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Authors
Barry, W
Byrd, J
Johnson, J
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Accelerator & Fusion Research Division

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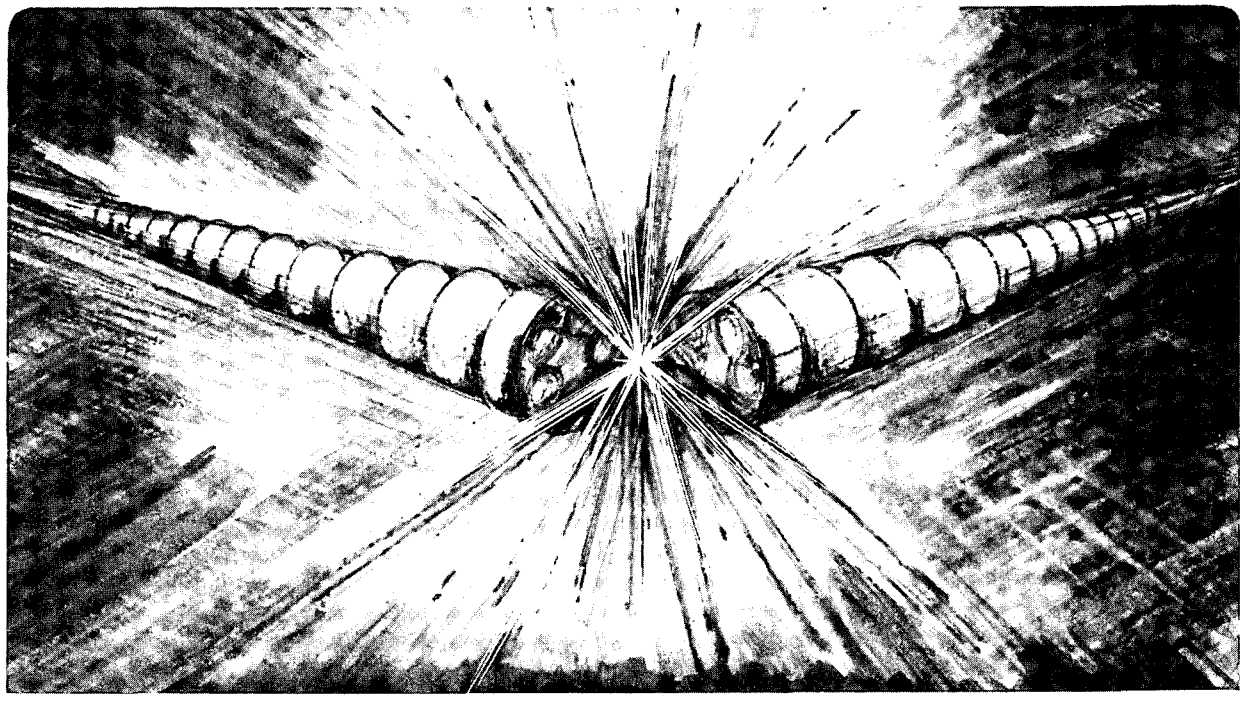
A Collection of Complex Permittivity and Permeability Measurements

W. Barry, J. Byrd, J. Johnson, and J. Smithwick

February 1993



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Accelerator & Fusion Research Division
Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720

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A Collection of Complex Permittivity and Permeability Measurements*

W. Barry, J. Byrd, J. Johnson, and J. Smithwick
Beam Electrodynamics Group
Center for Beam Physics
Lawrence Berkeley Laboratory
Berkeley, CA 94720 USA

Abstract

We present the results of measurements of the complex permittivity and permeability over a frequency range of 0.1 - 5.1 GHz for a range of microwave absorbing materials used in a variety of accelerator applications. We also describe the automated measurement technique which uses swept-frequency S-parameter measurements made on a strip transmission line device loaded with the material under test.

Introduction

There are a variety of applications for microwave absorbing materials in particle accelerators. Ultimately, the absorbing materials generally end up serving one or both of two major purposes: attenuation of traveling waves in beamlines and damping of resonant fields in accelerator components, the most notable being higher order mode fields in RF cavities. In most cases, the absorbers are in contact with the accelerator vacuum and must meet stringent outgassing requirements. In addition, the absorbers must be radiation resistant and in some cases, capable of dissipating a large amount of RF power. These requirements tend to limit the choice of absorbers to lossy electric and magnetic (ferrite) ceramics.

A selection of such materials have been measured for complex permittivity and permeability over a frequency range of 0.1 to 5.1 GHz using the technique described in Ref. [1]. This frequency range was chosen with the specific application of higher order mode damping in mind. The frequency range, in general, covers the lowest frequency RF cavities in common use in accelerators to the highest cutoff frequencies of beamlines in common use. After a brief description of the measurement technique, the measurement results for 12 ceramic materials, donated by various manufacturers are presented. The results are presented with minimal commentary regarding their absorptive properties due to the dependence of absorption on, among other things, the geometry and field structure associated with a specific application.

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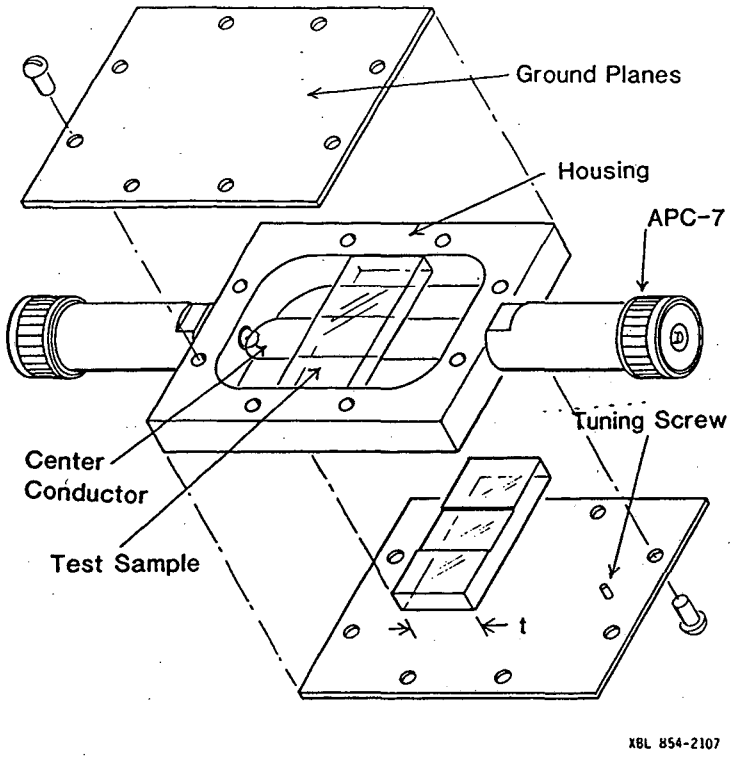

Figure 1: Stripline measurement device.

Measurement Technique for ϵ_r and μ_r

The measurement technique is described fully in Ref. [1]. A brief description is given here. The general technique for determining the relative complex permittivity and permeability, ϵ_r and μ_r, involves measuring the complex S–parameters of a waveguide or transmission line loaded with the material under test. The technique employed here utilizes a strip transmission line fixture, shown in Figure 1, into which blocks of the material to be measured may be inserted easily. An automated network analyzer system is used to make frequency-swept S–parameter measurements of the loaded stripline fixture. Values for ϵ_r and μ_r may then be calculated from the S–parameters.

Referring to Figure 1, an unknown sample of physical length, t, is placed in the center of the strip transmission line fixture whose unloaded terminal–to–terminal electrical length is $2L + t$. For this configuration, it can be shown that ϵ_r and μ_r of the sample are related to the S–parameters measured at the terminals of the fixture through the following equations:

$$\varepsilon_r = \frac{k}{k_0}\left(\frac{1-R}{1+R}\right) \tag{1}$$

$$\mu_r = \frac{k}{k_0}\left(\frac{1+R}{1-R}\right) \tag{2}$$

$$\cos(kt) = \frac{e^{-\jmath 4k_0 L} + S_{12}^2 - S_{11}^2}{2e^{-\jmath 2k_0 L} S_{12}} \tag{3}$$

$$R = \frac{S_{11}}{e^{-\jmath 2k_0 L} - S_{12} e^{-\jmath 2kt}} \tag{4}$$

where k is the complex wavenumber in the material, k_0 is the free space wavenumber, and R is the reflection coefficient.

It should be noted that the multivalued inverse cosine function in Eq. 3 can present computational difficulties. In our case, we treat $\cos^{-1} z$ as follows:

$$\cos^{-1} z = (\theta \pm 2\pi n) - \jmath \ln A \tag{5}$$

where

$$A = \left| z + \jmath\sqrt{1 - z^2} \right| \tag{6}$$

and

$$\tan\theta = \frac{Im\left(z + \jmath\sqrt{1 - z^2}\right)}{Re\left(z + \jmath\sqrt{1 - z^2}\right)} \tag{7}$$

From Eqs. 3 and 5, it is seen that $\theta \pm 2n\pi$ or $Re(kt)$ represents the phase delay through the material sample. The value of n must be changed at points where the electrical length of the sample is an integer number of quarter, half or full wavelengths depending or the algorithm used to compute the inverse tangent of θ in Eq. 7. In our case, the inverse tangent function returns the proper quadrant angle, $-\pi \geq \theta > \pi$. Therefore, $n = 0$ when the electrical length of the sample is between zero and one half wavelength, and in general, will be equal to the odd integer number of half wavelengths of electrical delay in the sample.

Of course, the electrical length of the test sample at any given frequency is not known a priori. This makes choosing values for n quite difficult, especially for materials suspected of having high dielectric constants. One solution to this problem, which we employ, is to make the physical sample length such that the electrical delay is less than one half wavelength at the highest frequency in the measurement band. Adopting this strategy, a sample length of $t = 0.5$ cm was chosen for the measurements. This length, for example, would allow the measurement of dielectrics with ϵ_r as large as 35 at 5.1 GHz without computational problems. On the other hand, at the lower end of the frequency band, short samples result in large measurement errors. Therefore, the measurements were also performed with 1 cm samples when possible with the hope of improving accuracy at low frequencies. Ideally, one would like to have many samples of each material with dimensions tailored to different parts of the frequency band. Unfortunately, lack of time and resources do not allow for this approach. Overall, the data presented in the next section is believed to be accurate on the $\pm 10\%$ level in the 0.1 to 5.1 GHz band. For the purpose of quickly evaluating a large number of absorbing materials for accelerator applications this accuracy is quite satisfactory. The questions of computational and measurement accuracy for this technique have been explored to a greater extent in a paper by Hartung [2] elsewhere in these proceedings. Finally, it is noted that this technique is unsuitable for measuring losses in

Material	Manufacturer
AlN 7% Glassy C	Ceradyne*
BeO 40% SiC	Ceradyne
MgO 5% SiC	Ceradyne
MgO 2.4% SiC	Ceradyne
AlN 40% SiC	Ceradyne
AlN 16% TiC	Ceradyne
AlN 15% Mo	Ceradyne
AlN 12% Mo	Ceradyne
TT2-111R Ferrite	Trans–Tech†
NZ–51 Ferrite	Emerson and Cuming‡
Ferramic 1928 Ferrite	Indiana General§
Ferramic 1927 Ferrite	Indiana General

*Ceradyne Inc., 3169 Redhill Ave.,Costa Mesa, CA 92626.
†Trans–Tech Inc., 5520 Adamstown Rd.,Adamstown, MD 21710.
‡Emerson and Cuming, 604 W. 182nd St., Gardena, CA 90248.
§Indiana General, no longer in business.

Table 1: Materials used in measurements.

low loss materials which are sometimes of interest in accelerator design (e.g. RF window materials) and for high precision measurements at a given frequency. For these types of measurements, the cavity perturbation technique with a dielectric bead or rod is a standard method for determining material properties.

Results

Shown in Table 1 is a list of the sample materials used in the measurements. Shown in Figures 2-13 are the results of the measurements for these samples. An HP8753C Network Analyzer was used to measure the S–parameters. When sample supplies allowed, measurements were made for sample lengths of 0.5 and 1 cm. The data for each sample length is only shown over the frequency range where there is less than a half–wavelength in the material. The data shown has not been averaged or smoothed. Some of the measurements show small apparent resonances in the data (e.g. AlN + 7% Glassy C). We believe these to result from the first resonant mode of the stripline chamber, the frequency of which is lowered into the frequency range of our measurement due the presence of dielectric material, and not from the inherent material properties.

Considerable sample–to–sample variations can be present in the material properties. For example, in the measurement of the Al N with 7% glassy C, the samples were acquired from three different sources but all originated with Ceradyne. One of the 1 cm sample measurements differs significantly from the others underscoring the variations in the material properties. Several other materials show similar variations. We did not track the specific origin of the samples.

Conclusions

The loaded stripline technique is useful for providing rapid evaluations of ϵ_r and μ_r for a large variety of microwave–absorbing materials over a broad frequency range.

Acknowledgements

We would like to thank the manufacturers for providing the samples used in the measurement. We would also like to thank R. Campisi and R. Pendleton for providing additional samples.

References

[1] W. Barry, *A Broadband, Automated, Stripline Technique for the Simultaneous Measurement of Complex Permittivity and Permeability*, *IEEE Transactions on Microwave Theory and Techniques*, **MTT-34**, p. 80-4 (January 1986).

[2] W. Hartung, D. Moffat, T. Hays, *Measurements of the Electromagnetic Properties of Some Microwave–Absorbing Materials*, in these proceedings.

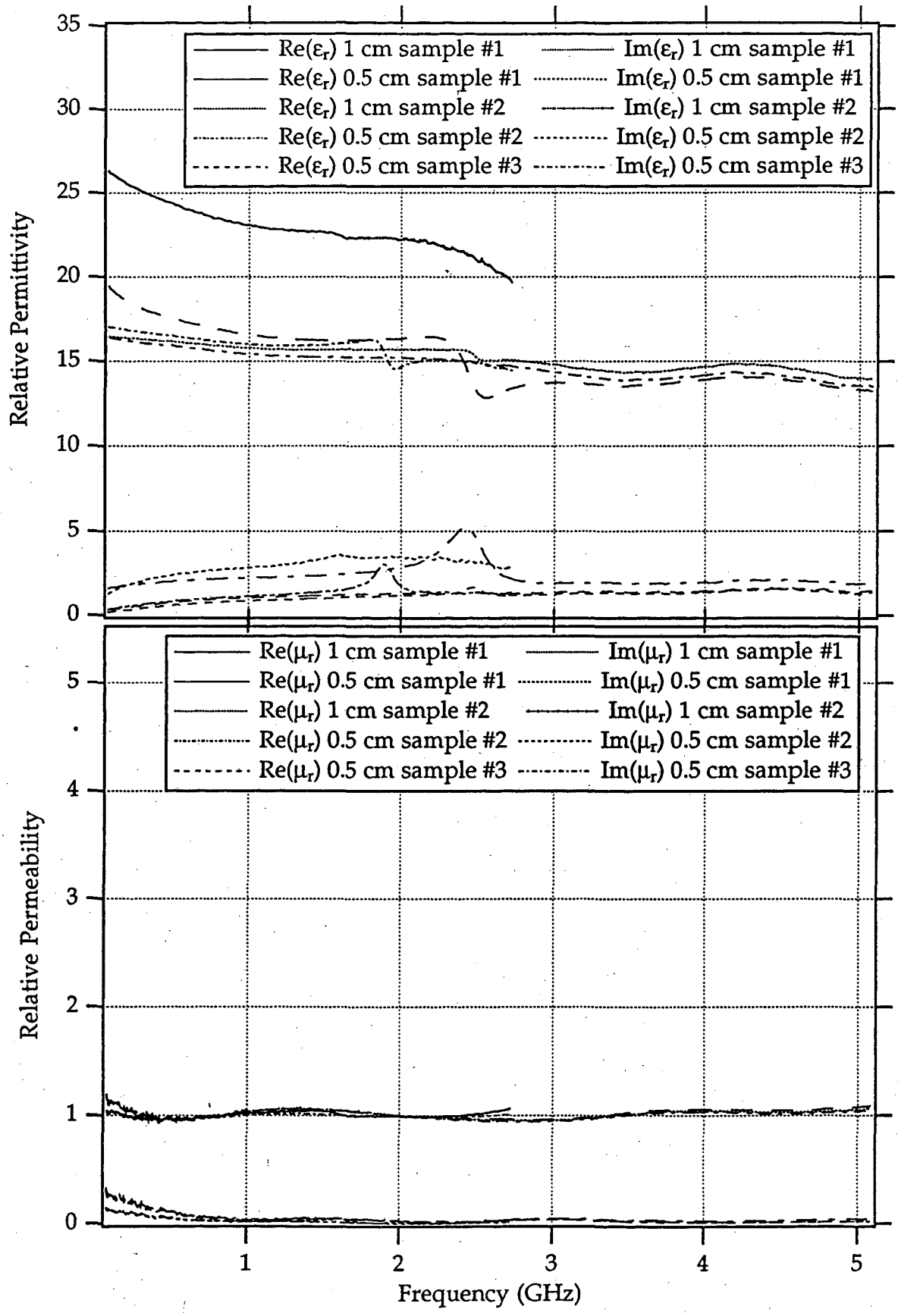

Figure 2. Complex ε_r and μ_r for AlN with 7% Glassy Carbon.

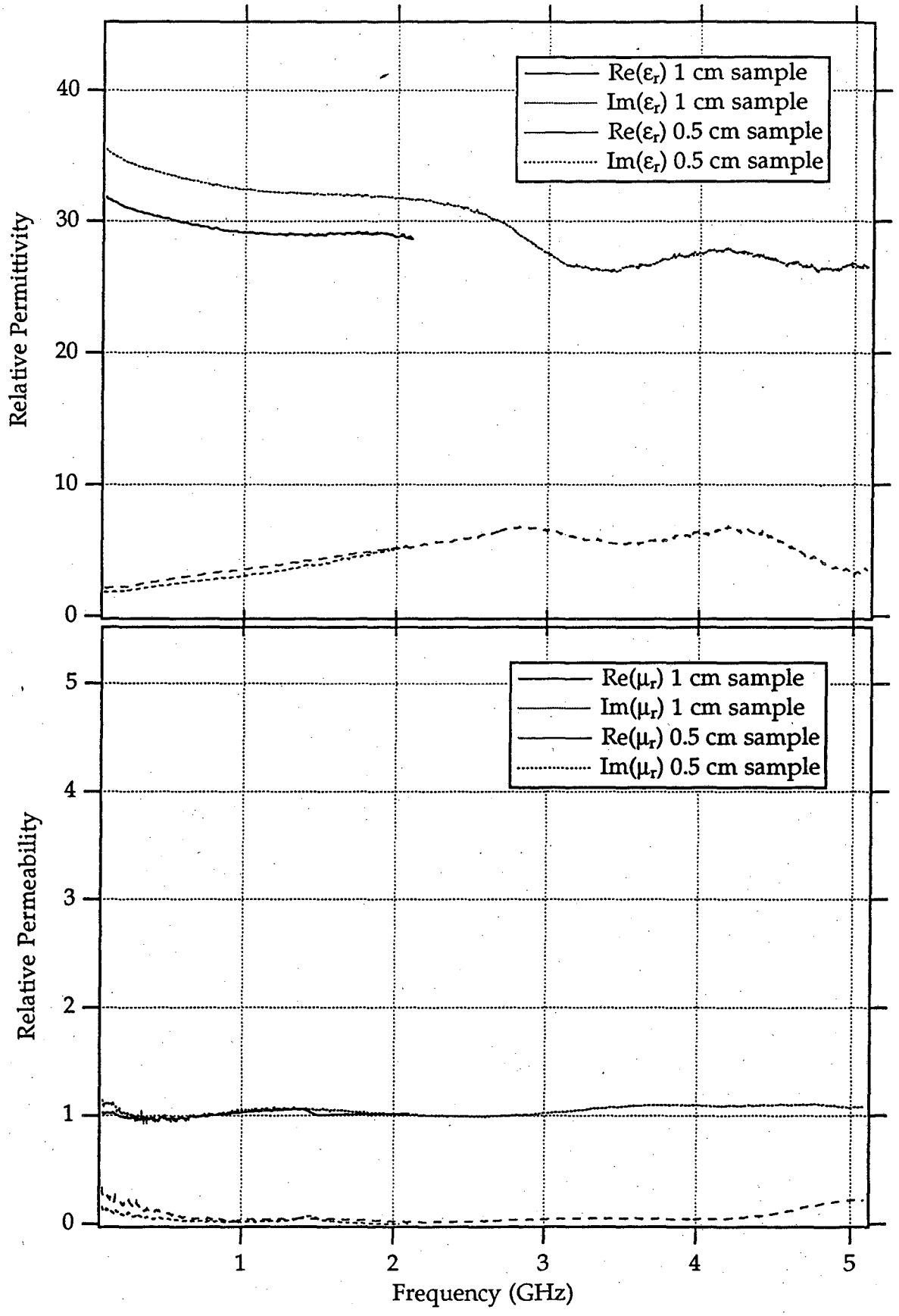

Figure 3. Complex ε_r and μ_r for BeO with 40% SiC.

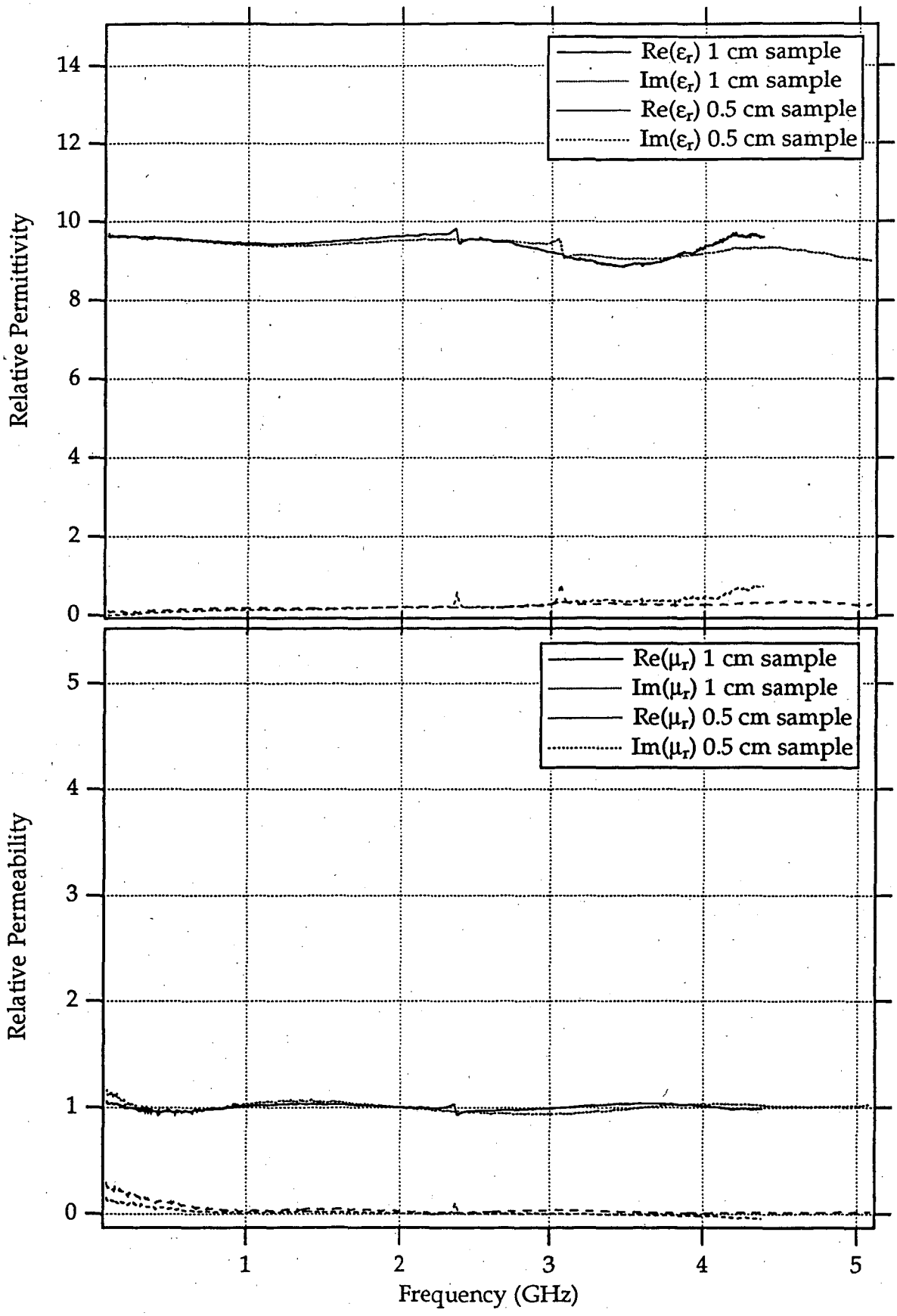

Figure 4. Complex ε_r and μ_r for MgO with 5% SiC.

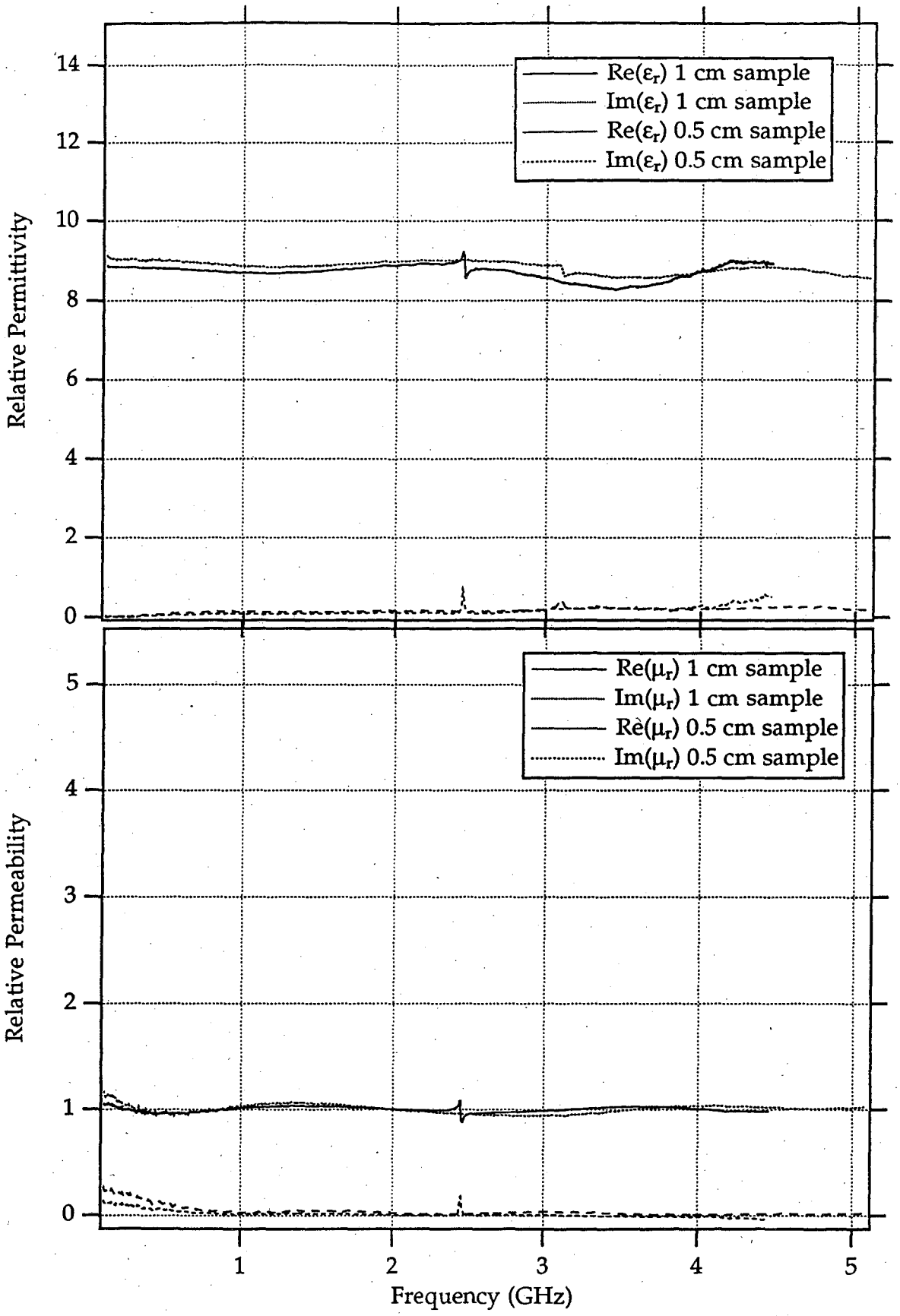

Figure 5. Complex ε_r and μ_r for MgO with 2.4% SiC.

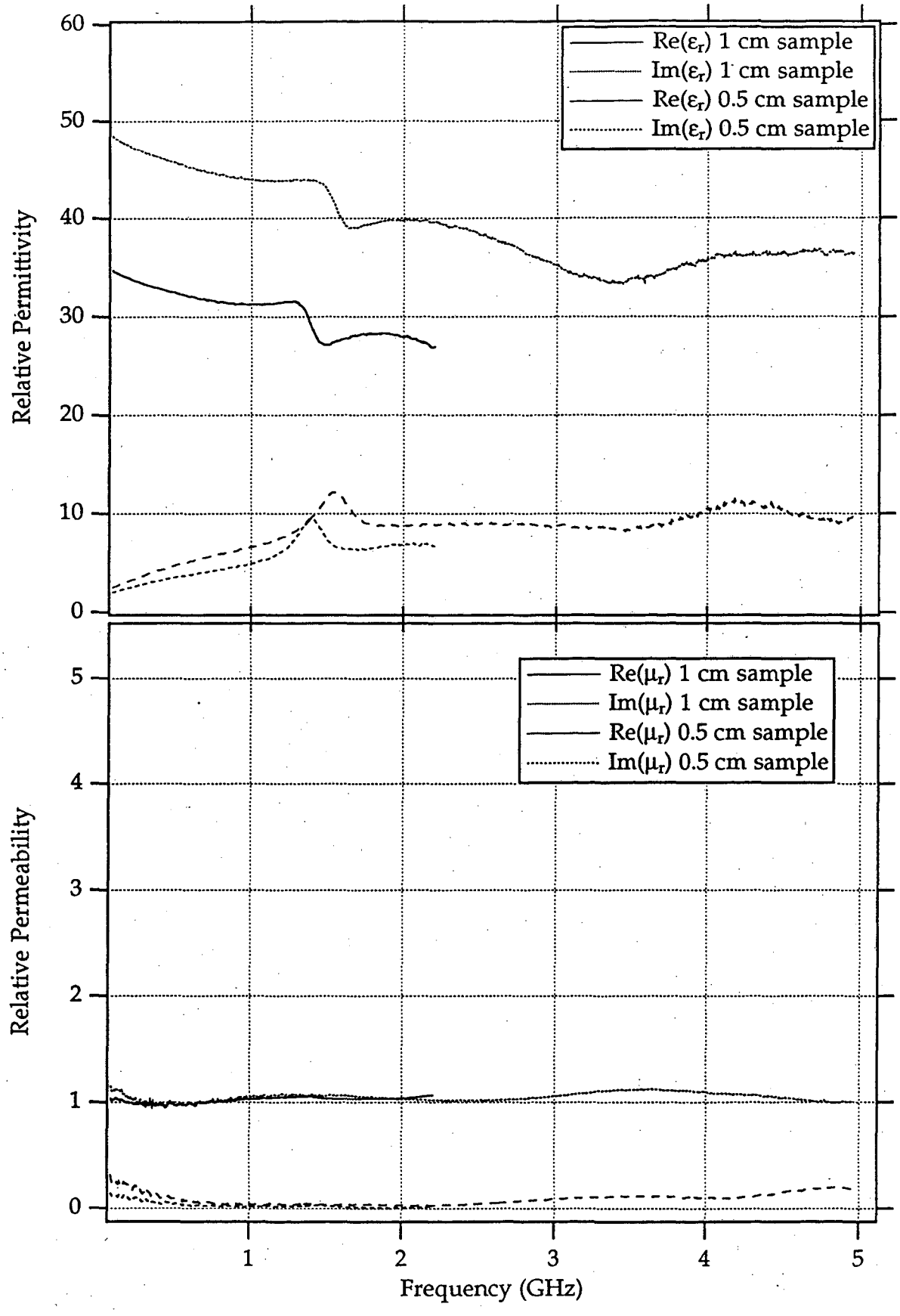

Figure 6. Complex ε_r and μ_r for AlN with 40% SiC.

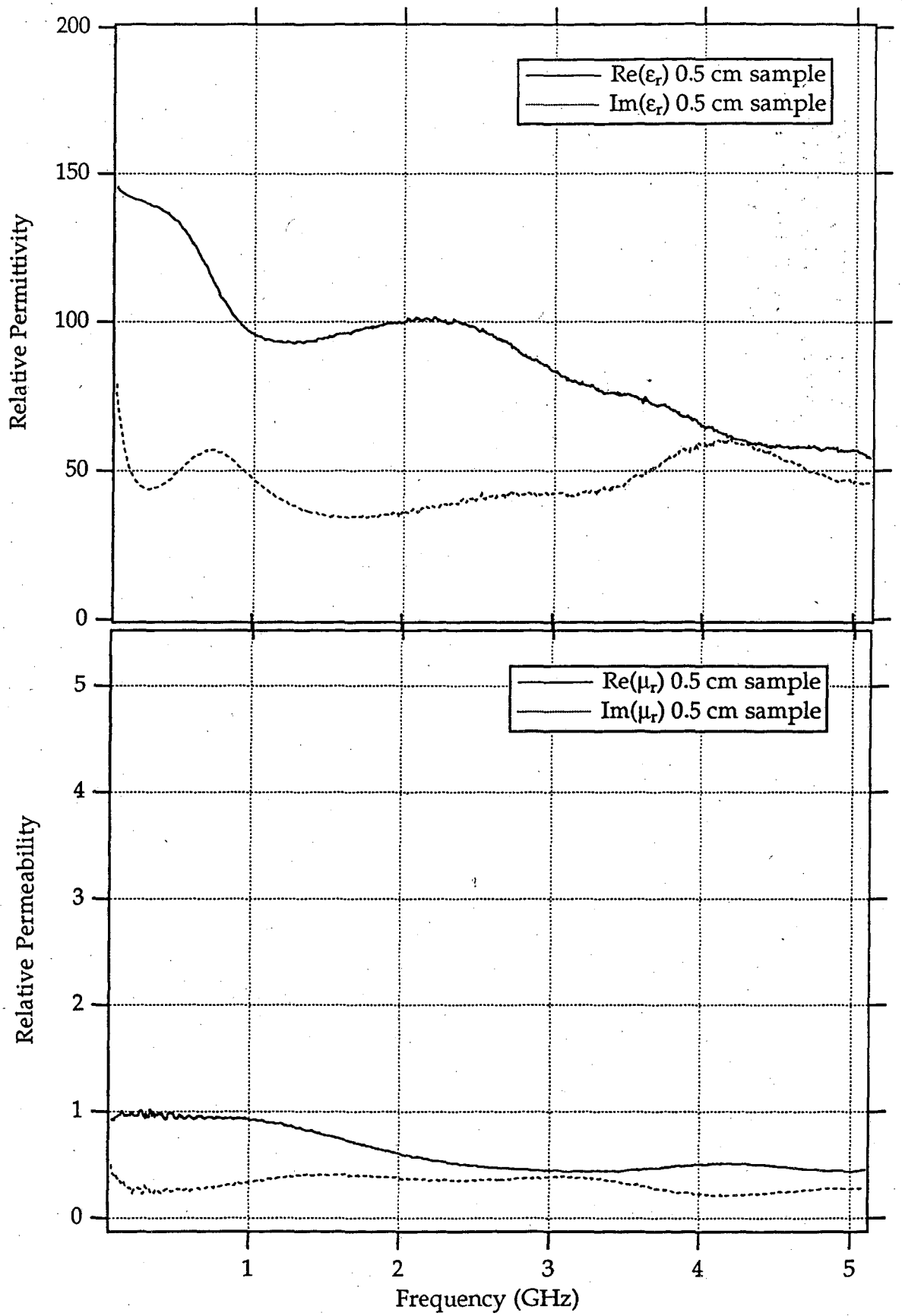

Figure 7. Complex ε_r and μ_r for AlN with 16% TiC.

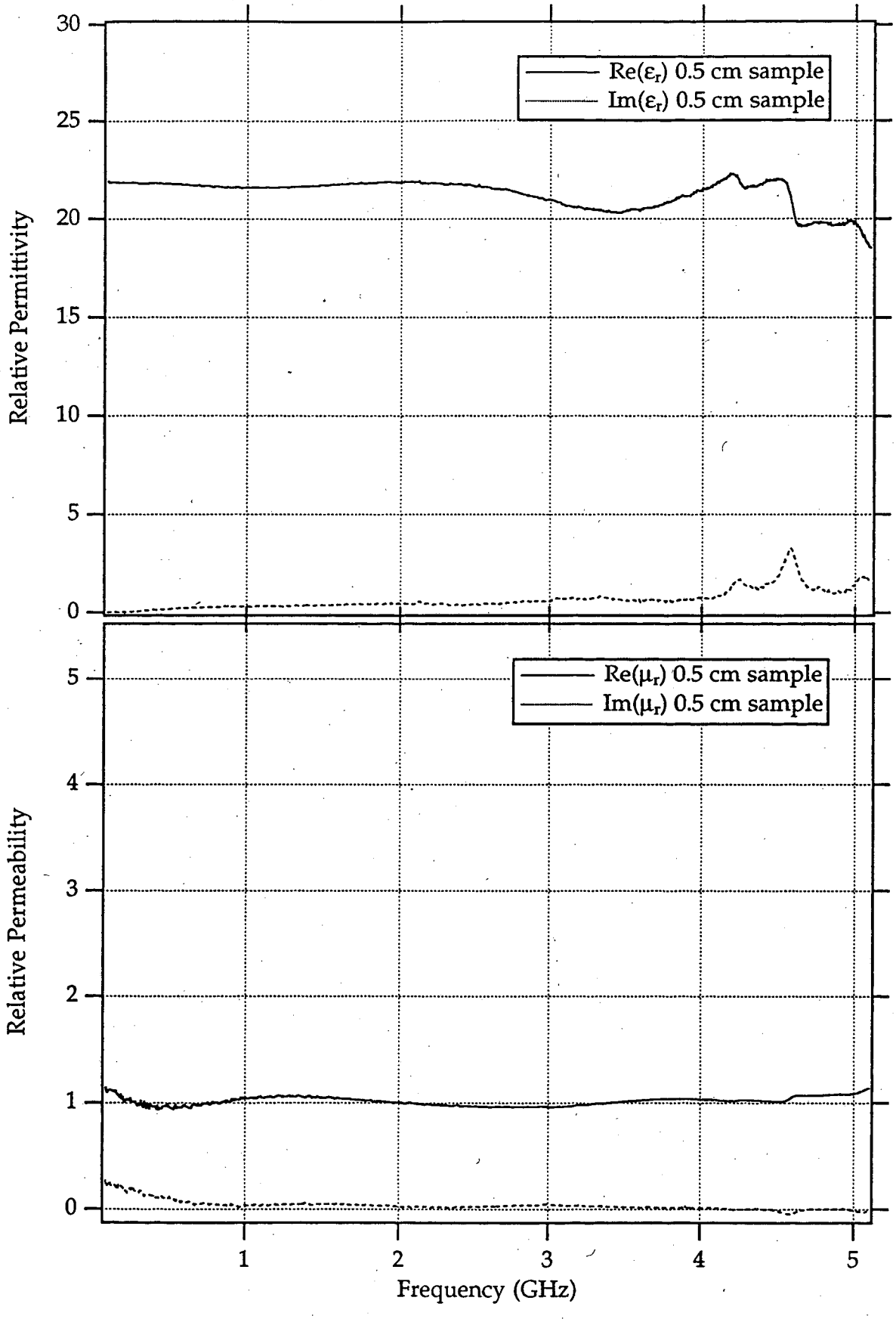

Figure 8. Complex ε_r and μ_r for AlN with 15% Mo.

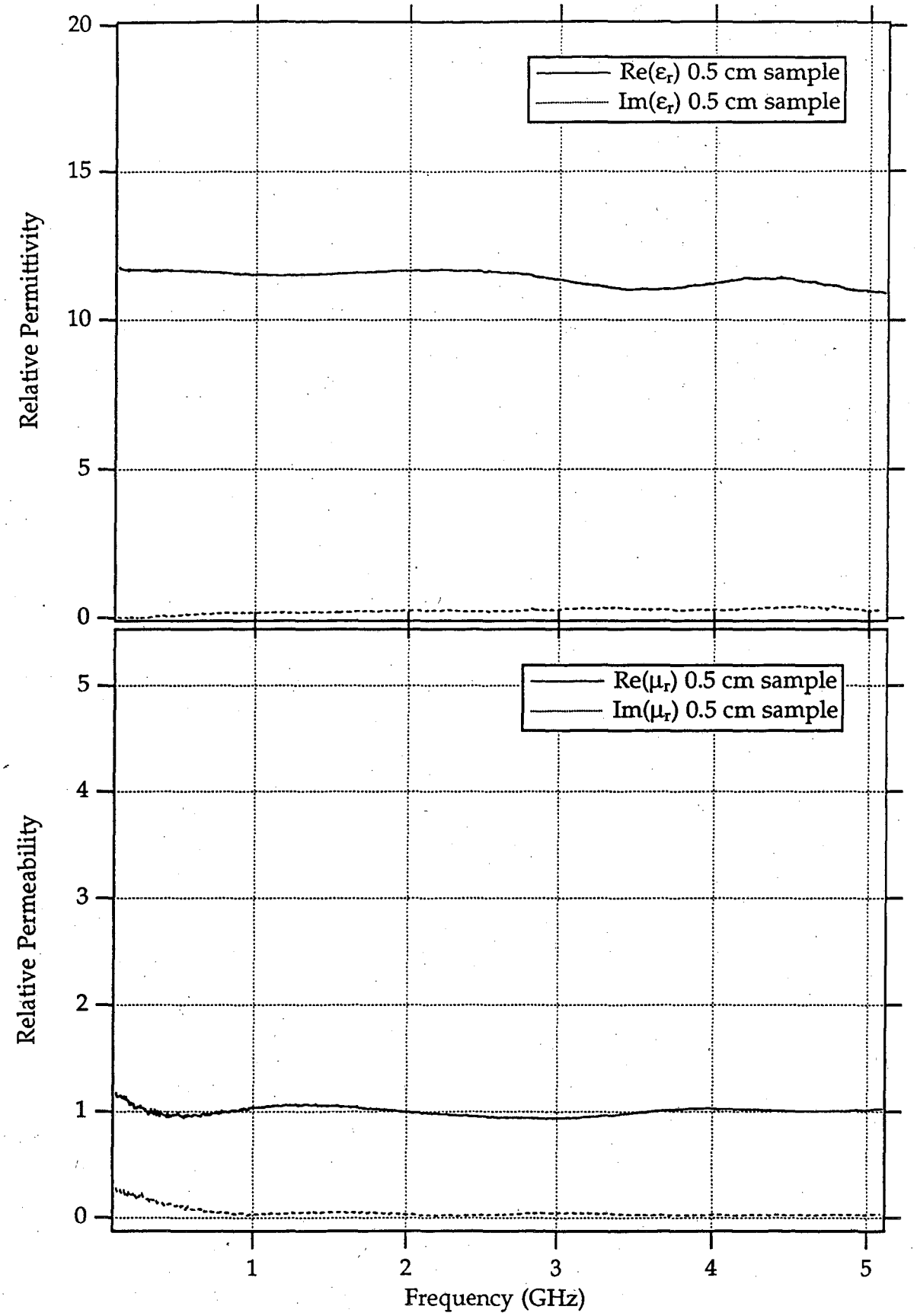

Figure 9. Complex ε_r and μ_r for AlN with 12% Mo.

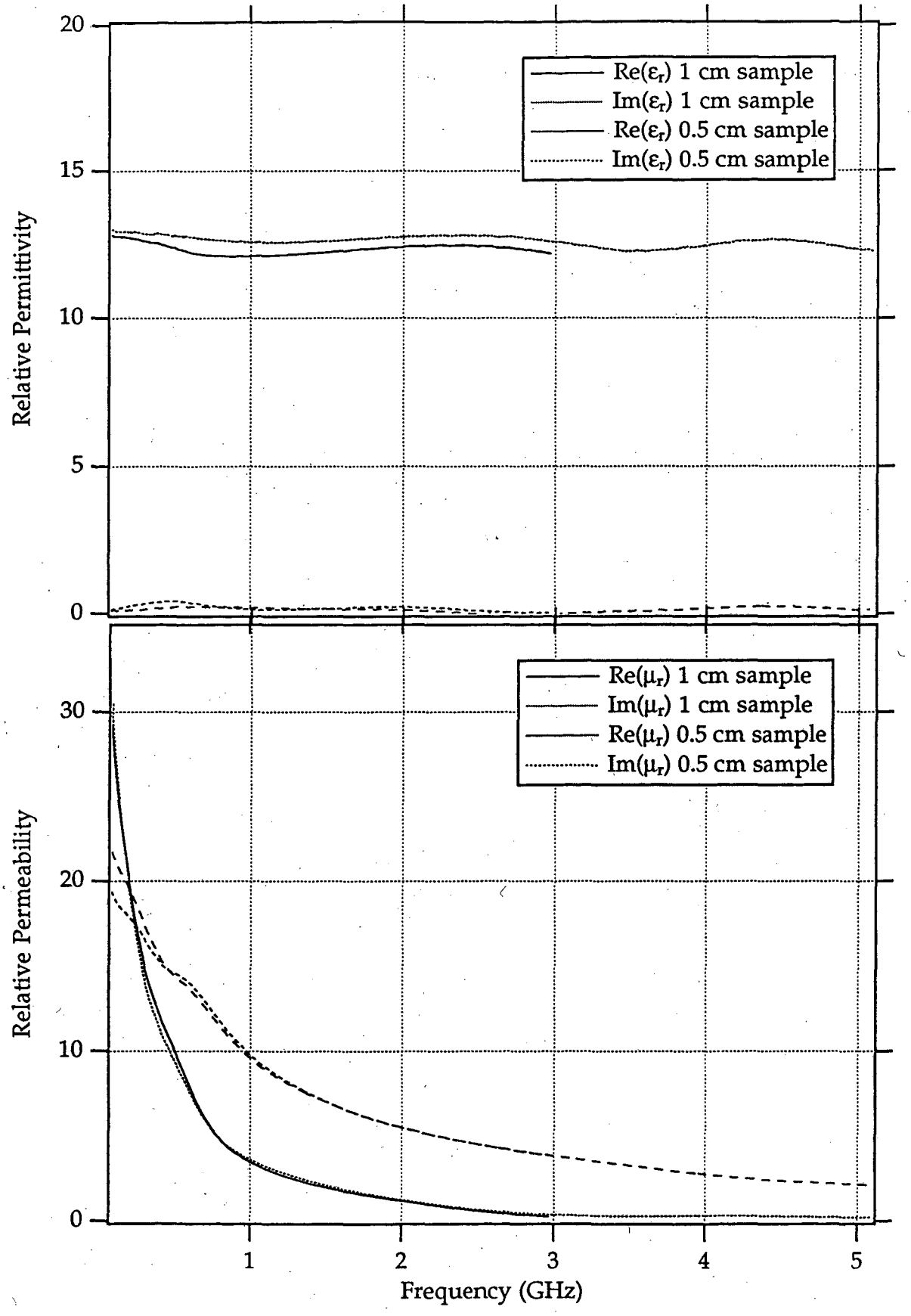

Figure 10. Complex ε_r and μ_r for Trans-Tech TT2-111R.

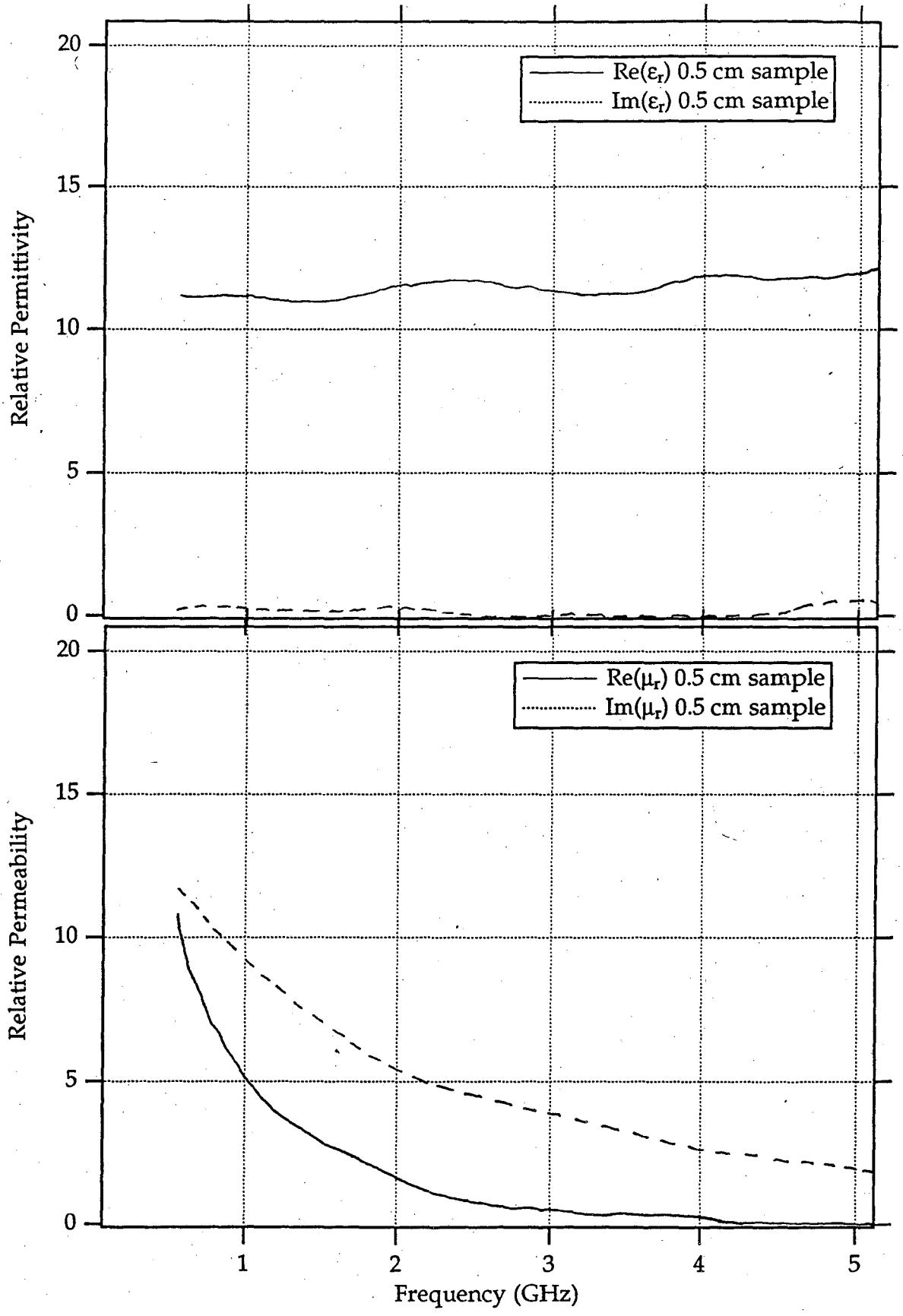

Figure 11. Complex ε_r and μ_r for NZ-51.

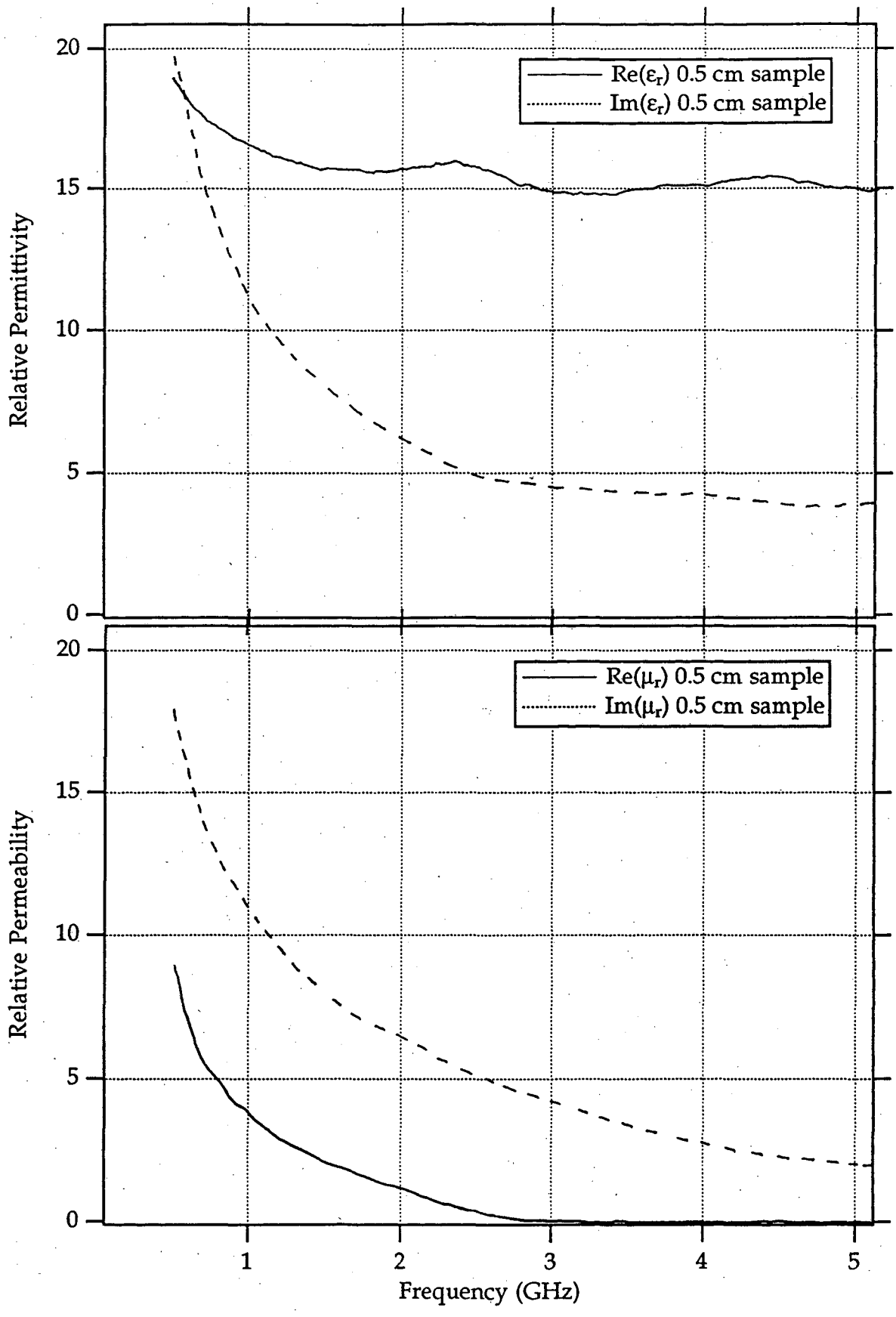

Figure 12. Complex ε_r and μ_r for Ferramic 1928.

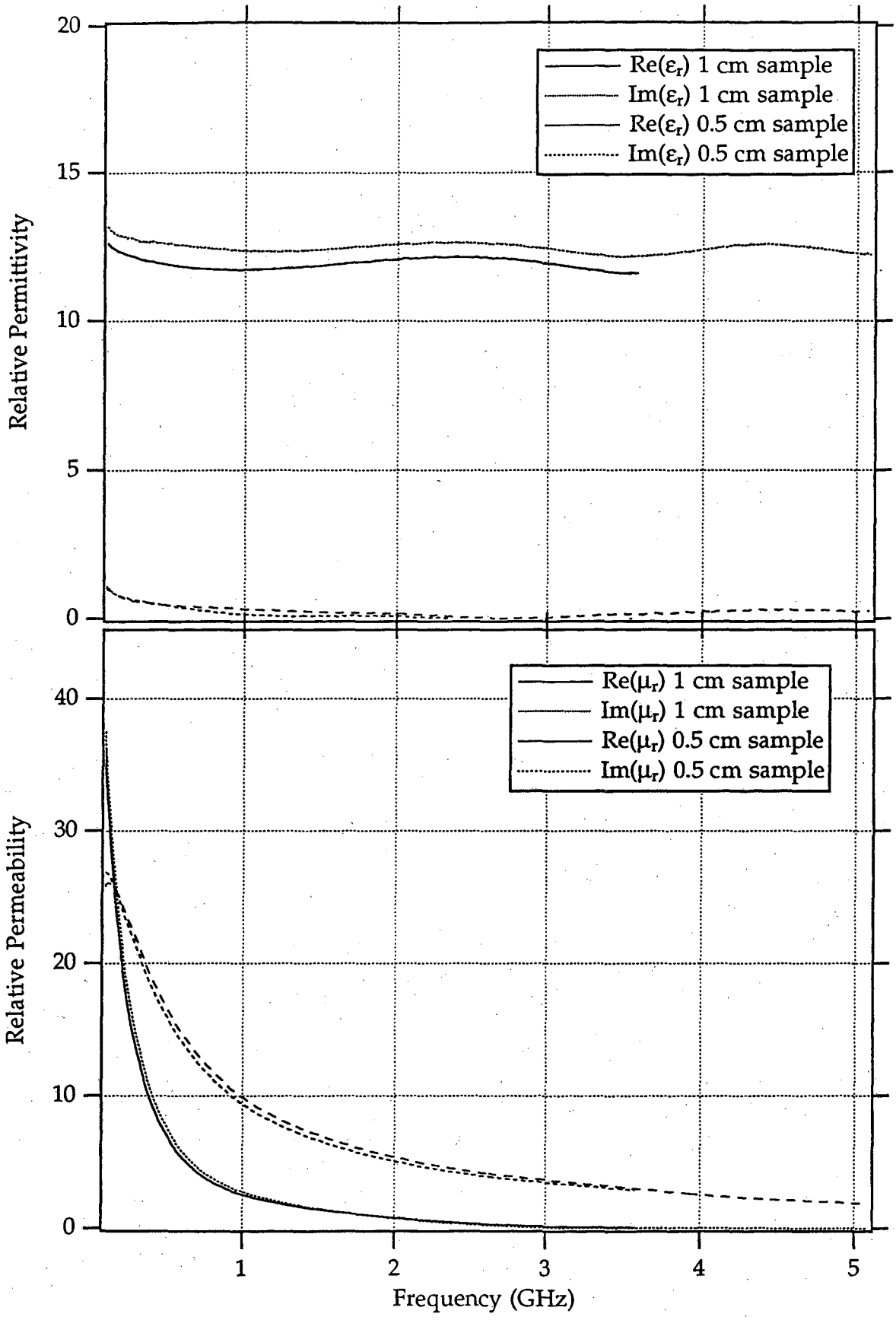

Figure 13. Complex ε_r and μ_r for Ferramic 1927.

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