Observation of Frequency Dependent Faraday Angle Resonance in Ferrites & New Ellipticity Characterisation of Freespace Faraday Rotators at MM-Wavelengths

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Abstract

This article, reports 'Frequency Dependent Faraday Angle Resonance' in a magnetic sample at millimetric frequencies for the first time using a fully automated rotary polariser quasi-optical system. This serves to compliment the original work performed by Raum at Terahertz frequencies in the Frequency independent region of a magnetic material. In addition, it is shown how the same instrument can be used further classify the performance of a Freespace Faraday Rotators, by the introduction of a new 'ellipticity' parameter measurement. This serves to identify what physical mechanism is responsible for the isolation that occurs across the device's operating region, hence, providing a further insight into the operation of the device.

1. Introduction

The motivation of the work is concerned with the classification of ferrite materials for Freespace Faraday Rotator[4,5] design. This involves determining the optimal thickness (L_{OPT}) that is needed to cause a 45^0 rotation in a magnetic sample. The first sections introduce the reader to the 'Faraday Effect'[1] and the Freespace Faraday Rotator design. This is followed by introducing the reader to 'Faraday Angle Resonance' method[10] which is later used to determine the optimal thickness of the ferrite to produce 45^0 rotation. It is then described how the fully automated rotary polariser quasi-optical system[9,2] was developed and how accurate rotations and ellipticity can be measured by the system. A polycrystalline magnetic sample is then classified using the rotary polariser quasi-optical system using the Faraday Angle Resonance method. Frequency Dependent Faraday Rotation is reported for the first time at mm-wavelengths. The reader is then introduced to the terminology necessary to understand Freespace Faraday Rotator assessment. The isolation of a Freespace Faraday Rotator measured by the conventional reflectance method is compared to the ellipticity measurements made by the quasi-optical system. It is shown how the system results can be used identify what physical mechanism is responsible for the isolation that occurs across the device's operating region. Conclusions of the work are then presented.

2. The Faraday Effect & Faraday Angle Resonance

2. 1 The Faraday Effect

The Faraday Effect [1] describes the interaction of a linear polarised incident beam of radiation upon a magnetised material. A linear polarised beam is the linear superposition of two circular counter-rotating polarised states that are equal in magnitude. These are described as the positive (+ve), right handed circular state, and the negative (-ve), left handed circular state. In a magnetised sample all the electrons precess at the 'Larmor frequency' (ω_0) in a specific handed sense. When an incident beam falls upon the magnetic material, the circular state that rotates in the same direction as the electrons precess interacts with them. This causes a 'forced precession of the electrons which is frequency dependent. The circular state that rotates in the opposite handed sense to the electrons interacts minimally with the electrons and diffracts through the material. Instead of both the circular states traversing the same path length through the material, the interacting circular state causes a different path length to be traversed in the material. The exiting beam has both its circular states out of phase with each other. These linearly combine to rotate the beam through an angle (θ), as shown in Figure 1. This is known as the Faraday Effect.

2.2 The Freespace Faraday Rotator

The 'Freespace Faraday Rotator' [3] is a magnetic device which consists of a magnetic material which is quarter-wave matched to freespace and employs the Faraday Effect [1] in its operation. The Faraday rotators are designed to have a thickness that causes a 45^0 of rotation to a linear polarised beam, as shown in Figure 1. The authors were involved in the production of such Faraday rotators at St.Andrews University [4,5] which consist of the following elements. The principle element is a $100mm^2$ square of ferrite material. The materials used at St.Andrews in the manufacture of such rotators are 'Polycrystalline, uni-axial, anisotropic Barium [7-8] or Strontium Hexaferrite' with a 'Magneto-plumbite' structure (referred to as BaM and SrM respectively). When the pulverised powdered form of BaM or SrM is embedded in a low loss polymer matrix it creates a composite semi-anisotropic material that is physically robust, known as a ‘Plastoferrite’.

The $100mm^2$ samples are cut such that the materials c-axis (which contains the 'easy axis') is perpendicular to the plane of the ferrite. This orientation is chosen since it allows for easy magnetisation of the sample. Conventional reflectance measurements [9] are then performed on the sample, to determine what the required thickness must be to produce 45° rotation on a single pass.

The ferrite is then ‘matched’ to freespace. Such ‘matching’ allows a Gaussian beam to couple in and out of the ferrite easily, thus, minimising reflections from its surface. A suitable material is then chosen which has a refractive index equal to the square-root of the refractive index (n) of the ferrite. The thickness of the matching layer should be a quarter of a wavelength of the operational frequency of the device. However, in practice three quarter wavelength matching is employed. This is because at millimetric wavelengths, quarter wavelength matching is extremely thin and hard to machine accurately to this tolerance. Finally, a single matching layer is affixed to either side of the ferrite with a thinned adhesive mixture, shown in Figure 1. The hexagonal structure of the BaM and SrM ferrites can limit their performance since the crystalline anisotropy of the material can serve to impose an ellipticity on the incident beam and to reduce isolation, described in section 4, of the device.

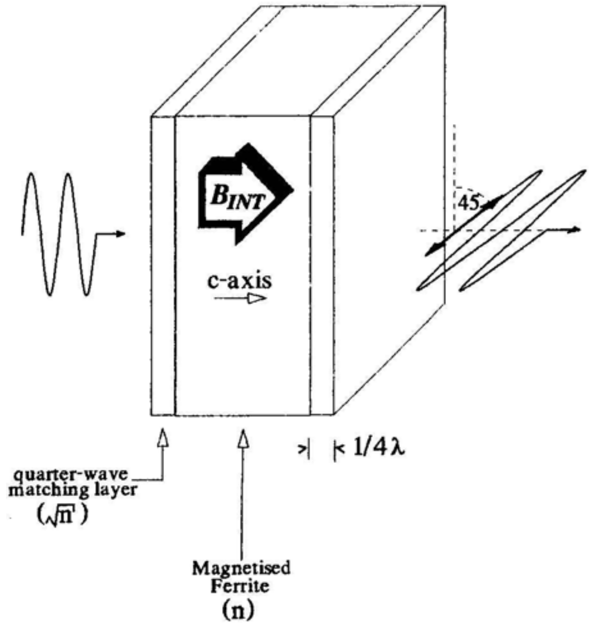

Figure 1 : A Freespace Faraday Rotator

The fully automated rotary polariser quasi-optical system presented has the ability to examine whether the isolation of a Faraday rotator is occurring due to ellipticity of the beam, as described in section 4.

2.3 The Faraday Angle Resonance

The exploitation of the phenomena known as ‘Faraday Angle Resonance’ is a relatively new method to determine material parameters of ferrite materials. The method of characterising magnetic samples was suggested and demonstrated experimentally by Raum [10] at 290GHz. Raum obtained results for Trans Tech TTI105 and Philips Ferroxdure 330 [7-8] which agreed very well to the manufacturer’s specification. This method of characterisation has advantages over the 'Reflectance/Transmission' measurements, described [9] which can take a skilled researcher ~1 week to complete. Other methods of characterisation for the interested reader are described in [11-12].

Advantages of the Faraday Angle Resonance method are: easy determination of material parameters from a single experimental run; parameters can be calculated from very simple formulas; determination of Faraday Rotation/single pass.

Faraday Angle Resonance exploits the internal multi-path reflections that occur within an unmatched ferrite. If a linear polarised wave passes through a ferrite it will be rotated by the Faraday Effect through an angle (θ). When it reaches the air/ferrite interface at the other side of the ferrite, part will be transmitted and part reflected back into the sample. The multiple reflections within the ferrite sample will also produce further transmissions at the same air/ferrite interface. However, these transmissions will have accumulated different amounts of Faraday rotation depending on the path-lengths traversed. Therefore, the resultant beam that travels toward a detector will be a linear superposition of all the transmissions which could be very different to the rotation incurred on a single pass through the ferrite. Raum calculated in his paper, that because of the multi-path effect the resultant Faraday angle will differ with frequency for an unmatched magnetised ferrite. Furthermore, he discovered that the Faraday Angle will oscillate with frequency between two extreme angles in a resonant type manner. These extreme angles are referred to as the 'Maximum' and 'Minimum Faraday angles", namely $\Delta\varphi_{MAX}$ and $\Delta\varphi_{MIN}$ respectively, shown in Figure 2. Raum demonstrated that by very simple measurement of these extreme angles one can determine the amount of Faraday rotation that occurs in a single pass ($\Delta\varphi$) through the ferrite. This is expressed in equation 1) below:

$$\Delta\varphi = \tan^{-1}\sqrt{\tan(\Delta\varphi_{MAX})\tan(\Delta\varphi_{MIN})} \qquad \text{.... (1)}$$

The optimum thickness (L_{OPT}) required for 45° rotation is given by :

$$L_{OPT} = L\pi / 4\Delta\varphi \qquad \text{....(2)}$$

where, (L) is the thickness of the ferrite sample. Furthermore, a slightly less robust measure of the product ($M_s\varepsilon_R$) can be calculated. Where (M_s) is the 'Saturation Magnetisation' of the ferrite and (ε_R) is the dielectric constant as described in [10]. Our work is concerned in the manufacture of Faraday rotators and isolators and thus we only report results for $\Delta\varphi$ and L_{OPT}.

The experiments that Raum performed were at 290GHz with ferrites that had a resonant frequency of (ω_0~50GHz). An operating region known as, 'The frequency independent region' exists at (~$4\omega_0$=200GHz for these materials), shown in Figure 2. In the frequency independent region of the ferrite $\Delta\varphi_{MAX}$ and $\Delta\varphi_{MIN}$ remain constant. This means that the rotation/single pass will remain constant and hence (L_{OPT}) will remain constant.

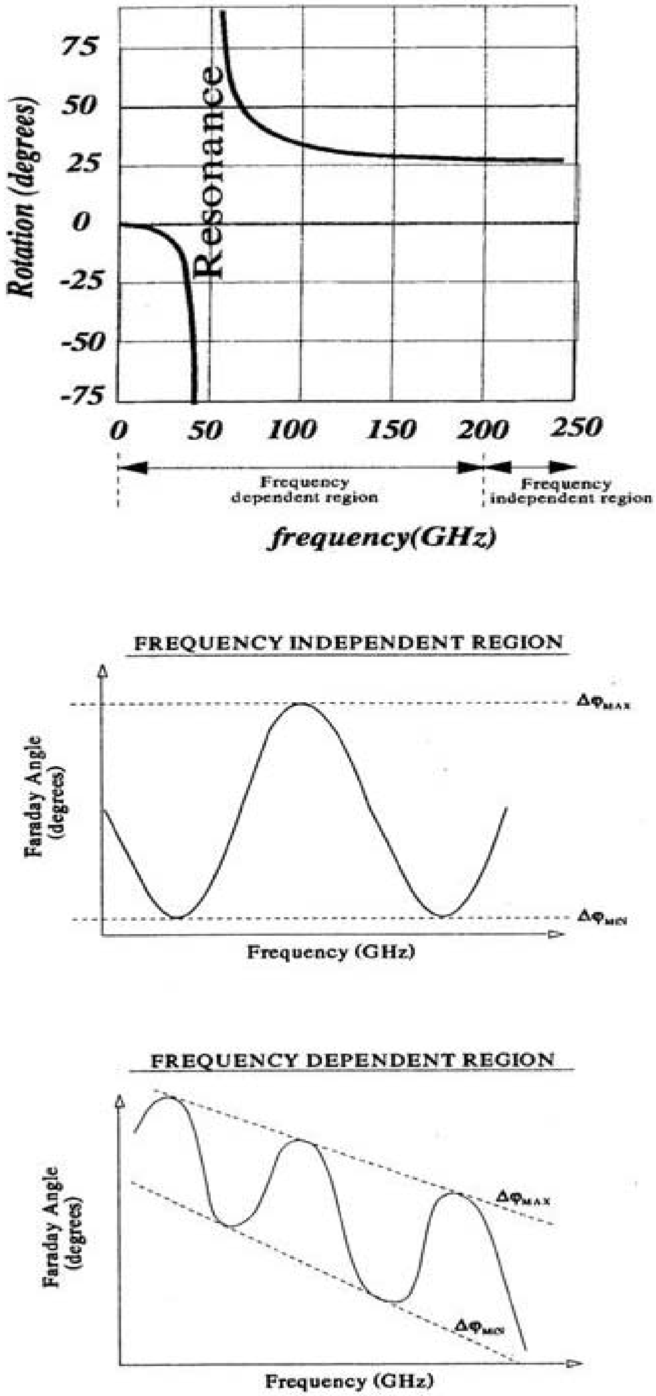

Figure 2 : (upper) Variation of Faraday Rotation with frequency for ω_0=50GHz; Schematic of (middle) Frequency Independent and (lower) Frequency Dependent Faraday Angle Resonance

In contrast to Raum's work[10], the 'Fully Automated Millimetric Rotary Polariser Quasi-Optical System'[9,2] would assess ferrites over 80-100GHz in the frequency dependent region of the ferrite, shown in Figure 2. Since the rotation is now varying with frequency one expects this to be evident in a variation of $\Delta\varphi_{MAX}$ and $\Delta\varphi_{MIN}$. The variation in $\Delta\varphi_{MAX}$ and $\Delta\varphi_{MIN}$ will also result in different optimal thicknesses being required for different frequencies. One motivation for this work was to validate such frequency dependent behavior experimentally for the first time at mm-wavelengths. It is hoped this will give a further insight into the study of Faraday angle Resonance and also to compliment the original work performed by Raum.

3. Experimental setup

Figure 3 shows the experimental setup of the fully automated system[9,2]. A brief overview of the system is now given.

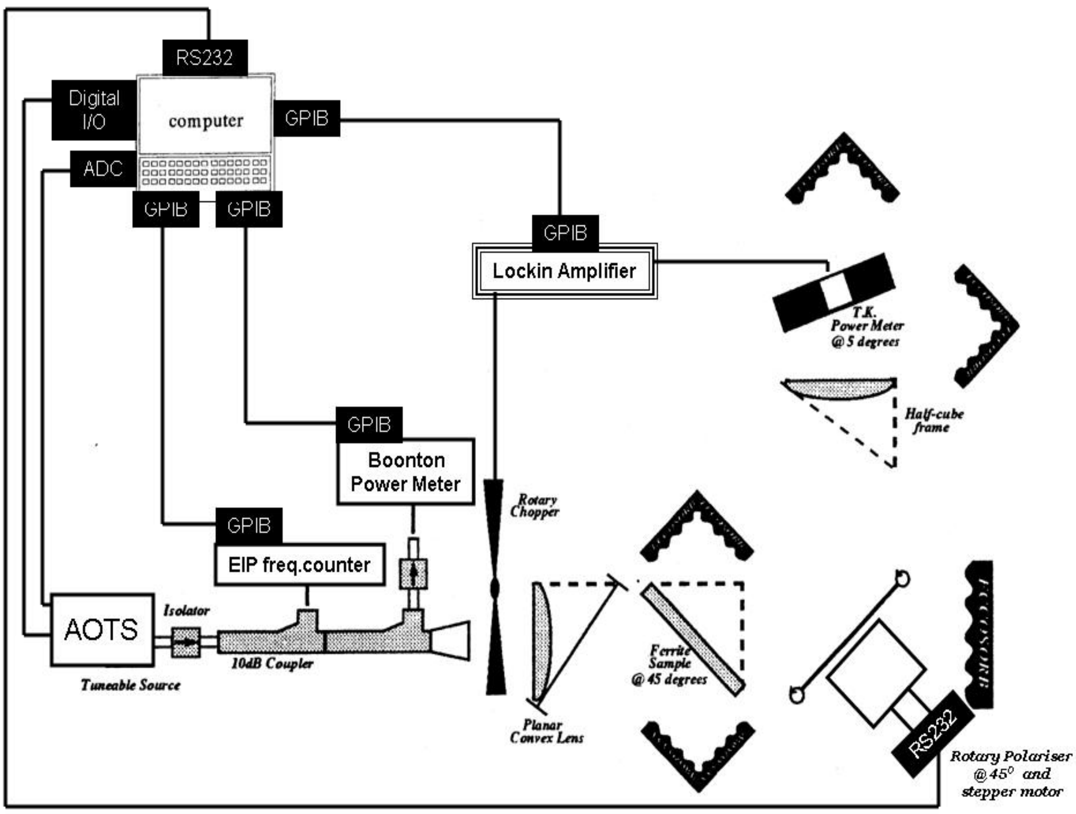

Figure 3 : The Fully Automated Rotary Polariser Quasi-Optical Setup

The ‘Automated Oscillator Tuning System’ (AOTS), was a piece of electronics developed in [9,13] to operate mechanical motors that were fixed to the frequency and backshort tuners of a coaxial cavity, resonant cap mm-wave oscillator [14]. By interfacing the AOTS to a computer, the frequency and power of the oscillator could be adjusted automatically by a computer program. The AOTS was used in the rotary polariser quasi-optical system to step through the dynamic frequency range of the mm-wave oscillator, at discrete intervals (up to 100MHz resolution) and then to adjust the backshort so as to maximise the oscillator’s power at each frequency. A control program operated the AOTS and took readings of frequency and power of the oscillator from an EIP frequency counter [15] and Boonton Power Meter [16] respectively. The computer used was an Acorn Archimedes Computer [17]. The interface from the computer to the AOTS was via a ‘Wildvision Card’ [17] which contained several digital I/O channels and ADC channels. All computer programs to control the AOTS and the rest of the system were written in the BBC Basic V[17]. The mm-wave radiation produced by the oscillator propagated through a waveguide (W27) isolator, through two waveguide 10dB couplers, a further isolator and a feedhorn which coupled it into freespace. The first 10dB coupler passed 90% of the radiation onto the next coupler and 10% to the EIP frequency counter. Similarly the second 10dB coupler passed 90% of the radiation onto the feedhorn and to freespace and 10% to a waveguide isolator which connected to the Boonton power meter. Both waveguide isolators served to protect both the source and the power meter from any reflections that could re-enter the waveguides and damage the devices.

The feedhorn propagated a vertically polarised mm-wave Gaussian beam into freespace. The beam would be chopped by a mechanical rotary chopper such that it could be detected later by a Thomas Keating (T.K) power meter. The beam was then focused by a high density polyethylene (H.D.P.E) planar convex PTFE located within a half-cube and through a horizontal polariser grid which only passed a vertical polarised wave. The beam would then propagate onto the magnetic sample or Faraday rotator inclined at 45% located in a half-cube. The vertically polarised beam would interact with the magnetic sample and be rotated through some angle (θ). In addition it could suffer some ellipticity if the material were anisotropic. The rotated beam would then propagate towards the rotary polariser where it would form its beam waist. The rotary polariser was controlled by the computer to move through a half revolution in 200 discrete steps. Only when the wires of the rotary polariser were parallel to the rotated beam would the full power of the beam be reflected towards the detector. Similarly, when the wires were orthogonal then the power would be dumped into the cavity of the rotary polariser and absorbed. Thus, powers ranging from zero to the maximum power within the beam would be reflected depending on the orientation of the wires of the rotary polariser. The reflected radiation would then pass to another planar convex HDPE lens located within a half-cube which would focus it to the pressure cell of the TK power meter angled at 5^0 to the incident radiation. The Lockin Amplifier would determine the voltage of the detector from the chopped signal and pass this to the computer. Hence, a control programs[9] were developed to classify magnetic sample and Faraday rotators.

Reflections from any optical component within the system whose plane is perpendicular to the direction of propagation of the radiation could create standing waves [18]. The implementation of 'blazed' planar convex lenses[19], waveguide isolators to protect the oscillator and Boonton detector, angling of the ferrite sample/rotator at 45°, use of 'Radar absorbent material' R.A.M. [20], angling the TK meter at 5° to the incoming radiation, design of the cavity of the rotary polariser and measurement of the 'Minor Faraday Angle', defined in section 4 all served to reduce reflections in the system.

4. Measuring the Faraday Angle & Ellipticity of a Gaussian Beam

Although the TK is only sensitive to the vertical polarisation state when at the Brewster angle, the voltage output for various power input remains the same for all frequencies. Thus, the T.K's Detectivity (D^*), is said to be frequency independent. When one angles the TK away from the Brewster angle, it becomes receptive to arbitrary polarised inputs but its detectivity becomes frequency dependent. Since this application was only concerned with measuring accurate rotated angles, due to the Faraday effect, the frequency dependency of the T.K's detectivity was not an issue. It was not an issue because although the detectivity was frequency dependent, the voltages from the T .K. at spot frequencies would remain relative to one another. The voltage would also be proportional to the power detected by the TK Hence, the largest voltage obtained will represent the largest power output. In relation to the Faraday angle, if a linear polarised beam were input into the system a maximum voltage would correspond to the position at which the Faraday Angle existed. If the magnetic sample had distorted the original linear polarised beam to produce an elliptically polarised beam, then the maximum voltage would represent the proportion of power in the major axis of the beam. Similarly, a minimum voltage would represent the proportion of power in the minor axis of the beam. This minimum voltage would also occur 90° away from the Faraday Angle. Therefore, by observing the maximum and minimum voltages one could define the ellipticity of the beam. From herein, the position at which the maximum voltage occurs will be referred to as the 'Major Faraday Angle' and the position at which the minimum voltage occurs will be referred to as the 'Minor Faraday Angle'. Thus, it was important to locate both the Major and Minor Faraday Angles and also to measure the voltage at each of these locations to determine the ellipticity of the beam. In [9,2] the ellipticity was defined to be :

Ellipticity = (Maximum Voltage/ Minimum Voltage) ….1)

Then various beam shapes could be identified. From the definition described in equation 1) it was found that when :

Ellipticity = 0 → (Linear Polarised Beam),
Minima located on x-axis

0<Ellipticity<1 → (Elliptical Polarised Beam),
Major axis at maxima, Minor axis at minima

Ellipticity = 1 → (Circular Polarised Beam),
Equal power distribution, major=minor axis

In [9,2] experimental time was reduced to 6hrs by tracking the major and minor Faraday angles. This reduction was significant in comparison to the conventional reflectance method [9] used to characterise ferrite materials. A parabolic curve fit described in [9,2] was used to accurately measure the Faraday angles through the noise floor of the detector. [9,2] determined that the Minor Faraday Angle gave the most accurate results as opposed to the Major Faraday Angle (described as the Faraday Angle) and measured by Raum [10]. This was because the Minor Faraday Angle occurred when all the power was dumped into the cavity of the rotary polariser and hence was a null measurement. This served to reduce reflections and standing waves significantly in the quasi-optical system as opposed to the Major Faraday Angle which occurred when the full power of the Gaussian beam was directed to the detector.

5. Experimental Results Using the Fully Automated System.

5.1 Faraday Angle Resonance Results for Sample 32

Sample 32 consisted of a single piece of a SrM polycrystalline ferrite known as Ceramic 8, supplied by Magnetic Developments [27]. The thickness of the sample was 4.97mm. Since the material was inclined at 45° to the incident radiation it has an optical thickness of 7.03mm. The Minor Faraday angle versus frequency and a plot of the ellipticity variation with frequency are displayed in Figure 4. It should be noted that the plot covers a 88-98GHz region due to the mm-wave oscillator becoming erratic for frequencies below the 88GHz. However, there is sufficient information in the results to highlight the 'Frequency Dependent' region that one expects to occur at W-band as described earlier in section 2.3. This result serves to compliment Raum's original result in the Terahertz region and also gives a further insight into the Faraday Angle Resonance phenomena at millimetric frequencies.

5.2 Results Analysis For Sample 32

Figure 4, highlights a definite slope in the minima's of the plot. As described in section 2.3. This implies that the material is operating in its 'frequency dependent' region and the rotation is varying with frequency. Performing the parabolic curve-fits, described in [9,2] resulted in the following location of the turning points, shown in Table 1.

Type of Turning Point	**Minor Faraday Angle**
1st Minima($\Delta\varphi_{1st\ MIN}$)	(90.85 GHz, 69.94°)
Maxima($\Delta\varphi_{MAX}$)	(93.25 GHz, 78.67°)
2nd Minima($\Delta\varphi_{2nd\ MIN}$)	(96.77 GHz, 59.32°)

Table 1 : Minor Faraday Angle locations for Sample 32

The corresponding Major Faraday Angles occur 90° away from the Minor Faraday Angles. For example, the first minima would occur at (90.85 GHz, -20.06°) or (90.85 GHz, 159.94°). As long as one is consistent in choice of whether the Faraday angle is ±90°, the results will remain consistent. By taking the first minima and the maxima, one can calculate the (Δφ) associated to the (90.85-93.25GHz) frequency region. Similarly, by taking the second minima and the maxima, one can calculate the (Δφ) associated to the (93.25-96.77GHz) frequency region.

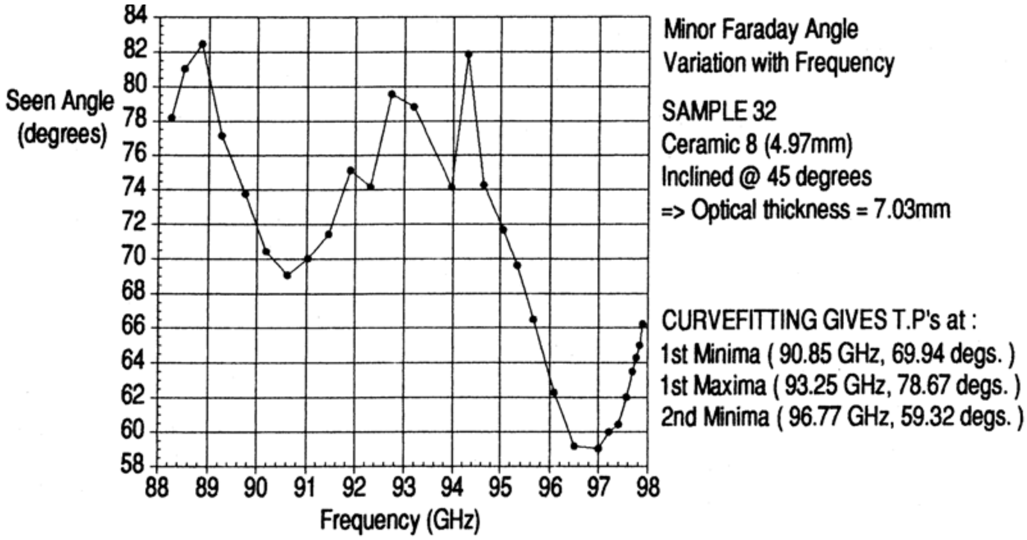

Figure 4 : Minor Faraday Angle results for Sample 32

The tabulated results for (Δφ) for the two different frequency regions is given in Table 2.

Frequency Region	Δφ / single pass	Rotation / mm
(90.85-93.25GHz)	76.86°	10.64°
(93.25-96.77GHz)	70.97°	10.09°

Table 2 : (Δφ) and (ε_R) results for Sample 32

Table 2, shows that the rotation/mm requires an optical thickness of 4.22mm for 45° rotation at the (90.85-93.25GHz) region. This translates to a sample of thickness of 2.98mm inclined at 45° to the incident radiation. Similarly, in the (93.25-96.77GHz) region an optical thickness of 4.46mm would be required for 45° rotation. This translates to a sample of thickness 3.15mm inclined at 45° to the incident beam.

6. Faraday Rotator Assessment

6.1 Conventional Characterisation of 'Freespace Faraday Rotators'

There are two parameters which characterise the performance of a Faraday rotator. These factors are termed the 'Isolation' and 'Insertion Loss'. The isolation is a measure of how efficiently the Faraday Rotator is rotating the (E) field through 45°. Therefore, a high performance rotator would have a very high isolation figure, expressed in dB's. The insertion loss is a measure of the material loss of the isolator in a single pass, measured in dB's. Manufacturers usually supply graphical records of the isolation and insertion loss for the range of operating frequencies of the device. Typical isolation plots are shown in the upper plots of Figures 5-6. When characterising rotators conventionally, the ellipticity is not measured. However, an ellipticity evoked upon the beam would tend to reduce isolation and increase the insertion loss figure. So it would be useful to understand by what mechanism the isolation was caused by. We examine the ellipticity of Faraday rotators here and suggest this may be a useful parameter that could be included in the characterisation process of Freespace Faraday rotators.

The Freespace Faraday Rotator (I9) is used to demonstrate the ability of the fully automated rotary polariser system to examine the ellipticity of the beam. The isolator I9 was a SrM semi-anisotropic plastoferrite. The Faraday rotator required 2 pieces of material that were affixed together with a thinned glue. Each of the 2 pieces were cut at 22.5^0 to the c-axis and three-quarter wave matching was affixed to each side of the rotator.

6.2 Results for Faraday Rotator (I9)

The Faraday Rotator (I9)'s isolation was measured using the conventional reflectance method, described in [9]. The rotator was cut at 22.5^0 to its c-axis in order to maximise the isolation in the forward direction. The rotator was placed in the system at a slight angle of 5^0 to the incident radiation to reduce standing waves within the system. Measurements were performed using the automated rotary polariser system and a plot of the Major and Minor Faraday Angle Variation with frequency together with a plot of the ellipticity variation with frequency was obtained. Both the manual and system measurements obtained for both sides of the isolator are shown in Figures 5-6. It was thought that I9 had demagnetized in storage slightly since the isolation was the same for sides A and B of the rotator.

Figure 5, shows the isolation and system results of side A of I9. The best isolation was ~ -15dB's at 89GHz. The system results show a rotation of 45° occurring at ~88GHz which corresponds to the lowest ellipticity value at this position. The system results also reveal that the low isolation that occurs below 88GHz is due to the rotator actually rotating less and the beam becoming more elliptical.

Above 88GHz the isolation is reduced because rotation is actually larger than 45° but not because of ellipticity. Thus, the system results reveal more information and are useful in the further classification of the Faraday rotator’s performance.

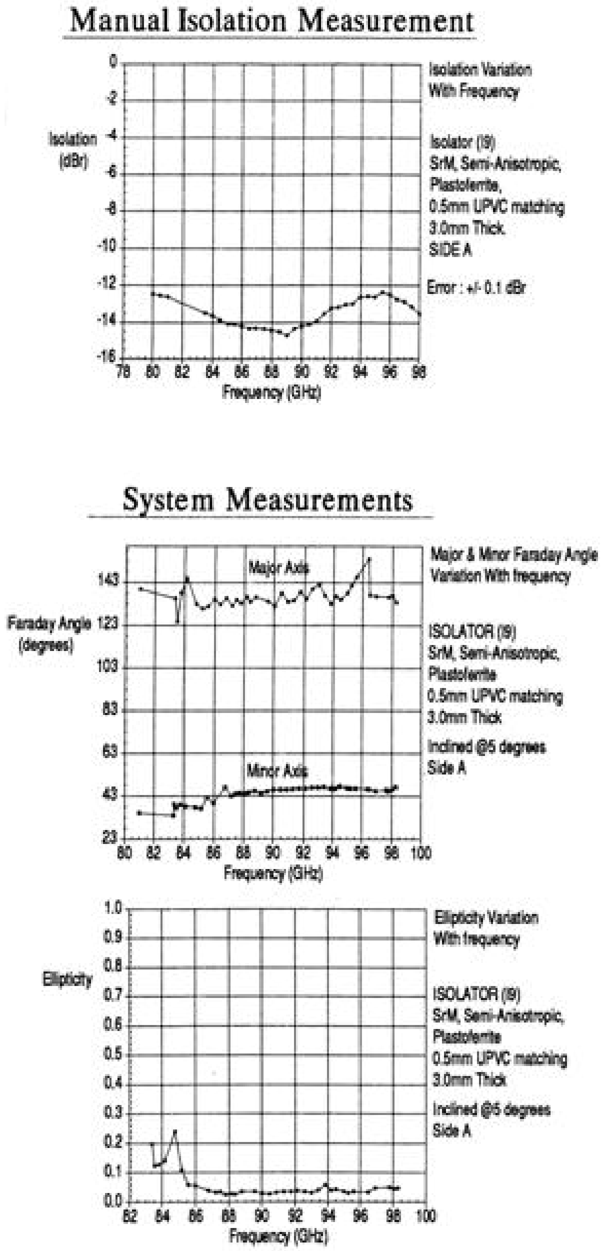

Figure 5 : Faraday Rotator I9, side A

In the reverse direction, Figure 6, the best isolation occurs at roughly the same frequency of 88GHz. At either side of this frequency, the isolation degrades slightly. From the system results, the rotation remains very close to the 45° but either side of this figure the ellipticity seems to be responsible for the drop in isolation.

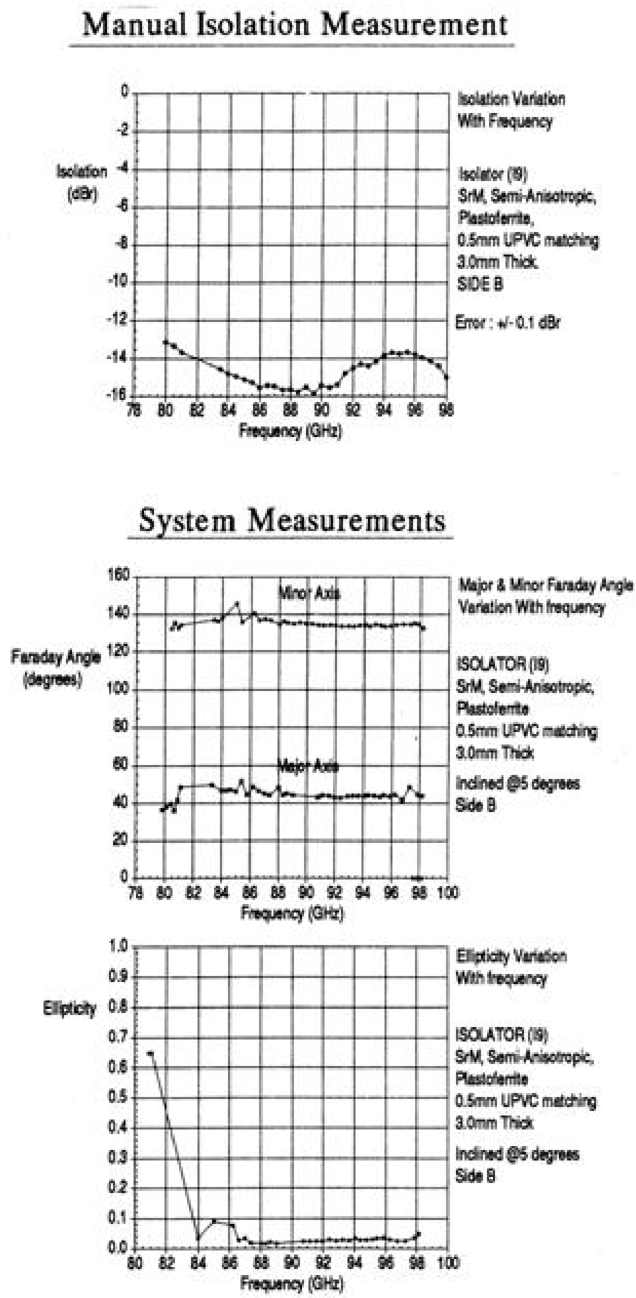

Figure 6 : Faraday Rotator I9, side B

In both sets of results presented here the Minor Faraday Angle again proves to give the smoothest profile giving further credence to its use preference over the Major Faraday angle. During both experiments the results showed erratic behavior of the oscillator occurring around the 84GHz region and below. Thus any results given below this frequency are probably inaccurate, as can be seen in the ellipticity measurement of side (B) of (I9) in Figure 6.

Conclusions

In this article, a fully automated rotary polariser quasi-optical system has been used to accurately measure the rotation of a linear polarised Gaussian Beam from a ferrite sample and Faraday Rotator. 'Frequency Dependent Faraday Angle Resonance was observed at millimetric frequencies for the first time. This serves to compliment the original work performed by Raum in the Frequency independent region of a magnetic material. A Faraday Rotator was also further classified by a new 'ellipticity' parameter measurement. This served to identify what physical mechanism was responsible for the isolation that occurs across the device's operating region.

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