Complex permittivity and permeability of barium and strontium ferrite powders in $X$, $K_U$, and $K$-band frequency ranges

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This paper presents accurate results for the complex permittivity, $\varepsilon = \varepsilon' - j\varepsilon''$ and permeability, $\mu = \mu' - j\mu''$ of barium ferrite powder ($\text{BaFe}_{12}\text{O}_{19}$) and strontium ferrite powder ($\text{SrFe}_{12}\text{O}_{19}$), in the frequency range from 8.0 to 26.5 GHz. The complex permittivity and permeability are determined via the waveguide transmission/reflection (TR) technique and the waveguide cavity resonator (CR) technique at 25 °C and relative humidity <75%. Measurements reveal that the real permittivities of $\text{BaFe}_{12}\text{O}_{19}$ and $\text{SrFe}_{12}\text{O}_{19}$ are, respectively, $2.497 < \varepsilon'_\text{Ba} < 2.678$, and $2.597 < \varepsilon'_\text{Sr} < 2.712$. $\text{BaFe}_{12}\text{O}_{19}$ has an average real permeability $\mu'_\text{Ba} = 1.078$ and $\text{SrFe}_{12}\text{O}_{19}$ has an average real permeability $\mu'_\text{Sr} = 1.063$. The imaginary permittivities are respectively $\varepsilon''_\text{Ba} < 0.081$ and $\varepsilon''_\text{Sr} < 0.077$. The imaginary permeabilities are respectively $\mu''_\text{Ba} < 0.095$ and $\mu''_\text{Sr} < 0.106$. © 2005 American Institute of Physics. [DOI: 10.1063/1.1853633]

INTRODUCTION

Solid hexagonal ferrites such as $\text{BaFe}_{12}\text{O}_{19}$ and $\text{SrFe}_{12}\text{O}_{19}$, have had extensive microwave applications as transformers and circulators and their complex permittivity and permeability have been determined accurately via several methods. Few works have however attempted to determine $\varepsilon$ and $\mu$ for these ferrites in powdered form. This was due to the limited applications of such powders but also due to the lack of appropriate techniques that were capable of handling powdered materials.

Recently, powdered $\text{BaFe}_{12}\text{O}_{19}$ and powdered $\text{SrFe}_{12}\text{O}_{19}$ of grain size ranging from 50 to 100 $\mu$m, have been investigated for their potential as soft microwave absorbers. This work therefore accurately determines their $\varepsilon$ and $\mu$ spectrum in the microwave frequency range. The transmission/reflection (TR) technique and the cavity resonator (CR) technique are used to determine their $\varepsilon$ and $\mu$ at 25 °C, with relative air humidity <75%. The above-mentioned methods are traditionally well suited to test hard solid materials but it has been shown by Wang and Afsar, and Raveendranath and Mathew, that they can be tailored to test powders too.

In the TR technique, an EM wave is incident on a sample placed in a waveguide (rectangular waveguide in this work). The scattering parameters ($S_{11}$, $S_{21}$) at the boundaries of the sample are measured and the complex permittivity and permeability are determined using Weir’s equations.

In the CR technique, the sample to be measured is placed in a waveguide resonator. The sample perturbs an original signal by shifting its resonant frequency and attenuating its magnitude. $\varepsilon$ and $\mu$ are then determined from the shift in frequency and the change in $Q$-factor of the signal. The $Q$-factor is a measure of the attenuation and is determined from the 3 dB bandwidth of the resonant signal. To determine $\varepsilon$, the sample is placed at the point of highest electric field and to determine $\mu$, the sample is placed at the point of highest magnetic field.

EXPERIMENTAL DETAILS

In preparing the samples for the TR method, one end of a waveguide shim is scotch taped. Wang and Afsar determined that the inclusion of scotch tape to hold a soft solid within the shim has a negligible effect on the scattering parameters. The powders are added to the cavity of the shim in small amounts. In each step, the shim is gently shaken from side to side to spread the powder evenly through the cavity and to avoid the formation of large air gaps within the layers. The powders are added until the shim is completely filled. Excess powder at the top is then shaved off gently such that a smooth surface is obtained. The weights of the empty shims and filled shims are monitored to keep the density of the powder inside the cavity is kept constant at 1.300 g/cm$^3$, for all frequency bands and for both powders. It is also ensured that the thickness of the waveguide shims is less than half the wavelength of the wave in the material. This is because the magnitude of $S_{11}$ is very small at frequencies that correspond to integer multiples of half-wavelength. This drop in magnitude manifests itself in the complex permittivity and permeability as a false resonance peak. A Vector Network Analyzer (HP8510C) is used to determine the scattering parameters after TRL calibration. $\varepsilon$ and $\mu$ are then determined from the measured parameters.

In preparing the samples for the CR method, the powders are inserted in thin capillary tubes. Capillary tubes are so fine that their effect on the resonance peak in a cavity resonator is negligible. The powders are inserted in small quantities such that large air gaps are avoided. The initial and final weights of the capillary tubes are monitored to keep the density of the powders constant at 1.300 g/cm$^3$. Empty capillary tubes have no effect on the undisturbed resonant peak if placed exactly at the point of highest magnetic field. Therefore, the shifted peak obtained when the capillary tube is filled with the powder can be used to determine the com-
plex permeability. When placed at the point of highest electric field, the empty tubes affect the undisturbed resonant peak noticeably. Therefore, the shifted peaks due to the empty capillary tubes are used as the undisturbed resonant peaks. The shifted peaks due to the powder-filled capillary tubes are used as the disturbed peaks. This correction ensures that the frequency shift and the attenuation are due to the powders only.

RESULTS AND DISCUSSION

The frequency dependence of $\varepsilon$ and $\mu$ for barium ferrite powder, solved via Weir’s method is shown in Fig. 1. Measurements are taken at 201 points within each frequency band ($X, KU, K$). The points shown in Fig. 1 are 60 selected points from those 603 points, spaced at equal frequency intervals. The real permittivity $\varepsilon'$ rises very gently from 2.497 to 2.678 from 8.0 to 26.5 GHz. The real permeability $\mu'$ varies very little and has an average value of 1.078. Within the $X$-band range (8.0–12.4 GHz) the magnetic absorption is so low that the values for $\mu'$ are very close to zero. At higher frequencies, the magnetic absorption $\mu''$ increases slightly and can clearly be seen in Fig. 1 at frequencies higher than 12.4 GHz. The imaginary permittivity is small and approaches the zero line at 16.0 GHz, as the frequency increases.

The frequency dependence of $\varepsilon$ and $\mu$ for strontium ferrite powder is shown in Fig. 2. The real permittivity does not rise gently over the frequency range explored as was noticed in barium ferrite powder. Instead, it varies very little and has an average value of 2.631. $\mu'$ varies negligibly over the three frequency bands and has an average value of 1.063. $\mu''$, the magnetic absorption is very small at values that are always $<0.106$ but does not approach the zero line. $\varepsilon''$ is small and approaches the zero line just before 16.0 GHz.

Figures 3 and 4 show the frequency variation of $\varepsilon'$ and $\mu'$ for barium and strontium ferrite powder obtained from the TR and CR methods in the $X$-band range, respectively. In the CR method, a rectangular cavity resonator having a length of 89.8 mm is used and four resonant peaks are obtained. These resonant peaks are at 8.281, 9.385, 10.644, and 12.002 GHz, respectively. Measurements are taken at those four frequencies. The values obtained from the CR method are shown in Figs. 3 and 4 and are compared with the results obtained via the TR method in Table I. The results from the two methods agree well and therefore corroborate each other’s accuracy. A worst percentage discrepancy of 8.68% is registered in the measurement of the real permeability at 8.281 GHz in strontium ferrite powder.

Inaccuracies in the TR method may arise from the fact that the powder samples, though prepared meticulously may not consist of homogeneously dense layers of powder. Moreover, the thin scotch tape holding the powder affects the transmission factor $S_{21}$. It is also difficult to obtain a perfectly smooth layer of powder at the un-scotched end of the waveguide shim and reflection, $S_{11}$, from that surface is slightly affected. Also, moisture trapped between the grains may cause the permittivity to be higher.

In the CR method, the capillary tubes may only be placed at the points of highest magnetic and electric field...
within the accuracy of the experimenter’s eyesight. Also, the resonant peaks have very high $Q$-factors and are thin, sharp bell shaped curves. Since the Network Analyzer allows measurement at discrete frequency points only, it is difficult to determine the 3-dB attenuation point exactly although 801 points (the maximum allowed by the Vector Network Analyzer) were employed in the CR method.

**CONCLUSION**

The microwave spectrum for the complex $\varepsilon$ and $\mu$ of BaFe$_{12}$O$_{19}$ and SrFe$_{12}$O$_{19}$ powders has been determined for the first time via two methods. This paper shows that powdered BaFe$_{12}$O$_{19}$, with an average grain size of about 50–100 mm and density 1.300 g/cm$^3$, has $\varepsilon'$ that is $\sim$8 times less than solid BaFe$_{12}$O$_{19}$. In Ref. 1, polycrystalline BaFe$_{12}$O$_{19}$ has a real permittivity of $\sim$20 at 10 GHz. The real permittivity of Barium ferrite powder is slightly less than that of strontium ferrite powder. Also, it has been shown that both powders are weak microwave magnetic absorbers. There is a gradual but small decrease in the imaginary permittivity and a gradual but small increase in the imaginary permeability as the frequency increases. Future work may involve the determination of $\varepsilon$ and $\mu$ for the same powders packed at different densities, moistureless and in the presence of strong external magnetic fields.


