

# ACCURATE MEASUREMENT OF FERRITE GARNETS TO BE USED FOR FAST-TUNED LOADED CAVITIES IN THE RANGE OF 20-40 MHz

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## Abstract

For the implementation of ferrite-tuned cavities with orthogonally biased ferrites in the frequency range of 20-40 MHz, different types of ferrite garnets were evaluated in terms of their electromagnetic properties. This paper describes a precision measurement method applicable to small-sized ferrite samples of 1-square-inch surface and 1.8 mm thickness in the given frequency range by means of a one-port reflection method. The material samples are exposed to a magnetic bias field range with different orientations. We present a detailed description of this technique as well as material results obtained.

## INTRODUCTION

We intend to build a ferrite-tuned cavity covering a tuning range of 18-40 MHz by making use of the changing  $\mu$ -characteristics of ferrites being exposed to an external magnetic bias field range. For frequencies below 40 MHz, magnetic properties of ferrites are rarely available from manufacturers and especially material characteristics resulting from an exposure to an external magnetic bias field are unknown for most materials in our frequency range of interest. Hence, for the selection of the proper ferrite for the cavity, we carried out frequency-swept measurements in the range of 1-100 MHz on five different material samples. Since ferrite tiles of a small size (1-square-inch surface and 1.8 mm thickness) are readily available from industry, the challenge was to find a test set-up for a precise determination of material parameters in the MHz-range from these extremely small-sized tiles. In addition, the method has to allow the exposure of the samples to different *orientations* of the magnetic bias field with respect to the magnetic RF-field. The classical method of using toroidal shaped samples is therefore not possible as it would in practice not permit the application of all three bias field orientations. Consequently, a stripline test set-up was chosen in which the entire sample holder could be inserted into the aperture of a dipole magnet for being exposed to a homogeneous bias field. The requirement for our application is to reach a doubling of the resonance frequency in the cavity (i.e., to cover a tuning range of 18-40 MHz). As the resonance frequency is inversely proportional to the square-root of  $\mu'$ ,  $f_{res} \sim 1/\sqrt{\mu'}$ , the permeability has to cover a tuning range of five, at least. We express this change in the real part of the permeability with  $r_\mu$ , the ratio of the permeabilities taken at 18 MHz and 40 MHz, and the different bias fields. This way, we obtain:

$$r_\mu = \frac{\mu'(18 \text{ MHz}, H_{\text{bias,low}})}{\mu'(40 \text{ MHz}, H_{\text{bias,high}})}$$

## MEASUREMENT SET-UP

Our measurement set-up is closely related to the method described by Barry [1] and has been adopted to be suited to the sample size and frequency range. For our application, the main issue is to find a ferrite with  $\mu$ -characteristics that can provide the required tuning range in the cavity. Hence, the goal of the measurement is to accurately determine the complex relative permeability  $\mu_r$  of ferrites for a frequency range of 1-100 MHz while being exposed to a varying external magnetic bias field. The complex material parameter splits into a dispersive and a dissipative component that is expressed as

$$\mu_r = \mu' - j\mu''$$

Figure 1 shows a simplified diagram of the measurement set-up. The DUT (device under test) is connected

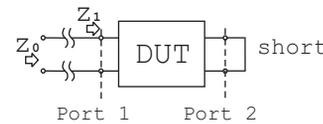


Figure 1: Simplified diagram of the measurement set-up.

to a Vector Network Analyzer (VNA) with characteristic impedance  $Z_0$ . The input impedance of the material under test is complex and is determined from the  $S$ -parameter  $s_{11}$  as  $Z_1 = Z'_1 + jZ''_1 = Z_0 \frac{1+s_{11}}{1-s_{11}}$ . This way, the real and imaginary parts of  $Z_1$  read:

$$Z'_1 = Z_0 \frac{1 - (s'_{11})^2 - (s''_{11})^2}{(1 - s'_{11})^2 + (s''_{11})^2}, \quad \text{and}$$

$$Z''_1 = Z_0 \frac{2s''_{11}}{(1 - s'_{11})^2 + (s''_{11})^2}.$$

We obtain the permeability of a ferrite of sample length  $l$  by terminating port 2 of the one-port line measurement with a "short". A calibration standard is used for this purpose. This way, the input impedance  $Z_1$  of the DUT reads:

$$Z_{1,\text{short}} = Z_S \frac{\alpha l + j \tan \beta l}{1 + j \alpha l \tan \beta l}.$$

The entity  $Z_S = \sqrt{\mu_r/\epsilon_r} Z_{ge}$  gives the dependency on permeability and  $Z_{ge}$  is the theoretical impedance of an unloaded stripline in vacuum, depending only on the stripline dimensions.

Due to the small sample length  $l$ , it is assumed that  $\alpha l$  and  $\beta l$  (attenuation and phase shift in the sample) are small. The assumption of  $\alpha l < 0.005$  is equivalent to  $e^{2\alpha l} = 1.01$ ,

thus is associated with an error of 1 % in the case that  $\alpha l$  is set to zero. Consequently, the input impedance reduces to the simple expression:

$$Z_{1,\text{short}} \approx j Z_S \beta l = j Z_{\text{ge}} \frac{2\pi l}{\lambda_0} \mu_r,$$

from which  $\mu_r$  can be determined. The impedance for the unloaded stripline,  $Z_{\text{ge}}$  can be found in textbooks [2]:

$$Z_{\text{ge}}/\Omega = \frac{94.25(1-t/h)}{\frac{w}{h} + \frac{2}{\pi} \ln\left[\frac{2-t/h}{1-t/h}\right] - \frac{t}{h\pi} \ln\left[\frac{t(2-t/h)}{h(1-t/h)^2}\right]}.$$

The formulae is valid for  $w/(h-t) \geq 0.35$  with an estimated error below 1.2 % as long as  $t/h \leq 0.25$ .

In our case, the stripline dimensions are  $t = 0.066$  mm and  $w = 3$  mm whereas the ferrite height  $h$  depends on the selected material sample. It is assumed that the RF-field is in TEM-configuration over the entire cross-section as is qualitatively shown in Fig. 2.

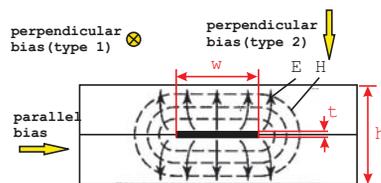


Figure 2: Stripline in ferrite with TEM field distribution in the cross-section, stripline dimensions, and different orientations of the external magnetic bias field.

## MEASUREMENT PROCEDURE

After connection of the test set-up and calibration, it was soon obvious that in spite of the usual standard port calibration being carried out on the VNA, neither the influence of the SMA connector lengths of the test set-up nor the actual position of the short termination which is slightly embedded in the calibration standard could be neglected. In view of the short lengths of the samples, it was a major concern that the electric lengths are determined precisely to correctly calculate  $\mu$  from the measured  $S$ -parameters. We have therefore first measured a teflon sample with the known material parameters  $\epsilon_r=2.1$  and  $\mu_r=1$  in the stripline assembly and then manually adjusted the electric lengths in the VNA settings for compensation of the lengths of the SMA connectors and the embedded terminations of the calibration standard. Figure 3 shows  $\epsilon'_r$  and  $\mu'_r$  measured on a teflon substrate. The different material samples in their sample holders were then put one after another into the aperture of the test magnet as shown in Fig. 4. The magnet was manually ramped while its magnetic bias field was monitored with a 3-axis Hall-effect Teslometer inside the magnet's aperture. The Teslometer underwent a calibration with a zero Gauss-chamber and reads with an accuracy of  $\pm 1$  % according to the equipment manufacturer. Due to the remanent field of the magnet, the lowest value obtainable

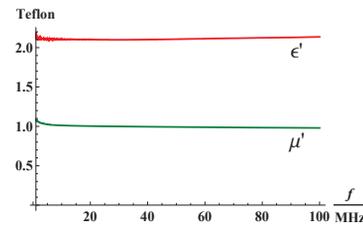


Figure 3: Stripline measurement on teflon substrate used to adjust the electrical lengths before measurement.



Figure 4: Aperture of the biasing magnet with sample holders and Hall-probe.

was around 0.012 T. The small size of the sample holder allowed the samples to be put entirely into the magnet's aperture so that exposure to a homogeneous external magnetic bias field was possible. With the assumption that the RF-field is in a TEM-configuration in the cross-section of the stripline set-up as shown in Fig. 2, there are three different principal possibilities for the orientation of the external magnetic field. These field orientations are of interest since for the cavity, the orientation of the ferrite tuning field could be perpendicular or parallel to the magnetic RF-field. Two possibilities exist to orient the external magnetic bias with respect to the magnetic RF-field in the case of perpendicular magnetic bias. Perpendicular bias, type 1 describes the case where the magnetic bias is applied in signal direction and thus perpendicular to the magnetic RF-field in the entire cross-section. Perpendicular bias, type 2 describes the case where the magnetic bias is applied perpendicular to the broad side of the stripline and thus perpendicular to the signal direction and to the major part of the magnetic RF-field. The applied magnetic bias field covers the range of approx. 0.012-0.100 T so that we start below the saturation magnetization of the different materials and in all cases reach sufficiently high values to fully saturate the sample.

## MEASUREMENT RESULTS

We tested five materials from different suppliers, namely RG-3 from AFT Microwave GmbH (Germany), Y36 from

Temex Ceramics (France), and G-300, G-510, G-810 from Trans-Tech Inc. (US). From our measurements, we observed a considerable difference in the real part of the permeability depending on the orientation of the external magnetic bias. In the case of *parallel biasing* none of the materials tested could provide the requested tuning range, as can be seen in table 1. The corresponding curves are therefore not shown. However, for materials G-510 and G-810, the required tuning range was reached for both cases of perpendicular magnetic bias and in the case of perpendicular magnetic bias, type 2, all investigated materials surpassed the required range of five. The measurements of materials G-510 and RG-3 are depicted in Fig. 5 and Fig. 6. As for the complex part of the permeability, we could see from the measurements that the reflection factor on these low-loss ferrites remains close to 1 in the frequency range covered. For the magnetic loss tangent,  $\tan \delta_m = \mu'' / \mu'$ , we expect values in the range of  $10^{-4}$ , i.e. for these materials, the measurement of reflection factor does not allow to determine  $\mu''$  with the required accuracy. We omitted this part and will report elsewhere about  $\mu''$ -measurements carried out. A summary of the measurement results for all materials is given in table 1. A larger value for  $\mu_r$  is to be expected for the case that the magnetic bias is tuned to values below 0.014 T (below the lower limit of the regulation range for our bias magnet).

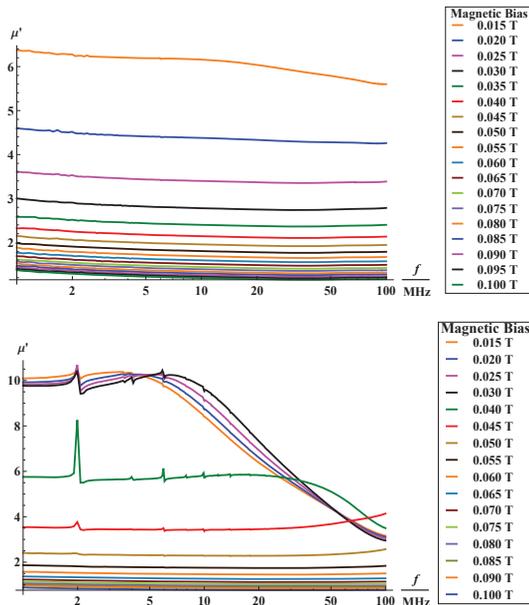


Figure 5: Measurement of  $\mu'$  vs. frequency on G-510 submitted to different orientations of the external magnetic bias field. Upper: Perpendicular bias, type 1; Lower: Perpendicular bias, type 2.

### CONCLUSION AND OUTLOOK

With the measurement results presented here, the construction of a full-sized cavity model has been started and

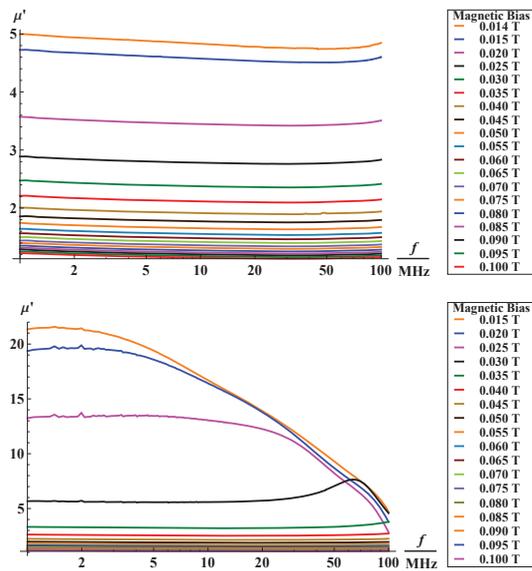


Figure 6: Measurement of  $\mu'$  vs. frequency on RG-3 submitted to different orientations of the external magnetic bias field. Upper: Perpendicular bias, type 1; Lower: Perpendicular bias, type 2.

Table 1: Ratio of permeabilities  $r_\mu$  as measured on the materials exposed to different bias fields orientations.

Material	$r_\mu$ with magnetic bias		
	parallel	perp., type 1	perp., type 2
Y36	1.25	4.1	11.1
G-300	1.27	3.7	9.0
G-510	1.45	5.2	8.7
G-810	1.46	7.2	8.5
RG-3	1.54	4.2	13.0

testing is currently under way. In a first step, we will use material G-510, however, in the case that perpendicular biasing, type 2 is successful, the use of RG-3 would be advantageous due to its large range. The final material has therefore not been decided yet. Results will be presented in a forthcoming paper.

### ACKNOWLEDGMENT

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### REFERENCES

- [1] W. Barry, "A Broad-Band, Automated, Stripline Technique for the Simultaneous Measurement of Complex Permittivity and Permeability", IEEE Trans. on Microwave Theory and Techniques, Vol. MTT-34. No. 1, 1986.
- [2] O. Zinke and H. Brunswig, "Hochfrequenztechnik, Band 1", Springer Verlag, Berlin, 1995.