Assessment of random and systematic errors in millimeter wave dielectric measurement

- Open resonator system, Fourier Transform Spectroscopy, W-band Spectrometer and broadband Free-Space measurements

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Abstract **_ Assessment of random and systematic error is done on the real part of permittivity (ε') and loss tangent (tan δ) of ceramics and polymers such as alumina, polyethylene, polypropylene, Teflon and TPX at millimeter wave frequencies by comparing four different measurement systems namely the open resonator system (using both the cavity length and the frequency variation techniques), the Dispersive Fourier Transform Spectroscopy (DFTS), the W-band spectrometer with Backward Wave Oscillator (BWO) and the broadband free-space measurement system. The data obtained from DFTS and W-band spectrometer were also compared over W-band frequencies (68-118 GHz) by generating ε' and tan δ plots of acrylic, fiberglass resin and nylon. Systematic error assessment of the data shows excellent agreement for ε' of the specimens measured by the four systems. It is observed that ε' of the specimens measured with DFTS and broadband free-space measurement system agree well with a standard deviation as highest as 0.009.**

I. INTRODUCTION

The ε' and tan δ of several ceramics and polymers were measured over the millimeter wave frequencies using four different measurement systems namely the open resonator system, the DFTS, the W-band spectrometer with BWO and the broadband free-space measurement system. Dielectric measurements have been performed at various frequencies using the four systems compared in this paper. Cullen and Yu applied the beam wave theory to a confocal open resonator containing a dielectric specimen and derived equations for calculating refractive index and loss tangent [1]. Open resonator methods were also used at 35 GHz by Cook et al [2] and at around 100 GHz by Komiyama et al [3]. Afsar et al [4] applied the full frequency variation technique using a super heterodyne receiver in an automated resonator system for precise complex and permittivity measurement of low absorbing materials as polyethylene and crystal quartz at 60 GHz. Such a technique has also been improved by Afsar et al [5] by scanning the Fabry-Perot cavity at a very fine step so as to provide a complete interferogram over the entire resonator peak. Afsar and Button also used the DFTS to measure dielectric values from 5 millimeter to the submillimeter wavelength [6]. The Mach-Zehnder interferometer (purely optical) with tunable source of radiation, such as BWO was employed at frequencies above 150 GHz with much higher error [7]. A special waveguide bridge/quasi-optical spectrometer built with BWO is applied for complex dielectric measurement below 150 GHz successfully with nominal error [8] .A broadband free-space measurement system [9] is used over the W-band frequencies.

In this paper, for the first time, random and systematic error assessments are performed on ε' and tan δ by comparing the dielectric data obtained from four different systems namely the full cavity length and the frequency variation techniques from the open resonator system, the DFTS, the BWO W-band spectrometer and the broadband free-space measurement system. A random and systematic error assessment is performed on a number of materials as alumina, high-density polyethylene, polypropylene, Teflon, and poly 4 methyl pentene-1 solid polymers (trade name TPX), acrylic, fiberglass resin and nylon at the W-band frequencies.

II. MEASUREMENT METHODS

The open resonator system, the DFTS, the W-Band spectrometer using BWO and the broadband free-space measurement system are used to measure ε' and tan δ of ceramics and polymers. In the 60 GHz automated open resonator system, the signal source, a 60 GHz Gunn oscillator, is mixed with a frequency phase locked 56 GHz local Gunn oscillator (stable to 10^9) to provide a sensitive superheterodyne 4 GHz receiver system. The Fabry-Perot resonator operates via a precision lock-in amplifier and uses an optically polished copper mirror and diamondturned flat copper mirror. The automatic system uses a computer-controlled motor, which allows the movement of the mirror in steps as small as 20 nm. Data is collected from the output of the lock-in amplifier as a function of cavity length. For both the full cavity length and the frequency variation techniques, the resonator length is swept from 1 to 19 mm with a step of 5 x 10^{-4} mm to obtain the position of each resonator peak with (loaded) and without (unloaded) the specimen inside the cavity. For the cavity length scan, the cavity is swept around the resonance peak (± 0.015 mm) with ultra fine step of 20 nm in a unidirectional scan. The latter ensures that there is no return-difference-error (backlash). During this operation, the specimen is placed or removed from the flat mirror. For the frequency scan, the same resonance peak is swept in the range of ± 2 MHz around the fundamental frequency of 300 MHz which is specified from the mechanical design of the resonator system. The resonance peak profile recorded using the cavity length scan has less scatter compared to its corresponding resonance peak profile recorded with the frequency scan. The frequency scan method uses a crystal quartz oscillator that is stable up to 10^9, however, instability causes scatter during the frequency scan. The sampling stability for the cavity length scan is always 20 nm. Thus, the results obtained from the full cavity-length variation technique can be more precise than those obtained from the frequency variation technique. In the DFTS, the specimen is placed in one of the active arms (mirror arm) of a two-beam interferometer rather than one of the passive arms (source or detector arms). 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. The phase and modulus spectra are ratioed and subtracted with the ones obtained without the specimen to yield complex refractive spectra. A DFTS system can provide a high degree of reproducibility for the refractive index (and the real part of permittivity, one part in 100,000). In the W-band waveguide bridge/quasi-optical spectrometer, an electronically sweeping backward oscillator (BWO) is used as a source of tunable coherent radiation in the W-band frequency range. The high output power of BWO (typically 50-100 mW at each frequency) and high sensitivity receiver system employing liquid helium cooled InSb detector enable the accurate transmission measurement of medium absorbing materials and the measurement of complex dielectric permittivity of lossy materials. In the broadband free-space measurement system, complex permittivity was measured in the 75 to 95 GHz range by measuring the transmission coefficient through planar samples for different angles of incidence and polarization states [9].

III. RESULTS

The ε' and tan δ of alumina, polyethylene, polypropylene, Teflon and TPX were measured by the 60 GHz open resonator system using the cavity length and the frequency variation techniques. The ε' and tan δ of the above specimens were compared with those obtained from the DFTS at frequencies of 60 GHz, 100 GHz, and 120 GHz [6], [10]. The ε' and tan δ of the specimens were also compared with those obtained from the W-band spectrometer using BWO [8] and with those obtained from the broadband free-space measurement system [9] over the W-band frequencies. All the ε' and tan δ of the specimens measured are listed in Table I. In Table I, there is a trend where the cavity length scan of the specimens gives a lower ε' and a higher tan δ when compared with the frequency scan. ε' is better reproducible by the cavity scan due to the small stepwise movement of 20 nm of the open resonator system's micrometer. On the other hand, the frequency scan provides higher Q-factor as compared to the cavity scan such that the former generates better tan δ. A systematic error assessment of the data from Table I is performed and the results are shown in Table II. The standard deviation, *s*, obtained when the ε' of the specimens measured by the DFTS at 60 GHz is compared with that of the 60 GHz open resonator system, is low (highest *s* observed is 0.01 between DFTS and the cavity scan and it is 0.007 between DFTS and the frequency scan), showing that the data from the two systems follow each other closely. By averaging the ε' of the specimens measured by the DFTS at 60, 100 and 120 GHz, the mean ε' is found. The same step is repeated to find the mean tanδ. The calculation shows that, the mean [ε'/ (tan δ x 10^4)] is 9.6002/5.330 for WESGO alumina 995, 2.3061/3.700 for polyethylene, 2.2552/7.233 for polypropylene, 2.0703/5.3000 for Teflon and 2.1277/5.8333 for TPX. When the mean of the ε' of the specimens measured by the DFTS was compared with the ε' measured by the W-band spectrometer and that measured by the free-space measurement system, the highest *s* in ε' obtained was 0.03 with the W-band spectrometer and 0.009 with the free-space system. Similarly, when the specimens measured by the open resonator system were compared with those measured by the W-band spectrometer and those measured with the free-space system, the highest *s* in ε' observed was 0.025 with the W-band spectrometer and 0.01 with the free-space system. This concludes that ε' of the specimens measured from the free-space measurement system follows that of the DFTS very closely.

Additionally, random and systematic error assessment of the ε' (Fig.1 and Fig.2) and tan δ (Fig.3 and Fig.4) of polymers such as acrylic, fiberglass resin and nylon was performed when the dielectric measurement obtained from the DFTS and the W-band spectrometer were compared at the W-band frequencies. The random error assessment of ε' and tan δ obtained from the graphs (Fig.1-Fig.4) is shown in Table III. A further systematic error assessment of ε' and tan δ is performed by finding the standard deviation, s, between DFTS and W-band spectrometer. The calculation shows that the s [ε' / (tan δ X 10^3)] is 0.0087/1.1062 for Acrylic, 0.0037/0.4425 for Fiberglass resin and 0.0209/1.3900 for Nylon. From Table III, it is seen that the s in ε' between the DFTS and the W-band spectrometer is low with the highest s of 0.02.

IV. CONCLUSION

A systematic error assessment of ε' and tan δ of ceramics and polymers was performed for the first time by comparing the open resonator system (using both cavity length and frequency variation techniques), the DFTS, the W–band spectrometer using BWO and the broadband free-space measurement system. When the four systems are compared, the ε' of the specimens measured is seen to have slight standard deviation. One important observation obtained from the paper was that the ε' obtained by the DFTS and by the broadband free-space measurement system are very close for such specimens as polyethylene, polypropylene and Teflon.

TABLE I

ε' and (tan δ x 10^4) of materials measured by the 60 GHz open resonator system (cavity length and frequency variation techniques), the DFTS (at 60,100 and 120 GHz), the W-band spectrometer (68-118 GHz) and the broadband free-space measurement system

		WESGO alumina 995	Polyethylene	Polypropylene	Teflon	TPX
Open resonator system at 60 GHz	Cavity length scan	9.5854 ± 0.003/ 4.9912±1.579	2.3024 ± 0.001/ 5.4508±3.145	2.2413 ± 0.016/ 14.5300±1.690	2.0625±0.003/ 5.2023 ± 1.043	2.1337±0.003/ 5.2023±1.043
	Frequency scan	9.6129±0.007/ 1.5686±0.489	2.3052 ± 0.454/ 1.8797 ± 0.690	-	-	2.1367±1.388/ 4.8308±0.669
DFTS	60 GHz	9.6025/ 4.7500	2.3068/ 3.6000	2.2554/ 8.9000	2.0707/ 5.2000	2.1282/ 4.5000
	100 GHz	9.5997/ 5.2500	2.3058/ 3.750	2.2551/ 7.4000	2.0701/ 5.3000	2.1276/ 6.3000
	120 GHz	9.5984/ 6.000	2.3056/ 3.7500	2.2550/ 6.9000	2.0700/ 5.4000	2.1274/ 6.7000
W-band spectrometer		-	2.2920±0.005/ -	-	2.0270±0.005/ 3.453	2.1260 ±0.005/ -
Free-space measurement		-	2.306 ± 0.002 / 5.0000 ± 1.300	2.2580 ± 0.002/ 5.0800 ± 3.450	2.0570 ± 0.004/ 7.7767±4.000	-

TABLE II

Assessment of systematic error of ε' and (tan δ x 10^4) of materials measured by the 60 GHz open resonator system (using cavity length & frequency variation techniques), DFTS, the W-band spectrometer and the broadband free-space measurement system

s between 2 techniques	Alumina 995	Polyethylene	Polypropylene	Teflon	TPX
cavity length scan and frequency scan	0.0194/2.4202	0.0020/2.5251	-	-	0.0021/0.2627
cavity length scan & DFTS (60 GHz)	0.0121/0.1706	0.0031/1.3087	0.0045/3.9810	0.0058/0.0016	0.0039/0.4966.
frequency scan & DFTS (60 GHz)	0.0074/7.7326	0.0011/1.2164			0.0060/0.2339
mean DFTS & W-band spectrometer	-	0.0099/ -	-	0.0306/1.3060	0.0012/ -
cavity length scan & W-band spectrometer	-	0.0074 -	-	0.0251/1.2355	0.0054/ -
frequency scan & W-band spectrometer	-	0.0093/ -	-	-	0.0076/ -
mean DFTS & free-space system	-	0.0002/0.9192	0.0020/1.3671	0.0094/1.7444	-
cavity length scan & free-space system	-	0.0028/0.3188	0.0118/6.1730	0.0040/1.8149	-
frequency scan & free-space system	-	0.0008/2.2064	-	-	-

TABLE III

Assessment of random error of ε'/ (tan δ x 10^3) of Acrylic, Fiberglass Resin and Nylon measured by DFTS and W-band spectrometer (BWO) over W-band frequencies.

Specimen	DFTS		W-band spectrometer(BWO)	
	Mean	s	Mean	s
Acrylic	2.6164/9.1614	0.0058/0.4860	2.6040/7.5695	0.0020/0.6072
Fiberglass Resin	2.9022/16.3283	0.0111/0.9624	2.9075/16.9541	0.0044/0.6035
Nylon	2.9963/9.2000	0.0054/0.1535	2.96667/7.2342	0.0000/0.5606

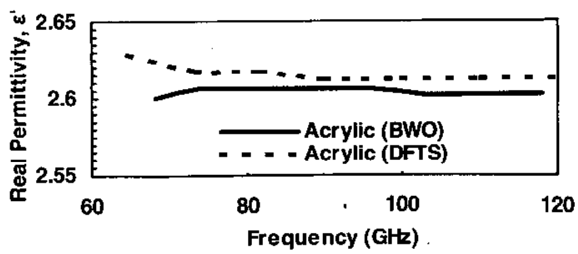

Fig.1. Spectra of ε' of Acrylic measured by W-band spectrometer and DFTS.

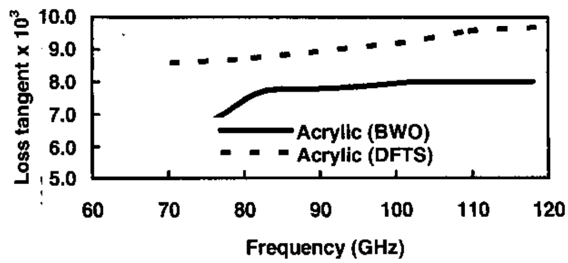

Fig.2. Spectra of tan δ of Acrylic measured by W-band spectrometer and DFTS.

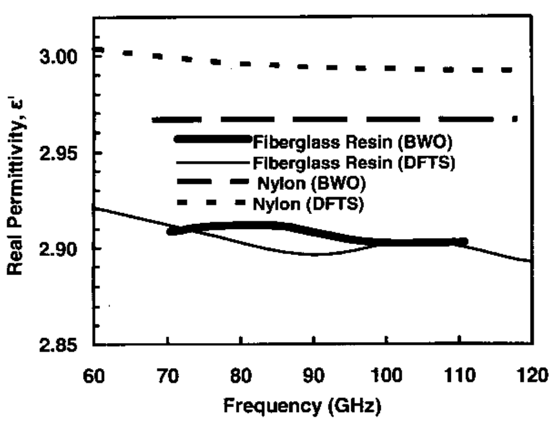

Fig.3. Spectra of ε' of Fiberglass Resin and Nylon measured by W-band spectrometer and DFTS

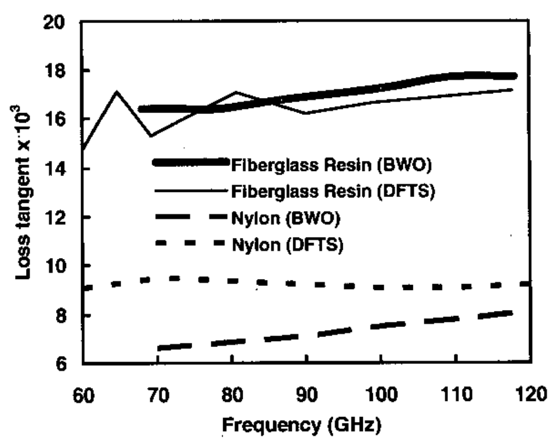

Fig.4. Spectra of tan δ of Fiberglass Resin and Nylon measured by W-band spectrometer and DFTS.

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