Dielectric Measurements of Millimeter-Wave Materials

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Abstract—**It is no longer necessary to use extrapolated microwave dielectric data when designing millimeter-wave components, devices, and systems. Precision measurements can now be made to generate highly accurate millimeter-wave (5 to 1/2 mm) continuous spectra on complex refractive index, complex dielectric permittivity, and loss tangent for a variety of materials such as common ceramics, semiconductors, crystalline, and glassy materials. The continuous spectra reveal an increase in dielectric loss with increase in frequency in this wavelength range for most materials. Reliable measurements also reveal that the method of preparation of nominally identical specimens can change the dielectric losses by many factors. These broad-band measurements were carried out employing dispersive Fourier transform spectroscopy applied to a modular two-beam polarization interferometer. Data obtained with Fabry–Perot open resonator methods at wavelengths of 5 mm and longer will also be compared.**

I. Introduction

UNTIL RECENTLY, there has been almost no reliable data available in the millimeter and near-millimeter wavelength (60–600 GHz) range because measurements of the dielectric properties of materials at these wavelengths are extremely difficult to carry out accurately. The millimeter-wave region lies beyond conventional microwave techniques and forms a "bridge" to the optical techniques. In the past, one could rarely trust the millimeter-wave dielectric data for use in precision engineering design because any extrapolated microwave method or extrapolated optical method that was used to make the measurements had many serious limitations and uncertainties. Until recently, engineers have been satisfied to know whether a material was "opaque" or "transparent" at millimeter waves. More recently, a measurement good to ten-percent accuracy was considered to be better than nothing; after all, it is inconvenient and expensive to acquire and use precision measurement facilities and sophisticated instrumentation. The real danger lies in the literature that is actually misleading. Most frequently, the misleading data get into the literature when someone uses a familiar microwave instrument, such as a waveguide interferometer, a cavity resonator, or a Fabry–Perot open resonator, beyond the limit of its classical capabilities. For example, the millimeter wavelengths are too short for the practical use of a microwave single-mode resonant cavity. The millimeter wavelengths are too long at this extreme end of the *optical* spectrum for a familiar black-body source, such as a mercury vapor lamp, to be used. It normally provides too little energy for millimeter-wave measurements with a Fourier spectrometer. Indeed, the use of a *conventional* plane-wave interference technique employing a mercury lamp to obtain millimeter-wave dielectric data is almost impossible. Nevertheless, the Fourier method has now been improved by the author to provide data from 5 mm (60 GHz) into the submillimeter range [1]. New theories were also developed by the author giving a full treatment of all beams and interface effects [2]–[6], and great care was taken to increase the efficiency of energy throughput and detection [1], [7], [8]. In such a special spectrometer, the phase determination in particular can be made very accurately when used in the asymmetric mode (dispersive Fourier-transform spectroscopy) leading to the determination of the real part of the dielectric constant to five or six significant figures [1], [8]. The imaginary part (and loss tangent) can be determined only to about 1 percent because the commercially available electronic amplifying equipment cannot ordinarily carry through amplitude information with higher precision and reproducability [1], [8].

Why should one go to all of this trouble and expense just to get another order of magnitude, or even a factor of three, higher accuracy, reproducibility, and reliability? Why wouldn't a quick measurement providing "engineering values" be suitable for the purpose of exercising the tradeoff process for the selection of materials for particular applications? The simple answer is that there are wide variations in the parameters of nominally identical specimens at millimeter wavelengths that microwave engineers rarely see at lower frequencies. When one is trying to determine the reasons for these variations so as to choose a "standard material" for millimeter application, ± 10 percent in reproducability of measurement is just not good enough.

It is very important to have highly reproducible data, so that one would be able to distinguish the different dielectric properties among nominally identical specimens; dielectric properties that vary among specimens from different suppliers, among specimens prepared by somewhat different methods, or among specimens having physical properties that are not precisely controlled during preparation.

New continuous spectra show significant variations in the dielectric properties of such common materials as SiO_2, the fused silica glass [1], [8] where the water content in the

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material plays the dominant role in absorption. There are notable differences in absorptions in common ceramics such as Al_2O_3, the ceramic alumina, and BeO, the ceramic beryllia, depending upon the source of the specimens and the degree of crystallinity. One would expect to find differences in absorption among high resistivity semiconductors, such as semi-insulating gallium arsenide and silicon. New results demonstrate that a higher cromium concentration is an advantage in suppressing long wavelength (millimeter-wave) free-carrier absorption in GaAs.

II. Measurement Methods

The dispersive Fourier-transform spectroscopic technique applied to a polarization two-beam interferometer is a quasi-optical technique and one measures directly the optical parameters, namely, the absorption coefficient (α) in Neper/cm and the refractive index (n) simultaneously [1]–[8]. Dielectric parameters, the complex permittivity $\hat{\epsilon} = \epsilon' - j\epsilon''$, and the loss tangent $\tan\delta = \epsilon''/\epsilon'$ are easily calculated via Maxwell's celebrated relation $\hat{\epsilon} = (\hat{n})^2$ from directly obtained α and n. The simple relationship between the fundamental optical quantities α and n and the dielectric quantities ϵ' and ϵ'' are as follows:

$$\epsilon' = n^2 - k^2 = n^2 - (\alpha/4\pi\tilde{\nu})^2 = n^2 - (c\alpha/4\pi\nu)^2 \quad (1)$$

$$\epsilon'' = 2nk = (\alpha n)/2\pi\tilde{\nu} = (\alpha cn)/2\pi\nu \quad (2)$$

where k is the imaginary part (absorption index) of the complex refractive index $\hat{n} = n - ik = n - i(\alpha/4\pi\tilde{\nu})$ and ν = frequency in Hertz, $\tilde{\nu}$ = wavenumber per centimeter, and c = velocity of light in vacuum. It is convenient to note that

$$1 \text{ wavenumber (per cm)} = 30 \text{ GHz}.$$

The present dispersive Fourier-transform spectroscopic (DFTS) technique of the author measures the refractive index spectrum and, simultaneously, the absorption coefficient spectrum from the analysis of the amplitude and phase information that the specimen has contributed to the output signal [1]–[9]. The phase information (together with the amplitude information) is carried through to a determination of the refractive index (and the real part of the dielectric permittivity) to an accuracy of five or six significant figures for a low-loss material.

Several other classical methods are being improved in efforts to provide some kind of data, if not the best, to this barren region of the spectrum.

1) The Fabry–Perot open resonator provides about an order of magnitude less accuracy in the measurement of loss tangent and only three significant figures in the dielectric constant, but in some ways it is more convenient to use [10]–[13]. Today, the most significant improvement in the Fabry–Perot system would be the use of a superheterodyne receiver with highly stabilized, phase-locked Gunn oscillators [14]. 2) The Mach–Zehnder type of spectrometer used with Gunn or IMPATT sources also produces dielectric data at the typical IMPATT frequencies [15], [16]. Precision data in this case again can only be obtained by the use of a specially constructed highly stable spectrometer system with a high degree of statistical fitting [17]. Various other techniques (such as 3) rotation of a parallel slab specimen with input and output devices [18], 4) waveguide reflectometers [19]–[21], 5) oversize cavity resonators [22]–[24], and 6) oversize waveguide interferometers [25]–[27]) also produce dielectric data in the range 10–2 mm, but the accuracy is again limited to about 10 percent in most of these techniques. Among all of these methods, the DFTS is the best for the millimeter and submillimeter range. Other methods, such as these six mentioned above, have their particular applications, such as other wavelength ranges, odd specimen sizes, and different physical properties, such as liquids and gases [28].

Attempts have been made during the past decade to extend various classical cavity techniques and quasi-optical techniques toward the millimeter-wave region. As microwave methods are extended toward the millimeter wavelengths, Q-values become very low, particularly for closed cavities. Therefore, it is practical to discuss only quasi-optical techniques here, namely a) dispersive Fourier transform spectroscopy (DFTS), b) Mach-Zehnder-IMPATT spectrometer (MZI), and c) open-resonator method. The author's present facilities include all of these techniques.

The dispersive Fourier-transform spectroscopic technique applied to a polarization two-beam interferometer and a special detector consisting of a helium-cooled InSb hot-electron bolometer generates high-accuracy broad-band data in the range 3–0.25 mm and is limited only on the microwave end of its range (around 5 mm) by the weak radiative power from its mercury vapor lamp. Therefore, at the microwave end of the range, other methods, such as a Mach–Zehnder interferometer together with an IMPATT [15], [16] or Gunn oscillator or an open-resonator technique [10]–[14], [28], can be used. In experienced hands, these methods can provide excellent, reliable data on both dielectric and magnetic parameters, ϵ', ϵ'', μ', and μ'' through the long wavelength gap in the spectrum.

A. Dispersive (Asymmetric) Fourier-Transform Spectroscopy

In a dispersive Fourier-transform spectroscopic (DFTS) technique, the specimen is placed in one of the active arms (mirror arm) of a two-beam interferometer rather than in one of the passive arms (source or the detector arm) as shown in Fig. 1. This gives the phase information from the specimen in addition to the amplitude information into a recorded interferogram. The Fourier transform of this interferogram contributes phase and amplitude information of the specimen into the complex frequency spectra. These phase and modulus spectra are ratioed and subtracted with ones obtained without the specimen to yield complex refractive index spectra. This is a high-precision technique where contributions from each interface of the specimen and from the mirror are fully accounted for to give highly accurate refractive index and absorption coefficient spectra simultaneously—the refractive index to five or six significant figures for a low-loss material and the absorption coefficient to about one-percent reproducability. This

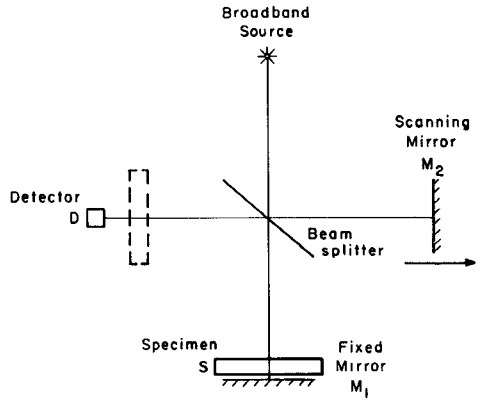


Fig. 1. Ray diagram of a two-beam Michelson interferometer. S is the specimen.

method is not yet widely used because the complicated theory has only recently been developed and perfected by the author [1]–[9] and adapted to the millimeter-wave range.

An interferogram is produced by moving the mirror M_2 in Fig. 1 so that the path difference x creates constructive and destructive interferences. If the interferogram recorded with the specimen present is $F_s(x)$ and if the reference interferogram without the specimen is $F_o(x)$ where x is the path difference the ratio of the full Fourier transform $\mathcal{F}$ gives the complex positional insertion loss $\hat{\mathcal{L}}(\tilde{\nu})$

$$\mathcal{F}\{F_s(x)\}/\mathcal{F}\{F_0(x)\} = \hat{\mathcal{L}}(\tilde{\nu}) = \text{function}\,[\hat{n}(\tilde{\nu})\text{: position}].$$

The relationship between the complex insertion loss $\hat{\mathcal{L}}(\tilde{\nu})$ and the complex refractive index $\hat{n}(\tilde{\nu})$ depends upon both the nature and the location of the specimen. The full interferogram $F_s(x)$ may contain a number of interference signatures arising from reflections at various interfaces, before and after transmitting through the specimen and from multiple reflections between parallel surfaces within the specimen, as shown in Fig. 2. The interferogram $F_s(x)$ is the sum of $F_R(x)$, $F_T(x)$, and $F_M(x)$, so that $F_s(x) = F_R(x) + F_T(x) + F_M(x)$, where $F_R(x)$ represents interference signatures after reflections from front and rear surfaces of the specimen. The strong $F_T(x)$ signature represents the interference signature arising after transmitting through the specimen, reflecting from the mirror M_1 and transmitting through the specimen again. The multiply reflected signatures are represented by $F_M(x)$ signatures. For a relatively low absorbing material, a thick specimen is required in order to satisfy the condition such that the transmissive loss is higher than the reflective loss. The use of a thick specimen also leads to a good separation of $F_R(x)$, $F_T(x)$, and $F_M(x)$ signatures and any of these edited signatures or a combination of edited signatures and $F_o(x)$ signatures could be used to evaluate complex refractive index spectra. It is obviously preferable to use the main strong transmission component signature $F_T(x)$ together with the strong $F_o(x)$ signature to evaluate $\hat{n}(\tilde{\nu})$.

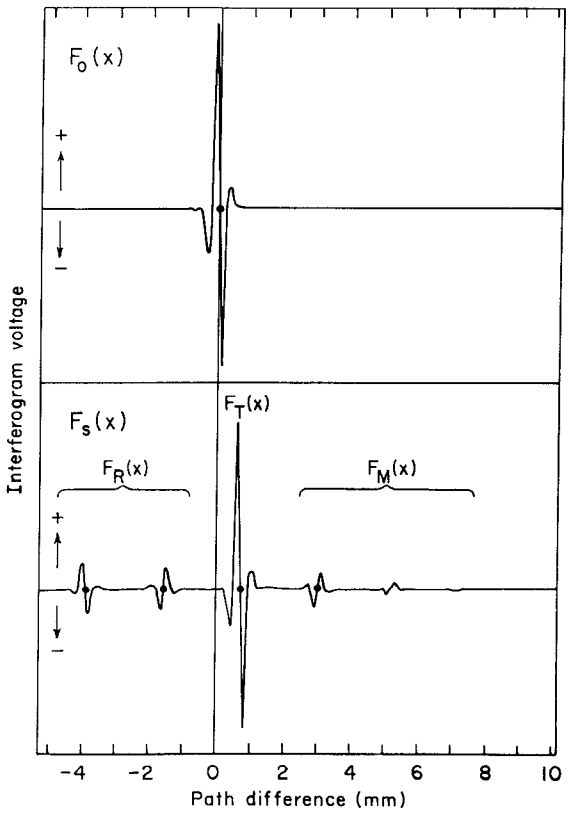


Fig. 2. Phase modulated antisymmetric interferograms recorded using a polarizing interferometer for dispersive Fourier-transform spectroscopy. $F_o(x)$ is the reference interferogram recorded without the specimen and $F_s(x)$ is the interferogram recorded with a T.P.X. specimen.

One then has the transmission insertion loss

$$\hat{\mathcal{L}}_T(\tilde{\nu}) = \mathcal{F}\{F_T(x)\}/\mathcal{F}\{F_0(x)\} = \hat{S}(\tilde{\nu})\exp\{-4\pi i\tilde{\nu}[\hat{n}(\tilde{\nu})-1]\,d\}\hat{M}(\tilde{\nu})$$

where $\hat{S}(\tilde{\nu})$ and $\hat{M}(\tilde{\nu})$ represent, respectively, surface reflection loss and multiple reflection loss contributions of the incident beam. The refractive index and the absorption coefficient spectra are then calculated via an iterative procedure. The full iterative procedure developed by the author [2]–[6] takes care of all interface effects and produces highly precise absorption coefficient and refractive index data. It is therefore no longer necessary to adjust the absolute level of absorption coefficient and refractive index spectra with other methods. Therefore, these DFTS measurements may be considered to be the *absolute* standard.

As mentioned earlier, the preferred type of interferometric configuration to be used in the millimeter-wave region is the polarization configuration [1]–[8]. In a polarization, wire-grid polarizers replace the usual single-dielectric (plastic myler) beam splitter, in order to polarize the incident unpolarized beam, split, recombine, and analyze before reaching the detector. The mylar or dielectric beam splitter, used in a two-beam interferometer, suffers from strong frequency dependence of the transmissivity due to multiple reflections within the beam-splitting material. Free-standing polarizing wire grids are free from multiple internal reflections and the transmissitivity is flat up to a high

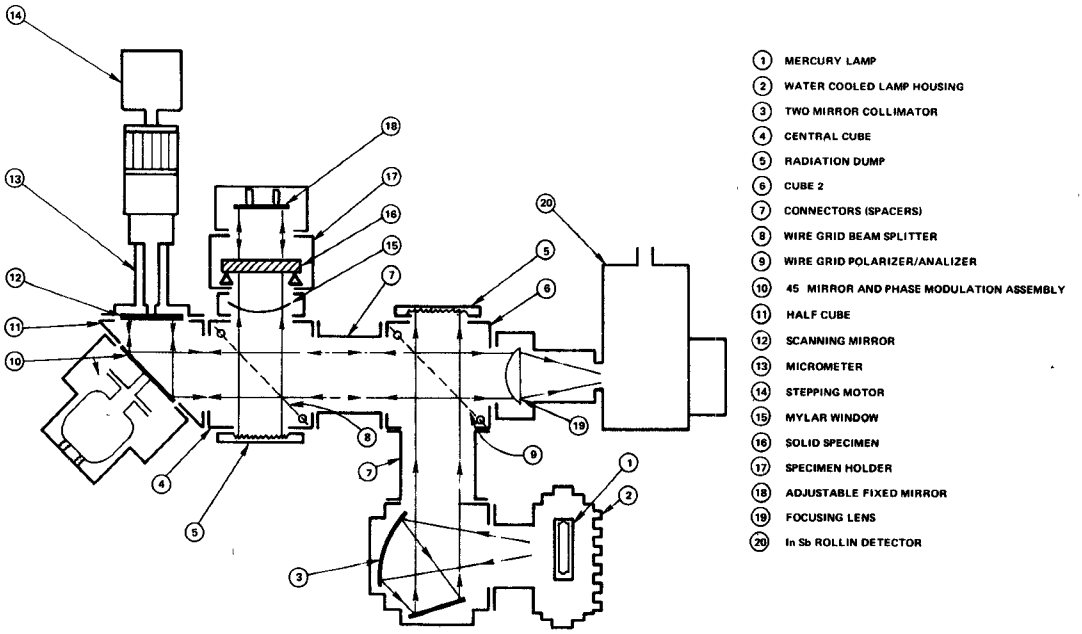


Fig. 3. Modular polarization interferometer for dispersive Fourier-transform spectroscopy for millimeter-wave measurements of complex refractive index and complex dielectric permittivity of low-loss solids.

cutoff frequency, which is inversely proportional to the wire spacing.

The specially constructed polarizing interferometric configuration used for the present dielectric measurement on solids is shown in Fig. 3. A pair of free-standing wire-grid polarizers made up from 10-μm-diam tungsten wire spacing of 25 μm (center to center) was used. One of the grids acts as a polarizer and analyzer, and the other acts as a beam splitter. The high-frequency cutoff with 25-μm spacing is 200 wavenumber/cm (50-μm wavelength). The orientation of wires of the beam splitter grid is at 45° compared to the polarizer/analyzer grid so that the perpendicular component of the polarized beam transmits to the scanning mirror arm and the parallel component reflects to the specimen and fixed mirror arm. Both beams recombine at the beam splitter grid and get analyzed by the polarizer/analyzer grid before reaching the detector. A liquid helium-cooled fast hot-electron effect InSb Rollin-type bolometer [29], operating on the principle of free-carrier absorption, is found to be most suitable in the millimeter-wave region [1]–[9].

The DFTS method requires a highly stable reproducible interferometric system in order to generate precise phase information. The temperature of the interferometer arms are therefore controlled by circulating fluids from a temperature control bath. Specimen surfaces were flattened to about 1/4 wavelength in the visible and made parallel to about 1 s. For a low-loss material, large specimen thickness has to be chosen in order to make the transmissive loss greater than the reflective loss. The electronic components need to be stabilized before recording any run. A step change in the attenuator or the gain knob in a lock-in amplifier, and the inclusion of the marked gain factor in the calculation, can lead to a systematic change in absorption data. The gain is therefore kept unchanged during sets of measurement and the interference signal is resolved by higher digital discrimination (22 bit).

B. Mach–Zehnder — Single-Frequency Source Spectrometer

Since the dispersive Fourier transform spectroscopy applied to a polarization two-beam interferometer uses a black-body continuum source of radiation, there are cases where the throughput of energy is too weak, particularly when one tries to measure highly absorbing materials. In that case, a high-power monochromatic source of radiation, together with a Mach–Zehnder interferometer, may be used [30]–[32]. A Mach–Zehnder interferometer is specially suited to be used with a monochromatic source because no beam returns to the source to make it unstable. This method provides data at a single fundamental frequency and at harmonic frequencies whenever these can be generated. Considerable success has been achieved by the author with such a system in the submillimeter-wave range, where molecular gas lasers provided an excellent stable, high-power source [30]–[32]. Recently Birch [15], [16] employed a CW 20-mW, 100-GHz, IMPATT oscillator together with a Mach–Zehnder interferometer for dielectric measurement of liquids. The author's present spectrometric configuration is shown in Fig. 4. The solid specimen is rotated in order to vary the specimen thickness. Provisions were made so that the Mach–Zehnder spectrometer can be moved easily to any of the sources, such as an optically pumped laser tunable to hundreds of different frequencies, and 60-GHz and 90-GHz Gunn oscillators. The complete interference pattern is recorded at small intervals of angle

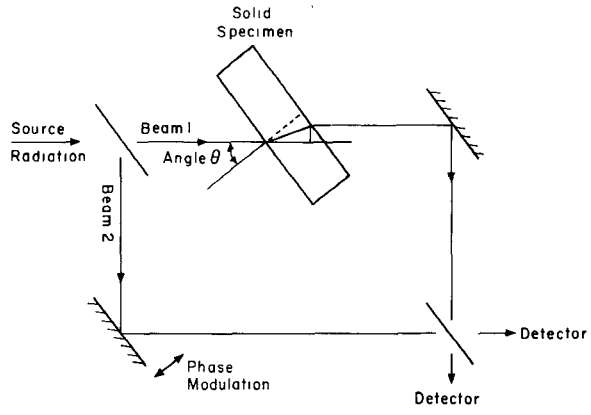


Fig. 4. Mach–Zehnder interferometer configuration for dielectric measurement of solids. The thickness is varied by rotating the specimen in small steps.

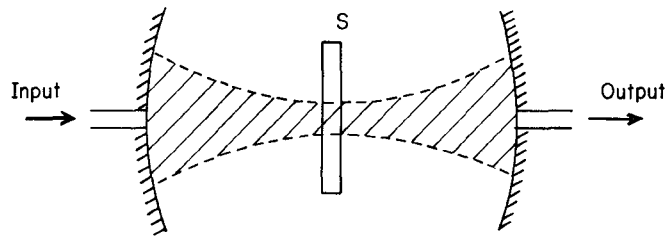


Fig. 5. The confocal Fabry–Perot open resonator for millimeter-wave dielectric measurement. S represents the specimen position. The shaded areas show the extent of the millimeter-wave beam in the resonator.

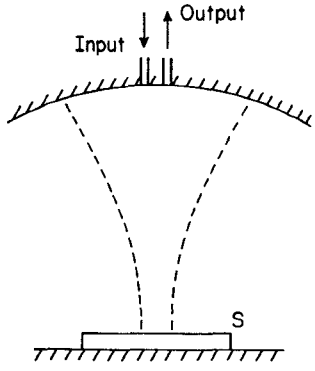


Fig. 6. The hemispherical type of open resonator for millimeter-wave dielectric measurement. The specimen, in this case, rests on the flat mirror of the resonator.

of rotation of the specimen (by means of a stepping motor). Both absorption coefficient and refractive index values are determined with a high degree of statistical fitting.

C. Open Resonator Method

At millimeter wavelengths, a microwave closed cavity becomes small and inconvenient, and at short millimeter wavelengths it becomes impractical to prepare specimens for the resonant closed cavity. Fabry–Perot open resonator methods have been used successfully at these wavelengths [10]–[14], [28], [33]. A confocal resonator is shown in Fig. 5. It provides high-Q (small diffraction loss) because it has two large concave mirrors facing each other with the specimen placed in the center. At wavelengths longer than 1 mm, the electromagnetic energy is coupled in and out of the resonator by waveguides. A small coupling hole in each mirror is used to transmit the energy to and from the input and output waveguides. It is important to have the coupling hole at the center of each of the mirrors because an off-center hole is one of several ways that higher modes of oscillation of the cavity can be introduced [34]. The theoretical analysis of the data is dependent on the fundamental mode; higher mode degeneracy must be avoided [10]–[12].

The author's facility employs a hemispherical-type resonant structure similar to ones successfully used by Jones [12]. A hemispherical resonator employs one concave and one plane mirror as shown in Fig. 6. The specimen rests on the mirror. The use of a plane mirror allows liquid specimens to be measured in addition to solids. The input and output waveguides are attached at the back of the concave mirror. At frequencies greater than 100 GHz, the waveguides become more difficult to use. Certainly beyond 300 GHz, the energy must be focused by a lens through a small hole in a mirror [35], although sometimes a beam splitter coupling [36] can be used.

The theory of open resonator systems for confocal configurations has been developed by Cullen and Yu [10], [11] via a Gaussian beam formulation. Recently, Yu and Cullen [37] used a vector field theory based on an exact solution of Maxwell's equations. A simplified approximate formula for the electric- and magnetic-field vectors are then derived. A variational formula of the resonant frequency of an open resonator is then developed with the use of these simplified formulas.

Jones [12] adapted the Gaussian beam formula for use with the hemispherical resonator. Open resonators are very convenient for the measurement of low-loss materials because Q values can be made very much higher than a closed resonant cavity at millimeter wavelength region. The typical Q of our 13-cm-long, 15-cm-diam, hemispherical resonator at 60 GHz is 160000. The real part of the dielectric permittivity can be measured to an accuracy ranging from ± 0.2 to 1 percent and the $\tan\delta$ to an accuracy ranging from 2 to 10 percent in most open resonator systems.

Recently, newer detection devices such as the heterodyne receiver have been used by Kolbe and Leskovar [28] to achieve faster response times and greater sensitivity. Our open resonator system [14] employs a high-Q resonator and two highly stable phase-locked (locked to a frequency standard with stability of 5×10^{-12}) Gunn oscillators (tunable signal-frequency oscillator of 60-GHz and 56-GHz fixed-frequency local oscillator). Both oscillators, together with a GaAs FET IF amplifier, make the extremely low-noise sensitive superheterodyne receiver. The measurement of $\tan\delta$ as low as micro-radians is now expected. Table I compares some n, ϵ', and $\tan\delta$ results obtained by open resonator methods.

TABLE I
MILLIMETER-WAVE DATA OBTAINED WITH OPEN RESONATOR SYSTEMS

Material	λ(mm)	Freq(GHz)	n	ϵ'	$\tan\delta$ (μ rad)	Ref.
Alumina	8.834	33.906	3.119 ± 0.015			38
Polyethylene (High Density)	.87	344.83		2.31 ± 0.05		39
	2.1	142.86		2.31 ± 0.05		39
	8.57	35	1.5218 ± 0.0015	2.316 ± 0.004	134 ± 7	39
Polyethylebe (Rigidex 2000)	8.6	34.88	1.5360 ± 0.0015	2.3593 ± 0.0042	173 ± 9.9	40
Polypropylene	8.718	34.38	1.5858 ± 0.0004			41
	8.862	34.80	1.5012 ± 0.0004			38
	8.57	35	1.5014 ± 0.002	2.254 ± 0.004	154 ± 8	40
Teflon (Sintered)	.87	344.83		2.07 ± 0.04		39
	2.1	142.86		2.07 ± 0.04		39
	6	50	1.433 ± 0.007	2.052 ± 0.020	315 ± 26	33
	8.6	34.88			250 ± 30	41
Teflon (unsintered)	8.6	34.88		1.952 ± 0.007	48 ± 3.9	40
TPX	8.677	34.57	1.4589 ± 0.0013			38
	8.508	35.26	1.458 ± 0.002	2.126 ± 0.004	427 ± 21	40
Polystyrene	.87	344.83		2.57 ± 0.05		39
	2.1	142.86		2.56 ± 0.05		39
	6	50	1.590 ± 0.008	2.528 ± 0.025	721 ± 58	33
	8.6	34.88			520 ± 60	41
Plexiglass	.87	344.83		2.61 ± 0.05		39
	2.1	142.86		2.60 ± 0.05		39
	6	50	1.599 ± 0.008	2.557 ± 0.026	3270 ± 262	33
Crystal Quartz (Ordinary ray)	8.57	35		4.430 ± 0.004		42
(Extra-Ordinary ray)	8.57	35		4.633 ± 0.004		42
Slip-Case Fused Silica	3.18	94.34	1.812 ± 0.003	3.285 ± 0.007	2640 ± 142	43
Liquid Cyclohexane	8.436	35.56		2.014 ± 0.003	79 ± 4	44
	4.167	72		2.018 ± 0.002	154 ± 8	44
	2.083	144		2.016 ± 0.004	294 ± 8	44

III. RESULTS

When reliable and reproducible millimeter-wave data become available for a sufficiently large variety of materials, the origin of the losses can be discussed. Materials need to be studied as a class, and some parameters need to be varied in order to understand absorption processes and to fabricate materials for special purposes, such as windows for high-power sources (e.g., gyrotrons and waveguides and lenses for other millimeter-wave applications). In glasses and ceramics, variables will be water content, degree of crystallinity, and crystallite size. For semiconductors, purity and dopant may be varied in order to suppress the tail of the high-frequency multiphonon absorption bands and millimeter-wave free-carrier absorptions. Materials have to be specially prepared with specifications of variables. Meanwhile, we have made broad-band measurements on a variety of materials available either commercially or on loan, and have been able to develop a few clues which should be helpful in the engineering design because many of these materials are widely used in modern electronic systems.

A. Common Ceramics

Ceramics such as beryllia (BeO) or alumina (Al_2O_3) are good candidates as low-loss dielectrics, and as window materials for high-temperature applications. The refractive index of both kinds of ceramics are high, suggesting possible application as dielectric waveguides. The absorption coefficient spectra for four types of Al_2O_3 are shown in Fig. 7(a). Both "COORS" alumina 999 and "WESGO" alumina 995 were cold pressed and sintered. The flux used for the "WESGO" alumina 995 contained less than 0.5-percent $CaOMgSiO_2$ and for the "COORS" alumina 999 contained less than 0.1-percent MgO. The hot-pressed $MgAl_2O_4$ spinel was also prepared by "COORS" Porcelain Co., CO. The single-crystal Z-cut sapphire was a Crystal Systems Inc., MA, product. It is surprising to see that the "WESGO" alumina 995 had lower losses than "COORS"

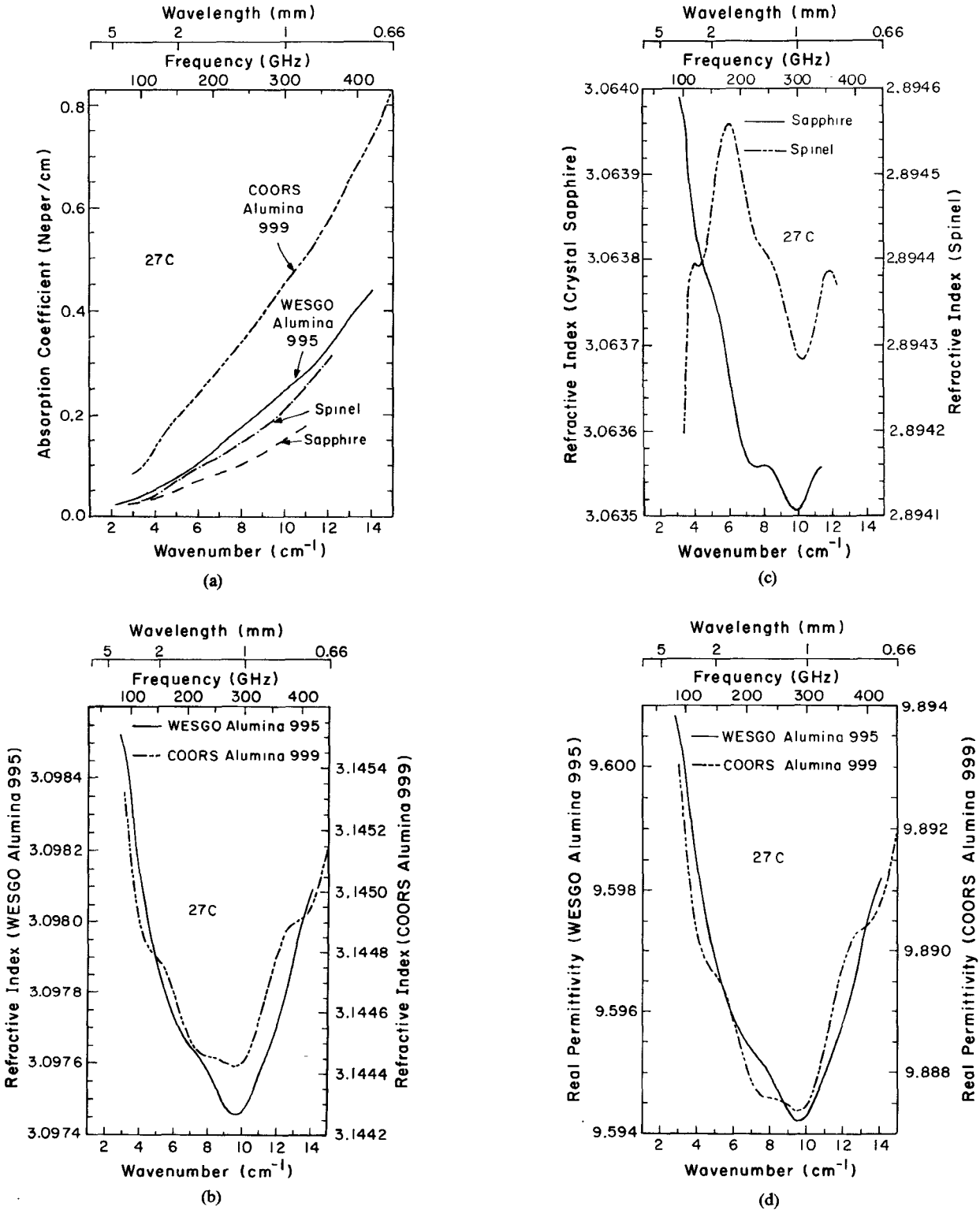
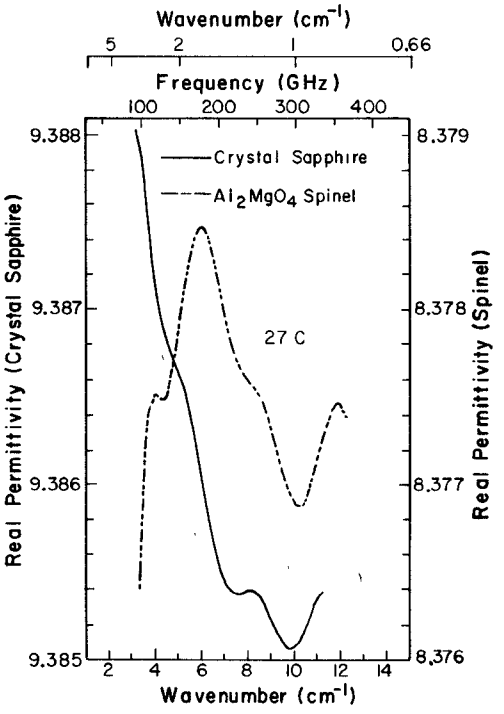


Fig. 7. (a) Comparison of absorption coefficient spectra of 'WESGO' alumina 995, 'COORS' alumina 999, single crystal Z-cut sapphire and $MgAl_2O_4$ spinel. (b) Refractive index spectra for 'WESGO' alumina 995 and 'COORS' alumina 999. (c) Refractive index spectra for single-crystal Z-cut sapphire and $MgAl_2O_4$ spinel. (d) Spectra for the real part of the dielectric permittivity for 'WESGO' alumina 995 and 'COORS' alumina 999. (e) Spectra for the real part of the dielectric permittivity for Z-cut crystal sapphire and $MgAl_2O_4$ spinel. (f) Spectra showing comparison of imaginary part of the dielectric permittivity of 'COORS' alumina 999, 'WESGO' alumina 995, $MgAl_2O_4$ spinel, and Z-cut crystal sapphire. (g) Comparison of loss tangent spectra of 'WESGO' Alumina 995, 'COORS' Alumina 999, $MgAl_2O_4$ spinel, and Z-cut crystal sapphire.

alumina 999 despite the presumption that the latter had higher purity. The $MgAl_2O_4$ spinel showed about a 17-percent advantage in absorption loss, which is mainly due to the higher degree of crystalinity which occurred while hot pressing. As expected, the crystal sapphire (Al_2O_3) exhibited only half the absorption loss compared to any ceramic alumina.



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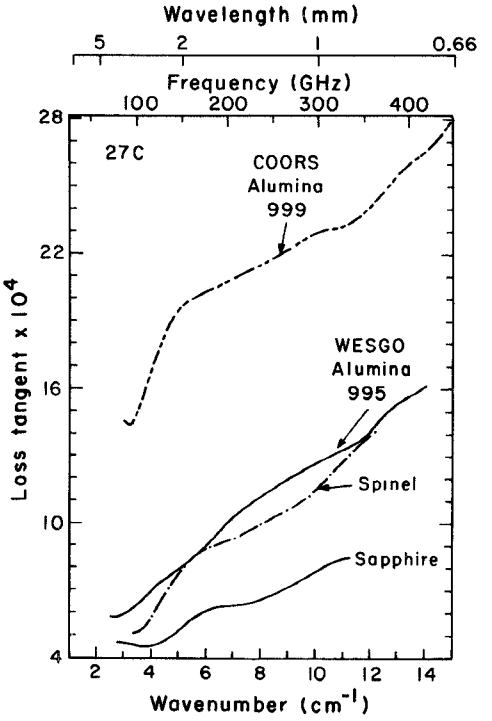
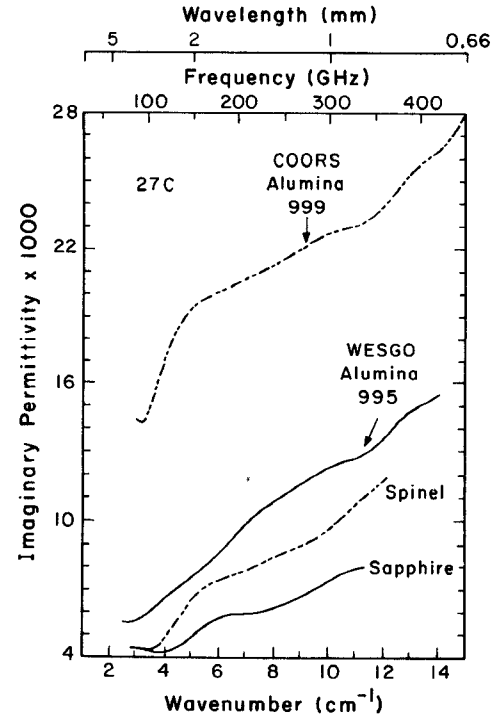


(g)



(f)

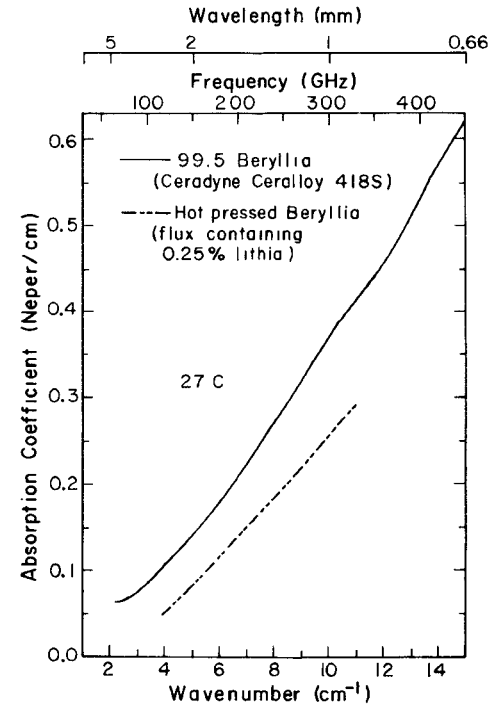
Fig. 7. (*Continued*)

The refractive index spectra for "WESGO" alumina 995 and "COORS" alumina 999 are shown in Fig. 7(b), and for crystal sapphire and $MgAl_2O_4$ spinel are shown in Fig. 7(c). The DFTS technique is especially sensitive in phase measurement, reflecting five or six figure data in refractive index. One can now observe massive features as a function of frequency in the fifth significant figure, and fine structures in the sixth figure. It is important, in comparing nominally identical materials, to observe differences among siblings in a batch of material, different sources of the same material, different methods of preparation, different aging processes (such as neutron irradiation of high-power electromagnetic radiation), and environmental changes in properties caused by assimilation of water vapor or chemical pollutants. The spectra for the real part of the dielectric permittivity are shown in Fig. 7(d) and (e). These materials are extremely low loss, leading the ϵ' values to be almost equal to the square of the refractive index values. Spectra for the imaginary part and loss tangent for Al_2O_3 materials are shown in Fig. 7(f) and (g).

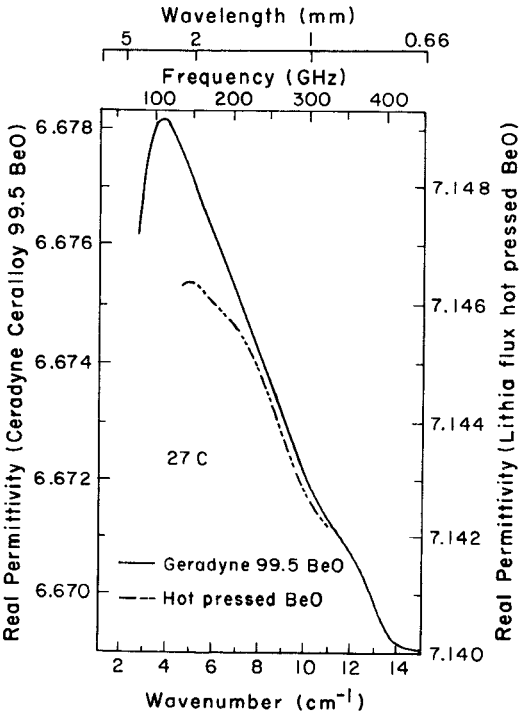
So far we have studied only two kinds of beryllia (BeO): one is the cold-pressed "Ceradyne" Ceralloy 418 S 99.5 beryllia containing about 0.5-percent magnesium tri-silicate flux, and the other is the Union Carbide hot-pressed beryllia containing 0.25-percent lithia flux. Fig. 8(a) shows the absorption spectra for both types of BeO. Again, it seems like the degree of crystalinity is playing the dominant role in low absorption. For example, the hot-pressed BeO shows 42 percent less absorption at 300 GHz compared to the cold-pressed BeO. Fig. 8(b) shows the spectra for the real part of the permittivity for both types of BeO.

B. Fused Silica Glass

Although fused silica glass is well known as near opaque material in the entire far-infrared (submillimeter wave), its absorption is extremely low in the millimeter-wave frequency. We have studied three different fused silica specimens: "Corning" UV-grade SiO_2, "Corning" titanium silicate with 7-percent TiO_2, and water-free fused silica (spectrasil) from the Thermal American Fused Quartz

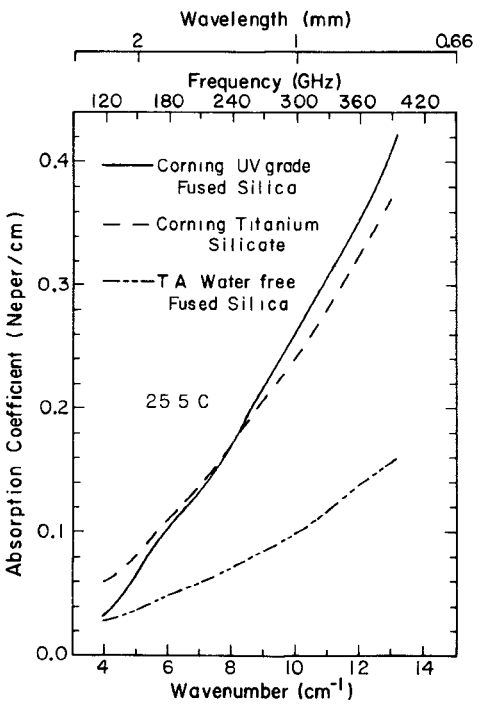


(a)

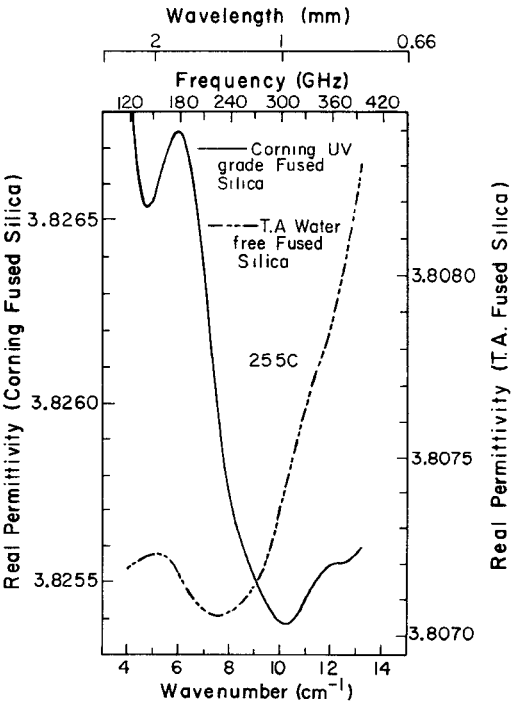


(b)

Fig. 8. (a) Comparison of absorption coefficient spectra of Ceradyne Ceralloy 418 S, 99.5 Beryllia, and Union Carbide lithia densified, hot-pressed beryllia. (b) Spectra for the real part of the dielectric permittivity for Ceradyne Ceralloy 418 S, 99.5 Beryllia, and Union Carbide lithia densified, hot-pressed Beryllia.

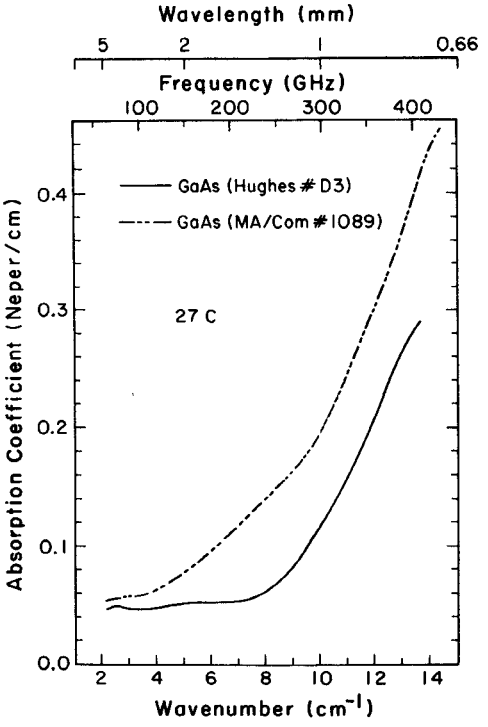


(a)

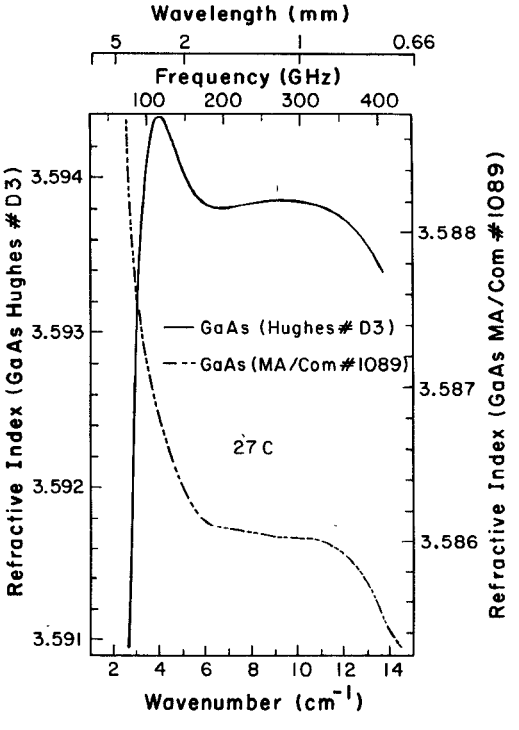


(b)

Fig. 9. (a) Comparison of absorption coefficient spectra of Corning 7940 UV-grade fused silica, Corning 7971 titanium silicate (7 wt percent TiO_2), and Thermal American water-free fused silica "Spectrasil WF." (b) Comparison of the real part of the dielectric permittivity of Corning UV-grade fused silica and Thermal American water-free fused silica.



(a)



(b)

Fig. 10. (a) Absorption coefficient spectra for Hughes D3 and MA/COM 1089 Cr-doped single-crystal high-resistivity ($\rho > 5\times10^7$ Ω/cm) gallium arsenide specimens. The increase in absorption with frequency is due to a multiphonon absorption peak centering around 0.5 mm (600 GHz). (b) Spectra for the refractive index for Hughes D3 and MA/COM 1089 Cr-doped single-crystal high-resistivity ($\rho > 5\times 10^7$ Ω/cm) gallium arsenide specimens.

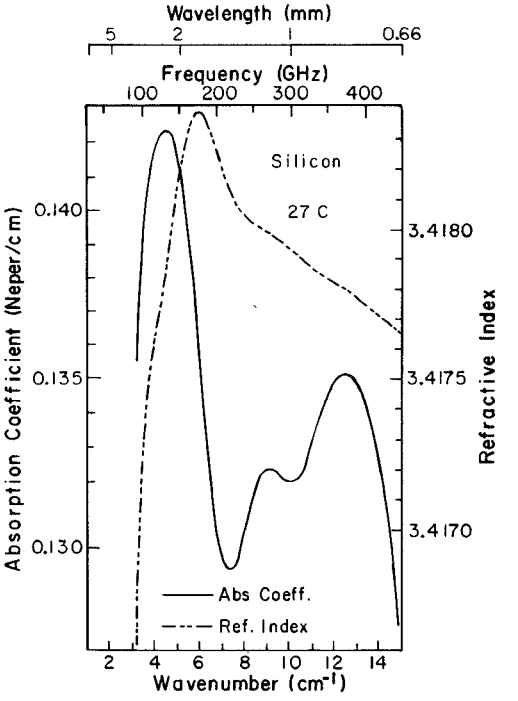


Fig. 11. Spectra for the absorption coefficient and the refractive index for General Diode Corporation undoped monocrystal high-resistivity (~ 8000 Ω/cm) silicon.

Company. The absorption coefficient spectra are compared in Fig. 9(a). The water-free fused silica from Thermal American exhibited about a third absorption loss than the UV-grade SiO_2, and it is the lowest loss material we have ever studied. The absorption coefficient profile of the UV-grade SiO_2 is nearly the same as the titanium-silicate reflecting the insensitivity of the absorption to heavy ion (TiO_2) contamination. Fig. 9(b) compares the spectra for the real part of the permittivity for the UV-grade and the water-free fused silica.

C. Semiconductors

At millimeter wavelengths, the most important loss mechanism in semiconductors can be free-carrier absorption. High purity and low dislocation density is one good way to achieve high resistivity, which in turn implies a low concentration of charge carriers. Another good way to achieve low concentration of free carriers is to introduce (dope) deliberately a "deep trap impurity." We have measured two Cr-doped high-resistivity ($\sim 10^7$ Ω-cm) GaAs specimens. One was obtained from Hughes Aircraft and the other from MA/COM. The Hughes specimen has a Cr-concentration of $2\times10^{16}/cm^3$ and the MA/COM specimen has a Cr-concentration of $5\times10^{15}/cm^3$. Absorption coefficient spectra for these GaAs are shown in Fig. 10(a). The Hughes specimen with higher Cr-concentration shows almost a near-plateau from 70 to 250 GHz. The rapid rise in absorption at higher frequencies is due to a multiphonon absorption band centering around 600 GHz [45]. The refraction spectra are shown in Fig. 10(b).

Silicon is another strong candidate as semiconductor material for millimeter-wave applications. Multiphonon

absorptions are centered well into the infrared frequencies (18 THz) and the only absorption process present in the millimeter wave is the free-carrier absorption. Our specimen is an undoped monocrystal obtained from the General Diode Corporation. The resistivity is of the order of 8000 Ω cm. The spectra for the absorption coefficient and the refractive index are shown in Fig. 11.

Acknowledgment

The author wishes to thank his colleague K. J. Button for his encouragement in this work.

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Computed Modal Field Distributions for Isolated Dielectric Resonators

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Abstract—**Electric- and magnetic-field patterns for five of the lowest resonant modes in cylindrical dielectric resonators are displayed in various planes of intersection. The computational procedure is based on a method-of-moments solution of the surface integral equation for bodies of revolution. Improvement of the numerical stability through the normalization of the matrix is discussed, and an algorithm for the evaluation of the modal field components is described.**

I. Introduction

THE resonant frequencies and the Q factors of various modes in isolated dielectric resonators can be accurately computed by using the surface integral equation formulation for bodies of revolution as described in [1]. In this paper, we present results for the computed field distributions of several modes of an isolated resonator which were obtained by applying this formulation. In the first section of the paper, a normalization procedure used in [1] is described. Numerical implementation of the integral equation approach may lead to numerical instabilities when higher order modes are studied if the moment matrix is not adequately normalized. It is shown that a straightforward normalization can significantly improve the condition number of the matrix [2], and consequently remove or reduce the numerical difficulties.

Traditional applications of the method of moments to problems involving perfectly conducting bodies have been either an E-field or an H-field integral equation [3], [4]. In either case, all the components of the unknown column vector are automatically expressed in the same physical units for most structures so that the normalization of the matrix is not an issue. The integral equation utilized here,

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