

MEASUREMENTS OF THE MICROWAVE PROPERTIES OF SOME ABSORBING MATERIALS

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"Our loss is your gain."

INTRODUCTION

Present plans for CESR-B, the proposed upgrade of the Cornell Electron Storage Ring into a B factory, call for superconducting cavities with strongly damped higher-order modes ($Q < 100$).¹ A layer of dissipative material on the inside surface of a large-diameter beam tube is to provide this strong damping, while avoiding harmful interaction with the beam.^{2,3} Several commercially-available microwave-absorbing materials are being considered for this application. To help us choose the right material, we need to predict the mode damping and beam coupling for the possible materials. Such predictions require knowledge of the microwave properties of the materials, which, for the most part, is not available over the relevant frequency range. We decided, therefore, to measure the properties of some of the more promising materials. Eight materials have been measured.

The materials were assumed to be linear (in their response to electric and magnetic fields), homogeneous and isotropic, so that their microwave properties may be described by a complex magnetic permeability μ and a complex electric permittivity ϵ . Since the materials are assumed isotropic, μ and ϵ are scalars, rather than tensors. The permeability and permittivity were measured using the coaxial transmission line technique.⁴ In this paper, we will cover the main points of the theory of the measurement, our experimental methods, the preliminary results of our measurements, and a few interpretations. Details on all aspects of our measurements and a discussion of an improved analysis procedure for materials with known μ or known ϵ may be found in a separate report.⁵ Mode damping calculations and preliminary beam coupling predictions based on our measured μ and ϵ values are also discussed elsewhere.^{2,3}

THEORY OF THE MEASUREMENTS

Some highlights of the theory underlying the measurement technique will now be mentioned. Details may be found in the literature.^{4,6,7} The basic strategy is to fill part of a transmission line with the material, measure the reflection and

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transmission coefficients at the frequencies of interest, and calculate μ and ϵ from these coefficients.

Consider a travelling wave propagating through a coaxial transmission line. We assume that the actual voltage and current are the real parts of complex quantities. When introducing complex quantities, we must choose a sign convention. We will suppose that the time dependence in the complex voltage and current is given by $e^{i\omega t}$, where ω is the angular frequency (the convention used by our network analysers). With this sign convention, we expect the imaginary parts of μ and ϵ to be negative in a microwave-absorbing material.

We can deduce μ and ϵ from the complex characteristic impedance Z of the line and the complex propagation wavenumber k_z :

$$\mu = \frac{k_z Z}{\omega}; \quad \epsilon = \frac{k_z}{Z\omega}. \quad (1)$$

The impedance and wavenumber, in turn, can be deduced from "reduced" transmission and reflection coefficients T and Γ :

$$k_z = \frac{i}{d} \ln(T); \quad Z = Z_0 \frac{1 + \Gamma}{1 - \Gamma}. \quad (2)$$

In (2), T is the complex ratio of the voltages (in a forward-travelling wave) at two planes a distance d apart; Γ is the "single-bounce" reflection coefficient at the interface between a vacuum-filled length of line and a material-filled length of line; Z_0 is the characteristic impedance of the vacuum-filled line (vacuum and air are indistinguishable at the level of precision of our measurements). T and Γ cannot be measured directly, but they can be calculated from the transmission and reflection coefficients S_{21} and S_{11} corresponding to the situation depicted in Figure 1. One can show that

$$\Gamma = \chi \pm \sqrt{\chi^2 - 1}; \quad T = \frac{S_{11} + S_{21} - \Gamma}{1 - (S_{11} + S_{21})\Gamma}, \quad (3)$$

where

$$\chi = \frac{S_{11}^2 - S_{21}^2 + 1}{2S_{11}}. \quad (4)$$

Equations (1) through (4) allow us to deduce μ and ϵ from measured values of S_{11} and S_{21} for a sample of length d inserted into a coaxial line.

A sign choice must be made in (3). This choice determines the signs of k_z and Z (corresponding to two different directions of propagation). However, because μ and ϵ depend only on $k_z Z$ and k_z/Z , the final result is independent of which sign we choose in (3). We chose the sign to make $|\Gamma| < 1$, which should give $\text{Re } k_z > 0$.

A phase ambiguity also arises from the complex logarithm in (2): the imaginary part of $\ln(T)$ is ambiguous by an integer multiple of 2π . This ambiguity reflects the fact that $\text{Re } k_z d$ is the phase change for a wave travelling from $z = 0$ to $z = d$;

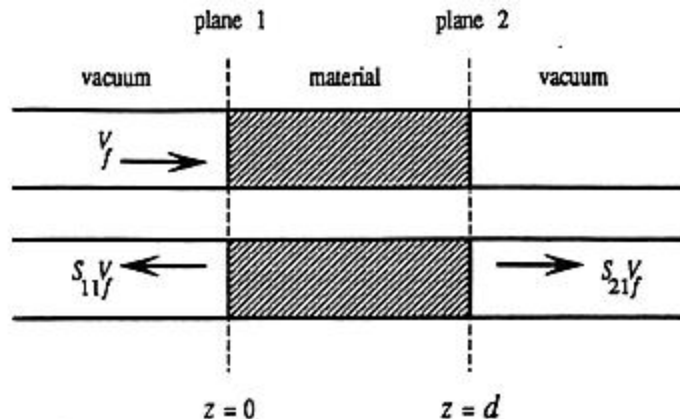


Figure 1. A transmission line filled with a length d of material with vacuum on both sides. A *TEM* wave with complex amplitude V_f is incident from the left; the phases are measured relative to the reference planes (dashed lines).

knowing only T , we cannot deduce the total phase change without knowing the number of whole wavelengths that exist in the length d . We can write

$$k_x d = 2\pi n + i \text{Ln}(T), \quad (5)$$

where $\text{Ln}(T)$ is the "principal value" of $\ln(T)$, whose imaginary part is between 0 and -2π (so that $\text{Re } i \text{Ln}(T)$ is between 0 and 2π), and n is an integer (equal to the number of whole wavelengths that fit in the length d). We can calculate $\text{Ln}(T)$ directly from T , but we need to know n in order to get $k_x d$. Two methods have been used to resolve this dilemma. The first, introduced by Weir,⁴ is, in effect, to determine n by comparing the phase velocity to the group velocity. Since this approach only works for materials in which $\mu\epsilon$ is constant, it is not so useful for our materials, whose properties depend strongly on frequency. The other method, used by Barry,⁷ is to make sure that the sample length is less than the wavelength in the material

$$\lambda_x = 2\pi / (\text{Re } k_x) \quad (6)$$

over the entire frequency spectrum, in which case $n = 0$. In practice, this is a reasonable solution because there are usually maxima in the measurement error near frequencies at which d is an integer multiple of $\lambda_x/2$, so samples shorter than λ_x yield better results. Nevertheless, because we were concerned about reproducibility and needed to look at different sample lengths, we wanted to analyse data with $d \geq \lambda_x$, so we sought another method of determining n .

It is convenient to divide the problem into two parts: (i) What is the correct value of n at the starting frequency in the spectrum? (ii) At what frequencies must we change n as we sweep through the frequency spectrum? Question (ii) is the more straightforward one. We can expect $k_x d$ to be a continuous function of frequency. However, $\text{Re } i \text{Ln}(T)$ will jump from about 2π to about 0 at frequencies

where n increases by 1. We found that the variation in $i\text{Ln}(T)$ with frequency allowed us to easily identify the frequencies at which we needed to change n under most circumstances.

Question (i) is more complicated. We cannot deduce the starting value n_0 of n from measurements on a single sample, since we do not know *a priori* how many whole wavelengths fit in a length d at the starting frequency. The only way to find n_0 in general is through repeated measurements with different sample lengths: if we choose the n_0 's correctly, we expect that $k_z d$ will depend on d but k_z will not. We made guesses for the n_0 's and compared the resulting $\text{Re } k_z$ values for different samples. The choice of $n_0 = 0$ (at 300 kHz) gave consistent results in all cases. It is difficult to rule out all the other possible values of n_0 with this method. However, in the case of ferrite-50, whose microwave properties were measured at 2.4 GHz using the resonator technique (which does not suffer from phase ambiguities) by our colleagues at Chalk River,⁸ we have an independently determined value for $\text{Re } k_z$ which agrees with our choice of $n_0 = 0$.

EXPERIMENTAL TECHNIQUES

Samples of the material to be measured were machined into cylindrical "beads" using diamond-coated tools (all the materials were ceramics). The samples were measured in custom-made 7 mm coaxial air lines. Precision 7 mm connectors were used, as they were found to give less systematic error than type N connectors. The S-parameters of the air line with its material insert were measured from 300 kHz to 20 GHz using two Hewlett-Packard network analysers, an 8753C and an 8720A. All four S-parameters were measured. The analysers were interfaced to an HP 9816 computer; BASIC programs were written to control the S-parameter measurements and analyse the data.

The network analysers were calibrated using the standard "full 2-port" procedure. The reference planes were extended to the faces of the sample using the analysers' port extension feature and the known lengths of the air line and sample. The sample location inside the air line could not be controlled very well because of the spring-loaded centre conductor; to ensure that the reference planes coincided with the faces of the sample, the phases of S_{11} and S_{22} were compared after extending the ports and the port extensions were adjusted to eliminate any systematic phase differences.

In order to get reproducible results, we found it necessary to machine the samples to relatively close tolerances and further improve the contact between the sample and air line with a layer of liquid metal. We used a eutectic alloy of gallium and indium with a melting point of 16°C. Filling the gaps between the sample and the air line without coating the faces of the sample with metal or leaving drops of liquid metal in the air line proved to be a difficult technique to master, so we would not call this an ideal solution.

To check the validity of our techniques, some dielectric materials were measured. These measurements were done in commercially-made air lines without

Table I. Characteristics of the absorbing materials.

Material	Manufacturer	Type	DC Resistivity [Ωm]
Ferrite-50	Trans-Tech	Nickel-zinc	0.25 $^{+0.75}_{-0.15}$
TT2-111-series	Trans-Tech	Nickel-zinc	8 to 10^5
CMD10	Ceramic Magnetics	Nickel-zinc	10^5
IB-004	TDK	Manganese-zinc	
MN60	Ceramic Magnetics	Manganese-zinc	2
MN67	Ceramic Magnetics	Manganese-zinc	1.5
MN80	Ceramic Magnetics	Manganese-zinc	2
Al-N-C	Ceradyne	Non-ferrite ^a	

^aglassy carbon in aluminum nitride

liquid metal. The results suggest that our measurement techniques are valid, but sensitive to the fit between the sample and air line, and susceptible to large errors for some combinations of sample length and wavelength.

RESULTS

Selected information for the materials we measured is given in Table I. There is significant variation in the properties of the TT2-111-series material, primarily due to the interest in higher DC conductivity that we expressed to the manufacturer. The TT2-111-series measurements presented herein were done on a batch with a stated DC resistivity of $435 \Omega\text{m}$, which we designate "TT2-111V" (the manufacturer's designation for all varieties is TT2-111R). The variation in properties of ferrite-50 batches we received was less extreme (stated DC resistivities ranged from 0.14 to $0.50 \Omega\text{m}$).

The μ and ϵ values were measured with liquid metal for two or more samples of different length (ranging from 0.8 to 10.9 mm) for each material. In almost all cases, different samples of the same material were machined from the same piece. We tried to choose the sample length d to minimise the error in our μ and ϵ values. We followed the usual strategy for choosing d , a rationalisation for which can be found elsewhere.⁶ Briefly stated, the strategy is to (i) avoid having d close to an integer multiple of $\lambda_z/2$ (which produces a minimum in S_{11} and a maximum in S_{21}) and (ii) avoid having $\lambda_z \gg d$. Constraint (i) is not as important in absorbing materials as it is in low-loss materials. As a rule of thumb, we tried to satisfy the following condition:

$$\frac{\lambda_z}{8} \leq d \leq \frac{3\lambda_z}{8} \quad (7)$$

The choice of $\lambda_z/8$ was rather arbitrary (and difficult to adhere to). We used (7) to choose the "best" sample length for each frequency in the spectrum, dividing the spectrum into several ranges. Forward (from S_{11} and S_{21}) and reverse (from S_{22} and S_{12}) values were treated as independent in order to get some indication of the accuracy.

Our results for ferrite-50 are shown in Figure 2. Values measured at 2.4 GHz using the resonator method⁸ are also shown. The resonator results agree relatively well with ours. The measured values of $\text{Im } \epsilon$ are close to what one would expect from the DC resistivity for purely Ohmic losses.

Results for TT2-111V, CMD10, and IB-004 are shown in Figure 3. Both the real and imaginary parts of ϵ are quite a bit smaller than in ferrite-50. Barry⁷ has measured the properties of NZ-51 material from Emerson & Cuming, which is said to be similar to the TT2-111-series material; our results for TT2-111V are quite close to his. In TT2-111V, $\text{Im } \epsilon$ appears to be Ohmic at low frequencies. In CMD10 and IB-004, $\text{Im } \epsilon$ is small enough to make it difficult to measure with this technique. For the ferrites shown in Figure 3, we approach full transmission ($S_{11} = 0$ and $S_{21} = 1$) at low frequencies, which amplifies the error in the results. Fortunately for us, the rapid increase in μ and ϵ as the frequency decreases prevents λ_z from increasing as fast as it would ordinarily, thereby giving us better results at low frequencies than we might otherwise expect.

Results for the MN ferrites are shown in Figure 4. There is significant noise in the measured values at higher frequencies, particularly in the real parts of μ and ϵ . It is clear, nevertheless, that all components except $\text{Im } \epsilon$ are much larger than for the other ferrites. The MN ferrites provided a more challenging measurement, because $|\Gamma|$ was close to 1 over a large frequency range, which made $|S_{21}|$ small and the error in k_z large. Reducing the sample length and averaging many measurements helped reduce the noise.

Results for the Al-N-C material are shown in Figure 5. Low-frequency errors are especially pronounced in the results because μ and ϵ are much smaller (compared to the ferrites) at low frequencies; good low-frequency measurements for this material would require much longer sample lengths. Discounting the low-frequency effects, it is difficult to say much about μ except that $\mu \simeq \mu_0$ to the accuracy of the measurement.

DISCUSSION

The measured values of μ and ϵ in the ferrites show features that might be considered extreme: significant variation with frequency, large values at low frequencies (μ/μ_0 and ϵ/ϵ_0 as large as 10^6), and very small values at high frequencies in some cases, with $\text{Re } \mu/\mu_0$ sometimes less than 1. Nevertheless, all of these features have been seen in previous measurements of nickel-zinc ferrites.⁹

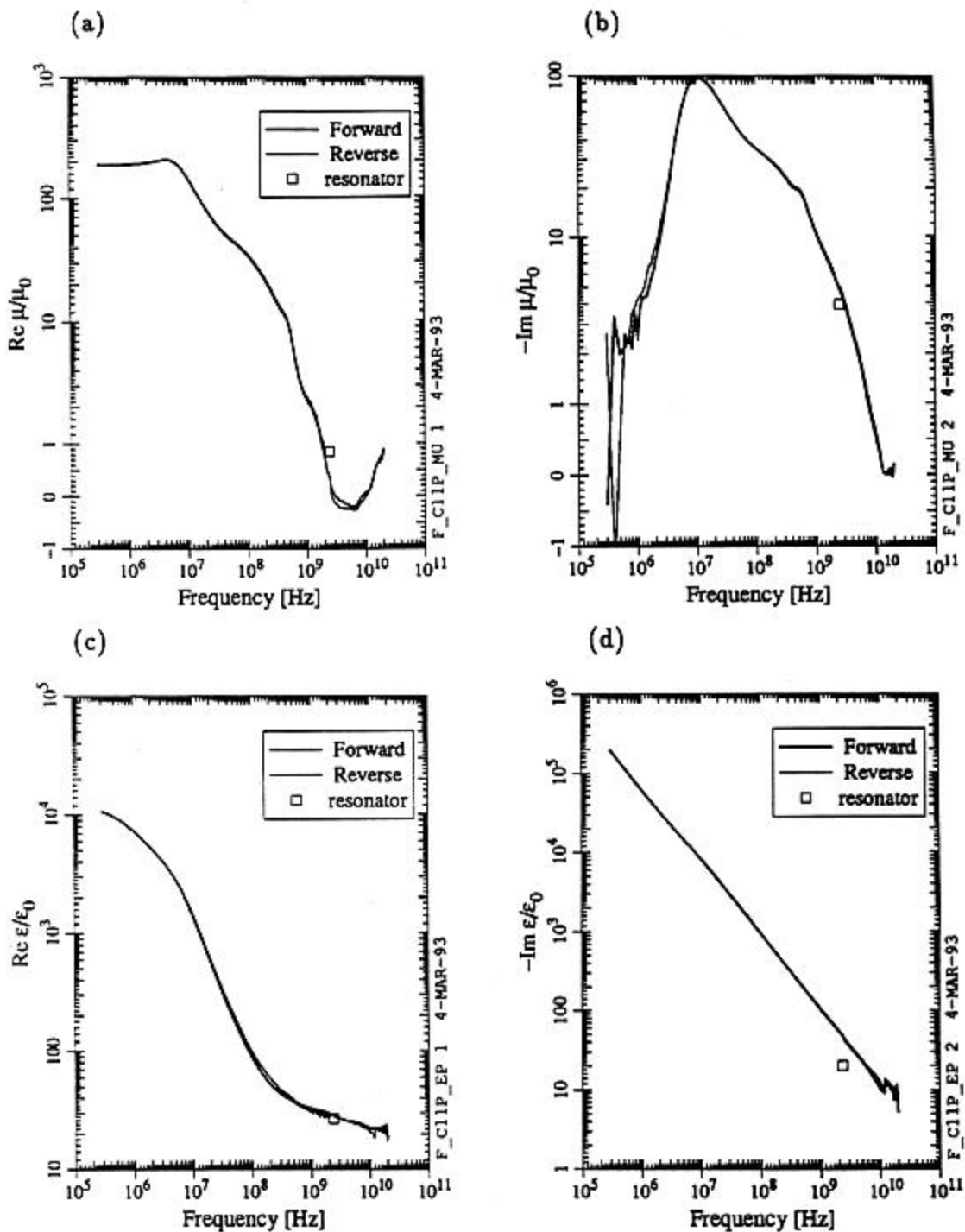


Figure 2. Measured values of (a) the real part of μ , (b) the imaginary part (times -1) of μ , (c) the real part of ϵ , and (d) the imaginary part (times -1) of ϵ for ferrite-50. Values measured using the resonator method⁹ are also shown.

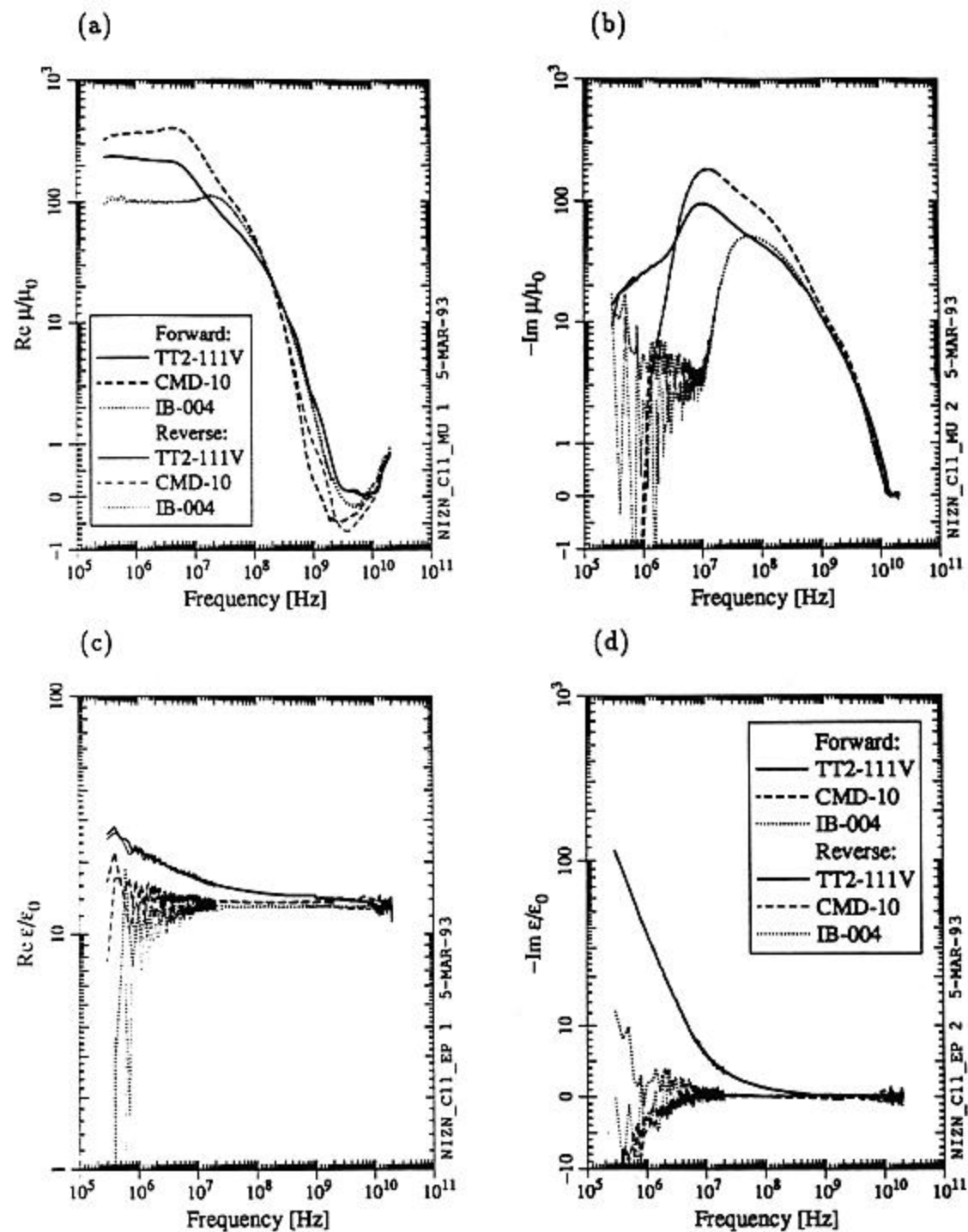


Figure 3. Measured values of (a) the real part of μ , (b) the imaginary part (times -1) of μ , (c) the real part of ϵ , and (d) the imaginary part (times -1) of ϵ for TT2-111V, CMD10, and IB-004 ferrites.

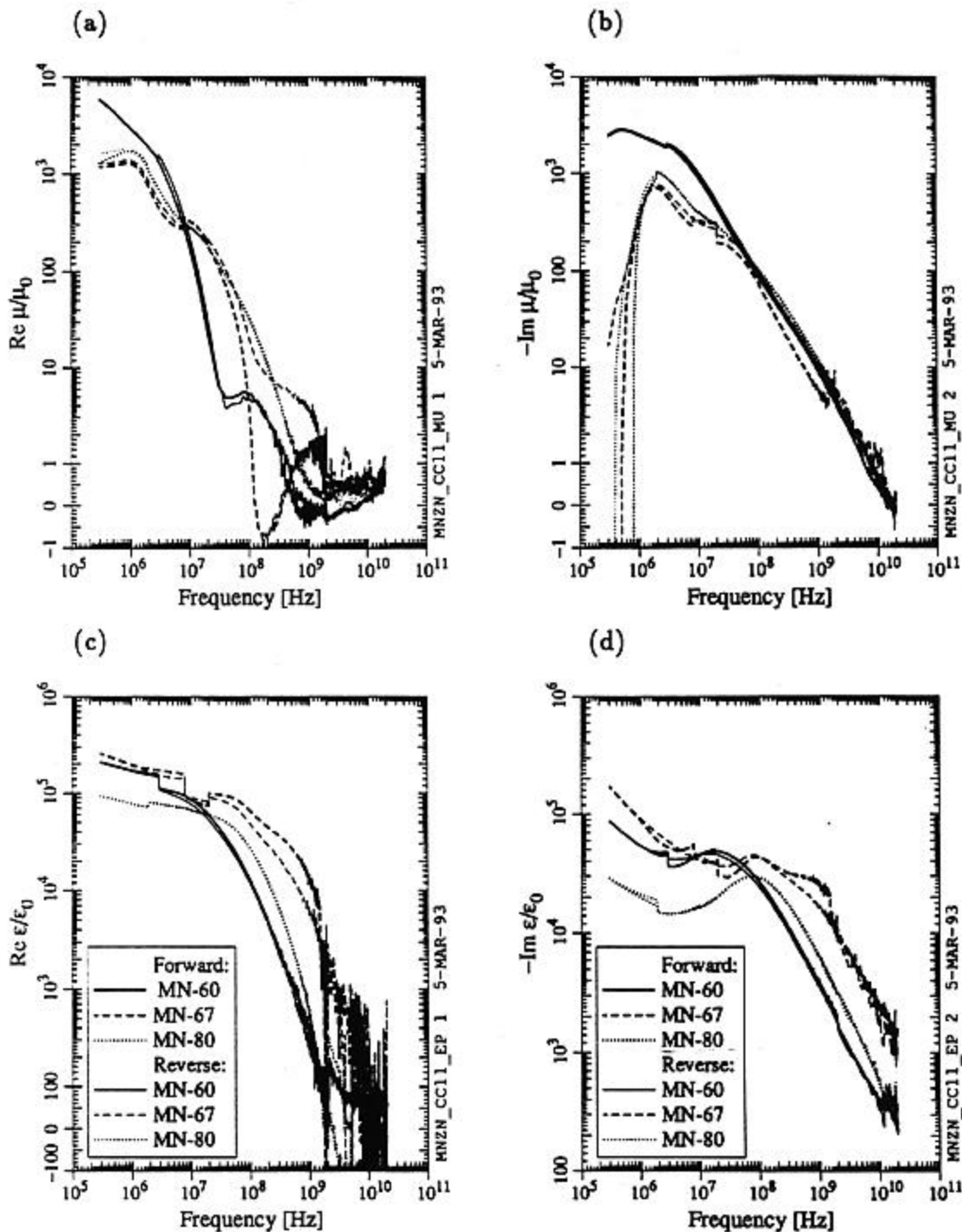


Figure 4. Measured values of (a) the real part of μ , (b) the imaginary part (times -1) of μ , (c) the real part of ϵ , and (d) the imaginary part (times -1) of ϵ for MN60, MN67, and MN80 ferrites.

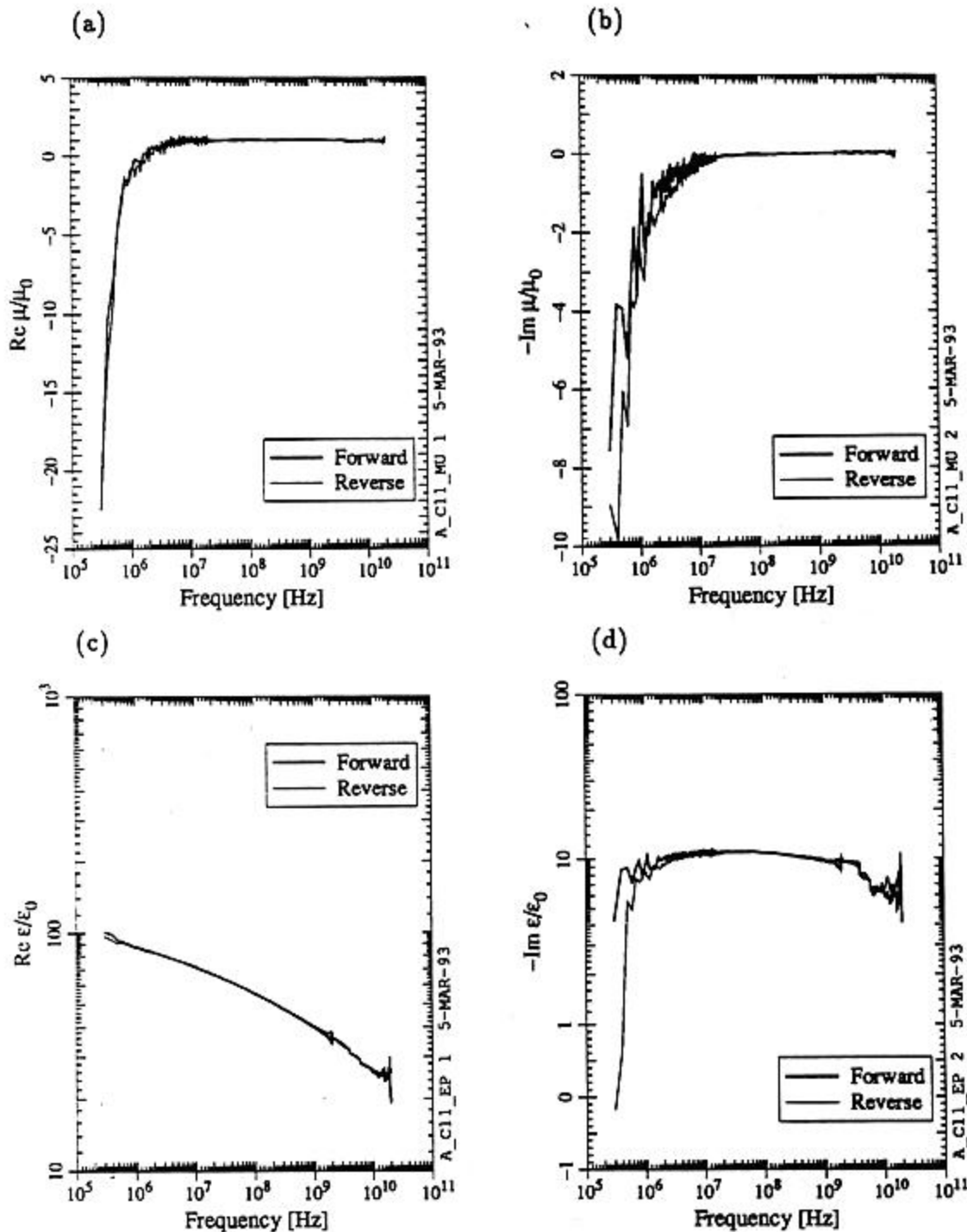


Figure 5. Measured values of (a) the real part of μ , (b) the imaginary part (times -1) of μ , (c) the real part of ϵ , and (d) the imaginary part (times -1) of ϵ for the Al-N-C material.

The Influence of Air Gaps. Measurements were done on ferrite-50 and TT2-111-series ferrite to evaluate the effect of air gaps. Three cases were examined: (i) samples machined without tight tolerances, which fit loosely inside the air line, (ii) samples with tighter tolerances, which fit snugly inside the line, and (iii) samples with slightly relaxed tolerances, but with liquid metal present in the gap between the sample and air line. The ϵ values changed dramatically between different cases in ferrite-50 and less dramatically in the TT2-111-series ferrite; the effect was most pronounced for the largest ϵ values. The reproducibility of the ϵ results was found to improve in going from method (i) to method (iii). Very little change in μ values was seen.

A simple DC analysis can provide a qualitative explanation for these observations. In the static limit, k_z and Z are determined by the inductance per unit length L' and the capacitance per unit length C' . In the case of a coaxial line that is completely filled with material, as assumed in the standard analysis, L' and C' are proportional to μ and ϵ , respectively. If there are air gaps between the material and the air line, however, the proportionality is no longer exact: extra terms appear which depend on the gap size. The correction term for μ is always small as long as the gaps are small compared to the inner and outer conductor radii a and b and as long as μ is not small compared to μ_0 . Thus we can expect that air gaps will not have a strong influence on measured μ values under most circumstances. The correction term for ϵ , on the other hand, is small if the gaps are small compared to a and b and ϵ is not large compared to ϵ_0 . If ϵ/ϵ_0 is an appreciable fraction of a (or b) divided by the gap length, we can expect a significant correction due to the air gaps. These conclusions are qualitatively consistent with our observations.

Reproducibility. Small steps can be seen in the values shown in Figures 2, 3, and 5; larger steps are evident in Figure 4. These occur when we change our choice of sample. Differences between the results for different samples can give us some clues about the reproducibility of the measurements. The worst reproducibility was seen in the MN ferrites, particularly MN60 and MN67. To illustrate, measured values of $\text{Re } \mu$ for four MN67 samples are shown in Figure 6a. There are significant differences in $\text{Im } \mu$ and in ϵ also. It would be worthwhile to do some more measurements on the MN ferrites to see whether better reproducibility can be found. Better reproducibility was seen in the other ferrites. For example, results for $\text{Im } \mu$ for three ferrite-50 samples are shown in Figure 6b. The results for other nickel-zinc ferrites show more prominent spikes (occurring when d is an integer multiple of $\lambda_z/2$) and more noise at low frequencies (when $d \ll \lambda_z$); for TT2-111V, we also see more variation in $\text{Im } \epsilon$.

To identify the source of this irreproducibility, three measurements on TT2-111V were compared: (i) a first measurement on a short sample, (ii) a second measurement on the same sample, done after removing and re-applying the liquid metal, and (iii) a measurement on a second sample of about the same length. The

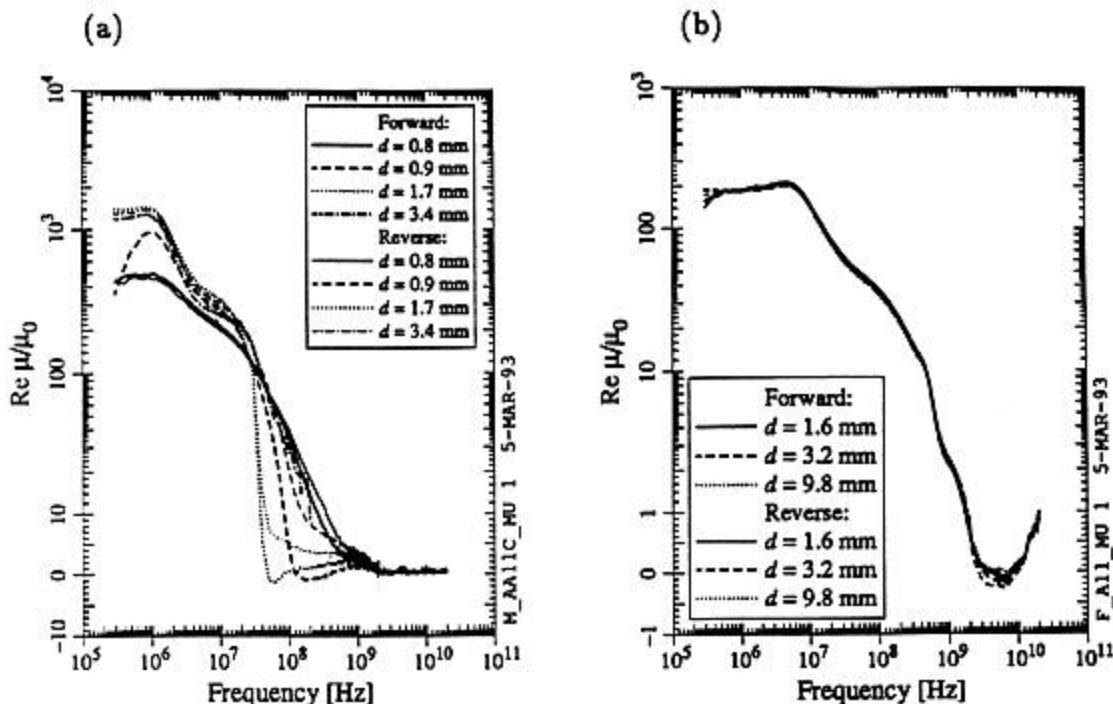


Figure 6. Measured values of the real part of μ , for (a) four MN67 samples and (b) for three ferrite-50 samples of different length. For MN67, values above 1500, 800, and 200 MHz are omitted for sample lengths of 0.9, 1.7, and 3.4 mm, respectively.

μ results for the three cases do not show much difference, but the two measurements of ϵ on the first sample agreed significantly better with each other than they did with the measurement on the second sample. Similar agreement between repeated measurements on a longer sample was also seen. This suggests that the reproducibility problems stem mostly from variation in the properties or the machining from one sample to another. The sample faces were touched up with a hand-held grinding wheel to remove the chip from the final saw cut, which might account for some of the problems we see.

CONCLUSION

The coaxial transmission line method seems to be adequate for the measurement of microwave properties of the absorbing materials we have examined, if precautions are taken to eliminate air gaps. We cannot accurately measure real or imaginary parts of μ or ϵ that are close to zero with this method, however. The biggest problem with the measurements we have done so far is the lack of reproducibility between different samples. Our results are in reasonable agreement with the measurements we have seen in the literature.

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