MICROWAVE, MILLIMETER WAVE AND SUB-MILLIMETER WAVE FREE-SPACE FARADAY ROTATORS

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Abstract - We report new loss and dispersive measurements on SrM hexagonal ferrites both in sintered form and in a plastic matrix showing their potential for providing high performance, free-space Faraday Rotators over large frequency ranges. SrM polycrystalline ferrites show a strong dispersion at frequencies below 150GHz which helps to account for their wideband performance at W-band. These ferrites have the advantage that they operate in their remnant state and require no external magnetic field and can act as isolators over extremely large apertures.

1.0 Introduction

Free space four port circulators or isolators may be produced by positioning a 45 degree free-space Faraday rotator between two polarisers angled at 45 degrees as shown in Figure 1. These type of isolators have been described before at 40GHz[1] and 285GHz [2] with respective isolations of 40dB and 18dB, and respective insertion losses of 0.1dB and 2dB. More recently a free-space reflection isolator has been described for high power applications at 40GHz [3] and Faraday rotation measurements have further indicated the potential for free space isolators at 290GHz [4]. All these isolators used ferrites biased into saturation using external magnets, and had relatively small apertures.

Free-space Faraday rotators using permanently magnetised ferrites were first examined by D.Martin and R.Wylde who surveyed a number of ferrites and produced an isolator with 17dB isolation and 1.0dB insertion loss at 115GHz [5]. This work was extended by M.R.Webb [6] who produced small aperture isolators with isolations ~30dB at W-band, with losses <0.5dB. Recently, we reported isolators with apertures of 100mm x 100mm which gave isolation >50dB with insertion loss ~0.3dB at spot frequencies, and isolations >20dB across most of W-band [7].

These isolators used thin sheets of anisotropic polycrystalline SrM hexaferrite ($Sr\,Fe_{12}\,O_{19}$) with the c-axis perpendicular to the plane of the material. Sr hexaferrites are characterised by high resistivity and a very large magnetic anisotropy field along the c-axis, which acts as an effective internal magnetic field of around 20 kOe. Because of this large internal field the hexaferrites have been suggested for applications at mm-wave frequencies by many authors [9, 10], and Taft [11] has described resonance isolators operating from 60 - 94GHz using doped Sr ferrite. Faraday rotators with zero field have also been demonstrated at 24GHz by Beljers [8].

In this paper we report further high frequency measurements of anisotropic polycrystalline SrM and isotropic and semi-anisotropic plastic ferrites in the 75GHz - 500GHz range. These show that polycrystalline SrM has a very strong dispersion below 150GHz which helps to account for the large isolation bandwidth previously obtained at W-band [7]. We also show that plastic ferrites potentially offer high

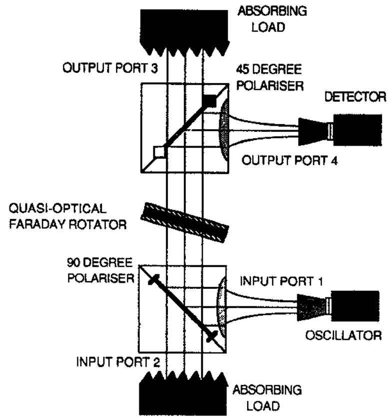

Figure 1. Schematic diagram of a quasi-optical 4 port circulator using a Faraday rotator between angled polarisers. Any reflection back from the detector at port 4 will be dumped into the absorbing load at port 2.

performance at mm-wave frequencies, with the advantage of being more rugged, easier to match as well as being available in large areas. However, their performance is limited at present by unwanted birefringence in the plane of the material.

2.0 Theory

The reason that the hexagonal ferrites are able to act as free space Faraday rotators without any external field is due to their very large anisotropy field. This enables the spins to remain aligned even when the demagnetisation factor ~1. The effective internal magnetic field B_{int} within the ferrite is given by:

$$\mathbf{B_{int}} = \mu_0 (\mathbf{M} - \mathbf{H_d} + \mathbf{H_A}) \quad (1)$$

where μ_0 is the permeability of free space, **M** is the magnetisation, $\mathbf{H_A}$ is the effective field due to the crystal anisotropy and $\mathbf{H_d}$ is the demagnetisation field. The anisotropy field H_A is inversely proportional to the saturation magnetism M_S and normally accurately represented as $2K_1/M_S$ where K_1 is the first order anisotropy constant. The demagnetisation field H_d is given by N_dM where N_d is the demagnetisation factor and is geometry dependent. In the case where the magnetisation is perpendicular to a large thin sheet $N_d \sim 1$ (SI units) and $\mathbf{H_d}$ will have almost the same magnitude as the magnetisation.

The physical basis of Faraday rotation is that the magnetisation field **M** starts to precess when it interacts with a propagating electromagnetic beam. The torque acting on the magnetisation **M** is due to the anisotropic field $\mathbf{H_A}$ and the demagnetisation field $\mathbf{H_d}$, and leads to the following Larmor resonance frequency

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$$\omega_0 \sim \gamma\mu_0(H_A - H_d) \quad (2)$$

where γ is the gyromagnetic ratio. Resonance occurs when the precession of the electron spin is matched in frequency and direction by the rotating magnetic field of an electromagnetic wave. The net effect is to cause different propagation rates (different complex refractive indices) for each of the two circular polarisation states.

If the magnetic field associated with the electromagnetic wave is assumed to be small compared to the magnetic field of the ferrite, then the propagation constants $\beta_\pm$ at a frequency ω for the two circularly polarised beams are given by [12]:

$$\beta_\pm = \omega\sqrt{(\varepsilon\mu_\pm)} = \omega\sqrt{(\varepsilon_r\varepsilon_0\mu_0)}\ (1 + \omega_m/(\omega_0 \mp \omega)) \quad (3)$$

where ε_r is the relative permittivity of the ferrite and ω_m is a frequency related to the magnetisation of the ferrite ($\omega_m = \gamma\mu_0 M$). It can be shown that differential propagation rates between circular polarisation states produces a rotation θ of a linearly polarised beam. This rotation angle θ is given by:

$$\theta = (\beta_- - \beta_+).(d/2) = d.\Delta n_c.(\omega/2c) = \pi.d.\Delta n_c/\lambda \quad (4)$$

where d is the length of the ferrite, and Δn_c is the difference in refractive index between the two circular polarisation states at frequency ω. Thus the required length of ferrite for 45 degree rotation (for use in isolators and circulators) is $d = \lambda/4\Delta n_c$.

Figure 2 shows the theoretical rotation plotted as a function of frequency for typical values of ω_0 and ω_m, assuming a constant refractive index. The rotation has a 1/f dependence above resonance [10], with the rotation tending towards a limiting value independent of frequency as $\omega >> \omega_0$. It is then only dependent on the refractive index n ($= \sqrt{\varepsilon_r}$) and the magnetisation M and is given by:

$$\theta = d.\,n.\,(\omega_m/2c) = \pi.\,d.\,n/\lambda_m \quad (5)$$

where $\lambda_m = \omega_m/(2\pi c)$. Thus for 45 degree rotation, the required length of ferrite is $d = \lambda_m/4n$, which is independent of frequency when the operating frequency ω is well above ω_0 and ω_m.

The rotation θ is the single pass rotation. The effect of matching to free space is also very important as multiple reflections cause different transmissions and reflections for each polarisation state [7]. This causes both the polarisation and phase angle (ellipticity) of the output beam to vary. To reduce this effect some form of quarter wavelength matching must be used to match the ferrite to free-space.

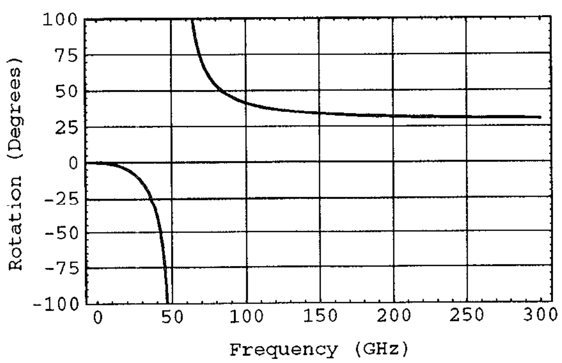

Figure 2. Illustrative diagram showing the theoretical rotation per unit length for a ferrite with a resonance frequency ω_0=52GHz, and a constant refractive index. The rotation is quite strongly frequency dependent between 75-110GHz, but becomes frequency independent at higher frequencies.

3.0 Size Considerations

One of the advantages of using the permanently magnetised ferrites is that, to a very good approximation, the rotation is independent of the size of the Faraday rotator (when the demagnetisation factor ~1). This slightly surprising result is due to the anisotropy field being very much larger than the demagnetisation field. Thus even though the external measured field is very low, the effective internal field may still be very high.

This has been confirmed for samples of isotropic plastic ferrite as large as 400mm x 400mm, where the measured difference in refractive index Δn_c between the two circular polarisation states was found to be:

a) virtually constant over the entire 400mm x 400mm area and
b) the same as samples of area 200mm x 200mm and 100mm x 100mm, at frequencies around 94GHz.

4.0 Material Measurements

There appear to be relatively few previously published measurements for the dielectric constant in the hexagonal ferrites, although it is known that a serious loss mechanism may be due to electron hopping between Fe^{2+} and Fe^{3+} ions. This may be caused if oxygen is lost during sintering or if excess iron is introduced during production. Labeyrie [13] has reported single crystal results at 94GHz, using spheres of the ferrites as dielectric resonators. Labeyrie measured the real part of the dielectric constant as 16±3 (basal plane) and 25 ±3 (c-axis) for Barium hexaferrite (BaM), and 17±3 (basal plane) and 26±3 (c-axis) for Strontium hexaferrite (SrM), and found values of tan δ as low as 1.8×10^{-3} for single crystal BaM. Measurements made at Portsmouth University on BaM polycrystalline samples [14] at X-band and U-band showed a similar anisotropy in the real part of the dielectric constant, but also indicated a very large anisotropy in the dielectric losses. For one sample at X-band tan δ was $1.4 \pm 0.3 \times 10^{-4}$ in the basal plane compared to $6.5 \pm 1.1 \times 10^{-2}$ on the c-axis. Similar results were obtained at U-band.

5.0 Fourier Transform and Reflection Measurements

We have made Fourier transform phase transmission measurements on unmagnetised ferrites over large frequency ranges using a polarising Martin-Puplett interferometer.

When the ferrite is magnetised it becomes difficult to extract data from measurements using linear polarisation states. However using the measurement technique described in [7] we are able to derive the refractive index of the two circular polarisation states from reflectivity measurements at spot frequencies.

Polycrystalline SrM

We previously reported a refractive index of 5.3 at W-band [7] for polycrystalline SrM based on reflection measurements at W-band and assuming a constant refractive index. However, further material measurements now appear to indicate that the material is in fact highly dispersive for frequencies below 150GHz. Strong dispersion was also noted by Asfar et al. [15] (although there are large apparent discrepancies between his results and ours). Figures 3 and 4 show the measured refractive index and loss for an unmagnetised sample of Ferroxdure 330.

A typical reflection measurement for a magnetised sample of Ferroxdure 330 is indicated in Figure 5. This indicates that the refractive index for the two circular polarisation states around 95GHz is 4.18 and 3.66 giving Δn_c = 0.53. Using Eq.(4) this gives an optimum length of 1.49mm for 45 degree rotation.

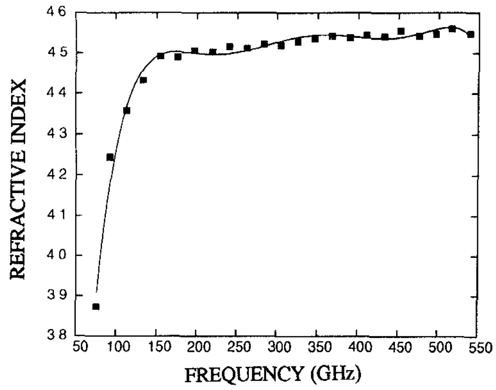

Figure 3. Graph illustrating the measured refractive index as a function of frequency for a sheet of unmagnetised anisotropic polycrystalline SrM (Ferroxdure 330).

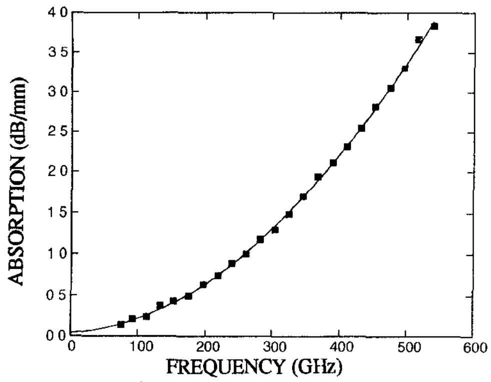

Figure 4. Graph illustrating the measured loss as a function of frequency for an unmagnetised anisotropic polycrystalline SrM (Ferroxdure 330).

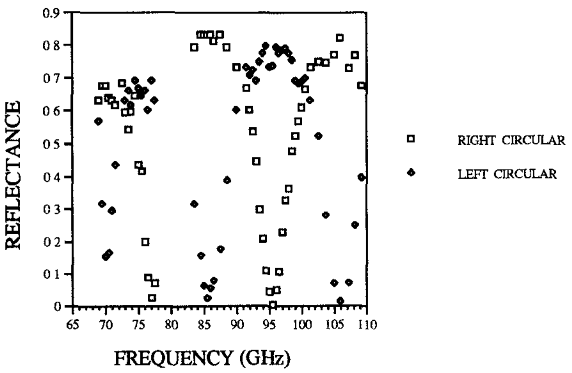

Figure 5. Graph illustrating the measured reflectance versus frequency for a 1.5mm thick sheet of Ferroxdure 330, magnetised through the plane. The experimentally measured reflectances of the two circular polarisation states are indicated by the squares and diamonds.

Plastic Ferrites

Figure 6 indicates the measured and loss in dB/mm for an unmagnetised semi-anisotropic plastic ferrite sheet (Vynon) for frequencies in the range 100-500GHz for one linear polarisation state. The losses per unit rotation are greater than those measured for the polycrystalline ferrite. However, reflection measurements made at W-band indicate that the losses are rather lower after magnetisation.

Fourier transform and reflection measurements indicated little or no dispersion above 90GHz, although there was some evidence to suggest a drop in refractive index around 75GHz. Measurements made on both isotropic and semi-anisotropic plastic ferrites have indicated a linear birefringence in the plane of the material. The strength of the birefringence being measured by the difference in refractive index Δn_L between the two principal axis. Typically we have measured $\Delta n_L = 0.07$ ($n_x = 3.22$, $n_y = 3.15$) and $\Delta n_L = 0.17$ ($n_x = 3.27$, $n_y = 3.10$) for semi-anisotropic and isotropic plastic ferrites respectively.

After being magnetised into saturation, reflection measurements on isotropic and semi-anisotropic plastic ferrites have shown $\Delta n_c = 0.24$ and $\Delta n_c = 0.27$ respectively. Thus, around 94GHz the thickness required for 45 degree rotation for an isotropic plastic ferrite is ~3.3mm, and we have obtained isolations >40dB for this thickness, in this frequency range. When appropriately matched we have also obtained insertion loss as low as 0.3dB. However, the isolation bandwidth appears slightly reduced compared to the polycrystalline ferrites, which is attributed to the lower dispersion observed.

Performance has also been limited by the linear birefringence. This effect manifests itself in showing a strong dependence on the angular orientation of the ferrite with respect to the input and output polariser. This becomes greater at high frequencies as the material approaches the thickness required for a quarter-wave plate. A full analysis, taking into account Faraday rotation and linear birefringence requires a 4x4 matrix representation [3]. However, a basic understanding may be gained by reference to Figure 7. An elliptical beam will be produced if the input polarisation rotates through a plane at 45 degrees to the two principal axis. However, if the Faraday rotator is angled such that the input beam rotates through one of the principal planes the effect of ellipticity will be minimised. In practice, it is usually more important to orientate the isolator to give optimal isolation and slightly increased insertion loss.

It is thought likely that the birefringence is caused by a preferential orientation of the particles along the plane during manufacture. It is hoped that this may be eliminated by making a truly isotropic material with random orientation of the particles or by using an anisotropic plastic ferrite, where the particles may be better aligned.

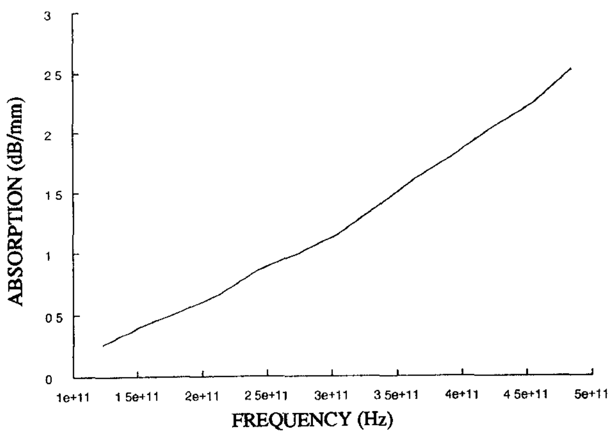

Figure 6. Graph illustrating the measured loss as a function of frequency for an unmagnetised semi-anisotropic Sr plastic ferrite (Vynon).

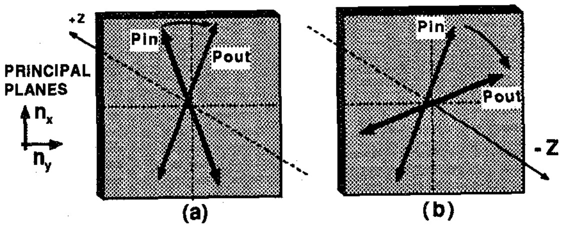

Figure 7. Diagram illustrating the effect of birefringence on the performance of an isolator. If the isolator is angled such that the input polarisation state rotates through one of the principal axis (a), then the effect of ellipticity is minimised. However, any return beam will be rotated through another 45 degrees (b) and suffer maximum ellipticity.

6.0 MM-wave ESR Measurements

Preliminary measurements have been made to determine the effective anisotropy field of the samples using a mm-wave ESR spectrometer operating at 92GHz [16]. It is of interest to make measurements in this frequency range because one is operating well above the expected zero field resonance frequency. Initial measurements have been made on powder samples of SrM which have random orientation. These gave broad peaks at the two Larmor resonance frequencies corresponding to the two cases of the magnetic field parallel and perpendicular to the c-axis [17].

$$\omega = \gamma(H_0 + H_A) \quad \text{and} \quad \omega = \gamma(H_0(H_0 - H_A))^{1/2}$$

where H_0 is the applied field and $H_A = 2K_1/M_S$ is the anisotropy field (and where the demagnetisation field has been omitted for clarity). However, this experiment also showed anomalous magnetic losses that did not seem directly related to the Larmor resonance frequency [16]. Losses attributed to preferential absorption or dispersion of one circular polarisation state with respect to the other, indicated a zero field resonance frequency about 52GHz, as reported by other researchers [18].

7.0 Discussion

The strong dispersion observed below 150GHz helps to explain the large isolation bandwidths that have been obtained at W-band [7]. Figure 2 indicates that the rotation is expected to be strongly frequency dependent at W-band for a Larmor resonance frequency of 52GHz, if the refractive index is constant with frequency. However, a decreasing refractive index reduces the amount of rotation, counteracting the natural increase in rotation as resonance is approached. It is also certainly possible to increase the bandwidth by intentionally mis-matching the ferrite to free space [7].

However, at sub-millimetre wave frequencies the rotation is expected to be frequency independent and the losses indicated are not prohibitive. Moreover, we believe there is some potential for reducing the losses even further, making this material extremely interesting for sub-millimetre wave applications.

In addition, Beljers [8] has demonstrated that BaM may be used as a Faraday rotator at frequencies below resonance, and showed that the ferrite had relatively low loss at 24GHz. We believe that large area plastic ferrites have considerable potential at microwave frequencies and we hope to report results in the near future.

It is also interesting that isotropic plastic ferrites should have such a large Faraday rotation. Isotropic materials may offer lower loss than anisotropic materials, and plastic ferrites offer the potential for rugged large area isolators.

8.0 Applications

These Faraday Rotators have already been used very successfully in a large number of quasi-optical applications at W-band [7], including mm-wave Radar systems, plasma diagnostic systems and the quasi-optical Electron Spin Resonance spectrometer mentioned above[18]. They also have applications at the front end of antennae systems and may prove useful in quasi-optical oscillator or detector systems. They also have great potential at sub-millimetre wave frequencies where no convenient alternative exists.

9.0 Conclusions

Hexagonal ferrites both in sintered and plastic form potentially offer simple inexpensive solutions to providing isolation over large frequency ranges and over large apertures.

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