APPLICATION NOTE

No. 658: Permeability Spectra of Ferrimagnetic Materials

Introduction

We have seen that ferrimagnetic materials employed in microwave applications exhibit high insulating and passive dielectric properties. Propagating electromagnetic waves are thus able to couple efficiently with the magnetic characteristic enabling us to obtain device action. In this article we will describe some of the properties of ferrite permeability.

The relationships between R.F. magnetic field (h) and R.F. magnetic induction (b) inside of a ferrite are dependent upon its state of static magnetization and the frequency of operation. Also, a time varying magnetic field will generally dissipate energy. The relationship between the h and b fields defined as the permeability (p) 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 $(\mu\text{-}1)\ H$.

1. Scalar permeability

If we apply a small R.F. magnetic field to a demagnetized ferrite specimen so as to avoid hysteresis losses, the relationship between h and b can be described by the introduction of a factor μ_i known as the initial permeability. This factor is complex to account for residual losses.

$$b = \mu_i h \quad \mu_i = \mu_i' - j_{\mu i}'' \qquad (1)$$

where μ_i is the real part of the permeability. Energy dissipation is usually expressed as tan $\delta m = \mu_i'/\mu_i''$. The energy loss is then proportional to grand both components of μ_i can vary with frequency.

A typical spectrum of initial permeability is shown in Figure 1. Microwave ferrites exhibit low frequency μ_i values between about 10 and 100. Two regions of dispersion and absorption are generally observed. They are attributed to domain wall and rotational resonance effects at the low and high frequencies, respectively. Note that at frequencies where microwave devices are employed μ_i' is approximately unity.

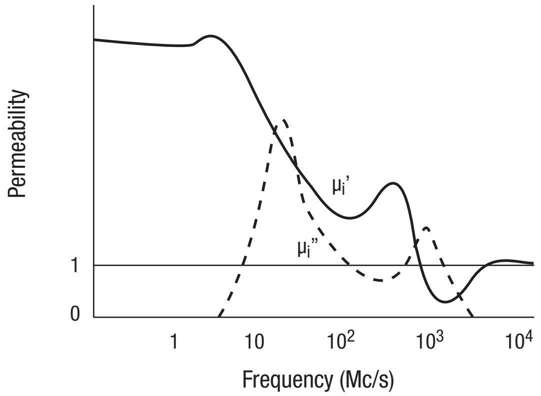

Figure 1

2. Tensor permeability

The magnetization resulting from an internal static magnetic field (H_i) may be coupled to the R.F. magnetic field through ferromagnetic resonance processes. It is found that components of R.F. 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 wave guides. For such a medium, saturated by a field (H_i), we have

$$b = \begin{bmatrix} \mu & -jk & 0 \\ jk & \mu & 0 \\ 0 & 0 & 1 \end{bmatrix} h \qquad (2)$$

Neglecting losses, the components of the tensor permeability are

$$\mu = 1 + \frac{4 \quad M_S H_i \quad ^2}{^2 H_i^2 - \quad ^2} \qquad (3a)$$

$$k = \frac{4 \quad M_S \quad ^2}{^2 H_i^2 - \quad ^2} \qquad (3b)$$

where (M_S) is the ferrite magnetization and (γ) is the gyromagnetic ratio. Two cases are of interest. These are for a plane wave propagating perpendicular and parallel to the applied static field (H_i).

Case I—For the plane wave propagating perpendicular to H_i, and with the R.F. magnetic field parallel to H_i, the plane wave will see an effective permeability (μ_{effll}) equal to unity. For the R.F. magnetic field perpendicular to both Hi and the direction of plane wave propagation we have

$$\mu_{eff1} = \frac{\mu^2 - k^2}{\mu} \qquad (4)$$

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

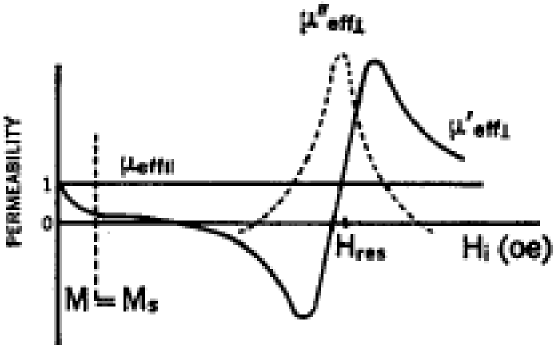

Figure 2

Case II—When a plane wave propagates parallel to H_i, the observed effects can best be described if we represent the plane wave 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.

$$\mu+ = \mu - k \quad \mu\_ = \mu + k \qquad (5)$$

The properties of these permeabiiities are shown in Figure 3. The loss component $\mu''\_$ (not shown) has a form similar.to $\mu'\_$ but a much smaller magnitude. A negatively circular polarized wave can thus be obtained from a propagating plane wave with sufficient ferrite path length and magnitudes of H_i close to resonance. At low values of H_i, the losses are about equal but a plane wave will experience a change in phase due to the difference $\mu'\_$ and $\mu'+$. Notice that $\mu'+$ 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.

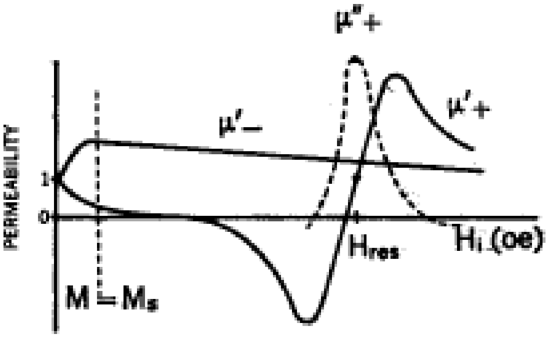

Figure 3

Application

The variation of R.F. 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 utilized to design circulators, isolators, switches; amplitude modulators, single-sideband modulators, and phase shifters in, circular waveguide employing Faraday rotation effects. At resonance fields the loss characteristic is used to design isolators, principally in rectangular waveguide. Field displacement and differential phase shift devices such as circulators and duplexer detectors usually operate between, the unsaturated and resonance regions.

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