Hexagonal Ferrite Materials for Phase Shifter Applications at Millimeter Wave Frequencies

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Abstract—**The effect of anisotropy field and saturation induction on phase shift at millimeter wave frequencies has been examined for hexagonal ferrite materials. The analysis was done for both uniaxial and planar anisotropy at three particular frequencies of technological interest, 30, 60, and 90 GHz. The work was concerned primarily with materials; a simple thin slab device configuration was used for the analysis. Limitations on materials parameters due to propagation cutoff, phase error degradation over a specified bandwidth, and low field loss were also considered. The results indicate that any improvement in phase shift over conventional cubic ferrites will require a high saturation magnetization comparable to that of Li–Zn ferrite and moderate (6–10 kOe) to large (20–30 kOe) anisotropy fields, depending on the frequency. Even with such materials, the phase shift enhancement (over Li–Zn ferrite) will be modest, below a factor of two, and at the expense of increased phase error and reduced bandwidth.**

I. Introduction

With the renewed interest in ferrite devices for millimeter wave radar applications, the materials problem is of key importance. Hexagonal ferrites have been proposed as one possible solution to this materials challenge [1], [2]. The high-anisotropy fields can be used to advantage by reducing the need for external high field magnets, and the losses in the millimeter wave regime appear to be within acceptable limits. Many issues remain to be resolved, however. One such issue concerns the optimum *type* of anisotropy, uniaxial or planar. Rodrigue [3], [4] has suggested that planar hexagonal ferrites may hold more promise than uniaxial materials for millimeter wave digital phase shifter applications because of the possible reduced drive power and fields required to switch the toroid between opposite remanent states. Whether this is true in practice will depend on the specific mechanisms for magnetization reversal, toroid design, etc. In any event, [3] and [4] presented calculated curves of effective permeability and phase shift for various planar materials which were encouraging.

The present work was motivated by the ideas in [1]–[4]. The basic purpose here was to 1) extend the calculations of [3] and [4] to include *both* uniaxial and planar materials, 2) examine the *materials* factors which affect the realizable phase shift, and 3) determine the ranges of anisotropy field (H_a) and saturation induction ($4\pi M_s$) which would be needed for hexagonal ferrites to offer superior device possibilities compared to conventional materials, such as Li–Zn ferrite, for example. The specific results consist of calculated curves of a materials phase shift factor (F_D) as a function of anisotropy field (H_a) and saturation induction ($4\pi M_s$) for three representative millimeter wave frequencies: 30, 60, and 90 GHz. Curves are presented for planar anisotropy and uniaxial anisotropy materials with $4\pi M_s$ values of 2, 4, and 6 kG, and a variation in anisotropy field from zero to 30 kOe. Complications associated with propagation cutoff (negative effective permeability), bandwidth, and low field loss are also included in the analysis.

Even though the analysis is relatively straightforward and based on well-established formulas, the results do appear to provide a new and useful perspective to the question of hexagonal ferrites for millimeter wave applications. The paper has been written with this perspective in mind. It is to be emphasized that this is a *materials* study. Specific waveguide configurations and device design strategies may further modify the conclusions presented on the relative merits and problems for hexagonal materials, planar or hexagonal, vis-a-vis conventional isotropic ferrites, along the lines of [4].

II. Calculation

The analysis of wave propagation in an isotropic ferrite medium and application of the results to the thin slab nonreciprocal phase shifter problem are well known [5]. Both the effective permeability for wave propagation in a transversely magnetized ferrite medium and the materials factors that determine the scale of the differential phase shift depend on the various components of the internal microwave permeability tensor. The permeability tensor for uniaxial materials may be obtained by simply replacing the internal field H_0 in the component equations for an isotropic ferrite by $H_0 + H_a$, where H_a is the uniaxial anisotropy field, typically in the 2–30-kOe range. The planar case is somewhat more complicated but can be obtained from the analysis of Bady [6] or Sodha and Srivastava [7], for example. While the basic geometry and working equations are fairly standard, the key materials effects derive directly from the pertinent expressions. The key relations are summarized in the following.

We consider the geometry of the conventional thin-slab ferrite nonreciprocal phase shifter, with an x–y–z coordinate system for the slab as indicated in Fig. 1. The static

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magnetic field and the static magnetization are taken to be along the y direction (vertical) in the figure. For the uniaxial hexagonal ferrite case the easy axis and magnetization are along the y axis in Fig. 1. For the planar hexagonal ferrite case, the magnetization is still along the y direction, but the easy plane of the material is the x–y plane. The waveguide mode propagation is in the z direction. As pointed out in [7], this kind of planar configuration with the easy plane perpendicular to the direction of propagation yields much more realizable phase shift than the configuration in which the propagation direction (z axis) and the y axis define the easy plane. It is to be emphasized that this simple device geometry is used here only as a basis to define the *materials* problem. Current device configurations are much more sophisticated. The conclusions which follow pertain to materials and must ultimately be viewed in context for the actual device of interest, following the approach of [4], for example.

The effective permeability for the ferrite medium is given by

$$\mu_{\text{eff}} = \frac{\mu_1\mu_2 - \kappa^2}{\mu_1} \tag{1}$$

where μ_1, μ_2, and κ are particular elements of the internal microwave permeability tensor. These elements depend on the nature of the ferrite. In the case of a lossless uniaxial material, these elements are given by

$$\mu_1 = \mu_2 = \mu_u = 1 + \frac{\omega_m(\omega_0 + \omega_a)}{(\omega_0 + \omega_a)^2 - \omega^2} \tag{2}$$

and

$$\kappa = \kappa_u = -\frac{\omega_m\omega}{(\omega_0 + \omega_a)^2 - \omega^2} \tag{3}$$

where ω_0, ω_m, and ω_a are frequency parameters related to the internal field H_0, the saturation induction $4\pi M_s$, and the anisotropy field H_a:

$$\omega_0 = \gamma H_0 \quad \omega_m = \gamma 4\pi M_s \quad \omega_a = \gamma H_a. \tag{4}$$

In (4), γ denotes the gyromagnetic ratio, approximately 2.8 GHz/kOe in practical units ($1.76 \times 10^{+7}$ rad/s · Oe).

In the case of a planar material and the configuration of Fig. 1, the appropriate expressions for μ_1, μ_2, and κ are [3], [6]

$$\mu_1 = \mu_p^{(1)} = 1 + \frac{\omega_m(\omega_0 + \omega_a)}{\omega_0(\omega_0 + \omega_a) - \omega^2} \tag{5}$$

$$\mu_2 = \mu_p^{(2)} = 1 + \frac{\omega_m\omega_0}{\omega_0(\omega_0 + \omega_a) - \omega^2} \tag{6}$$

$$\kappa = \kappa_p = -\frac{\omega_m\omega}{\omega_0(\omega_0 + \omega_a) - \omega^2}. \tag{7}$$

The differential phase shift between the two propagating waveguide modes for ferrite slabs magnetized parallel or antiparallel to the y direction (Fig. 1) is given by [3], [5]

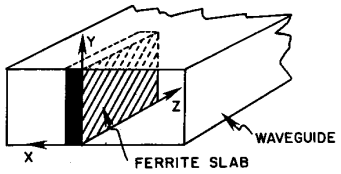

Fig. 1. Ferrite thin slab nonreciprocal phase shifter geometry.

$$\beta = (\kappa/\mu_1) \times D \tag{8}$$

where the multiplier D contains all parameters related to the waveguide mode, slab thickness, slab position, etc., and all materials related parameters combine as (κ/μ_1). We will define a *materials* phase shift factor

$$F_D = \kappa/\mu_1 \tag{9}$$

and use F_D as a *materials* figure-of-merit parameter for the realizable differential phase shift for different ferrites.

The choice of μ_1 instead of μ_2 for the planar case is related to the easy plane orientation perpendicular to the z axis in Fig. 1, as discussed earlier. For any real device, our thin slab will be part of a toroid configuration of some sort, and an easy x–y plane for the slab section used here is probably most appropriate.

In addition to the materials phase shift factor F_D, there are three other materials considerations of importance: propagation cutoff, bandwidth, and low field loss. Propagation cutoff usually occurs when the internal effective field is so large, or the frequency is so small, that the μ_{eff} in (1) becomes negative and the waves of interest cannot propagate in the ferrite medium. For zero internal field (the case in point for this study), cutoff in uniaxial materials occurs for

$$\omega_a > \omega - \omega_m \tag{10}$$

and for

$$\omega_a > \frac{\omega^2 - \omega_m^2}{\omega_m} \tag{11}$$

in planar materials. These cutoff constraints will place various upper limits on the usable values of anisotropy field H_a. These limits will change with frequency and saturation induction according to (10) and (11). The results in the next section consist of calculated curves of the materials phase shift factor F_D versus anisotropy field H_a for various $4\pi M_s$ values and frequencies of interest. All curves will be truncated at cutoff.

For many latching phase shifter applications, bandwidth is an important consideration. It is important to maintain a reasonably constant phase shift over a range of frequencies around a central frequency. For purposes of comparison a phase error parameter (PE) has been defined as the percent change in phase shift over a ten-percent bandwidth at the specified frequency (30, 60, or 90 GHz). PE contours and/or values are included in the results

whenever appropriate. Again, it is to be emphasized that these parameters relate to the various materials aspects of the phase shift problem rather than to actual device bandwidths.

Low field loss is a general problem associated with remanent devices. Because of relaxation of the magnetic state from complete saturation to some remanent state of magnetization, there may be various effective fields due to demagnetization effects, anisotropy, etc., which can cause local regions in the ferrite to be biased at or near ferromagnetic resonance (FMR). Such regions will experience increased losses, often termed "low field losses," because they occur only under unsaturated conditions which generally occur at low fields. To avoid low field loss, it is important to keep the maximum effective field ($H_{\text{eff}}^{\max}$) small enough or the frequency large enough so that the FMR condition cannot be satisfied, e.g.,

$$H_{\text{eff}}^{\max} < \omega/\gamma. \tag{12}$$

For uniaxial anisotropy and zero applied field ($H_0 = 0$), we have

$$H_{\text{eff}}^{\max} = H_a + 4\pi M_s. \tag{13}$$

For planar anisotropy, the corresponding maximum effective field is given by

$$H_{\text{eff}}^{\max} = \left[4\pi M_s(H_a + 4\pi M_s)\right]^{1/2}. \tag{14}$$

The foregoing formulas are only approximate. The details of the domain structure can introduce multiplying factors for $4\pi M_s$ as well as other complications. The H_a values are precisely the same as those which give propagation cutoff for $H_0 = 0$. The only additional stipulation that is really required, therefore, to avoid low field loss is to operate at an anisotropy field *well below* propagation cutoff.

III. Results

This section presents calculated curves of the materials phase shift factor F_D versus anisotropy field H_a for the range of such fields which can be realized in real hexagonal ferrites, typically 0–30 kOe. Results are presented for both uniaxial and planar anisotropy at three frequencies of interest for millimeter wave applications, 30, 60, and 90 GHz. In each case, curves are presented for three values of $4\pi M_s$, 2, 4, and 6 kG. Typical room temperature values of $4\pi M_s$ for hexagonal ferrite lie in the 2–4-kG range. The 6 kG value also provides a useful reference point since $4\pi M_s = 6$ kG and $H_a = 0$ corresponds closely to Li–Zn ferrite, the cubic spinel ferrite which is commonly used in present-day millimeter wave ferrite device development.

Figs. 2, 3, and 4 show the results of the materials phase shift factor calculations for 30, 60, and 90 GHz, respectively. The nomenclature for all the figures is the same. The individual curves are identified by a letter–number code. The letter, U or P, identifies the anisotropy as uniaxial or planar. The number, 2, 4, or 6, denotes the value of $4\pi M_s$ in kG. P4, for example, denotes planar anisot-

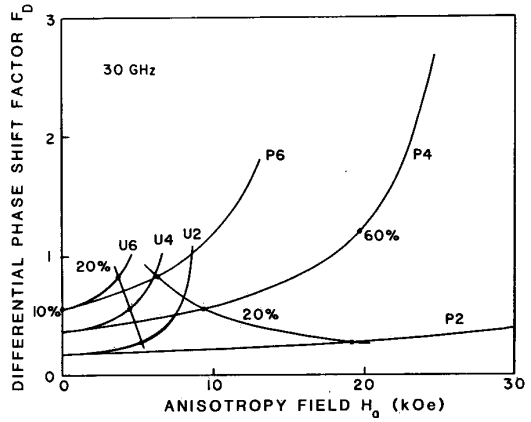

Fig. 2. Materials phase shift factor F_D versus anisotropy field H_a for uniaxial (U curves) and planar (P curves) materials at 30 GHz. Number part of label for each curve denotes saturation induction $4\pi M_s$ in kG. Phase errors are indicated in percent at ten-percent bandwidth. Curves which do not extend to right border are truncated at appropriate H_a value for propagation cut-off.

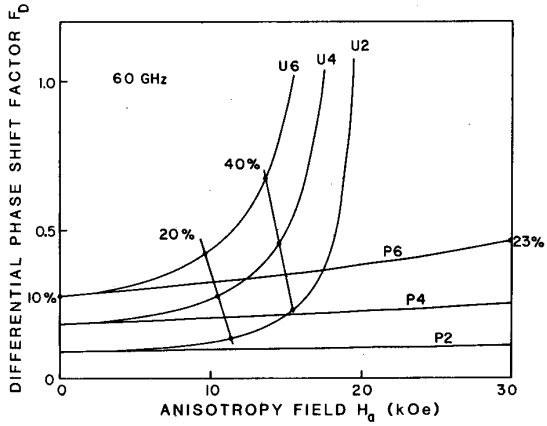

Fig. 3. Materials phase shift factor F_D versus anisotropy field H_a for uniaxial (U curves) and planar (P curves) materials at 60 GHz. Nomenclature is same as for Fig. 2.

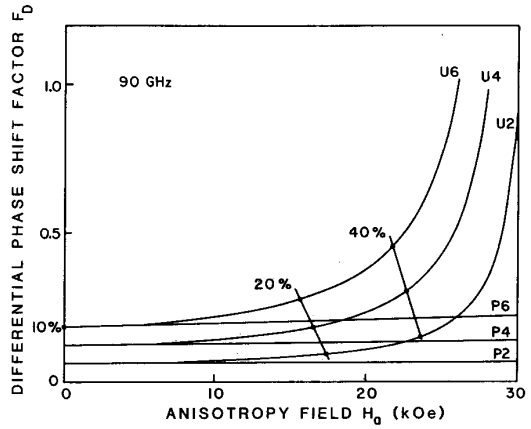

Fig. 4. Differential phase shift factor F_D versus anisotropy field H_a for uniaxial (U curves) and planar (P curves) materials at 90 GHz. Nomenclature is same as for Fig. 2.

ropy and $4\pi M_s = 4$ kG. Any curve which does not extend to the right border, $H_a = 30$ kOe, has been truncated at the appropriate H_a value for propagation cutoff. Phase error values and phase error contours are indicated in percent. Note that the intersection point along the F_D axis ($H_a = 0$) for the P6 and U6 curves corresponds to our reference phase shifter material, the Li–Zn spinel ferrite.

A. Phase Shift at 30 GHz

The results for 30 GHz are summarized in Fig. 2. First consider curves $U2$, $U4$, and $U6$ for the uniaxial materials. At 30 GHz, all three uniaxial curves truncate at cutoff anisotropy field values below 10 kOe. The corresponding F_D values for these curves at cutoff are all close to unity, compared to 0.56 for Li–Zn ferrite (curve $U6$ at $H_a = 0$). We see, therefore, that the biggest possible phase shift enhancement over Li–Zn ferrite by going to a uniaxial hexagonal ferrite would be a factor of about two or less.

As discussed earlier, however, a maximum F_D is not the only consideration. Low field loss and phase error must be taken into account as well. As discussed in Section II, it is important to move away from cutoff (to lower H_a values) to avoid low field loss complications. An optimum operating point might correspond to the 20-percent phase error contour for the U curves in Fig. 2. The corresponding phase shifts at the intersections of the U curves and the 20-percent PE contour show an enhancement, relative to Li–Zn ferrite, *only* for $U6$. This operating point, for $4\pi M_s = 6.0$ kG and $H_a = 4.0$ kOe, gives an enhancement ratio of $0.83/0.56 \sim 1.48$. Even this modest enhancement in phase shift is at the cost of a factor-of-two increase in phase error. The PE values at $H_a = 0$ for the three U curves are all about ten percent (this applies to 60 and 90 GHz as well).

Turn now to the planar materials and the P curves in Fig. 2. We see that the trend of these curves is the same as in the uniaxial case. The initial increase in phase shift with H_a is more gradual. Cutoff occurs at both higher F_D values and higher H_a values. As before, however, operation close to cutoff is to be avoided due to low field loss and very large phase errors. Even for curve $P4$ at $H_a \sim$ 20 kOe, the phase error is greater than 60 percent. The problem of large phase errors for the planar situation was also pointed out in [5].

If we stipulate a more reasonable phase error tolerance at 20 percent for the planar materials, the phase enhancement degrades severely. Only the $P6$ curve intersection with the 20-percent PE contour gives a phase shift factor which is above the F_D value of the Li–Zn ferrite reference material. This intersection corresponds to $4\pi M_s = 6$ kG, $H_a = 6.2$ kOe, and $F_D \sim 0.83$. The gain over Li–Zn ferrite, therefore, is about the same as for the optimum uniaxial case discussed earlier, but for a somewhat larger H_a value. As before, however, the gain in phase shift is at the expense of a two-fold phase error increase.

Of course, there are possible applications where a large phase error (or narrow bandwidth) can be tolerated. In such cases, it would be possible to select operating points near $H_a \sim 10$ kOe for $P6$ or $H_a \sim 20$ kOe for $P4$ and obtain phase shift enhancements of a factor of two or more.

B. Phase Shift at 60 and 90 GHz

Calculated curves in the same format as Fig. 2 are shown for 60 and 90 GHz in Figs. 3 and 4, respectively. The basic effect of the higher frequencies is to push the "knee" of any given curve out to higher values of H_a. This effect is most apparent for the U curves. For planar anisotropy the "knees" are off scale at values of H_a well beyond any realizable anisotropy field in a practical hexagonal ferrite with a reasonable saturation induction.

First consider the situation for uniaxial materials. Here again, there are reasonable gains in phase shift to be realized but only for applications where the large phase errors can be tolerated. An operating point on the $U6$ curve between the 20- and 40-percent phase error contours will give a factor of 2–3 phase enhancement over Li–Zn ferrite. For $U4$ ($4\pi M_s = 4$ kG), the F_D parameter is above the Li–Zn reference point ($H_a = 0$ for $U6$ or $P6$) only for phase errors above 30 percent or so. The optimum materials would have anisotropy fields in the 10–15-kOe range for 60 GHz and 17–23 kOe for 90 GHz.

The results in Figs. 3 and 4 indicate that planar hexagonal ferrites with anisotropy fields of 30 kOe or less offer little advantage in terms of phase shift enhancement over Li–Zn spinels at 60 and 90 GHz. An extremely high anisotropy and a high saturation induction ($4\pi M_s - 6$ kG), if such a material could be produced, could offer some phase shift enhancement ($0.46/0.28 \sim 1.6$) at a 23-percent phase error for 60 GHz.

IV. Materials Considerations

The previous discussion has considered a particular materials-related phase shift factor and examined the various trade-offs between this factor, cutoff problems, and phase error for a range of materials parameters and three frequencies of general interest; 30, 60, and 90 GHz. The materials situation for applications in which phase error must be kept within tolerable limits is summarized in Table I. The basic points are as follows.

a) The materials-related phase shift enhancements which can be realized by going to hexagonal ferrites are modest, at best, and will probably not exceed a factor of two.

b) To achieve even these enhancements, it will be necessary to develop hexagonal ferrite materials with a high-saturation induction, $4\pi M_s \sim 6$ kG, on the order of the $4\pi M_s$ in Li–Zn spinel ferrite.

c) If such materials can be developed, the resulting phase shifters will have large phase errors, roughly double those for Li–Zn ferrite devices.

d) Some reduced phase enhancement can be achieved with more conventional hexagonal ferrite materials with $4\pi M_s \sim 4$ kG but at the cost of even larger phase errors.

TABLE I
HEXAGONAL FERRITE PHASE-SHIFTER MATERIALS

Frequency (GHz)	Anisotropy Type	Saturation Induction $4\pi M_s$ (kG)	Anisotropy Field H_a (kOe)	Phase-Shift Enhancement Ratio	Phase Error (percent)
30	*U*	6.0	4.0	1.5	20
	P	6.0	6.2	1.5	20
60	*U*	6.0	9–14	1.5–2.4	20–40
	P	6.0	30	1.6	23
90	*U*	6.0	17–23	1.5–2.4	20–40

e) Planar materials may be used to advantage at lower millimeter wave frequencies (e.g., 30 GHz) but appear to offer little or no phase shift advantage over Li–Zn ferrite at the higher frequencies.

Two important aspects of the materials problem which have not been considered in the foregoing analysis concern microwave losses and temperature stability. While the FMR linewidths of hexagonal ferrites are typically large, on the order of hundreds of Oe at millimeter wave frequencies, single crystal linewidths of 50 Oe or less have been reported in the literature [8]. There is no *a priori* reason for hexagonal ferrite linewidths to be any greater than those in good spinels or garnets. A recent study [9] indicates that a large part of the hexagonal ferrite linewidth for both single crystals and oriented polycrystals is inhomogeneity related. Hexagonal ferrites in remanent devices are likely to have a substantially reduced effective linewidth and offer attractive insertion loss possibilities in spite of the large FMR linewidths. The large anisotropy field values which are needed for hexagonal ferrites to have a phase shift advantage over conventional materials will also lead to temperature stability problems. Large variations in H_a with temperature go hand in hand with large H_a values.

The challenge for millimeter wave hexagonal ferrites appears to be in the development of high-magnetization materials, just as it is for other candidate ferrite systems. Most of the anisotropy fields listed in Table I are fairly moderate and readily achievable for both planar and uniaxial hexagonal ferrite systems, albeit at $4\pi M_s$ values in the 2–4-kG range. Materials with room-temperature $4\pi M_s$ values in the 5.0-kG range have also been reported in the literature. A dated but reasonably comprehensive review of the possibilities is given in [8].

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