Measured Backscatter from Conductive Thin Films Deposited on Fibrous Substrates

Kristan P. Gurton, Charles W. Bruce, and J. B. Gillespie

***Abstract*— The functional dependence of the electromagnetic backscatter by thin, straight, dielectric fibers with metallic coatings was measured as a function of coating thickness and conductivity at a wavelength of 0.86 cm (35 GHz). Cu and Ni coatings were applied to fibrous glass substrates (having a nominal diameter of 5.50 μm) using an evaporative process. Thicknesses of the thin films were directly measured by scanning electron microscopy (SEM) and ranged from 0.02 to 0.70 μm. Measurements were conducted using single fibers. Measured quantities agreed well with calculations based on recently developed theory.**

***Index Terms*—Electromagnetic scattering, measurements, thin films.**

I. Introduction

HISTORICALLY, plane wave interaction with thin cylinders of finite length and conductivity represents one of the more manageable problems appropriate for direct application of classic electromagnetic theory [1]–[3]. Similarly, fundamental antenna analysis typically involves the prediction of induced surface currents on finite conductors such as thin cylinders, wires, and/or rods. Although numerous numeric and analytic techniques have been developed to calculated these currents for thin finite conducting cylinders, good experimental analogs necessary for comparison have been lacking [4]–[7]. The few studies that do exist have been primarily restricted to homogeneous cylinders only [8], [9].

In this study, we directly measure the absolute backscatter cross section at a microwave frequency of 35 GHz for a single dielectric fiber coated with a thin metallic films of varying thicknesses and conductivities. The technique used here, which employs phase-sensitive detection of a modulated target, is similar to the approach originally taken by Scharfman and King [8].

Previous studies involving the measurement of scattered and absorbed microwave radiation for moderate and highly conductive fibers was primarily restricted to homogeneous materials [10]–[13]. These studies provided a comparison with calculated features as described in a series of published papers by Waterman and Pedersen [14], [15]. Results showed agreement in form and magnitude with computed scattering and absorption coefficients, but certain issues remained that were relevant to the sponsors of this work. Such issues include, but are not limited to, the evaluation of predictive electromagnetic calculations for *inhomogeneous* thin cylinders and possible enhanced mass-normalized scattering efficiencies for mettalically coated fibers. In lieu of these questions, Waterman and Pedersen have extended their modified Galerkin technique to include electromagnetic interactions with inhomogeneous cylinders. Although other theoretical approaches were considered for evaluation, i.e., volume integral, principal-valued integral, moments methods, etc., the null-field approach used by Waterman and Pedersen was chosen due to its general applicability and modest computational requirements.

The metallic coatings chosen for this study were Ni and Cu (iron coatings were also produced, but proved too unstable and could not be well characterized). Coatings were applied to glass substrates via an evaporative process. Coating thicknesses ranged from 0.02 to slightly above 0.70 μm. Metallic films were characterized by direct dc conductance measurements as well as scanning electron microscopy (SEM). Because of several factors involving the deposition of thin metallic films the dc values of the conductivity, in some cases, were less than their respective bulk values. As a result, a series of coatings was produced with both varying thicknesses and conductivities. A continuous conductance profile was determined for each metal film as a function of thickness and when convolved with theory resulted in reasonable agreement.

II. Fiber Preparation

Each glass fiber substrate was coated with an evaporative thin film of either Ni or Cu. Both metals were chosen primarily for their relatively high conductivity values. Nickel was purposely chosen to contrast a conventional metal with a ferrite. To reduce the likelihood of contamination, metals were evaporated in a high vacuum at pressures never greater than 1×10^{-6} Torr. The vacuum system used consisted of a 6-in diffusion pump coupled in series with a similar sized cryogenic trap. The system was thoroughly cleaned, baked, and pumped for a period of several days until a vacuum on the order of 10^{-7} Torr could be routinely reached during a typical pumping cycle. Uniform cylindrical coatings were produced by a "rotisserie-like" arrangement that could horizontally rotate up to five fiber substrates. Each glass fiber was thoroughly cleaned with an alcohol/acetone rinse, baked at a temperature in excess of 200 °C, and attached across a stainless steel wire "spit." In order to minimize variation in coating thickness along the fiber's length, substrates were kept long and only a small segment from the center was used for the measurement.

Manuscript received April 18, 1997; revised June 30, 1998. This work was supported by J. Hale of the U.S. Army Edgewood Research Development and Engineering Center.

K. P. Gurton is with the Army Research Laboratory, AMSPL-IS-E, Adelphi, MD 20783 USA.

C. W. Bruce and J. B. Gillespie are with the Army Research Laboratory, White Sands Missile Range, White Sands, NM 88002 USA.

Publisher Item Identifier S 0018-926X(98)08888-7.

Fibers were positioned horizontally on the rotisserie at different distances from the evaporative source in order to take advantage of the inverse-square relationship between deposition rates and the fiber to source separation distance. In order to produce a set of fibers with good variation in thicknesses, fiber to source distances ranged from 15 to 45 cm. We found this arrangement sufficient to produce nearly an order of magnitude of difference between the thinnest and thickest coated fibers.

Ultrapure wire (99.999% nickel or copper) was weighed and wound evenly to a 6-in tungsten helix evaporative filament. Each "charge" was thoroughly cleaned and baked along with the rotisserie before insertion into the vacuum chamber (the term "charge" is commonly used to describe the filament/wire combination). Typical wire masses ranged from 0.2 to 2.0 grams per charge.

The vacuum system was sealed, and a pressure of 1×10^{-6} Torr was maintained during the entire duration of the rotisserie/evaporative process. Typical coating periods ranged from several seconds for light runs to as long as 20 s for the heavier coatings. Deposition rates were on average about 80 A/s.

After deposition, each fiber was removed and cut from the spit and the dc resistance per unit length was measured (see coating analysis). Fibers were then trimmed to a length sufficiently long to avoid resonant effects seen at smaller lengths (for example, the primary scattering resonance at 35 GHz occurs at fiber lengths slightly less than 0.43 cm) [11]. Each fiber was then pinioned at each end using a very small amount of cyanoacrylate adhesive across a thin nonconducting Teflon mounting ring. Prior studies showed this adhesive to be electromagnetically inert at 35 GHz [12]. This ring served as a convenient way of quickly interchanging fibers within the backscatter apparatus and reduced the amount of handling required.

III. Coating Analysis

It was recognized early on that evaporated thin metal films have acquired a reputation of being poor specimens when their electrical properties are compared to those of bulk. A number of effects have contributed to this reputation [16]–[18]. Typical problems encountered may include one or more of the following: 1) the introduction of various contaminates, i.e., poor or dirty vacuum conditions; 2) the tendency of very thin films to lump or agglomerate due to poor surface mobility; and 3) the formation of thin films with a high density of crystal imperfections, usually caused by adverse condensation conditions driven by large temperature gradients across the substrate. Exact diagnosis of a particular problem is complex and usually difficult to identify exactly. Nevertheless, it was not the authors intention to produce coatings that mirrored their respective bulk properties, just as long as their behavior remained Drude-like [19]. Rather, the primary criteria for the coatings used here were that they be well characterized, highly conductive, and span as wide a range of values as possible for both thickness and conductivity. Based on these criteria, the sets of thin films generated were considered satisfactory.

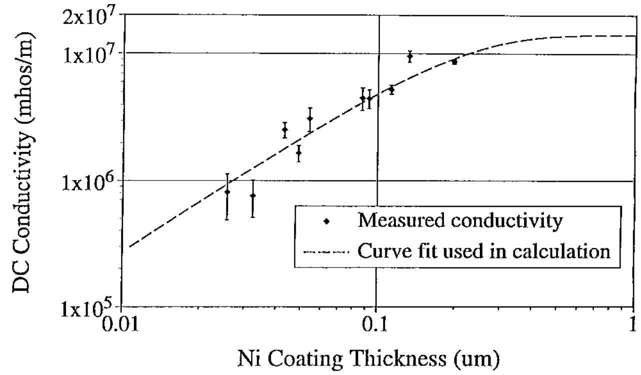

Fig. 1. Measured nickel conductivity profile.

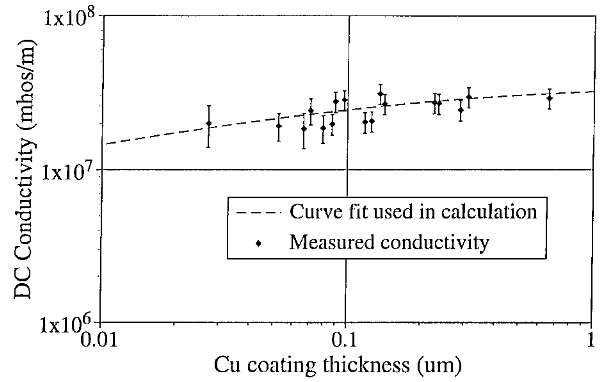

Fig. 2. Measured copper conductivity profile.

After the backscatter response for each fiber was measured, thin film surface integrity and thickness values were determined directly using scanning electron microscopy (SEM) analysis. Each fiber was mounted in a polymer matrix and cleaved into several very short pieces. We examined photographs of these pieces to determine coating thickness, total diameters, and granular composition.

Measurement of the dc resistivity for each coatings was achieved by using a specially designed gold-plated circuit board that was etched to allow simultaneous resistance measurements to be conducted at varying distances along the fiber. Probes coated with gold-leaf were gently brought in contact with each fiber and a controlled, highly reproducible, pressure was applied using a clamping micrometer. A small current was applied across varying distances along the fiber and the drop in potential for each position was recorded. From these measurements, a resistance versus length curve was generated. If correct, uniformly coated fibers should yield a linear form (ohmic) with the y-intercept corresponding to the contact resistance of the circuit board. Coating thicknesses were converted to cross-sectional areas and combined with the resistive measurements to produce a conductivity profile for each metal (see Figs. 1 and 2). The dashed lines seen in each curve represents a functional curve-fit used in the corresponding backscatter calculation.

It should be noted that the conductivity profiles were very sensitive to small variations in coating thickness since the conductance per unit length were inversely proportional to the thickness squared. This was especially troublesome in

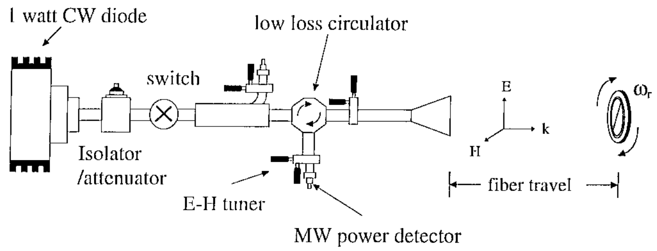

Fig. 3. Schematic of the backscatter measurement.

determining conductivity values for the thinnest of coatings in which the uncertainty in the measurement was greatest and was the primary source for the large error bars seen in the profiles.

IV. Backscatter Measurement

We chose to measure backscatter because of its strong functional dependence with changes in certain parameters of interest, i.e., coating thickness and conductivity. Because of the relatively small magnitude of the backscattered signal, the target was modulated and phase-sensitive amplification was used. Individual fibers were rotated at a fixed frequency of approximately 10 Hz in the plane perpendicular to the propagation vector $\vec{k}$. Plane wave lumination was achieved via a well characterized modified open-ended waveguide horn used in many of our experiments. A motor-driven micrometer was used to vary the distance between the spinning fiber and horn. This allowed for continuous monitoring of the far-field behavior and for detection and identification of any spurious reflected fields. The received backscatter signal was recorded and integrated as a function of horn-to-fiber distance to determine a relative measure of the backscatter response for each fiber. Various solid metallic fibers with known backscatter cross sections provided normalization and served as a convenient means for checking the system's linearity. A schematic of the device used to measure the backscatter from a rotating fiber can be seen in Fig. 3.

The fiber rotation assembly consisted of a nonconducting circular mounting bracket to which the Teflon fiber ring was attached. This mounting bracket was designed to rotate a fiber in the E–H plane of the irradiating field at an angular frequency ω_r. Triggering for the lock-in amplifier was achieved by using a LED/detector combination that was mounted to the outer diameter of the rotating assembly. A small Teflon flap was attached to the outer circumference of the spinning fiber ring that passed between the LED and detector. Great care was taken to ensure that all components remotely illuminated were made of inert materials so as to minimize any unwanted reflections. Nevertheless, all mounting components capable of producing such reflections were designed to exhibit a high degree of rotational symmetry. This was done to eliminate any time varying signal that could be misinterpreted as the scattered field from the modulated fiber. Conformation of this was achieved by removing the test fiber from the system and noting that the resulting signal fell well within the ambient noise of the lock-in amplifier. The rotation assembly was designed to transverses a lateral distance of approximately 20 cm and allowed for continuous recording of backscatter response as a function of fiber distance from the horn. The millimeter-wave source used was a Hughes 1-W IMPATT diode operating continuously at 35 GHz. Total power output was monitored using a diode detector that was attached in the forward direction of a 20-dB directional coupler. The remaining signal was fed through a low-leakage circulator and radiated to the spinning fiber through a specially flared piece of WR-28 waveguide [12]. Several E–H tuners were mounted at various locations about the circuit to minimize any impedance mismatches and reduce the overall voltage standing wave ratio (VSWR). The resulting modulated backscatter was fed back through the circulator and into a tuned detector where the corresponding voltage was amplified approximately 40 dB through a lock-in amplifier tuned to $2\omega_r$, i.e., the fiber aligns twice with the E field per revolution.

The motor-driven micrometer was started, and the modulated backscatter signal for each fiber was recorded by a data acquisition system as a function of fiber distance from the horn. This process was repeated several times in both the forward and reverse directions with results averaged together. This constituted one measurement.

The fiber was then removed and the next fiber/ring assembly was snapped into place. Each fiber was measured at least six times over a period spanning several days. Output power from the IMPATT was continuously recorded to ensure that any fluctuations were identified and if necessary corrected for. Between trials a calibration fiber consisting of either solid Ni or Cu, with known backscatter response and diameter, was inserted and measured.

Finally, backscatter as function of transverse distance was integrated over a set interval with the resulting area taken to be proportional to actual backscatter cross section. Values were then made absolute by normalizing to the solid fiber data. The reproducibility of backscatter measurements taken over multiple sessions was considered very good, but did worsen for some of the thinner coatings as the signal to noise diminished. Error analysis conducted on this portion of the study showed uncertainties associated with the measurement to be less than $\pm 5\%$.

V. Results

Figs. 4 and 5 show the normalized measured backscatter cross sections as a function of film thickness for either a Ni or Cu coated glass fiber, as well as the associated Waterman calculated values (dashed line). As seen in both graphs, when the corresponding conductivity profiles are used in the computations, agreement is quite reasonable. Although these results are not totally definitive, the agreement here and in prior studies lend support to the modified Galerkin approach used by Waterman and Pedersen to calculated the induced surface currents for composite and homogenous finite thin cylinders.

An important question that was raised during this study was, "For a metal-coated dielectric fiber, what is the minimum thickness necessary for the fiber to still appear *solid* to an incident electromagnetic wave?" The question is best answered by considering the measured backscatter for the Cu-coated

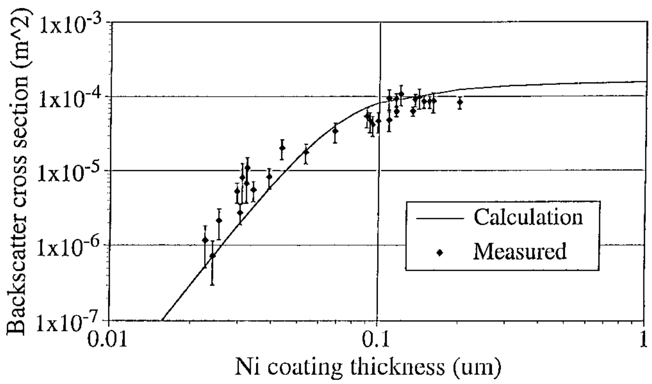

Fig. 4. Absolute backscatter cross section for a single nickel-coated glass fiber (nominal glass diameter 5.5 μm).

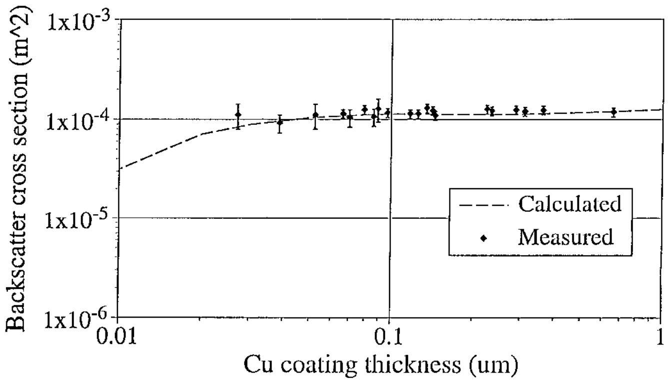

Fig. 5. Absolute backscatter cross section for a single copper-coated glass fiber (nominal glass diameter 5.5 μm).

fibers seen in Fig. 5. For these fibers one can see that the conductivity profile remained relatively constant for most thicknesses (see Fig. 2). Fig. 5 shows that the backscatter response approaches a plateau for Cu-coated glass at a coating thickness on the order of $\delta/10$, where δ is the classically defined skin depth. At 35 GHz the skin depth for nickel and copper are 0.70 and 0.35 μm, respectively. It should be noted that Waterman and Pedersen have reported that the minimum thickness necessary could be an order of magnitude lower, assuming that the bulk values for the conductivity could be maintained for such thin films.

One interesting point seen in both curves is that for coating thicknesses above 0.1 μm the backscatter is rather insensitive to moderate changes in conductivity. In a separate study the backscatter was measured for four identically dimensioned solid fibers, Cu, Ni, Fe, and Al. The results showed that for a change in conductivity of more than a factor of five, the backscatter was effected by less than 10%. Corresponding calculations yielded similar results. In general, when considering enhanced backscatter, one can conclude that for good conductors (i.e., greater than 5.0×10^6 mhos/m) there is little to be gained by further increasing the conductivity.

ACKNOWLEDGMENT

The authors would like to thank the Army Research Laboratory for their continued support and, in particular, they would like to give special praise to the New Mexico State University SEM facility for their efforts. They would also like to thank P. Waterman and J. Pedersen for their computational support and expertise.

REFERENCES

[1] J. H. Van Vleck, F. Bloch, and M. Hamermesh, "Theory of radar reflection from wires or thin metallic strips," *J. Appl. Phys.*, vol. 18, p. 274, 1947.
[2] L. Peters, Jr., "End-fire echo area of long thin bodies," *IRE Trans. Antennas Propagat.*, vol. 6, p. 133, 1958.
[3] E. S. Cassedy and J. Fainberg, "Back-scattering cross section of cylindrical wires of finite conductivity," *IRE Trans. Antennas Propagat.*, vol. 8, p. 1, 1960.
[4] C. T. Tai, "Electromagnetic back-scattering from cylindrical wires," *J. Appl. Phys.*, vol. 23, p. 909, 1952.
[5] J. H. Richmond, "Scattering by imperfectly conducting wires," *IEEE Trans. Antennas Propagat.*, vol. AP-15, p. 802, 1967.
[6] E. H. Newman, "A unified theory of thin material wires," *IEEE Trans. Antennas Propagat.*, vol. 39, p. 1488, 1991.
[7] N. J. Champagne, J. T. Williams, and D. R. Wilton, "The use of curved segments for numerically modeling thin wire antennas and scatterers," *IEEE Trans. Antennas Propagat.*, vol. 40, p. 682, 1992.
[8] H. Scharfman and D. D. King, "Antenna measurement by modulation of the scatterer," *Proc. IRE*, vol. 42, p. 854, 1954.
[9] S. Hong, S. L. Borison, and D. P. Ford, "Short-pulse scattering by a long wire," *IEEE Trans. Antennas Propagat.*, vol. AP-16, p. 338, 1968.
[10] C. W. Bruce, A. V. Jelinek, J. C. Pedersen, and P. C. Waterman, "Millimeter wavelength attenuation efficiencies of fibrous aerosols," *J. Appl. Phys.*, vol. 74, p. 3688, 1993.
[11] A. V. Jelinek and C. W. Bruce, "Extinction spectra of high conductivity fibrous aerosols," *J. Appl. Phys.*, vol. 78, p. 2675, 1995.
[12] K. P. Gurton and C. W. Bruce, "Parametric study of the absorption cross-section for a moderately conducting thin cylinder," *Appl. Opt.*, vol. 34, p. 2822, 1995.
[13] C. W. Bruce, D. R. Ashmore, P. C. Pittman, N. E. Pedersen, J. C. Pedersen, and P. C. Waterman, "Attenuation at a wavelength of 0.86 cm due to fibrous aerosols," *Appl. Phys. Lett.*, vol. 56, p. 791, 1990.
[14] P. C. Waterman and J. C. Pedersen, "Electromagnetic scattering and absorption by finite wires," *J. Appl. Phys.*, vol. 78, p. 656, 1995.
[15] ——, "Scattering by finite wires of arbitrary ε, μ, and σ," *J. Opt. Soc. Amer.*, vol. 15, pt. A, no. 1, p. 174, 1998.
[16] L. I. Maissel and R. Glang, *Handbook of Thin Film Technology*. New York: McGraw-Hill, 1970.
[17] R. L. Ramey and T. S. Lewis, "Properties of thin metal films at microwave frequencies," *J. Appl. Phys.*, vol. 39, no. 3, 1968.
[18] J. D. Rancourt, *Optical Thin Films: A User's Handbook*. Bellingham, WA, SPIE Opt. Engrg. Press, 1989.
[19] C. F. Bohren and D. R. Huffman, *Absorption and Scattering of Light by Small Particles*. New York: Wiley, New York, 1983.

Kristan P. Gurton received the Ph.D. in physics (specialty in applied optics/electromagnetic theory) from New Mexico State University, Las Cruces, in 1994.

He is currently an Experimental Physicist for the Army Research Laboratory (ARL), Adelphi, MD, conducting research in the area of electromagnetic propagation through the atmosphere and investigating various image enhancement techniques that utilize photon polarization state information. Prior to his appointment at ARL he held a Research Associateship with the National Academy of Sciences where he conducted research to determine various optical properties of fibrous aerosols at millimeter wavelengths. He has been involved in both millimeter and infrared (IR) aerosol photo-acoustics for nearly nine years. During this period he developed the first "single-particle" millimeter wave spectrophone capable of measuring absorption characteristics for an individual micron-sized particles.

Charles W. Bruce received the B.S. degree in physics from Union College, Schenectady, NY, in 1959, and the M.S. and Ph.D. degrees from New Mexico State University, Las Cruces, in 1968 and 1970, respectively.

He investigated high-density laser-induced plasmas and developed high-power laser instrumentation at the Air Force Weapons Laboratory in the early 1960's and studied low-density resonant plasmas (plasmoids) for his dissertation. At the Army Atmospheric Sciences Laboratory, White Sands Missile Range, White Sands, NM, and at the Physics Department, New Mexico State University, he measured molecular spectra for a variety of gases and atmospheric particulates using photo-acoustical systems that he developed including the first flow through aerosol system. Later he developed and applied photoacoustic and other techniques for submillimeter- and millimeter-wavelength spectroscopy.

J. B. Gillespie, photograph and biography not available at the time of publication.