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Hyperspectral Terahertz Tomography in Amplitude Contrast

Miguel A. Banuelos-Saucedo and Krikor B. Ozanyan, Senior Member, IEEE

Abstract—Hyperspectral tomography in THz amplitude contrast is presented using a time-domain spectroscopy system in the spectral range 0.3 - 2.5 THz. The Fourier transformed signal data is used to reconstruct test objects' cross-sections at multiple frequencies using standard filtered backprojection. The full hyperspectral set of images reconstructed at around 300 adjacent spectral points is used to trace the combined contribution of Beer-Lambert volume attenuation, Fresnel reflection losses and Rayleigh roughness scattering losses, which is in good overall agreement with the experimental results. The image quality for Styrofoam (refractive index around 1.02, attenuation coefficient $< 1 \text{ mm}^{-1}$) test objects is best in the range 0.8 - 2.0 THz depending on the porosity of the material.

Index Terms— THz, hyperspectral imaging, hard-field tomography, Rayleigh roughness, time-domain spectroscopy.

I. INTRODUCTION

THz radiation has the ability to penetrate some dielectric materials such as paper, cardboard, ceramics, plastics and textiles [1]. This has motivated the development of imaging and tomography systems at these frequencies [2, 3]. Applications include spectroscopic identification and imaging, non-destructive evaluation, security inspection and defect detection, among others. Many THz systems require a bulky laser but, in search of practical applications, there has been a growing interest in developing THz portable systems [4, 5]. Advances in technology have enabled the development of reduced footprint THz systems based on communications lasers around $1.5 \mu\text{m}$. It is expected that continuous wave (CW) THz sources, such as a quantum cascade laser (QCL) will have a greater role in the development of compact THz imaging systems.

Examples of THz tomography imaging have been reported to date using THz pulsed [1, 6-8], or continuous wave (CW) sources [1, 9-11]. Results achieved by time-of-flight or phase contrast with pulsed sources are the most convincing yet. These methods employ the time domain characteristics of the signal and do not depend on the various mechanisms competing in the

attenuation of the transmitted photon flux. However, with the progress in the CW THz sources, imaging in amplitude contrast is expected to rise to a greater relevance. CW narrowband systems will allow imaging in THz amplitude contrast at discrete wavelengths important for security and non-destructive testing. To achieve indirect imaging from the amplitude of the transmission beam hard-field tomography, it is also essential to understand and manage the soft-field scattered component in the transmitted THz signal; problems associated with THz computed tomography include Snell and Fresnel refraction [12-15], and Gaussian THz beam profile [16]. The novelty in this work is that using a pulsed THz tomography system wide spectral information is accessed, over one order of magnitude in wavelength, to study the quality of the hard-field reconstructed images as a function of wavelength. This allows to infer the wavelength dependent scattering contributions and thus potentially the wavelength range where reliable hard-field imaging is still possible.

II. EXPERIMENTAL SETUP

The implemented system is based on a THz time-domain spectroscopy system (THz-TDS), built around a Ti:Sapphire laser (Coherent MIRA 900), pumped by a solid-state laser (Coherent Verdi V18). The Ti:Sapphire laser produces 150 fs pulses @ 76 MHz with 800 nm wavelength. A large aperture ($400 \mu\text{m}$) GaAs photoconductive antenna, biased at 180 V DC and electronically modulated at 10 kHz, is used to generate the THz pulsed radiation. Detection is performed by electro-optic sampling in a 2 mm thick ZnTe crystal. A quarter-wave plate (Newport 10RP14-28), a Wollaston prism (Thorlabs WP10) and a balanced detector (Newport 2007) are used to analyze the signal. Demodulation is achieved by a lock-in amplifier (Signal Recovery 7265)[17].

The tomography setup (Fig. 1) utilizes two identical sets comprising a couple of metallic off-axis collimating and focusing parabolic mirrors (EFL= 50.8 mm and 177 mm), producing a THz beam waist that is used to probe the attenuation path integrals of the imaged object. A couple of 4

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mm iris diaphragms (apertures) are placed in front of and behind the object to suppress off-waist scattered photons and favor the detection of hard-field photons. Knife-edge test estimates indicate a beam waist diameter of 5 mm @ 0.586 THz with an effective Rayleigh range of 67 mm @ 0.586 THz. Similar to [6], each tomography projection (i.e. a set of multiple parallel beams at a fixed angle) is acquired by moving the object across the THz beam waist using a linear translation stage. Projections at additional angles are generated by placing the imaged object on a rotational table. In the chosen configuration, the THz radiation incident to the test objects used is s-polarized.

Fig. 1. Experimental setup of a THz time-domain spectroscopy system adapted for tomography.

Unavoidably, the iris diaphragms substantially reduce the signal, since they block a portion of the THz beam, thus affecting the noise performance of the system. The signal-to-noise ratio (SNR) of the system was estimated as

$$SNR_{dB} = \log \frac{\text{mean amplitude}}{\text{standard deviation of amplitude}} \quad (1)$$

for a set of ten consecutive measurements. The SNR of the system is plotted in Fig. 2. A minimum of 25 dB dynamic range is obtained in the operating range of 0.3 THz to 2.5 THz. This threshold may limit the dynamic range of reconstructed images and it is set substantially below the common SNR figures found in the literature for THz-TDS systems (60 dB and above) due to the use of apertures imposing an order of magnitude amplitude reduction. Nevertheless, the obtained threshold is justified, as shown further, by the overall satisfactory quality of the THz images reconstructed in that frequency range. Above 2.5 THz, the response is limited by the finite bandwidth content of the signal pulse and frequency limitations of the electro-optic sampling performed with the ZnTe crystal.

This work takes advantage of the spectral information contained in the transmitted THz pulse. The access to a wide uninterrupted operating spectral range in THz-TDS allows a

Fig. 2. Signal-to-noise ratio of the THz tomography system.

“hyperspectral” approach to tomography imaging.

III. HYPERSPECTRAL THZ TOMOGRAPHY

THz-TDS typically operates at wavelengths between 0.12 mm and 1 mm. Under these conditions, imaging of objects with sub-centimeter spatial detail may involve diffraction phenomena. One of the first reports on THz computed tomography based on a THz-TDS was presented by Ferguson et al. [18] in 2002. Reconstruction using diffraction tomography using pulsed THz sources has been covered in [6], and a review of THz tomography techniques is available in [1]. In practice, hard-field tomography (HFT) is easier to implement and may be able to provide faster access to important information of the analyzed object, if diffraction and scattering effects are understood and managed.

Imaging in time-of-flight contrast is the most straightforward tomography use of a TDS system. Nevertheless, the broadband frequency content of the THz source discussed in Section II, can be analyzed using a Fast Fourier Transform (FFT), and the amplitude can be used to reconstruct a separate image at each frequency component. This carries the inconvenience of sharing the signal power across the frequency components, but reconstruction can still be satisfactory with an appropriate SNR.

In typical spectroscopy applications it is common to acquire 1024 or 2048 sample points for each THz pulse. However, having complete flexibility in this regard, it was practical to reduce the number of points in order to shorten the total acquisition time at the cost of being able to reconstruct images at fewer frequencies. This is justified by the results obtained, as the set of images do not vary sharply with frequency. With this rationale, THz-TDS pulse signals were acquired at 128 sample points, zero padded to 1024. The application of FFT gives 512 frequency bins for the whole spectral range in Fig. 2, allowing to reconstruct amplitude contrast images at 350 different adjacent and equally spaced frequencies between 0.8 THz and 2.5 THz.

Test objects (“phantoms”) were scanned transversally using 1 mm steps, where each step allows the measurement of a path integral associated with a single projection beam (a single

projection point). A set of 25 projections are acquired by rotating the object from 0° to 180° using 7.5° increments. The reconstruction area is 65 mm by 65 mm.

There are a range of materials suited for THz tomography study such as polypropylene, polyethylene, nylon and polyester [9]. For transmission measurements in particular, it is convenient to use materials with THz absorption coefficients between 0.1 mm⁻¹ and 10 mm⁻¹. In order to minimize refraction effects, a low THz refractive index is needed. These conditions are satisfied by Styrofoam, which was used to manufacture the phantoms used in this work.

The HFT approach is justified if refraction and scattering effects are suppressed. In the HFT framework, the Radon transform is applied to the projection data [19]

$$p(\theta, t) = \iint f(x, y) \delta(x \cos \theta - y \sin \theta - t) dx dy, \quad (2)$$

where δ is the Dirac's delta function, t varies in a direction orthogonal to the path integral direction, and θ is the projection angle. A standard MATLAB function (*iradon*) was used to

Fig. 3. Image reconstruction in normalized amplitude contrast of the cross-section of a 63 mm diameter Styrofoam cylinder at 1.992 THz.

reconstruct the images using filtered backprojection with linear interpolation and Hamming filtering [20].

Fig. 3 shows the image reconstruction with pixel size 1 mm x 1 mm, of a 63 mm diameter Styrofoam cylinder cross section, using the signal amplitude at 1.992 THz. The shape of the cylinder is not an exact circle due to limitations on the tools used for making it. The reconstruction presents an apparent region of strong attenuation at the edge of the object while the inner volume appears almost transparent, despite the relatively long beam path. Image reconstructions of a set of four non-centrosymmetric Styrofoam phantoms of various more complex shapes are shown in Fig. 4.

The amplitude contrast reconstructions at several representative wavelengths/frequencies, along with the time-of-flight contrast reconstructions [7], are shown in Table I. In amplitude contrast, all tested shapes manifest excessive

attenuation at the edges. The contour fidelity is better at low frequencies: e.g. the cylindrical bore inside a cylindrical phantom is reconstructed at 0.586 THz and 0.996 THz, but not at the higher frequencies 1.992 THz and 2.520 THz.

It is notable that reconstructions in time-of-flight contrast (bottom of Table I) do not manifest excessive attenuation at the edges.

While all tomographic modalities are expected to provide some information on the inner structure of the object, amplitude contrast yields the spatial map of the attenuation coefficient of the material, whilst time-of-flight contrast yields a map of the refractive index. Overall, since the phantoms comprise of a single homogenous material, ideally, cross-section images of constant refractive index and constant attenuation coefficient should be expected. The apparent excessive attenuation at the phantom edges implies the involvement of additional surface-related loss mechanisms, potential candidates for which are identified, modelled and explained in the following section.

IV. ANALYSIS OF SURFACE LOSSES

Surface effects are typically ignored in the application of the Radon transform HFT theory, e.g. in the case of x-rays for medical imaging, as their contribution is negligible. However, compared to x-rays, the interpretation and use of tomography images in THz amplitude contrast require careful consideration of the surface-induced effects, due to the many orders of magnitude difference in the photon energy and wavelength.

A. Styrofoam attenuation coefficient and refractive index

According to the Beer-Lambert law, the THz beam amplitude is given by

$$A = \sqrt{A_0^2 e^{-\mu L}}, \quad (2),$$

where A_0 is the initial beam amplitude and μ is the attenuation coefficient averaged along path L . The losses can be calculated using the path length through a cylinder

$$L = 2\sqrt{r^2 + x^2}, \quad (3)$$

Fig. 4. Set of Styrofoam phantoms. A) Quarter of cylinder. B) Cylinder with cylindrical bore. C) 'Xbox controller' shape. D) Square.

TABLE I
IMAGE RECONSTRUCTION IN AMPLITUDE CONTRAST AND TIME-OF-FLIGHT OF FOUR STYROFOAM PHANTOMS

		A. Quarter of a cylinder	B. Cylinder with hollow	C. 'Xbox controller' shape	D. Square
Amplitude contrast	f=0.586 THz λ=0.512 mm				
	f=0.996 THz λ=0.301 mm				
	f=1.582 THz λ=0.190 mm				
	f=1.992 THz λ=0.150 mm				
	f=2.520 THz λ=0.119 mm				
Time-of-flight contrast					

where r is the radius and x is the beam distance to the center of the cylinder.

Given two samples of different thickness, the attenuation coefficient can be estimated [21] using

$$\mu(f) = \frac{-2 \ln \left(\frac{A_2(f)}{A_1(f)} \right)}{x_2 - x_1}, \quad (4)$$

where f is the frequency, x_1 and x_2 are the thicknesses of the samples and A_1 and A_2 are their amplitude responses, respectively. Using the same two samples, the refractive index is given by [21]

$$n(f) = 1 + \frac{c(\Phi_2(f) - \Phi_1(f))}{2\pi f(x_2 - x_1)}, \quad (5)$$

where Φ_1 and Φ_2 are the respective phase shifts as a function of frequency and c is the speed of light in the sample.

The spectra of the attenuation coefficient and the refractive index for the THz working range from 0.2 THz to 2.5 THz, are calculated using (4) and (5) in our case and plotted in Fig. 5. The refractive index can be considered constant over the range. A couple of small spikes can be observed at 1.099 THz and 1.165 THz which are due to water vapor [22]. They are attributed to the air supply line being fed through a drying cylinder, yielding 8% relative humidity inside the testing

Fig. 5. Attenuation coefficient and refractive index of Styrofoam.

chamber. The spikes found above 2.0 THz result from the noise as SNR degrades.

B. Surface reflection

According to the Fresnel equations for an s-polarized beam, as it is the case for the THz beam, incident at angle θ_i , the transmittance from a perfect surface is:

$$T_s = 1 - \frac{\left| \frac{n_1 \cos \theta_i - n_2}{n_1 \cos \theta_i + n_2} \right|^2}{\left| \frac{n_1 \cos \theta_i - n_2}{n_1 \cos \theta_i + n_2} \right|^2 + \left| \frac{n_1 \sin \theta_i - n_2}{n_1 \sin \theta_i + n_2} \right|^2}, \quad (6)$$

where n_1 and n_2 are the refractive indices of the two media. Fig. 6 shows the effect of including the contribution of surface reflection losses, calculated from (6), to the overall attenuation. The Fresnel reflection losses produce a zone of apparent high attenuation at the edge of the circular cross-section, represented by the spikes at the two ends of the plot in Fig. 6. Since increased reflection results in reduced transmission, the reflection losses at the edge appear as attenuation in agreement with our observations in the amplitude contrast images. Since substantial reflection losses occur only at high θ , their contribution is minimal at normal entry into the cylindrical

Fig. 6. Normalized attenuation losses due to Beer-Lambert law only and Beer-Lambert law plus Fresnel reflection, for a Styrofoam cylinder of 90 mm diameter @ 1 THz.

phantom, in which case Beer-Lambert attenuation is dominating. The thickness of the high-attenuation ring at the periphery of the reconstructed object in Fig. 3 is seemingly larger than the width of the prominent Fresnel reflection losses, as indicated by the spikes in Fig. 6. This can be a consequence of inadequate spatial resolution due to the geometry of the THz beam. However, other surface-related attenuation mechanisms, such as surface scattering, need to be considered as well.

C. Surface scattering

At THz frequencies, Styrofoam has a rough surface where

Fig. 7. Scattering from an interface with small refractive index contrast. A) smooth surface, beams transmitted without notable deviation even at moderate incidence angles; B) rough surface, the angle of incidence is substantially increased for some beams.

incident beams will be arriving at a range of incidence angles, therefore producing scattered transmitted beams and reducing the total amount of detected photons (Fig. 7). For refractive index close to 1 It is possible to model the Styrofoam surface scattering using the Rayleigh roughness factor[23]:

$$\rho = e^{-g}, \quad (7)$$

given

$$g = \left(\frac{4\pi\sigma \cos \theta_i}{\lambda} \right)^2, \quad (8)$$

where σ is the standard deviation of the surface roughness, θ_i is the beam angle of incidence, and λ is the free space wavelength. The roughness factor ρ represents the mean power scattered along the specular direction [23], dominating the signal at small values of g . The diffuse scattered component, contributing to transmission loss caused by surface roughness, is dominating at large incidence angles when $g \gg 1$. In the case of tomography in amplitude contrast, the apparent transmission is modelled by correcting the Beer-Lambert attenuation for the contribution from ρ :

$$T_{m_s} = \rho T_s \quad (9),$$

where T_{m_s} is the modified transmittance for an s-polarized beam, T_s is the Fresnel transmittance in the absence of roughness given by (6) and ρ is the Rayleigh roughness factor given by (7). To model the transmission losses through a surface with non-negligible roughness, the effects of the beam scattering given by (9) are combined to the Beer-Lambert attenuation and Fresnel reflection losses.

TABLE II

NORMALIZED ATTENUATION PROFILE ALONG THE DIAMETER OF A CYLINDRICAL PHANTOM AND RECONSTRUCTED IMAGES FOR TWO STYROFOAM MATERIALS, AT 1 THz. FRESNEL AND FRESNEL PLUS SURFACE SCATTERING PLOTS ARE ARBITRARILY SHIFTED BY 0.25 AND 0.5 RESPECTIVELY.

To compare the cumulative contribution of the three mechanisms with experimental images, calculations and tomography measurements were undertaken with cylindrical phantoms of identical diameters, cut from two Styrofoam materials of different porosity ($180 \pm 60 \mu\text{m}$ and $470 \pm 120 \mu\text{m}$, respectively, as established by microphotography and image processing). Using (4), (6) and (9), the calculated attenuation profiles and the images reconstructed from experimental data, at 1 THz, are presented in Table II. The profile model shows enhanced edge attenuation because of high reflectance at near grazing incidence. The contribution of surface roughness is more prominent at smaller σ , in agreement with (8).

Further, the cumulative contribution of the three transmission loss mechanisms was modelled, for the larger porosity cylindrical phantom, at three different THz wavelengths. Using (4), (6) and (9), the modelled profiles and the experimental images are shown in Table III. Higher frequencies notably suppress the influence of surface roughness, as expected from (7), (8) and (9): the surface roughness losses should decrease exponentially with the square of the frequency. Volume attenuation gains prominence with frequency as implied by both, the simulated attenuation profile and the images reconstructed from experimental data. In the reconstructed images, the thickness of the high attenuation edge zone does not decrease with frequency as strongly as the modelling implies. This may indicate the limitations of applying the random rough

TABLE III

NORMALIZED ATTENUATION PROFILE ALONG THE DIAMETER OF A CYLINDRICAL PHANTOM OF LARGE POROSITY STYROFOAM AND RECONSTRUCTED IMAGES AT 3 DIFFERENT THz FREQUENCIES. FRESNEL AND FRESNEL PLUS SURFACE SCATTERING PLOTS ARE ARBITRARILY SHIFTED BY 0.25 AND 0.5 RESPECTIVELY.

surface approach (7) (8) to our THz transmission model (9). In HFT based purely on the Beer-Lambert attenuation (dashed line plots), the excessive attenuation apparent at the edges is considered as an artefact. The latter, however, if well understood and managed, can be useful in THz imaging applications where emphasizing the contour of an object is a priority.

The demonstrated hyperspectral THz tomography capability was further applied to two composite phantoms, with identical geometry shown in Fig. 8, cut from the two Styrofoam materials of different porosity. Although such composite phantoms are closer to realistic imaging scenarios, the modelling of transmission losses with account to surface roughness becomes prohibitively complicated, because of the large variation in incidence angles: a) at beam entry and beam exit for each constituent object; b) spread in incidence angles within the

Fig. 8. Composite Styrofoam phantom: a circle and half-moon, similar to the phantom used in [7] for time-of-flight THz tomography.

beam waist for small size objects or features; c) variation across the different parallel beams at each projection angle. Therefore, only the image reconstructions are presented in Table IV. Overall, the phantom geometry is reproduced with reasonable fidelity. Although at low THz frequencies Styrofoam is transparent, the phantom contour is discernible at frequencies as low as 0.234 THz. The contour becomes more accentuated as the frequency increases, indicating a strong attenuation at the edges, in accord with the Rayleigh-Rice perturbation theory [24]. Furthermore, at higher frequencies, the inner region of the constituent objects becomes more visible, in accordance with the frequency response of the Beer-Lambert attenuation (Fig. 5). Efficient enhancement of surface roughness losses is expected at higher frequencies according to (9), however, implicit to the model is that the free space wavelength λ is small enough compared to σ . This is not the case within the whole of the hyperspectral span studied here. Indeed, at the largest wavelengths the effect of roughness due to the pores will be weak, while much coarser roughness, induced by the imperfect cutting of the shapes, is likely to affect almost the whole of the hyperspectral span.

Table IV is a small excerpt from the complete hyperspectral set of around 350 images of each object, since the available spectral resolution is much finer than the spectral scale over which image properties are observed to vary. At some of the frequencies the quality of imaging is affected by excessive noise and/or atmospheric absorption. The complete hyperspectral sets of tomography images are available, as animated image sequence files attached to this paper, for the composite phantom (Fig. 8) cut from the two porosity materials <composite 180 um.avi> and <composite 470 um.avi>.

V. CONCLUSION

The frameworks of THz-TDS and HFT are combined to generate hyperspectral tomography images of test objects, in the range 0.3 - 2.5 THz, in amplitude attenuation contrast. Depending on the shape and surface roughness of the object, the HFT path attenuation contribution can be weaker than attenuation due to surface losses and for some wavelengths the object contour becomes the most prominent reconstructed feature. This can be useful in THz imaging applications where capturing the contour of an object is a priority.

Modelling of cross-section transmission loss profiles,

TABLE IV:
IMAGE RECONSTRUCTION FOR TWO PHANTOMS OF IDENTICAL CROSS-SECTIONS MADE OF TWO STYROFOAM MATERIALS

Styrofoam with pore size 180 ± 60 μm	Styrofoam with pore size 470 ± 120 μm
f=0.234 THz, λ=1.282 mm	
f=0.586 THz, λ=0.512 mm	
f=0.703 THz, λ=0.427 mm	
f=0.996 THz, λ=0.301 mm	
f=1.231 THz, λ=0.244 mm	
f=1.582 THz, λ=0.190 mm	
f=1.992 THz, λ=0.150 mm	
f=2.285 THz, λ=0.131 mm	
f=2.520 THz, λ=0.119 mm	

sensitive to wavelength and object geometry, combining Beer-Lambert volume attenuation, Fresnel reflection losses and roughness scattering losses, are in good overall agreement with the experimental results for a cylindrical object. For more complex and composite objects, the contour is reconstructed reasonably well over the whole hyperspectral range, but volume attenuation becomes prominent only in a limited frequency band. An “optimal” frequency for reconstruction would be one with high dynamic range and low scattering, for example, $f=0.996$ THz.

In addition to motivating the development of narrowband THz systems targeting particular objects, the hyperspectral THz tomography approach allows the translation of tomography methods and solutions developed theoretically, but difficult to implement experimentally at shorter wavelengths, such as the IR. An example is secondary multi-parameter contrast imaging based on spectral fitting[25]. This requires attenuation contrast images at a substantial number of spectral points, which is easier to achieve by TDS in the THz.

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