Journal of Magnetism and Magnetic Materials 324 (2012) 3393–3397

Contents lists available at SciVerse ScienceDirect

Journal of Magnetism and Magnetic Materials

journal homepage: www.elsevier.com/locate/jmmm

Consequences of magnetic anisotropy in realizing practical microwave hexaferrite devices

Anton Geiler [a,*], Andrew Daigle [a], Jianwei Wang [b], Yajie Chen [b,c], Carmine Vittoria [b,c], Vince Harris [b,c]

[a] *Metamagnetics, Inc., Sharon, MA 02067, USA*
[b] *Center for Microwave Magnetic Materials and Integrated Circuits (CM3IC), Northeastern University, Boston, MA 02115, USA*
[c] *Department of Electrical and Computer Engineering, Northeastern University, Boston, MA 02115-5000, USA*

ARTICLE INFO

Available online 28 February 2012

Keywords:
Ferrite
Spinel
Hexaferrite
Ferromagnetic resonance
Magnetocrystalline anisotropy
Antenna
Electromagnetic bandgap metamaterial
Circulator
Isolator
Inductor
Electromagnetic interference device

ABSTRACT

With the rapidly growing demand for bandwidth in wireless communication systems and increasing frequencies of operation of electronic devices, in recent years resurgence in scientific interest in highly anisotropic hexagonal ferrites has been noted. This interest stems in part from a number of emerging applications that pose significant materials challenges that cannot be addressed using traditional rf and microwave ferrite materials. In this manuscript, several specific applications that could benefit from the unique properties of hexagonal ferrites are discussed. Fundamental principles of operation, materials requirements, as well as unique device design and modeling challenges are reviewed. Applications of textured magnetically uniaxial hexagonal ferrite composites in microwave and mm-wave non-reciprocal ferrite control devices are discussed. Applications of textured magnetically planar hexagonal ferrite composites as antenna and electronic bandgap metamaterial substrates, rf inductors and transformers, and electromagnetic interference suppression devices are reviewed. Suggestions on directions for future research and development are provided.

1. Introduction

Hexagonal M-type barium ferrite (BaM) belongs to a family of ferrimagnetic oxides possessing closely related hexagonal crystal structures [1]. One of the most practical and important magnetic properties of hexagonal ferrites is the high crystalline anisotropy field. The immediate outcome of the anisotropy field is the existence of "easy" and "hard" magnetization directions. In M-type materials, the high uniaxial anisotropy field is along the *c*-axis of the crystal. There is also basal plane anisotropy (in the plane perpendicular to the *c*-axis) that exhibits six-fold symmetry.

Hexagonal Y- and Z-type ferrites are closely related to the M-type structure. In Y-type ferrites, for most compositions, the magnetocrystalline anisotropy field H_θ aligns the magnetization perpendicular to the crystallographic *c*-axis, in the basal plane of the unit cell. There exists an additional, weaker anisotropy field H_φ in the basal plane that possesses six-fold symmetry [2]. The competition between uniaxial and planar magnetocrystalline anisotropy fields in both Y- and Z-type hexaferrite allows for materials exhibiting easy magnetization direction, cone, or plane, depending on the species and amounts of substitutional cations in the unit cell. This inherent flexibility of the hexagonal ferrite family, combined with the relatively high magnitudes of magnetocrystalline anisotropy fields, allows for unique opportunities in device design.

The magnetic structure of all hexaferrite materials is determined by superexchange interactions among the various magnetic iron sublattices in the unit cell. For M-type hexaferrite, for example, there are five different sublattices of iron cations of either tetrahedral, octahedral, or bipyramidal symmetry. For barium M-type hexaferrite (BaM) the net ferrimagnetic moment is 20 μ_B. The saturation magnetization of this material at room temperature is typically in the 4500–4800 G range [1]. For Y- and Z-type hexaferrites, the saturation is typically somewhat lower. For zinc-doped barium Y-type hexaferrite (ZnY), for example, the saturation magnetization is approximately 2000 G [2]. For cobalt-doped barium Z-type hexaferrite (CoZ) the corresponding value is approximately 3300 G [3]. The uniaxial anisotropy field H_A of BaM is typically in the 16,500–17,500 Oe range [1]. In comparison, the planar anisotropy field H_θ of ZnY is approximately 10,000 Oe and that of CoZ is in the 9000–12,000 Oe range [3]. All of the above compounds are characterized by high electric resistivity, which makes them well-suited for applications in rf, microwave, and mm-wave devices. The magnetic and electric properties of hexagonal ferrites are a strong function of the composition, with a wide variety of cation substitutions in the unit cell leading to unparalleled tunability of the frequency response [2–4]. These

* Corresponding author. Tel.: +1 781 562 0756; fax: +1 781 253 3913.
E-mail address: geiler@metamagneticsinc.com (A. Geiler).

0304-8853/$ - see front matter © 2012 Elsevier B.V. All rights reserved.
doi:10.1016/j.jmmm.2012.02.050

properties, and their utility in developing next generation electromagnetic devices, will be discussed in more detail in the following sections.

2. Numerical modeling and device design using hexagonal ferrites

A number of commercially available numerical solvers implementing finite element and finite difference methods allow for the modeling of ferrite materials and facilitate device design. When it comes to hexagonal ferrites, however, there are several important limitations that prevent these types of solvers to be effectively applied. First, a symmetrical permeability tensor of the form

$$[\chi] = \frac{M}{(H_1 H_2 - \omega^2/\gamma^2)} \begin{bmatrix} H_1 & -j\omega/\gamma \\ j\omega/\gamma & H_2 \end{bmatrix} \equiv \begin{bmatrix} \chi_{11} & \chi_{12} \\ \chi_{21} & \chi_{22} \end{bmatrix}, \quad (1)$$

where M is the saturation magnetization, ω is the radial frequency, γ is the gyromagnetic ratio, and H_1 and H_2 are effective internal magnetic fields, is assumed for the ferrite materials, meaning that the diagonal elements in (1) are equal to each other, or $H_1 = H_2$. This condition, however, is only true for isotropic ferrite materials, including garnets and spinels. For hexagonal ferrites this condition is not valid. Consider for example the M-type hexaferrite composite with the individual grains aligned with their crystallographic *c*-axes parallel to the surface and with the external magnetic field applied in the same direction. The effective internal magnetic fields given by [5]

$$H_1 = H + H_A + 4\pi M, H_2 = H + H_A \quad (2)$$

Clearly, $H_1 \neq H_2$ and therefore diagonal elements of the permeability tensor are not equal to each other. Specialized numerical modeling tools need to be developed in such cases. One example is the application of the Galerkin's method in spectral domain to derive the dispersion relations and design a microwave phase shifter based on ZnY ferrite [6].

In certain special cases, such as the design of Y-junction circulators and isolators utilizing hexagonal ferrites, commercially available solvers can still be applied. The reason for this is the fact that the effective internal fields H_1 and H_2 in a textured M-type hexaferrite aligned perpendicular to the surface and with the external magnetic field applied in the same direction are equal to each other. This equality results in a symmetric permeability tensor that can be accurately described using commercial solvers by incorporating the uniaxial magnetocrystalline anisotropy in the total magnetic field applied to the ferrite material [17]. One other limitation generally present in commercial solvers is the fact that the ferrite material is assumed to be magnetically saturated. This assumption allows the Landau–Lifshitz magnetization equation of motion for a single magnetic domain to be applied. This assumption however, may not be valid for certain hexaferrite devices, such as self-biased circulators and isolators. In order to accurately capture the response of a ferrite material in its remnant state specialized techniques need to be applied [8]. These techniques seek to describe the multi-domain state and the non-uniform field distribution of the self-biased material, thus improving the accuracy of the simulations.

The modeling of hexagonal ferrites in the rf frequency range is generally well facilitated by commercially available tools. This is mainly due to the fact that the response of the material in this regime is satisfactorily described by the scalar permeability, as opposed to the tensor one. This is true for inductors, antennas, electromagnetic band gap metamaterials, etc. In order to obtain accurate simulation results, the frequency dispersion of the complex permeability must be specified. There are numerous examples of rf device designs using commercial solvers in the literature and some ferrite material manufacturers are now establishing product lines of planar hexaferrite components to address the growing demand for higher frequencies of operation.

3. Processing and emerging microwave applications of M-type hexaferrites

One of the most promising microwave and mm-wave applications of M-type hexaferrites is in low bias and self-biased Y-junction circulator and isolator devices [9]. M-type hexaferrite composites can be prepared with strong crystallographic texture, such that the easy axes of individual particles are aligned perpendicular to the surface of the composite [10]. The microstructure of the composite can be further tailored to provide sufficiently high remnant magnetization ($>90\%$), while maintaining relatively low FMR linewidths (<1000 Oe) [11]. There have been numerous attempts to construct self-biased circulator devices in waveguide, stripline, and microstrip geometry at mm-wave frequencies (>30 GHz) based on barium and strontium textured M-type hexaferrite compacts [9]. The relatively high frequencies of operation are determined by the high magnetocrystalline anisotropy field of barium and strontium hexaferrites ($>16{,}000$ Oe) that sets the zero-field FMR frequency above 30 GHz, and the need for self-biased circulator devices to operate near and below FMR or above FMAR, such that the ratio of off-diagonal to diagonal permeability tensor elements provides for adequate splitting in the resonance frequencies of the counter rotating modes supported by the junction [12,13]. Self-biased circulator prototypes constructed thus far exhibited relatively high insertion loss (2–3 dB) [9]. This less than satisfactory performance can be attributed to the relatively broad FMR linewidth of textured hexaferrite compacts (1000–2000 Oe), [11] much broader than that of spinel or garnet ferrites (10–300 Oe) [14] utilized in the construction of commercially available circulator and isolator devices biased with a permanent magnet. Narrower FMR linewidths (<20 Oe) are achievable with single crystal barium and strontium hexaferrites [15]. Devices based on these materials do require an external magnetic bias field, although its magnitude is much smaller than would have been required for a cubic ferrite material in order to operate at the same frequency [16].

Recent advances in the processing and packaging of textured M-type hexaferrites have produced significant improvements in the microwave losses of these materials. For example, FMR linewidths of less than 300 Oe were demonstrated for polycrystalline barium M-type hexaferrite films produced using a screen printing technique capable of depositing thicknesses in the 100–500 μm range [17]. To induce crystallographic texturing, the as-deposited films were subjected to a strong magnetic field ($\sim 10{,}000$ Oe) and subsequently dried and sintered. Magnetic hysteresis loop squareness ratios above 90% were demonstrated. Further FMR linewidth reductions were shown possible by applying pressure to the films during the sintering process [18]. This approach is promising for the fabrication of low loss self-biased circulator and isolator devices because it allows a conducting ground plane to be deposited on the dielectric substrate prior to the printing of the ferrite film. Further process improvement is necessary before this technique can be adapted in industrial scale manufacturing of devices, including the elimination of cracks and other defects in large surface area (>1 sq. in.) deposits [19]. Significant improvements in the formation of textured polycrystalline compacts of intrinsic and substituted barium M-type hexaferrite were also achieved [20]. Similarly to thick films, these compacts are subjected to a strong magnetic field and subsequently sintered. Using