A Novel W-Band Spectrometer for Dielectric Measurements

Mohammed Nurul Afsar, *Fellow, IEEE*, Igor I. Tkachov, and Karen N. Kocharyan, *Member, IEEE*

***Abstract*—A new spectrometer for the precision measurement of dielectric permittivity and loss tangent is presented. The new instrument is capable of providing high-resolution data for the first time over an extended W-band (68–118 GHz) frequency for specimens with a large range of absorption values, including highly absorbing specimens that otherwise would not be possible. A novel technique based on the unbalanced bridge is developed for the measurement of the phase of the wave passed through the specimen in free space (quasi-optical) with reference provided by a waveguide arm. Specially constructed precision waveguide and quasi-optical components allowed reliable broadband operation. A number of common dielectrics are measured, and results are compared with previously reported data.**

***Index Terms*—Dielectric constants, dielectric materials, Gaussian beams, millimeter waves, permittivity, quasi-optics, W-band, waveguide bridge.**

I. Introduction

VARIOUS methods of dielectric measurements in millimeter-wave range have been reported in recent years. Detailed review and comparison of these methods can be found elsewhere [1], [2]. Most of the methods below 150 GHz (Fabry–Perot resonators, methods with solid-state sources of radiation) provide data at a single frequency. A few (different) measurement systems must be employed to obtain data over a broader band. Fourier transform spectrometry (FTS), a standard reliable broadband measurement method for frequencies above 120 GHz, cannot perform well at lower frequencies [1], [2]. The extremely low power of the thermal source is the major reason of deteriorated low-frequency performance. A typical frequency resolution of FTS of tens of gigahertz also limits its application below 120 GHz. The present day network analyzer cannot provide sufficient power for the measurement of absorbing materials, although the frequency can be swept at centimeter and longer millimeter-wave frequencies. Various techniques based on generation of subharmonics of a low-frequency source does not perform well for even moderately absorbing specimens because the generated power is low, and loss in quasi-optical channel can not be compensated by a sensitive detection method. Errors arising from the air gap between a specimen and a waveguide corrupt the waveguide measurements.

The Mach–Zehnder interferometer (purely optical) with a tunable source of radiation, such as a backward wave oscillator (BWO), was successfully employed at frequencies above 150 GHz [3]. The new system presented here expands the application of BWO for complex dielectric measurements below 150 GHz for the first time. The spectrometer is capable of providing the unique broadband data for specimens with a large range of insertion losses.

The use of the guided wave for the phase reference of the system we developed here simplified the system over the Mach–Zehnder interferometer. The combination of quasi-optical specimen channel and waveguide reference channel makes this bridge inherently unbalanced. A new theory for the measurement of real and imaginary parts of complex dielectric permittivity with the unbalanced bridge is developed here. The employment of the unbalanced bridge allowed us to perform measurements of the real part of dielectric permittivity of absorbing materials with high accuracy. The measurement of the real part of permittivity values for such materials would be hard to implement with other available techniques. The frequency tuning of the stable tunable source of radiation eliminates the mechanical scanning of the bridge. Careful design of the system based on Gaussian beam optics allowed us to extend the working range of the BWO based system to W-band. The systematic errors caused by nonflat wave-front incident on the specimen are avoided in this case. The diameter of the material specimen can be as small as 15 mm.

Routine measurements of absorbing materials such as Mylar, polyester, Macor[1] (machinable ceramic), and water can now be made with ease. We are presenting reliable data for the real and imaginary part of complex dielectric permittivity for acrylic, plexiglas, nylon, delrin, polyethylene, TPX, epoxy resin, Teflon, polystyrene, Mylar, alumina, Macor, zinc selenide, zinc sulfide, high conductivity germanium, and silicon from 70 to 117 GHz. New data are compared with previously published results measured at other frequencies.

II. Measurement Techniques

The block diagram of the new W-band spectrometer is shown in Fig. 1. The radiation from the W-band BWO tube is modulated by a ferrite modulator. A 3-dB directional coupler divides the incident beam into two arms. In the direct beam, we use two corrugated horn antennas, four focusing lenses, and a pair of

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[1]Macor is a trademark of Corning Inc.

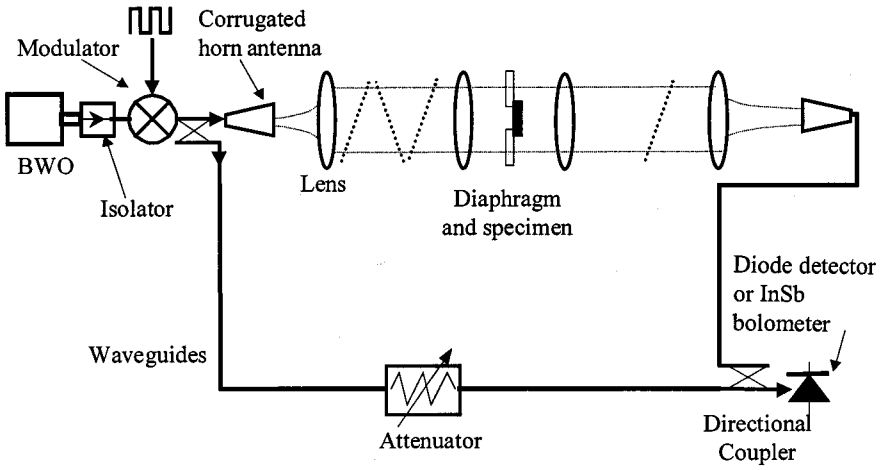

Fig. 1. The block diagram of a new W-band unbalanced bridge spectrometer. A specimen is placed in the quasi-optical arm of the bridge. A number of free-standing wire-grid polarizers are employed to control attenuation and polarization of the beam. The reference arm employs specially constructed full-band components. Both room-temperature Schottky diode detector and liquid helium cooled InSb detectors were employed for detection of energy.

free-standing wire-grid polarizing attenuators. A specially manufactured corrugated W-band horn antenna allows the W-band energy to take the shape of a Gaussian beam, which transmits through a polyethylene lenses. A specimen, prepared in the form of a flat parallel slab of material, is placed in the central waist on a carbon-loaded absorbing diaphragm. A direct-reading precision attenuator is used in the reference arm. The second 3-dB directional coupler combines radiation of both arms. The recombined beam is then detected using the Schotky diode detector or a specially constructed liquid helium cooled sensitive InSb detector when high sensitivity is needed.

Usually, interferometric measurements are performed by balancing two arms of an interferometer [3], [7], [16]. If an electronically tuned radiation source is used, such as a BWO, the measurements can be realized without balancing the arms of the bridge. In fact, it is impossible to balance this bridge over the entire W-band because of the significant difference in the propagation constants of the waveguide and the free space. In an unbalanced bridge, with the power nearly equally divided between two channels, the output signal recorded as a function of frequency is an oscillating function with sharp minimums resulting from the interference of two coherent waves. The plane parallel specimen, placed in a quasi-optical arm, changes the optical length of the channel, which results in a frequency shift of an interferogram. The change of frequency positions of the minimums enables us to obtain the phase shift information related to the refractive index of a specimen material. Minimums in frequency spectrum appear very often because of the significant misbalance between bridge arms. This misbalance, arm length difference, determines the resolution of the data obtained with the new technique. The frequency positions of the minimums can be found from the equation of interference of two waves:

$$\lambda_k = \frac{4kl_g a^2 + 2al_0'\sqrt{l_0'^2 - l_g^2 + 4k^2a^2}}{l_0'^2 + 4k^2a^2} \tag{1}$$

where a is the dimension of the W-band waveguide, l_g is the length of the guided channels, l_0 is the length of the free-space channels, k is the propagation constant in free space, and k is the whole number corresponding to the number of the minimum. The period of oscillations can be found from the difference equation $F = f_m - f_{m+1}$. The analysis of this equation shows that the period of oscillation depends on the operation frequency and changes drastically over the W-band (75–110 GHz) because of the rapidly changing propagation constant in the waveguide part of the system. The insertion of a specimen in the free-space arm of the interferometer causes the increase of the period of interferogram oscillations. The slightly increased period leads to the drift of the relative positions of minimums and maximums. An example of the experimentally recorded interferogram is presented in Fig. 2. The solid line represents recording without specimen in the measurement arm, and the dashed line represents the measurement with a specimen. The expanded part of the interferogram illustrates the procedure of the phase calculation. Despite a lengthy derivation, the recipe for the phase measurement is fairly simple. The phase is calculated with the formula

$$\varphi = \left(\frac{\Delta f}{F} + l\right) \cdot 2\pi \tag{2}$$

where Δf is the distance between two neighboring minimums and F is the period of oscillations of the reference scan. The refractive index of a specimen can be found with

$$n = \frac{c\varphi}{df} + 1 \tag{3}$$

where c is velocity of light, f is frequency of radiation, and d is thickness of a specimen.

The frequency resolution of the interferometer is determined by the distance between minimums and therefore depends on the degree of misbalance of interferometer. The length of the arms was chosen as a compromise between the resolution and uncertainty in the determination of phase. This uncertainty is related to the smallest frequency step size, which can be generated by the source of radiation, a combination of BWO and DAC, which controls it. The smallest phase change that can be detected by

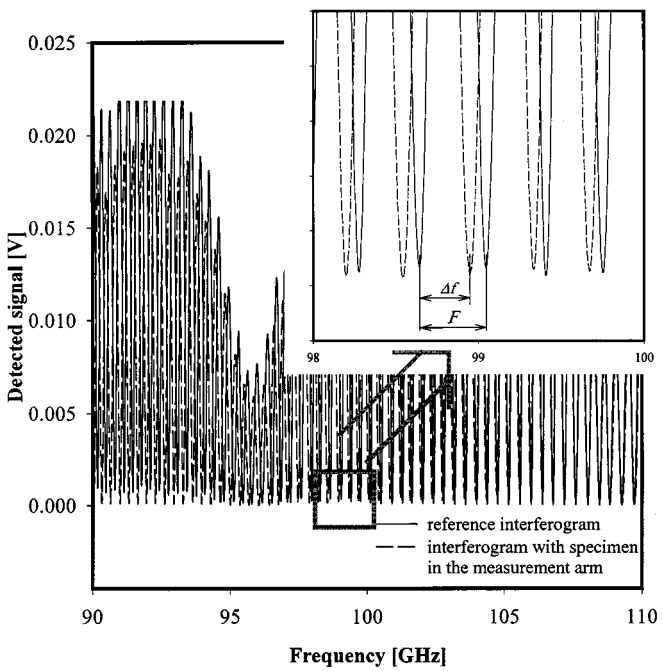

Fig. 2. Two interferograms recorded as a function of frequency. One interferogram was recorded with a specimen in the quasi-optical arm and the other without the specimen. The change in phase can be determined from shifted positions of interferogram minima. The ratio $\Delta f / F * 360$ gives the phase shift of the wave passed through the specimen.

the interferometer is a ratio of the smallest step size to the period of the recorded interferogram.

An example of a phase spectrum recorded with the new instrumentation is shown in Fig. 3. The spectrum was recorded with a Macor specimen. The resolution of this spectrum varies from 70 MHz around 70 GHz to 150 MHz around 115 GHz. The error in determination of the phase does not exceed 15°. This error in determination of phase translates into precision of refractive index on the order of 0.005 for this specimen. The resulting spectrum of refractive index shows slight dispersion with the mean value of 2.379 in W-band, which is in excellent agreement with previously reported data [1], [2] and with the values obtained from the periodic pattern of transmittance spectra.

The transmittance spectra of specimens of materials were recorded without the waveguide reference arm. The transmittance spectra of specimens with various values of absorption are shown in Fig. 4. The high resolution of the instrumentation allows the determination of dielectric permittivity for thick low-loss specimens with high precision by analyzing the periodic structure of the spectra. For the absorbing specimens with transmittance below 10%, such as low-resistivity germanium ($\sim$5 Ω-cm) shown in Fig. 3, the periodic structure is normally not clear or absent. One cannot therefore obtain dielectric permittivity data from transmittance results. Only the phase measurements performed with the unbalanced bridge can provide the information for the determination of dielectric permittivity.

The channel method is one of the simplest and most effective methods in free-space broadband spectroscopy. The transmittance characteristic of a flat parallel slab of the material is measured and analyzed. The transmittance is defined as the ratio

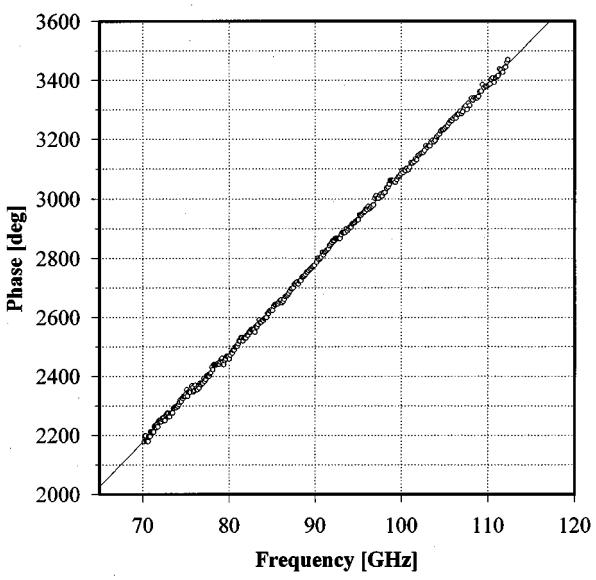

Fig. 3. Phase spectra for the 18.687-mm-thick Macor specimen. The wave passing though the specimen experiences multiple rotations ($\times 360°$) of phase. The solid line is the linear fit of the experimental data passing through the origin. The average of the refractive index spectra, derived from this phase measurement, is 2.379.

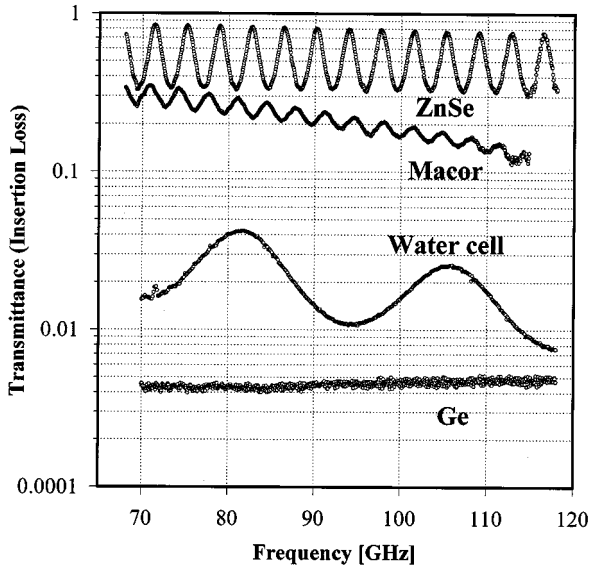

Fig. 4. Transmittance spectra for (from top to bottom) 13.262-mm-thick ZnSe specimen, 18.687-mm-thick Macor specimen, fused silica cell with 0.450-mm layer of water (recorded with liquid helium cooled InSb detector), 9.955-mm-thick low resistivity, and $\sim$5 Ω-cm, germanium specimen. Note that the channel effect diminishes with decreasing transmittance. For the high-conductivity germanium specimen, the transmittance is less than 0.004 (0.4%).

of the power passed through the specimen to the power incident on the specimen and ranges from zero (very high losses as in metals, for example) to one (no losses in the material). In the case of relatively transparent materials with transmittance level above $\sim$0.1, the transmittance is an oscillating function of frequency. The maximums of this function correspond to the constructive interference, and the minimums correspond to the

destructive interference of the radiation passed through a specimen many times after reflection on the specimen interfaces (multiple reflections). The transmittance can be expressed with well-known equations

$$
\begin{aligned}
T &= E\frac{(1-R)^2+4R\sin^2\psi}{(1-RE)^2+4RE\sin^2(\alpha+\psi)},\\
R &= \frac{(n-1)^2+k^2}{(n+1)^2+k^2},\\
\varphi &= \alpha+\arctan\frac{ER\sin^2(\alpha+\psi)}{1-ER\cos^2(\alpha+\psi)}\\
&\quad+\arctan\frac{k}{n^2+k^2+n}-\arctan\frac{k}{n+1}\\
E &= \exp(-2\beta)=\exp\left(-\frac{4\pi k\,d\nu}{c}\right),\quad \alpha=\frac{2\pi n\,d\nu}{c}\\
n+ik &= \sqrt{\varepsilon^*\mu^*},\quad \psi=\arctan\frac{2k}{n^2+k^2-1}
\end{aligned}
\tag{4}
$$

where n, k, μ, and ε are respectively refractive index, absorption coefficient, magnetic permeability, and dielectric permittivity of the layer of a material; and T, R, and φ are, respectively, the power transmittance, reflectance, and phase of the transmitted wave. The function ψ is slow changing and small (typical $k \sim 0.1$ and typical n about 1.6), and the oscillations of the transmittance are produced by the squared sinusoid in the denominator of the expression. The peak of the transmittance happens every time the phase in the denominator satisfies the equality $\alpha+\psi=\pi l$. Thus, the refractive index can be evaluated from the distance between two maximums of the transmittance spectra. The imaginary part of the refractive index k (absorption index) responsible for the attenuation can be evaluated from the amplitude of the transmittance in the peak. Often a peak-fitting procedure is used for the determination of both n and k in every peak of the transmittance curve to improve the accuracy of results. The evaluation of both optical parameters n and k in the entire measurement range is possible from the oscillating transmittance curve by fitting the expression with n and k as parameters. In the case of transmission curve fitting, the resolution of real and imaginary parts is effectively equal to the resolution of the transmission spectrum. n and k are represented with the polynomial of first, second, or third order. The precision of the refractive index data often is comparable with data obtained with dispersive Fourier transform spectrometry. The absorption index data are usually more reliable when obtained with channel method then with any other indirect technique.

III. Results

The real (ε') and imaginary (ε'') part of dielectric permittivity of a number of common materials are measured with the new W-band spectrometer. As an example, dielectric spectra of two materials are presented in Figs. 5 and 6. The Macor (55% mica crystal, 45% matrix glass) specimen is 18.687 $\pm$ 0.005 mm thick. The transmittance spectrum of this specimen, shown in Fig. 4, possesses the interference pattern, which allows the determination of the real part of dielectric permittivity by the transmission channel method. The unbalance bridge method,

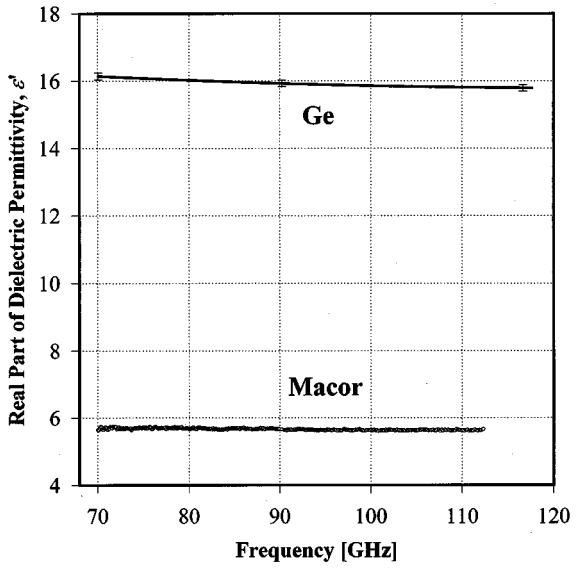

Fig. 5. Spectra of real part of dielectric permittivity for Macor and low-resistivity germanium, 5 Ω-cm. The scatter or the uncertainty for the real-part spectrum for the germanium specimen is shown with bars. We cannot see any scatter for the real-part spectrum for the Macor specimen in this figure.

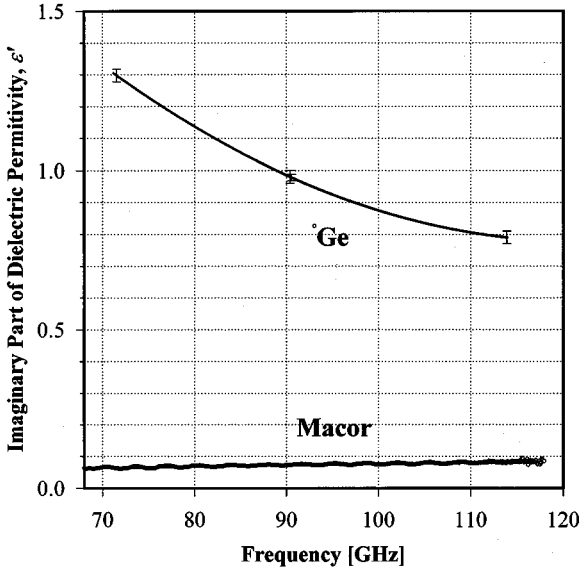

Fig. 6. Spectra of imaginary part of dielectric permittivity for Macor and low-resistivity germanium specimens. The imaginary-part value for this germanium specimen drops from 1.3 at 75 GHz to 0.79 at 115 GHz. This is due to the presence of the free carrier absorption band present for this semiconductor at longer wavelengths. The imaginary-part value for Macor is almost flat and increases monotonically with increasing frequency.

however, provides better resolution of the data and higher accuracy of results. The agreement between these two methods is excellent. The thickness of the second specimen, high conductivity (resistivity of ~5 Ω-cm) germanium (obtained from CVD Inc.), is 9.96 $\pm$ 0.01 mm. The transmittance spectrum for this specimen is also shown in Fig. 4. One can see that the transmittance lies between 0.3 and 0.45%. No interference channels can be seen in this spectrum. Only the unbalanced bridge technique

TABLE I
REAL AND IMAGINARY PARTS OF COMPLEX DIELECTRIC PERMITTIVITY OF COMMON MATERIALS MEASURED WITH THE NEW W-BAND SPECTROMETER AND COMPARISONS WITH PUBLISHED DATA

	ε' (this work)	ε' previously published	ε" (this work)	ε" previously published
Acrylic	2.618 ± 0.010	2.595 (120 GHz) [6]	0.018÷0.023 ±0.001	0.021 (120 GHz) [6]
Plexiglas	2.615±0.005	2.590±0.003 [13] 2.590 [6]	0.020÷0.025 ±0.001	0.019±0.007 [13] 0.02 [6]
Nylon	2.969 ± 0.020	2.993 (120 GHz) [6] 2.958 (35GHz) [16] 2.9814 (150GHz) 3.06 [Abbas 98] 2.991±0.002 [13]	0.013÷0.022 ±0.001	0.026 (120 GHz) [6] 0.029 (35 GHz) [16] 0.030 (150GHz) 0.025±0.008 [Friedsam97]
Delrin	2.826 ± 0.010		0.033÷0.041 ± 0.0015	
Polyethelene	2.292±0.005	2.306±0.002 [13] 2.306 [6] 2.36 [8] 2.319 [2]		0.0013±0.0003 [13] 0.02 [6]
TPX	2.126±0.005	2.128 [6] 2.150 [9]		0.0011 [6] 0.001 [9]
Epoxy resin	2.90± 0.01	2.69 [12] @ 10GHz	0.049±0.004	
Teflon	2.027± 0.005	2.060±0.004 [14] @ 8.5 GHz 2.057±0.004[13] 2.00 ±0.05[8] 2.09±0.05 [11] 2.06 [9] 2.070 [6]	$7\pm1*10^{-4}$	0.0015±0.0006 [13] 0.0011 [6]
Polystyrene	2.509±0.005	2.545±0.003 @10GHz [15]	$3\pm1*10^{-4}$	$5.3\pm0.3*10^{-4}$ @10GHz [15]
Mylar	3.023±0.005		0.027±0.003	
Alumina	9.585±0.001	9.600±0.001 [4] 10±1 [Abbas 98]		0.005±0.001 [4]
Macor	5.65 ± 0.02	5.68± 0.01 [4] 5.66 [2]	0.078±0.002	0.08 [4]
ZnSe	9.054 ± 0.05	9.092 (120 GHz) [1]	0.015 ± 0.004	0.021 (120 GHz) [1]
ZnS	8.352 ± 0.035	8.395 (120 GHz) [1]	0.010± 0.003	0.016 (120 GHz) [1]
Ge(~5 Ohm*cm)	15.9 ± 0.2	15.923 (890GHz)[10]	1.00 ± 0.05	
Si (~50~100 Ohm*cm)	11.80 ± 0.08	11.880 [4] 11.2±0.5 [14]	0.25 ± 0.02	

can provide data for the determination of the real part of dielectric permittivity. No other instrumentation would have allowed the transmittance and phase measurements of these specimens at these frequencies. The resulting imaginary part of the complex dielectric permittivity spectrum shows an increasing absorption toward low frequencies. The real part of dielectric permittivity has slight dispersion as well. This unusual behavior is imposed by an absorption band of free carriers located in microwave range. The typical imaginary part of dielectric permittivity decreases toward lower frequency, as can be seen in the case of Macor. There is a good agreement of real part data shown here with earlier published work [5], [6] on higher resistivity (>50 Ω-cm) Ge.

New real and imaginary parts of permittivity results of measurements for some common materials are summarized in Table I. The real part of dielectric permittivity is usually uniform (almost the same) across the entire W-band. In this table, we are presenting the real part of permittivity values up to three decimal positions. The uncertainty is shown with + and − signs. The transmittance channel method was used to determine the imaginary part of permittivity values. Here we are presenting imaginary-part values with the spread over the entire W-band frequencies (70–115 GHz) with a dashed line for some materials. Again, we are presenting imaginary-part values up to three decimal positions. The error or uncertainty for the imaginary part values are shown with + and − signs. The transmittance channel method was also used for the measurement of the real part of dielectric permittivity for most specimens presented in order to compare results with the new interferometric technique. The imaginary part of dielectric permittivity changes across the W-band, and two numbers are used here to show the range of the parameter. The sensitivity of the transmittance method (single pass of radiation through the specimen) used here is not sufficient to measure low absorption loss for such materials as TPX and polyethylene. Table I also shows a comparison of the real and imaginary part

of complex dielectric permittivity values for acrylic, plexiglas, nylon, delrin, polyethylene, TPX, epoxy resin, Teflon, polystyrene, Mylar, alumina, Macor, zinc selenide, zinc sulfide, high-conductivity germanium, and silicon with data published earlier at various frequencies employing various techniques. Results from the reference column are for 100 GHz unless otherwise shown. Most of the comarison results were obtained with Fourier transform spectroscopy [1], [4], [6], [7]. Slight variation from one work to another was usually explained by variation of properties of materials from specimen to specimen, especially for the polymer materials.

IV. Conclusions

We have used the W-band BWO and a novel quasi-optical waveguide bridge technique for the first time for the direct measurement of the phase of the wave passed through planar specimens, inclusive of highly absorbing and near-opaque specimens. We have employed this new shift of the minimums technique to determine the real part of permittivity accurately for a number of materials.

The new technique now generates a precise imaginary part of dielectric permittivity data. The high BWO power, extra sensitive low-noise receiver system, precision waveguide components, and careful and thorough alignment of the quasi-optical channel eliminate the scatter and the noise in data in the range 70–118 GHz for absorbing materials. This is the first time a tabulation is made for the real and imaginary part of complex dielectric permittivity data for a number of common materials at extended W-band frequencies. Additionally, these highly accurate data are compared with real and imaginary parts of permittivity results published earlier at various frequencies employing various measurement techniques.

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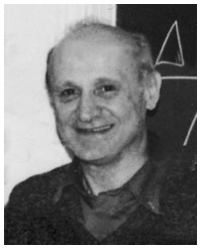

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Dr. Kocharyan is an Elected Member of the Armenian Academy of Sciences and a member of the IEEE Microwave Theory and Techniques Society.