Submillimeter Wavelength Modeling of Dielectric Materials in Polarimetric Radar Approaches

R.H. Giles, A.P. Ferdinand, M.J. Coulombe, J. Waldman
University of Lowell Research Foundation
450 Aiken Street, Lowell, MA 01854
and
W. Nixon, W. Reinhold
U.S. Army Foreign Science and Technology Center
220 Seventh Street, N.E., Charlottesville, VA. 22901

Abstract

Development of two measurement techniques has made polarimetric study of dielectric materials at submillimeter wavelengths possible. The first technique, a linearly polarized(LP) transmit/receive measurement system probes polarimetric behavior of a dielectric material through observation of the material's Brewster angle. The second technique, utilizes the recently developed submillimeter quarter wave plate(QWP) to perform ellipsometric determination of the dielectric material's complex refractive index[1]. In this paper submillimeter wavelength measurement techniques are used to polarimetrically characterize a variety of dielectric materials and demonstrate the feasibility of modeling clutter at microwave and millimeter wavelengths.

Introduction

The concept of using scaled reproductions and scaled wavelengths for modeling full-scale radar was established during the 1940's by individuals such as Sinclair[2] and Stratton[3]. Analysis of this concept reveals that modeling can be readily performed when working with materials that have high conductivities such as metals and metal alloys. However submillimeter wavelength modeling of millimeter radar scattering from materials other than metals requires precise characterization of the dielectric materials.

Ellipsometry is the preferred technique for characterizing the polarimetric properties of dielectric materials. Submillimeter ellipsometers require a combination of wire grids and quarter wave plates to measure the polarization behavior of radiation reflected from the dielectric. Analysis of the material's complex refractive index is then performed using the ellipsometer data in conjunction with the Fresnel equations.

To provide physical modeling of many types of terrain and other full scale dielectrics a wide variety of materials including conducting polymers and artificial dielectrics have been studied.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **1988**	2. REPORT TYPE	3. DATES COVERED **00-00-1988 to 00-00-1988**

4. TITLE AND SUBTITLE **Submillimeter Wavelength Modeling of Dielectric Materials in Polarimetric Radar Approaches**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **University of Lowell Research Foundation,450 Aiken Street,Lowell,MA,01854**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
Proceedings of the NATO Advanced Research Workshop on Direct and Inverse Methods in Radar Polarimetry , Bad Windsheim, Federal Republic of Germany, September 1988

14. ABSTRACT
Development of two measurement techniques has made polarimetric study of dielectric materials at submillimeter wavelengths possible. The first technique, a linearly polarized(LP) transmit/receive measurement system probes polarimetric behavior of a dielectric material through observation of the material's Brewster angle. The second technique, utilizes the recently developed submillimeter quarter wave plate(QWP) to perform ellipsometric determination of the dielectric material's complex refractive index[1]. In this paper submillimeter wavelength measurement techniques are used to polarimetrically characterize a variety of dielectric materials and demonstrate the feasibility of modeling clutter at microwave and millimeter wavelengths.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**9**	

The conductivity of the polymers is controlled over a wide range during growth and reduction stages thereby effecting their dielectric properties[4]. Artificial dielectrics are created and controlled by uniformly loading materials such as polyurethane or silicone resins with stainless steel flakes, which are dimensionally small compared to the modeling wavelength[1]. Measurements of these materials and other dielectrics are made using the linearly polarized(LP) measurement technique and the ellipsometric measurement technique. The results, which are then compared to microwave dielectric constants of specific types of clutter, using the requirements of electrodynamic similitude, demonstrate the feasibility of clutter modeling.

The Submillimeter Wavelength Measurement Techniques

Polarimetric analysis of dielectric materials has been performed using two submillimeter wavelength measurement techniques. The first technique utilizes the LP transmit/receive measurement system shown in Figure 1. Since this transmitter/receiver is monostatic, materials are configured with a metal plate to form a dihedral and allow specular reflectivity to be measured over a continuous range of incident angles.

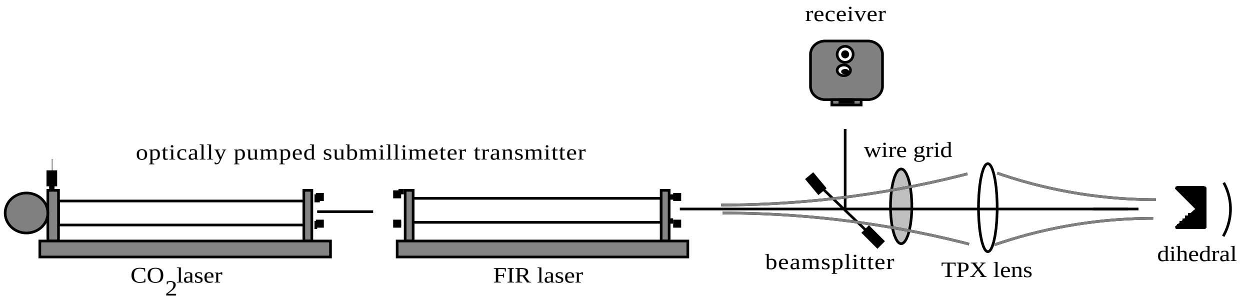

Figure 1 The submillimeter wavelength LP transmit/receive measurement system

A free standing wire grid has been incorporated into the measurement system so any linearly polarized state may be transmitted while receiving the co-polarized signal. Rapid acquisition rates of approximately 10 measurements/second are adequate for continuous scanning techniques while the dielectric dihedral's depression angle is stepped incrementally from 0° to 90°. By this method the system can provide reflectivity data at a range of depression angles and one can make comparisons to full scale phenomena as in Figures 3,4 and 5. In this type of polarimetric characterization technique, the LP transmit/receive polarization state is aligned parallel to the dielectric material's plane of incidence(i.e. p-wave). Then features such as levels of reflectivity and location of Brewster angles are used to determine the material's dielectric properties.

In conjunction with the p-wave reflectivity measurements, a second technique involving ellipsometry is used to provide a precise measure of the material's complex refractive index(or dielectric constant). A submillimeter ellipsometer, shown in Figure 2, has been designed to

---

[1] Artificial dielectrics are available in the form of commercial products such as SteelIt™ metallic paints.

measure the amplitude and phase of the radiation scattered from materials[2]. This polarimetric measurement configuration uses the recently developed submillimeter quarter-wave plate(QWP) technology and has polarization flexibility in the transmitter and receiver. Measuring the receive states for three LP transmit states, any two of which must be non-orthogonal, at a given dihedral orientation(material incident angle) allows one to calculate a Jones matrix. Knowing the Jones matrix at a variety of incident angles affords determination of a material's complex refractive index via Fresnel equation analysis[6].

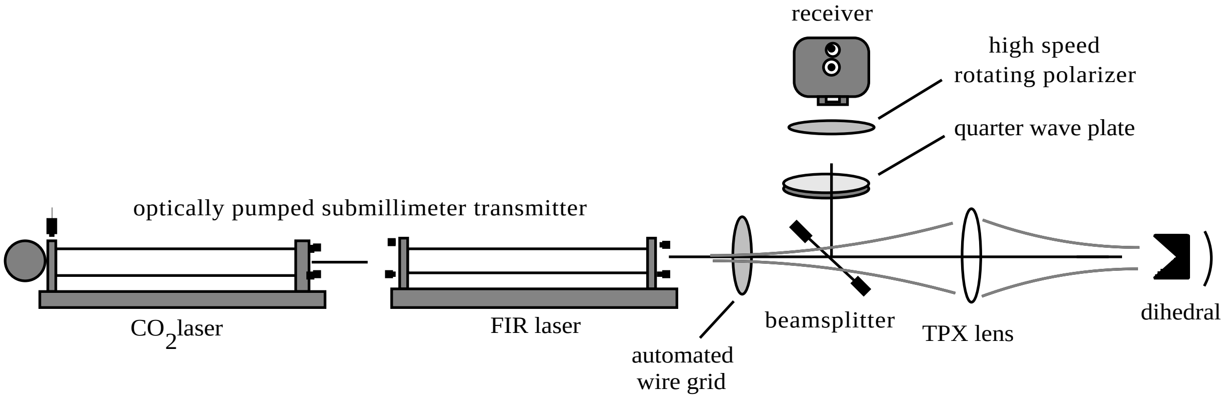

Figure 2 The submillimeter wavelength ellipsometric measurement system

Polarimetric Behavior of Dielectric Materials

Submillimeter wavelength modeling of dielectric materials utilize the general principle of electrodynamic similitude. This condition requires that the two characteristic quantities C_1 and C_2, first derived from Maxwell's equations by Stratton[3] as

$$\mu\xi\left[\frac{l}{\tau}\right]^2 = C_1 \quad \text{and} \quad \mu\sigma\frac{l^2}{\tau} = C_2 ,$$

be invariant to a change in scale. This invariance may be achieved for C_1 by decreasing the characteristic length, l, and the electric field's period, τ, with equal scale factors while maintaining the same magnetic permeability, μ, and relative electric permittivity, ξ. (ξ is also referred to as the dielectric constant.) When a change of scale is performed in this manner, an invariance of C_2 is achieved by increasing the material's conductivity by the scale factor. One must, however, note that the relationships for C_1 and C_2 are not necessarily independent, since a material's dielectric constant is a function of its conductivity.

To scale microwave polarimetric properties of dielectrics using the relationships for C_1 and

---

[2] Design and fabrication of the submillimeter ellipsometer, as well as, the analysis techniques necessary for the refractive index determination of dielectric materials, was performed in partial fulfillment of a Ph.D. thesis at the University of Lowell[5].

C_2, scaling materials are chosen which have the same complex dielectric constant (ξ^s) at submillimeter wavelengths that the full scale media has in the microwave (ξ^m).

$$\xi^s = \xi^m = \xi_r + i\,\xi_i$$

Since the dielectric constant's real and imaginary components (ξ_r and ξ_i respectively) are functions of frequency, proper scaling requires use of an entirely different material at submillimeter wavelengths from the dielectric measured in the microwave. (It is assumed that $\mu = 1$ for both scaled and unscaled wavelengths.)

Dielectric materials, which model smooth land and water surfaces, can be characterized polarimetrically using Jones matrix theory. With transmitted and received polarizations expressed in an HV linear basis as E^t and E^r, bistatic matrix representation of specular scattering from a material with complex dielectric constant(ξ) has the form:

$$\mathbf{E}^r = \mathbf{P}(\xi,\theta)\,\mathbf{E}^t \qquad (1)$$

where

$$\mathbf{P}(\xi,\theta) = \begin{vmatrix} r_s(\xi,\theta) & 0 \\ 0 & r_p(\xi,\theta) \end{vmatrix} \quad , \qquad (2)$$

and where θ is the depression angle. Matrix diagonalization, in equation 2, results from H and V axes alignment to the s and p reflection components, which are a function of the Fresnel equations. The dielectric's polarimetric behavior is described by its surface properties since the materials used are thicker than several skin depths. The s and p reflection components are expressed as:

$$r_s(\xi,\theta) = \frac{\sin\theta - (\xi - \cos^2\theta)^{1/2}}{\sin\theta + (\xi - \cos^2\theta)^{1/2}} \qquad (3)$$

and

$$r_p(\xi,\theta) = \frac{\xi\sin\theta - (\xi - \cos^2\theta)^{1/2}}{\xi\sin\theta + (\xi - \cos^2\theta)^{1/2}} \quad . \qquad (4)$$

Dielectric materials are configured with a metal plate in a diplane arrangement, as shown in Figure 3, to allow specular reflectivity measurements to be performed at non-normal incident angles using a monostatic measurement system. Polarimetric representation of the diplane introduces a 180° phase shift between s and p components of the matrix expression in equation 2. Calculations for radar background configured in the diplane arrangement have been performed using equations 1 through 4 using the background's dielectric constant measured at microwave frequencies. Results of radar background are then compared in Figures 4, 5 and 6 to reflectivity data measured at submillimeter wavelengths of dielectric materials with similar polarimetric behavior.

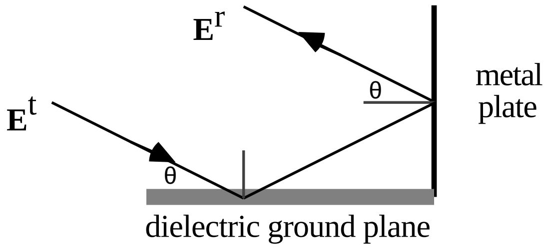

Figure 3 Simulation of ground plane to target scattering

Submillimeter Reflectivity Data of Dielectric Materials

R(θ) measurements using p-wave radiation were performed at a frequency of 1.5 THz on a wide variety of dielectrics such as metallic paints and conducting polymers, as well as, materials including acrylic, polycarbonate, foamed polyvinyl chloride, polystyrene and glass. Three materials have been chosen to exemplify the reflectivity measurements because of the close agreement to radar background.

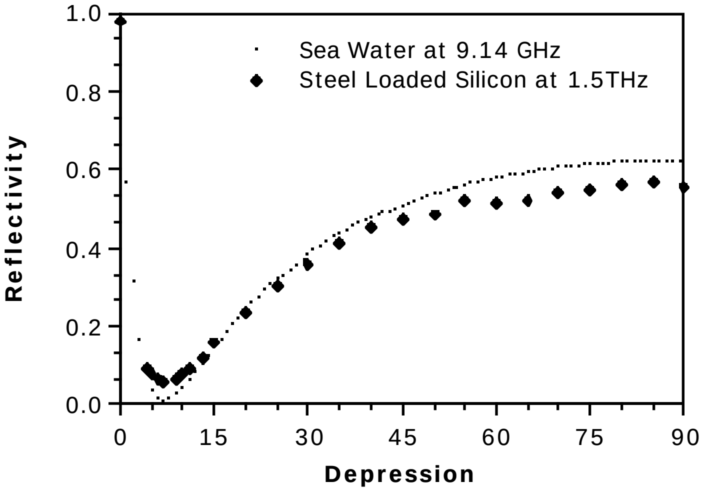

Figure 4 VV reflectivity for a sea water to metal double bounce as a function of depression.

Figure 4 summarized measurements performed on a dihedral, one plane coated with a metallic paint. Also shown in Figure 4 is the calculated reflectivity of sea water at 9.14 GHz using a dielectric constant of (ξ = 61+ i31) as cited by Stogryn[7]. The silicone resin based metallic paint, SteelIt™ HPC 5903, is uniformly loaded with stainless steel flakes dimensionally small compared to the modeling wavelength. The LP co-polarization(VV) behavior shown demonstrates the similarity between full-scale and modeling material.

Figure 5 contains reflectivity measurements performed on a dihedral with one plane made of acrylic. Also shown in this figure is the reflectivity of very dry ground at 9.14 GHz calculated using a dielectric constant (ξ = 2.8+ i0.014) measured on Austin, Texas Soil[8].

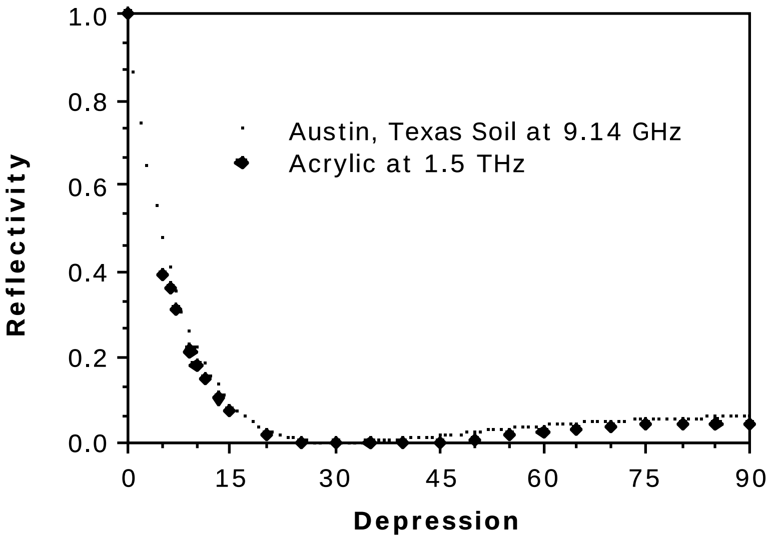

Figure 5 VV reflectivity for a dielectric ground plane(ξ = 2.8 + i0.014) to metal double bounce as a function of depression.

Figure 6 contains reflectivity measurements performed on a dihedral, one plane coated with a metallic paint(SteelIt™ HPC 1002). Also shown in this figure is the reflectivity of very wet sandy loam at 3.3 GHz calculated using a dielectric constant (ξ = 24+ i32.4) measured on Austin, Texas Soil[8].

In each of the three materials, the depression angle at which the minimum occurs for p-wave reflectivity is in close agreement with the dielectric constants of three types of background measured at microwave frequencies. This closely matched angle, referred to as Brewster's angle (or the pseudo-Brewster angle if the reflectance minimum does not approach zero), can be used to calculate the real component of the material's refractive index (n). Brewster's angle, θ_B, can be measured to a precision of ±0.1° using the submillimeter LP transmitter/receiver which allows one to determine n to approximately 1%. However, to completely specify a material's polarimetric behavior, one must determine the refractive index's imaginary component (k). The relation between a material's complex dielectric constant (ξ) and refractive index is: $\xi = (n + i\,k)^2$

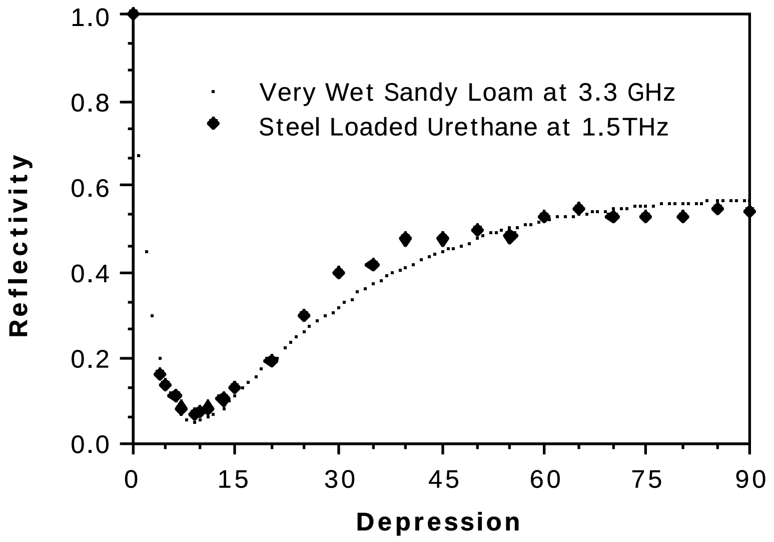

Figure 6 VV reflectivity for a dielectric ground plane($\xi = 2.4 + i32.4$) to metal double bounce as a function of depression.

While the LP transmit/receive measurement system provides a method of comparing polarimetric behavior of dielectric materials quickly and allows determination of the real part of the refractive index, it does not provide an adequate means of measuring k. Variations in reflectivity level can be as high as ±5% where as a 2% variation changes the calculated extinction coefficient by as much as an order of magnitude.

Submillimeter Ellipsometric Measurements of Dielectric Materials

The submillimeter ellipsometric measurement system provides the most precise method of measuring a material's complex refractive index (i.e. dielectric constant). It has been demonstrated that the refractive index of germanium, both real and imaginary components, can be determined to better than ±0.0001[5]. The dielectric's ellipsometer data can be analyzed by arranging equations 1 through 4 to produce the fundamental equation of ellipsometry.

$$\frac{E_s^t}{E_p^t} \times \frac{E_p^r}{E_s^r} = \frac{r_p(\xi,\theta)}{r_s(\xi,\theta)} \equiv \tan\psi \, e^{i\Delta} \qquad (5)$$

The optical constants are then determined from a sequence of Δ and ψ values, a pair for each incident angle(i.e. each Jones matrix measured). Sufficient ellipsometric data must be obtained to construct an experimental Δ, ψ curve which can be fit by a calculated curve with an unambiguous choice of the refractive index (or dielectric constant).

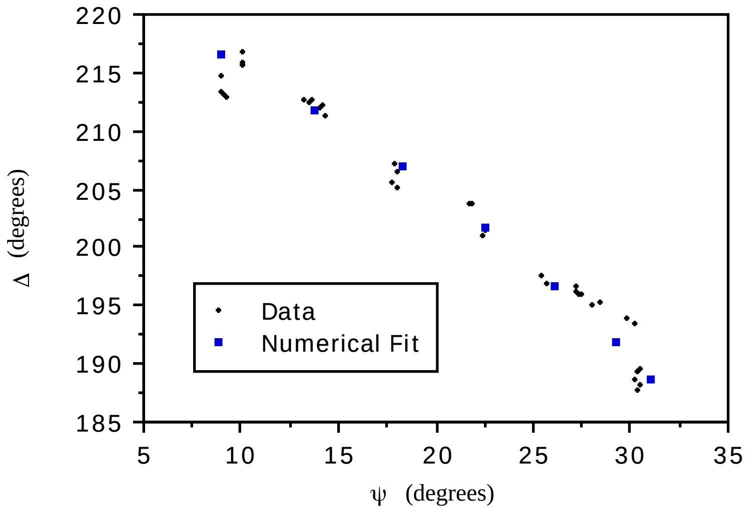

Figure 7 Ellipsometrically measured Δ, ψ values for germanium compared with values calculated from the numerical fit.

To demonstrate the submillimeter wavelength ellipsometric technique, measurements were performed on a germanium etalon at a frequency of 1.3 THz, with the results shown in Figure 7. The material's complex refractive index was determined from the measurements using equations 1 through 4 with the fundamental equation of ellipsometry in a numerical fitting technique. Because germanium has a low extinction coefficient making the etalon's thickness (t) much less than the skin depth, equation 5 was redefined as:

$$\tan\psi\, e^{i\Delta} = \frac{r_p(\xi,\theta)\,[1 - e^{-2i\delta}]}{1 - r_p^2(\xi,\theta)\, e^{-2i\delta}} \times \frac{1 - r_s^2(\xi,\theta)\, e^{-2i\delta}}{r_s(\xi,\theta)\,[1 - e^{-2i\delta}]} \tag{6}$$

where

$$\delta = \left[\frac{2\pi t}{\lambda}\right]\sqrt{\xi - \cos^2\theta}$$

to account for multiple reflections between the front and back surfaces. Using the ellipsometric data shown in Figure 7, the complex refractive index was determined as:

$n = 4.0061 \pm 0.0001$
$k = 0.00085 \pm 0.00005$

Conclusions

The modeling measurements cited in this study (Figures 3-5) along with those of other materials such as glass, polycarbonate and conducting polypyrrole demonstrate a wide range of polarimetric behavior in available materials at submillimeter wavelengths. Choice of materials used to scale dielectric properties depends primarily on the physical constraints of each application. Metallic paints appear best suited for modeling high loss dielectrics where coating unusually shaped substrates or large ground planes is required. Use of plastics allows modeling of lower loss dielectrics where surfaces must be machined or molded. The modeling measurements described have demonstrated the feasibility of submillimeter dielectric scaling and have provided two measurement techniques for polarimetrically characterizing materials at submillimeter wavelengths.

References

1) R.H. Giles, and M.J. Coulombe: "Design of a Submillimeter Ellipsometer for the Measurement of Complex Indices of Refraction of Materials", Tenth International Conference on Infrared and Millimeter Waves, December 1985

2) G. Sinclair: "Theory of models of Electromagnetic Systems", Proceedings of the Institute of Radio Engineering, November 1948

3) J.A. Stratton: Electromagnetic Theory, McGraw-Hill Book Company, New York, NY, pp. 488-490; 1941

4) G.C. Phillips, R.H. Giles, S.K. Tripathy, J. Waldman, "The Far Infrared Dielectric Properties of Conducting Polymers", 12th Annual IEEE Conference on Infrared and Millimeter Waves, Dec., 1987

5) R.H. Giles: "Design of a Submillimeter Ellipsometer and Application to the Measurement of Complex Indices of Refraction Materials", University of Lowell Ph.D. Thesis, Lowell, Massachusetts, June 1986

6) R.M.A. Azzam and N.M. Bashara, Ellipsometry and Polarized Light, (North Holland 1979)

7) A. Stogryn: "Equations for Calculating the Dielectric Constant of Saline Water", IEEE Transactions on Microwave Theory and Techniques, August 1971

8) M.W. Long, Radar Reflectivity of Land and Sea (Artech House, Inc. 1983) page 101.