Orientation Dependence of THz Scattering from Cylindrical Strands

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***Abstract*—Scattering of terahertz radiation from cylindrical strands is explored as a means of studying the effects of hair on the results of bio-tissue analysis. Strands of fiberglass are aligned either parallel or perpendicular to the polarization vector of the incoming terahertz beam. Spectroscopic results reveal that the material's intrinsic THz transmission properties are highly dependent on fiber orientation.**

I. Introduction and Background

Terahertz (THz or T-ray) spectroscopy, either in reflection or transmission mode, has in recent years been demonstrated as a viable imaging modality for a vast array of applications, ranging from drug detection[1] to quality control of cork[2]. Extracting spectral features of materials in the THz range is a common method of identification; spectral peaks and/or absorption gradients can help distinguish one sample from another. This form of identification however is not without error; recent studies have shown that scattering from a sample can influence detection reliability[3,4,5]. Moreover, orientation of the sample can also affect the measured optical properties[6]. This paper investigates the effect of hair strands upon analysis of bio-tissue samples[7] by studying scattering of pulsed THz radiation from cylindrical fiberglass strands. Results show a dependence on fiber orientation that alters the material's intrinsic THz transmission properties. Orientation could therefore be intentionally applied to filter THz radiation.

II. Experiment

The transmission mode Time-Domain Spectroscopy (TDS) THz system is based on the generation of a THz pulse using an ultrafast (90 fs) near-infrared laser, with coherent detection *via* electro-optic (EO) sampling. Fiberglass strands are obtained from woven fiberglass cloth (plain weave E glass, weight 7.5 oz/yd^2). Each strand is approximately 10 μm in diameter, and 15 mm in length. The strands are aligned in a single layer, each strand placed as close as possible to its adjacent strands. The fiberglass strands are placed orthogonally in the path of the incoming THz beam in one of four orientations, with respect to the vertically polarized THz beam: parallel, perpendicular, +45° and -45°.

III. Results

Fig. 1 shows the attenuation coefficient (α) derived from transmission at the four orientations. It is evident from the high α values from all four orientations that fiberglass is highly opaque to THz radiation. However, there is a significant increase in attenuation for the parallel/+45° cases. This is likely due to scattering loss. Scattering studies of granular materials[4,5] have shown that material attenuation, which increases with frequency, is dependent on particle size; this is consistent with Mie spherical scattering theory. The same phenomenon in this study could instead be due to orientation-dependent birefringence from the cylindrical-shaped strands. The variation in refractive index in Fig. 2 indicates that orientation-dependent birefringence is likely to be a property of the strands. However the difference between the +45° and -45° cases is unexpected as the strands are assumed to be symmetrical in shape and composition about their long axis.

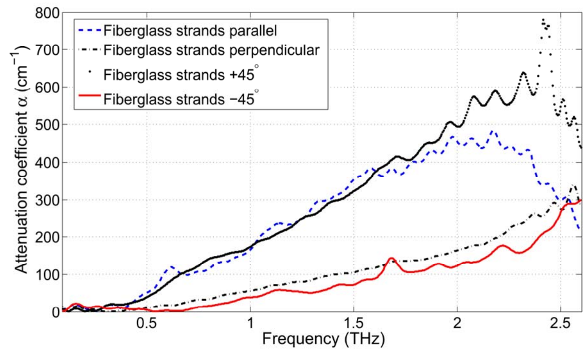

Fig 1: Attenuation of the THz signal after transmission through fiberglass strands in various orientations with respect to the direction of the incident electric field.

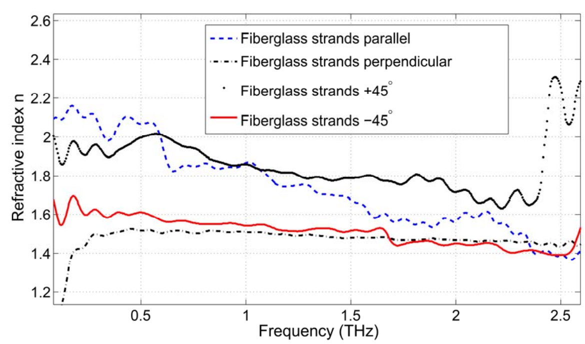

Fig 2: The refractive index of the fiberglass strands varies according to the fiber orientation, indicating that the strands are birefringent.

Given that the length of the fiberglass strands is 1500 times larger than the diameter, and that the incident THz radiation is perpendicular to the long axis of the strands, a scattering model based on infinite right circular cylinders[8] can be used to verify our results. This model is an extension of Mie's spherical scattering theory in cylindrical polar coordinates.

In this model, a cylinder (i.e., fiberglass strand) is assumed to be stationary and the long axis of the cylinder is taken as the z-axis. The incident electric field is initially parallel to the z-axis (similar to the parallel case used in Figs. 1 and 2), but it can also tilt at a zenith angle θ with respect to the z-axis. The intensity of the scattered wave I_{sca} is expressed in terms of the

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Stokes parameters as:

$$I_{\rm sca} = \frac{1}{\pi k r}\,|T_1|^2\,[1+\cos(\theta)]\ , \tag{1}$$

$$T_1 = \sum_{-\infty}^{\infty} b_{n,\,\rm I}\,e^{-in\Theta} = b_{0,\,\rm I} + 2\sum_{n=1}^{\infty} b_{n,\,\rm I}\cos(n\Theta)\ , \tag{2}$$

$$b_{n,\,\rm I} = \frac{J_n(mkr)\,J_n'(kr) - mJ_n'(mkr)\,J_n(kr)}{J_n(mkr)\,H_n^{(1)\prime}(kr) - mJ_n'(mkr)\,H_n^{(1)}(kr)}\ , \tag{3}$$

$$\Theta = \pi - \varphi\ , \tag{4}$$

where φ is the azimuth (observation or scattering direction); n is the refractive index of the strands; m is the relative refractive index (= n for this case); k is the wavenumber; r is the radius of a strand; $J_n(mkr)$ is the Bessel function of the first kind; $H_n^{(1)}(kr)$ is the Hankel function; the order of $J_n(mkr)$ and $H_n^{(1)}(kr)$ is denoted by the n subscript. $I_{\rm sca}$ is a measure of the power in the scattered wave. It can be used to estimate properties of the attenuation coefficient α because attenuation is due to scattering and absorption[8] in a sample. Assuming that absorption is invariant to orientation, then the differences in attenuation are likely due to scattering only.

In Fig. 3, the outer axis denotes azimuth φ. The incident THz arrives at φ = 180°. The forward scattering direction is -90° ≤ φ ≤ 90°, while 90° < φ < 270° is the backscattering direction. Scattering for a single infinite cylinder with very small diameter (10 μm) is dominantly backward regardless of the zenith θ of the incident THz beam. Scattering is identical for θ = -45° and θ = +45°, and for θ = -90° and θ = +90°. The absence of sidelobes and nulls implies that destructive interference due to scattering from neighboring strands can be ignored when considering multiple infinite cylinders.

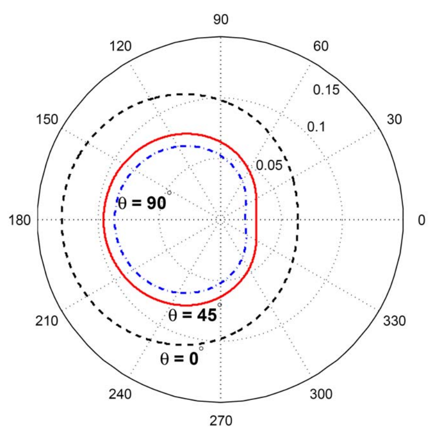

Fig 3: Scattering intensity $I_{\rm sca}$ over the entire range of φ (outer axis) for an infinite cylinder with diameter of 10 μm, refractive index 2 + j0.3; $I_{\rm sca}$ shown here is summed over all THz frequencies. Angle θ is the zenith of the incident wave vector with respect to the z-axis.

For a single cylinder, the total power lost to scattering is the summation of $I_{\rm sca}$ over the range 0° ≤ φ ≤ 360°. The resultant $I_{\rm sca}$ is as shown in Fig. 4 for two different diameters. It is evident that regardless of the diameter, a cylinder aligned in parallel with the incoming radiation (zenith θ = 0°) scatters most strongly, thus will have a higher attenuation coefficient as shown in Fig. 1 because less THz signal is detected; a cylinder aligned orthogonal to the incoming radiation (θ = 90°) scatters weakly, thus will have a lower attenuation coefficient. The scattered signal of a cylinder tilted at θ = ±45° is similar to that at θ = 0° until around 1.6 THz. This is consistent with our observation in Fig. 1 for the parallel/+45° cases (dot and dash plots), but the -45° is inconsistent with the mathematical theory presented here thus further investigation is needed.

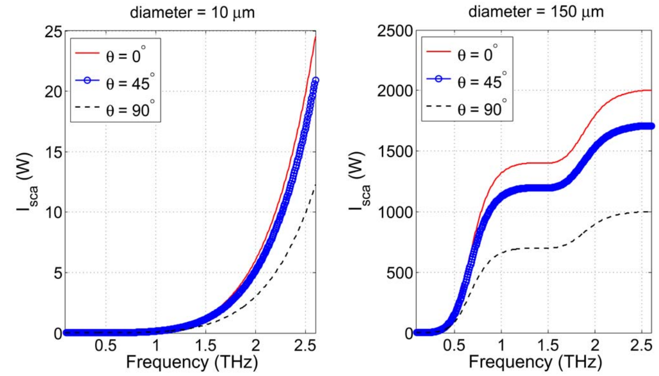

Fig 4: A comparison of the scattering intensity $I_{\rm sca}$ from cylinders with refractive index 2 + j0.3 but with different diameters. Both plots show that scattering is strongest when zenith θ = 0°.

IV. CONCLUSION

The results of this study show that the orientation of cylindrical strands strongly alters the measured THz signal. In bio-tissue analysis, hair strands may therefore mask the true THz spectroscopic signature of underlying diseased tissue. A possible application of intentional alteration of the transmitted THz signal is filtering. Low-cost, flexible, phase-sensitive filters could be constructed from fiberglass strands. Such filters may also be used for masking spectral features, *e.g.*, by wrapping illicit objects (drugs, weapons, *etc.*) to prevent detection by THz. Our future study will elucidate the effect of birefringence via mathematical modeling. We will also explore the behavior of other cylindrical materials such as nylon.

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