HIGH–FREQUENCY EMI NOISE SUPPRESSION BY POLYMER–BASED COMPOSITE MAGNETIC MATERIALS

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Summary The complex permeability and EM–wave absorption properties of hybrid polymer–based composite magnetic materials (with MnZn and LiZn ferrite fillers and PVC matrix) prepared with constant total filler content (65 vol%) and particle size (0–250 μm) have been investigated in the 1–1000 MHz frequency range. Within this filler concentration the permeability of composites changed continuously with the change of ferrite filler content ratio between two types of ferrite fillers. The observed relaxation type of permeability dispersion was due to the domain wall and natural ferromagnetic resonance phenomena and was also attributed to the high damping of spin motion. Measured values of permeability were used to determine the EM–wave absorption properties (return loss RL, matching frequency f_m, matching thickness d_m and bandwidth Δf for $RL \leq -20$ dB). The calculation of these properties was based on a model of single–layered absorber backed by a perfect conductor using transmission–line and EM–field theory. The composite with the volume fraction ratio of hybrid MnZn:LiZn ferrite filler set to 0.5:0.5 has shown a return loss of −57 dB (> 99 % power absorption) at f_m = 714 MHz with the −20 dB bandwidth of Δf = 232 MHz for an absorber thickness of 7.79 mm. The prepared composites can fruitfully be utilized for suppression of conducted and/or radiated EMI noise especially in wireless and portable electronic equipments.

1. INTRODUCTION

Advances in electronic and telecommunication industry have led to the increase of utilized frequencies and frequency bands. Electromagnetic interference (EMI) is the result of electromagnetic (EM) emissions through radiated and/or conducted path with unwanted EM noises. Light weight EMI absorbers are needed to protect the workspace and environment from radiation coming from computers and communication equipments as well as for protection of sensitive electronic circuits on printed circuit boards. Compared to conventional metal–based EMI absorbers (which are expensive, heavy, susceptible to oxidation, etc.), polymer–based composite magnetic materials have gained popularity recently because of their low weight, resistance to corrosion, flexibility and processing advantages. Hybrid composites with dual magnetic filler and single polymeric matrix have been a subject of considerable interest in recent years [1]. We have examined PVC–polymer–based composites with different kinds of single ferrite fillers: NiZn, MnZn and LiZn ferrite [2–5] and have found that the complex permeability had characteristic frequency dispersion and was attributed to the resonance of oscillating domain walls and the natural ferromagnetic resonance of precessing magnetic moments in domains. The dispersion of permeability changed from resonance type in case of sintered ferrites to relaxation one in case of composites and the permeability was mainly dependent on ferrite content and almost independent of ferrite particle size. We have also investigated the EM–wave absorption characteristics of NiZn ferrite/PVC polymer composites as a function of ferrite concentration [4] and also particle size [5], and found these materials as good EM–wave absorbers suitable for applications such as EMI suppressors (or shields) in telecommunication equipments at frequencies above 100 MHz. In this work, we study the complex permeability and EM–wave absorption properties of the hybrid MnZn/LiZn/PVC composite materials.

2. THEORY OF MULTI–LAYER EM–WAVE ABSORBER

The model of a multi–layer absorption structure is based on the concept of transmission (cascade) matrices known from the transmission–line theory.

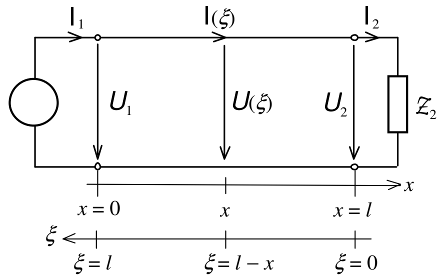

Fig.1. The electric circuit with a transmission line

Concerning the input and output, the transmission line (Fig.1) may be considered as a two–port network (Fig.2) that is passive and longitudinally symmetrical [6]. Its transmission (cascade) equations follow from:

$$\begin{aligned} \mathrm{U}(\xi) &= \cosh(\gamma\xi)\cdot \mathrm{U}_2 + Z_o \sinh(\gamma\xi)\cdot \mathrm{I}_2 \\ \mathrm{I}(\xi) &= \mathrm{Y}_o \sinh(\gamma\xi)\cdot \mathrm{U}_2 + \cosh(\gamma\xi)\cdot \mathrm{I}_2 \end{aligned} \tag{1}$$

when substituting $\xi = l$ and taking into account the reference direction of the output current I_2 as shown in Fig.1:

$$\begin{aligned} U_1 &= U(l) = \cosh(\gamma l)\cdot U_2 + Z_o \sinh(\gamma l)\cdot I_2 \\ I_1 &= I(l) = Y_o \sinh(\gamma l)\cdot U_2 + \cosh(\gamma l)\cdot I_2 \end{aligned} \qquad (2)$$

with U(ξ) and I(ξ) the phasors of voltage and current at position ξ (measured from the end of the line); U_1, I_1 and U_2, I_2 the phasors of input (index 1) and output (index 2) voltage and current; $\gamma = \alpha + j\beta$ the propagation constant (α is the attenuation constant and β is the phase constant); Z_o and $Y_o = 1/Z_o$ the wave impedance and admittance of the line, respectively, and l the length of the line. Thus the relationship between input and output quantities (U_1, I_1 and U_2, I_2) of the transmission line can be given by (Fig.2):

$$\begin{bmatrix} U_1 \\ I_1 \end{bmatrix} = \begin{bmatrix} \cosh(\gamma l) & Z_o \sinh(\gamma l) \\ Y_o \sinh(\gamma l) & \cosh(\gamma l) \end{bmatrix} \cdot \begin{bmatrix} U_2 \\ I_2 \end{bmatrix} \qquad (3)$$

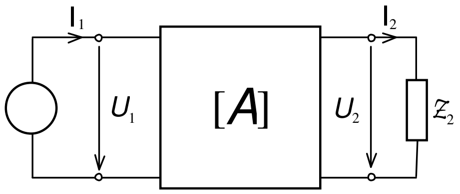

Fig.2. The transmission line represented by a two–port network

The geometry of a multi–layer EM–wave absorber is shown in Fig.3.

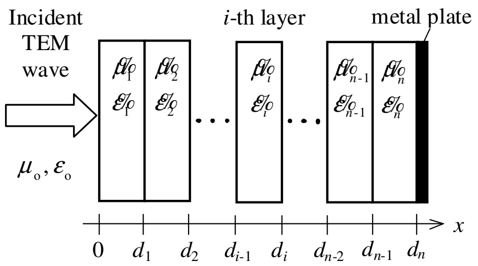

Fig.3. The concept of a multi–layered EM–wave absorber

A transversal electromagnetic (TEM) wave propagating along the positive x–direction is incident normally upon the absorber surface and gives rise to a series of waves travelling in the positive and reflected waves travelling in the negative x–direction within the layers. Let d_i, $\tilde{\varepsilon}_i$, $\tilde{\mu}_i$, and Z_i ($Y_i = 1/Z_i$) denote the thickness, the complex permittivity, complex permeability and intrinsic (or effective medium) impedance (admittance) of the i–th layer, respectively ($i = 1,2,\ldots,n$), ε_o and μ_o are permittivity and permeability of free space ($\varepsilon_o = 8.854\cdot 10^{-12}$ F/m, $\mu_o = 4\pi\cdot 10^{-7}$ H/m). The electrical conductivity for individual layers of the absorbers (besides the metal plate, which is considered as an (n+1)–th layer) is assumed to be zero. If the absorber structure has n layers where 0 is air and n+1 is metal, each of the n layers can be described by means of a transmission (cascade) matrix:

$$[A_i] = \begin{bmatrix} \cosh(\gamma_i d_i) & Z_i \sinh(\gamma_i d_i) \\ Y_i \sinh(\gamma_i d_i) & \cosh(\gamma_i d_i) \end{bmatrix} \qquad (4)$$

In general, the intrinsic (or effective medium) impedance Z_i depends on polarization of the EM–wave and on propagation constant γ_i [7]:

$$Z_i^{\mathrm{TE}} = \frac{j\omega\tilde{\mu}_i\mu_o}{\gamma_i} \qquad Z_i^{\mathrm{TM}} = \frac{\gamma_i}{j\omega\tilde{\varepsilon}_i\varepsilon_o} \qquad (5,6)$$

TE and TM stand for incident transversal electric and magnetic EM–wave, respectively. In the case of TE wave, E field is parallel to all media (layer) boundaries and in the case of TM wave, H field is parallel to all media boundaries. The propagation constant γ_i is different from $\gamma_i^{\mathrm{TEM}} = j\omega\sqrt{\tilde{\mu}_i\mu_o\tilde{\varepsilon}_i\varepsilon_o}$ (the propagation constant for TEM wave in free space). Also Z_i in Eq.(4) is not identical with the wave impedance of the TEM wave for free space:

$$Z_i^{\mathrm{TEM}} = \frac{j\omega\tilde{\mu}_i\mu_o}{\gamma_i^{\mathrm{TEM}}} = \frac{\gamma_i^{\mathrm{TEM}}}{j\omega\tilde{\varepsilon}_i\varepsilon_o} \qquad (7)$$

The transmission (cascade) matrix [A] of the whole absorber structure is given by:

$$[A] = [A_1]\cdot[A_2]\cdots[A_n] = \prod_{i=1}^{n}[A_i] \qquad (8)$$

The complex reflection coefficient for $x = 0$ (at the air/first–layer interface) also depends on the polarization of the EM–wave:

$$\tilde{\Gamma}^{\mathrm{TE}}(0) = \frac{\left[A_{21}^{\mathrm{TE}}\right] - Z_o\left[A_{22}^{\mathrm{TE}}\right]}{\left[A_{21}^{\mathrm{TE}}\right] + Z_o\left[A_{22}^{\mathrm{TE}}\right]} \qquad (9)$$

$$\tilde{\Gamma}^{\mathrm{TM}}(0) = \frac{\left[A_{21}^{\mathrm{TM}}\right] - Z_o\left[A_{22}^{\mathrm{TM}}\right]}{\left[A_{21}^{\mathrm{TM}}\right] + Z_o\left[A_{22}^{\mathrm{TM}}\right]} \qquad (10)$$

where $\left[A_{pq}^{\mathrm{TE}}\right]$ or $\left[A_{pq}^{\mathrm{TM}}\right]$ is a cascade submatrix, which is given by omitting the p–th row and q–th column in the whole matrix $[A]$.

In this paper, we have measured the complex permeability of the prepared composites using coaxial transmission–line method (a composite sample of the toroidal form was placed at the shorted end of a coaxial segment [8]) and therefore TEM−wave concept can be considered for all next calculations. For single−layer absorber the cascade matrix in Eq.(8) can be reduced to:

$$[\mathrm{A}]=\begin{bmatrix} \cosh(\gamma d) & Z_{\mathrm{o}}\sqrt{\dfrac{\tilde{\mu}_{\mathrm{r}}}{\tilde{\varepsilon}_{\mathrm{r}}}}\sinh(\gamma d) \\ \mathrm{Y}_{\mathrm{o}}\sqrt{\dfrac{\tilde{\varepsilon}_{\mathrm{r}}}{\tilde{\mu}_{\mathrm{r}}}}\sinh(\gamma d) & \cosh(\gamma d) \end{bmatrix} \tag{11}$$

with $Z_{\mathrm{o}}=\sqrt{\dfrac{\mu_{\mathrm{o}}}{\varepsilon_{\mathrm{o}}}}\approx 377\ \Omega$ ($\mathrm{Y_o} = 1/\mathrm{Z_o}$) the wave impedance (admittance) of the free space, $\tilde{\mu}_{\mathrm{r}}=\mu'_{\mathrm{r}}-\mathrm{j}\mu''_{\mathrm{r}}$ and $\tilde{\varepsilon}_{\mathrm{r}}=\varepsilon'_{\mathrm{r}}-\mathrm{j}\varepsilon''_{\mathrm{r}}$ the complex relative permeability and permittivity, respectively. The complex reflection coefficient in this case is given by:

$$\tilde{\Gamma}=\frac{Z_{\mathrm{in}}-Z_{\mathrm{o}}}{Z_{\mathrm{in}}+Z_{\mathrm{o}}} \tag{12}$$

where

$$Z_{\mathrm{in}}=Z_{\mathrm{o}}\sqrt{\frac{\tilde{\mu}_{\mathrm{r}}}{\tilde{\varepsilon}_{\mathrm{r}}}}\tanh\left(\mathrm{j}\frac{2\pi f}{c}\sqrt{\tilde{\mu}_{\mathrm{r}}\tilde{\varepsilon}_{\mathrm{r}}}\,d\right) \tag{13}$$

with c the velocity of light in free space ($c\approx 3\cdot 10^{8}$ m/s). If the thickness of the single−layer absorber d is small enough compared with the wavelength λ of the incident TEM wave, then the input impedance at the air/composite interface can be approximated by [4,5]:

$$Z_{\mathrm{in}}\approx \mathrm{j}Z_{\mathrm{o}}\frac{2\pi}{\lambda}\tilde{\mu}_{\mathrm{r}}d \tag{14}$$

Finally the return loss, RL, in (dB) was calculated using the following relation:

$$RL=20\log_{10}\left|\tilde{\Gamma}\right|=20\log_{10}\left|\frac{Z_{\mathrm{in}}-Z_{\mathrm{o}}}{Z_{\mathrm{in}}+Z_{\mathrm{o}}}\right| \tag{15}$$

We utilized the Eqs.(11−15) to make a computer program in MATHCAD environment for the design of single−layer absorbers based on prepared composites.

3. EXPERIMENTAL

Two different kinds of ferrites (a commercially available MnZn ferrite of composition $Mn_{0.52}Zn_{0.43}Fe_{2.05}O_4$ and LiZn ferrite of composition $Li_{0.575}Zn_{0.4}Ti_{0.55}Fe_{1.475}O_4$ synthesized by a solid state ceramic process at 1000 °C for 3.5 hours [9]) were used as magnetic fillers. The volume fraction ratio of hybrid MnZn:LiZn filler in composites was adjusted to 0:1, 0.2:0.8, 0.5:0.5, 0.8:0.2, and 1:0. The total content and particle size of the double ferrite filler in all composite samples were kept at 65 vol% and 0−250 μm, respectively. Polymer−based composites were produced by mixing MnZn, LiZn, and PVC (polyvinylchloride) powders together, followed by a dry low−temperature hot−pressing procedure. After compression moulding process (at 5 MPa), toroidal samples (with 9 mm in outside diameter, 3.6 mm in inside diameter, and 3 mm in thickness) were thermally processed at 135 °C for 1 hour. The complex−permeability spectra of produced samples have been measured over the frequency range of 1−1000 MHz using a vector analyzer (HP4191A) at room temperature [8]. EM−wave single−layer absorbing properties of prepared composites were optimised by numerical simulations in the MATHCAD environment.

4. RESULTS AND DISCUSSIONS

Figure 4 shows the measured frequency dependences of complex relative permeability $\tilde{\mu}_{\mathrm{r}}=\mu'_{\mathrm{r}}-\mathrm{j}\mu''_{\mathrm{r}}$ for hybrid MnZn/LiZn/PVC composites. In this case, the relaxation type of frequency dispersion was observed. The permeability of composites changed continuously with the change of ferrite filler content ratio between two types of ferrite fillers. The value of μ'_{r} decreased from about 25 for bi−component MnZn/PVC composite to about 14 for LiZn/PVC composite. The resonance frequencies of composites at which μ''_{r} had a maximum value raised from about 190 MHz for MnZn/PVC composite to about 480 MHz for LiZn/PVC composite. This is attributed to the demagnetizing field H_{d} formed by magnetic poles on the surfaces of filler particles dispersed in the polymer matrix, which leads to a decrease of the low−frequency value of μ'_{r} and simultaneously it also leads to an increase of the resonance frequency (see also [4,5]).

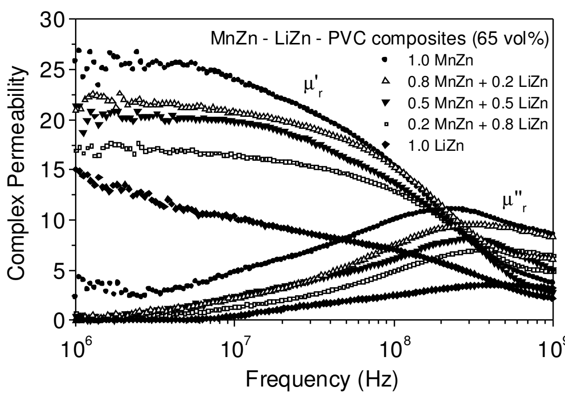

Fig.4. Complex permeability spectra of hybrid composites

Figure 5 depicts the calculated EM−wave absorbing characteristics (return loss, RL, in decibels, dB, as a function of frequency and ferrite filler content ratio) for the produced hybrid composites by means of their measured complex−permeability spectra. With the configuration change from MnZn/PVC composite structure to LiZn/PVC, the bandwidth Δf (for $RL \le -20$ dB) almost linearly raised from 139 to 336 MHz, the matching frequency f_m increased from 344 to 938 MHz, and the matching thickness d_m decreased from 11.29 to 6.62 mm (see Table 1).

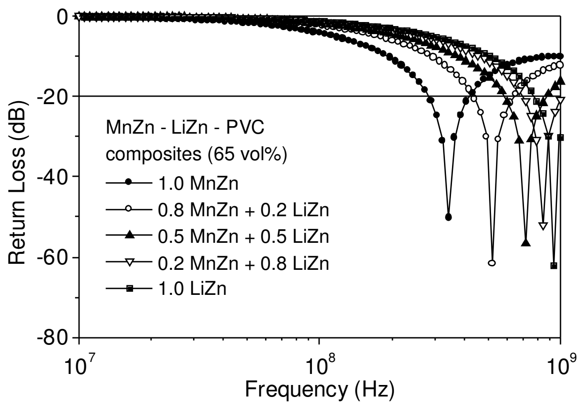

Fig.5. The frequency dependences of return loss for hybrid composite materials

Table 1 EM−wave absorption properties of single−layer absorbers.

Sample	Δf (MHz)	f_m (MHz)	d_m (mm)
1.0 MnZn	139	344	11.29
0.8 MnZn + 0.2 LiZn	194	522	8.46
0.5 MnZn + 0.5 LiZn	232	714	7.79
0.2 MnZn + 0.8 LiZn	306	845	7.03
1.0 LiZn	336	938	6.62

5. CONCLUSION

The frequency dependences of complex permeability of polymer−based hybrid composite materials have been investigated using coaxial transmission−line method in the frequency band of 1−1000 MHz. The relaxation type of permeability dispersion was observed in the synthesized hybrid composites samples. The observed frequency dispersions in the composites originated from the resonance of oscillating domain walls and precessing magnetization vectors in domains. The real part of complex permeability at low frequencies decreased and the resonance frequency shifted towards the higher frequency region with the configuration change of hybrid ferrite filler from MnZn to LiZn ferrite by increasing the demagnetizing field in composites. We have also studied EM−wave absorbing characteristics on prepared hybrid composites using proposed formulas by means of computer simulations (in MATHCAD). The presented results showed that not only complex permeability but also EM−wave absorbing characteristics can be better tuned in hybrid composites than in those with single ferrite fillers. The prepared composite materials have significant potential for EM−wave absorbing applications such as suppression of EMI noise (conducted and/or radiated) in modern wireless and mobile electronics.

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