CPEM '88 DIGEST DIRECT MEASUREMENTS OF COMPLEX MAGNETIC PERMEABILITY AND COMPLEX DIELECTRIC PERMITTIVITY OF MAGNETIC MATERIALS*

Mohammed Nurul Afsar
Department of Electrical Engineering
Tufts University
Medford, Massachusetts 02155

ABSTRACT

The dispersive Fourier transform spectroscopy was used with the specimen at the center of a high intensity "Bitter" solenoid magnet to measure the real and imaginary parts of complex magnetic permeability and real and imaginary parts of the complex dielectric permittivity of cubic and hexagonal ferrite materials at millimeter wavelength region.

INTRODUCTION

For a magnetic material, the real and the imaginary parts (ε' and ε'') of the complex dielectric permittivity ($\hat{\varepsilon}$) can be derived from laboratory measurements only if the magnetic polarizability is quenched during the measurements of dielectric parameters. The peak of the induced ferromagnetic resonance occur at frequency higher than the desired measurement range. This can be termed as the resonance technique. Alternatively the dielectric polarizability can also be quenched during the determination of magnetic parameters. In most of our quasi-optical techniques we directly measure both the real (n) and the imaginary (k) parts of the complex refractive index ($\hat{n}$) as a continuous function of frequency. The real part n is the refractive index and the imaginary part k is the absorption index. The absorption index k is related to the commonly known absorption coefficient (α) via $k = \alpha c/4\pi\nu$, where c is the speed of light in vacuum and ν is the frequency in Hz. If either of the two polarizability is not quenched, for a magnetic material both and n measurements would contain contributions from both the dielectric and magnetic properties of the material media. When a microwave cavity is used for such a measurement instead of a quasi-optical technique, 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, namely the real(ε') and the imaginary(ε'') parts of the dielectric permittivity and real(μ') and the imaginary(μ'') parts of the complex magnetic permeability($\hat{\mu}$), unless two of the latter are quenched or temporarily rendered constant. The real(ε') and the imaginary(ε'')parts of the complex dielectric permittivity($\hat{\varepsilon}$) can be measured over the frequency range 50 to 400 GHz by applying an external magnetic field of 150,000 Gauss (15 Tesla) which "locks up" the magnetic dipoles in the specimen at the precise frequency of 420 GHz, namely the magnetic resonance. The dispersive Fourier transform spectroscopic (DFTS) technique developed earlier by the author[1 - 5] can then be used in the well established way in order to make the routine measurement of ε' and ε'' over the frequency band 50 GHz to 390 GHz (except in the vicinity of 420 GHz). The use of the stable interferometric system in the polarization configuration together with a Rollin Indium Antimonide hot electron bolometer detector enable us to cover this millimeter wavelength region. With the specimen arm inside the magnet bore, 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. The repeated measurement at zero magnetic field contains all four parameters from which the real and imaginary parts of complex magnetic permeability can be subtracted out.

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MEASUREMENT TECHNIQUE

The dispersive Fourier transform spectrometric technique developed by the author[1 - 5] have demonstrated the capability to measure the real part of the dielectric permittivity ε' to an accuracy of six significant figures for a low absorbing material. The accuracy of the imaginary parts of the dielectric permittivity is limited to one percent because of the use of present amplifying equipments. In this 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 the real and the imaginary parts of the dielectric permittivity. The new interferometer build for magnetic materials extends into a four inch bore high intensity field d.c. magnet("Bitter" solenoid type). The length of arms of the interferometer had to be made long enough in order to pass through the magnet bore and to avoid stray magnetic field which influence interferometer parts such as phase modulator generator, stepping motor and the detector. Figure 1 shows the ray diagram of our present interferometric confuration. The source of radiation is a medium pressure quartz encapsulated mercury lamp. The collimated radiation from the lamp is polarized by a free standing wire grid. The orientation of wires of the second free standing wire grid are at 45 degree to the orientation of wires of the first grid. The polarized component perpendicular to wires of the second wire grid passes through and gets reflected by a 45 degree mirror to go through the bore of the magnet to reach the fixed mirror. The scanning mirror arm had to be made equally long to produce interference within the range of the micrometer on which the scanning mirror is mounted. The phase modulation was accomplished by introducing a second 45 degree mirror mounted on a vibration generator motor in the scanning mirror arm.

FERRITE MATERIALS

The real and the imaginary parts of the complex magnetic permeability can be determined in two ways if the material is ferromagnetic because this is the strongest type of magnetic property. Two cases will be distinguished, namely the cubic spinel ferrite of ferrimagnetic material (and its near relatives) and the magnetoplumbite uniaxial magnetic material which is sometimes carefully referred to as "hexagonal ferrite". All of these are non-conducting oxide crystallites which can be pressed into a ceramic solid or suspended in a fluid or in a paint. In the case of a cubic spinel ferrite, the theory tells us that the magnetic loss, μ'' will be very small, if measurable, in the millimeter and submillimeter wavelength range 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 magnetic field of say 100,000 Gauss (10 Tesla), a sharp symmetrical Gaussian resonance loss curve will appear centered at 280GHz. On either side of this narrow resonance curve, $\mu' = 1$ and $\mu'' = 0$, so that the dielectric parameters, ε' and ε'' can be measured without interference from the response of the magnetic diples to the electromagnetic driving field. When the experiment is repeated at different values of the magnetic field, the same dielectric parameters will be measured providing that there are no magnetic losses at millimeter

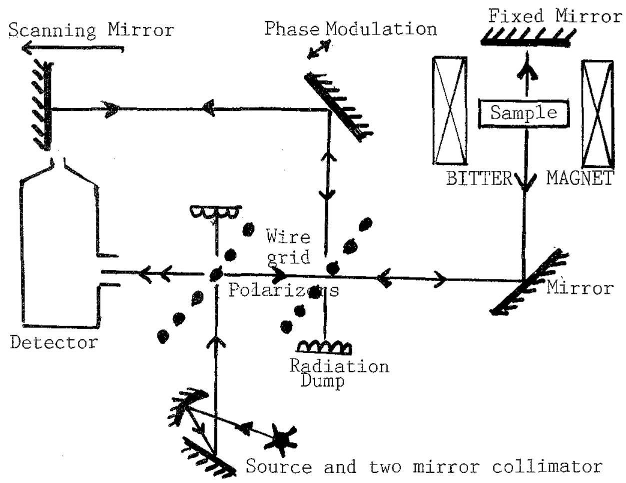

Figure 1. The ray diagram of the new millimeter wave Polarization dispersive Fourier transform interferometer for direct measurement of complex magnetic permeability and complex dielectric permittivity of magnetic materials

wavelengths. If 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 curve to the overall spectrum. The curve will be broad, assymetric, not centered at a particular frequency but covering a range of frequencies depending upon the chemical constitutes of the crystallites and their orientation within the bulk. In short, we shall have a magnetic loss mechanisms 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 100,000 Gauss or larger is essential in order to over-ride the internal orientation of the magnetic dipoles in the crysatallites. The natural ferromagnetic resonance of the magnetoplumbites must be quenched to some extent 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.

CUBIC FERRITES AND HEXAGONAL FERRITES

The ferrite crystallite has a preferred direction of magnetic moment with respect to the crystal axis. This has been called as the magnetic anisotropy. A cubic crystal is almost isotropic, that is the magnetic anisotropy is small. One would expect the cubic symmetry to exhibit nearly-isotropic properties. Nevertheless the small preferential alignment produces a magnetization just as if an external magnetic field had been applied. The fictitious (or "effective") magnetic field has been called the anisotropy field and it is used to calculate the frequencies at which the "natural ferromagnetic losses" will occur. The frequency in MHz is equal to 2.8 times the anisotropy field in Gauss. The highest anisotropy field for a cubic ferrite is about 2,500 Gauss. Therefore the highest frequency at which the resonant loss occur is 2.8 x 2,500 = 7 GHz. This has been verified experimentally about 30 years ago [6, 7].

The hexagonal crystal structure of magnetoplumbites exhibit much higher magnetic anisotropy because of the uniaxial symmetry perpendicular to the hexagonal planes of the atoms. Anisotropy fields of the order of 30,000 Gauss have been measured. This means that the higher

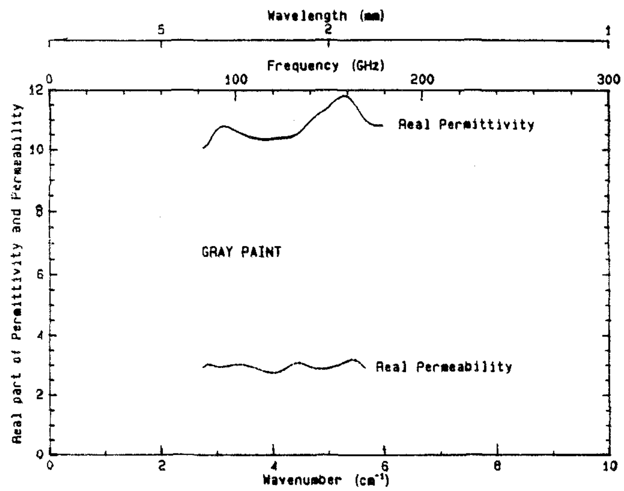

Figure 2. Spectra for the real part of the Complex Dielectric Permittivity and Complex Magnetic Permeability for a cubic type ferrite paint.

frequency at which the "natural ferromagnetic resonance" loss can occur is 84 GHz (3mm). If special magneto plumbites were prepared, one can speculate that 50,000 Gauss could be achieved to reach 150 GHz (2mm) and 80,000 Gauss could be achieved to reach 240 GHz (1.4 mm). From inorganic analysis and x-ray diffraction studies one could easily table whether the ferrite material(solid, composite or paint form) is lossy in a particular frequency region or not.

SOME RESULTS

We have studied two types of ferrite paints. A cubic spinel type ferrite paint(gray color) and a hexagonal ferrite paint (black in color). It was relatively easy to move the "induced" ferromagnetic resonance by simply varying the applied magnetic field intensity. A magnetic field intensity of about 80,000 Gauss moved the peak of the induced ferromagnetic resonance to about 230 GHz. allowing extraction of complex dielectric and complex magnetic permeability data upto 190 GHz. Figure 2 shows ε', μ' data for the cubic type ferrite paint(gray in color) A detailed information on the behavior of natural ferromagnetic resonance at millimeter wavelength will be given.

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