

ELECTROMAGNETIC PROPAGATION AND ABSORBING PROPERTY OF FERRITE-POLYMER NANOCOMPOSITE STRUCTURE

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Abstract—We have synthesized ferrite-polymer nanocomposite structures and theoretically and experimentally investigated electromagnetic propagation, absorption properties of these nanocomposite materials at 8–20 GHz in microwave guides. The microwave properties of the samples were investigated by transmission line method, and reflection loss of -59.60 dB was found at 12 GHz for an absorber thickness of 2 mm. These nanocomposites may be attractive candidates for microwave absorption materials.

1. INTRODUCTION

In recent years, the applications of electromagnetic (EM) wave have been very useful in high GHz ranges, including wireless telecommunication systems, radar, local area network, medical equipment, etc. [1–4]. With applications of electromagnetic (EM) wave in the high GHz ranges, the electromagnetic interference (EMI) problems have attracted more attention recently due to the extensive growth in the application of electronic devices and security, such as computer local area networks, mobiles phones, laptops, microwave oven, etc. [5–7].

Ferrites serve as better electromagnetic interference (EMI) suppressors than their dielectric counterparts on account of their excellent magnetic properties. Ferrite materials exhibit various electrical and magnetic properties of which complex permeability and complex permittivity, in particular, are important in determining their high frequency characteristics [8–11].

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In this work, we synthesized ferrite-polymer nanocomposite structures, and theoretically and experimentally investigated electromagnetic propagation, absorption properties of nanocomposite materials thin films at 8–20 GHz in microwave guides. The microwave properties of samples were investigated using network analyzer, and measurements were made by vibration sample magnetometer (VSM) technique.

2. THEORY

The two methods generally are used for materials characterization with network analyzer. They are:

1. Free Space Method
2. Transmission Line Method

2.1. Free Space Method

Free space is an important wave transmission scheme in communication and materials research. In radar and satellite communication, electromagnetic waves propagate through free space. In materials property characterization, free space provides much flexibility in studying electromagnetic materials under different conditions [12].

In recent years, there has been increasing interest in using free space techniques for the measurement of electromagnetic properties of materials. Because horn lens antennas have far field focusing ability, it is possible to make accurate free space measurements at microwave frequencies [12].

But this method may not be good for small samples. So we used transmission line method which can be used for this purpose [13].

2.2. Transmission Line Method

In a transmission/reflection method, the material under test is inserted in a piece of transmission line, and the properties of the material are deduced on the basis of the reflection from the material and the transmission through the material [13]. This method is widely used in the measurement of electromagnetic properties of materials. Because microwave guides have field focusing ability, it is possible to make accurate measurements at microwave frequencies [13]. Electromagnetic waves propagate through microwave guides. The samples are put in two waveguides, and experimental investigation is carried out.

Figure 1(a) shows a rectangular waveguide with width a and height b . Rectangular waveguides can transmit TE and TM modes. Usually, two subscripts m and n are used to specify TE or TM modes,

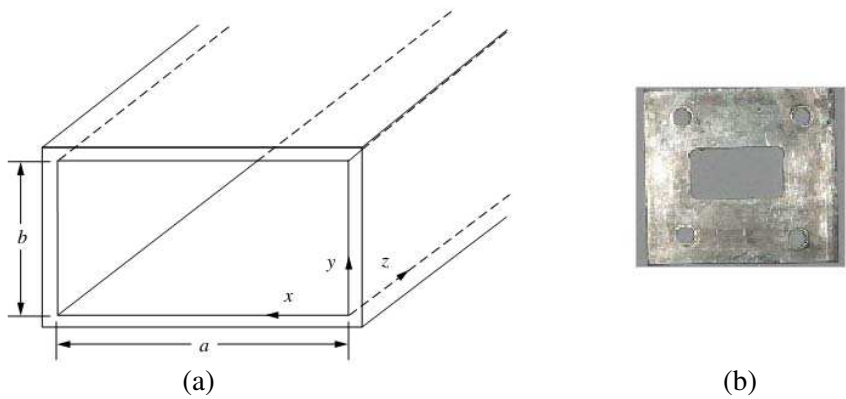


Figure 1. (a) Rectangular waveguide. (b) Special manufacture sample holder.

so the propagation mode is often denoted as TE_{mn} or TM_{mn} . The subscript “ m ” indicates the number of changing cycles along width a , while the subscript “ n ” indicates the number of changing cycles along height b [12].

The field components of TE_{mn} wave are

$$\begin{aligned} H_x &= A \frac{\gamma_{mn}}{k_c^2} \frac{m\pi}{a} \sin\left(\frac{m\pi}{a}x\right) \cos\left(\frac{n\pi}{b}y\right) \\ H_y &= A \frac{\gamma_{mn}}{k_c^2} \frac{n\pi}{a} \cos\left(\frac{m\pi}{a}x\right) \cos\left(\frac{n\pi}{b}y\right) \\ H_z &= A \cos\left(\frac{m\pi}{a}x\right) \cos\left(\frac{n\pi}{b}y\right) \\ E_x &= Z_{TE} H_y \\ E_y &= -Z_{TE} H_x \\ E_z &= 0 \end{aligned} \tag{1}$$

The constant A is related to the power of the wave. The parameters γ_{mn} and k_c are listed in Table 1 [12].

Table 1. Properties of empty rectangular waveguide.

	TE_{mn} Mode	TM_{mn} Mode
Cutoff wave number, k_c	$\sqrt{\left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2}$	$\sqrt{\left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2}$
Propagation constant	$\sqrt{k_c^2 + k_0^2}$	$\sqrt{k_c^2 + k_0^2}$

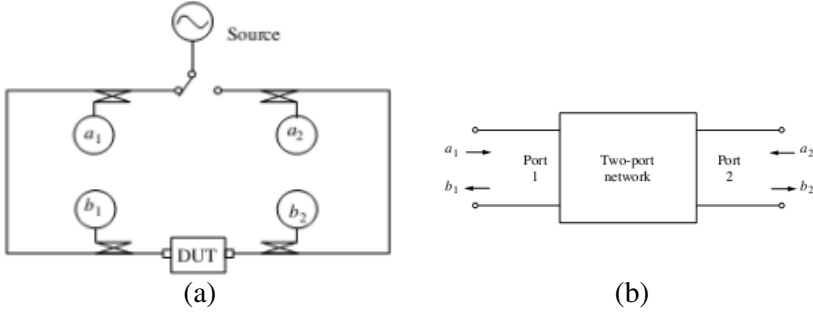


Figure 2. (a) The block diagram for network analyzer. (b) A two port network with “ a ”s and “ b ”s defined.

The field components of TM_{mn} wave are:

$$\begin{aligned}
 E_x &= B \frac{\gamma_{mn}}{k_c^2} \frac{m\pi}{a} \cos\left(\frac{m\pi}{a}x\right) \sin\left(\frac{n\pi}{b}y\right) \\
 E_y &= B \frac{\gamma_{mn}}{k_c^2} \frac{n\pi}{a} \sin\left(\frac{m\pi}{a}x\right) \cos\left(\frac{n\pi}{b}y\right) \\
 E_z &= A \sin\left(\frac{m\pi}{a}x\right) \sin\left(\frac{n\pi}{b}y\right) \\
 H_x &= -\frac{1}{Z_{TM}} H_y \\
 H_y &= \frac{1}{Z_{TM}} H_x \\
 H_z &= 0
 \end{aligned} \tag{2}$$

The constant B is related to the power of the wave [12]. The parameters γ_{mn} , k_c , parameters are listed in Table 1. The constants A and B in equations affect the amplitude of the fields, but do not affect the field distribution. The field distributions of several typical TE and TM modes are shown in [12].

2.3. Principle of Network Analyzers

Network analyzers are widely used to measure the four elements in a scattering matrix: S_{11} , S_{12} , S_{21} , and S_{22} . As shown in Figure 2(a), a network analyzer mainly consists of a source, signal separation devices, and detectors. Basically, a network analyzer can measure the four waves independently: two forward traveling waves a_1 and a_2 , and two reverse traveling waves b_1 and b_2 [12].

As shown in Figure 2(b), the responses of a network to external circuits can also be described by the input and output microwave waves [12]. The input waves at port 1 and port 2 are denoted as a_1 and a_2 , respectively, and the output waves from port 1 and port 2 are denoted as b_1 and b_2 , respectively. These parameters (a_1 , a_2 , b_1 , and b_2) may be voltage or current, and in most cases, we do not distinguish whether they are voltage or current [12]. The relationships between the input wave $[a]$ and output wave $[b]$ are often described by scattering parameters $[S]$:

$$[b] = [S][a]; \quad [S] = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix}$$

$$S_{jj} = \frac{b_j}{a_j} \quad (j = 1, 2) \quad (3)$$

$$S_{ij} = \frac{b_i}{a_i} \quad (i \neq j; i = 1, 2; j = 1, 2)$$

The reflection coefficient [12];

$$\Gamma_j = S_{jj} = \frac{b_j}{a_j} \quad (4)$$

The transmission coefficient [12];

$$T_{j \rightarrow i} = S_{ii} = \frac{b_i}{a_i} \quad (5)$$

The scattering parameters can then be obtained by the combinations of these four waves according to Eqs. S_{ii} and S_{ij} . The four detectors, labeled by a_1 , a_2 , b_1 , and b_2 are used to measure the four corresponding waves respectively, and the signal separation devices ensure the four waves to be measured independently [12].

Nicolson and Ross [14] and Weir [15] combined S_{11} and S_{21} and derived explicit formulas for the calculation of permittivity and permeability. The algorithm is usually called Nicolson-Ross-Weir (NRW) algorithm [12].

In the NRW algorithm, the reflection and transmission are expressed by the scattering parameters S_{11} and S_{21} . The reflection coefficient is given by [12];

$$\Gamma = K \pm \sqrt{K^2 - 1} \quad (6)$$

with

$$K = \frac{(S_{11}^2 - S_{21}^2) + 1}{2S_{11}} \quad (7)$$

The transmission coefficient [12];

$$T = \frac{(S_{11} + S_{21}) - \Gamma}{1 - (S_{11} + S_{21})\Gamma} \quad (8)$$

3. EXPERIMENTAL

3.1. Preparation of Nano-particles $\text{Co}_x\text{Mn}_{1-x}\text{Fe}_2\text{O}_4$

Nanoparticles of $\text{Co}_x\text{Mn}_{1-x}\text{Fe}_2\text{O}_4$ have been prepared by surfactant-assisted hydrothermal process using CTAB. According to this method, 0.003 mol. surfactant cetyltrimethylammonium (CTAB) was dissolved in 35 ml. deionized water to form a transparent solution. The synthesis processes have been presented in detail by Bayrakdar [13].

3.2. $\text{Co}_x\text{Mn}_{1-x}\text{Fe}_2\text{O}_4$ Nanoparticles and Acrylated Epoxy Composite Process

Powders of $\text{Co}_x\text{Mn}_{1-x}\text{Fe}_2\text{O}_4$ and Acrylated epoxy are taken in weight ratio of 5 : x : 1 (x is not disclosed) in a glass bottle, which were thoroughly mixed, and then silver hexafluoroantimonate was used as initiator for polymerization process in the glass bottle in the oven at 150°C. They were mixed and waited for 2 days for polymerization process. After this polymerization process was finished, this polymer was homogenized in mortar and then poured in the mould with $a = 19.4$ mm, d (cross section length) = 21.5 mm and c (thickness) = 2 mm and waited 20 min. at room temperature [13].

3.3. Measurements

The electromagnetic properties of samples were investigated using Agilent 8364B PNA Vector Network Analyzer.

Particles were measured by Size Malvern Instruments Zeta Sizer Nano-ZS.

Magnetic measurements were carried out with a Quantum Design Vibrating Sample Magnetometer (VSM) Model 6000.

SEM imaging was performed using a Philips XL30 SFEG.

4. RESULTS AND DISCUSSION

4.1. Structural Properties

Figure 3 shows SEM micrographs of $\text{Co}_x\text{Mn}_{1-x}\text{Fe}_2\text{O}_4$ ferrites nanoparticles. Nanoparticles of $\text{Co}_x\text{Mn}_{1-x}\text{Fe}_2\text{O}_4$ were analyzed by XRD in order to investigate the crystalline phases. XRD results were investigated in [13]. Particles' size of $\text{Co}_x\text{Mn}_{1-x}\text{Fe}_2\text{O}_4$ NPs was obtained as 62 nm for $x = 0$, 60 nm for $x = 0.5$, and 58 nm for $x = 1$ from nanosize measure of Zeta Sizer Nano-ZS instrument results [13, 16].

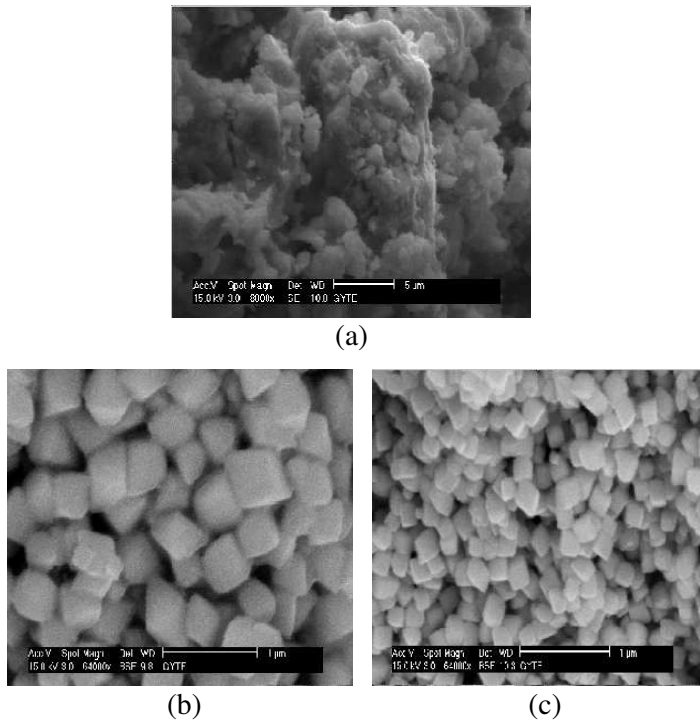


Figure 3. SEM images of (a) CoFe_2O_4 , (b) $\text{Co}_{0.5}\text{Mn}_{0.5}\text{Fe}_2\text{O}_4$ and (c) MnFe_2O_4 spinel ferrites.

Table 2. Saturation magnetization values of $\text{Co}_x\text{Mn}_{1-x}\text{Fe}_2\text{O}_4$ nanoparticles at room temperature.

$\text{Co}_x\text{Mn}_{1-x}\text{Fe}_2\text{O}_4$	M_s (emu/gr)
$x = 0.0$	31.98
$x = 0.5$	1.46
$x = 1.0$	84.90

4.2. Magnetization Measurements

Magnetization measurements of $\text{Co}_x\text{Mn}_{1-x}\text{Fe}_2\text{O}_4$ nanoparticles were performed using the VSM technique, and the results of M - H curves of the sample were showed in Figure 4 at room temperature. Saturation magnetization values (M_s) of $\text{Co}_x\text{Mn}_{1-x}\text{Fe}_2\text{O}_4$ nanoparticles were given in Table 2.

Figure 4 shows the magnetization loops of the $\text{Co}_x\text{Mn}_{1-x}\text{Fe}_2\text{O}_4$ at

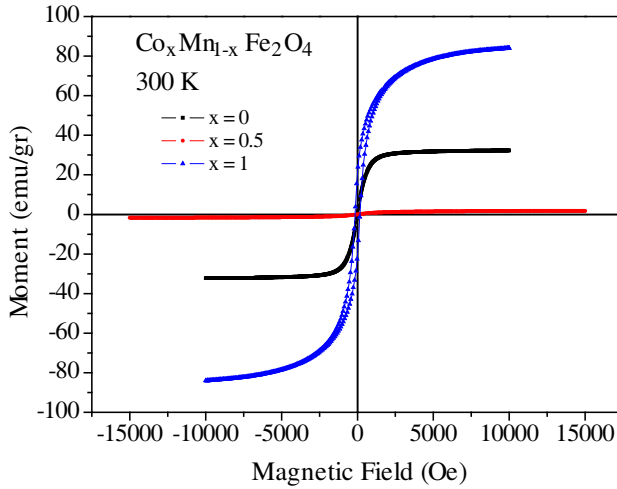


Figure 4. The hysteresis loops of this nanocomposite material the room temperature.

room temperature, and magnetic moment values are shown in Table 2. The coercivity (H_c) of a magnetic material is generally a measure of its magneto-crystalline anisotropy [17–21]. CoFe_2O_4 magnetic moment value is higher than other samples. These results show that Co contents attributed to the anisotropic properties of Mn [17–21]. Magnetization measurements of $\text{Co}_x\text{Mn}_{1-x}\text{Fe}_2\text{O}_4$ samples were performed using the quantum design vibrating sample magnetometer (VSM) technique, and the M-H curves of the sample were investigated at room temperature for all samples. As a result, a typical superparamagnetic ‘S’-like shape of hysteresis curves (without open loops-coercive fields are zero) were observed. These results can be explained as that Co contents attributed to the anisotropic properties of Mn [17–21].

These materials can be used for EMI and absorbing materials [22].

4.3. Microwave Measurements

Measurements were made using rectangular waveguide technique. The experimental setup and theory of absorbing were investigated in [13].

Special manufacture sample holder is shown in Figure 1(b), and this sample holder is very regular. Samples were put into a rectangular-shaped holder of size $a = 19.4\text{ mm}$, d (cross section length) $= 21.5\text{ mm}$ and c (thickness) $= 2\text{ mm}$ to fit in rectangular waveguides and connected between two waveguides with screws [13]. A special manufacture sample holder is well connected between two

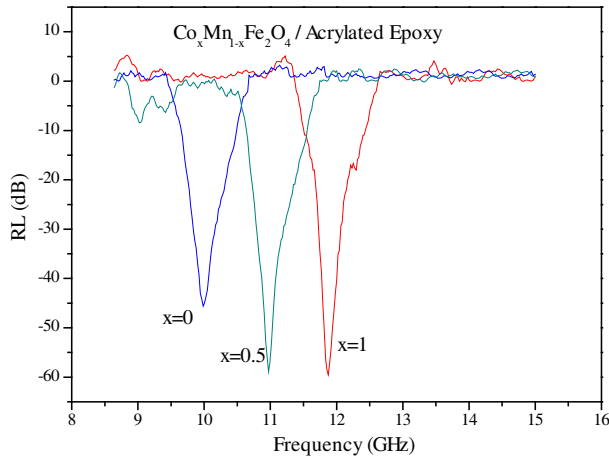


Figure 5. Absorption spectra of nanocomposites samples.

Table 3. Reflection loss values of $\text{Co}_x\text{Mn}_{1-x}\text{Fe}_2\text{O}_4$ /Acrylated epoxy nanocomposites.

$\text{Co}_x\text{Mn}_{1-x}\text{Fe}_2\text{O}_4$	Reflection Loss (dB)
$x = 0.0$	-45.57
$x = 0.5$	-58.08
$x = 1.0$	-59.60

rectangular waveguides with screws, and they are not separated from each other. So, microwave does not come out. Figure 5 shows the measured absorption spectra for prepared polymer-nanoparticles composites. In the present studies, optimized thickness is 2 mm for the sample. This sample shows maximum reflection loss of -59.60 dB and given in Table 3. These can be explained on basis of the impedance matching criterion of a very good absorber [14, 20–34] as follows: In case of a single layered absorber, the normalized input impedance (Z) with respect to the impedance in free space and reflection loss (RL) with respect to the normal incident plane wave are given by [7, 12, 13, 16, 17, 22–36]:

$$Z = \sqrt{\mu_r/\varepsilon_r} \tanh \left[\frac{-i2\pi f d}{c} \sqrt{\mu_r \varepsilon_r} \right] \quad (9)$$

$$RL \text{ (dB)} = -20 \log_{10} \left[\frac{Z - 1}{Z + 1} \right]$$

where, μ_r and ε_r are the relative complex permeability and permittivity

of the absorber medium. f and c are the frequency of microwave in free space and the velocity of light, respectively. d is the sample thickness. The reflection loss for sample thickness of 2 mm in the frequency range of 8–20 GHz was made for preparing these composites [7].

5. CONCLUSION

Ferrite-polymer nanocomposite structures have been successfully synthesized. The electromagnetic propagation and absorption properties of these nanocomposite materials at 8–20 GHz in microwave guides were theoretically and experimentally investigated. The microwave absorption, magnetization, EMI shielding of $\text{Co}_x\text{Mn}_{1-x}\text{Fe}_2\text{O}_4/\text{Acrylated Epoxy}$ nanocomposite were analyzed. These microwave absorbers using synthesized prepared composite have been fabricated and successfully demonstrated for a maximum reflection loss of -59.60 dB at 12 GHz with a bandwidth of approximately 2 GHz in a sample with thickness of 2 mm. Our results indicate that the nanocomposite substructures exhibit good absorption performances. The reflection loss is very high, and the bandwidth is higher than that normally reported. It can be said that these samples will provide great benefits for electromagnetic applications and EMI shielding characteristics. In conclusion, the ferrite-polymer ($\text{Co}_x\text{Mn}_{1-x}\text{Fe}_2\text{O}_4/\text{Acrylated Epoxy}$) nanocomposites exhibited good EM absorption properties. The nanocomposites showed higher EM absorption frequency and wider absorption bandwidth ($\text{RL} < -20$ dB) due to the larger magnetic anisotropy of Co ferrite nanoparticles. Our work suggests that ferrite-polymer ($\text{Co}_x\text{Mn}_{1-x}\text{Fe}_2\text{O}_4/\text{Acrylated Epoxy}$) nanocomposites can be used as a good EM absorption material in 8–20 GHz range.

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