, figure 1 shows a photograph of a sample of healthy human skin tissue, along with corresponding cw-THz images taken at two distinct, monochromatic frequencies. It is clear that the use of multiple frequencies reveals different contrasts present between the tissue types in the sample. The origin of these contrasts has been the subject of much debate, and may be attributed to a difference in water content, increased cell densities, or the presence of particular proteins.

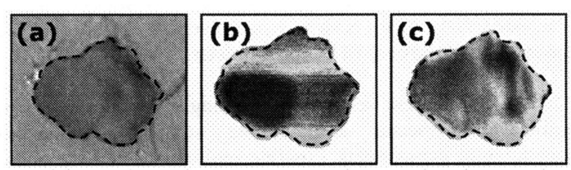

Fig. 1. *(a) Visible photograph of human tissue sample; (b) cw terahertz image at 0.31 THz; (c) cw terahertz image at 0.53 THz.*

More recent studies have been since made to explore the possible use of THz technology to examine excised breast tissue for malignant tissue during surgical procedures [10]. Comparisons with histology have suggested that it is possible to distinguish between healthy and diseased tissue in this case, but again, the source of the contrast is not well understood. Significantly, it is found that in reflection, this contrast is not manifested in the frequency domain as a spectroscopic signature: instead, the information is derived from subtle changes in the shape of the THz electric field pulse in the time domain [10]. Regardless of the ultimate physical origin of this contrast, an obvious question is raised: can these phase contrasts be observed using cw-THz technology?

In principle, all of the information provided by the phase of a reflected THz broadband pulse could also be probed using a cw-THz system, so long as *a priori* knowledge is assumed regarding the frequencies of interest, and a phase-sensitive detector is used. Our cw-THz system (figure 2) is driven by

two independent TOPTICA Photonics distributed feedback (DFB) diode lasers operating at around 860 nm, and combined using a quartz beamsplitter. The resulting beams are focused onto the emitter and detector photomixers, with a time-delay stage in the detector beam. The combined optical power at the emitter and detector is 60 mW and 30 mW, respectively.

For our photoconductors, we have used highly resistive low-temperature-grown gallium arsenide (LT-GaAs) with sub-picosecond carrier-trapping times [9]. At the feed points of each antenna are interdigitated finger photomixers, 8 μm square. A bias of ±20 V is applied to the emitter electrodes, which draw up to 1 mA of current. THz power is coupled out of the emitter using a hyper-hemispherical silicon lens. The emitted THz beam is brought to a focus on a horizontal imaging plate using off-axis f/1 parabolic mirrors. Automated translation stages are then used to move the sample through the THz focal point in the (*x,y*) plane. For detection, the output signal is fed to a lock-in amplifier, referenced to a 25 kHz modulation in the emitter bias.

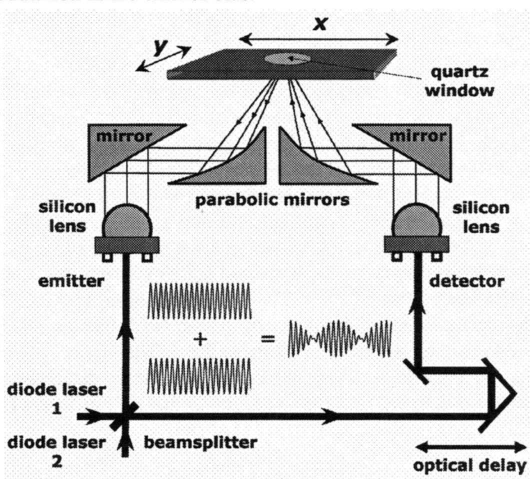

Fig. 2. *Cw-THz schematic diagram of the beamsplitter, optical delay line and imaging mirrors. The THz beat of the overlapped optical beams is shown inset.*

This system is able to obtain monochromatic images at frequencies in the continuous range 0.1-1 THz, and the amplitude and phase parameters are best extracted using a multi-pixel curve fitting function in the time domain. Comparison of data from two or more images at different frequencies allows the differential phase change of the reflected waveform to be plotted. The cw-THz system presented here is ideal for such studies, since the frequency can be precisely tuned by remotely varying the temperature of the cavity.

In order to investigate the simultaneous acquisition of multiple frequencies, two diodes were forced into a multi-frequency output by deliberately misaligning an external cavity. The result was highly-stable, multi-longitudinal mode lasing, yielding up to six modes. In figure 3(a), we show the time domain interferogram at a nominal central frequency of 0.4 THz. The signal-to-noise ratio is of order 100:1, and is modified from a simple sinusoidal form, owing to the multiple frequency content. The spectral data is recovered from a Fourier transform, as shown in figure 3(b).

The distribution of components would appear to be consistent with the allowed external and internal cavity modes. The 'comb' of multimode frequencies generated from each diode laser is essentially up-converted – by cross-correlation with the other laser – to provide THz power centred on the higher difference frequency. The spectrum is the linear superposition of all the available difference frequency modes.

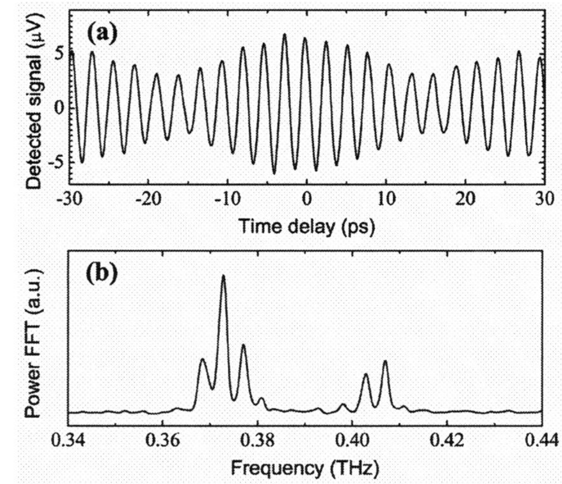

Fig. 3. *Cw-THz emission from a multimode photomixing system. (a) the time-domain waveform with multiple frequency components; (b) the Fourier transform.*

In summary, we have demonstrated a multi-frequency quasi-spectroscopic cw-THz system. Preliminary analysis indicates potential for reproduction of contrasts seen in the analysis of pulsed THz time domain waveforms. This is particularly important for the imaging of soft tissues that exhibit low spectral contrasts.

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