Journal of Electroceramics, 8, 203–208, 2002

Microwave Studies on Strontium Ferrite Based Absorbers

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Submitted May 16, 2001; Revised December 10, 2001; Accepted March 4, 2002

Abstract. Single layer microwave absorbers based on strontium ferrite-epoxy composites have been fabricated and their reflection loss characteristics studied in the X-band (8–12.4 GHz) of microwave frequencies. Permittivity ($\in_r' - j\in_r''$) and permeability ($\mu_r' - j\mu_r''$) of Co and Ti added strontium ferrite $SrCo_xTi_xFe_{12-2x}O_{19}$ ($x = 0.1$ to 0.9 in steps of 0.2), have been measured. Thickness of the absorber is an important criterion influencing the absorption characteristics. Composites of 3 mm thickness are found to absorb over a reasonable range of X-band frequencies. A minimum reflection loss of -36.5 dB is observed for the composite with $x = 0.3$.

Keywords: microwave, strontium ferrite composites, absorbers, dielectric constant, permeability, electrical thickness

Introduction

Electromagnetic wave absorbers [1–4] are becoming increasingly indispensable in keeping with the 'wave pollution' caused by the fast emerging telecommunication technologies. Also, the increased measurement accuracy of antennas and receivers demands reduction of reflection at the measurement sites. Besides, microwave absorbers are of immense importance in stealth technology, electronic devices and anechoic chambers. Many types of materials such as carbon fibre and graphite utilizing their conducting loss property for absorption [5, 6], and magnetic materials such as iron and iron compounds which absorb through their hysteresis losses, have been employed as microwave absorbers. Spinel ferrites such as nickel-zinc ferrites have also been used as absorber materials. Absorbers based on these ferrites are now commercially available under the trade name Eccosorb and are operable at frequencies below 1 GHz [7]. Such absorbers in practice are, however, heavy and brittle and are usually 6–8 mm in thickness. More recently hexagonal ferrites have entered the scene as they allow better absorption at higher frequencies (X-band) and in thinner layers [8–12]. Thickness of absorber is an important criterion in stealth applications specially for aircrafts where weight considerations are very important. Therefore, maximum absorption in minimum thickness of absorber is desirable. Absorbers capable of responding to wide frequency bandwidth of radar signals are required. Large bandwidths are easily achieved by stacking a number of absorber layers of varying thickness [13–16]. This increase in the bandwidth is clearly accompanied by increase in absorber thickness. Thus, there is a trade-off between the bandwidth and the thickness of the absorber. Single layer absorbers, nevertheless, would be more useful in applications where weight is a major consideration. The hexaferrites employed so far as absorbers are mostly those based on barium. There do not seem to be any reports on strontium based ferrites as absorbing materials. In the present work, single layer strontium based ferrite-polymer composites have been synthesized for microwave absorption studies. The complex permittivity ($\in_r' - j\in_r''$) and complex permeability ($\mu_r' - j\mu_r''$) are known to determine the absorbing characteristics of the material. Therefore, various compositions of strontium based ferrite in which the iron component has been partly substituted by Co and Ti have been prepared, and their dielectric and magnetic properties studied. The polymer used is an epoxy resin. Although the properties of the ferrite are modified by adding polymer, yet the polymer imparts mechanical strength to the otherwise brittle ferrite and enables easy coating on metal surfaces.

Theoretical Considerations

A single layer metal-backed absorber in air works on the principle of matching of impedance $Z_0(=[\mu_0/\epsilon_0]^{1/2})$ of air and the impedance $Z(=[\mu_r\mu_0/\epsilon_r\epsilon_0]^{1/2})$ of the absorber material. μ_0 and ϵ_0 are respectively the permeability and permittivity of air or vacuum while μ_r and ϵ_r are the relative permeability and relative permittivity of the material. A perfect impedance match, $Z = Z_0$ allows electromagnetic waves to propagate from the free space to the inside of the absorber without any reflection. Variations in the matching of the two impedances give rise to reflections at the surface of the absorber. For the condition $Z_0 = Z$, μ_r and ϵ_r are required to be equal. Once the electromagnetic wave has entered the absorber, the process of absorption of microwaves occurs as a result of various interactive loss processes of magnetization and polarization in the ferrite material. This requires the lossy or the imaginary parts, μ_r'' and ϵ_r'' of the complex permeability and complex permittivity to be high. The absorption also depends sensitively on the thickness of the absorber. Minimum sample thickness for maximum absorption is dependent upon the permeability and permittivity of the material.

For a metal-backed absorber, the reflection loss R can be expressed as

$$R(\mathrm{dB}) = 20\log(|\eta - 1|/|\eta + 1|),$$

where,

$$\eta = (\mu_r/\epsilon_r)^{1/2}\tan h\{-j\omega d(\mu_0\epsilon_0\mu_r\epsilon_r)^{1/2}\};$$

ω and d stand for the angular frequency of the microwaves and the thickness of the absorber layer respectively [7].

Experimental

Material Preparation

Strontium ferrite compositions substituted with Co and Ti, $SrCo_xTi_xFe_{12-2x}O_{19}$ ($x = 0.1$ to 0.9 in steps of 0.2), have been prepared by the standard ceramic technique. The raw materials used were strontium carbonate (98%, Aldrich U.S.A.), ferric oxide (99.5%, Cerac USA), titanium dioxide (99.5%, Loba Chemie India) and cobalt carbonate (99%, CDH India). The powders were weighed according to their stoichiometric proportion and ground together in acetone medium. This powder mixture was subjected to calcination at 1000°C for 5 hours, reground and finally sintered at 1300°C in air for 5 hours. X-ray diffraction analysis (Rigaku Geiger Flex 3 kW x-ray diffractometer) showed the magnetoplumbite type of crystal structure for these samples. The sintered powder was ground and mixed with epoxy in 1:1 weight ratio so as to obtain a homogeneous mixture. The ferrite-epoxy mixture thus obtained was cast into rectangular pellets and cured at 75°C for 30 minutes. The composites thus prepared were polished and mounted on an aluminium foil so as to obtain the single layer metal-backed absorber which was made to exactly fit into the measuring wave-guide.

Microwave Measurements

The reflection loss of the absorber was calculated from the SWR (standing-wave-ratio) measured as a function of frequency in the configuration shown in Fig. 1 using microwave Network Analyzer (HP 6719 ES). The network analyzer was fully calibrated before use.

The complex permittivity and permeability measurements were also made on the Network Analyzer using cavity perturbation method [17]. The cavity was made up of a standard X-band brass wave-guide of length 13.5 cm (Fig. 2). The upper broad wall of the guide had a thin slot ~4 cm in length and 1.2 mm in

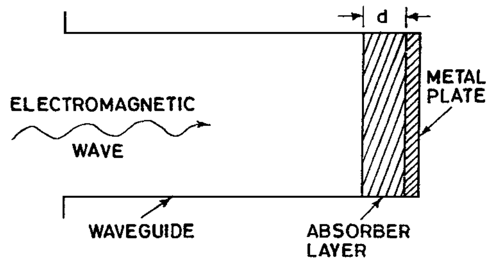

Fig. 1. Schematic representation of a single layer metal-backed absorber in a wave-guide.

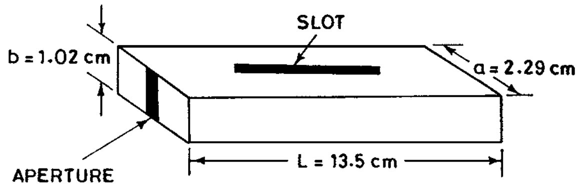

Fig. 2. Rectangular cavity resonator with dimensions $L = 13.5$ cm, $a = 2.29$ cm and $b = 1.02$ cm. Slot is 4 cm × 1.2 mm and the width of the aperture is 2.5 mm.

width. Conducting plates with small aperture opening (2.5 mm wide) on either side of the guide provided inductive coupling to the cavity. The number of resonance peaks being dependent on the length of the cavity, the cavity was excited into 5 modes (TE_{105}–TE_{109}) utilizing the swept frequency option of the analyzer. Accordingly, five resonant peaks corresponding to the frequencies around 8.6, 9.36, 10.18, 11.06 and 11.97 GHz appeared on the screen of the analyzer. Looking at the field configuration in the cavity, when we consider symmetrical loading of the specimen in the cavity, the specimen will be in maximum electric field for odd modes and it will be in maximum magnetic field for even resonant modes (e.g. TE_{106} and TE_{108}). Therefore, the odd resonant modes give the electrical parameters while the even modes, the magnetic parameters. Rectangular samples about 2 mm in width and 1 mm thick were placed straight through the slot such that the electric field is tangential to the sample surface, and the sample surface with the sample ends resting on the cavity walls. Measurements of resonant frequencies, quality factors and geometrical parameters of the cavity and of the specimen enabled the calculation of the complex permittivity and permeability.

The real ($\in_r'$) and imaginary ($\in_r''$) parts of the complex permittivity were calculated using the relations [18]: $\mu_r' - 1 = [1/k][V_c/V_s][(f_1 - f_2)/f_2]$ and $\mu_r'' = [1/2k](V_c/V_s)[1/Q_2 - 1/Q_1]$, where f_1 and Q_1 are resonant frequency and quality factor of the empty cavity and f_2 and Q_2 are the corresponding quantities for the perturbed case. V_c and V_s are the volumes of cavity and sample respectively. The real (μ_r') and imaginary (μ_r'') parts of the complex permeability are calculated using the equations [19]: $\mu_r' - 1 = [1/k][V_c/V_s][(f_1 - f_2)/f_2]$ and $\mu_r' = (V_c/V_s)[1/Q_2 - 1/Q_1]$ where, $k = 2a^2/(a^2 + l^2)$; l and a are respectively the length and breadth of the cavity. Percentage absorption is calculated using the relation $(1 - I_r/I_0) \times 100$ where, I_0 and I_r are the incident and reflected radiation intensities respectively.

Results and Discussion

The reflection-loss/absorption characteristics of metal-backed single layer Co and Ti substituted strontium ferrite-epoxy composites of 3 mm thickness are shown in Fig. 3. Composites of 2 mm and 4 mm thickness were also prepared. It was found that the 2 mm thick composites showed maximum absorption at the higher

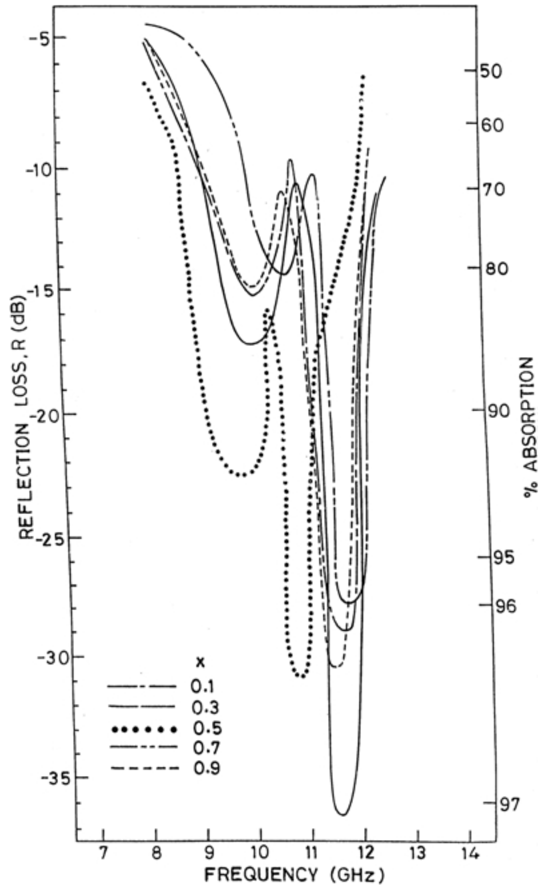

Fig. 3. Microwave absorption characteristics of 3 mm thick strontium ferrite-epoxy composites with different x values of the composition $SrCo_xTi_xFe_{12-2x}$.

limit (12.4 GHz) of the X-band while the composites of 4 mm thickness showed maximum absorption at the lower limit (~8.2 GHz) of the X-band. In order to have absorbers which absorb well within the X-band range of frequencies, composites of 3 mm thickness were used in the present study. Figure 3 shows the presence of two absorption peaks; one appearing between 11 and 12 GHz with more than 95% absorption and the other of smaller magnitude appearing at around 10 GHz with around 80% absorption. Occurrence of the smaller peak at lower frequency is due to body resonance associated with multiple internal reflections in the absorbers. Although there is no marked variation in the maximum absorption with composition of the samples, the composite corresponding to $x = 0.3$ shows a maximum absorption of 97%. It may be noted that the observed variation of maximum absorption with

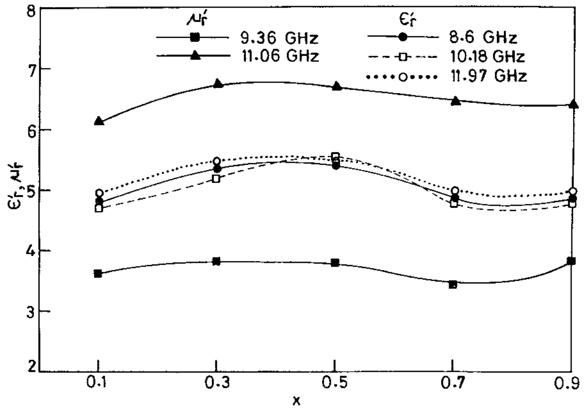

Fig. 4. Variation of real parts ∈′ and μ' of the complex permittivity and permeability with various x values of the strontium ferrite composition $SrCo_xTi_xFe_{12-2x}O_{19}$.

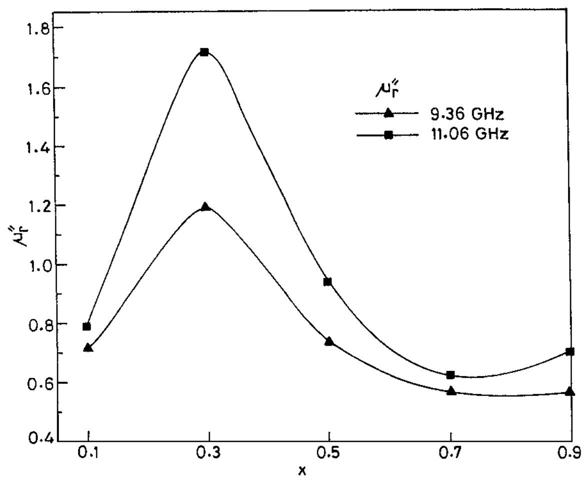

Fig. 5. Variation of the magnetic loss μ'' with x of the hexaferrite composition $SrCo_xTi_xFe_{12-2x}O_{19}$.

composition is identical to those of $\in'_r$, $\in''_r$, μ'_r, and μ''_r with composition, Figs. 4–6. Since the variation of μ''_r with frequency is more pronounced as compared to that of $\in''_r$, the primary variation of reflection loss with frequency can be considered to be magnetic rather than dielectric in nature. Magnetic resonance arises as a result of the internal anisotropy field that results in a force tending to keep the magnetization vector of domains aligned along a preferred crystal axis. Absorption takes place due to coupling of energy to material by spin relaxation.

The energy absorbed by a sample is sensitive to its thickness and the frequency of the radiation. The

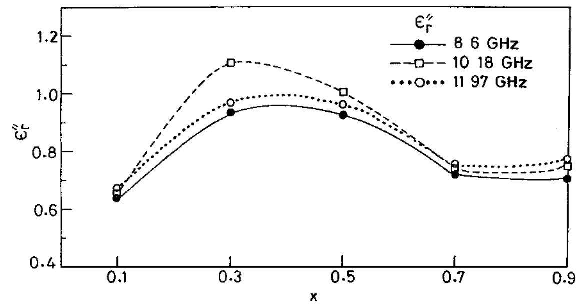

Fig. 6. Variation of the dielectric loss ∈″ with x of the hexaferrite composition $SrCo_xTi_xFe_{12-2x}O_{19}$.

maximum absorption is known [20] to occur at a frequency corresponding to a quarter wavelength $\lambda_{gs}/4$ (or its odd multiple), where λ_{gs}, is the guide wavelength in the sample. The guide wavelength is related to the dielectric constant by the relation $\in = (\lambda_0/\lambda_{gs})^2 + (\lambda_0/\lambda_c)^2$, where λ_0 is the free space wavelength of electromagnetic radiation and λ_c is the cut-off wavelength. Measuring the values of ∈ and knowing λ_c and λ_0, the electrical thickness, $\lambda_{gs}/4$, of the samples can be estimated. Table 1 gives the obtained values of electrical thickness (quarter wavelengths) of composites of various ferrite compositions for frequencies 8.6 GHz, 10.18 GHz and 11.97 GHz. It can be seen that the electrical thickness decreases with frequency. In the frequency range 11–12 GHz samples of thickness 3 mm are expected to show maximum absorption which indeed is observed to be the case, Fig. 3. As the dielectric constant does not vary much with ferrite composition, Fig. 4, there is hardly any variation in the electrical thickness, and hence the frequency shifts in absorption peaks with composition are not significant. Although the samples studied are magnetic with permeability greater than one, the high frequency dielectric constant

Table 1. Electrical thickness $\lambda_{gs}/4$ at different frequencies for composites of various ferrite compositions $SrCo_xTi_xFe_{12-2x}O_{19}$.

Composition (x)	$\lambda_{gs}/4$ (mm) at 8.6 GHz	$\lambda_{gs}/4$ (mm) at 10.18 GHz	$\lambda_{gs}/4$ (mm) at 11.97 GHz
0.1	4.27	3.55	2.92
0.3	4.00	3.42	2.76
0.5	3.90	3.20	2.75
0.7	4.20	3.50	2.90
0.9	4.00	3.39	2.78

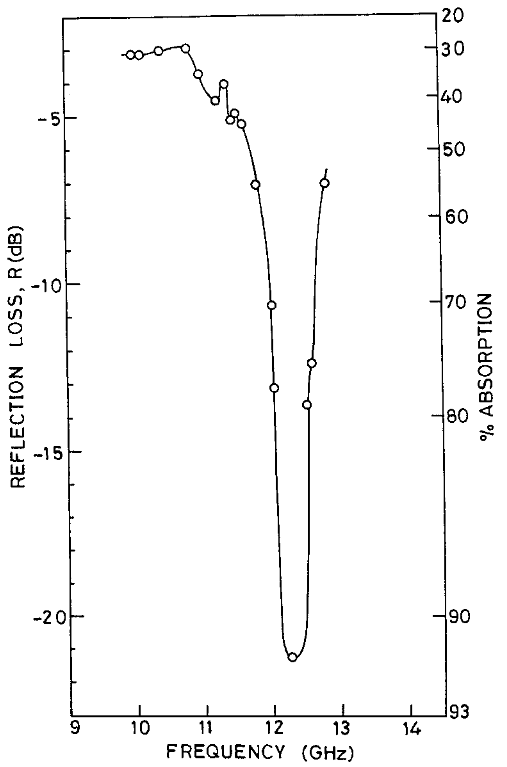

Fig. 7. Microwave absorption characteristics of 2 mm thick strontium ferrite-epoxy composite with ferrite composition $SrCo_{0.3}Ti_{0.3}Fe_{11.4}O_{19}$.

and permeability values being close to each other, the electrical thickness can be considered to be nearly equal to a quarter wavelength. This is supported by the fact that maximum absorption is indeed observed in the frequency range 11–12 GHz for 3 mm thick samples.

A good quality absorber should have large reflection coefficient, large bandwidth and small electrical thickness. It is, however, difficult to obtain all these attributes in one single absorber. Absorption studies on barium ferrite based single layer absorbers have reported [21] a reflection loss of about −30 dB at 10 GHz with a bandwidth (full width at half maximum) of 0.2 GHz. Another study [22] shows absorption peaks with bandwidths of 0.4–0.7 GHz but with a reflection loss of only −15 dB in the frequency range 9–9.5 GHz for barium ferrite based absorbers. Studies on spinel based absorbers, such as nickel-zinc ferrite, report [23, 24] absorption below the GHz range, with relative bandwidth of about 0.4 GHz, in samples of thickness greater than 4 mm. The present work shows that the strontium ferrite based absorbers exhibit better absorption and at comparatively higher frequencies of 11–12 GHz, with an absorption bandwidth of 0.7 GHz. These absorbers can be used at still higher frequencies but with reduced thickness. Studies on 2 mm thick composites with $x = 0.3$ show a maximum absorption frequency of 12.3 GHz but with a slightly lower absorption of 92%, Fig. 7.

Results and Discussions

From the foregoing discussions it is clear that strontium ferrite based materials have great potential as absorbers at high frequencies.

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