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Study of Frequency-Dependent Electromagnetic Shielding Parameters of Al-Doped M-Type Ba-Hexaferrite

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Abstract:
Use of electronic and communication systems has become more intense with the time. A problem of electromagnetic interference (EMI) has arisen, and this makes it necessary to provide a lightweight and unobtrusive solution. Chemically stable, environmentally friendly materials that can diffuse unwanted electromagnetic radiation from the solution. In this work, Al-substituted M-type barium hexaferrite, $BaFe_{12-x}Al_xO_{19}$ (x = 0.00, 0.02, 0.04, 0.06, and 0.08), was investigated as a multifunctional ferrite material for electromagnetic shielding applications. The sample was prepared by the citrate precursor method. Thereafter they underwent proper thermal treatment, and their electromagnetic response was systematically evaluated as a function of Al concentration and frequency. The analysis of the shielding effectiveness was done based on reflection loss (SE_R). Using the measured scattering, total shielding effectiveness was calculated. The results show that the substitution of Al has a significant effect on the magnetic response of M-type barium hexaferrite. The SEA is still relatively low, rises with frequency up to about 6GHz and rises with frequency. The composition that was investigated in this work is represented by x. The higher SE_R (4.09 dB) and SE_T are measured for the 0.02 sample at 12GHz. The 0.06 composition has comparatively higher shielding and reflection-related effectiveness. The shielding behaviour is frequency-dependent for both reflection and absorption. The attenuation of incident electromagnetic radiation is caused by reflection and absorption. The observed compositional dependency is due to the alteration of the Electromagnetic parameters and related polarisation and magnetic loss processes induced by Al^{3+} substitution. The result set the Al-substituted M-type barium hexaferrite is a potential candidate for the field of EMI shielding and microwave attenuation, which has applications in communication, electronics, and high-frequency fields and electromagnetic protection technologies.

Keywords: M-type ferrite, Al dopant, citrate precursor method. EM shielding parameter

1. INTRODUCTION

The growth in the use of electronic equipment, wireless communication systems, high-frequency circuits, radar systems, and electrically powered buildings and structures has led to an increasingly electromagnetic environment where unwanted electromagnetic radiation can disrupt the normal operation of electronic equipment. Electromagnetic interference (EMI) may cause distortion of signals, malformation of electronic systems and decrease in the reliability of communication [1–3]. Therefore, the research on the efficient electromagnetic shielding and microwave absorbing material has been attracted the interest of researchers. In particular, shielding materials are expected to have good attenuation effect, low weight, good chemical stability, thermal stability and compatibility with the practical device architectures, especially the modern materials. The promising properties of ferrite-based materials are their interesting magnetic properties, high electrical resistivity, good chemical stability and interaction with electromagnetic radiation in wide range of frequency. Hexagonal ferrite is one of the significant classes of magnetic materials due to its crystal structure and magnetic properties which can be modified by chemical substitution and microstructural control. M-type barium hexaferrite ($BaFe_{12}O_{19}$) has received much interest because of its high magnetocrystalline anisotropy, hard magnetic properties, chemical stability, and importance in technology. Its use and investigation for the application of permanent magnets, magnetic devices, high-frequency applications, electromagnetic shielding, and microwave absorbing systems have followed these properties [4–6]. The distribution of Fe^{3+} ions among the crystallographically nonequivalent sites of M-type hexaferrite has a strong influence on the magnetic and electromagnetic properties. Hence, the substitution of Fe^{3+} by proper cations results in very fine control of the structural, magnetic dielectric and microwave properties of the material. The development of ferrite-based materials has also been regarded as relevant to sustainable technologies for electrical energy because of their potential to replace materials containing critical and expensive elements [7,8]. Incorporation of Al^{3+} into the M-Type barium hexaferrite lattice is of special interest among different substitution methods. The magnetic sublattice interactions and the magneto crystalline anisotropy, coercivity and microstructure may be modified by substituting Al for Fe^{3+} ions. Al substitution has been shown to greatly affect the magnetic characteristics of hexaferrites in previous studies. The overall magnetization can also be affected, by the substitution of Fe^{3+} by Al^{3+} which are non-magnetic. It is of special interest to obtain a desired balance of magnetic and electromagnetic properties for relatively low concentrations of Al. Previous research has claimed the modification of M-type ferrites with the introduction of Al and all other cations for use in the development of permanent magnets in electrical vehicles [8].

Besides the magnetic properties, M-type barium hexaferrites have also good potential for attenuation of electromagnetic waves. Absorption is due to interaction between incident electromagnetic wave and the dielectric and magnetic response of the absorber. Complex permittivity, complex permeability, impedance matching, dielectric polarization, magnetic resonance and other electromagnetic loss mechanisms are all factors governing the effectiveness of an absorber. The incident electromagnetic wave needs to penetrate the absorber without being mainly reflected at the air material interface, to ensure efficient absorption. Electromagnetic energy entering the material is lost by dielectric loss and magnetic loss. Therefore, it is crucial to simultaneously control the impedance matching and energy dissipation mechanisms to develop an optimum microwave absorber. The three basic processes of electromagnetic shielding are reflection, absorption, and multiple internal reflection [9–12]. The contribution of these mechanisms is more or less depending on electrical, dielectric, magnetic structure, and geometrical properties of the shielding material. The shielding effectiveness can thus be divided into reflection-related shielding effectiveness (SE_R), absorption-related shielding effectiveness (SE_A), and total shielding effectiveness (SE_T). The overall protection is frequently given as the sum of the reflection and absorption. The microwave-measured scattering parameters can be used to evaluate these parameters. The current manuscript takes this line of thought and investigates the frequency dependent shielding properties of Al- substituted M- type barium hexaferrite. A significant benefit of the ferrite-based shielding material is that the magnetic response of these materials can be controlled without the need for highly conductive metallic phases. A material with high conductivity can give a good reflection, but too high a reflection can cause secondary electromagnetic pollution. Magnetic ferrite, on the other hand, can offer attenuation by reflection, absorption, magnetic resonance, dielectric polarization, and interfacial processes [13]. It is significant to develop ferrite-based materials with controlled absorption and reflection properties, particularly in the field of application where electromagnetic energies have to be attenuated. Another important consideration on frequency dependency of EMI shielding is the wide frequency bandwidth required by modern communication and electronic systems. A material that functions well at one frequency could not be as effective at another frequency [10]. Therefore, an investigation of the SE_R, SE_A, and SE_T is more complete when extended over a wide range of frequencies and leads to the discovery of composition-frequency combinations that are appropriate for the application to understand the effect of controlled Al substitution on the electromagnetic shielding response of the Al-substituted M-type barium hexaferrite ($BaFe_{12-x}Al_xO_{19}$). Scattering parameter-based calculations of reflection, absorption, and total shielding effectiveness were used to analyze the shielding characteristics. Special attention was given to determining which composition provides the greatest shielding effectiveness at various frequency ranges and to gaining insight into the relative contribution of reflection and absorption. The findings give insight into the effect of Al substitution on the electromagnetic response of M- type barium hexaferrite and its potential application in ferrite-based EMI shielding.

2. Experimental Details

M-type barium hexaferrite with the nominal chemical formula $BaFe_{12-x}Al_xO_{19}$ ($0.00 \le x \le 0.08$) was synthesized by the citrate precursor method [14,15]. The citrate precursor route was chosen as it allows for the constituent cations to be homogenously mixed and as compositional control is possible during the formation of ferrite powders. The synthesis method is complexation of metal ions with citric acid, precursor formation and then thermal treatment. The starting materials used were barium nitrate [$Ba(NO_3)_2$], ferric nitrate [$Fe(NO_3)_3 \cdot 9H_2O$], aluminum nitrate [$Al(NO_3)_3 \cdot 9H_2O$] and citric acid ($C_6H_8O_7$). The amount of aluminum precursor was adjusted based on the nominal substitution level and the amount of iron precursor was adjusted based on the amount of aluminum precursor to maintain the $BaFe_{12-x}Al_xO_{19}$ stoichiometry. The ratio of citric acid and total metal nitrates was kept at 1:1. All the precursors used were individually dissolved in deionized water and then combined to form a homogenous precursor solution. The precipitate was slowly evaporated in the resulting solution to yield a fine and soft precursor material. The dried precursor was then subjected to the calcination process at 700°C. The calcinated powder was then sintered at 850 °C for 5h to encourage the formation of ferrite and the crystallization. The powders were then subjected to structural, morphological, magnetic and electromagnetic characterization. The citrate precursor approach and the use of controlled Al – substitution are in line with the synthesis strategy outlined in the manuscript.

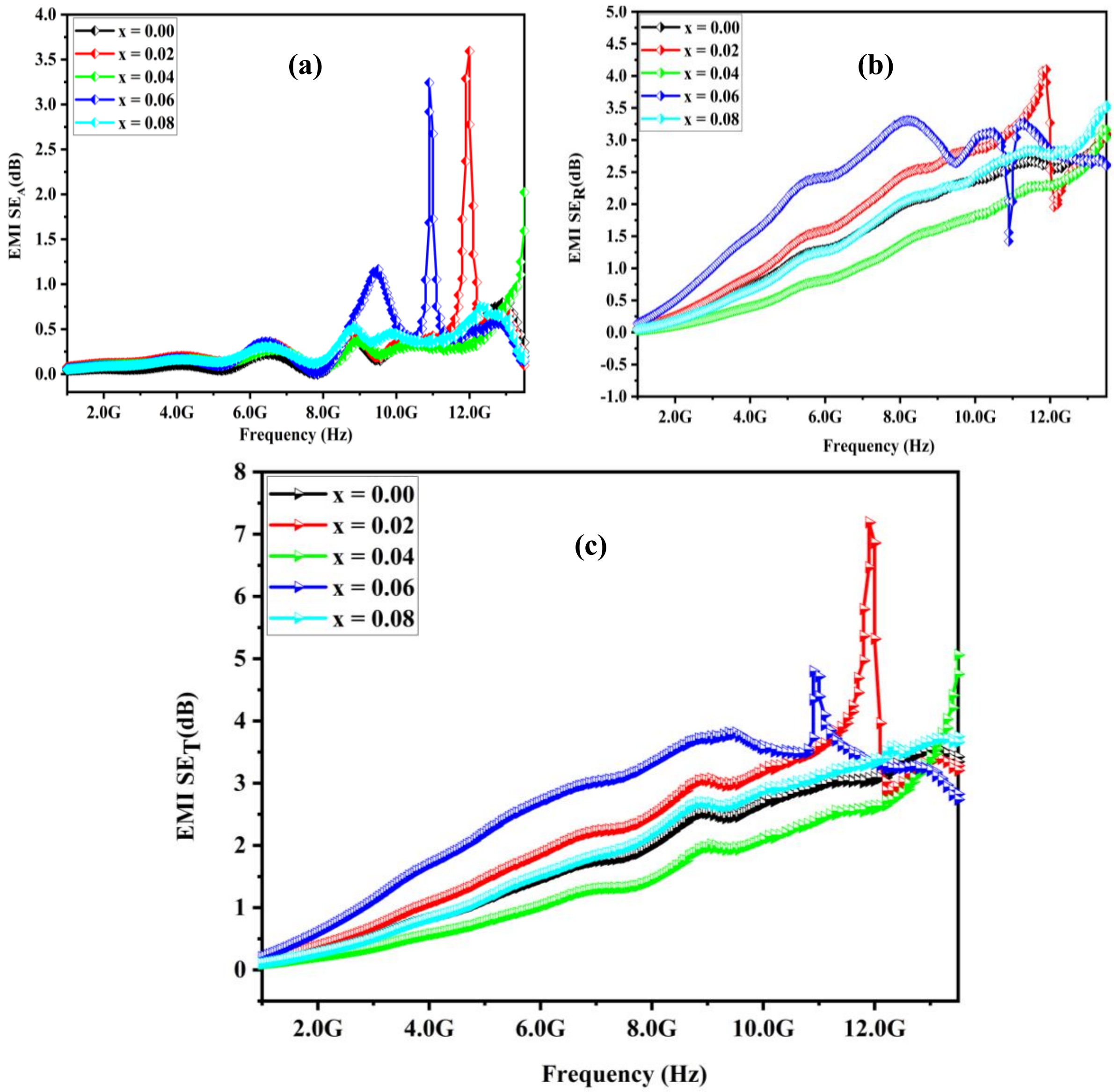

Figure 1: (a-c) SE_R, SE_A and SE_T parameters of unit Ba $Al_xFe_{12-x}O_{19}$, where x = 0.00, 0.02, 0.04, 0.06, and 0.08

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EMI-Shielding Parameters

Absorption and reflection are the two mechanisms that underlie the EMI shielding capabilities of materials. The EM wave transmission line model is used to explain the EMI reflection from the shielding film. The reflection coefficient is the amount of EMI that is reflected when the incident EMI is facing the shielding film surface[16,17]. The EMI shielding properties can be used to evaluate the materials' SE (shielding efficiency) [18]. Energy absorption is referred to as absorption loss (SEA), while energy dissipation during reflection, which can result from an impedance mismatch with the EM radiation, is referred to as reflection loss (SER). The scattering transmission parameter can be written via Equations 5, 6, and 7 as [19]

$$SE_T\,(\text{dB}) = SE_R + SE_A = 10 log \frac{1}{T}\,(dB) \qquad \text{.........(5)}$$

$$SE_R = -10\log(1-R) \qquad \text{.......... (6)}$$

$$SE_A = -10\log\left(\frac{T}{1-R}\right) \quad \text{.......... (7)}$$

R, A, and T are the physical parameters of reflection, absorption, and transmission provided in Equations 8, 9, and 10 are:

$$R = |S_{11}|^2 = \frac{P_R}{P_1} \quad \text{............ (8)}$$

$$T = |S_{21}|^2 = \frac{P_T}{P_1} \quad \text{.......... (9)}$$

$$A = 1 - R - T \quad \text{.......... (10)}$$

where the reflected, incident, and P_R, P_I, and P_T denote transmitted powers. The efficiency of efficient absorption A_{eff} is given in Equation 11 as:

$$A_{eff} = \frac{1-R-T}{1-R} \quad \text{.......... (11)}$$

Figure 1 (a-c) gives the frequency-dependent shielding effective parameters for Al-doped BHF, $BaAl_xFe_{12-x}O_{19}$, where x = 0.00, 0.02, 0.04, 0.06, and 0.08. For the whole composition range, or from x = 0.00 to 0.08, up to the frequency range of 6 GHz, the SEA value falls within the range of 0.05 dB. SEA begins to rise after 6 GHz and, for composition x = 0.02, reaches a maximum value of 3.5 dB at 6 GHz. On the other hand, SE_R starts with the initial value of 0.02 dB, and it increases as the frequency increases. The maximum value of SE_R reaches up to 4.09 dB, at the composition of x = 0.02 and at the frequency of 12 GHz. Between the frequency range of 1-8 GHz, the maximum value of SE_R is for the composition of x = 0.06. Based on equation 6 , the total shielding effective (SE_T) value is the sum of SE_A and SE_R. As seen in Figure 1 (c), the SET value starts at 0.02 dB and rises monotonically with frequency. In comparison to other compositions, the greatest value is for x=0.06 up to the frequency range of 11 GHz. But at 11.9 GHz, the maximum value of 7.18 dB is attained for the composition of x = 0.02.

3. Conclusion:

The Al- substituted M- type barium hexaferrite $BaFe_{12-x}Al_xO_{19}$ (x = 0.00, 0.02, 0.04, 0.06 and 0.08) is studied as a ferrite-based material for electromagnetic interference shielding and microwave attenuation applications. The study shows that the electromagnetic shielding response of M- type barium hexaferrite is considerably altered by the controlled Al substitution and it can be effectively utilized to tailor the balance of reflection and absorption of the incident electromagnetic (EM) radiation. The EMI shielding analysis indicates that the role of absorption is relatively small up to about 6 GHz for the compositions studied and become higher with increasing frequency. The composition of x = 0.02 shows the highest SEA of ~3.5 dB at 6 GHz, which indicate a higher absorption related attenuation for this composition. The reflection contribution also grows as the frequency increases, with the highest SER around 4.09 dB at x = 0.02 and f = 12 GHz. The x = 0.06 composition has relatively high reflection related shielding efficiency in the frequency range 1-8 GHz, The overall shielding effect (reflection and absorption) rises with frequency throughout the range of frequencies studied. The x = 0.06 composition offers the highest SET from the frequencies investigated up to about 11 GHz while the x = 0.02 sample shows the maximum SET of ~7.18 dB at 11.9GHz. The results show that the best shielding response is not determined by just one composition in the whole frequency range and depends on the concentration of Al and the operating frequency. The shielding effect values obtained can be explained with the effect of Al^{3+} substitution on the electromagnetic response of the M- type ferrite. The magnetic and dielectric properties properties of the material can change with the cation substitution, affecting way the material interacts with the incident electromagnetic radiation and therefore changing the reflection/absorption ratio. Therefore, compositional control is a practical method of adjusting the shielding response as desired for the operating frequency. The overall findings show that the Al substituted M-type barium hexaferrite is a promising material for use in EMI shielding and microwave attenuation application of a ferrite. The material is chemically stable and has an electromagnetic response which can be manipulated by planed cation substitution. The shielding effects shown to be frequency and composition dependent are significant for electromagnetic protection in communication and electronic systems and other high frequency situations where the propagation of unwanted electromagnetic radiation is to be controlled.

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