Microwave and Magnetostatic Characterization of Ferrite LTCC for Tunable and Reconfigurable SiP Applications

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Abstract — **The material property extraction techniques for an emerging commercial ferrite LTCC (Low Temperature Co-fired Ceramic) tape are presented. These properties are evaluated in the context of tunable and reconfigurable microwave components for wireless communications. Relevant parameters for microwave design, including relative permittivity ε_r, relative permeability μ_r and loss tangent tanδ, are presented. Measurements performed at 9.86 GHz and 27.2 GHz yield an ε_r of 13.6 and tanδ values of 0.004 and 0.001 respectively. For the first time, a completely embedded LTCC toroid transformer is utilized to extract the magnetostatic properties with greater accuracy than a solenoid transformer. These measurements reveal a saturation flux density of nearly 400 mT, a remanence of 250 mT, and a coercivity of 430 A/m. The peak relative linear permeability of the ferrite is 370. The low loss tangent and the high degree of variability of the ferrite properties with bias indicate its suitability for tunable and reconfigurable microwave SiP (System in Package) applications.**

Index Terms — **Ferrite, LTCC, microwave measurements, magnetic hysteresis, SiP.**

I. Introduction

With the ever growing need of compact, highly integrated and small size transceiver systems in the wireless industry, LTCC (Low Temperature Co-fired Ceramic) technology offers many attractive features and possibilities to achieve these goals. The size of an LTCC substrate can be reduced considerably because of its 3D capabilities and because passive components such as capacitors, resistors, inductors and antennas can be embedded, which facilitates a high degree of integration [1]. Efficient passive elements can be designed in LTCC because of its low losses. The introduction of ferrite material in the package not only helps in the miniaturization of the components but it also permits the control of the devices made from it. Ferrite allows the properties of the package to be dynamically altered, meaning that the package will have the ability to control the signals that are passing through it [2]. Therefore ferrite LTCC is a perfect candidate for tunable passive elements. The System-in-Package (SiP) work is an attempt to push the package beyond merely providing embedded passives, wiring, and physical protection: the package itself would become the device. This concept is useful for applications like DBS-TV (Direct Broadcast Satellite Television) reflect array, where reconfigurable coverage is required, or for multi-band wireless sensor systems. This paper investigates the suitability of ferrite LTCC for SiP designs.

Ferrite integration in the LTCC medium is a fairly new concept. A limited number of experimental ferrite tape materials are currently available and can be used as stand alone systems or sandwiched between standard LTCC dielectric layers. It is therefore necessary to characterize these substrates for their material properties such as ε_r, μ_r, dielectric loss tangents, and saturation magnetization. This work is focused on the extraction of these properties for an experimental ferrite LTCC tape system ESL 40012 [3]. Generally, material characterization of ferrite substrates has been limited to microwave properties and very little work has been done to explore their magnetostatic properties [4], which are equally important. Previous work that we have performed at microwave frequencies could only extract the product of ε_r and μ_r, as well as the loss tangent [5]. In the present work, the individual values have been isolated independently using a cavity resonance technique. Magnetostatic characterization is also performed in this paper, employing both solenoid and toroid transformers that are completely embedded in the LTCC material under test. The novel toroid transformer has been chosen to eliminate the end-effects and magnetic flux leakage that are associated with solenoid transformer designs.

II. Microwave Characterization

Microwave frequency characterization is required to extract ε_r, μ_r and the loss tangents of the LTCC ferrite substrate. Here we obtain these properties for the substrate in the unbiased state; biasing considerations are discussed in Section III. Generally, transmission line methods are used to obtain the material parameters; they are wideband and simple, but are less reliable. In contrast, resonant cavity methods measure complex permittivity and permeability at discrete frequencies but are very accurate. The resonant method employed here has been applied in many studies and compared to many other methods [6]. This technique does not require any preparation of the sample (cutting, polishing, or metallization) and makes no theoretical approximations. The test substrate is inserted between the two halves of a cylindrical cavity. It is excited in the $TE_{01,2q+1}$ mode to minimize the measurement uncertainties. Indeed, using the $TE_{01,1 \text{ or } 3 \text{ or } 5}$ modes, the electric field is parallel to the plane of the sample and has negligible values close to the gap between the sample and the cavity wall. The frequency band for material characterization is defined by the inner diameter of the cavity. The minimum lateral dimension of the substrate must be larger than the inner diameter of the cavity (∅ = 45 mm at 10 GHz and 18 mm at 25 GHz). The thickness of the sample must be as thin as possible (between 100 to 500 μm) to avoid resonant modes inside the sample. Given the substrate thickness, two cavities with resonant frequencies near 10 and 25 GHz have been used. In such a configuration, the resonant frequency and quality factor of the resonant cavity mode can be computed exactly. Based on iterative computation, the complex permittivity and permeability of the sample can be extracted from the measured resonant frequency and quality factor. The loaded quality factor of one of the $TE_{01,2q+1}$ modes is used to compute the power losses due to the metallic walls. As it is explained in [7], to determine the permittivity and the loss tangent of the substrate we only need the measurement of the resonant frequency and of the loaded quality factor of the cavity loaded with the sample. The uncertainties of ε_r and tanδ are due to the uncertainties of the measured quality factors and resonant frequencies and of the manufacturing tolerances of the cavity (radius and height) and of the sample thickness.

Two samples have been tested and characterized. In both cases, the unbiased state is considered, and the permeability μ_r is found to be 1. Due to the sample size constraints, the lowest measurement frequency was 9.86 GHz. It is well known that the initial permeability of the ferrite materials goes to 1 at frequencies higher than a few GHz, which is consistent with the measured results. Table 1 presents the ε_r and tanδ parameters for the two samples at two frequencies.

TABLE 1
MEASURED ε_R AND TANδ PARAMETERS

	Frequency (GHz)	Thickness ($t \pm dt$) μm	$\varepsilon_r \pm d\varepsilon_r$	(tanδ ± dtanδ) 10^{-3}
Sample 1	9.86	230 ± 10	13.70±0.59	4.24±0.37
Sample 2	27.2	230 ± 10	14.14±0.65	1.11±0.10

In addition to the resonant cavity method, the TRL (Thru-Reflect-Line) calibration technique has also been utilized with printed CPW lines to assess the line losses for the ferrite under test. The attenuation constant α was extracted from the calibration structures built on the ferrite substrate and is shown in Fig. 1.

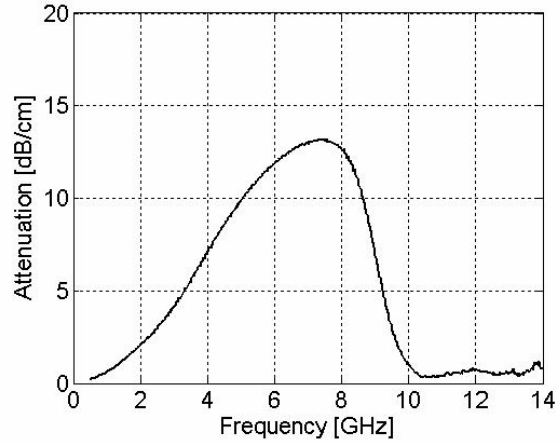


Fig. 1. Attenuation constant extracted from TRL calibration

Except for the 2-9 GHz band, the α values of around 0.5 dB/cm in Fig.1 confirm the low loss behavior of this material. However, the large loss observed in Fig.1, which peaks around 7 GHz, is due to the resonance of domain wall rotation inside the ferrite. It is a phenomenon that is related to low-field losses in unsaturated polycrystalline ferrites. For practical circuit applications, the domain wall resonance and associated loss would be removed by adequately magnetizing the ferrite material [8].

III. MAGNETOSTATIC CHARACTERIZATION

Magnetostatic characterization is done through hysteresis measurements. These measurements allow us to extract important ferrite characteristics such as the relative permeability, saturation magnetization, squareness and coercivity. The hysteresis curve (magnetic flux density B versus magnetic field H), should be measured at DC but it is also acceptable in the lower frequency range. The 1 kHz test circuit used to perform magnetostatic characterization is shown in Fig. 2 and it employs embedded transformers built in the ferrite under test. The primary side of the transformer is connected to an oscillator followed by an audio power amplifier to provide variable current to the winding. The series resistor R_1 has a value of 3.5 Ω and is used to measure the voltage V_H across it. The voltage V_H is directly proportional to the magnetic field H inside the transformer core and it is applied to the horizontal deflection of an oscilloscope.

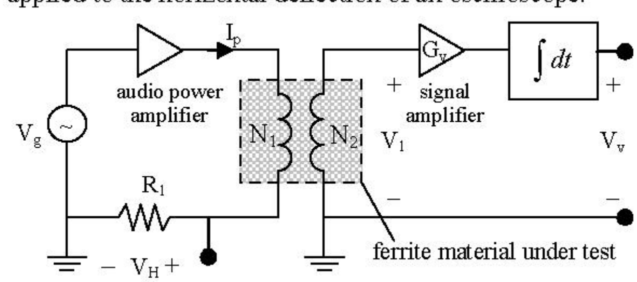
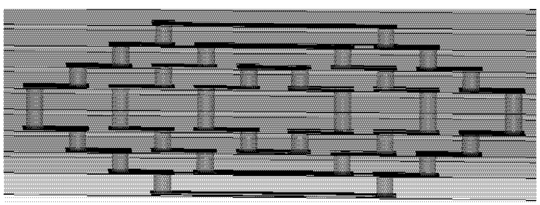


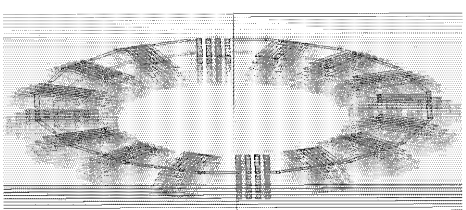
Fig. 2. Magnetic hysteresis measurement test circuit.

It is easily shown that the voltage at the output of the integrator is directly proportional to the magnetic flux density B in the core and this voltage is applied to the vertical deflection of the oscilloscope. The desired hysteresis curve can be viewed directly on the oscilloscope by plotting V_v versus V_H.

Two different types of transformers have been designed for this work. A straight solenoid transformer completely embedded within the ferrite LTCC material under test was first designed, similar to previous work [5]. The front cross-sectional view of a unit cell is shown in Fig. 3(a). The turns are made of 200 μm wide silver conductors that are connected to the top and bottom conductors through 150 μm diameter vias, and the pitch between conductors is 375 μm. Each unit cell is comprised of 7 primary turns and 3 secondary turns. The complete transformer fits into a 10 layer thick ferrite LTCC module with each layer being 124 μm thick. In order to fit the solenoid transformer in a maximum permissible part size of 20 mm × 20mm, 11 unit cells are used. The complete solenoid employs 77 primary and 33 secondary turns which required 1198 transitions and 1108 vias in all.



(a)



(b)

Fig. 3. LTCC (a) solenoid transformer unit cell cross section and (b) toroid transformer tilted front view.

A finite-length solenoid is subject to end-effects which can introduce errors in the measurements. Further, leakage out of the sides of the solenoid is also a concern, which can potentially lead to overestimates of the flux inside its core. A toroid, on the other hand, entirely encloses the magnetic fields within its core and is less prone to leakage effects. A toroid transformer has also been designed in which unit cells are closely spaced and the fields are more tightly contained within the windings, as shown in Fig. 3(b). The 112 primary turns and the 48 secondary turns are completely embedded in 10 ferrite LTCC layers. The inner diameter of the toroid transformer is 10.3 mm and the outer diameter is 18.7 mm. It has 16 unit cells which are spaced at 171 μm on the inner side and 1.28 mm at the outer side.

The measurement procedure consists of incrementing the primary current periodically and recording the corresponding V_H and V_v voltages which are then converted to actual values of H and B, respectively. The results are then plotted to obtain the $B(H)$ curves for every current setting. The major $B(H)$ curve, which was obtained at saturation using the solenoid transformer, is shown in Fig. 4 by a dashed line.

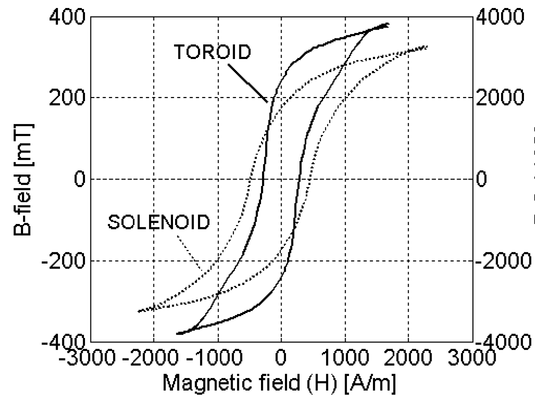


Fig. 4. Measured hysteresis curves from the LTCC transformers.

The major hysteresis loop was obtained by energizing the primary winding with a peak current of 650 mA. Based on the solenoid measurements, the saturation flux density B_s is 330 mT for an applied magnetic field of 2100 A/m. The remanent flux density B_r is 180, the squareness is 0.55, and the coercive magnetic field H_c is 520 A/m. The same procedure was used for the toroid. Due to the curvature of the toroid, the resulting turn density of the primary winding of the toroid is lower than that of the solenoid by a factor of 0.6. The maximum $B(H)$ curve for the toroid, is shown in Fig. 4 by a solid line.

A comparison of the curves in Fig. 4 and the results obtained from the toroid indicate that ESL 40012 is easier to magnetize than it would appear to be with the solenoid. This is expected since the toroid suffers from less leakage effects than the solenoid. This difference is clearly evident in Fig. 5, which plots the peak B field versus the peak H field for each current setting. Although saturation could not quite be achieved with the toroid, the trend clearly indicates that the saturation magnetization B_s approaches 400 mT instead of the 330 mT obtained using the solenoid. For the toroid, B_r = 250 mT, the squareness is approximately 0.63, and $H_c \approx$ 330 A/m.

The results of Fig. 5 may be used to calculate the linear permeability of the material. For any given operating point, the linear permeability μ_{lin} is the slope of the line that extends from the origin to that operating point. The resulting curves for the solenoid and the toroid are shown in Fig. 6. The maximum μ_{lin} of 205 is achieved for an H-field of 715 A/m for the solenoid, whereas it is estimated to be 370 at an H-field of 430 A/m for the toroid.

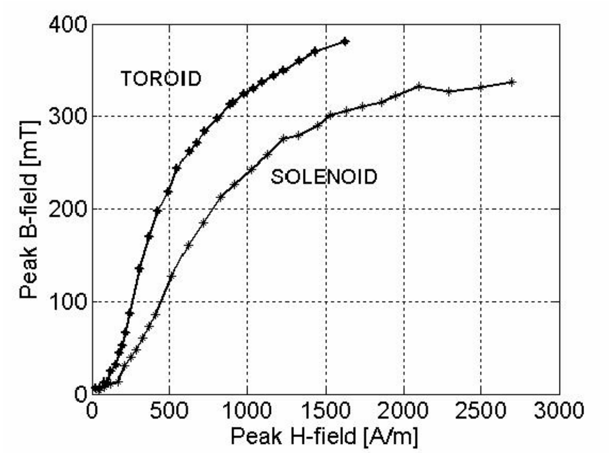


Fig. 5. Measured peak *B* versus peak *H* for ESL 40012 LTCC.

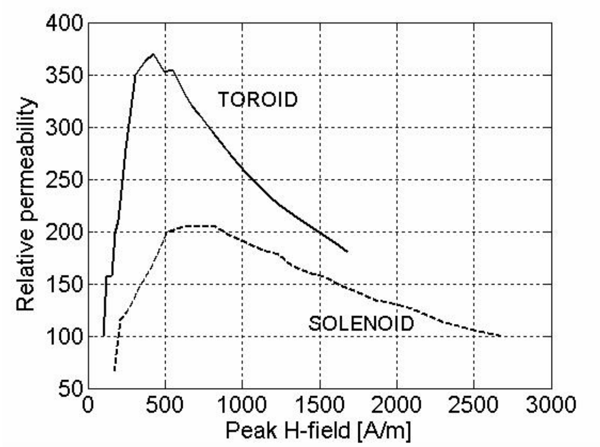


Fig. 6. Measured relative linear permeability of ESL 40012.

IV. Ferrite Ltcc Sip Implications

A number of important observations can be made based on the microwave and magnetostatic measurement results. The value of ε_r falls in the range of typical microwave substrates useful for circuit and antenna designs. In the unbiased state, the measured loss tangents of the ferrite are quite low and decrease with frequency. Though not shown here, the value of initial permeability varies from 4 to 3 in the range of 0.1 to 2 GHz before eventually going to 1 at about 6 GHz. Since the guided wavelength is a function of both ε_r and μ_r, this will help miniaturize antenna and passive elements design.

In the biased state, the high value of $B_s \approx 400$ mT indicates that a large degree of magnetic control can be achieved with ESL 40012, which is beneficial for the design of in-package reconfigurable and tunable microwave components. The measured results also indicate that the remanent magnetization is sufficient to yield practical nonreciprocal devices operating at remanence. The measured high values of μ_{lin} also indicate that high Q inductors and transformers can be manufactured with this material.

These results are encouraging as far as the implementation of microwave components in ferrite SiP is concerned. The low loss makes it an attractive substrate for in-package passive element design in the microwave frequency range. However, the true advantage of ferrite LTCC is its ability to change its permeability tensor with applied magnetic bias, thereby giving an additional dimension of freedom to microwave designers.

V. Conclusion

ESL 40012 experimental ferrite LTCC tape has been characterized for its microwave and magnetostatic properties. Microwave measurements performed at 9.86 GHz and 27.2 GHz reveal an ε_r value of 13.6 and tanδ values of 0.004 and 0.001. Novel embedded LTCC transformers have been used to measure the magnetostatic properties. These measurement results show that B_s is nearly 400 mT for an applied magnetic field approaching 2000 A/m. The remanent flux density B_r is 250 mT, the squareness is 0.63, and the coercive magnetic field H_c is 430 A/m. The results confirm that this ferrite material is suitable for tunable and reconfigurable microwave designs.

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