VAPOR-GROWN CARBON FIBERS FOR ELECTROMAGNETIC SCATTERING AND ABSORPTION

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INTRODUCTION

Theory predicts that particles of high aspect ratio and moderate electrical conductivity will strongly attenuate electromagnetic radiation [1,2], the greatest effects being at wavelengths about two orders of magnitude larger than the particle diameter. Vapor-grown carbon fiber (VGCF) [3] can be grown with a wide range of diameter, extending down to 0.1 micron, making it a good candidate for a multispectral obscurant, useful through the infrared.

Obscurant capability is characterized by extinction cross section, σ_{ext}. Extinction is the sum of two attenuative processes, absorption and scattering, with associated cross sections, σ_{abs} and σ_{scat}. While each of these cross sections can, in principle, be measured directly in field tests, the small quantities of VGCF currently available require means to evaluate these parameters which are amenable to the laboratory.

According to theory, developed over the past three decades by Pedersen and various others, the cross sections of whisker-shaped particles can be calculated if the bulk optical constants of the material are known [4-7]. At a given frequency, two optical constants (associated with propagation and dissipation) are sufficient to describe an isotropic material. These can be expressed as the real and imaginary parts of any of a number of quantities, including reflectivity, refractive index, dielectric constant, impedance, or conductivity, [8] the choice being a matter of personal preference or experimental convenience. In the past, the Pedersen theory has taken as input only the real dc conductivity, with the frequency-dependent complex conductivity assumed by extrapolation according to metallic models. In the current work, efforts have been made to determine actual frequency-dependent optical constants through reflectance measurements over a broad spectrum. This should lead to a more accurate determination of fiber cross sections.

EXPERIMENTAL

We determined the cross sections for the fibers in three steps, one observational and two computational. First we measured reflectance of the bulk material over a wide spectrum. We then applied Kramers-Kronig analysis to convert this data to optical constants. Finally, we used Pedersen theory to calculate the cross sections.

The reflectance measurements were made with a Fourier transform spectrometer. The primary challenge lay in sample preparation, the major threat to accurate results being signal reduction due to light scattered from an uneven surface. We made some attempts to encapsulate the fibers in an epoxy matrix with the surface polished smooth. However, this gave unsatisfactory results at low frequency, where the composite performed as would be expected for a material with the low conductivity of the epoxy only. (The results were better at very high frequency, a regime where even individual fibers are large enough to appear as a smooth surface.) The preferred method of preparation was to crush the fibers into a smooth pellet with a hydraulic press. This was not successful with every fiber specimen, as pellets would often crumble on removal from the die. But, microscopic inspection of surviving pellets showed that the process, while breaking the fibers into shorter lengths, did not adversely affect their diameters, and thus should not have disturbed the bulk optical properties. The pellets appeared to give good reflectance results, and the low frequency, real conductivities later derived from these findings showed reasonable agreement with dc conductivity measurements on individual fibers.

Reflectance alone gives only one optical constant, the magnitude of the reflectivity, r. Information about the phase, ϕ, is lost in the measurement process, and must be restored. If data has been gathered over a wide enough range, the Kramers-Kronig relations allow ϕ to be calculated at any one frequency, ω_0, via an integral of r over all frequencies, and vice versa.

$$\phi(\omega_0) = -\frac{2}{\pi} P\int_0^\infty \frac{\omega_0 \ln|r(\omega)|}{\omega^2 - \omega_0^2} d\omega \,. \qquad (1)$$

Here P indicates the Cauchy principal value. Since reflectance can only be measured over a finite range, estimates, called wing corrections, must be made to fill in the rest of the data. However, the factor of $\omega^2 - \omega_0^2$ in the denominator limits the effect of these corrections and we simply take the reflectance to be constant outside the measured range.

Calculations of absorption, scattering, and extinction cross sections can be completed using the theory of Pedersen, et al. [4] The optical constants and assumed fiber dimensions allow derivation of the surface impedance, which is then used to compose an integral equation for the surface current in the fiber. Once the surface current wavefunction is solved via a variational algorithm, standard antenna theory allows the absorption and the far-field re-radiation (i.e., scattering) amplitude to be calculated, leading to the appropriate cross sections. The results of the theory are valid provided the fiber aspect ratio is high — that is, the length is much greater than the diameter — and the wavelength is greater than the diameter.

RESULTS AND DISCUSSION

The results shown here are for 1 μm diameter VGCF, with an aspect ratio of 200. The fiber satisfies the Pedersen theory requirement for high aspect ratio. Figure 1 shows plots of measured reflectance and calculated phase versus wavelength. It is of course unwise to fully trust all of the data shown. Reflectance data near the short wavelength end can be affected by surface roughness of the pellet, while phase data may be affected on either end of the range due to improper extrapolation of the reflectance data. However, data in the middle of the range should be viable.

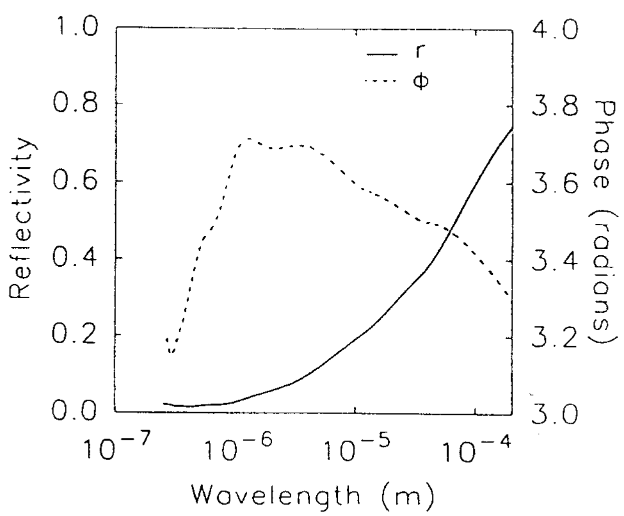

Fig. 1: Reflectance and phase of VGCF vs. wavelength.

Figure 2 shows the calculated cross sections using these data input to the Pedersen-Waterman theory. Absorption dominates scattering, and extinction improves as the wavelength approaches the fiber diameter.

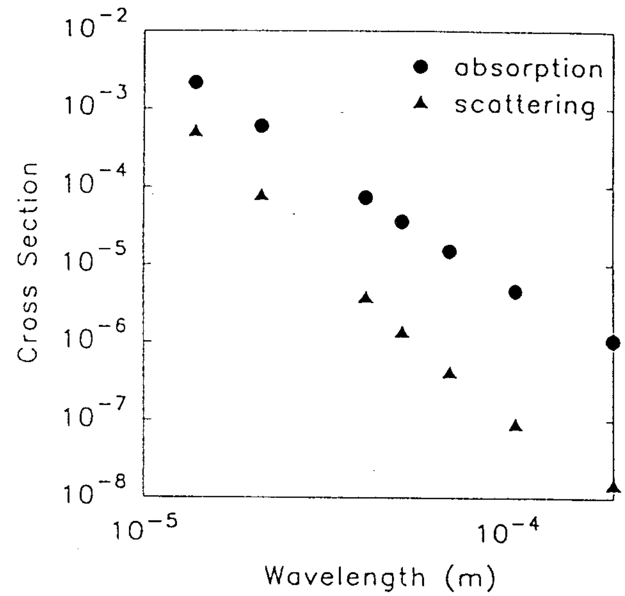

Fig. 2: Cross sections of VGCF vs. wavelength.

CONCLUSION

A method for determining the absorption, scattering, and extinction cross sections from small quantities of fibers has been demonstrated. The method uses bulk optical properties measured through reflectance, and assumed fiber dimensions as input to a theoretical calculation of the current that would be induced in the fiber by radiation. Indications so far are consistent with the expectation that highly graphitic VGCF has excellent extinction, particularly in the infrared.

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