APPLICATION NOTE

Permeability Spectra of Ferrimagnetic Materials

Introduction

Because ferrimagnetic materials used in microwave applications exhibit high insulating and passive dielectric properties, propagating electromagnetic waves are able to couple efficiently with the magnetic characteristic to obtain device action. This Application Note describes some of the properties of ferrite permeability.

The relationships between the RF magnetic field (h) and RF magnetic induction field (b) inside of a ferrite are dependent upon its state of static magnetization and the frequency of operation. Also, a time varying magnetic field generally dissipates energy. The relationship between the h and b fields defined as the permeability (μ) may be described in terms of a scalar or tensor quantity depending upon the conditions of operation.

Basic Theory

The origin of ferrimagnetism is found in the cooperative behavior of electronic spins. Strong exchange forces between the electrons of the constituent magnetic ions enforce a spatial ordering of their spin orientations within the ferrite. This results in large volumes of material, called domains, being spontaneously magnetized. In a macroscopically demagnetized sample, these domains are arranged with haphazard orientations. When a static field is applied, the domain magnetization tends to orient parallel to it. This increases the observed magnetism by the amount (μ-1) H.

Scalar Permeability

If a small RF magnetic field is applied to a demagnetized ferrite specimen to avoid hysteresis losses, the relationship between the h and b fields can be described by the introduction of a factor known as the initial permeability (μ_i). This factor is complex to account for residual losses:

$$b = \mu_i h \quad \mu_i = \mu_i' - j\mu_i'' \qquad \textbf{(1)}$$

Where:

b = RF magnetic induction field.
μ_i = Real part of the permeability.
h = RF magnetic field.
j = Imaginary unit.

Energy dissipation is usually expressed as:

$$\tan \delta m = \mu_i''/\mu_i' \qquad \textbf{(2)}$$

Where:

δm = Magnetic loss.
μ_i = Real part of the permeability.

The energy loss is then proportional to μ_i, and both components of μ_i can vary with frequency.

Figure 1 shows a typical spectrum of initial permeability. Microwave ferrites exhibit low frequency μ_i' values between about 10 and 100. Two regions of dispersion and absorption are generally observed, which are attributed to domain wall and rotational resonance effects at the low and high frequencies, respectively.

Note: *At frequencies where microwave devices are used, μ_i' is approximately unity.*

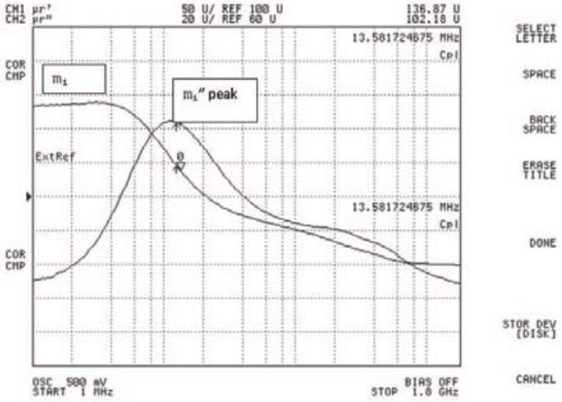

Figure 1. Magnetic Spectrum of a Typical Ferrite (TT2-111)

Tensor Permeability

The magnetization that results from an internal static magnetic field (H_i) may be coupled to the RF magnetic field through ferromagnetic resonance processes. It is found that components of RF magnetic induction can be generated in several directions in this manner. This is the origin of the tensor nature of the permeability and the realization of nonreciprocal microwave devices.

Tensor permeability is most tractable when described in terms of plane wave propagation through an infinite ferrite medium. This theory quite readily predicts the properties exhibited by finite samples inside waveguides. For such a medium saturated by a field (H_i):

$$b = \begin{bmatrix} \mu & -jk & 0 \\ jk & \mu & 0 \\ 0 & 0 & 1 \end{bmatrix} h \qquad \textbf{(3)}$$

Where:

$\mu = \mu'$ (real part of the complex permeability).
j = Imaginary unit.
$k = \mu''$(imaginary part of the complex permeability).

Neglecting losses, the components of the tensor permeability are:

$$\mu = 1 + \frac{4\pi M_s H_i \gamma^2}{\gamma^2 H_i^2 - \omega^2}$$

$$k = \frac{4\pi M_s \gamma \omega}{\gamma^2 H_i^2 - \omega^2} \qquad \textbf{(4)}$$

Where:

M_s = Ferrite magnetization.
H_i = Applied static field.
γ = Gyromagnetic ratio.
ω = Frequency ($2\pi F$).

Two cases are of interest for a plane wave propagating perpendicular and parallel to the applied static field (H_i).

Case 1

For the plane wave propagating perpendicular to H_i and with the RF magnetic field parallel to H_i, the plane wave sees an effective permeability (μ_{effll}) equal to unity. For the RF magnetic field perpendicular to both H_i and the direction of plane wave propagation:

$$\mu_{eff1} = \frac{\mu^2 - k^2}{\mu} \qquad \textbf{(5)}$$

Where:

μ_{eff1} = Effective permeability.
$\mu = \mu'$ (real part of the complex permeability).
$k = \mu''$(imaginary part of the complex permeability).

Figure 2 shows the properties of the effective permeability at constant frequency. When H_i has the magnitude required for resonance, μ_{effl} exhibits large dispersions. Both the real and loss components are indicated. Values of μ'_{-eff1} are typically 5 to 40. Below saturation ($M < M_s$), these equations do not strictly apply, but show qualitatively what occurs as the permeability reverts to its scalar condition.

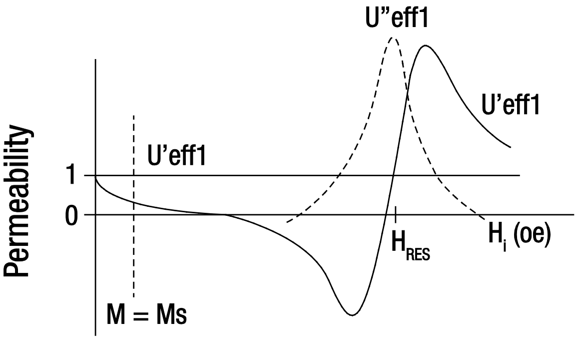

Figure 2. Properties of Effective Permeability at Constant Frequency (Plane Wave Perpendicular to H_i)

Case 2

When a plane wave propagates parallel to H_i, the observed effects can best be described if the plane wave is represented by two contra-rotating circularly polarized components. Permeabilities can then be defined for the positive and negative sense of rotation. The positive sense is clockwise when viewed in the direction of H_i.

$$\mu_+ = \mu - k \quad \mu_- = \mu + k \qquad \textbf{(6)}$$

Where:

$\mu = \mu'$ (real part of the complex permeability).
$k = \mu''$(imaginary part of the complex permeability).

Figure 3 shows the properties of these permeabilities. The loss component μ''_- (not shown) has a form similar to μ'_-, but with a much smaller magnitude. A negatively circular polarized wave can then be obtained from a propagating plane wave with sufficient ferrite path length and magnitudes of H_i close to resonance.

The losses are about equal at low values of H_i, but a plane wave experiences a change in phase due to the difference of μ'_- and μ'_+. The μ'_+ is qualitatively similar to μ'_{eff1}. It is found experimentally that a plane wave propagating perpendicular to H_i exhibits the same effects as a circularly polarized wave propagating parallel to H_i. Regions where the permeability is zero result in reflection of incident waves.

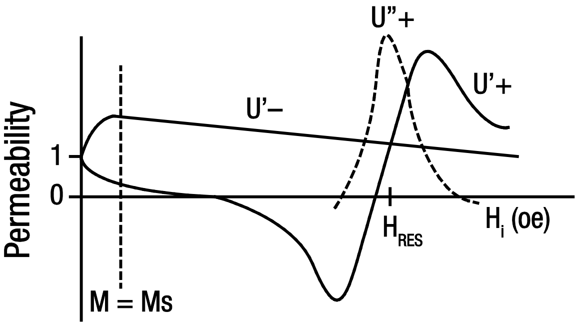

Figure 3. Properties of Effective Permeability at Constant Frequency (Plane Wave Parallel to Hi)

Application

The variation of RF permeability is of major importance in the design of microwave ferrite devices. In the unsaturated region, the difference in permeability of two circularly polarized waves is used to design circulators, isolators, switches, amplitude modulators, single-sideband modulators, and phase shifters in a circular waveguide using Faraday rotation effects.

At resonance fields, the loss characteristic is used to design isolators, principally in rectangular waveguides. Field displacement and differential phase shift devices such as circulators and duplexer detectors usually operate between the unsaturated and resonance regions.

Figure 4 shows how measurement of the unmagnetized spectrum is carried out with an impedance analyzer.

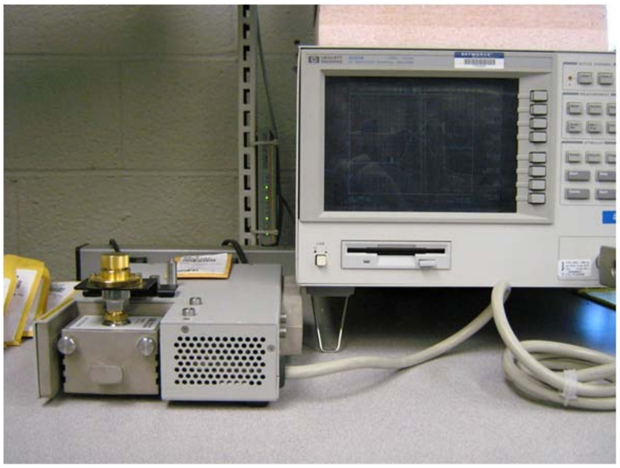

Figure 4. Impedance Analyzer

Copyright © 2013, Trans-Tech Inc., Inc. All Rights Reserved.

Information in this document is provided in connection with Trans-Tech, Inc. ("Trans-Tech"), a wholly-owned subsidiary of Skyworks Solutions, Inc. These materials, including the information contained herein, are provided by Trans-Tech as a service to its customers and may be used for informational purposes only by the customer. Trans-Tech assumes no responsibility for errors or omissions in these materials or the information contained herein. Trans-Tech may change its documentation, products, services, specifications or product descriptions at any time, without notice. Trans-Tech makes no commitment to update the materials or information and shall have no responsibility whatsoever for conflicts, incompatibilities, or other difficulties arising from any future changes.

No license, whether express, implied, by estoppel or otherwise, is granted to any intellectual property rights by this document. Trans-Tech assumes no liability for any materials, products or information provided hereunder, including the sale, distribution, reproduction or use of Trans-Tech products, information or materials, except as may be provided in Trans-Tech Terms and Conditions of Sale.

THE MATERIALS, PRODUCTS, AND INFORMATION ARE PROVIDED "AS IS" WITHOUT WARRANTY OF ANY KIND,WHETHER EXPRESS, IMPLIED, STATUTORY, OR OTHERWISE, INCLUDING FITNESS FOR A PARTICULAR PURPOSE OR USE, MERCHANTABILITY, PERFORMANCE, QUALITY, OR NON-INFRINGEMENT OF ANY INTELLECTUAL PROPERTY RIGHT; ALL SUCH WARRANTIES ARE HEREBY EXPRESSLY DISCLAIMED. TRANS-TECH DOES NOT WARRANT THE ACCURACY OR COMPLETENESS OF THE INFORMATION, TEXT, GRAPHICS, OR OTHER ITEMS CONTAINED WITHIN THESE MATERIALS. TRANS-TECH SHALL NOT BE LIABLE FOR ANY DAMAGES, INCLUDING BUT NOT LIMITED TO ANY SPECIAL, INDIRECT, INCIDENTAL, STATUTORY, OR CONSEQUENTIAL DAMAGES, INCLUDING WITHOUT LIMITATION, LOST REVENUES OR LOST PROFITS THAT MAY RESULT FROM THE USE OF THE MATERIALS OR INFORMATION,WHETHER OR NOT THE RECIPIENT OF MATERIALS HAS BEEN ADVISED OF THE POSSIBILITY OF SUCH DAMAGE.

Trans-Tech products are not intended for use in medical, lifesaving, or life-sustaining applications, or other equipment in which the failure of the Trans-Tech products could lead to personal injury, death, or physical or environmental damage. Trans-Tech customers using or selling Trans-Tech products for use in such applications do so at their own risk and agree to fully indemnify Trans-Tech for any damages resulting from such improper use or sale.

Customers are responsible for their products and applications using Trans-Tech products, which may deviate from published specifications as a result of design defects, errors, or operation of products outside of published parameters or design specifications. Customers should include design and operating safeguards to minimize these and other risks. Trans-Tech assumes no liability for applications assistance, customer product design, or damage to any equipment resulting from the use of Trans-Tech products outside of stated published specifications or parameters.