Mathematical Methods for Terahertz Interrogation in Biomedical Imaging and Homeland Security Applications

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1 Project Description

The past decade has seen a plethora of activity in the field of Terahertz imaging. The timing is mainly due to the recent development of highly efficient Terahertz generation and detection devices [17] which allow more researchers to have access to experimentation; the popularity is due to the wide range of applications the technology applies to, and the phenomenal success these methods have achieved when compared to previous approaches (c.f., [17] and the numerous references therein). The particular frequency band of the Terahertz regime is able to penetrate many materials better than signals with higher frequencies, and yet the sub-millimeter wavelength provides increased resolution over lower frequencies.

Of great importance to the public are the implications in biomedical imaging [18]. Tumor detection can be greatly enhanced, including much earlier diagnosis of skin cancer [13]. Other applications include the detection of explosive substances hidden among other materials. Nearly all substances have a characteristic “fingerprint” by means of frequency dependent reflection/refraction coefficient. The fact that these pulses have a very broad-band frequency component means that even more information is available. Terahertz biochips are already in use for the detection of illicit drugs, even when mixed with other powders [9]. Many explosive compounds have been shown to have distinct fingerprints in the Terahertz regime as well [11], however accurate identification in the presence of reflections/transmissions from the substrate requires sophisticated signal processing filtering techniques and/or mathematical modeling and parameter identification methods.

The current proposal is to develop, and validate, accurate models for Terahertz frequency wave propagation in complex dielectric media with applications including biomedical imaging and explosives detection. I intend to collaborate with Dr. Lisa Zurk of the ECE Department at Portland State University. Dr. Zurk is the director of the Northwest Electromagnetics and Acoustics Research Laboratory (NEARLab) at PSU, and is heavily involved in the engineering aspects of Terahertz generation, detection, and imaging applications. I will be able to complement her group by extending my previous experience in developing and simulating models of Terahertz interaction with dielectrics [2, 4, 3, 1] to applications including bio-sensing and explosives detection; areas which are relatively new for me, but very promising with respect to funding opportunities and broad impact to the general public. Also, the NEARLab has recently acquired a Picometrix THz machine, exactly the same model as the one I have used previously in research at NASA Langley on interrogation of Space Shuttle foam (c.f. [1]).

The two problems I intend to investigate are detection of defects in biological tissue, and explosives detection. The approaches to solving these two problems differ in a fundamental way: the characteristic fingerprint used to distinguish substances in a composite material is given in the frequency domain (c.f. [10]), while the reflectometry of biological tissue is computed from the amplitude of a reflected signal in the time domain (see, for example, [15]). The physical mechanisms involved in attenuating the signal also differ between tissue, which has a high water content, and other (non-aqueous) materials. In materials comprised mostly of water, polarization induces dissipation of energy. However, in powders or other dry materials, the attenuation is due to scattering from the granular structure [16]. Both mechanisms are wavelength (and therefore frequency) dependent, but the dependencies are not equivalent. Furthermore, neither attenuation mechanism is well understood, especially for the regime where the microstructure size is on the same order as the wavelength, as traditional approximation theories and mixing formulas do not apply.

1.1 Explosives Detection

The propagation of sub-millimeter waves in dielectrics with particulate sizes approximately equal to the wavelength of the interrogating field is a difficult yet important problem in non-destructive evaluation. For spherical inclusions, a Mie approximation may be used. In [11], a Quasi-crystalline approximation is applied to non-spherical scatterers. In this method, a statistical configurational average is used for the random particle position. We have applied periodic unfolding to Maxwell's equations in heterogeneous materials in [5]. There the shape of the inclusion was arbitrary but predetermined. I intend to compare these homogenization methods to Monte-Carlo simulations of Terahertz propagation in random media in order to determine which method is most accurate and efficient in characterizing the time domain scattering for various particle configurations.

1.2 Biomedical Imaging

I propose to employ an inverse problem formulation for the determination of the shape and characterization of defects in human tissue. One dimensional computations have been successful for the parameter identification problem [2] and the geometric inverse problem [4] separately, however in this project we hope to solve both problems simultaneously in two dimensions.

The key to correctly modeling the interactions between Terahertz radiation and tissue is to properly account for the polarization effects. Previous researchers have employed the Debye model [12] as it seems to accurately describe water; a two mode Debye model was used in [7]. However, data fitting to a model which generalizes the Debye model (namely the Cole-Cole model) showed that even a four mode Debye model is not sufficient to characterize the heterogeneous mixture that is human tissue [14]. We anticipate that these effects are due to scattering mechanisms in the material, and the work of [8] seems to validate this expectation. We hope to devise a physical model which will include time-domain scattering effects and distributions of dielectric parameters. Previously, we have used experimental data in determining these unknown distributions [6]. I intend to extend these results to non-parameterized distributions.

1.3 Numerical Techniques

Numerical methods will be an integral component of this proposed effort. For each of the model problems, forward simulations of Terahertz propagation of complex media will be required. For the spatial discretization I intend to employ a finite element method (FEM) using edge elements. Futher, I propose to develop efficient numerical methods for the simulation of the PDEs with distributions of parameters, based on polynomial chaos and stochastic collocation. Various cost functionals and optimization routines will be considered for the inverse problems, and sensitivity analyses will be performed on the resulting optimal solutions (see, for example, [2, 4]).

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