High-Resolution High-Power Quasi-Optical Free-Space Spectrometer for Dielectric and Magnetic Measurements in Millimeter Waves

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Abstract—This paper presents a high-resolution high-power free-space dielectric and magnetic measurement technique for evaluating the complex dielectric permittivity and complex magnetic permeability of solid materials in millimeter waves at room temperature. This method enables us to obtain broad-band high-resolution transmittance spectra using a quasi-optical free-space spectrometer equipped with an extended V-band (40–90 GHz) backward-wave oscillator as a high-power tunable source of coherent radiation. Due to the sufficiently strong energy throughput in the transmission and a very fine frequency sweep step of the measurement, this instrumentation is superior in obtaining reliable complex permittivity and complex permeability of absorbing dielectrics and ferrites with great stability and reproducibility over a much broader millimeter-wave frequency range. Simultaneous determination of dielectric permittivity and magnetic permeability can be achieved from a single set of measurements. Measurement results are reported for a variety of dielectrics and ferrites and compared with previously published data.

Index Terms—Backward-wave oscillator (BWO), ferrites, magneto-optical, millimeter waves, permeability, permittivity, quasi-optical spectrometer.

I. Introduction

THE millimeter-wave spectral range, which bridges microwave and optical regions, is of particular significance mainly due to a rapidly growing number of millimeter-wave applications and components [1]–[4]. The frequency range of 40–90 GHz is heavily utilized for millimeter-wave radar applications. It is also used for high-capacity terrestrial millimeter-wave communications systems: 60 GHz is the standard frequency for commercial automobile collision-avoidance radars and secure point-to-point wireless systems. In addition, frequencies at 70, 80, and 90 GHz have also been allocated

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for multigigabit wireless communications. Therefore, knowledge of the complex permittivity and complex permeability of involved dielectric and/or magnetic material over a wide millimeter-wave frequency band is necessary and important for both designers and manufacturers to understand the physical processes and phenomena that occur when the material interacts with an external electromagnetic field.

However, conventional microwave methods suffer from stray capacitances and effects that are related to finite cable lengths and thus prevent precise measurement of the components of the optical conductivity. Optical methods, on the other hand, become progressively ineffective as the frequency decreases below 600 GHz due to the insufficient radiation source and associated problems with finite-sample-size effects. For instance, Fourier transform spectroscopy cannot provide reliable and accurate data below 120 GHz due to the use of an extremely low-power (on the order of nanowatts) thermal radiation source.

Dielectric and magnetic measurement techniques can be categorized into waveguide methods [5]–[7], resonator methods [8]–[10], and transmission line/free-space methods [11]–[13] at microwave and millimeter-wave frequencies. The main disadvantage of the waveguide method is that it requires a specific preparation of the sample under test. The sample shape variations and the presence of air gap between the waveguide and the sample may introduce large errors in the measurement result. Resonators have been considered as one of the most accurate characterization methods of low-loss materials, yet they are not suitable for high-absorbing-material measurements. This method generally restricts the sample size and filling factors. Rather than producing broad-band continuous spectra of a certain dielectric parameter, the resonator method usually operates at a limited frequency range or even at one particular frequency point [9].

High-power millimeter-wave quasi-optical spectroscopy of solid dielectric and amorphous materials, as well as dielectric and magnetic measurements of ferrite ceramics, have recently been reported at the Instrumentation and Measurement Technology Conference (IMTC) 2007 [14], [15]. This paper presents a free-space method for the direct determination of the complex permittivity and complex permeability of materials at the extended V-band (40–90 GHz) from a single set of measurements. It utilizes an ultrahigh-voltage power supply (0–6000 V) to feed an extended V-band backward-wave oscillator (BWO) tube, which operates as the millimeter-wave monochromatic coherent radiation source over a much broader frequency range.
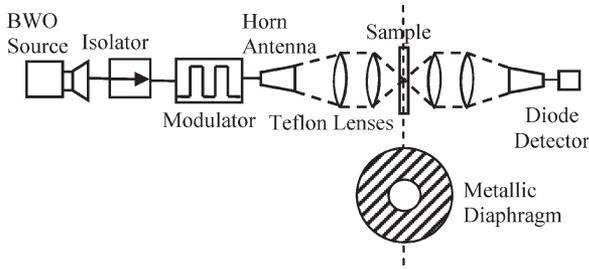
Fig. 1. Schematic of the high-resolution quasi-optical millimeter-wave spectrometer in the transmittance mode, with an extended V-band BWO as the radiation source.

During the dielectric measurement, the frequency is continuously swept at a step size of as small as 6 MHz, with the average output power accordingly ranging from 15 to 45 mW in real time to register high-resolution interference patterns with relatively high power energy.

II. MEASUREMENT TECHNIQUE

The evaluation of the dielectric and magnetic properties of a planar parallel solid sample can be performed using the free-space quasi-optical spectrometer in the transmittance or reflectance mode. The simplified schematic of the measurement system is shown in Fig. 1.

The system is composed of a high-vacuum high-power replaceable BWO tube operating in the extended V-band, a full-band isolator, a modulator, two pyramidal horn antennas, four sets of focusing lenses, and a Schottky diode detector. For highly absorbing specimens, a specially designed liquid-helium-cooled InSb detector would be utilized to enhance the measurement sensitivity. In the quasi-optical path, the radiation of the BWO tube is modulated at a frequency of 3 kHz by a ferrite modulator. A specially fabricated pyramidal horn antenna transforms the obtained energy into the paraxial Gaussian beam. Four lenses along the wave propagation path from the source antenna to the receiver antenna control the diameter and waists of the Gaussian beam. The specimen under test, which was prepared in the form of a planar parallel plate, is placed at the central waist, tightly pressed against a metallic diaphragm. The reference is recorded without the sample in the quasi-optical channel. Then, the sample is positioned in the holder to record the transmittance profile.

The transmittance and reflectance can be expressed using the following well-known expressions [16]:

$$T = E \frac{(1-R)^2 + 4R\sin^2\psi}{(1-RE)^2 + 4RE\sin^2(\alpha+\psi)}$$
$$R = \frac{(n-1)^2 + k^2}{(n+1)^2 + k^2}$$
$$\varphi = \alpha + \arctan\frac{ER\sin^2(\alpha+\psi)}{1-ER\cos^2(\alpha+\psi)}$$
$$+ \arctan\frac{k}{n^2+k^2+n} - \arctan\frac{k}{n+1}$$
$$E = \exp\left(\frac{4\pi kdf}{c}\right) \quad \alpha = \frac{2\pi ndf}{c}$$
$$n + ik = \sqrt{\varepsilon^*\mu^*} \quad \psi = \arctan\frac{2k}{n^2+k^2-1}. \tag{1}$$

Here, c is the speed of light; d is the thickness of the sample; n and k are the refractive and absorption indexes, respectively; and μ and ε are the magnetic permeability and dielectric permittivity of the sample, respectively. T, R, and φ are the transmittance, reflectance, and phase of the transmitted electromagnetic wave, respectively.

In the set of equations (1), the dielectric permittivity ε and magnetic permeability μ are equal in rights. For magnetic materials (such as ferrites), measurement of the dielectric spectra should be performed with the determination of the magnetic spectra. A millimeter-wave spectroscopy technique for the planar parallel layer requires the measurement of parameters T, R, φ, and ψ. To calculate the real and imaginary parts of permittivity of nonmagnetic substances, two parameters that characterize the millimeter-wave interaction with the sample have to be measured. It is usually a pair of T and φ for transparent samples and R and ψ for opaque samples. For magnetic materials ($\mu \neq 1$), dielectric measurements become significantly complicated. In the case of magnetic materials, all four parameters of the millimeter-wave interaction with the sample, namely, T, R, φ, and ψ, turn out to be independent. To determine the real and imaginary parts of permittivity (ε' and ε'', respectively) and permeability (μ' and μ'', respectively), all the parameters T, R, φ, and ψ should be measured. In many practically important cases, difficulties can be simplified. The magnetic permeability of the substances at the millimeter-wave frequency range is usually small, except for the quite narrow parts of the spectra near the resonance frequency. For pure, aluminum-substituted, and gadolinium-substituted YIG and nickel ferrite materials that were presented in this paper, ferromagnetic resonance has been observed at frequencies well below the millimeter-wave range under this work [17]. This fact gave us an opportunity to use the set of equations (1) to calculate dielectric permittivity.

For the calculation of complex magnetic permeability, the Schlöemann's equation [18] for partially magnetized ferrites has been used as follows:

$$\mu_{\text{eff}} 2/3 + 2/3\left\{\left[(H_A + 4\pi M_s)^2 - (\omega/\gamma)^2\right]/\left[H_A^2 - (\omega/\gamma)^2\right]\right\}^{1/2} \tag{2}$$

where ω is the frequency, H_A is the anisotropy field, M_s is the saturation magnetization, and γ is the gyromagnetic ratio.

A typical transmittance interferogram is a periodic function of frequency with pronounced maxima and minima. The evaluation of the real and imaginary parts of permittivity is achieved by fitting each peak of the measured oscillating transmittance curve to a theoretical function parameterized with a pair of variables, namely, the refractive index n and the absorption index k. Therefore, the resolution of the real and imaginary permittivity values is effectively equal to the resolution of the transmission spectrum. For medium to highly absorbing materials, the transmittance spectra are subjected to distortion and noise to a certain degree. As a result, the curve fitting can become quite inefficient and biased due to the fact that the peak fitting at a particular frequency point is forced into a local-maxima contour fitting. Such curve fitting deteriorates the accuracy of the measurement. This spectrometer is capable
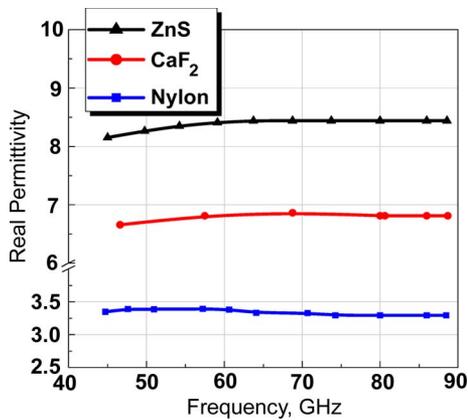
Fig. 2. New extended V-band spectrometer measurement results of the real part of permittivity versus frequency for zinc sulfide, nylon, and calcium fluoride.
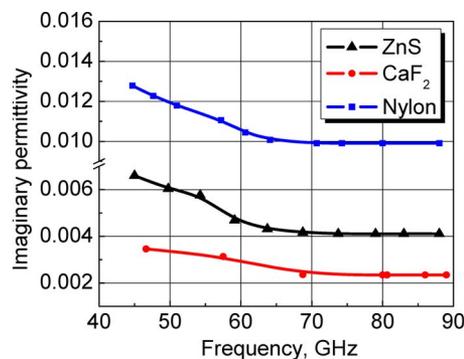

Fig. 3. New extended V-band spectrometer measurement results of the imaginary part of permittivity versus frequency for zinc sulfide, nylon, and calcium fluoride.

of incrementing the voltage in steps of as small as 90 mV over the voltage range of 0–1500 V. With the smallest increase in the cathode input voltage, the frequency resolution can be achieved as accurately as 6 MHz. Thus, it produces high-resolution transmittance spectra for materials with a wide range of absorption values over a much broader frequency range (40–90 GHz at one experiment run), including highly absorbing materials that otherwise would not be possible.

Moreover, when we covered the same frequency range with separated Q-, V-, and W-band quasi-optical spectrometers, there was always a mismatch in data at the overlapping frequency region, which can now be avoided by the use of a single extended V-band quasi-optical spectrometer.

III. Results and Discussion

A. Dielectric Measurement

Dielectric measurements have been made on three polished planar specimens: 1) zinc sulfide (ZnS); 2) nylon; and 3) calcium fluoride (CaF_2). Figs. 2 and 3 show the frequency dependences of the complex permittivity (real and imaginary parts) spectra for the three specimens. It shows that the real part of the permittivity values are relatively stable in the measured frequency range for all three samples and in very good agreement with previously published data obtained by free-space quasi-optical spectroscopy, as well as an unbalanced
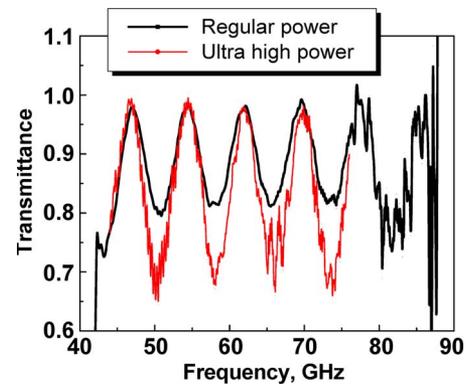

Fig. 4. Two transmittance interferograms have been recorded as a function of frequency of Glass-81807DG14 using a regular power supply with an average output power of 30 mW and a new ultrahigh-power supply with an output power in the range of 15–45 mW.
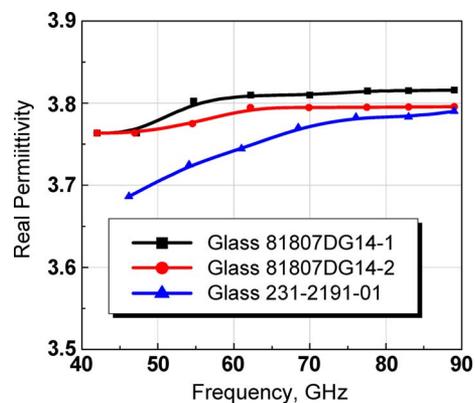

Fig. 5. New extended V-band quasi-optical free-space spectrometer measurement results of the real part of permittivity versus frequency for the three absorbing HPFS specimens.

waveguide bridge spectrometer [19], [20]. The imaginary part of the permittivity values for all three dielectrics, however, gradually decreases with increasing frequencies, and the trend is more distinct for both nylon and ZnS. It can partially be attributed to the fact that as a polymer, nylon tends to exhibit a secondary and a principal relaxation process located at lower frequencies [19]. The two relaxation processes are indicated by peaks in the imaginary part of permittivity, which might result in the value slightly decreasing at higher frequencies.

Complex dielectric permittivity measurements have also been made on three newly fabricated glass specimens from Corning, Inc.: Glass-81807DG14-1, Glass-81807DG14-2, and Glass-231-2191-01 are cubic high-purity fused silica (HPFS) specimens with a thickness of 10 mm. As shown in Fig. 4, two transmittance interferograms of Glass-81807DG14-2 have been recorded as a function of the frequency with different resolutions and power supplies. It manifests that for absorbing materials, such as Glass-81807DG14-2, the transmittance can greatly be enhanced by 10% with the new method. The new transmittance interferogram results in a more pronounced periodic structure of the transmittance spectrum in Fig. 4.

The complex permittivity spectra of the three glass specimens are shown in Figs. 5 and 6. The real parts of the permittivity values of both Glass 81807DG14 samples are about 3.81 and 3.79, respectively. Even with a very similar chemical
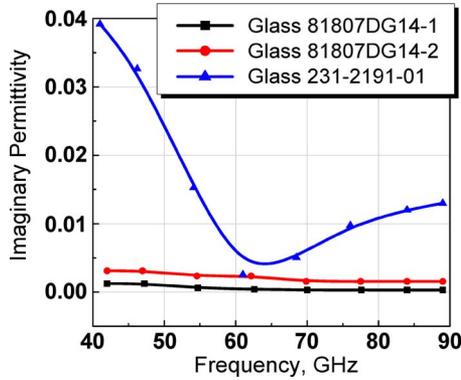
Fig. 6. New extended V-band quasi-optical free-space spectrometer measurement results of the imaginary part of permittivity versus frequency for the three absorbing HPFS specimens.

TABLE I
MAGNETIC PROPERTY DATA OF PURE YIG, AL-YIG, Gd-YIG, AND Ni-Fe MATERIALS EXPERIMENTALLY OBSERVED FROM BWO-BASED TRANSMITTANCE SPECTRA AND/OR PROVIDED BY THE MANUFACTURER IN MILLIMETER WAVES

Sample	$4\pi M_S$ (gauss) (Manuf)	H_A (kOe) (BWO)	G (BWO)	Resonance Linewidth ΔH @3dB (Oe) (Manufact)	Curie Temper. T_C (°C) (Manuf.)
YIG1	1800	1.76	0.001	≤ 20	270
Al-YIG	1000	0.63	0.001	25	230
Gd-YIG	1200	1.21	0.001	85	280
Ni-Fe	5000	5.52	0.0012	≤ 200	375

composition, both samples can clearly be differentiated in the V-band spectra. The imaginary parts of both samples are about 0.002 and remain constant through the whole frequency range.

Note that for Glass-231-2191-01, the real permittivity value slightly increases from 3.7 to 3.78 and flattens out at the end of the spectrum. Its imaginary part of the permittivity value decreases to the lowest point around 62 GHz and then slightly increases with frequency. This phenomenon repeats itself during a number of measurements, which deserve more attention and study.

There are a number of possible sources of error in the free-space quasi-optical technique. The samples should meet rather flexible requirements at the millimeter wavelength. In contrast to optics, measurements in the millimeter-wave range are complicated by the considerable effect of diffraction. Focusing the beam onto a sample may significantly reduce the distortion of the spectrum originating from the diffraction. The combined effects of diffraction and displacement of the focal plane can significantly be reduced by imposing the following restriction on the sample dimension: $D \geq 8\lambda$ and $d \leq 3\lambda$ [21], where D is the diameter (or width in the case of a slablike sample), d is the thickness of the planar parallel sample, and λ is the wavelength of the radiation. To estimate the uncertainty of the dielectric permittivity measurements, a set of measurements on a precision high-resolution 60-GHz Fabry–Pérot open resonator system [23] has been performed on well-known materials. The accuracy of the high-Q Fabry–Pérot open resonator system operated in a 10-nm step size was found to be much higher compared with the other millimeter-wave measurement technique [23]. After the comparison of the permittivity data obtained by the free-space and open resonator techniques, the uncertainty of real permittivity is evaluated to be less than 1% for all the measurements, yet it is well controlled below 0.2% for imaginary permittivity data.

In our previous work [23], from W-band spectrometer measurement results obtained through a regular power supply, we observed and concluded that both HPFS 81807DG14 glass specimens basically have similar dielectric behaviors from 70 to 120 GHz, with a little variation in terms of the real and imaginary parts of permittivity values. The newly obtained data from the extended V-band spectrometer reported in this paper show excellent agreement.

The measurement results of both HPFS specimens using a dispersive Fourier transform spectrometer in the frequency range of 100–800 GHz have also been presented earlier in [19]. It shows that the real parts of permittivity for Glass 81807DG14-1 and Glass 81807DG14-2 are 3.823 and 3.785, respectively. The near-identical imaginary permittivity values of both specimens almost linearly change with increasing frequencies. From light- and neutron-scattering experiments, it is well known that at terahertz frequencies, the "boson peak" occurs in the scattering function of glassy materials [24], [25], which is directly related to the imaginary part of the susceptibility. The increasing dielectric loss with frequency can be attributed to the boson peak. It is noted that a variety of physical understandings of the boson peak has been proposed [26], [27], yet no consensus on a detailed explanation of this feature has been achieved so far.

B. Magnetic Measurement

Disk-shaped optically polished commercial ferrite samples have been studied with and without an external transverse magnetic field. The 99.9% pure, aluminum-substituted, and gadolinium-substituted YIG samples have been provided by Pacific Ceramics, Inc., Sunnyvale, CA. The nickel ferrite samples have been provided by TransTech, Adamston, MD. The ferrite samples have been placed between the poles of an electromagnet, which provides a transverse magnetic field of up to 1 T. The millimeter-wave measurements have been performed in a frequency sweep mode. After obtaining the transmittance spectra of the ferrite materials, optimization procedures were applied to extract the best-fit dielectric and magnetic parameters of the measured samples [19]. The magnetic characteristics of the ferrite samples, including the calculated anisotropy field H_A and the dissipation parameter G-factor, are presented in Table I.

Saturation magnetization $4\pi M_S$ data, as shown in Table I, are provided by manufacturers and have been used in the magnetic permeability calculations. The resonance linewidth and Curie temperature are also provided by manufacturers. Compared with the results of pure YIG, metal-substituted materials have either slightly different permittivity in millimeter waves, and these results are consistent with the measurements at lower frequencies [17]. The real and imaginary parts of complex permittivity data are shown in Table II. Both the real and imaginary parts of permittivity for all ferrite samples remain constant in the whole V-band millimeter-wave frequency range.

TABLE II
DIELECTRIC PARAMETER DATA OF PURE YIG, Al-YIG, Gd-YIG,
AND Ni-Fe MATERIALS EXPERIMENTALLY OBSERVED AND/OR
PROVIDED BY THE MANUFACTURERS IN MILLIMETER WAVES

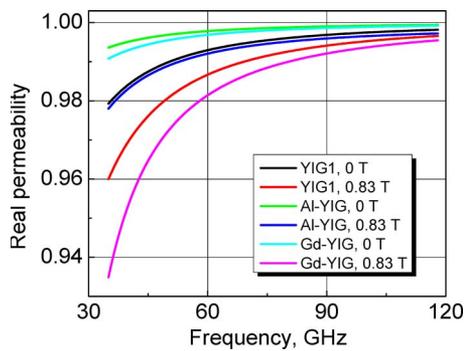| Sample	ε' (Manufacturer)	ε' (BWO)	ε" (BWO)
YIG1	14.4	15.68	0.008
Al-YIG	14.6	15.56	0.0095
Gd-YIG	15.1	15.74	0.0087
Ni-Fe	12.5	13.74	0.023

Fig. 7. Real part of the magnetic permeability of YIG and metal-substituted samples at 0- and 0.83-T transverse magnetic fields.
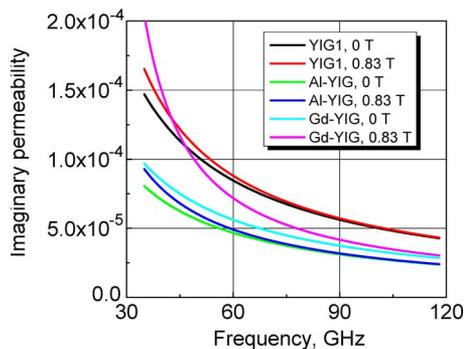

Fig. 8. Imaginary part of the magnetic permeability of YIG and metal-substituted samples at 0- and 0.83-T transverse magnetic fields.

The real and imaginary parts of magnetic permeability for pure and metal-substituted YIG samples at 0- and 0.83-T transverse magnetic fields, which were obtained by matching the calculated curves to the experimental transmittance spectra, are shown in Figs. 7 and 8, respectively. No significant changes in the magnetic permeability of the YIG samples have been found in the transverse magnetic field. However, all YIG samples manifest more curvature (bending) of permeability toward low frequencies in the transverse magnetic field. YIG materials are known as common soft ferrites. Natural ferromagnetic resonances for these materials have been observed at microwave frequencies of about or even below 4 GHz [28], [29]. In millimeter waves, in our experiments, the real and imaginary permeability values are close to their values in vacuum. These results are consistent with other soft ferrite measurements [29], where μ' approaches unity as the frequency increases far above the ferromagnetic resonance. The lowest millimeter-wave frequency in our measurements (40 GHz) is still well above the ferromagnetic resonance, where dramatic changes in magnetic permeability are expected [30], [31].
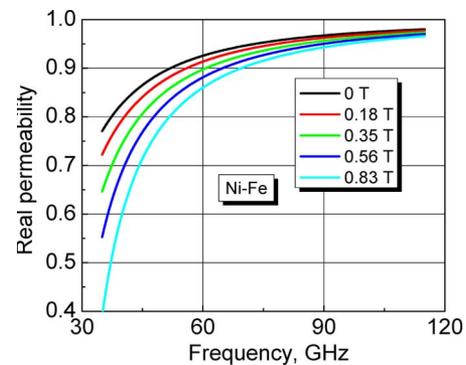

Fig. 9. Real part of the magnetic permeability for nickel ferrite in the transverse magnetic field.
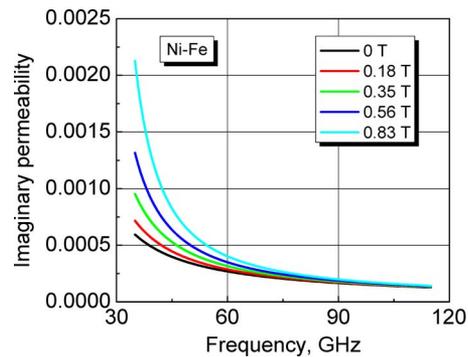

Fig. 10. Imaginary part of the magnetic permeability for nickel ferrite in the transverse magnetic field.

The real and imaginary permeability values for the nickel ferrite ceramic in different transverse magnetic fields are shown in Figs. 9 and 10. The ferromagnetic resonance for the nickel ferrite material has been observed at frequencies around 14 GHz [17]. The starting frequency in our measurements is 30 GHz, which seems to be not that far away from the ferromagnetic resonance frequency for the nickel ferrite. Due to the stronger anisotropy field H_A of this ferrite specimen compared with that of YIG materials (see Table I), the resonance is shifted and is observed at higher frequencies. The resonance frequency value can also be achieved by linearly extrapolating the curves of real and imaginary permeability values to lower frequencies. The ferromagnetic resonance is shifted even more to higher frequencies in the transverse magnetic field.

The transverse external magnetic field dependences of the real and imaginary parts of magnetic permeability values taken at a frequency of 60 GHz are shown in Figs. 11 and 12. For pure and Al-substituted YIG samples, no significant changes in permeability versus transverse magnetic field have been observed. On the other hand, the Gd-substituted YIG samples, particularly the nickel ferrite materials, show the beginning of the "resonance-like" behavior in the permeability dependence in the magnetic field. One can conclude that for Gd-YIG materials, the ferromagnetic resonance occurs at higher frequencies compared with pure YIG and Al-YIG ferrite samples. The magnetic field dependence of permeability observed for the nickel ferrite ceramic material seems to be much stronger compared with that in pure YIG and metal-substituted YIG ferrites. The nickel ferrite material is found to be characterized by much
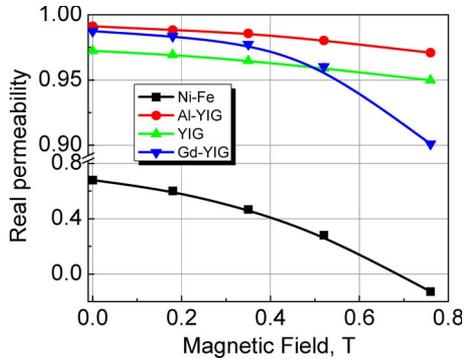
Fig. 11. Real part of the magnetic permeability values of ferrites in the transverse magnetic field taken at a frequency of 60 GHz.
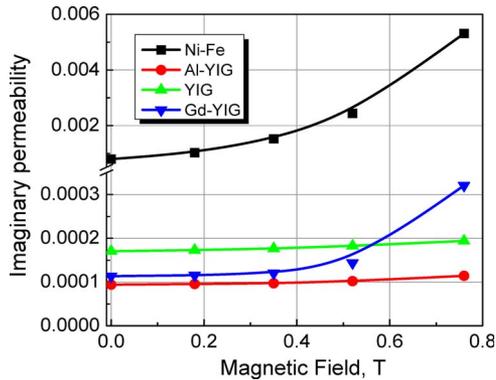

Fig. 12. Imaginary part of the magnetic permeability values of ferrites in the transverse magnetic field taken at a frequency of 60 GHz.

stronger magnetic parameters, such as the anisotropy field, saturation magnetization, and resonance frequency linewidth (see Table I).

A linear-like shift of the resonance frequency, as well as a change in the magnetic permeability of the external magnetic field, has recently been observed for diluted barium and strontium ferrite materials [30]–[31]. Similarly, the real and imaginary parts of permeability are closer to their vacuum values outside the ferromagnetic resonance and drastically change as the frequency becomes closer to the resonance.

IV. ERROR ANALYSIS

The accuracy of the transmittance and reflectance measurements at millimeter waves can be affected by several factors: the resolution of the transmittance/reflectance measurements, the random errors in the transmittance/reflectance measurements originating from the thermal instability of the generator, the dynamic range or the signal-to-noise ratio, the standing-wave errors, and the systematical errors arising from the uncertainties in the alignment of the quasi-optical channel [16], [19], [22], [32]–[34].

The resolution chosen in this paper allows us to resolve all the necessary features of the transmittance spectrum. It also provides a smooth and slow frequency scan to ensure the thermal stability of the source. The repeatability of the experimental results is found to be better than 0.1%. It means that the random errors contributed by the instability of the

source of millimeter-wave radiation to the final transmittance spectrum do not exceed 0.001.

The dynamic range of this magneto-optical approach depends on the type of detector employed in the measurement. The dynamic range with the Schottky diode detector is about 10^{-4} and can greatly be improved to 10^{-6} with the InSb detector.

The reflection of the radiation from the elements of the quasi-optical channel and an inserted specimen form the distinctive pattern in the transmittance spectrum. The employment of film- and carbon-loaded foam absorbers along the quasi-optical path helps to essentially reduce the standing-wave pattern but does not completely eliminate it. The distribution of the standing waves is changed when a specimen is introduced into the measurement channel. The standing waves repeatedly appear in the transmittance spectrum as high-frequency noise. They do not yield any ambiguity in the results, because they occur with high frequency and their average level gives the true value of the transmittance.

V. CONCLUSION

A quasi-optical free-space millimeter-wave spectrometer, which is equipped with a new specially developed high-power BWO source of radiation, operates at much extended V-band frequencies (40–90 GHz). The transmittance spectra of various dielectric, amorphous, and ferrite materials in millimeter waves have successfully been obtained with high resolution over this frequency range, which covers nearly three extended bands: the Q-band, the V-band, and part of the W-band. Complex permittivity and permeability measurements of the dielectric and ferrite materials have been calculated from the transmittance spectra in the entire extended V-band frequency range. The technique developed in this paper is noncontact and nondestructive, and suitable for solid or granulated materials, such as absorbing glasses, ferrites, and ceramics, which cannot easily be machined. It even has the potential of providing broad-band continuous high-resolution, accurate, and highly reproducible transmittance spectra for human and animal tissues.

For various ferromagnetic materials, such as hexagonal ferrites, the ferromagnetic resonance is usually observed at a frequency range of 50–65 GHz. The new extended V-band spectrometer shows great potential in the study of ferromagnetic-resonance-related phenomena from a single set of measurements. It is also applicable for materials that are widely used for satellite-to-satellite communications and for a collision-avoidance radar at the oxygen absorption frequency range (55–80 GHz).

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