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The losses of microwave ferrites at communication frequencies

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Abstract

Microwave ferrites have been used for many years in non-reciprocal devices such as circulators and isolators. These are widely used in base stations to protect the high power amplifiers from mismatch and subsequent damage. At the current time the international standard for the measurement of ferrite losses is the measurement of linewidth at 9.4 GHz at GyroMagnetic Resonance (GMR). Unfortunately most ferrite devices are used at much lower frequencies, especially 1.8 GHz, and there is significant uncertainty in how the losses vary as a function of frequency. Also most ferrite devices are never operated at GMR as this is the point of maximum magnetic loss. Therefore a measurement system has been developed to characterise both real and imaginary parts of the tensor permeability matrix. This can be done for ferrite materials at communication frequencies, such as those used in a typical circulator, and at varying bias levels. Results are presented for a range of commercial materials.

Keywords: Ferrites; Communications; Magnetic properties

1. Introduction

Ceramic ferrite materials, particularly yttrium aluminium iron garnet (YIG), find widespread use in microwave circuits for their non-reciprocal properties, and are employed in many different structures and configurations.

In communication systems ferrites are often employed in non-reciprocal devices such as circulators and isolators. In a non-reciprocal device the path that energy, or a signal takes, is dependent upon which direction it is entering the device. For example, in Fig. 1, if a signal enters the circulator at Port 1 then it will emerge at Port 2, but if it enters at Port 2 it will emerge at Port 3. In this way a circulator is said to be a non-reciprocal device, and it is this property that makes it so useful in so many microwave circuits. In Fig. 1 if one of the ports has a load attached (which perfectly absorbs microwave power) then the device is called an isolator. The permeability tensor of a ferrite material, when a dc magnetic field is applied along its z-axis, is described by a well-known Polder Tensor[1] as given in Eqs. (1)–(3).

$$\vec{\mu} = \mu_0 \begin{bmatrix} \mu & j\kappa & 0 \\ -j\kappa & \mu & 0 \\ 0 & 0 & \mu_Z \end{bmatrix} \tag{1}$$

$$\mu = 1 + \frac{\omega_0 \omega_{\rm m}}{\omega_0^2 - \omega^2} \tag{2}$$

and

$$\kappa = \frac{\omega \omega_{\rm m}}{\omega_0^2 - \omega^2} \tag{3}$$

where μ_0 is the free space permeability (H/m); $\omega_0 = \mu_0\gamma_0$, the Larmor frequency (rad/s); $\omega_{\rm m} = \mu_0\gamma M_{\rm s}$, the magnetisation frequency (rad/s); ω the microwave frequency (rad/s) and $M_{\rm s}$ is the saturation magnetisation (kA/m)

At the present time the overwhelming use of ferrite materials is as isolators, primarily for application in mobile communication equipment at 900 or 1800 MHz. However, although these materials are primarily used at 900/1800 MHz, their microwave losses are invariably characterised at 9.4 GHz in accordance with relevant standards.[2] In such standard techniques the samples are measured in the form of very small spheres within a much larger cavity. This measurement technique is called the standard linewidth and the power transmitted through the cavity is monitored as the applied magnetic biasing field is varied. The loss of

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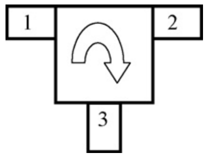

Fig. 1. Schematic of a circulator.

the ferrite is then measured when it goes through GyroMagnetic Resonance (GMR). This is the value of the magnetic biasing field which gives rise to maximum loss in the ferrite. As the spherical sample occupies only a tiny part of the overall volume of the cavity, this can gives rise to very poor sensitivity to the ferrite losses. This is particularly true of YIG doped with calcium and vanadium, which has extremely low losses at these frequencies. The surface finish of such samples also becomes very important and they often require considerable surface polishing which can be difficult to achieve in a spherical sample. Consequently it can be difficult to distinguish between samples of different quality unless they are obviously particularly poor. What is required is a sensitive measurement technique that can also evaluate the samples at 1800 MHz. This latter point is important because there is significant uncertainty in exactly how the magnetic losses vary with frequency, particularly over such a large frequency range. It is also much more appropriate to measure the ferrite, at a similar value of constant biasing field that it will experience in a real isolator.

This paper reports on a sensitive characterisation technique that can measure the losses of ferrite materials at GSM 1800 frequencies. The structure used is shown in Fig. 2 and essentially consists of a ferrite rod inserted down the centre of a circular dielectric ring resonator (DRR).

The structure can be divided up into three regions, I, II and III, which correspond to the ferrite rod, the dielectric ring and the surrounding air, respectively. The DRR also has copper plates resting upon both end faces and this kind of configuration is often called a Hakki–Coleman configuration. A constant magnetic biasing field is applied along the axis of the ferrite rod to bias the ferrite sample under test. Standard cylindrical coordinates are assumed with the *Z*-axis along the axis of the ferrite sample and the *X*–*Y* plane is assumed to be transverse to *Z*. The radius of the ferrite rod and the outer radius of the DRR are assumed to be *a*, and *b*, respectively.

Some work on a similar structure has already been performed[3] at 9.4 GHz using alumina DRR. However the work at 9.4 GHz used the Rayleigh Ritz method, so a detailed mathematical analysis was never published. Also that work was confined solely to isotropic DRR. This analysis uses the radial mode matching (RMM) method, which permits a detailed mathematical analysis and also considers the case where the DRR may be an-isotropic single crystal material, such as sapphire or titanium dioxide (rutile). This latter point is very important as to perform magnetic loss measurements at 1800 MHz requires low loss high permittivity DRR. Low losses are essential to increase the *Q* and hence make the system more sensitive. High permittivity is required to reduce the size of the DRR and also increase the fraction of magnetic field energy inside the ferrite sample. This latter point is important because the larger the fraction of magnetic field energy inside the ferrite, the greater its sensitivity to the ferrite losses.

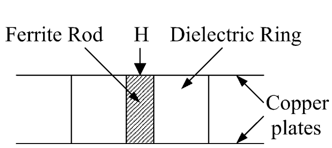

Fig. 2. Schematic of the measurement system.

The shape of a thin cylindrical ferrite sample was chosen specifically to avoid any serious concerns about the size of the biasing field inside the ferrite. Providing the length of a ferrite rod is significantly longer than its diameter then it is a reasonable approximation to state that the internal field inside the ferrite is the same as the external biasing field. This is certainly not the case in a typical ferrite circulator where the ferrite is usually in the form of a thin disc. In this geometry although a uniform external biasing field may be applied over the surface of the disc it has been shown that the resultant internal biasing field can be quite different in size from the external field. It has also been shown that even though the external field is completely uniform, due to demagnetising effects, the size of the internal field varies quite considerably in a radial direction.[4]

2. Experimental arrangement and design simulation

To perform loss measurements at 1.8 GHz two different types of Hakki–Coleman resonators were designed, one made from single crystal rutile and the other from commercially available isotropic dielectric with an ε_r of 45, called CTNA. Single crystal rutile is an-isotropic material and this sample was grown with an ε_r of 165 along the axis of the DRR and an ε_r of 85 in the transverse plane.[5] CTNA or $CaTiO_3$–$NdAlO_3$ is a commercially available ceramic. It is widely used in microwave applications such as resonators and filters due to its high dielectric constant, low losses and excellent temperature stability. CTNA is typically used for dielectric resonators operating around 1.8 GHz and has a loss tangent of 3.0×10^{-5} at this frequency. Both resonators were designed for an operating frequency of 1.784 GHz and could accommodate a ferrite sample that was 20 and 5 mm in length and diameter, respectively. The length of 20 mm was chosen to minimise the conductor losses in the overall resonator. In essence the longer the resonator, the smaller the contribution from conductor losses in the end plates and therefore the more sensitive the measurement system becomes. But there are practical limitations set on the length. If the resonator is made too long then there can be significant radiation from the side-walls and several resonant modes can overlap, making measurements difficult. The size of the ferrite sample is also a difficult choice, as a bigger sample means greater sensitivity to ferrite losses, but requires a significantly larger rutile resonator. Since the single crystal rutile material is extremely expensive care must be taken to try and minimise its size.

For accurate loss measurements of the ferrite two resonators are needed for each type of DRR. In essence measurements are performed with and without the ferrite sample in place and from

Table 1
Comparison of filling factors for single crystal rutile and CTNA resonators operating under an applied field, H_0 of 140 kA/m at 1.8 GHz

Ferrite properties used for both the rutile and CTNA resonator (G-113NLW)

$4\pi M_s$	ε_f	μ	κ	μ_Z
1800	15	2.146	0.42	1

Mode	P_{ε_f}	P_{μ}	P_{κ}	P_{μ_Z}
Rutile resonator				
TE011	0.00277	0.00155	0.0000058	0.17305
HE + 111	0.05336	0.20201	0.03943	0.00065
HE − 111	0.05696	0.11785	−0.02311	0.00052
CTNA resonator				
TE011	0.00087	0.00049	0.0000018	0.05559
HE + 111	0.04695	0.10955	0.02138	0.00003
HE − 111	0.05121	0.06687	−0.01305	0.00002

the change in frequency and Q it is possible to calculate the real part and imaginary part of the permeability, respectively.[3] To perform measurements on the ferrite then, for each type of material, two DRR's were needed, one operating in the TE011 mode and the other in the HEM111 mode. In Table 1, the dielectric and magnetic filling factors are displayed for both the isotropic CTNA resonator and the one made from rutile single crystal. P_{ε_f} is the fraction of electric field energy contained within the ferrite rod. P_{μ}, P_{κ} and P_{μ_Z} are the fraction of magnetic field energy stored in the ferrite rod for μ, κ and μ_Z, respectively. For the same sized ferrite sample and operating at the same resonant frequency the rutile resonator has filling factors, and hence sensitivity, that is twice than that of the isotropic one. This is due to the much larger permittivity of the rutile single crystal resonator compared to that of the CTNA. For the purposes of the modelling below, in both the rutile and CTNA resonators the size of the ferrite sample was 5 and 20 mm in diameter and length, respectively. The biasing field was also 140 kA/m in each case. The real part of the permeability values used in Table 1 was calculated, at 1.8 GHz, from the standard polder tensor permeability for saturated ferrite material. Although these filling factors appear small they are actually quite large compared to alternative measurement systems. In essence the TE011 mode is most sensitive to the value of μ_Z while the HEM modes are most sensitive to the values of μ and κ, but predominantly μ. In the experimental setup, the DDR has a ferrite sample inserted into its centre hole. Both are then held together tightly by clamping in the centre of the designed jig, with coupling probes connected to the network analyser (NA) before placing them in the middle of the electromagnet as shown in Fig. 3. The resonant frequency and unloaded Q is then measured from the NA at certain biasing field by gradually applying a dc biasing field across the Z-axis of the composite structure. These procedures were repeated for different types of DDR and ferrite samples. The practical results were then analysed using the RMM method to compute the magnetic losses for the ferrite.

The results in Table 1 show that for the HE − 111 mode P_{μ} and P_{κ} are nearly twice as large for the rutile resonator than that for the CTNA resonator. Nearly all circulators manufactured for operation at 1800 MHz are designed so that the ferrite material is used above GMR and the ferrite material is selected so that is in saturation. Therefore measurements of ferrite losses were focused on materials that are commonly used in 1800 MHz circulators and at biasing fields where those materials were above saturation.

The total losses of the structure in Fig. 2 can be divided into a series of contributions from different loss mechanisms, and hence the overall unloaded Q, Q_u can be divided up as in Eq. (4). Where Q_c represents the conductor losses in the metal end plates, Q_{eDRR} represents the dielectric losses in the DRR, Q_{ef} represents

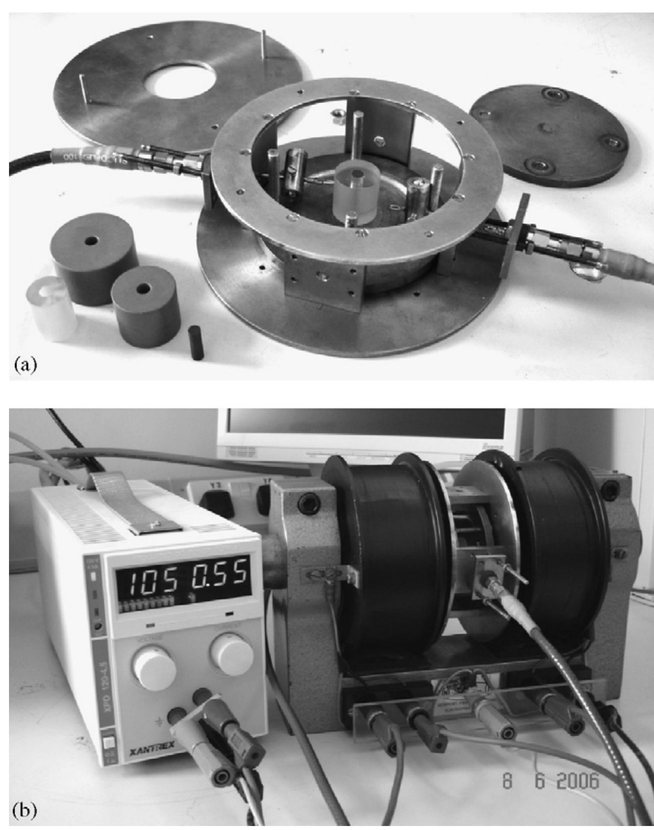

Fig. 3. Apparatus setup (a) measurement jig; (b) electromagnet and power supply for ferrite losses measurement system.

Table 2
Properties of ferrite samples

Ferrite material	4piM_s (G)	3 dB linewidth (Oe)
TTVG-1000	1011	8
G-113NLW	1800	20
G4256	1544	79
G1004 + MN + Ho	837	105
TT2-111	5037	152
TT2-125	2059	485

the losses due to the dielectric loss of the ferrite sample and Q_{Mag} represents the sum of the magnetic losses.

$$\frac{1}{Q_u} = \frac{1}{Q_c} + \frac{1}{Q_{\text{eDRR}}} + \frac{1}{Q_{\text{ef}}} + \frac{1}{Q_{\text{Mag}}} \tag{4}$$

Thus,

$$\frac{1}{Q_{\text{Mag}}} = \frac{1}{Q_u} - \frac{1}{Q_c} - \frac{1}{Q_{\text{eDRR}}} - \frac{1}{Q_{\text{ef}}} \tag{5}$$

Similarly it is possible to subdivide the overall magnetic losses, represented by Q_{Mag}, into individual contributions, where Q_μ represents the losses due the magnetic losses in μ, Q_κ represents the losses due the magnetic losses in κ, and $Q_{\mu Z}$ represents the losses due the magnetic losses in μ_Z.

$$\frac{1}{Q_{\text{Mag}}} = \frac{1}{Q_\mu} + \frac{1}{Q_\kappa} + \frac{1}{Q_{\mu Z}} \tag{6}$$

where

$$Q_\mu = \frac{1}{P_\mu \tan \delta_\mu} \tag{7}$$

Finally the individual magnetic Q's, such as Q_μ can be related to the filling factor P_μ and the magnetic loss tangent for μ via Eq. (7). Similarly Q_κ and $Q_{\mu Z}$ can be related to an individual filling factor and loss tangent.

3. Results and discussion

The results of simulations and practical results are presented in Table 3 for case of the empty resonators, i.e. with no ferrite present. Table 2 summarises the material properties of the ferrite, giving the saturation magnetisation, 4piM_s, and the standard 9.4 GHz linewidth. As can be seen from Table 3 the agreement between predicted and measured Q was quite good for three of the resonators but that of the rutile HEM111 resonator was significantly lower, as was its resonant frequency. This latter point meant that the results were at a much lower frequency and hence it was more difficult to scale the results up to 1.8 GHz. For this reason it was decided to use only the CTNA resonator for measurement in the hybrid modes.

Fig. 4(a) compares the modelled resonant frequency of the TE011 mode, calculated using the radial mode match method, with actual measured values. In this case the DRR was made from CTNA and the ferrite was a G113NLW sample, which is essentially a YIG based material. As the biasing field is increased the permeability of the ferrite changes which gives rise to a corresponding change in frequency. The agreement between predicted and measured frequency is extremely good, typically within 1 or 2 MHz which at 1800 MHz represents an error on the order of 0.1%. At very low biasing fields <40 kA/m the real part of the permeability is modelled using the equations by Green and Sandy.[6] Fig. 4(b) compares the modelled resonant frequency of

Table 3
Properties of the empty CTNA and rutile DRR

Mode	CTNA	Rutile
TE011		
Freq (GHz)	1.745	1.754
Q_c from CST	12918	27848
T and scaled to 1.745 GHz	5.1×10^{-5}	3×10^{-5}
Q_u from simulation	7790	12553
Q_u measured	7050	11129
Percentage of theoretical Q attained	90.5%	88.6%
HEM111		
Freq (GHz)	1.8643	1.656
Q_c from CST	7382	6854
T and scaled to 1.864 GHz	5.4×10^{-5}	2.75×10^{-5}
Q_u from simulation	5291	5776
Q_u measured	4700	4435
Percentage of theoretical Q attained	88.8%	76.8%

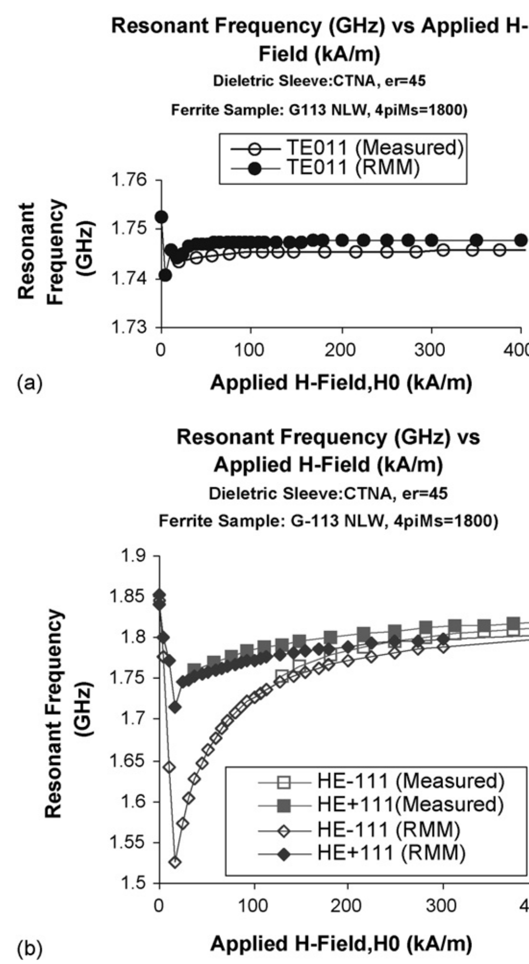

Fig. 4. (a) Comparison between measured and prediction resonant frequency for TE011; (b) comparison between measured and prediction resonant frequency for HE ± 111.

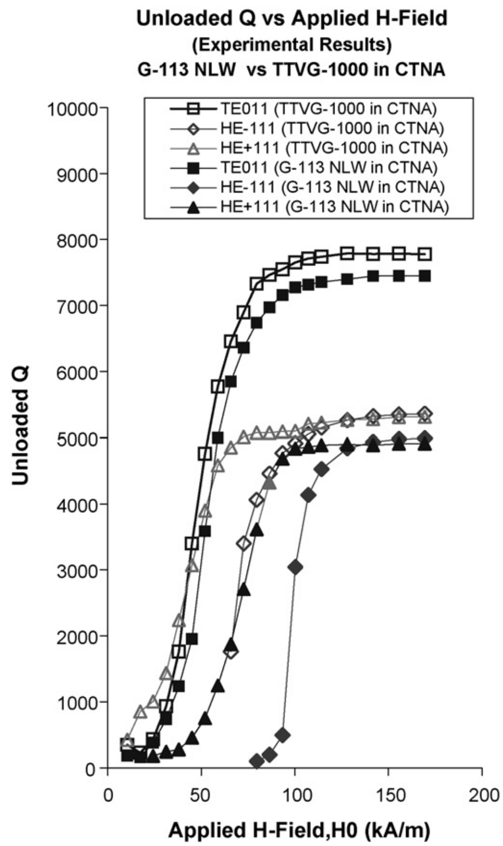

Fig. 5. Q_u vs. H_0 for G-113 NLW and TTVG-1000 in CTNA for TE011 and HE ± 111.

the HEM ± 111 modes, calculated using the radial mode match method, with actual measured values. The DRR was again made from CTNA and the ferrite was the same sample. The agreement is generally good, typically within 10 or 20 MHz which at 1800 MHz represents an error on the order of 1–2%. It was not possible to measure the resonant frequencies of the resonator at very low applied biasing fields as the ferrite was so lossy it was not possible to identify the resonance. Fig. 5 shows the measured Q values for the G-113 NLW and TTVG-1000 (based on CVG) materials in the CTNA resonator. Results are presented for the both the TE011 and HEM ± 111 modes for each material. G-113 NLW and TTVG-1000 are amongst the lowest loss ferrites available for isolators operating at 1800 MHz, having linewidths of 20 and 8 Oersted (Oe) respectively. In both cases the Q's are very close to those measured when the resonators were empty, suggesting that the magnetic losses of these materials must be extremely small. Since the errors in the repeatability of the Q measurements were ±150 it is not conclusively possible to say which is the better material, but in all measurements the TTVG-1000 always had a slightly higher Q. At low values of applied biasing field the material is not saturated and hence the ferrite losses are very large, due to low field losses.[7] As the biasing field is increased the material becomes saturated and the losses are substantially reduced. Fig. 6 shows the unloaded Q versus biasing field for the TE011 mode only when sample G-113 NLW and G1004 was measured in both the CTNA and rutile resonators. This clearly shows the larger Q achieved in the rutile resonator

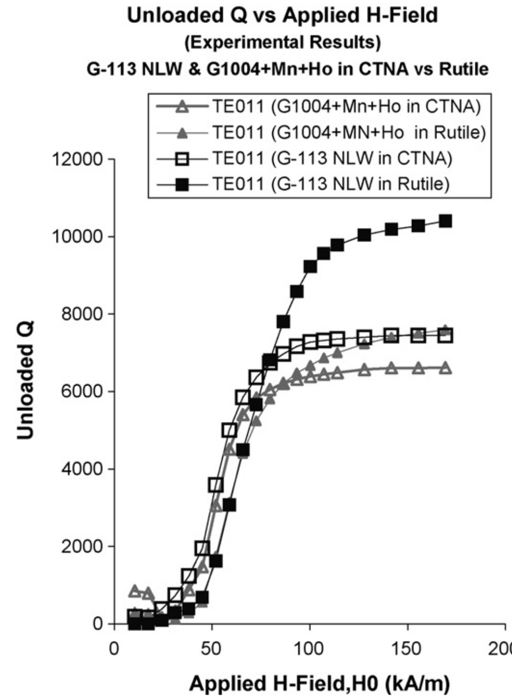

Fig. 6. Q_u vs. H_0 of TE011 mode for rutile and CTNA with various samples.

which therefore implies much greater sensitivity to the losses of the ferrite. The much lower Q of the G1004 is also apparent. Fig. 7 shows the unloaded Q versus applied biasing field for G1004 and G4256. For G1004 the Q of the hybrid mode rises quite rapidly at low applied field compared to that of the G4256. This is because the saturation magnetisation of G1004 is approximately half that of the G4256 and hence it will saturate at much lower fields with a consequent reduction in loss. However

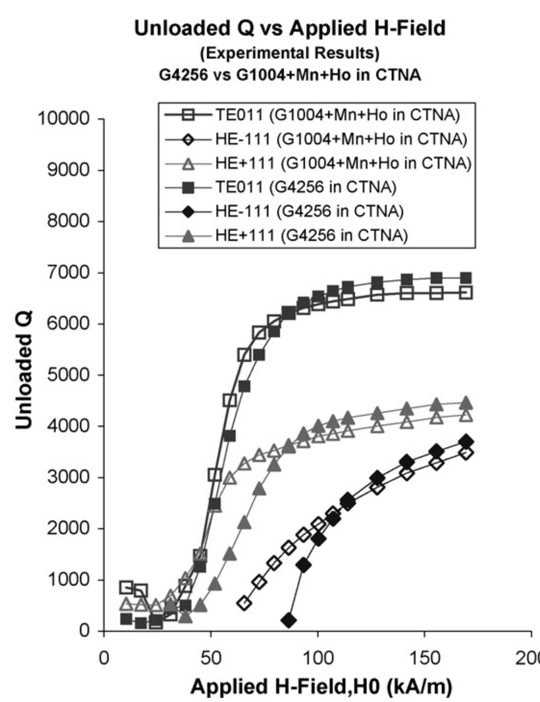

Fig. 7. Q_u vs. H_0 for G1004 + Mn + Ho and G-4256 in CTNA.

Table 4
Summary table of magnetic loss tangent for various ferrite material at about $H_0 = 140$ kA/m

Ferrite material	4piM_s (G)	3 dB linewidth (Oe)	Mode	Q_u	Q_m	tan $\delta_{\mu Z}$	tan δ_u
G-113 NLW	1800	20	TE011	7444	−1231462	−0.0000146	
			HE + 111	4881	124816		0.00008643
			HE − 111	4937	149930		
G4256	1544	79	TE011	6964	118617	0.0001519	
			HE + 111	4346	31140		0.00090350
			HE − 111	3303	9467		
G1004 + MN + Ho	837	105	TE011	6603	61400	0.0002955	
			HE + 111	4083	21402		0.00103851
			HE − 111	3087	7916		

once both samples are fully saturated around 160 kA/m, the Q of the G4256 is noticeably higher, in agreement with the linewidth, which is 79 and 105 Oe, respectively for the G4256 and G1004.

Table 4 gives a summary of the measurements upon the three ferrite samples measured here. The unloaded Q of each material is listed along with the corresponding mode. These Q's were all measured at a biasing field of 140 kA/m when all of these materials were well saturated. From each of these unloaded Q's the magnetic Q was calculated along with a breakdown for the individual magnetic loss tangents of μ_Z and μ. Since the filling factor for κ is small in both HEM ± 111 modes it is subject to quite significant error. Consequently the calculated magnetic loss tangent of κ has been deliberately excluded.

In Table 4 the negative number stated for Q_m and tan $\delta_{\mu Z}$ essentially prove that the loss tangent of tan $\delta_{\mu Z}$ is too small to measure with the current measurement system. So for the G-113 NLW materials the quoted number for tan δ_μ is probably an upper limit and might actually be smaller than this. Estimates for the errors in the magnetic loss tangents for G4256 and G1004 could be as high as 50%. These errors seem very large but other alternative techniques such as coaxial resonator measurements would suffer even larger errors due to the lower Q's and the pre-dominance of the conductor losses in such structures. This probably explains why there is a remarkable scarcity of information on the losses of microwave ferrites at 1.8 GHz.

Judging by the much larger difference in the Q of the hybrid modes, for materials G4256 and G1004 it would suggest that tan δ_κ is much larger in these materials than in G-113 NLW. Also since the Q of the TTVG1000 material was consistently slightly higher than that of the G-113 NLW it seems reasonable to suppose that the magnetic losses for this material must be even lower.

4. Conclusion

Preliminary measurements have been taken, of the magnetic losses of ferrite materials used in 1800 MHz isolators. Measurements at 1.8 GHz are significantly more difficult than at 9.4 GHz as the sample size is much smaller compared to the overall resonator size. As a consequence sensitivity tends to suffer and also at high biasing fields the permeability values become smaller resulting in very small filling factors. It is interesting to speculate that the magnetic losses of G-113NLW and TTVG-1000 must both be significantly less than 10^{-4} at 1800 MHz. This might explain why there has been a gradual shift by the circulator manufacturers away from CVG materials, such as the TTVG-1000 towards YIG based materials such as the G-113 NLW. Since in a circulator if the magnetic losses are $\ll 10^{-4}$ then the conductor losses will be heavily dominant.

Future work could utilise a CTNA resonator with a much larger ferrite sample. However since many CVG materials are fired in oxygen large sections might result in an oxygen deficit core, with subsequent poorer performance. Further work to try and reduce the conductor losses of the resonator would be particularly useful as it is the predominant source of loss in the system.

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