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Felix A. Miranda and William L. Gordon
Case Western Reserve University
Cleveland, Ohio

and

Vernon O. Heinen, Ben T. Ebihara,
and Kul B. Bhasin
Lewis Research Center
Cleveland, Ohio

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Felix A. Miranda and William L. Gordon
Case Western Reserve University
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Vernon O. Heinen, Ben T. Ebihara, and Kul B. Bhasin
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio

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SUMMARY

A knowledge of the dielectric properties of microwave substrates at low temperatures is useful in the design of superconducting microwave circuits. In this paper, we report the results of a study of the complex permittivity of sapphire (Al_2O_3), magnesium oxide (MgO), silicon oxide (SiO_2), lanthanum aluminate ($LaAlO_3$), and zirconium oxide (ZrO_2), in the 20 to 300 K temperature range, at frequencies from 26.5 to 40.0 GHz. The values of the real and imaginary parts of the complex permittivity were obtained from the scattering parameters, which were measured using a HP-8510 automatic network analyzer. For these measurements, the samples were mounted on the cold head of a helium gas closed cycle refrigerator, in a specially designed vacuum chamber. An arrangement of wave guides, with mica windows, was used to connect the cooling system to the network analyzer. A decrease in the value of the real part of the complex permittivity of these substrates, with decreasing temperature, was observed. For MgO and Al_2O_3, the decrease from room temperature to 20 K was of 7 and 15 percent, respectively. For $LaAlO_3$, it decreased by 14 percent, for ZrO_2 by 15 percent, and for SiO_2 by 2 percent, in the above mentioned temperature range.

INTRODUCTION

The successful application of thin films, made with the new high temperature superconductor oxides, in the development of microwave circuits, rest considerably on the dielectric properties of the different substrates used for film deposition. For microwave applications, it is desirable to have substrates with low dielectric constant and loss tangent, (ref. 1) if good performance from microwave components is expected.

Until now, Y-Ba-Cu-O films deposited on $SrTiO_3$, have shown the highest quality when compared with films deposited on other substrates. Nevertheless, due to its extremely temperature dependent dielectric constant, with a value for 300 at room temperature, around 1000 at 77 K, and over 18000 at helium temperatures, and its considerably high loss tangent, (ref. 2) its microwave applicability is rather limited. Although other materials as MgO, $LaAlO_3$, and ZrO_2 are now being used as substrates, information about their dielectric properties at temperatures below room temperature, and for some of them even at room temperature, is rather scarce.

In this paper, we report on the measurements of the microwave complex permittivity of MgO, Al_2O_3, $LaAlO_3$, ZrO_2, and SiO_2, in the 20 to 300 K temperature range and as a function of frequency. The measurements were taken following a method previously reported by other authors (refa. 3 to 5). This method allows the determination of both parts of the complex permittivity in a rather simple way, and is very convenient for cases in which a fast determination of the dielectric constant of a material is needed. Nevertheless, the method has a high uncertainty in the measurement of the imaginary part of the complex permittivity for materials with very low loss tangent.

ANALYSIS

In order to determine the value of the real and imaginary parts of the complex permittivity for the various substrates under consideration, we have followed the method proposed by Nicolson and Ross, (ref. 3) as modified by Wier, (ref. 4) and following the implementation suggestions of reference 5. In an ideal case, consider a piece of material installed in a rectangular wave guide with characteristic impedance Zo, as shown in figure 1.

After solving the corresponding boundary conditions at $x = 0$ and $x = d$, the scattering parameters, $S_{11}(\omega)$ and $S_{21}(\omega)$, can be related with the reflection, Γ, and transmission, T, coefficients, as follows,

$$S_{11} = \frac{(1 - T^2)\Gamma}{1 - \Gamma^2 T^2}, \qquad S_{21} = \frac{(1 - \Gamma^2)T}{1 - \Gamma^2 T^2} \tag{1}$$

The reflection coefficient, when the length of the material is infinite, is given by

$$\Gamma = \frac{Z - Z_o}{Z + Z_o} = \frac{\sqrt{\frac{\mu r}{\epsilon r}} - 1}{\sqrt{\frac{\mu r}{\epsilon r}} + 1} \tag{2}$$

Also, the transmission coefficient, when the length of the material is finite, is given by,

$$T = \exp(-j\omega \quad \mu\epsilon \; d) = \exp[(-j\omega/c) \quad \mu_r \epsilon_r \; d] \tag{3}$$

Thus, the reflection and transmission coefficients can be derived by measuring $S_{11}(\omega)$ and $S_{21}(\omega)$, and in turn they can be used to obtain the value of the permittivity.

The experimental configuration used for the measurements of the reflection, $S_{11}(\omega)$, and transmission, $S_{21}(\omega)$, scattering parameters for the samples under consideration, is shown in figure 2. The measurements were made using an HP-8510 automatic network analyzer, properly connected by an arrangement of Ka-band (26.5 to 40.0 GHz) wave guides, to a cooling system. The cooling system consist of a CTI-Cryogenics closed cycle helium refrigerator, associated with a Lake Shore Cryotronics temperature controller, model DRC 91C, which allows measurements to be taken at the required low temperatures.

The measurements were performed under vacuum ($<10^{-3}$ torr), in an aluminum vacuum chamber specifically designed to fit on the top of the external shield of the refrigerator and to give access to the set up of wave guides connecting the network analyzer with the refrigerator. In order to preserve the vacuum inside the chamber, two mica windows were placed at its ends. The material for the windows was selected due to its very low loss and transparency in this frequency range.

In order to measure the scattering parameters, the sample was held in a sample holder which was suspended between two wave guide flanges, as shown in figure 3. The wave guide flanges were in direct contact with a copper plate, which in turn was attached to the cold head of the refrigerator. The two supporting wave guides inside the vacuum chamber, were specially designed to be used at low temperatures. They are made of stainless steel, a relatively poor thermal conductor. A gold plating of their internal surfaces was performed, in order to reduced the microwave losses. Finally, in an attempt to reduce the errors induced in the measurements, possibly due to linear thermal contractions of the wave guides as the temperature decreases, the system was calibrated at all the temperatures at which measurements were taken. These calibrations were stored, so that they could be recalled to be used in later measurements.

RESULTS

The thickness of the substrates used in this study, varies from 0.285 mm for MgO, to 1.641 mm for SiO_2. The thicknesses for the Al_2O_3, $LaAlO_3$, and ZrO_2 samples are 0.496 mm, 0.432 mm, and 0.494 mm respectively. Figures 4 to 7 and table I show the measurement results for the real part of the complex permittivity of the samples, at room temperature and at 20 K. The value for the dielectric constant of MgO at room temperature agrees well with values quoted by other researchers (refs. 6, 7, 9). For Al_2O_3 and SiO_2, the values of the dielectric constant obtained at room temperature, are also in good agreement with the values quoted by Zahopoulos (ref. 8) and Von Hippel (ref. 7) respectively. Although for ZrO_2 there appear to be no data for comparison in this frequency range, the value for its dielectric constant at room temperature is consistent with the one reported by Gorshunov, et al., (ref. 9) at frequencies within 10^{11} to 10^{12} Hz. In the case of $LaAlO_3$, the value obtained for its dielectric constant at room temperature is not consistent with the value of 15.3 reported by Simon, et al. (ref. 1). Due to this discrepancy, measurements were performed in four different $LaAlO_3$ samples, each one made from different batches, in order to determine if the disagreement was due to intrinsic properties of the sample. The value of the dielectric constant obtained from these measurements was practically the same for all the samples and was consistent with our previously determined value. Nevertheless, since not much information for the value of the dielectric constant of this substrate is available yet, additional experimental verification will be appropriate.

Table I shows the real and imaginary parts of the complex permittivity, at four different temperatures and at 32.9 GHz. A decrease in the value of the real part of the complex permittivity is clearly observed in all the substrates under consideration. For MgO and Al_2O_3, a decrease of 6 and 14 percent down to 70 K, and of 7 and 15 percent down to 20 K respectively, is observed. For $LaAlO_3$ and ZrO_2, the value of the real part of the complex permittivity is lowered by 10 and 13 percent respectively, at temperatures around 70 K, and goes down 14 percent for $LaAlO_3$ and 15 percent for ZrO_2, at 20 K. For SiO_2, the dielectric constant is lowered by 1 percent at 70 K and by 2 percent for temperatures around 20 K.

From comparison of the data of table I with that of the references mentioned, it can be seen that there is relatively good agreement for the real part of the complex permittivity but wider variation for the imaginary part. For example, a comparison of the value for the loss tangent for MgO at room temperature, 8×10^{-2}, obtained from the data in table I, with the value quoted by Von Hippel, 3×10^{-4}, reveals a difference of two orders of magnitude. Due to this fact, it is very difficult to observe a particular temperature and frequency dependence for this parameter. This is an intrinsic limitation of the technique, when applied in the calculation of the imaginary part of the complex permittivity for materials of low loss tangent, as mentioned in the introduction.

The frequency of 32.9 GHz was selected for construction of table I as being typical of the largest variations with temperature. Finally, for these measurements, the statistical error in the real part of the complex permittivity is ±0.02, while the variation in the imaginary part is larger.

CONCLUSIONS

The real and imaginary parts of the complex permittivity for MgO, Al_2O_3, $LaAlO_3$, ZrO_2 and SiO_2 have been measured. A decrease in the value of the real part of the complex permittivity, with decreasing temperature, was observed in all the substrates. Nevertheless, no considerable change was observed as a function of frequency. The results obtained in this study show that, at least from the stand point of the dielectric constant, the substrates considered appear to be better suited than $SrTiO_3$, for use with the new high temperature superconductors in microwave applications.

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TABLE I. - COMPLEX PERMITTIVITY OF MICROWAVE SUBSTRATES AT 32.9 GHz

[ϵ'_r = real part of complex permittivity. ϵ''_r = imaginary part of complex permittivity.]

Substrate	MgO		Al_2O_3		$LaAlO_3$		ZrO_2		SiO_2	
Temperature, K	ϵ'_r	ϵ''_r	ϵ'_r	ϵ''_r	ϵ'_r	ϵ''_r	ϵ'_r	ϵ''_r	ϵ'_r	ϵ''_r
300	9.88	0.556	9.51	0.675	21.9	1.70	25.4	1.72	3.82	0.516
150	9.45	.726	8.52	.925	21.6	1.48	23.6	1.75	3.80	.159
70	9.26	.351	8.19	.695	19.7	2.98	22.0	2.50	3.78	.688
20	9.19	.420	8.11	.613	18.8	3.71	21.6	2.23	3.75	.298

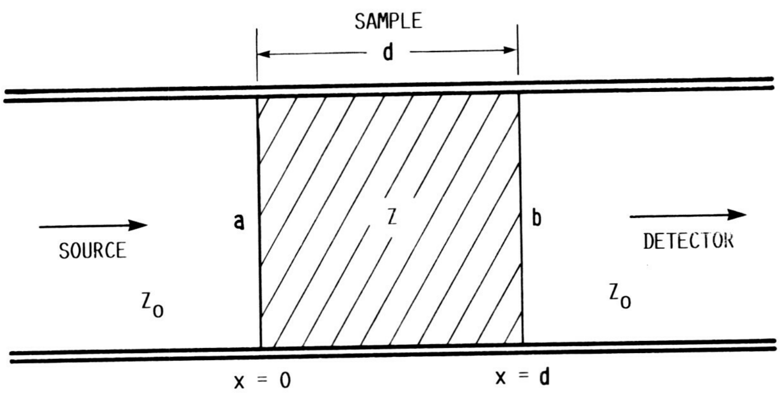

FIGURE 1. - WAVEGUIDE WITH FILLED MATERIAL.

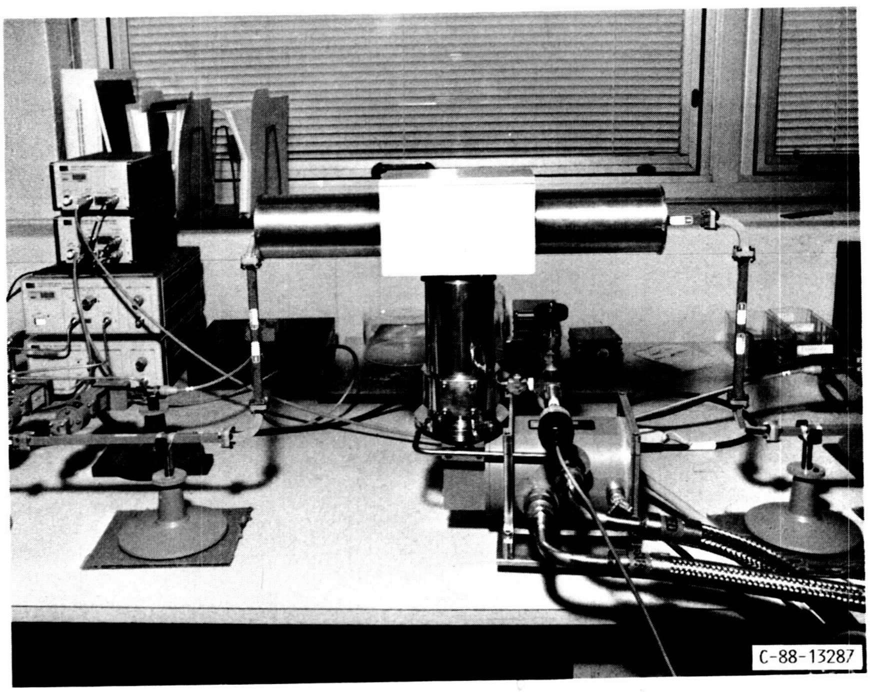

FIGURE 2. - EXPERIMENTAL SETUP.

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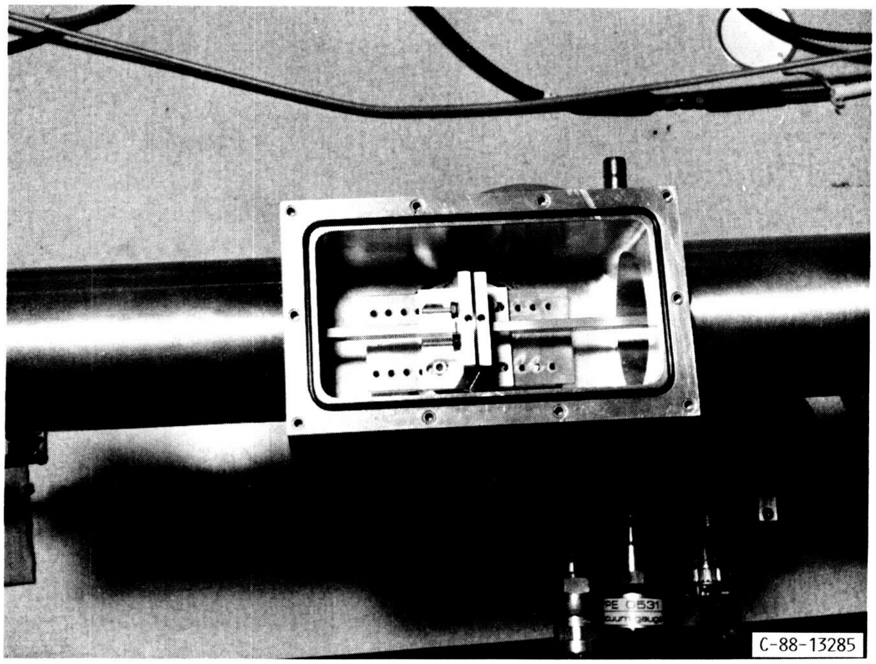

FIGURE 3. - SAMPLE SUSPENSION SETUP.

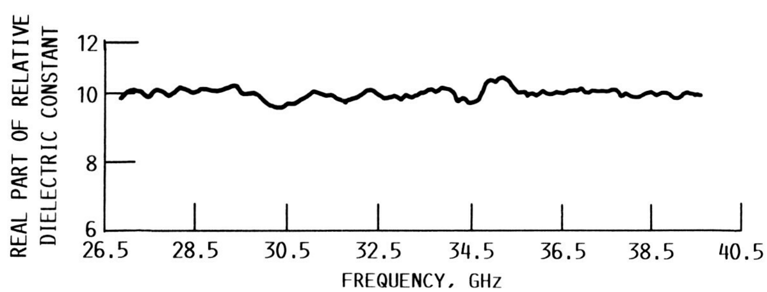

FIGURE 4. - MgO SUBSTRATE AT ROOM TEMPERATURE.

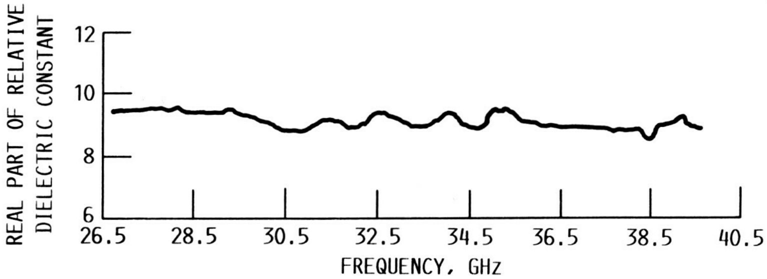

FIGURE 5. - MgO SUBSTRATE AT 20 K.

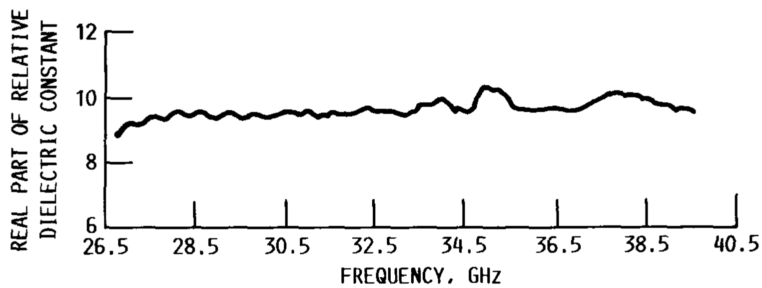

FIGURE 6. - SAPPHIRE SUBSTRATE AT ROOM TEMPERATURE.

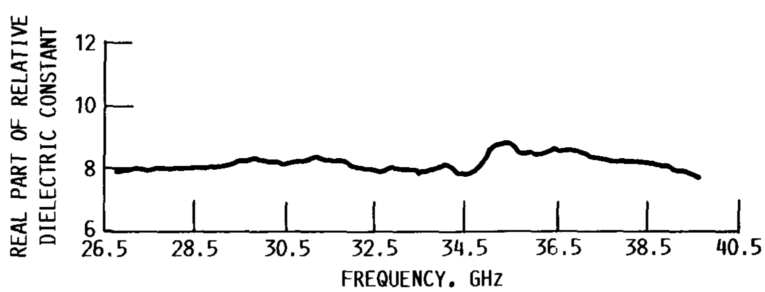

FIGURE 7. - SAPPHIRE SUBSTRATE AT 20 K.

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15. Supplementary Notes

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16. Abstract

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