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DIELECTRIC PROPERTIES OF MILLIMETER WAVE MATERIALS*

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ABSTRACT

It is no longer necessary to use extrapolated microwave dielectric values when designing millimeter wave components, devices and systems. We are now furnishing highly accurate millimeter wave (5 mm to 1/2 mm) data on complex dielectric permittivity and loss tangent to engineers for a variety of materials such as common ceramics, semiconductors, crystalline and glass materials. For most materials the dielectric loss increases with frequency in the millimeter, unlike the microwave, is an important feature of our new data. Reliable measurements also reveal that the method of preparation of nominally identical specimens can change the dielectric losses by many factors.

Until recently there has been almost no reliable data available in the millimeter and near millimeter wavelength (60 GHz to 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 waveguide interferometer or 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 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 one of us (Afsar) to provide data from 5 mm (60 GHz) into the submillimeter. [1] New theories were also developed by Afsar 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] Since we employ a quasi-optical technique, we measure directly the optical parameters, namely, the absorption coefficient (α) and the refractive index (n) simultaneously. Dielectric parameters (ε',ε'') and loss tangent (tan δ) are easily calculated via Maxwell's relations. The present day dispersive Fourier transform spectroscopic (DFTS) technique of Afsar 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] Although the phase information can be carried through to a determination of the refractive index (and the real part of the dielectric permittivity) to an accuracy of five or six

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significant figures for a low loss material, the absorption coefficient (and loss tangent) can be determined only to about 1% because the commercially available electronic amplifying equipment can not ordinarily carry through amplitude information with higher precision and reproducability. [1,8]

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 wavs 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. [4] (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 obtainable 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 reflectometer, [19-21] (5) oversize cavity resonator [22-24] and (6) oversize waveguide interferometer [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]

Why should we 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 trade-off 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 we are trying to determine the reasons for these variations so as to choose a "standard material" for our application, ± 10% in reproducability of measurement is just not good enough.

Attemps 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-valves become very low, particularly for closed cavities. Therefore, it is practical to discuss only quasi-optical techniques here, namely (1) Dispersive Fourier Transform Spectroscopy (DFTS) (2) Mach-Zehnder-IMPATT Spectrometer (MZI) and (3) Open Resonator Method. Our current M.I.T. National Magnet Laboratory facilities include all of these techniques.

The highest-accuracy absorption coefficient and refractive index data can be obtained from dispersive Fourier transform spectroscopy when it employs a polarizing two-beam interferometer and a special detector consisting of a helium cooled InSb hot-electron bolometer. [1-8] This system generates high accuracy data in the range 3 mm - 0.25 mm and is limited only on the microwave and 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 Mach Zehnder interferometer together with a 20 mw 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 millimeter_ submillimeter gap in the spectrum.

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. In our recent dispersive Fourier transform spectroscopic dielectric measurement work, we have found significant variations in the dielectric properties of such common materials as SiO_2, fused silica glass. [1,8] There are notable differences in absorption coefficient in Al_2O_3, ceramic alumina, depending upon the source of the alumina specimens. For example, hot pressed ceramic beryllia, BeO, has much lower losses than cold pressed beryllia. We would expect to find differences in absorption among high resistivity semiconductors such as semi-insulating GaAs, and large differences were found. [1] Therefore, it is essential now that a full description of a material be available along with accurate, reproducible measurements of its dielectric properties. Thus, it has now been shown that not only is a microwave measurement of loss tangent untrustworthy at millimeter wavelengths but also traditional microwave methods used at millimeter wavelengths also can be inaccurate and irreproducable.

The important differences in nominally-identical specimens can only be detected, verified and understood by using the most sophisticated-highly sensitive-highly stable equipment backed by most detailed evaluation of the theory of the technique. Therefore, it is important to rely upon a "center of excellence" as a source of practical data. Our "Digest of Millimeter Wave Materials Information and Measurement" is now available for distribution. Some typical examples of our new millimeter wave data are shown in Figs. 1-3

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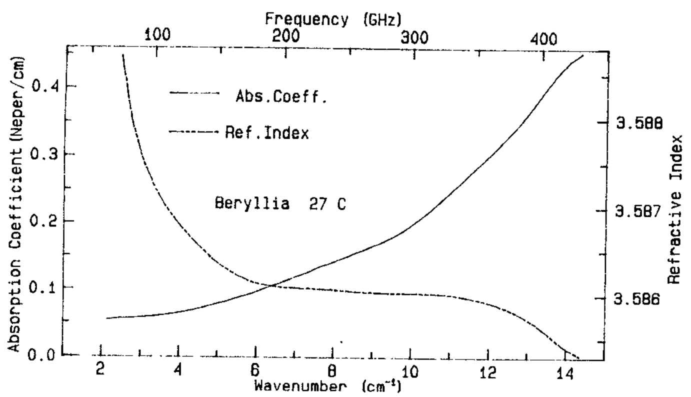

Fig.1 Absorption Coefficient and Refractive Index of Ceradyne Ceralloy 418S Beryllia

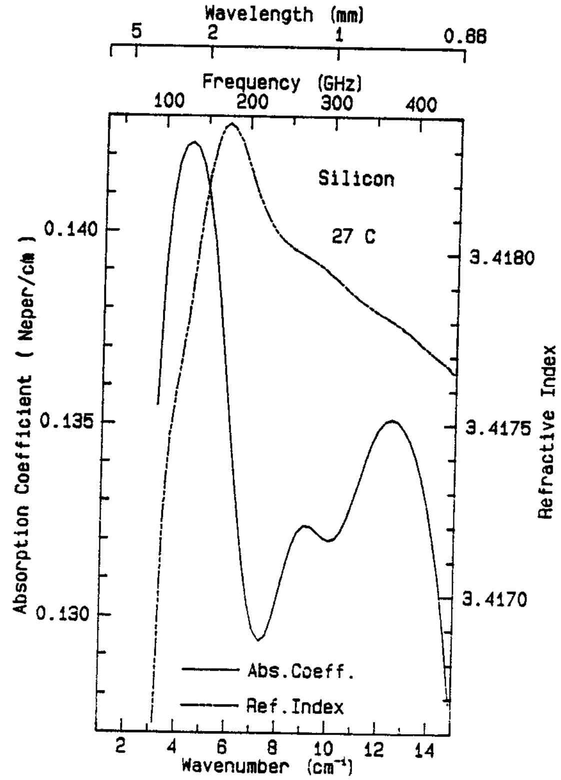

Fig.2 Absorption Coefficient and Refractive Index Spectra for mono-crystal silicon

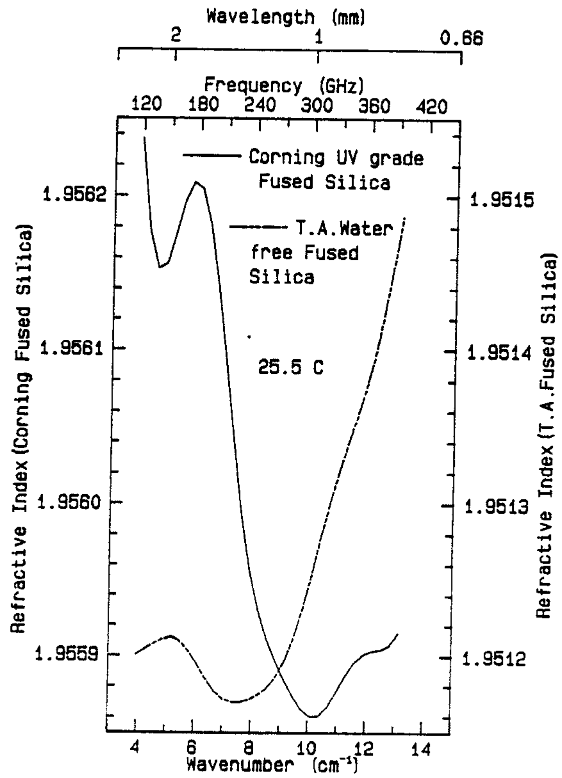

Fig.3 Comparison of Refraction spectra of Corning UV grade and Thermal American Fused Silica