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Intercomparison of Permeability and Permittivity Measurements Using the Transmission/Reflection Method in 7 and 14 mm Coaxial Air Lines

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We discuss a measurement intercomparison, designed as a follow-up to that reported by Vanzura et al. In this effort, 13 participants performed broadband (3 MHz to 10 GHz) measurements of the magnetic and dielectric properties of five different ferrite samples using the transmission/reflection (TR) method in 7 and 14 mm diameter coaxial air lines. Agreement within ±5 percent was obtained for the measured permeability data for frequencies between 50 and 100 MHz. However, consistent with the findings of the earlier study, significant variability (±15 percent) was found to exist in the permittivity data, due to air-gap effects.

Key Words: coaxial air line; dielectric properties, ferrites; intercomparison; magnetic properties; materials; measurements; microwaves

1. INTRODUCTION

As part of a major effort to assess the national quality of RF electromagnetic properties of materials measurements, the National Institute of Standards and Technology (NIST) has organized a number of national measurement intercomparisons involving industry and government laboratories. For these, it is obviously necessary to select a well-known and standardized measurement technique that potential participants are familiar with and for which they have ready access to needed fixtures, instrumentation, and operating software. The T/R method in coaxial air lines is a well-known technique that has been implemented in many laboratories for the broadband characterization of medium-to-high loss materials in the RF-microwave spectrum. It has recently been documented as a standardized measurement method by ASTM [1].

In this method, a toroidal sample of the material under test is precisely machined to the air line's dimensions and positioned inside the line. Transmission line scattering parameters, both reflected and transmitted, are then measured over a broad frequency range, usually by means of an automatic network analyzer (ANA). Data on the complex relative permittivity, $\epsilon_r^* = \epsilon_r' - j\epsilon_r''$ and permeability, $\mu_r^* = \mu_r' - j\mu_r''$ are derived from measured scattering parameter data using various available reduction algorithms [3-6] (see section 3, below).

The coaxial air line method was selected by NIST for use in two separate measurement intercomparisons that have been conducted over the past six years. In the first study, 11 participants, including NIST, measured the complex permittivity of five different bulk low-loss dielectrics with ϵ_r' ranging from approximately 6.8 to 50. This study, which was completed in 1993 and has been reported on by Vanzura et al. [2], was primarily intended to compare measurements of ϵ_r', the real part of ϵ_r^*. However, participants were also asked to measure the imaginary part, ϵ_r''. The ready availability of very accurate reference data obtained using the NIST 60 mm diameter cylindrical cavity [6] at X-Band frequencies (7 to 11 GHz) was the primary reason that NIST selected low-loss dielectrics for use in this study. The cavity data provided a very accurate reference against which the coaxial line data could be compared.

The dielectric study did not provide a very satisfactory comparison of dielectric loss data, ϵ_r'' [2, § IV B] nor did it include any measurements of complex permeability. It is well known that characterization methods based on transmission line measurements cannot satisfactorily measure the dielectric loss of low-loss materials ($\epsilon_r'' < 0.05$) due to the low-Q characteristics of transmission line structures and resulting loss measurement insensitivity. Consequently, measured ϵ_r'' data for the low-loss dielectric samples were not very meaningful. NIST did include two medium-loss glass materials, with $\epsilon_r'' \geq 0.05$, in this study. Measurements of these did, therefore, provide some more meaningful comparisons of ϵ_r'' data. However, one of these materials (No. 2, lead-oxide glass) proved to be unreliable owing to problems of inhomogeneity and sample-to-sample variability. Such variability is a problem in any measurement intercomparison that involves multiple samples of the same material.

Because of the inadequacies in the first study, detailed above, NIST sought to organize a follow-up study involving both complex permeability and permittivity measurements of some bulk polycrystalline ferrites, using exactly the same measurement methodology. These materials, in their demagnetized state, exhibit medium-to-high magnetic loss at frequencies below gyromagnetic resonance, which for most ferrites is at nonrnicrowave frequencies less than 1 GHz. In this region, the coaxial air-line technique is well suited to the characterization of ferrites, so such a measurement intercomparison should produce more meaningful results. At microwave frequencies above 1 GHz, near or above gyromagnetic resonance, most demagnetized femtes exhibit only weak intrinsic permeability properties ($\mu_r' < 1$) with correspondingly low magnetic losses. Because of these factors, NIST deliberately tried to emphasize measurements at low frequencies. This is the reason that participants who possessed a low-frequency ANA were requested to perform their measurements over the frequency range 3 MHz to 3 GHz. Those who did not have this type of ANA available were requested instead to perform measurements over the range 50 MHz to 10 GHz, using the more commonly available high-frequency ANA.

The materials used in this study are summarized in Table 1. As in the earlier study, the composition of the samples was not disclosed to the participants until after the study was completed. For this study, there were 10 participants who had also taken part in the dielectric study, plus 4 new participants. NIST experience with all of these materials has shown that significant variability can exist from sample to sample, so a decision was made at the start of this study that only one kit, containing 7 mm diameter samples, would be circulated amongst participants, rather than the three used in the dielectric study. Thirteen participants, who were anonymously coded by the letters "A"

Table 1. Compositions of intercomparison ferrites with nominal permeability and permittivity properties as specified by their suppliers.

Material	Composition	μ_r'	μ_r''	ϵ_r'	ϵ_r''
1	Yttrium iron garnet, M_S = 142 kA/m	134 at 1 kHz		15 ± 5%	0.003
2	Nickel-zinc ferrite (Manufacturer A)	800 at 1 MHz	77 at 1 MHz		
3	Ferrite-loaded polymer	3.0 at 1 GHz	0.39 at 1 GHZ	17 at 1 GHz	1.2 at 1 GHz
4	Lithium ferrite, M_S = 135 kA/m	94 at 1 kHz		17 ± 5%	0.0085
5	Nickel-zinc ferrite (Manufacturer B)	1.2 at 1 GHz	12 at 1 GHz	19 at 1 GHz	8.2 at 1 GHZ

through" P, took part in measuring the 7 mm kit; usable data were obtained from **12** participants, including NIST, and are intercompared in Section **4.**

As the study progressed, it soon became apparent that having only one kit in circulation was unnecessarily impeding the progress of the study. NIST also happened to have available some **14** mm diameter coaxial samples in materials 1, 2, 3, and 5, which had been prepared for other investigations. In an attempt to speed up the progress of the study, we decided to circulate an additional kit containing these **14** mm samples to a few select laboratories who have the capabilities to perform measurements in a **14** mm coaxial transmission line. A secondary objective for using 14 mm diameter lines was to determine whether this improved measurement accuracies at all. Five participants (A, C, I, M, P) including NIST, took part in measuring the **14** mm kit, of which three (A, C, I) also measured the 7 mm kit. However, some of these were unable to perform measurements because the samples did not fit inside their 14 mm coaxial air line; this was true.of all samples for Participant I and of samples 3 and 5 for Participant C. Details regarding the circulation of the two sample kits among the participants are given in Section **2.**

Together with the sample kit, each participant received a cover letter of invitation plus measurement guidelines giving recommended procedures for performing measurements and reducing and reporting data, along with a data sheet that participants were asked to fill out. The data sheet was used to record information on the condition of the samples received, ANA configuration, details of ANA calibration used, air-line **dimensions,** laboratory environment, file names, and details of algorithm used for data reduction, as well as sample dimensions and method of gap correction used, if any (see Section 3B).

One of the key findings of the dielectric intercomparison [2] is that much of the variability seen in permittivity measurements can be attributed to whether or not participants corrected for the presence of air gaps between sample and air-line conductors. Hence, during this study, we tried to make participants more aware of this important issue by bringing it to their attention in the invitation letter and by including updated **NIST** data on sample dimensions in the participant data sheet (see Section 2). Participants were urged to measure the dimensions of their air-line fixtures and to repeat those for the samples, if possible, in order to develop their own air-gap estimates and correct for these. Many investigators, who use the coaxial **air-line** method, have avoided the need for air gap correction by using conductive fillers in the air gap. This works well, particularly for high-permittivity materials. However, because the intercomparison samples are porous and because the fillers contain emulsifiers that will migrate into the pores, participants were requested to refiain fiom using such fillers during this study.

2. INTERCOMPARISON SAMPLES

The five ferrite materials selected for use in this study are well known to NIST and have already been extensively characterized using various techniques. They are of possible interest to NIST as **future** RF magnetic reference materials. These materials are supplied in the form of tiles, bar stock, or cylindrical slugs that have been pressed and fired by the femte supplier. The 7 **mm** and **14** mm diameter toroidal samples were machined fiom these by a NIST subcontractor.

At the beginning of the study and **after** each round of measurements by a participating laboratory, the samples were **carefully** inspected by NIST personnel, replaced or **refaced** if necessary, dimensionally **remeasured** and then **recharacterized**. Sample replacement or **refacing** was necessitated by breakage and cumulative damage that occurred in these very brittle materials during the course of measurements by both participants and NIST. Following the fifth round of 7 mm kit measurements, both Samples 1 and **4** were found to be broken. NIST was able to replace Sample 1, but had no material on hand **from** which to prepare a replacement for Sample **4.** When we were informed by the **ferrite** supplier that several weeks lead time would be required to obtain a replacement material, we decided to withdraw Sample **4 from** circulation. Similarly, following the fourth round of 14 mm kit measurements, Sample 1 was found to be broken and the kit withdrawn fiom circulation. **All** samples in the 7 mm kit were **refaced after** the sixth and eleventh rounds. Samples 2 and **5** in the **14** mm kit had to be **refaced** after the first round and Sample 3 was **refaced** after the third round.

NIST measurements of sample length and diameter were conducted at the NIST-Boulder laboratory using a coordinate measuring machine (CMM) of specified uncertainty ± 1.5 **µm**. Measurements of inner and outer diameter were conducted at positions spaced every millimeter along the sample axis and an average and standard deviation were computed. These data, were subsequently recorded on the participant data sheets and furnished to participants.

Tables 2a and 2b provide details of changes made in the samples of both the 7 and 14 mm diameter kits, including dimensional changes, as well as which particular samples were measured by the various participants. As in the earlier study, participants are only identified by a letter code (A through P) in order to preserve the anonymity of measured data. In column 2 of Table 2, a code is used for sample identification; the first number denotes the original or replaced femte material, while the final letter denotes the original (1XXa) or refaced sample (1XXb, c, . . . , etc.).

Table 2a. NIST dimensional data for 7 mm diameter samples.

Mater-ial	Sample Code	Measured by Participant:	Length (mm)	Inner Diameter (mm)	Outer Diameter (mm)
1	1YG	A,D,E,F,K	7.406	3.0505 ± 0.003	6.9930
	2YGa	J	10.360	3.0524 ± 0.002	6.9890 ± 0.002
	b	A,B,C,G,H,I	8.900	3.0559 ± 0.004	6.9897 ± 0.001
	c	A,L,N	8.170	3.0548 ± 0.005	6.9904 ± 0.001
2	1FRa	A,D,E,F,J,K	7.722	3.0725 ± 0.012	6.991
	b	A,B,C,G,H,I	6.746	3.0756 ± 0.010	6.9859 ± 0.003
	c	A,L,N	6.607	3.0657 ± 0.010	6.9884 ± 0.002
3	1MFa	A,B,C,D,E,F, G,H,I,J,K	12.710	3.0754 ± 0.015	6.9688 ± 0.002
	b	A,L,N	12.640	3.0754 ± 0.015	6.9862 ± 0.012
4	1LF	A,D,E,F	12.71	3.0780 ± 0.009	6.991
5	1ZNa	A,D,E,F,J,K	6.281	3.0540 ± 0.004	6.992
	b	A,B,C,G,H,I	5.621	3.0593 ± 0.005	6.9874 ± 0.002
	c	A,L,N	5.614	3.0562 ± 0.004	6.9888 ± 0.001

TABLE 2b. NIST dimensional data for 14 mm diameter samples.

Mater-ial	Sample Code	Measured by Participant:	Length (mm)	Inner Diameter (mm)	Outer Diameter (mm)
1	1YG	A,C,I,M,P	6.931	6.2172 ± 0.0076	14.269 ± 0.0035
2	1FRa	A,M	7.052	6.2152 ± 0.0064	14.282 ± 0.0021
	b	A,C,I,P	6.571	6.2144 ± 0.0056	14.278 ± 0.0030
3	1MFa	A,I,M	12.800	6.2063 ± 0.0034	14.282 ± 0.0071
	b	A,P	11.020	6.2081 ± 0.0040	14.281 ± 0.0041
5	1ZNa	A,M	6.638	6.1999 ± 0.0049	14.273 ± 0.0018
	b	A,I,P	3.647	6.2100 ± 0.0014	14.266 ± 0.0035

3. MEASUREMENT METHODOLOGY

3.1 Data-Reduction Algorithms

The algorithm often used for deriving complex permittivity and permeability parameters from the measured S-parameters is that based on the explicit solution of Nicolson and Ross [3] and Weir [4]. It has been incorporated in the software of a major commercial instrument supplier and is widely used. As pointed out in the supplier's descriptive literature [5], this algorithm generally performs satisfactorily for medium- and high-loss materials, particularly ferrites.

One of the findings of the earlier dielectric intercomparison [2, § IIIA] is that this algorithm does not work well for low-loss dielectrics. This is because the Nicolson-Ross-Weir (NRW) solution is very sensitive to the inevitable phase errors in S-parameter measurements that arise whenever resonances of the sample-under-test are approached. These instabilities are manifested as periodic off-scale departures or "drop-outs" in the permittivity versus frequency plots. The lower the dielectric loss of the material under test is, the greater the Q of the resonant system is and the greater the magnitude of the instabilities are. Iterative algorithms, such as the NIST-developed code EPSMU3 [6], are better able to handle low-loss dielectrics. Data from the dielectric intercomparison [2] showed that those who had used an iteratively based code (all but two participants) obtained more stable and more accurate results. For high-loss materials, such as ferrites in the low-frequency regime, the resonances are largely damped out, so that the instabilities are no longer as apparent.

3.2 Air-Gap Corrections

As already discussed, air gaps between the inner conductor and sample inner diameter (inner gap) and between sample outer diameter and outer conductor (outer gap) must be dimensionally estimated and corrected for. This requires dimensional measurements of the sample's inner and outer diameter, as well as the inner and outer conductor diameter of the coaxial air line. The required correction, which increases significantly as material permittivity increases, is usually determined using a static coaxial capacitor model; this correction is included as an optional feature of the NIST software. In this model, the gaps are assumed to be of uniform thickness and are represented by two concentric capacitors in series [6, p. 111]. Because the electric field intensity is greatest near the center conductor, the correction for the inner gap is much greater than that for the outer gap.

4. DISCUSSION OF MEASUREMENT RESULTS

Intercomparison measurement results are shown in Figures 1 through 5, corresponding to each ferrite material measured. Table 3 relates the plot symbols used in Figures 1 through 5 with participant codes; the figure in parentheses denotes measurements of the 7 or 14 mm sample kit. Participants N and P are not included in Table 3 because, although they took part in the measurements, they did not submit usable data. Details of the reduction algorithm and method of air-gap correction used by the participants are also given in column 3 of Table 3 where EPSMU3 denotes use of the NIST-developed iterative code [5]. The numbers following, where provided, denote the version of the NIST software used. In most cases, these were early versions, such as Version 1.1, which have exhibited some problems of numerical implementation. Later versions of the NIST software (the latest is Version 3.4) contain significant improvements that have overcome the early problems. In column 3, "internal" denotes use of an internally developed code that is usually proprietary to the participant. In some cases, a few details of these codes were provided to NIST; they are generally based on the explicit NRW solution [3,4].

Column 4 gives details of whether or not participants applied an air-gap correction to their data. Where participants used the NIST code, they applied the gap correction feature available in the software. Corrections based on the same model were also available in some, but not all of the internal codes. Gap widths were computed by participants using either the sample dimensions supplied by NIST as well as their own coaxial line dimensions or sample and line measurements performed by participants. The latter case is denoted in Table 3 by "internal data." With some exceptions, most participants provided no details of how they performed dimensional measurements.

4.1 Reference Data

It is essential to provide the reader with some accurate reference points for these materials, against which measured data can be compared. This is particularly important where significant variation in the measured data is apparent. Such data need to have been generated using a technique that is more accurate than the coaxial air line method used in this study. In contrast to the earlier permittivity-only intercomparison study [2], where accurate X-band comparison data obtained using the NIST 60 mm diameter cylindrical cavity [7] were available for the low-loss dielectrics used in that study, it has not been straightforward to compile needed reference data for these materials. This is because a variety

Table 3. Key relating data symbol used to participant codes, plus details of data-reduction algorithms and gap correction used (if any).

Participant Code	Symbol	Algorithm Type	Air-Gap Estimation and Correction
A (7)	▽	EPSMU3	CMM measurements, gap corrected
A (14)	▿	EPSMU3	CMM measurements, gap corrected
B (7)	□	EPSMU3A	Internal data,.gap corrected
C (7)	▫	EPSMU3, 1.1	Used NIST data, gap corrected
C (14)	◇	EPSMU3, 1.1	Used NIST data, gap corrected
D (7)	⋄	Int. (NRW)	Not gap corrected
E (7)	○	Internal	Not gap corrected
F (7)	∘	Int. (NRW)	CMM measurements, gap corrected
G (7)	▿	EPSMU3	Internal data, inside gap corrected only
H (7)	▽	EPSMU3, 1.1	Used NIST data, gap corrected
I (7)	●	Int. (NRW)	Internal data, gap corrected
J (7)	◆	Int. (NRW) & EPSMU3	Internal data, gap corrected
K (7)	■	Internal	Inner dia. estimated with gauge pins, inside gap corrected only
L (7)	▲	Int. (NRW)	Not gap corrected
M (14)	▼	Internal	No gap correction, used silver paste
Reference Data	× ϙ	Permeameter Other (see 4.1)	

of alternate techniques are needed to derive the required reference permeability and permittivity data over the very broad 1 MHz to 10 GHz fiequency range used in this study. These are reviewed below.

At the lowest frequencies, 0.3 to100 MHz, μ_r^* and ϵ_r^* measurements are usually made using some type of impedance measuring technique involving an inductance-resistance measurement from which the complex permeability of magnetic materials is derived or a capacitance-conductance measurement from which the complex permittivity of dielectric materials is derived [8]. Though modem impedance analyzers work satisfactorily up to frequencies greater than 1 GHz, their application in accurate material measurements appears limited to less than 300 MHz. In two very similar methods, termed the permeameter [9] and permittimeter [10], a toroidal sample of the material under test is mounted inside the identical 7 or 14 mm diameter coaxial air lines used in this study. This means that the actual intercomparison samples can be conveniently measured in this way. NIST obtained some useful low fiequency μ_r^* reference data on Materials 2, 3, and 5 using the permeameter method. We did not attempt to use the permittimeter method for deriving low fiequency ϵ_r^* reference data, because it is very prone to air gap-errors.

Accurate measurements of both complex permeability and permittivity can be realized in the mid-fiequency region, 50 to 1000 MHz, using the coaxial re-entrant cavity method [11]. For permeability measurements, a toroidal sample of ferrite is placed at the end of the cavity [12]. However, we were unable to perform any permeability measurements using this method, because insufficient material was available to fabricate the large toroid needed for such measurements. Using the re-entrant cavity method, in which a disc sample of the ferrite under test is placed in the center conductor gap, we were able to obtain a single-frequency ϵ_r^* reference data point for Materials 2, 3, and 5, which is accurate to within ±2 percent. For these measurements, the upper and lower faces of the sample were coated with silver paste in order to reduce the air gap errors.

Another useful technique for mid-frequency permeability measurements is the air-filled stripline resonator method [13]. Because the method relies on small-perturbation theory for computation of μ_r^* and ϵ_r^* [14], it is not considered as accurate as the re-entrant cavity method and is not recommended for permittivity measurements. During the past five years, NIST has evaluated this technique and has used it for characterizing ferrites, including Materials 3 and 5 [13].

For the microwave region, 1 to 10 GHz, the most accurate and most sensitive method for characterizing demagnetized ferrites is the dielectric-post resonator (or "Courtney") method [15], in which a rod of the ferrite under test is resonated in the H_{011} mode between two parallel conducting plates. NIST has obtained extensive μ_r^* data on a variety of ferrites, including Material 1, over the range 2 to 20 GHz, using a variation of this technique [16]. Accurate characterization of ferrite permittivity in this frequency range requires that measurements be performed in the presence of a large (minimum 1200 kA/m) magnetic biasing field, as discussed by Courtney [15]. Data on the complex permittivity properties of a number of garnets are given in Courtney's paper [15, Tables IV, V] and have been included in Figure 1e for Material 1. NIST is currently fabricating a fixture specifically designed to measure the microwave dielectric properties of ferrites.

4.2 Complex Permeability Data

Measured data on relative permeability, μ_r' are presented in Figures 1a through 5a for all five materials using linear-log scales and in Figures 1b, 2b, and 5b for Materials 1, 2, and 5 using log-log scales. Logarithmic scales allow for permeability data to be displayed over the full amplitude range of $0.01 \leq \mu_r' \leq 1000$ that the transmission line technique is capable of resolving. However, because of logarithmic scale compression, these measurement data may appear to agree better than they really do. Similarly, measured data on magnetic loss, μ_r'' are presented in Figures 1c through 5c using linear-log scales and in Figures 1d, 2d, and 5d using log-log scales. For Materials 2, 3, 4, and 5 the measured μ_r^* data generally agree within ±5% of mean for frequencies between 50 and 1000 MHz, but much increased variability (up to ±20% or more of mean) is seen in both the μ_r' and μ_r'' data as frequency is reduced below 50 MHz, particularly for Material 2. An uncertainty analysis performed by NIST for the transmission line method [6, §2.5], shows that the measurement accuracy for both μ_r^* and ϵ_r^* degrades rapidly when the normalized sample length, $L/\lambda_m < 0.2$, due to the inability to resolve small phase differences. This is therefore consistent with the increased measurement variability seen below 50 MHz. For Material 1 (YIG), significantly greater variability (±25% of mean) is seen in the μ_r^* data (see Figures 1a through 1d) throughout the 0.003 to 1 GHz spectrum. The reasons for this are not clear, but may be caused by a well-known temperature sensitivity in YIGs.

The low-frequency μ_r^* comparison data, obtained using the permeameter method [9] are included in Figures 2a through 2d, 3a,c, and 5a through 5d; the uncertainty of these measurements is estimated to be ±1.5%. With the exception of Figure 2c, Participant A agreed very closely with these data. For Participants D and M, who were the only others to also attempt measurements below 50 MHz, the agreement with the comparison data was generally not as good.

Selected mid-frequency μ_r^* comparison data, obtained using the stripline resonator method [13], are also included with error bounds in Figures 2a through 2d, 3a,c and 5a through 5d. The agreement for Material 5 is very close for all participants, whereas that for Material 3 is not as good. The only applicable microwave comparison data available [15] are for Material 1 (YIG) and are shown in Figures 1b and 1d.

In general, it is seen that most measured μ_r^* data lie within the error bounds of the comparison data, thereby providing confidence in the validity of the participants' measured permeability data using the coaxial air line method.

4.3 Complex Permittivity Data

Measured data on relative permittivity ϵ_r' are presented in Figures 1e through 5e for all five materials using linear-log scales. These data show that there is generally more variability in the ϵ_r' data (±15 % about the mean) than in the μ_r' data. Comparison ϵ_r' data, obtained using the coaxial re-entrant cavity method [11] at about 500 MHz, are shown with error bounds (±2%) in Figures 2e, 3e, and 5e and it is seen that most of the measured data lie well below these reference levels. However, some of the participants obtained comparable results; the data for Participant A consistently lay within the error bounds of these comparison measurements for Materials 2, 3, and 5. Similarly, the data of Participant M agreed within these limits for Materials 3 and 5 and was only slightly low for Material 2. The data of Participants C, F, H, and I also agreed within the error bounds of the comparison data, but for only one material.

The only comparison ϵ_r' data available for Material 1 are shown on Figure 1e at about 6 GHz. It is obviously impossible to draw any meaningful comparisons with measured data at this fiequency. However, because of its very low dielectric loss properties, Material 1 (YIG) exhibits an almost constant ϵ_r' value with fiequency. Hence, it can be reasonably assumed that the comparison value for this Material lies in the range $\epsilon_r' = 15.7$ to 15.9 throughout the fiequency range measured. Figure 1e shows that the measured data of Participants A and H approach the closest to this level.

Reference to Table 3 shows that Participants A, C, F, H, and I, discussed above, included air-gap corrections, using either their own internally generated dimensional data or the NIST-provided data. Participant M was unaware of NIST instructions not to use any conductive fillers and used a silver paste as a gap-correction technique. This further confirms one of the principal findings of the earlier dielectrics-only study [2], that air-gap correction is essential for accurate complex permittivity measurements using the coaxial air line method.

Participants, A, C, and M who used the 14 mm diameter coaxial air line appeared to obtain ϵ_r' data that were consistently more accurate than those obtained using 7 mm diameter lines. This therefore suggests that use of the larger diameter 14 mm coaxial line yields somewhat more accurate ϵ_r' data. This is consistent with earlier findings that the influence of the air gap is proportionally reduced in larger-diameter air lines [6].

Measured data on dielectric loss ϵ_r'' are similarly presented in Figures 1f through 5f. For Materials 2 and 3, which possess measurable dielectric loss, the variability in measured dielectric loss, ϵ_r'' is seen in Figures 2f and 3f to be large, approaching ±50% or more about the mean at 100 MHz. For the remaining Materials 1, 4, and 5, which are all low-loss dielectrics, the ϵ_r'' data are seen in Figures 1f, 4f, and 5f to be meaningless. This again confirms what was learned in the earlier permittivity-only study [2], that the transmission line technique does not have sufficient measurement sensitivity to characterize low-loss dielectrics accurately.

Analysis of both the μ_r^* and ϵ_r^* data shows that either type of reduction algorithm (see Section 3.1) appeared to work equally well when measuring these materials at nonrnicrowave frequencies, less than 1 GHz. The sudden data drop-outs seen in Figures 2b, 2d, 3a, 3c, 3d, 5a, and 5c show evidence that the data-reduction algorithms used by Participants D, L, and M lost the correct root during the reduction process. All three used some type of internally developed algorithm for which few details are known. In most of the plots, there is also much evidence of algorithm instabilities around 10 GHz (for Material 1, these begin at about 6 GHz). These instabilities are most apparent for Materials 1 and 5, which possess relatively low dielectric loss. Such instabilities are attributed to TEM mode and higher-order mode resonances, that are no longer damped out by the high magnetic losses which exist at the lower frequencies, and are apparent for both type of algorithms.

5. CONCLUSIONS

This study has demonstrated that the coaxial air line technique very accurately measures the complex permeability properties of ferrites at frequencies above 50 MHz, but below the frequency of gyromagnetic resonance for the ferrite. For this specific application, the study demonstrated that all participants were able to obtain very accurate results using it, so it remains the preferred measurement method and is considered superior to any other. For the critical low-frequency region, below 50 MHz, where femtes exhibit very significant magnetic properties with $\mu_r' > 300$, the method rapidly loses accuracy due to its inability to resolve small phase differences. In this region, the permearneter technique [9] provides more accurate results and is preferred. For the microwave region, at frequencies equal to or above gyromagnetic resonance, the method is still remarkably capable of resolving values of μ_r' and μ_r'' down to approximately 0.01. However, due to its obviously inadequate measurement sensitivity, other measurement techniques such as the dielectric post resonator [16] are preferred for this frequency region.

The study also further confirmed the findings of the earlier NIST study [2] that use of the coaxial air line technique for performing broadband complex permittivity measurements of dielectrics remains problematic. The air gap remains a major source of error for ϵ_r' measurements and most participants were unable to adequately correct for it, despite our best efforts to alert them to the importance of this issue. Furthermore, the technique cannot satisfactorily resolve the dielectric loss of low-loss materials, including many fenites, due to its inadequate measurement sensitivity. For measurements above about 300 MHz, other resonator-type methods, such as the coaxial re-entrant cavity [11] or the dielectric rod resonator [15-17], provide much greater accuracy and sensitivity and are much preferred. While these methods are not broadband, they are nonetheless capable of providing multiple frequency data using a variety of different methods, such as cavity tuning and operation in different resonator modes.

For low frequencies in the range 3 to 300 MHz, the permittimeter technique [10] provides the best accuracy and sensitivity for low-loss dielectrics, provided that air-gap corrections are properly applied. When correctly used, the coaxial air line method works satisfactorily for medium-to-high loss materials at frequencies above 3 MHz. This study provided limited evidence that larger diameter (14, 77.5, and 155 mm) coaxial structures at these frequencies result in somewhat more accurate measurements of ϵ_r'.

Some of the internally developed reduction algorithms appeared to exhibit difficulties in staying on the correct root. The reasons for this are unclear. Both types of reduction algorithms used by participants, which are based either on the explicit NRW solution or the implicit iterative technique, generally appeared to work equally well for these materials.

6. ACKNOWLEDGEMENTS

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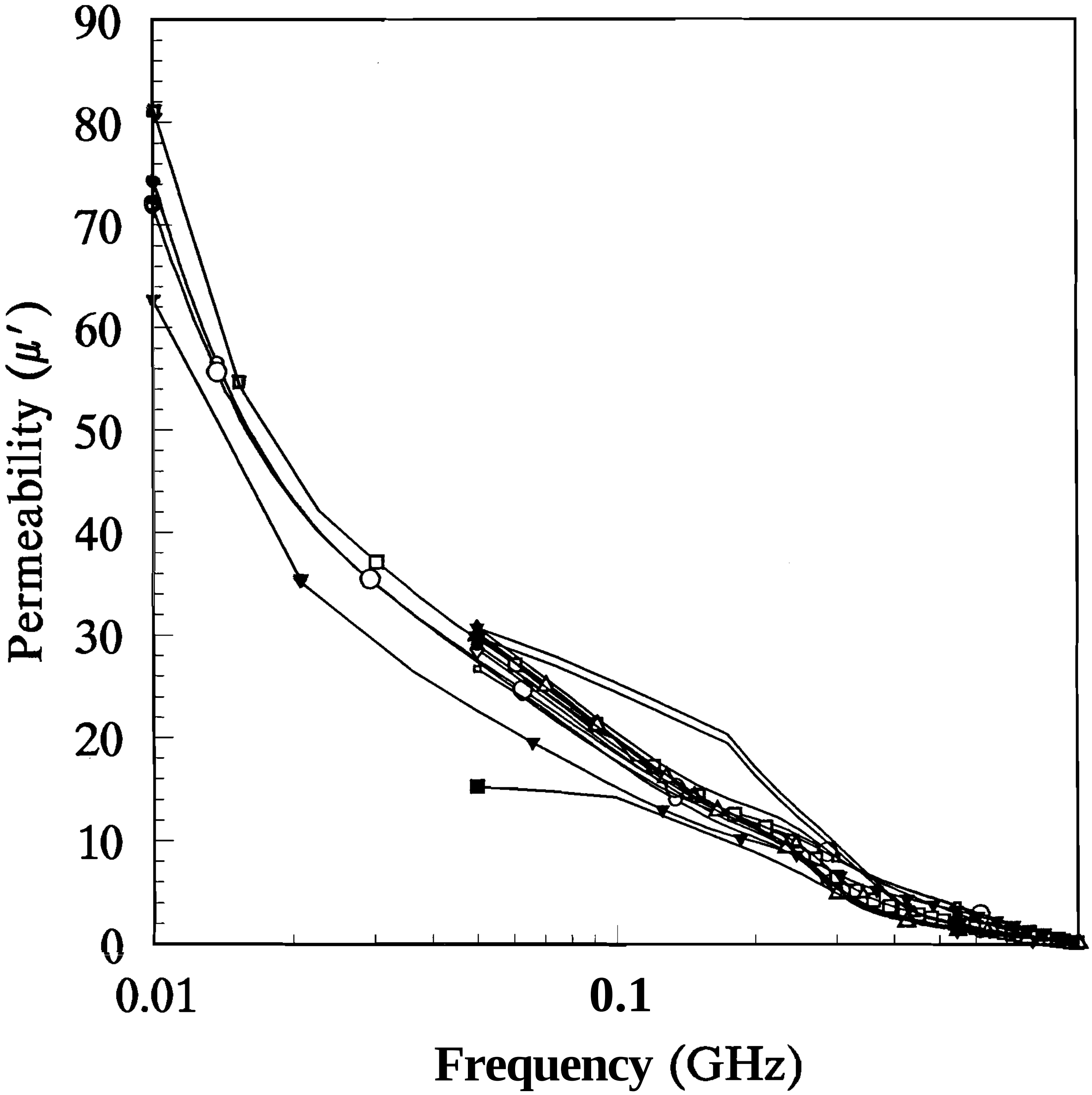

Figure 1a. Measured relative permeability, μ_r' for Material 1 (linear)

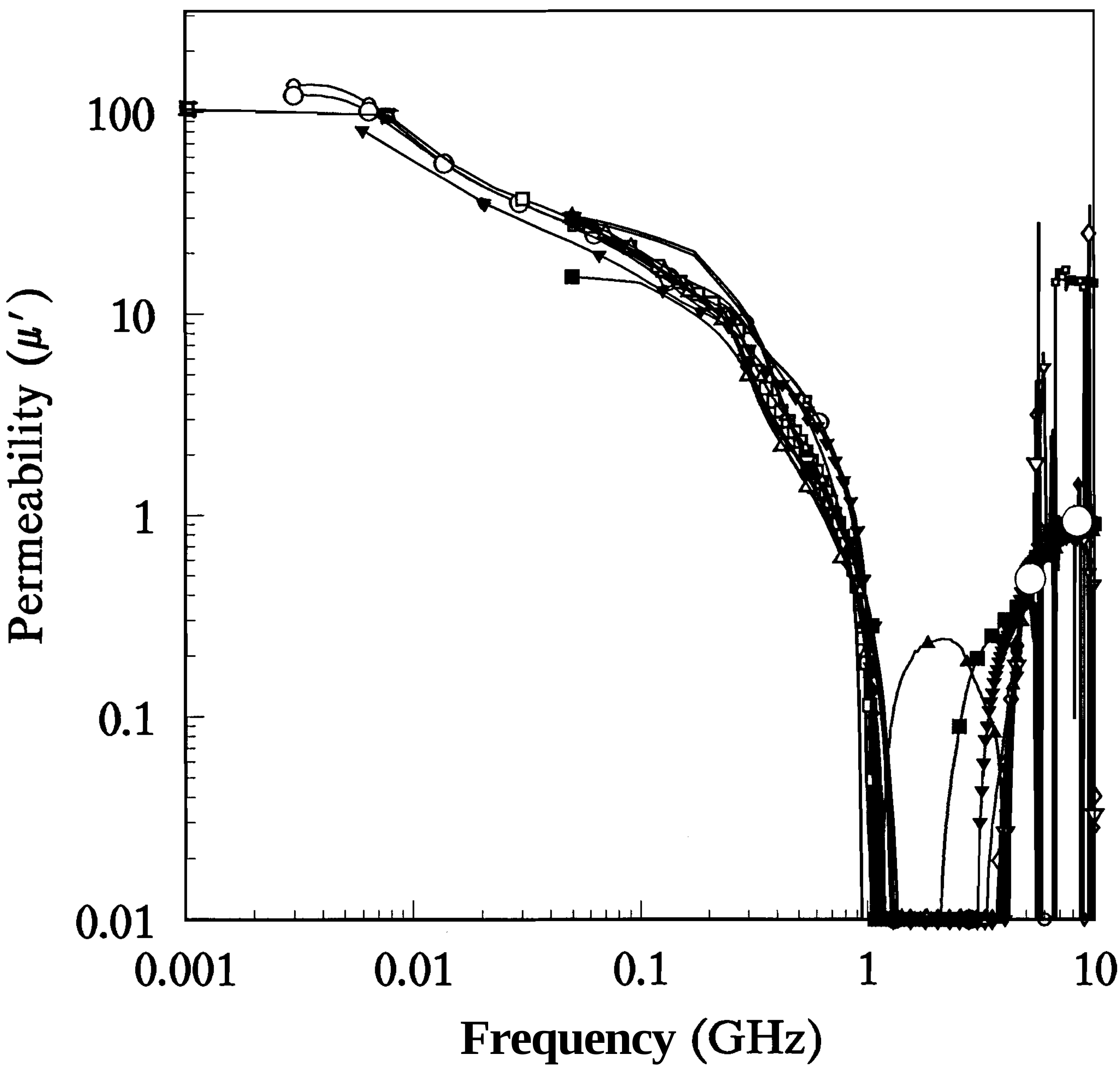

Figure 1b. Measured relative permeability, μ_r' for Material 1 (log)

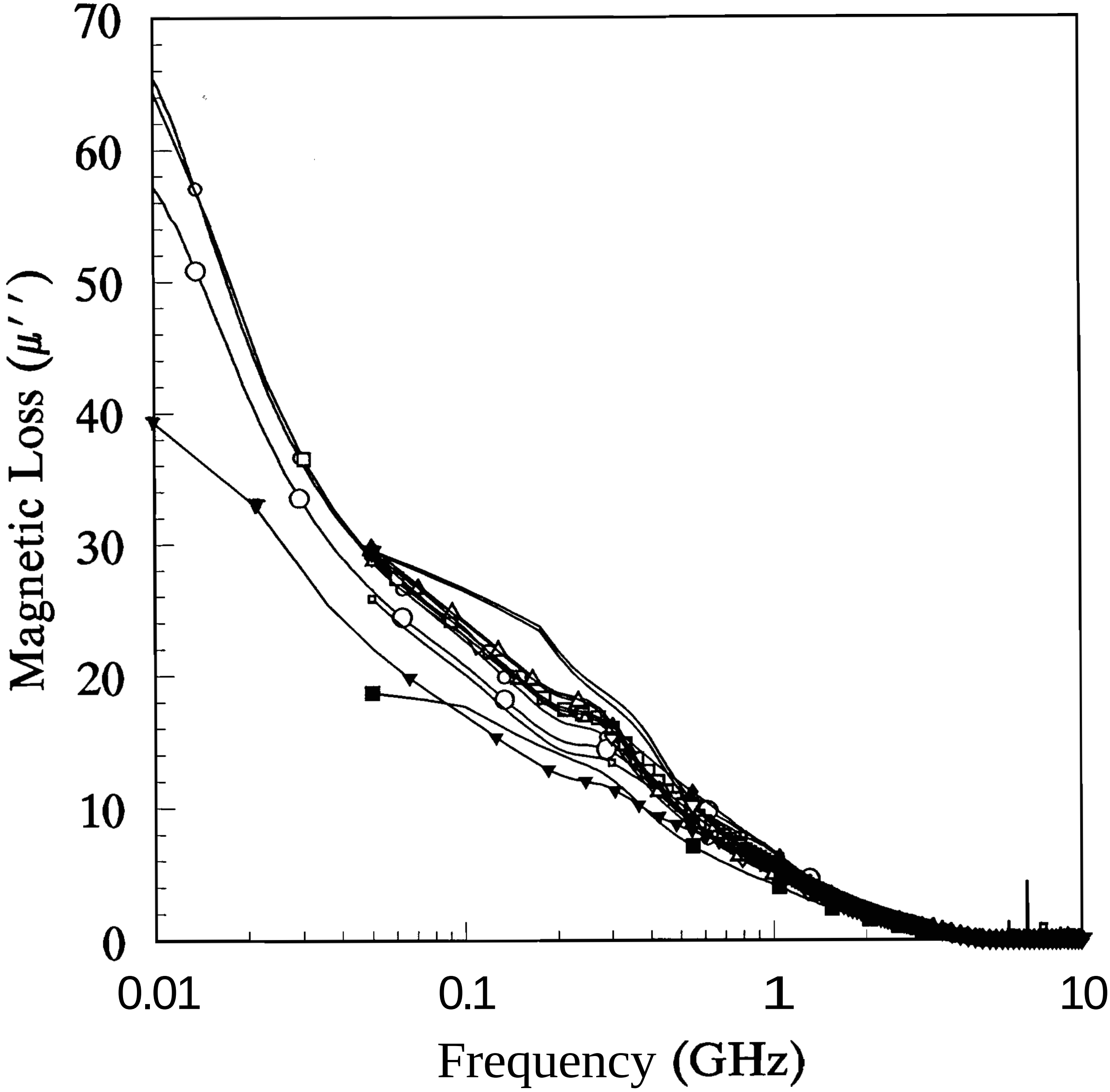

Figure 1c. Measured magnetic loss, μ_r'' for Material 1 (linear)

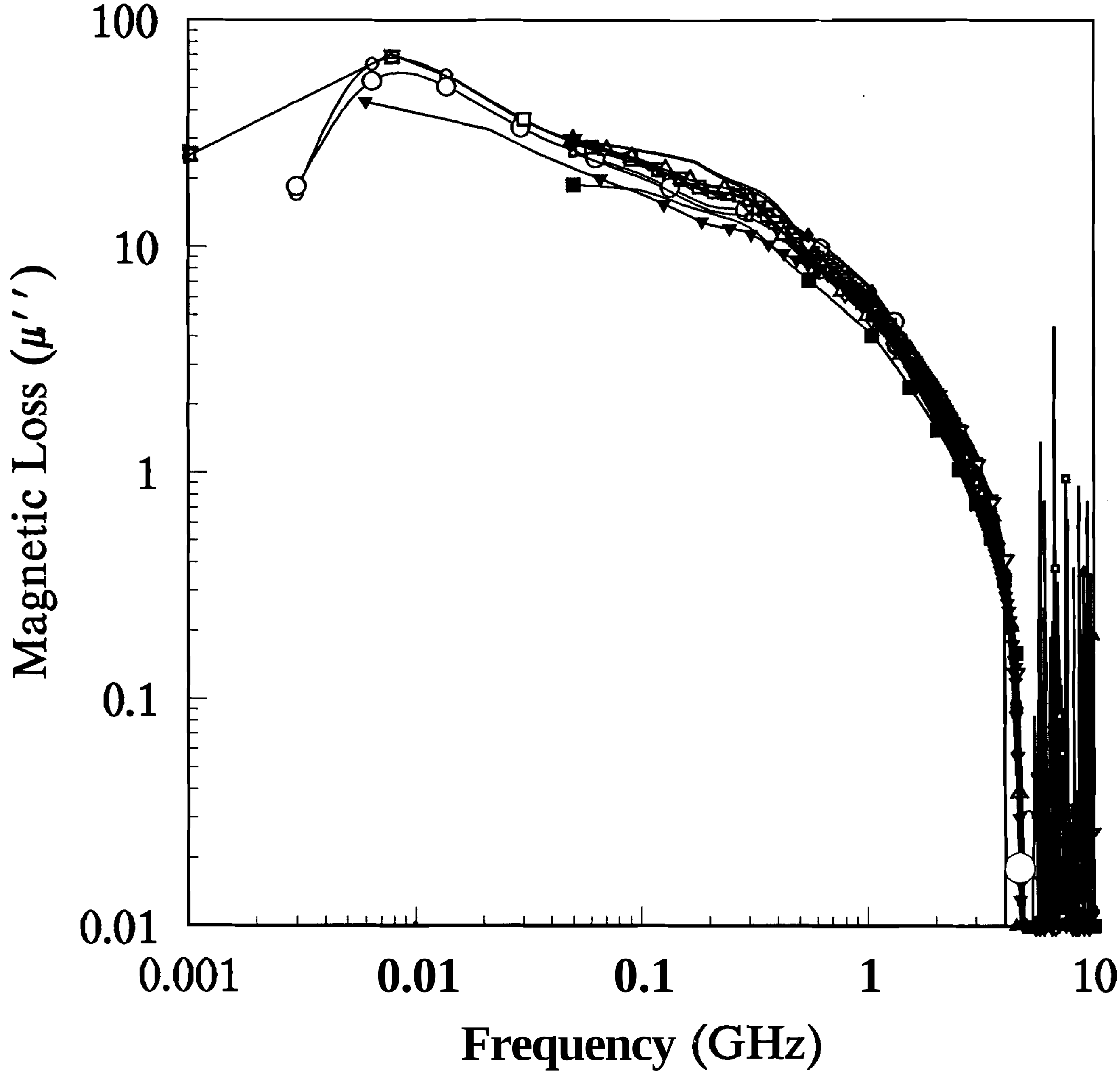

Figure 1d. Measured magnetic loss, μ_r'' for Material 1 (log)

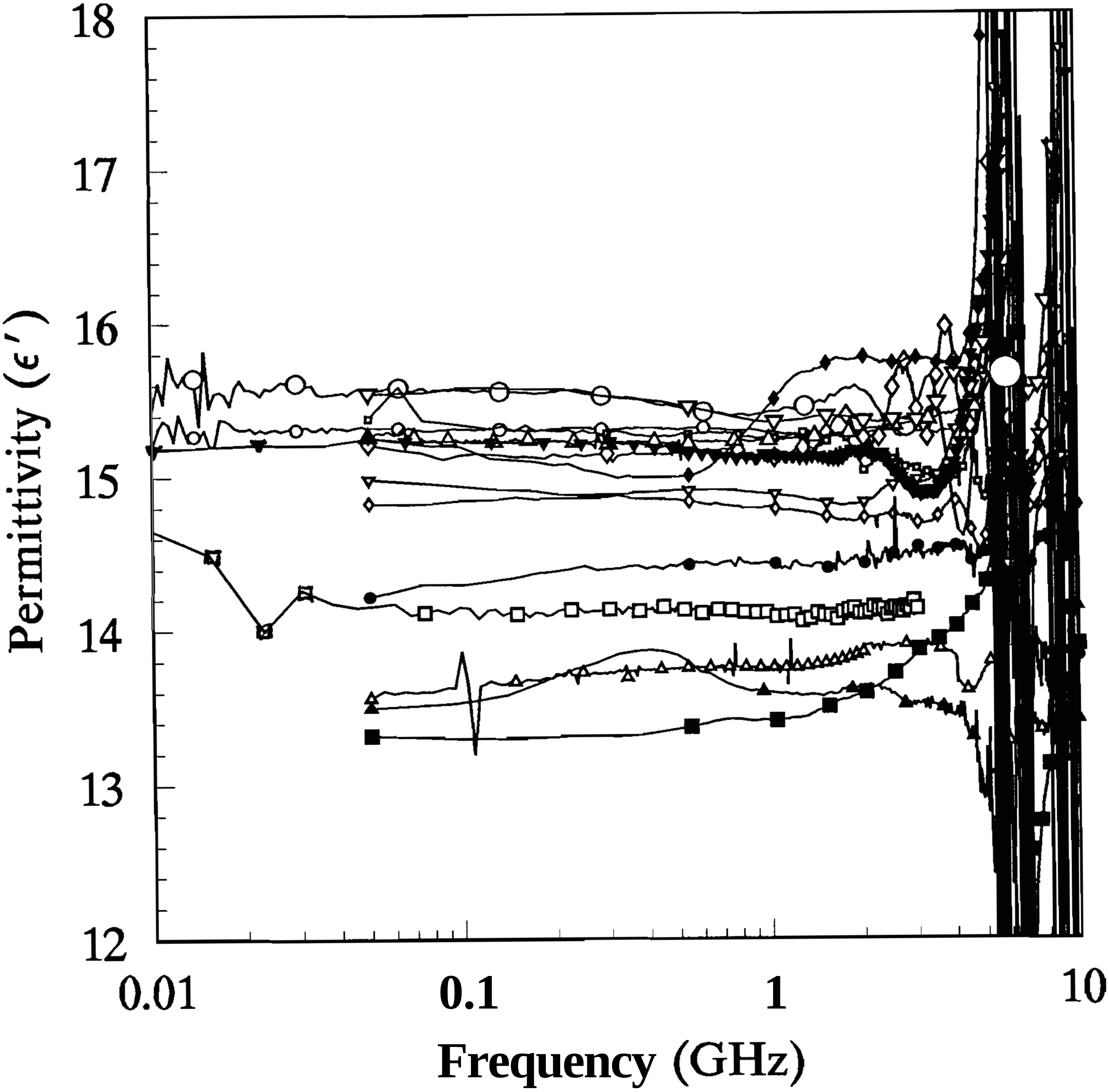

Table le. Measured relative permittivity, ϵ_r' for Material 1

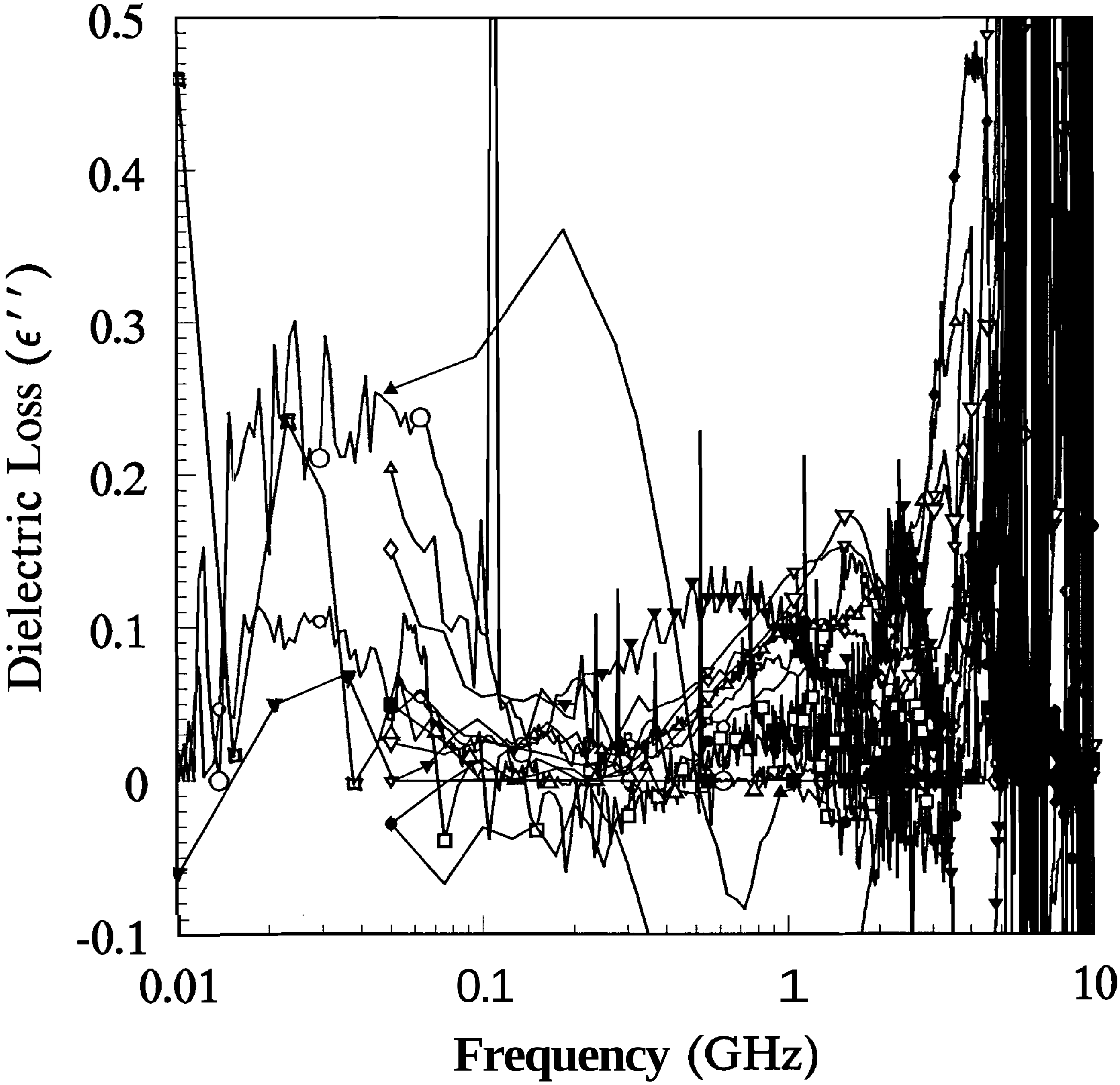

Figure 1f. Measured dielectric loss, ϵ_r'' for Material 1

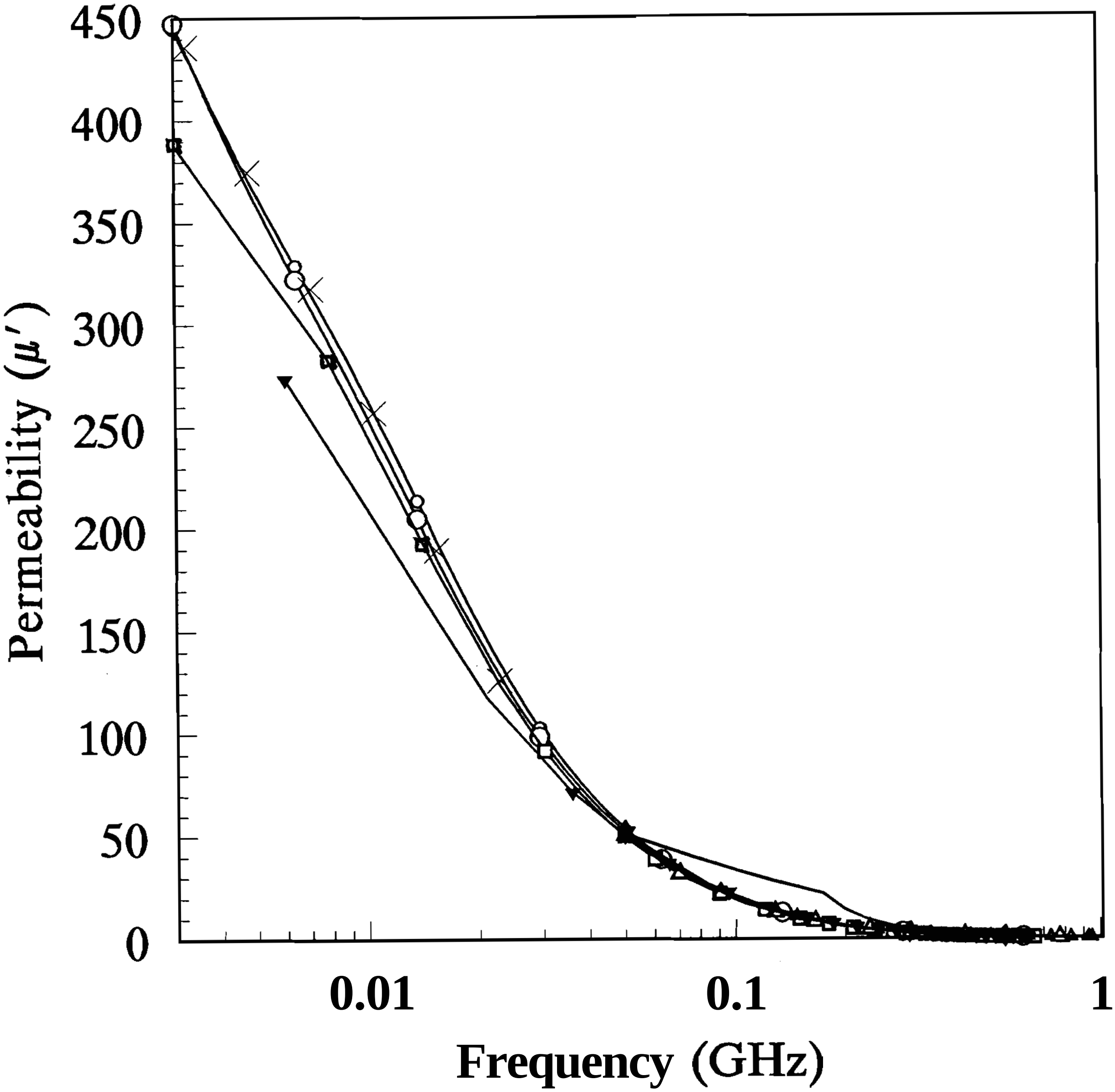

Figure 2a. Measured relative permeability, μ_r' for Material 2 (linear)

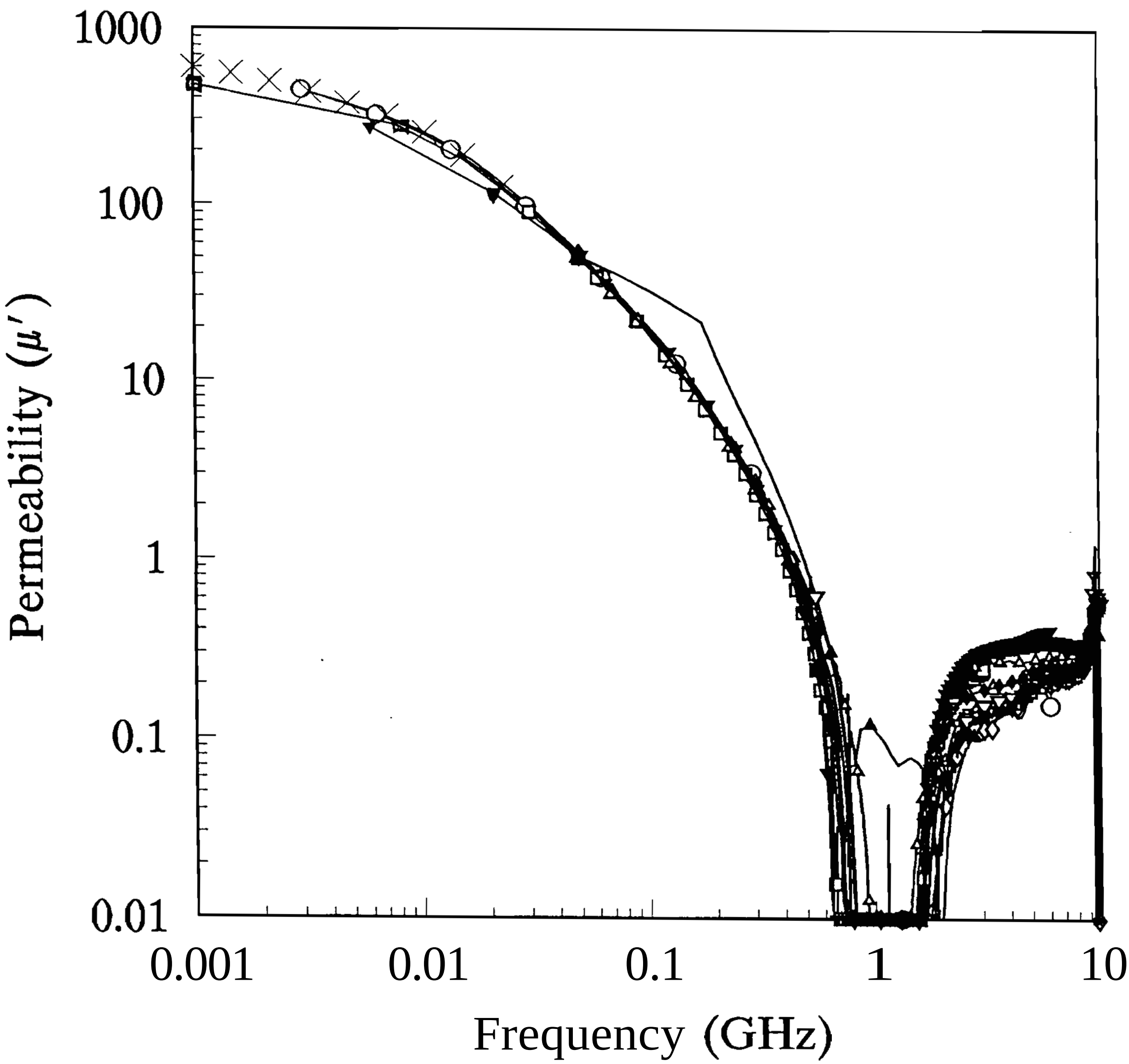

Figure 2b. Measured relative permeability, μ_r' for Material 2 (log)

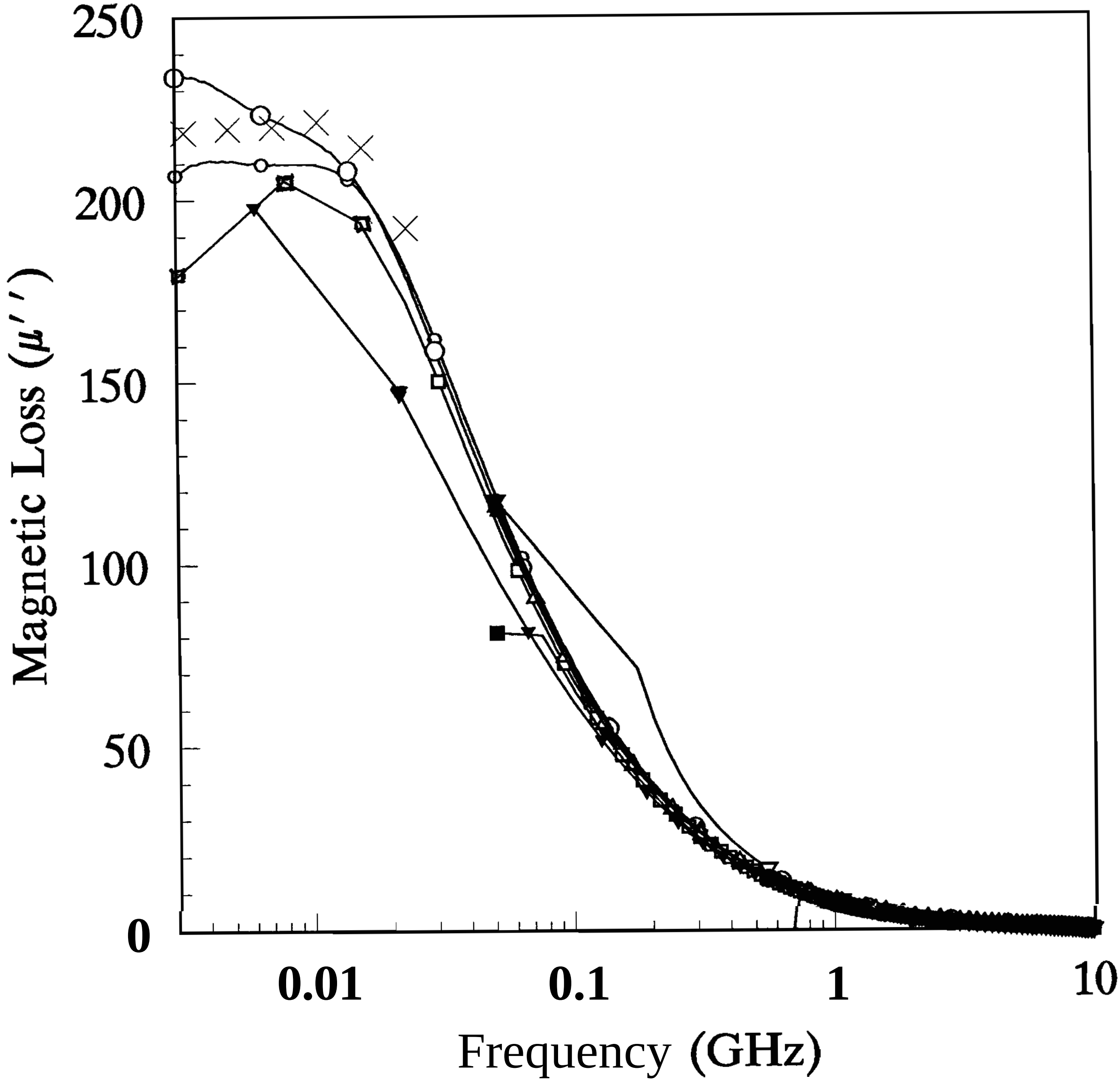

Figure 2c. Measured magnetic loss, μ_r'' for Material 2 (linear)

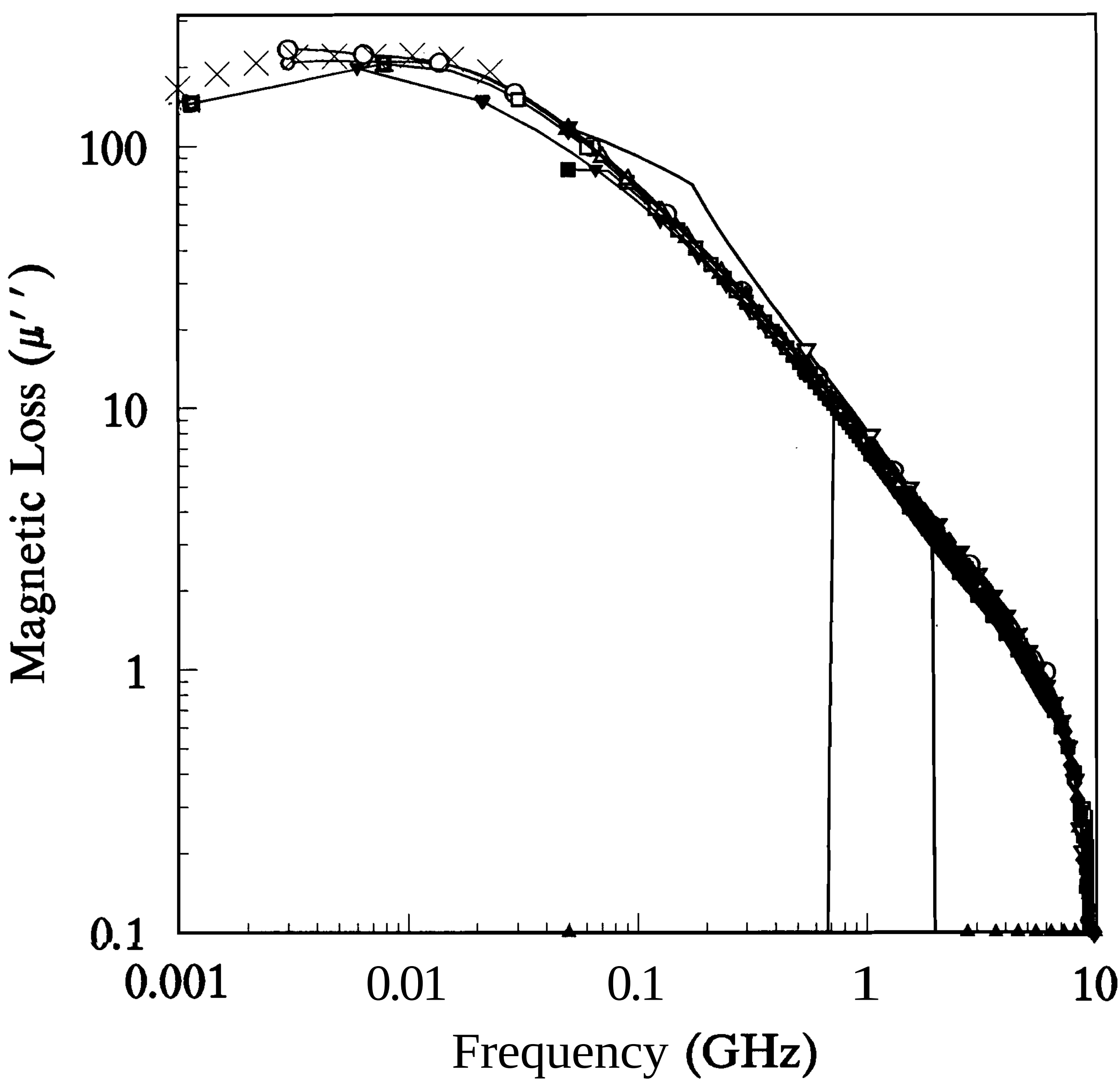

Figure 2d. Measured magnetic loss, μ_r'' for Material 2 (log)

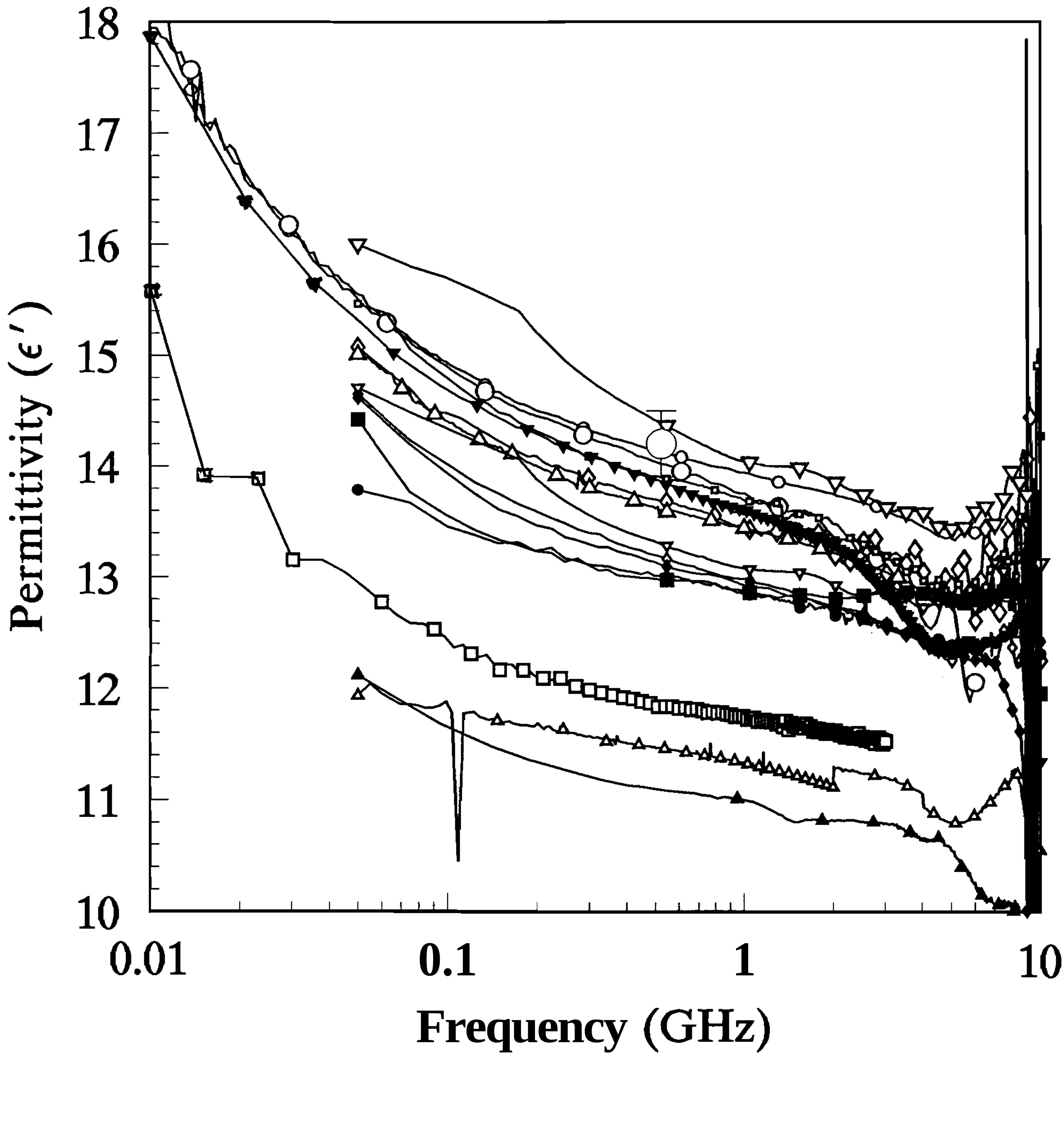

Figure 2e. Measured relative permittivity, ϵ_r' for Material 2

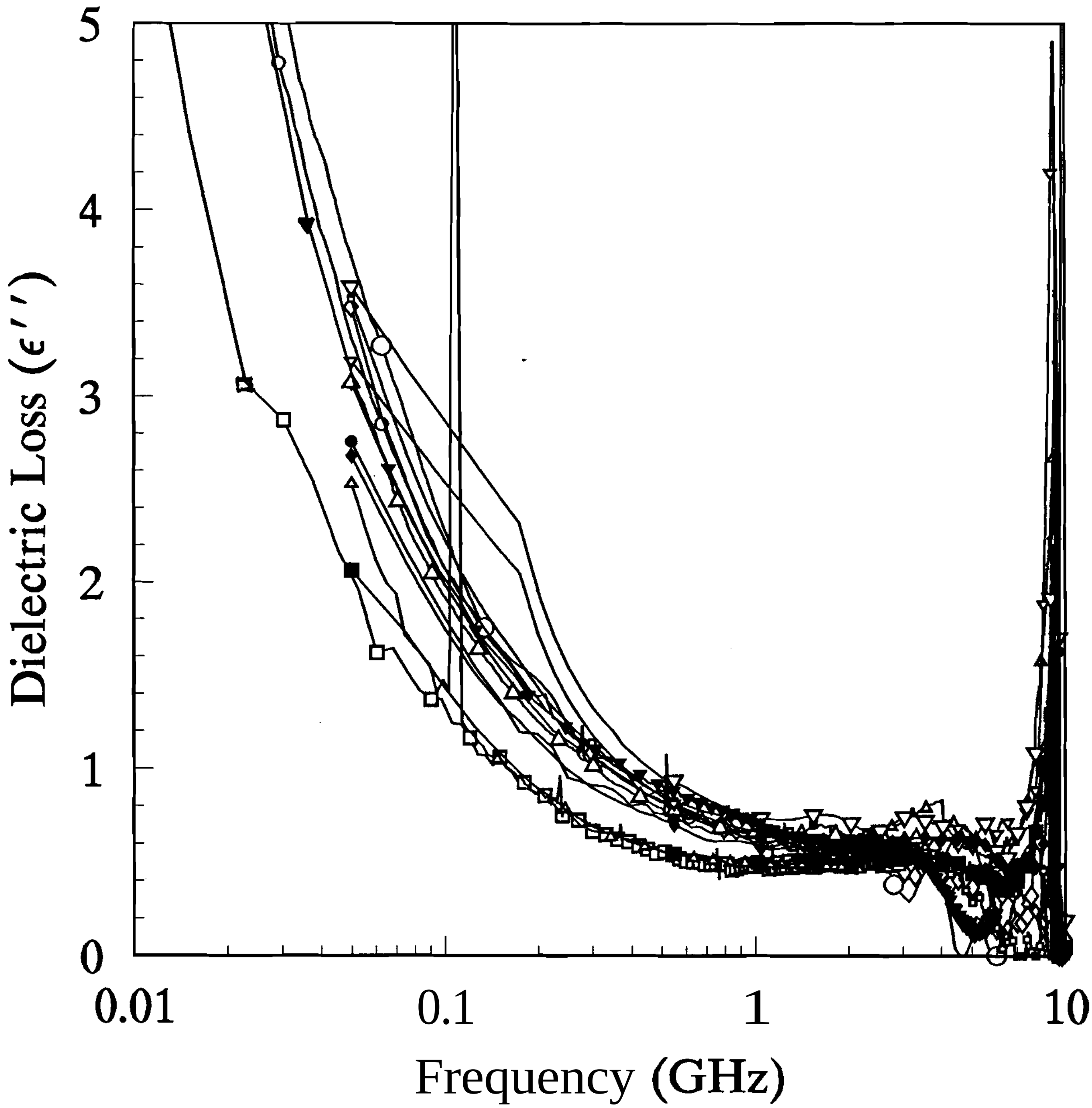

Figure 2f. Measured dielectric loss, ϵ_r'' for Material 2

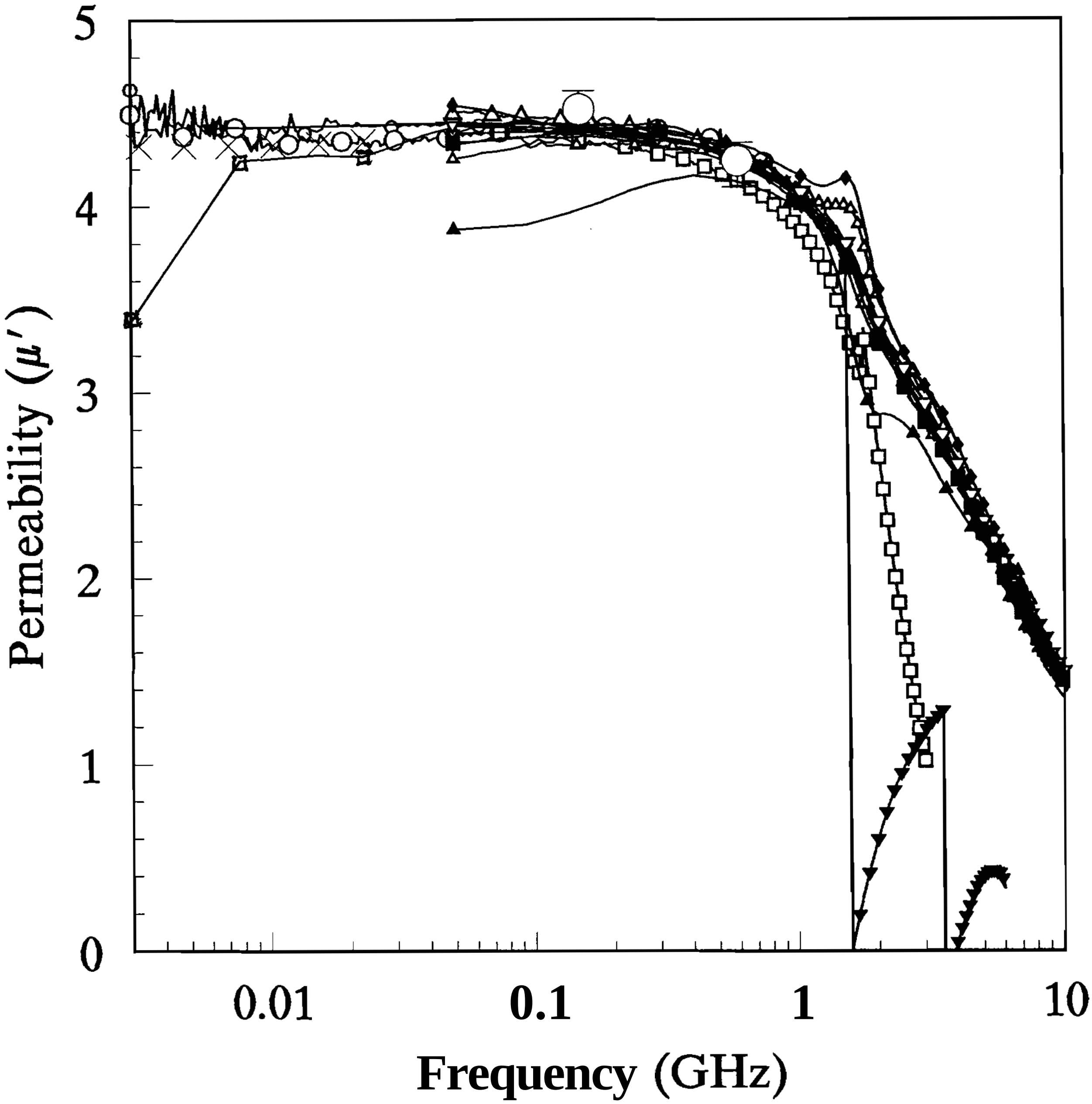

Figure 3a. Measured relative permeability, μ_r' for Material 3

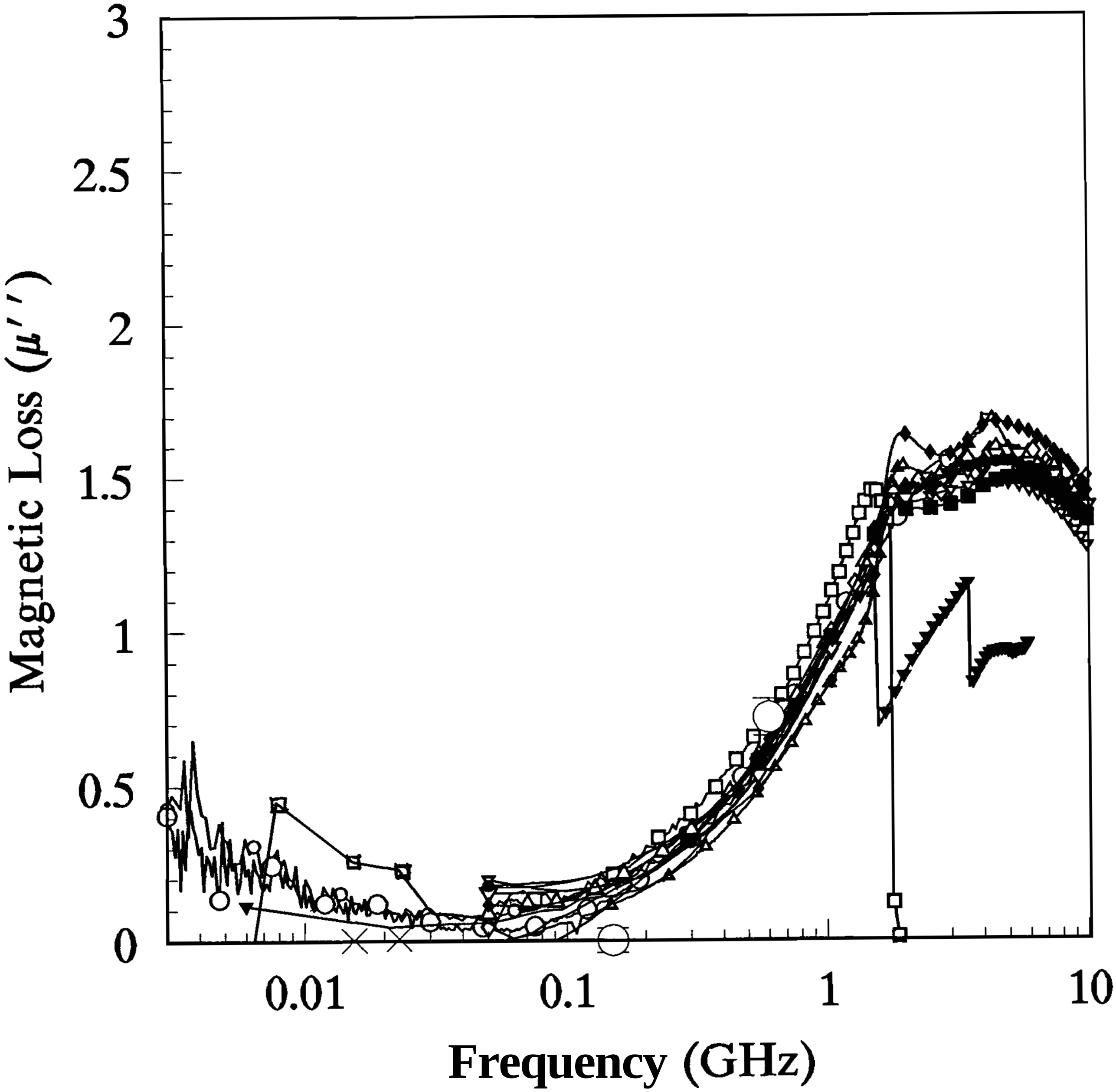

Figure 3c. Measured magnetic loss, μ_r'' for Material 3

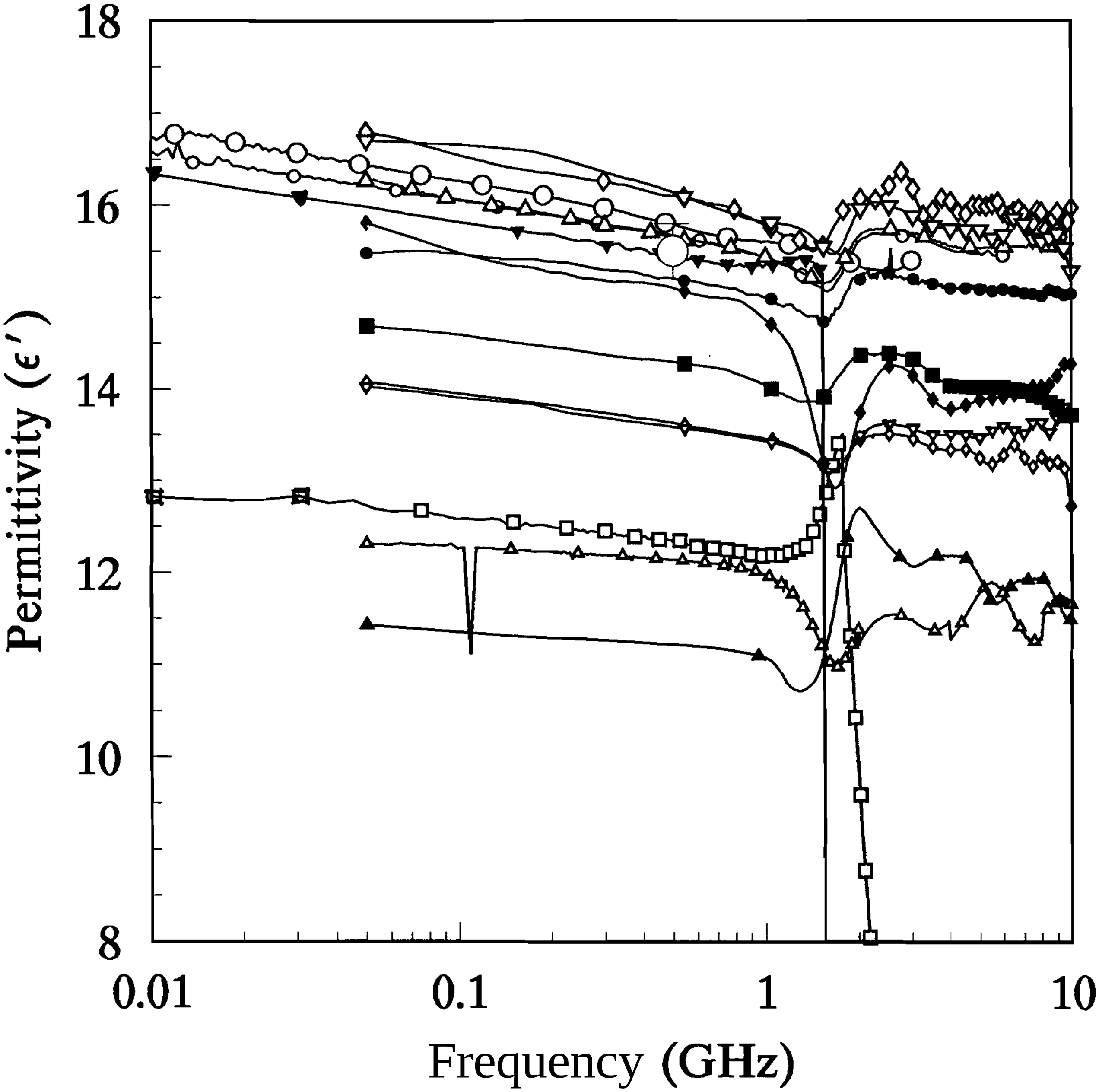

Figure 3e. Measured relative permittivity, ϵ_r' for Material 3

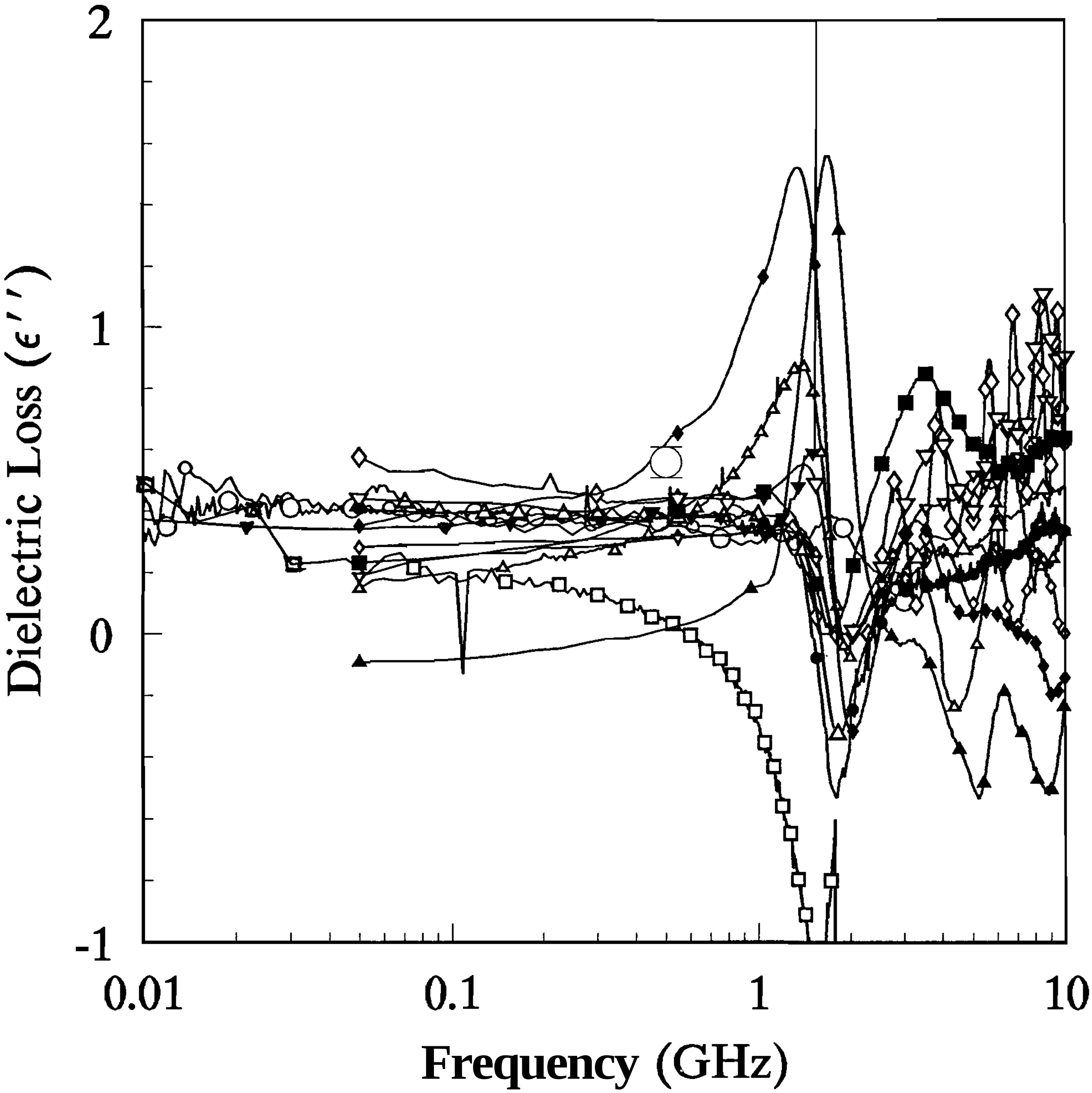

Figure 3f. Measured dielectric loss, ϵ_r" for Material 3

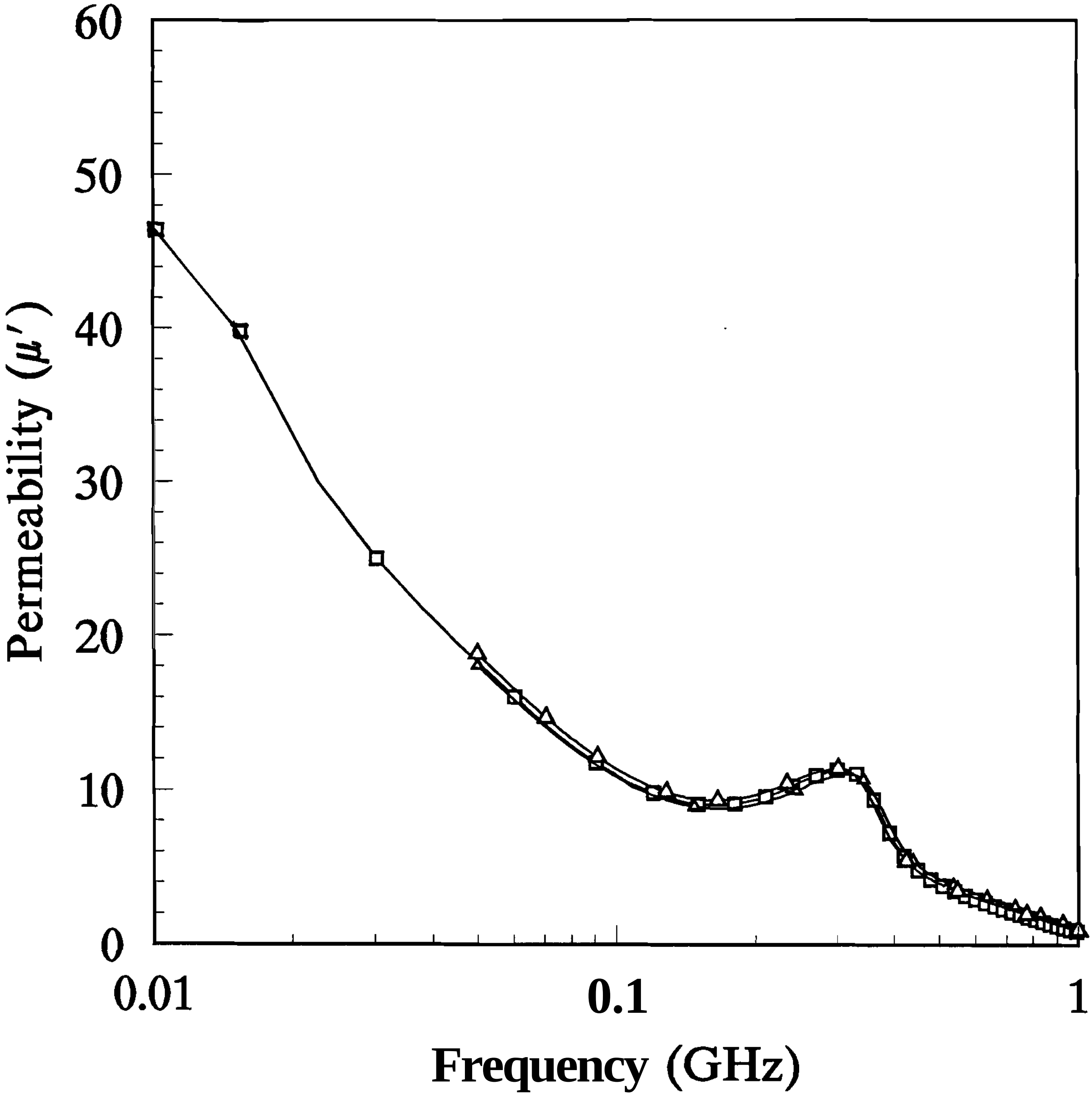

Figure 4a. Measured relative permeability, μ_r' for Material 4 (linear)

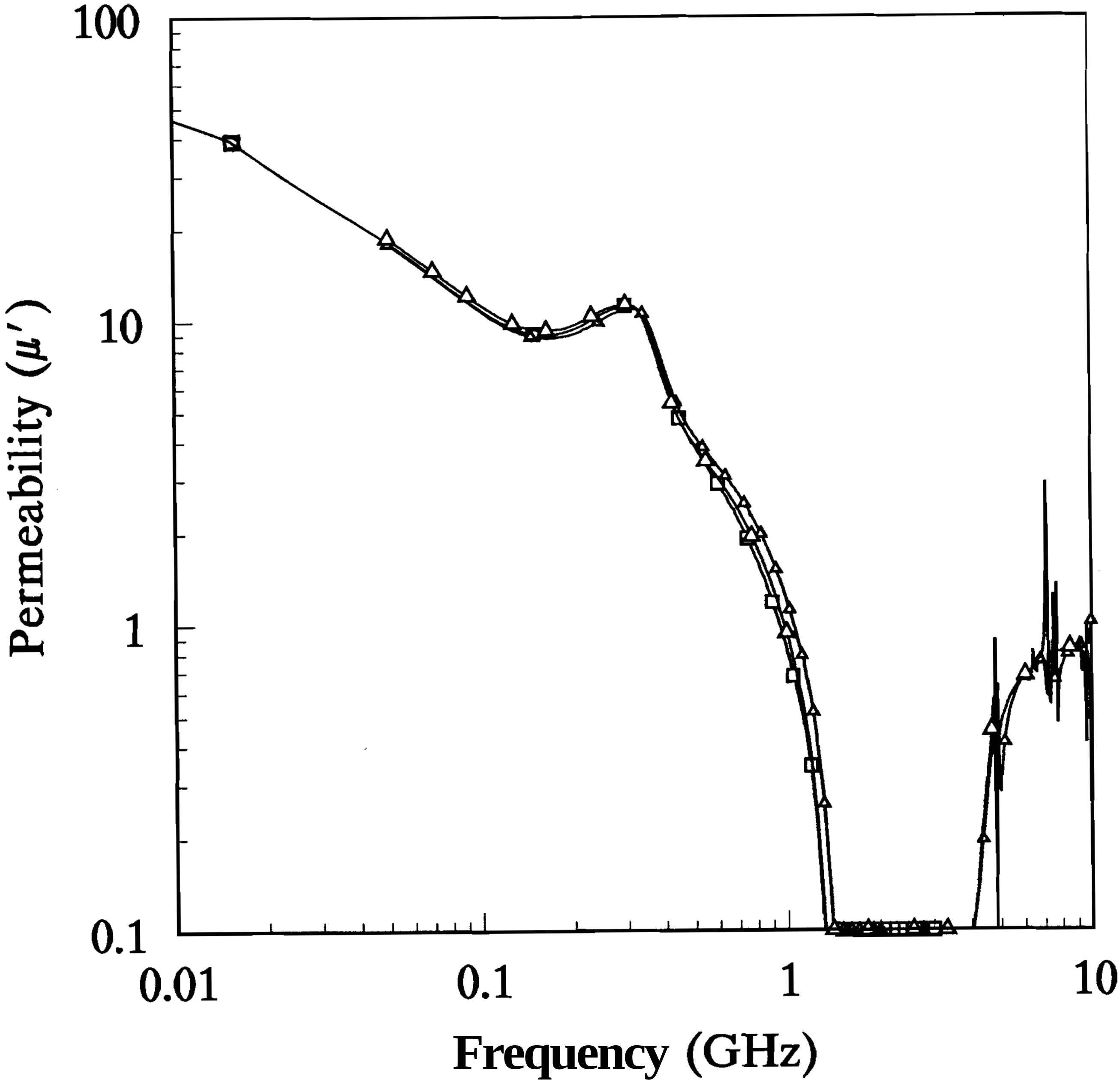

Figure 4b. Measured relative permeability, μ_r' for Material 4 (log)

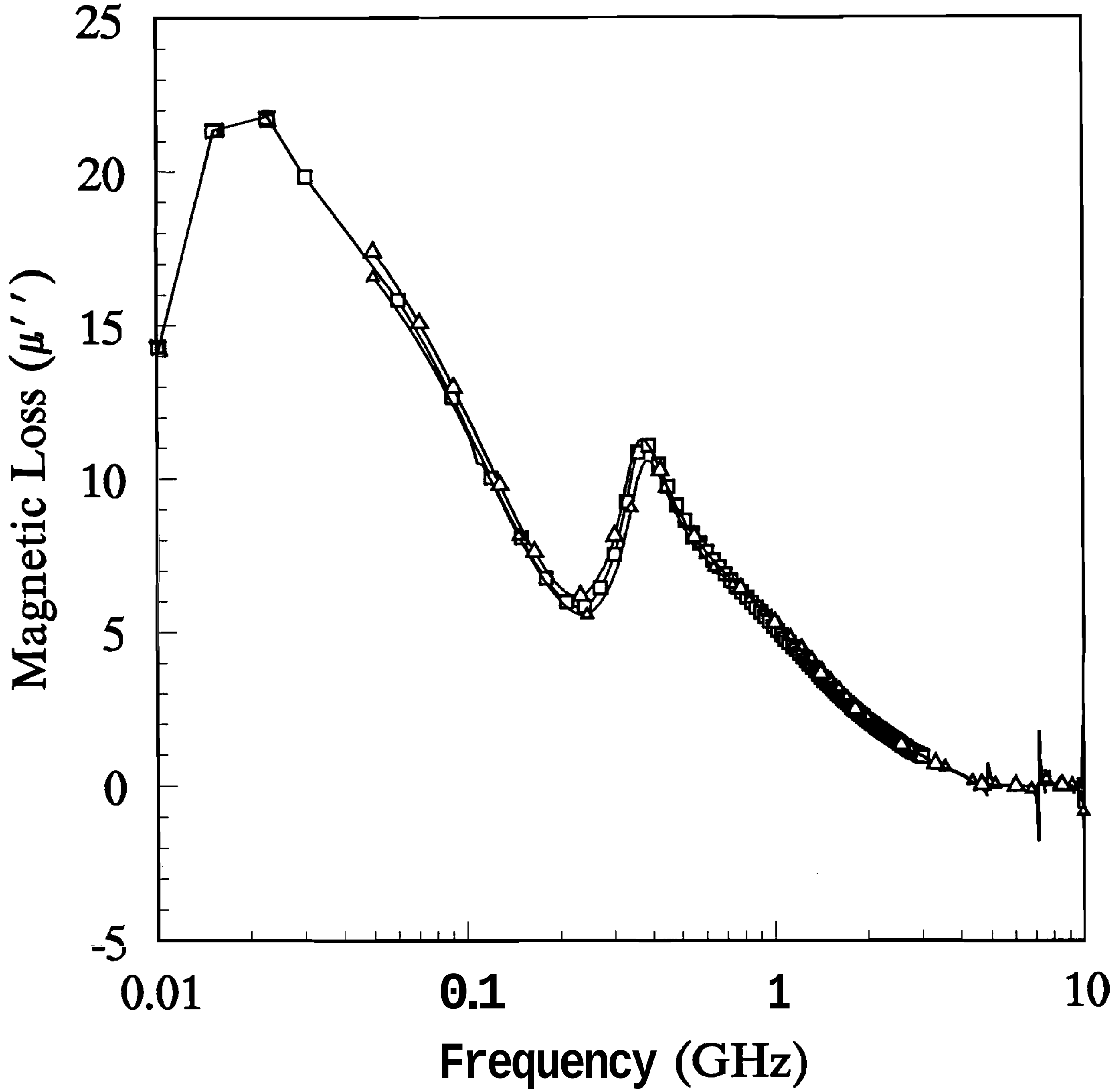

Figure 4c. Measured magnetic loss, μ_r" for Material 4

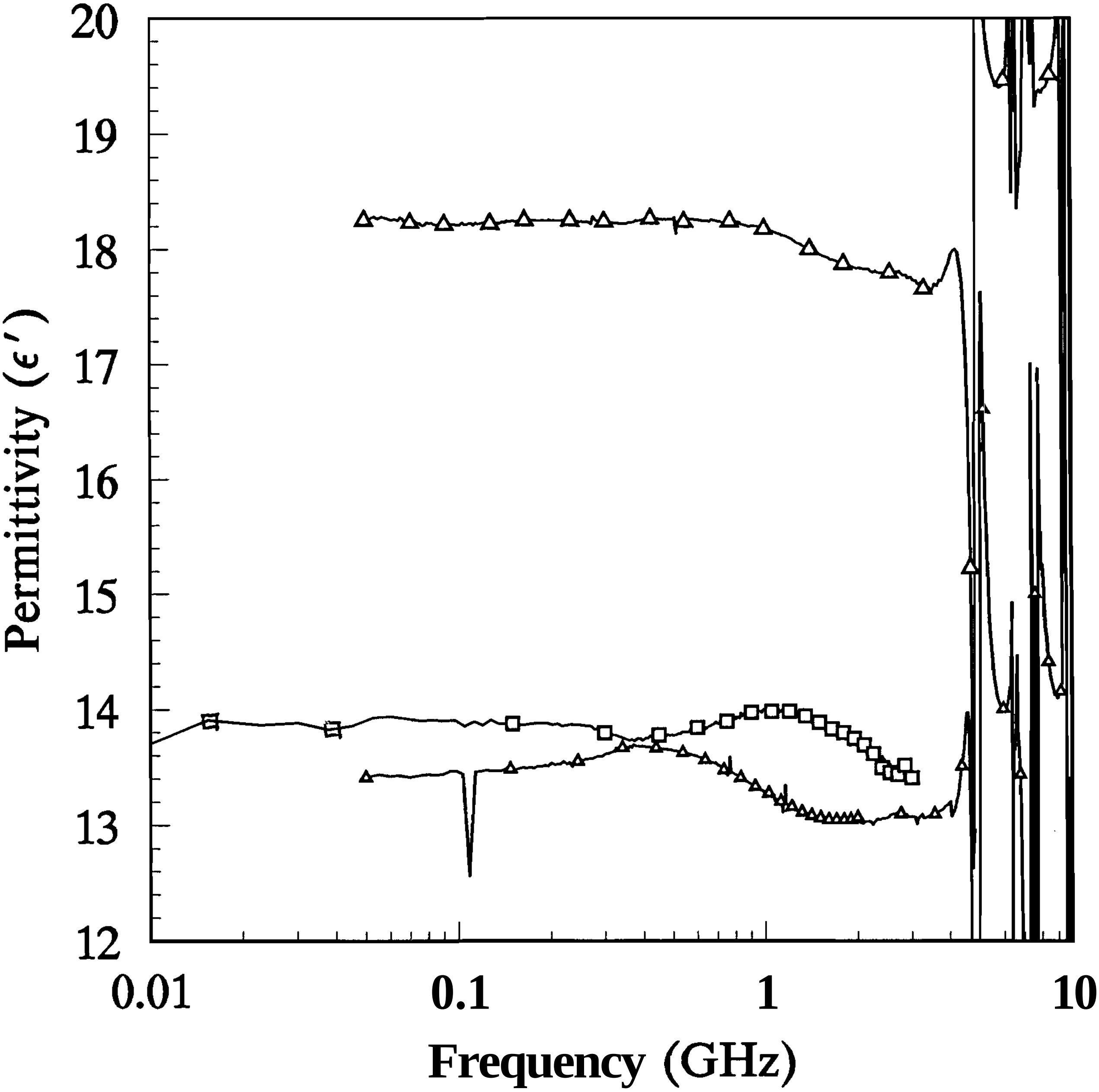

Figure 4e. Measured relative permittivity, ϵ_r' for Material 4

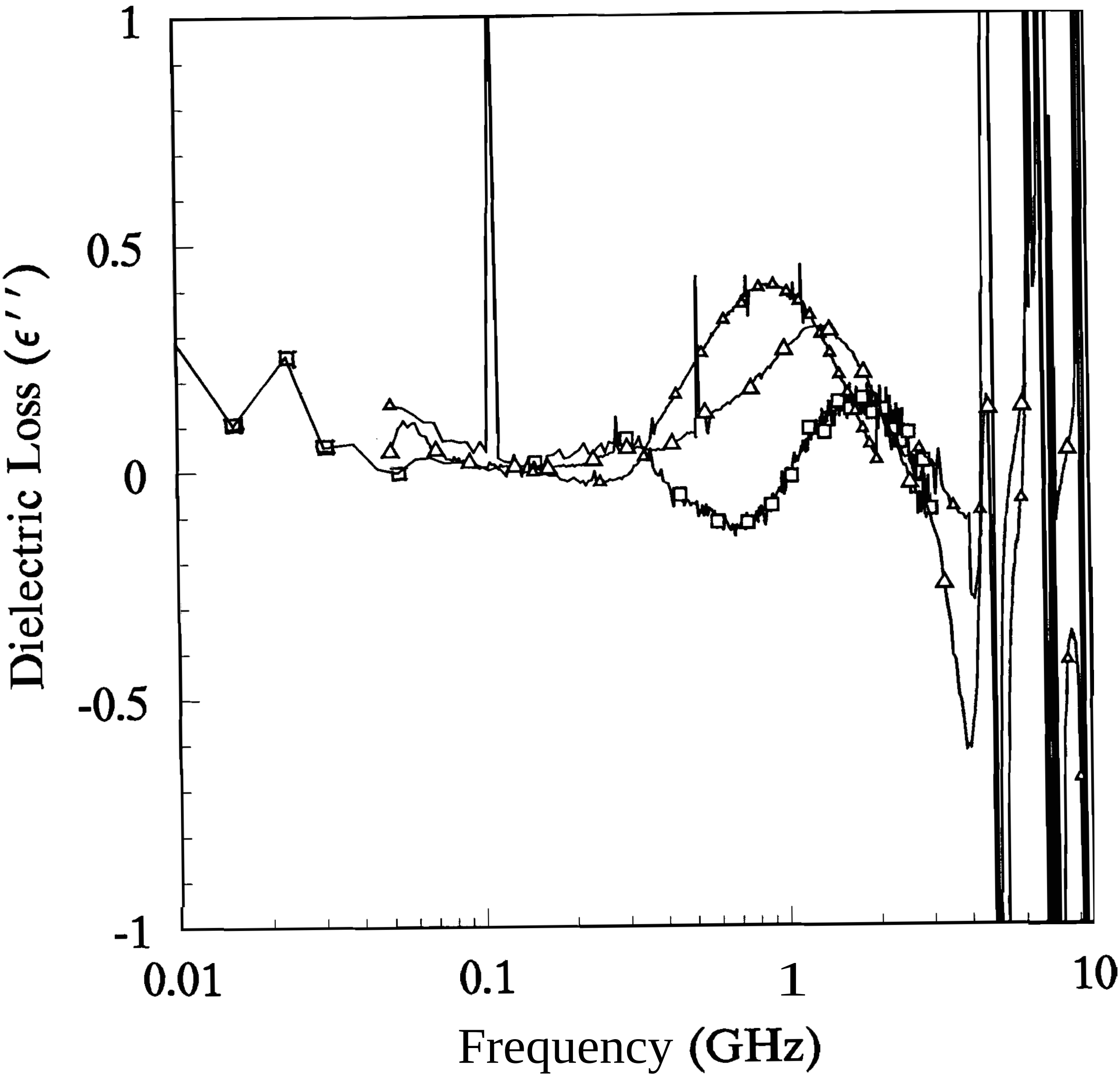

Figure 4f. Measured dielectric loss, ϵ_r'' for Material 4

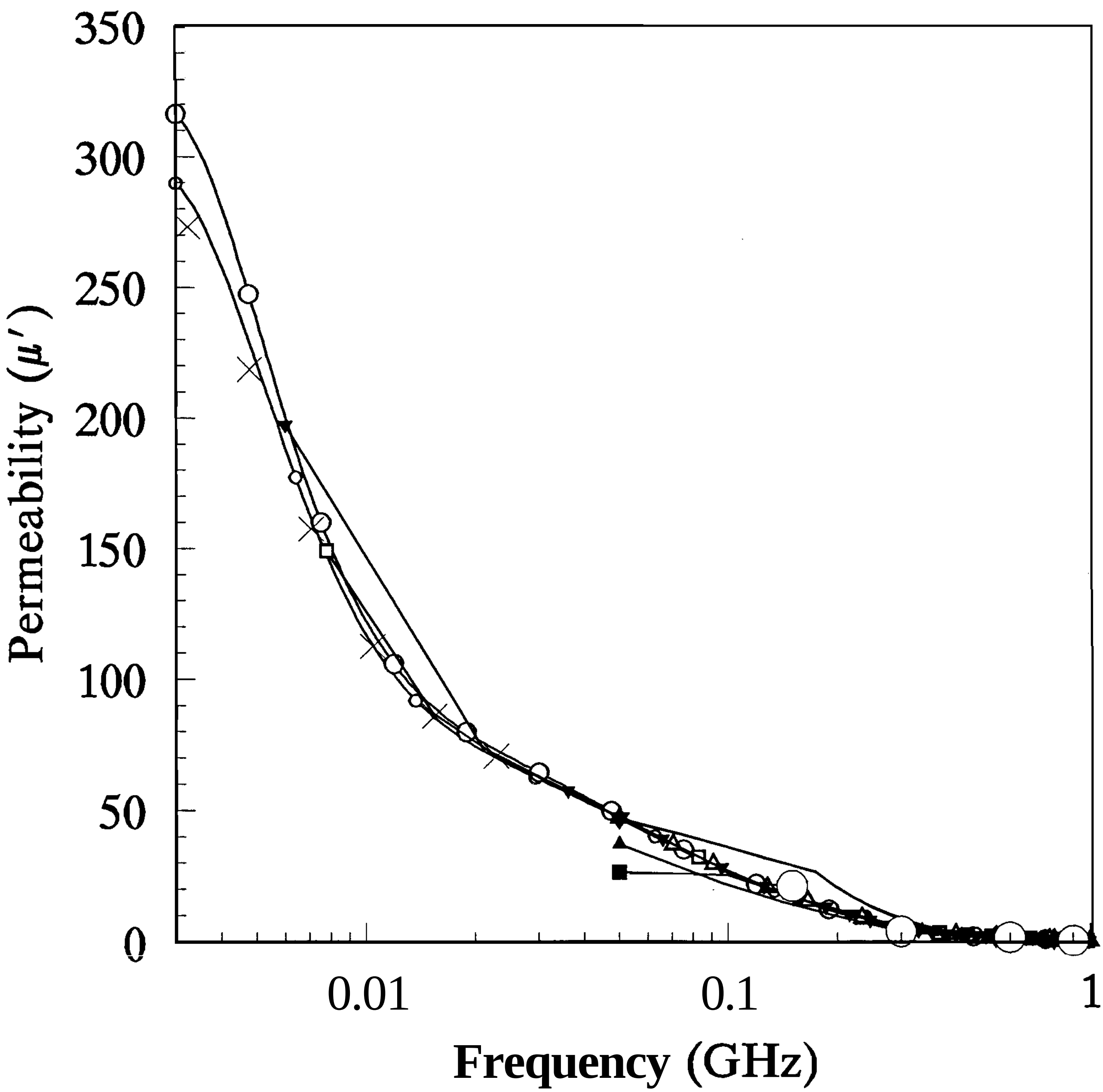

Figure 5a. Measured relative permeability, μ_r' for Material 5 (linear)

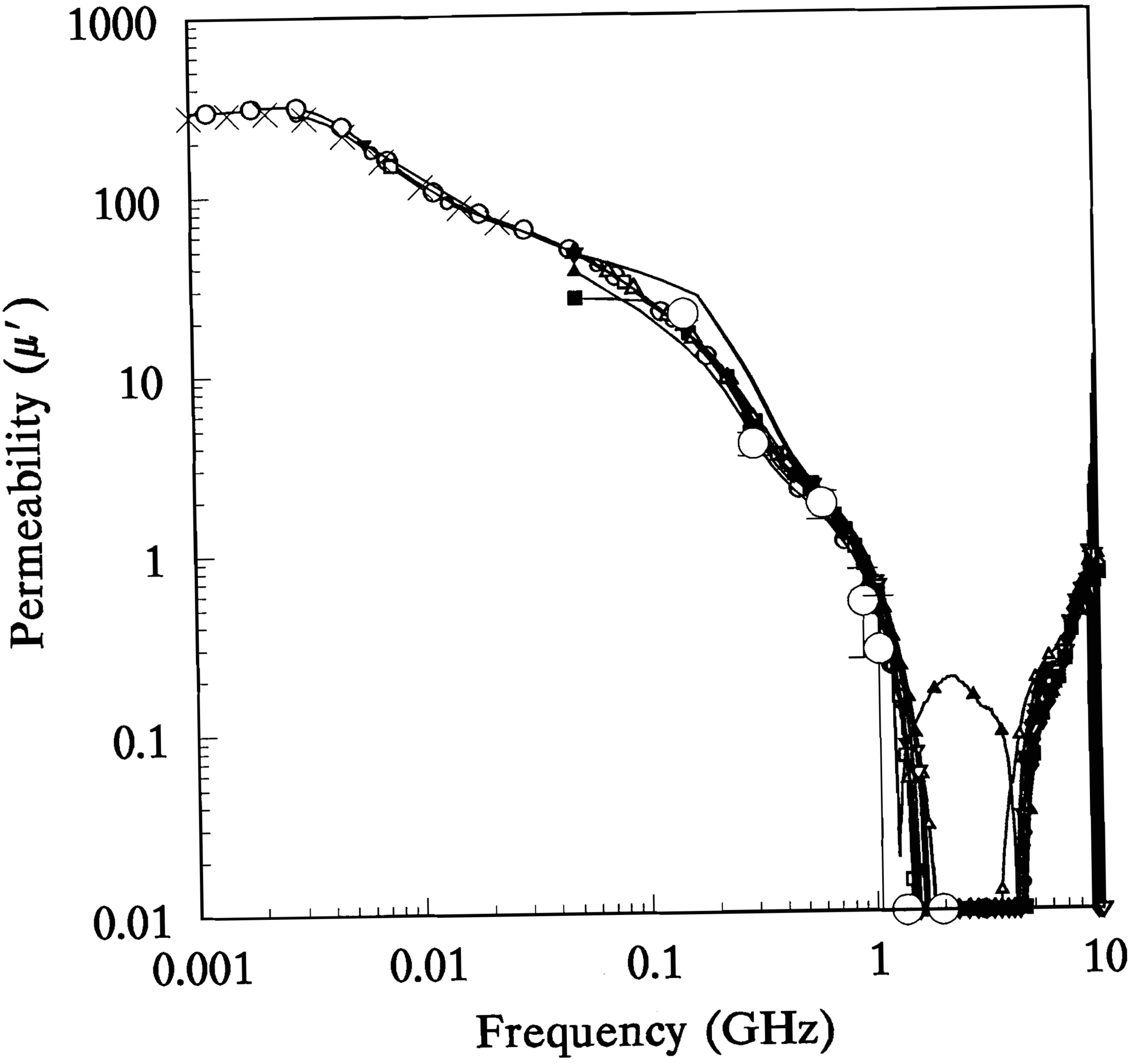

Figure 5b. Measured relative permeability, μ_r' for Material 5 (log)

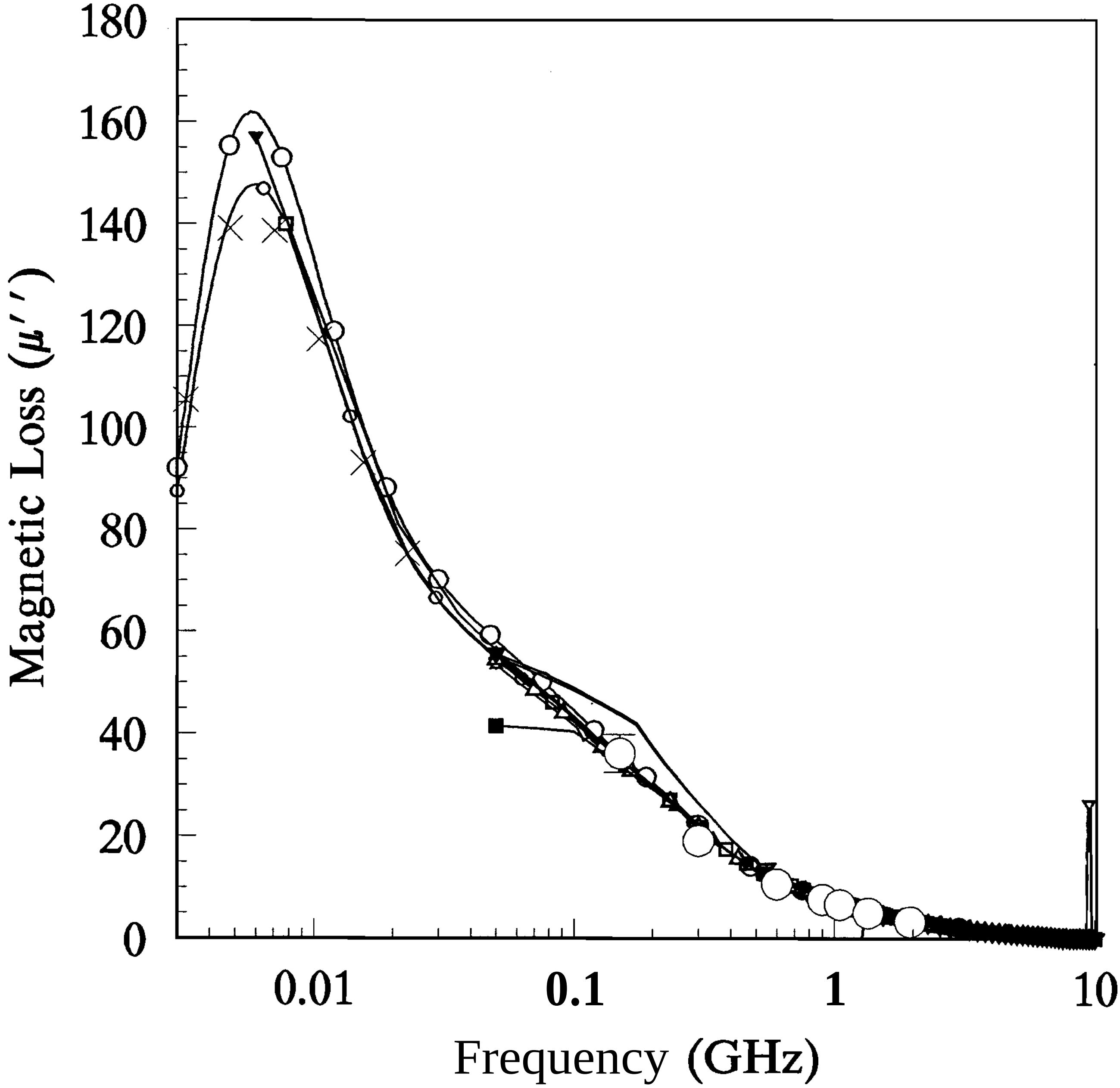

Figure 5c. Measured magnetic loss, μ_r'' for Material 5 (linear)

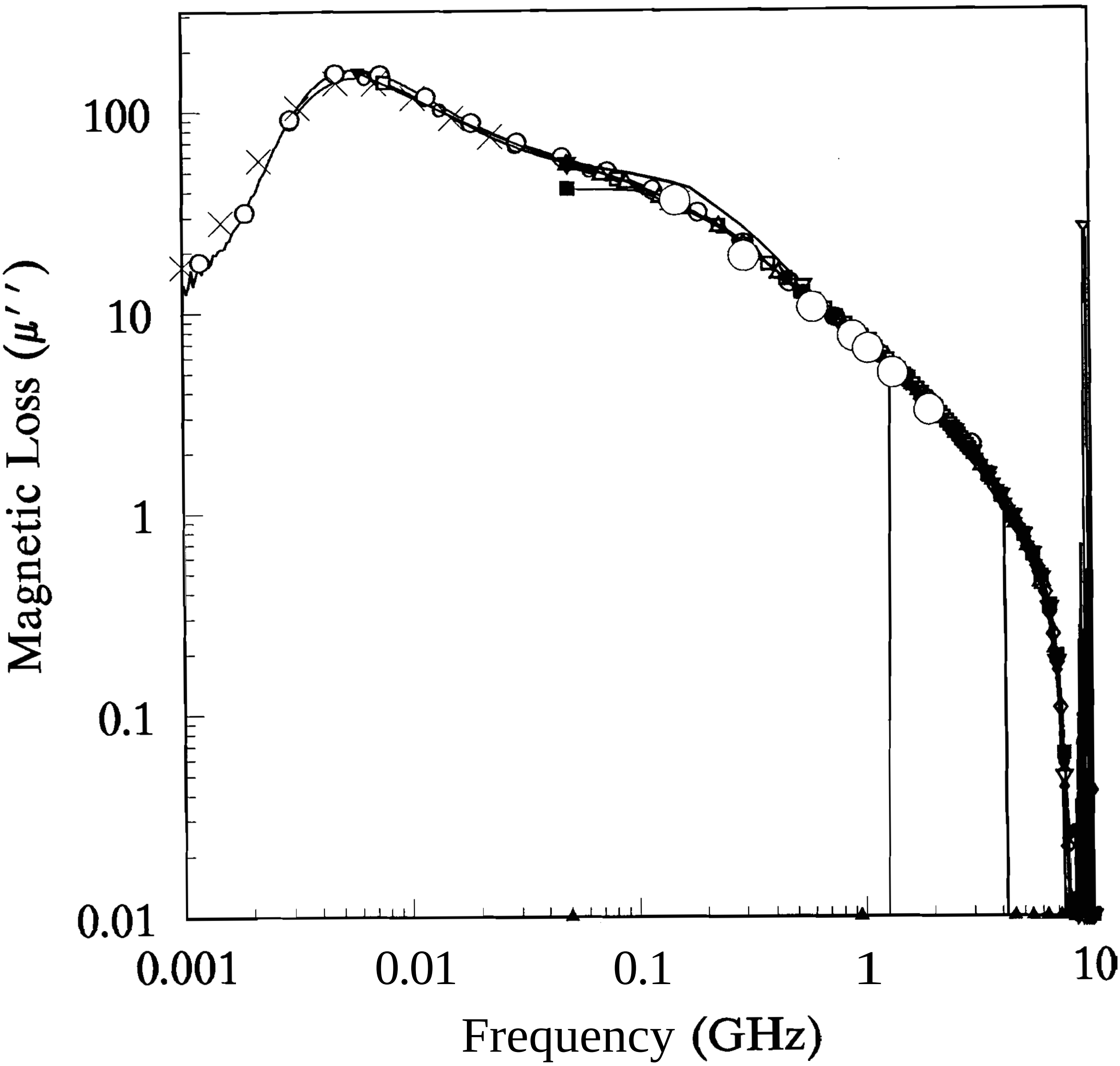

Figure 5d. Measured magnetic loss, μ_r'' for Material 5 (log)

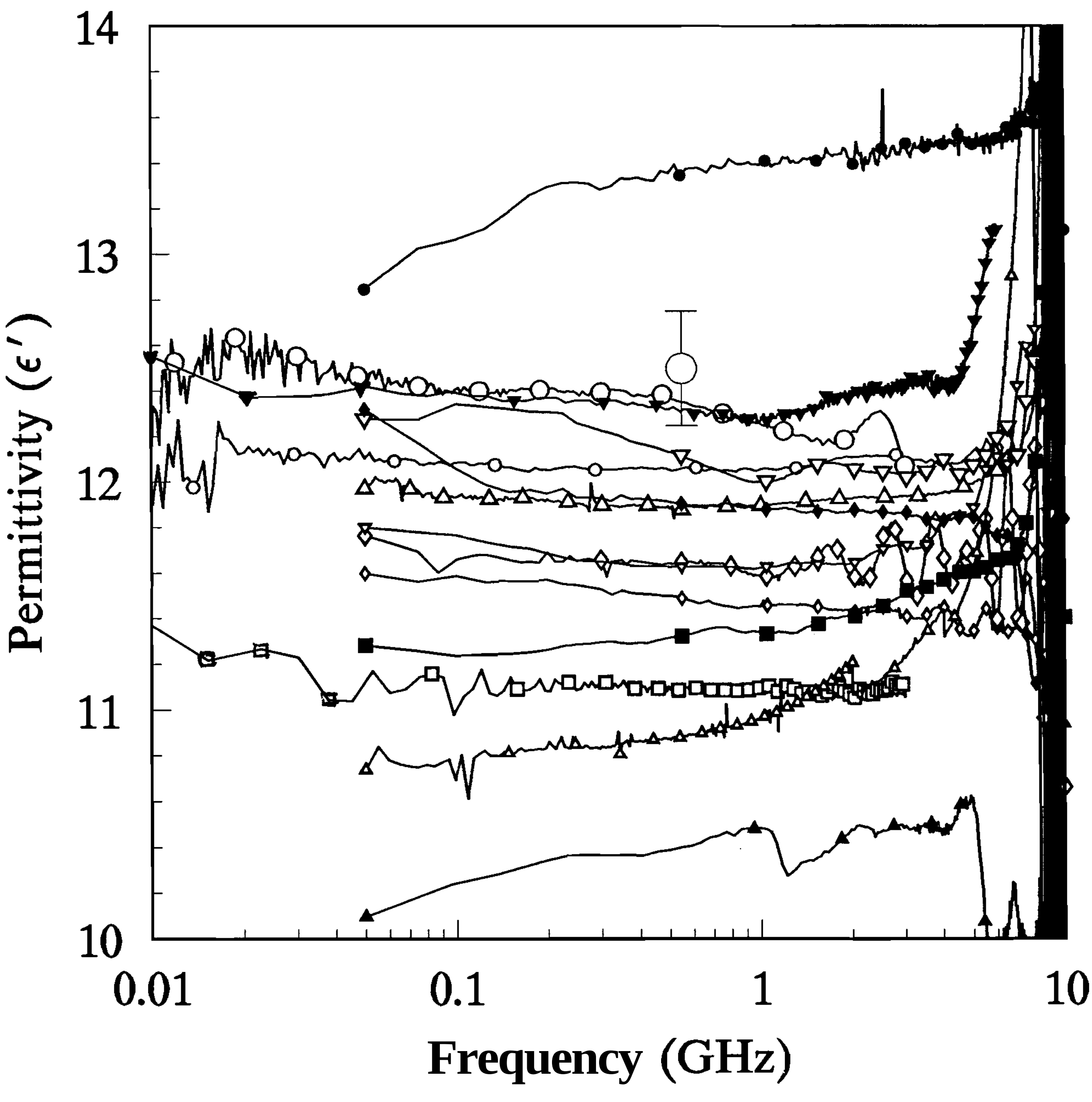

Figure 5e. Measured relative permittivity, ϵ_r' for Material 5

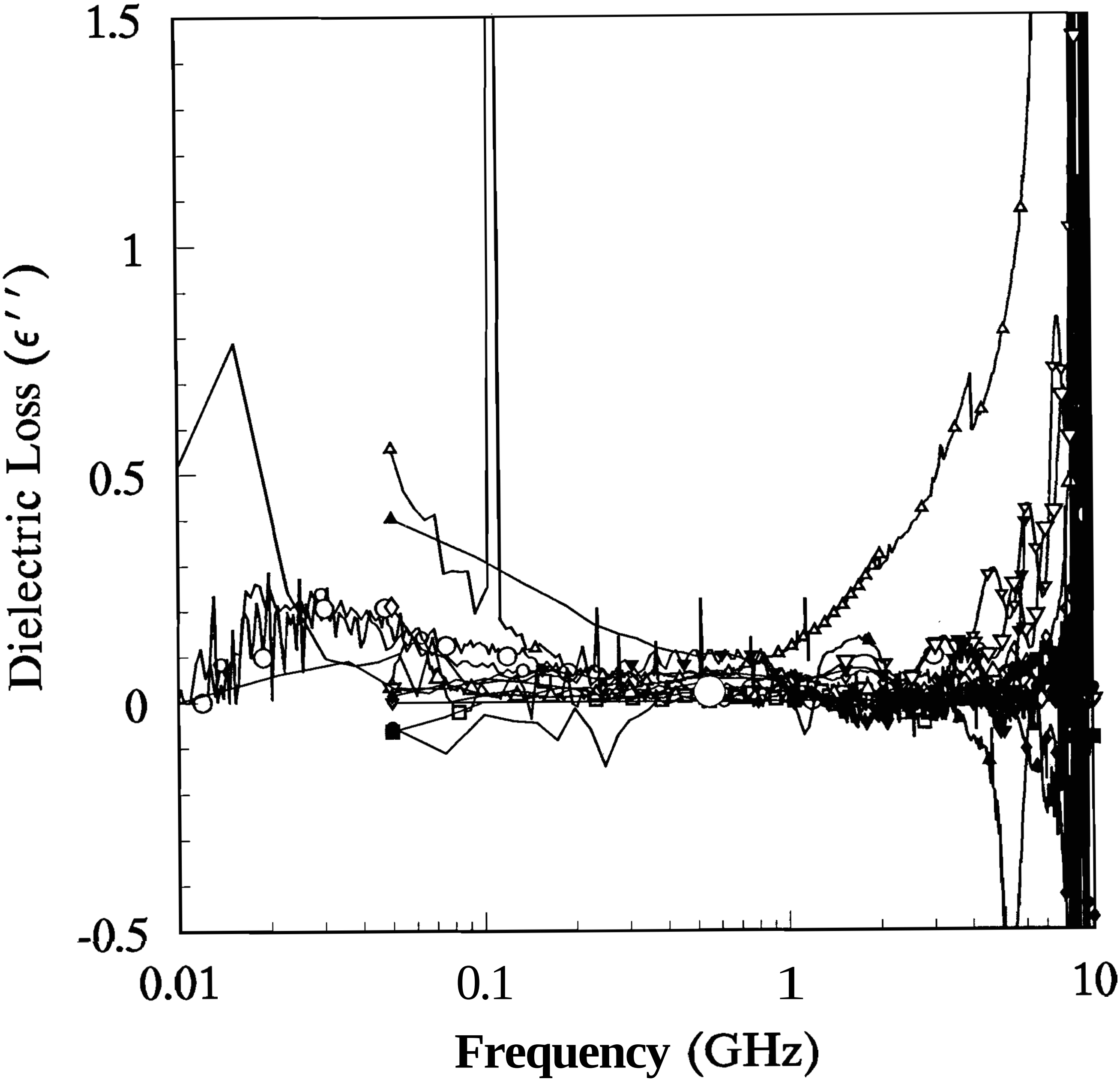

Figure 5f. Measured dielectric loss, ϵ_r'' for Material 5