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MILLIMETER WAVE FERROMAGNETIC RESONANCE IN CUBIC AND HEXAGONAL FERRITES

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ABSTRACT

Natural ferromagnetic resonance (in the absence of an externally applied DC magnetic field) has been observed for the first time at frquencies as high as 240 GHz in a powdered magnetoplumbite suspended in a thin layer of paint. "Induced" ferromagnetic resonance has been observed at many millimeter wave frequencies in the presence of an externally applied magnetic field according to the rule: $f = \gamma$ H. The specimen was placed at the center of a "Bitter" solenoid high intensity magnet in a dispersive Fourier transform spectrometric configuration to provide reliable broadband continuous data, for the first time, for magnetic permeability and dielectric permittivity in the entire millimeter wave frequency range.

INTRODUCTION

We have reproduced the classic "natural" ferromagnetic resonance experiment of Rado, Wright, and Emerson [1,2] at millimeter wave frequency region by using a powdered magnetoplumbite suspended in paint. Figure 1 shows the natural ferromagnetic resonance at about 240 GHz. The original experiment which was performed about 40 years ago in a cubic ferrite powder suspended in wax showed this resonance at about 2 GHz. This experiment established and demonstrated that ferrite magnetic dipoles will align spontaneously along an easy axis of magnetization thereby creating a magnetic anisotropy. This spontaneous alignment of dipoles has been described theoretically by inventing a fictitious "internal anisotropy field" which is a measure of the strength of the internal preferential alignment. "Natural" ferromagnetic resonance occurs in the "internal field" of a typical cubic ferrite between 2 GHz and 5 GHz, which would require a magnetic field of less than 1000 to about 2000 gauss.

Uniaxial crystals such as the magnetoplumbite (hexagonal ferrite) family exhibit preferential alignment which is between 20 and 200 times stronger. This permits us to observe "natural" ferromagnetic resonance in the millimeter wavelength range without the application of an external DC magnetic field.

FERROMAGNETIC LOSS MECHANISM

The natural ferromagnetic resonance at 240 GHz shown in Figure 1 is exactly the sort of resonance observed by Rado, Wright, and Emerson at 2 GHz. It was their purpose to show that two regions in the microwave and RF spectrum where losses were observed could be explained by two different mechanisms. The first is domain wall motion which appears at about 0.1 and 0.5 GHz and is driven by the electromagnetic field. The second is of interest to us,

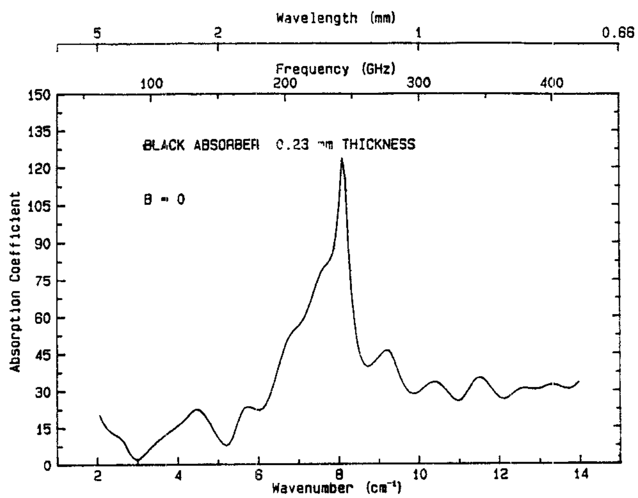

Figure 1 Natural ferromagnetic resonance observed for a hexagonal ferrite paint at 240 GHz.

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namely, magnetic dipole precession driven by the electromagnetic field appearing between 2 and 5 GHz. George Rado powdered his ferrite so that each crystallite was so small that it could support only a single domain. Thus,k in the absence of domain walls, the losses near 0.5 GHz did not appear but the "natural" ferromagnetic resonance near 2 GHz remained. They showed that the natural ferromagnetic resonance could not extend to frequencies higher than about 5 GHz in a cubic ferrite (except in cobalt ferrite). In the present experiment, powdered ferrimagnetic material was suspended in a black paint (magnetoplumbite material) and in a gray paint (consisting mostly of cubic ferrite material) for identification purpose. The supplier of the material for these initial observations was unwilling to furnish a description for publication.

We have applied an external magnetic field of about 75,000 gauss to the gray (cubic) absorber to demonstrate "induced" ferromagnetic resonance at about 210 GHz as shown in Figure 2. This induced ferromagnetic resonance can be made to move to other frequencies according to the rule: f= γH, where H is the intensity of the DC magnetic field and γ is the gyromagnetic ratio equal to 2.8 MHz per gauss for an electron g-factor of two.

When we applied an external magnetic field to the black absorber containing magnetoplumbite crystallites, the natural ferromagnetic resonance appeared in exactly the same place in the spectrum as if no external magnetic field had been applied. The induced ferromagnetic resonance obediently appeared near 85 GHz in compliance with f = γ H. It is gratifying to note, however, that the induced resonance appears as a doublet as shown in Figure 3, giving us a subject for future research. The doublet resolves and moves to a different frequency as the external DC magnetic field intensity is changed.

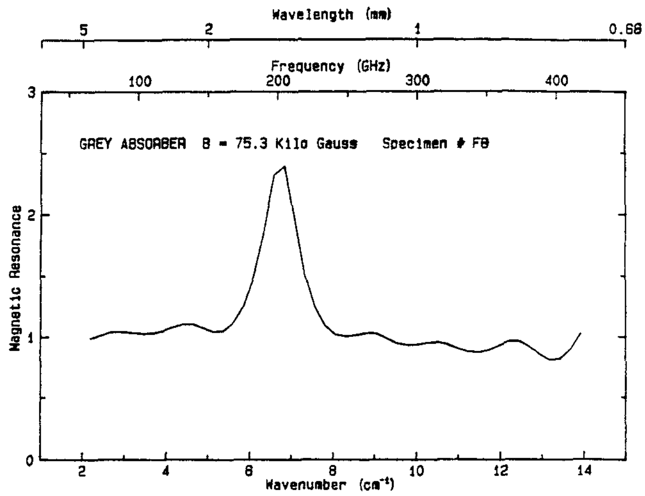

Figure 2 The "induced" ferromagnetic resonance observed around 210 GHz for a cubic type ferrite absorber with applied external magnetic field intensity of 75,000 Gauss.

NEW DIRECT MEASUREMENT TECHNIQUE OF PERMEABILITY AND PERMITTIVITY

The real (ϵ') and the imaginary (ϵ'') parts of the complex dielectric permittivity ($\hat{\epsilon}$) and the real (μ') and the imaginary (μ'') parts of the complex magnetic permeability ($\hat{\mu}$) can be derived from laboratory measurements only if the magnetic polarizability is quenched during the measurements of the dielectric parameters or if the dielectric polarizability is quenched during the determination of the magnetic parameters. If a quasi optical technique of measurement is used, the two quantities of the complex refractive index ($\hat{n}$), the absorption coefficient α and the refractive index n are normally evaluated. For a magnetic material both α and n would contain contributions from both the dielectric and magnetic properties of the material media.

When a microwave cavity is used for such a measurement, the two quantities would be the shift in resonant frequency of the cavity caused by the introduction of the specimen and the change in Q of the cavity. Therefore it is not possible to compute four quantities, ϵ', ϵ'', μ' and μ'' unless two of the latter are quenched or temporarily rendered constant. The real and the imaginary parts of the dielectric permittivity ϵ^r and ϵ'' can be measured over the frequency range 50 GHz to 450 GHz by applying an external magnetic field of intensity 150,000 Gauss (15 Tesla) which "locks up" the magnetic dipoles in the specimen at the precise frequency of 420 GHz, namely magnetic resonance. A dispersive Fourier transform spectrometric technique applied to a polarizing two beam interferometer [3 -4] can be used in a well established way in order to make the routine

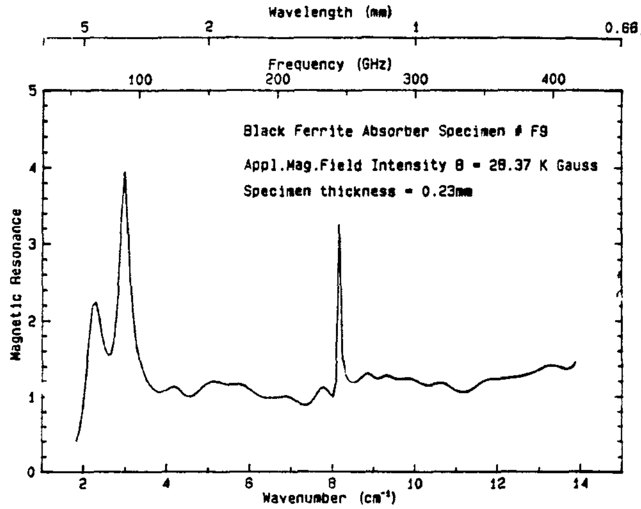

Figure 3 The "induced" ferromagnetic resonance appears as a doublet for a hexagonal magnetoplumbite ferrite for an externally applied magnetic field intensity of 28,370 Gauss. The natural ferromagnetic resonance appears in exactly the same place in the spectrum as if no external magnetic field had been applied.

measurement of ϵ' and ϵ'' over the frequency band 50 GHz - 390 GHz (except in the vicinity of 420 GHz). The measurement can be repeated at different magnetic field intensities. Under high intensity magnetic fields any specimen is purely a dielectric except at the specified magnetic resonance frequency. One then simply calculate the real and imaginary parts of the complex dielectric permittivity in an usual way [3,4]. The repeated measurement at zero magnetic field contains all four parameters from which the real and the imaginary parts of complex magnetic permeability values can be subtracted out.

The dispersive Fourier transform spectrometric (DFTS) technique developed by one of us (Afsar, Ref. 3,4) have demonstrated the capability to measure the real part of the complex dielectric permittivity ϵ' to an accuracy of six significant figures for a low absorbing material. The accuracy of the imaginary part of the dielectric permittivity is limited to one percent because of the use of present amplifying equipments. In DFTS technique the specimen rests in one of the active arms of the two beam interferometer, thereby producing phase information in addition to the amplitude information. The amplitude and the phase information are then translated to provide continuous spectra of real and imaginary parts of the complex dielectric permittivity.

The new interferometer build for magnetic materials extends into a four inch bore "Bitter" solenoid magnet. The arm lengths had to be made long enough inorder to avoid stray magnetic field which influences the interferometer parts such as the phase modulation vibration generator, the stepping motor and the detector. Figure 4 shows the ray diagram of the interferometer configuration

All of these ferrite materials are non-conducting oxide crystallites which can be pressed into ceramic solid or suspended in a fluid or in a paint. In the case of a cubic spinel

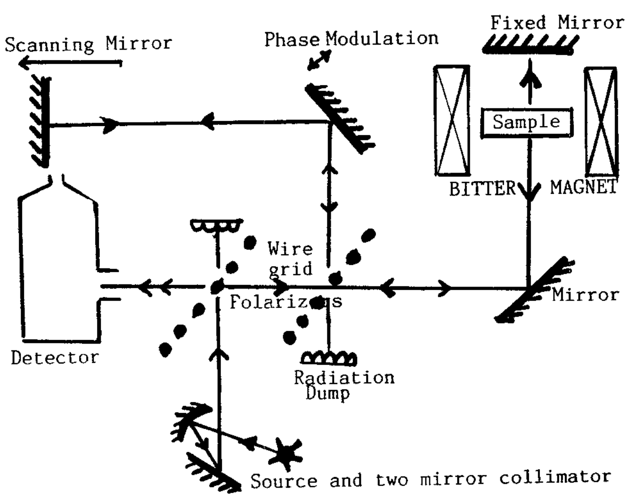

Figure 4 The New Millimeter Wave Polarization Dispersive Fourier Transform Interferometer for Magnetic Materials

ferrite the theory tells us that the magnetic loss, μ'', will be very small, if measurable, in the millimeter and submillimeter wave length region because the mechanism that cause magnetic loss in the microwave range (1 GHz to 30 GHz) have been studied, identified and will not contribute to loss at higher frequencies than about 10 GHz (in the absence of an external static magnetic field). Nevertheless, in an applied static external magnetic field of say 100,000 Gauss (10 Tesla), a sharp symmetrical Gaussian resonance loss curve will appear centered at 280 GHz. On either side of the narrow curve , $\mu' = 1$ and $\mu'' = 0$, so that dielectric parameters , ϵ' and ϵ'' can be measured without interference from the response of the magnetic dipoles to the electromagnetic driving field. When the experiment is repeated a different values of the magnetic field, the same dielectric parameters will be measured providing that there are no magnetic losses at millimeter wavelengths. If the magnetic crystallites are magnetoplumbites however, they will each constitute a small permanent magnet which supply their own static magnetic field thereby contributing their own ferromagnetic resonance loss curve to the overall spectrum. The curve will be broad, asymmetric, not centered at a particular frequency but covering a range of frequencies depending upon the chemical constituents of the crystallites and their orientation within the bulk. In short we shall have a magnetic loss mechanism that is very valuable for applications but which will be challenging to measure accurately and difficult to reproduce precisely from specimen to specimen. In this case, an external static magnetic field of about say 150,000 Gauss or larger is essential in order to over-ride the internal orientation of the magnetic dipoles in the crystallites. The natural ferromagnetic resonance of the magnetoplumbites must be quenched with the external magnetic field . Then the dielectric parameters, ϵ' and ϵ'' can be measured at frequencies below and above the induced ferromagnetic resonance. Then having determined the dielectric parameters, the measurement of the refractive index and the absorption coefficient will be repeated over the continuous frequency range 50 GHz to 450 GHz to reveal the contribution added by the magnetic properties of the magnetoplumbites.

It is possible to table the useful frequency range for a lossy ferrite impregmented paint by performing an inorganic analysis and by utilizing the powder X-ray diffraction technique. For example a paint is going to be a lossy material in the frequency range 2 to 7 GHz if an analysis indicates it to be a magnetite or a Ni, or a Mn or a Zn ferrite and the x-ray diffraction study indicates the material to be of the spinel ferrite type. But if the x-ray diffraction study indicates the material to be only 10% of the cubic spinel type, the remaining material could be of the hexagonal type if the inorganic analysis finds Pb indicative of magnetoplumbite $Pb_{O.6}Fe$. Nonmagnetic ions such as Ba or Ca can also be substituted for the Pb to make paint lossy enough in the 30 GHz - 150 GHz range.

PERMEABILITY AND PERMITTIVITY RESULTS

We have studied several type of ferrite paints similar to ones mentioned above in both solid and liquid form (dissolved in a solvent) and specimens made with iron spheres and whiskers. Figures 5 and 6 show real and imaginary parts of complex dielectric permittivity and complex magnetic permeability spectra for the "Gray" paint. It is supposedly of the cubic type. An applied external magnetic field intensity B = 75,300 Gauss pushed the induced ferrimagnetic resonance to about 200 GHz. The material was then a pure dielectric below 180 GHz.

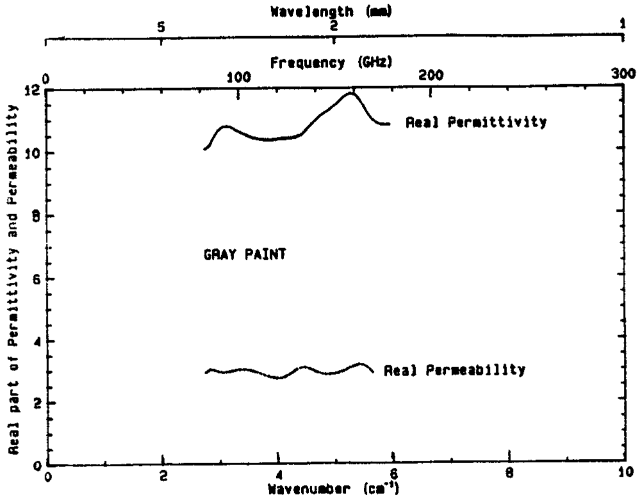

Figure 5 Spectra for the Real Part of the Complex Dielectric Permittivity and Complex Magnetic Permeability for a Cubic type of Ferrite Paint.

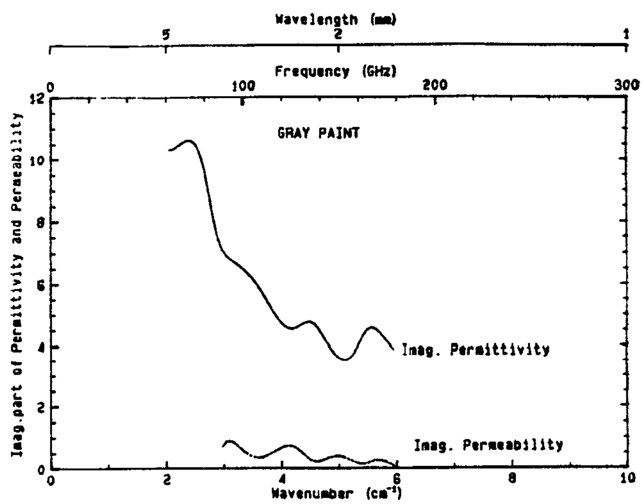

Figure 6 Spectra for the Imaginary Part of Complex Dielectric Permittivity and Complex Magnetic Permeability for a Cubic type Ferrite Paint. .

APPLICATIONS OF NATURAL FERROMAGNETIC RESONANCE

Many attempts have been made to devise thin coatings that would absorb a particular band of radar frequencies Such absorptive coatings would be particularly practical at millimeter wavelengths because the atmosphere already denies us the use of all but a few windows. It is only necessary to formulate different chemical compositions to furnish magnetoplumbite powder, each having a different natural ferromagnetic resonance frequency. Particular formulations that cover each of the windows with a resonant absorption would be mixed into the paint.

For example, ships entering a harbor in a fog wish to use millimeter wave radar to locate other ships for anticollision purposes. If a large bridge over the harbor dominates the radar return, the bridge can be erased by painting it with this concoction which resonantly absorbs each of the useful radar frequencies. It should be emphasized that this is not just simply a glossy coating; it is a resonant absorber.

Of course, if a ship would not like to appear on a radar,

ACKNOWLEDGEMENT

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