Applications of Terahertz Imaging

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1. Introduction

The recent advances involving imaging with sub-picosecond terahertz pulses [1,2] have opened up a wide range of possibilities in the applications of far-infrared technology. For the first time, a commercially viable terahertz imaging spectrometer seems a realizable prospect. However, several substantial engineering research challenges remain to be overcome before this goal can be achieved. One of these involves the necessity for a femtosecond laser system, required for gating the emitter and receiver antennas used in the THz-TDS system. Although the solid-state mode-locked laser systems have made substantial progress in recent years, they may not yet be suitable for a commercially viable spectrometer. An alternative laser source, the erbium-doped fiber laser is a better option, but adapting the THz-TDS system for use with this laser is not trivial.

A second challenge to be faced involves the signal processing used to extract information from measured THz waveforms. The demonstration experiments performed to date have employed rather crude signal processing algorithms. The shortcomings of these are evident in some of the results presented here, highlighting the need for a more sophisticated treatment. Although the details of the signal processing procedures will depend to a great degree on the particular application of interest, there are several core issues that are common to a wide range of problems. These include the deconvolution of instrument response functions and the implementation of effective noise removal procedures. Since the underlying waveforms in the THz system (e.g. Figure 1) closely resemble the elements of a *wavelet* basis, wavelet-based signal processing strategies are likely to be extremely effective.

2. Applications of THz Imaging

One of the most interesting characteristics of THz-TDS is the extremely short duration of the THz pulses. Because many materials have strong absorption or dispersion features in the far infrared, the temporal distortions which are imposed on the sub-picosecond pulses are characteristic of the materials with which the radiation has interacted. As a consequence, the distortions of the time-domain THz waveform can be used to identify or characterize the materials [3]. An example is shown in Figure 1, which depicts the waveforms (a) incident on and (b) transmitted through a block of epoxy. The strongly frequency-dependent refractive index of this material is evident in the 'chirp' exhibited by the transmitted waveform.

Figure 1 THz waveforms (a) incident on and (b) transmitted through a block of epoxy. The chirp imposed on the waveform is characteristic of the material, and may be used for materials identification, in conjunction with imaging.

Figure 2 THz image of a portion of an automobile dashboard, in which a small bubble in the impact foam is clearly evident (white area, at left).

Many industries require monitoring technologies which can perform quality control inspections through opaque materials such as cardboard or plastic. Because these materials are transparent in the THz range, this technology is well suited for such applications. An example is shown in Figure 2, which is a THz image of a portion of a dashboard from an automobile; this structure consists of two molded hard plastic shells with a soft shock-absorbent foam filling the region in between. An air bubble in the foam filling, invisible through the opaque plastic shells, is easily visible in the THz image. This image was generated using real-time signal processing on the transmitted terahertz waveforms [1,2].

This technique is quite general; images can be generated of a wide range of samples, including many packaged food products, and countless plastic and composite parts such as the packaging for

Figure 3 THz waveforms (a) incident on and (b) reflected from a 3.5-inch floppy disk. Curve (c) represents curve (b) after deconvolution of the instrument response.

radiation is attractive in many quality control applications, particularly in consumer products manufacturing. The coherent detection of the THz waveform also permits imaging of thermally active media, an ability possessed by no other far-infrared detection system. This may be of interest in high temperature materials processing such as ceramic sintering, or in the monitoring of moderate to high density plasmas. The extreme sensitivity of THz radiation to liquid water is of interest to the plastics industry. Other applications include cutaneous imaging for biomedical diagnostics, agricultural monitoring, and gas sensing and detection [3].

3. Towards a Commercially Viable THz Imaging System

A number of improvements must be made to the next generation THz-TDS system in order for any of the applications under consideration to be feasible. Primary among these is the issue of the femtosecond laser system. Currently, there exists no femtosecond laser that is sufficiently isolated from mechanical perturbation, except for the erbium-doped fiber laser systems. However, adapting the THz-TDS system for operation with a fiber laser raises a number of significant engineering challenges. Of equal importance is the need for robust signal processing methods, for extraction of meaningful data from the measured THz waveforms. The signal processing challenge in the THz system addresses the following question: given an input waveform (which may be taken as characterizing the system response) and a reflected or transmitted waveform (which has been modified by interaction with a sample), what is the optimal procedure for extracting the desired information about the sample under study? Of course, the information to be extracted varies with each application. Despite this, a number of common issues exist, including noise reduction, artifact removal, and deconvolution.

The engineering challenges which arise in modifying the THz-TDS system for use with a fiber laser lie primarily in the THz transmitter antenna. These antennas are typically lithographically defined on a gallium arsenide (GaAs) or low-temperature-grown GaAs (LT-GaAs) substrate, which acts as the photoconductive switch for the generation process. However, these semiconductors do not absorb light at the wavelength of the fiber laser.

One strategy for dealing with this difficulty involves shifting the wavelength of the output pulses via non-linear mixing. Frequency doubling the output of a femtosecond fiber laser has been explored by a number of researchers recently [5,6]. Average powers as high as 8 mW have been reported in the second harmonic pulses, at ~ 780 nm. While this power level is not sufficient for THz generation and detection, the recent advances in the development of periodically-poled non-linear materials are quite promising.

A second strategy is to develop new materials which are active at $1.55 \mu\text{m}$. For a photoconductor to efficiently generate and detect femtosecond electrical transients, it must meet the following benchmarks: 1) carrier lifetime less than one picosecond, 2) mobility greater than $100 \text{ cm}^2/\text{V-s}$, 3) resistivity greater than $10^5 \Omega\text{-cm}$, and 4) optical absorption greater than 10^4 cm^{-1} . Non-stoichiometric GaAs (LT-GaAs) possesses all of these qualities when pumped at a wavelength near 800 nm, as do other semiconductors of comparable band gap, such as InP [7]. Other materials, such as InSb [8], have been explored at longer pump wavelengths. A number of candidate materials exist for operation at the fiber laser wavelength, including ion-implanted germanium [9] and low-temperature-grown quantum wells [10].

Effective means for processing the measured THz waveforms, including noise removal, artifact and system response deconvolution, and advanced image formation, are a crucial component of a useful THz system.

integrated circuit chips. Images can also be generated in a reflection, rather than transmission, geometry. The sub-picosecond duration of the reflected waveform can be used in a tomographic imaging mode, to construct a three-dimensional image of the sample [4]. Figure 3 shows an example, in which an incident waveform (a) is reflected off of a conventional 3.5-inch floppy disk. Each of the dielectric interfaces which comprise the sample is visible in the reflected waveform (b), including the front and back surfaces of both the front and rear plastic cover, and the magnetic recording material. Curve (c) represents the results of curve (b) after deconvolution of the instrument response, represented by (a). This procedure permits resolution of the front and back surfaces of the thin magnetic recording material, unresolved in the raw waveform (b). This highlights the importance of a robust deconvolution procedure, which can be implemented in a real-time imaging mode.

The unique aspects of this new imaging technology have attracted interest from a number of industries, primarily in the manufacturing sector. The ability to image through most common packaging materials without the need for x-rays or other ionizing

Traditionally, signal processing has been carried out in the frequency domain using the Fourier transform, which analyzes and represents signals in terms of sinusoids of different frequencies. While the narrowband sinusoids of the Fourier representation may be an excellent match for continuous wave signals, these functions do not match the broadband, transient nature of THz pulses. Since THz pulses are localized in both time and frequency, they are naturally suited to signal processing methods based on *wavelets*. The wavelet transform performs a 'local Fourier analysis' by analyzing and representing signals in terms of shifted and dilated versions of time-localized, oscillating functions. It has been shown that noise removal, compression, and signal recovery methods based on wavelet coefficient shrinkage or wavelet series truncation enjoy excellent asymptotic performance and moreover, do not introduce excessive artifacts in the signal reconstruction [11]. The same properties are *not* shared by the Fourier representation. Thus wavelets are a natural tool for addressing the challenges presented by the THz-TDS system.

An excellent example of a case where wavelet signal processing will be extremely beneficial is in signal denoising. White Gaussian noise can arise in signal acquisition from a number of intrinsic sources, such as Johnson noise in the detectors. A simple yet effective approach to dealing with this is *wavelet thresholding* [12]. Since the basis functions of a wavelet analysis closely match the transient pulses of a THz waveform, the wavelet transforms of the THz waveforms are strongly peaked, with only a few coefficients of large amplitude required to represent the waveform. In contrast, the wavelet transform of white noise is distributed, with many coefficients of smaller amplitude. Thus, a simple strategy to separate signal from noise is to threshold the wavelet transform of the noisy signal. Figure 4 is an example which demonstrates the power of wavelet thresholding in signal denoising.

Another important source of noise in these measurements is the pulse-to-pulse amplitude fluctuations of the femtosecond laser. The spectrum of this noise source closely resembles a 1/f source [13]. Current wavelet denoising strategies are not optimized for colored noise, and so modified algorithms must be developed.

Figure 4 (a) Raw signal (typical waveform reflected from floppy disk; see Figure 3). (b) Curve a, supplemented by additive white Gaussian noise, to artificially simulate noisy data (c) Signal denoised with a Fourier method (convolution with a Butterworth filter) (d) Signal denoised using wavelet thresholding. Note how in addition wavelet thresholding can be used to remove most of the signal artifacts.

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