Complex Dielectric Constants for Selected Near-Millimeter-Wave Materials at 245 GHz

J. M. DUTTA, C. R. JONES, AND H. DAVÉ, MEMBER, IEEE

Abstract —**A double-beam instrument developed in this laboratory has been used to measure the complex dielectric constant of selected materials at 245 GHz. We report here the results for crystalline quartz, fused silica (Spectrosil WF and Dynasil 4000), beryllia (iso-pressed), boron nitride (hot-pressed), and a nickel ferrite (Trans-Tech 2-111). Results are compared with the data obtained by other researchers.**

I. Introduction

THERE IS A growing interest in potential applications for the near-millimeter-wave (NMMW) spectral region (defined approximately as wavelengths between 0.3 and 3 mm). This interest is not limited to laboratory studies of physical phenomena, but includes increasing military and civilian requirements. Rapid advances are being made in the development of sources, detector, mixers, etc. However, the development of functional systems in the NMMW region is dependent also on the availability of improved components, including windows, attenuators, isolators, modulators, switches, directional couplers, etc. The development of such devices requires accurate data on the dielectric properties of materials in this spectral region. An extensive survey of the literature [1] has revealed a serious shortage of data, particularly in the 100–300-GHz region. Even where data is available, disagreement in NMMW measurements by different researchers is not uncommon. This may be due to large measurement uncertainties or to differences between nominally identical samples.

The present work involves the use of a double-beam instrument developed in this laboratory for the accurate measurement of dielectric properties [2]. This instrument utilizes the power and coherence of a laser source and combines the use of "quasi-optical" techniques with the introduction of dielectric waveguides to limit diffraction of the radiation. The capability of this instrument to provide accurate values for the refractive index and absorption coefficient at 245 GHz has been demonstrated for several low-loss materials, including Rexolite, TPX, and fused silica. We report here on the extension of these measurements to a variety of dielectric materials which have potential for NMMW application.

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J. M. Dutta and C. R. Jones are with the Department of Physics, North Carolina Central University, Durham, NC 27707.

H. Davé was with North Carolina Central University. He is now with the Applied Research Corporation, Landover, MD.

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II. Experimental Design

All measurements were performed at a frequency of 245 GHz using an optically-pumped molecular laser (OPML) as the source. The lasing gas was $C^{13}H_3F$ excited by the P32 line of a CO_2 laser. The output is a stable, linearly-polarized, Gaussian beam which is well suited to the study of optical properties of materials. Details of the design and performance of this laser have been previously reported [2].

The double-beam interferometer which is used for the measurement of refractive index is shown in Fig. 1. A number of "quasi-optical" components are combined to make this a rather unique instrument. BS_1 is a wire-mesh reflector which transmits a small fraction of the laser output to detector D_1 for power-monitoring purposes. The reflected beam passes through a 20-cm focal length lens (L_2) which produces a mildly convergent beam (half-angle 4°). This beam is divided by the dielectric prism coupler (DPC) which functions by frustrated total internal reflection at the interface between two prisms. Several investigators [2]–[6] have described the performance of this device and its application as an adjustable beam splitter or calibrated attenuator. The transmitted beam from the DPC traverses a mechanical phase shifter (PS) before coming to focus, while the reflected beam comes to focus at the sample (S).

The beam waist at the sample has a radius of 0.6 cm while the effective aperture of the sample holder is 0.95 cm in radius. This results in transmission of greater than 99 percent of the incident power through the sample aperture. As the beams exit the sample and the phase shifter, they enter oversized, circular, dielectric waveguides (WG) which serve as low-loss transmission lines operating in the EH_{11} mode. Marcatili and Schmeltzer [7] first derived the electric field configuration and propagation constants for such dielectric waveguides. More recently, Steffen and Kneubühl [8] and Degnan [9] have treated this subject. Experimentally, several investigators [2], [10], [11] have reported on the performance characteristics of these guides with regard to the efficient coupling of a free-space Gaussian mode into the EH_{11} guide mode, the low-loss propagation of this mode in the guide, and the recoupling of the EH_{11} guide mode into a new free-space Gaussian mode. The far-field

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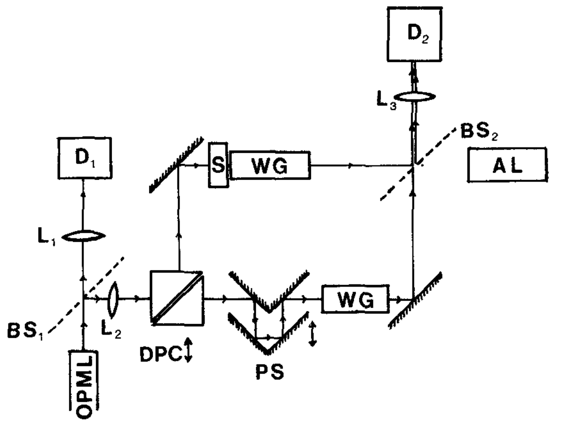

Fig. 1. A two-beam interferometer apparatus. D_1 and D_2: NMMW detectors; L_1, L_2, and L_3: TPX lenses; BS_1: wire-mesh beam splitter; BS_2: mylar-film beam combiner; DPC: double-prism coupler; PS: phase shifter; S: sample holder; WG: dielectric waveguides; AL: He–Ne alignment laser; OPML: optically-pumped molecular laser.

beam profile after exiting the waveguide has been shown to be well approximated by a Gaussian [2], as predicted by Degnan [9]. This type of dielectric waveguide provides a simple means of transmitting NMM radiation without diffraction spreading while maintaining good mode quality. After exiting the waveguides, the two beams are recombined by a mylar-film beam-splitter (BS_2). The final detector D_2 is a Golay cell. A He–Ne laser (AL) is boresighted to the beam for alignment purposes. The sample mount provides for rotation about a horizontal or a vertical axis and is on a rack and pinion drive to permit reproducible insertion and removal.

A refractive index measurement is accomplished by first inserting the sample and adjusting the phase shifter to obtain a null at detector D_2, then withdrawing the sample and advancing the phase shifter to return to a null condition. Withdrawing the sample produces a path change of K wavelengths where

$$K = \frac{(n-1)d}{\lambda_0}. \tag{1}$$

Here, λ_0 is the vacuum wavelength, d the sample thickness, and n the sample's refractive index. K may be expressed as the sum of an integer N and a fractional part f so that $K = N + f$. Solving for n then yields

$$n = 1 + \frac{N\lambda_0 + f\lambda_0}{d}. \tag{2}$$

The fractional path change $f\lambda_0$ is equal to L, the path change introduced by the phase shifter to restore the null condition after the sample is withdrawn. Therefore, the basic equation for the index becomes

$$n = 1 + \frac{N\lambda_0 + L}{d}. \tag{3}$$

N can be computed if an approximate value of the index is available; otherwise, measurements on at least two different sample thicknesses are required to determine N.

To obtain maximum precision, the expression for n in (3) must be modified to include the effect of multiple reflections which occur between the plane, parallel faces of the sample. The net effect of these reflections can be expressed [12] in terms of a small phase angle given by

$$\delta = \tan^{-1}\left[\frac{\rho\sin(2\varphi)}{1-\rho\cos(2\varphi)}\right] \tag{4}$$

where

$$\rho = Re^{-\alpha d} \quad \varphi = \frac{2\pi n\lambda_0}{d} \quad R = \frac{(n-1)^2}{(n+1)^2} \tag{5}$$

and α is the absorption coefficient of the material. The corrected expression for n is then

$$n = 1 + \frac{N\lambda_0 + L}{d} - \frac{\delta\lambda_0}{2\pi d}. \tag{6}$$

Since calculation of the correction requires values for the index and the absorption coefficient, a numerical iteration is used to obtain self-consistent values of the correction, the corrected index, and the absorption coefficient.

Measurement of the sample transmission for the purpose of determining the absorption coefficient is accomplished with minor modification of the instrument described above. The beam combiner (BS_2) and Golay cell detector (D_2) are removed. This gives access to the two beams from the DPC. Two identical pyroelectric detectors are then placed to intercept these two beams. Their outputs are amplified and input to a ratiometer which displays the ratio of the power in the sample beam to that in the other beam, which now serves as a reference. The first stage of this measurement is to adjust the DPC to produce a reading of unity on the ratiometer, with the sample removed. The sample is then inserted and the resulting ratio read as the fractional transmission of the sample T.

For the case of radiation normally incident on a plane, parallel plate of thickness d, the transmission is related to the absorption coefficient and the refractive index by [12], [13]

$$T = \frac{\rho(1-R)^2/R}{1+\rho^2-2\rho\cos(2\varphi)} \tag{7}$$

with ρ, φ, and R as defined above in (5). The expression for T in (7) can be solved for the parameter ρ, and the absorption coefficient is then given by

$$\alpha = \frac{-\ln(\rho/R)}{d}. \tag{8}$$

Computation of α from the measured transmission in this manner clearly requires an accurate knowledge of the sample's index and thickness.

III. Discussion and Results

The values of refractive index and absorption coefficient which we have obtained for a number of materials at room temperature are presented in Table I. Where available, the results obtained by other investigators are shown for comparison. The calculated loss tangent is also tabulated for convenience.

TABLE I
EXPERIMENTAL RESULTS

Material	This Work at 245 GHz				Literature	
	Thickness (mm)	n	α (cm^{-1})	Loss Tangent (10^{-4})	n	α (cm^{-1})
Quartz-O	37.145	2.1059 ± .0002	.011 ± .003	1.0 ± .3	2.106 [16]	
Quartz-E	37.145	2.1533 ± .0002	.016 ± .006	1.4 ± .5	2.154 [16]	
Fused Silica [a]	20.007	1.9516 ± .0002	.081 ± .004	8.0 ± .4	1.95117 [20]	0.07 [20]
Fused Silica [b]	9.990	1.955 ± .0013	.178 ± .008	18.0 ± .8		
Silicon	10.183	3.4182 ± .0008	.134 ± .016	7.6 ± .9	3.41805 [20]	.1303 [20]
Beryllia	20.629	2.6126 ± .0003	.100 ± .027	7.4 ± 2.0	2.60846 (44) [22]	.125 [22]
Boron Nitride	13.571	2.0727 ± .0004	.069 ± .004	6.4 ± .4	2.05 at 94 GHz [25]	
Nickel Ferrite	12.705	3.7298 ± .0008	.334 ± .026	17.4 ± 1.4	3.73 ± .043 [16]	.62 [16]

[a] Spectrosil WF
[b] Dynasil 4000

All samples were in the form of discs with diameters between 25 and 50 mm and smoothly polished faces. Measurements were made on the central 19 mm of the disc. The significant sources of error in the index measurements are the uncertainty in the sample thickness and the uncertainty in the path-length change of the phase shifter. Representative standard errors for sample thickness and path length change are 0.004 mm and 0.002 mm, respectively. The resulting standard errors in the index values are shown in Table I and are typically 0.02 percent or less.

The error in the absorption coefficient depends not only upon the uncertainty in the measured transmission, but also upon the uncertainties in the sample's index and thickness. This computation is rather involved, so a computer program is used to obtain the quoted estimates of error in the absorption coefficient. Because it is dependent upon many factors, this error ranges from a low of 0.003 cm^{-1} to as high as 0.027 cm^{-1} in these measurements.

A. Quartz

The sample used in this study was grown by Sawyer Research Products [4]. It was fabricated by Valpey-Fisher Corporation [15] to be X-cut within 5 min of arc, with faces polished optically flat and parallel. The sample thickness is 37.145 ± .003 mm, which is almost exactly 64 wavelengths for the ordinary ray at 245 GHz. The sample was mounted in a precision rotary stage and one axis aligned to the polarization of the laser output to within about 1° for measurement of the index and absorption coefficient of that axis. Our results for the index values, as shown in Table I, are in good agreement with those reported in [16]. The accuracy with which the absorption coefficient could be determined was limited, but results are consistent with a very low loss on the order of 0.01 cm^{-1}. To our knowledge, these absorption results are the first such data available.

Z-cut quartz is perhaps the premier low-loss material for general purpose usage. Large crystals of high quality are readily available and the absorption of quartz in the near-millimeter is so small that it is difficult to observe. In view of its very low loss, it is unfortunate that the thermal and mechanical properties of quartz often preclude its utilization for components which will be subjected to severe conditions.

B. Fused Silica

As expected, the amorphous form of silicon dioxide, fused silica, has a much higher loss than crystalline quartz. This loss is also sensitive to impurities, especially water content. Results are shown in Table I for two types of synthetic fused silica. The first is a very low-water content (less than 10 ppm) material produced by Thermal American Fused Quartz [17] and designated Spectrosil WF. The second is a commonly used optical window material produced by Dynasil Corporation [18] and designated Dynasil 4000. The water content is typically less than 1000 ppm. The latter results have been previously reported [2] but are included here for comparison. The absorption coefficient is seen to double for the high-water content sample, but even the low-water content sample is much lossier than crystalline quartz.

C. Silicon

Semiconductors, such as Si and GaAs, are, of course, important for the implementation of NMMW integrated circuits. High-resistivity semiconductors have relatively low losses for these wavelengths. The results reported here are for a mono-crystal silicon sample obtained from General Diode Corporation [19]. Crystallographically, the (111) plane is in the face of the disc. The sample was lightly doped with boron (0.18 ppb) and has a resistivity greater than 1500 Ω·cm. The values shown in Table I for the index and absorption coefficient agree very well with those reported in [20] for a sample which was undoped and has resistivity of approximately 8000 Ω·cm.

D. High-Temperature Ceramics

When components must withstand extremes of temperature and stress, ceramic materials may be the only choice available. Presently, there is very little data available on the NMMW properties of ceramics and where data is available there is often considerable variation among samples, depending upon the manufacturer, method of preparation, sintering agents used, etc. A variety of ceramic materials are being studied in this laboratory and initial results on samples of beryllia and boron nitride are shown in Table I.

The beryllia sample was obtained from the National Beryllia Corporation [21] and is 99.5-percent chemically pure, designated as K-150. This iso-pressed white disc has an average grain size of 22 μm and a nominal density of 2.90 gm/cm^3. Our results agree reasonably well with those reported in [22] on a similar sample from the same manufacturer. Sattler and Simonis [22] reported higher losses for samples from other manufacturers.

The boron nitride sample was Carborundum grade HP [23]. Its nominal composition is 42-percent boron, 53.5-percent nitrogen, and 1.5–2.5-percent oxygen. The density was given as 1.90 gm/cm^3. It is hot pressed with the pressing axis perpendicular to the face of the disc. No published absorption data could be found at this frequency for comparison with our results. In terms of NMMW dielectric properties, this material appears to be superior to both beryllia and alumina. It is available in a wide range of sizes and shapes, has excellent thermal and mechanical properties, high dielectric strength, and is machinable with conventional tools.

E. Nickel Ferrite

The sample studied is a commercial product of Trans-Tech, Inc. designated as Type 2-111 [24]. This material has been employed by various researchers in NMMW modulators and nonreciprocal devices. The saturation magnetization and resistivity are specified as 5200 gauss and 9×10^7 Ω·cm, respectively. The results shown in Table I for the index are in good agreement with a previously reported result [16], obtained by a laser technique similar to that employed here. However, our value for the absorption coefficient is approximately one-half that obtained by the same investigators using an FTS technique [16]. This value is still relatively large and may account for much of the insertion loss which is seen in device applications of this material.

IV. Conclusions

The limited data base on the NMMW dielectric properties of materials is slowly being expanded, primarily by the use of quasi-optical techniques. Reliable material standards are beginning to evolve. However, broad spectral coverage combined with high accuracy is still difficult to achieve. When the need for data over a wide range of temperatures is considered, the task of establishing a sufficient data base is still formidable.

The data reported here was measured at a single frequency; however, it can provide guidance at lower frequencies as well. Index values in the NMMW have very weak frequency dependence for most materials, while absorption values are almost universally increasing with frequency. Hence, the absorption coefficients observed at 245 GHz should represent an upper bound to the values at lower frequencies. Extension of this work to other materials, frequencies, and temperatures is currently in progress.

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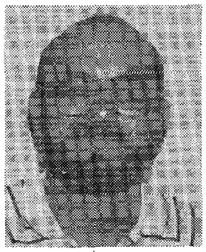
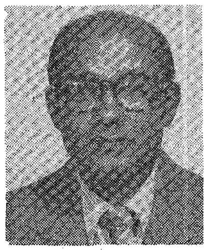


C. R. Jones was born in McComb, MS, on October 2, 1940. He received the B.S. and M.S. degrees in physics from Georgia Institute of Technology in 1962 and 1965, respectively, and the Ph.D. degree from the University of North Carolina in 1977.

From 1964 to 1967, he was engaged in research on optical data processing at the Lockheed-Georgia Research Laboratory in Marietta, GA. Since 1967, he has been on the faculty of North Carolina Central University in Durham, NC. His present research interests center upon the dielectric properties of materials in the near-millimeter spectral region.



J. M. Dutta received the B.Sc. and M.Sc. degrees in physics from Dacca University, Bangladesh, and the Ph.D. degree in physics from the University of North Carolina at Chapel Hill, NC.

From 1967 to 1970, he was on the faculty of North Carolina A and T State University in Greensboro, NC. Since 1974, he has been on the physics faculty of North Carolina Central University in Durham, NC. His present areas of research interest are far-infrared/near-millimeter-wave lasers and the dielectric properties of solids in the near-millimeter region.

Dr. Dutta is a member of the American Physical Society.

H. Davé (S'79–M'80) received the B.Sc. degree in physics from Guj'rat University, India, the M.S. degree in physics from Boston College, and the Ph.D. degree in applied physics from the University of Lowell.

From 1980 to 1984, he was on the faculty of North Carolina Central University in Durham, NC. He is currently an Associate Scientist with Applied Research Corporation in Landover, MD, where he is working on the fabrication of high-quality holographic diffraction gratings. His research interests include laser spectroscopy, coherent optics, integrated optics, holography, and millimeter-wave technology.