Electronic Materials Letters, Vol. 5, No. 2 (2009), pp. 67-71
DOI: 10.3365/eml.2009.06.067

Electromagnetic Properties of Dielectric and Magnetic Composite Material for Antenna

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Electromagnetic properties of dielectric and magnetic composite materials were studied with various weight fractions and particle sizes of ferrite. The composite materials were prepared through Ni-Zn spinel ferrite and silicon elastomer, and were characterized with regard to permittivity, permeability, loss tangent$_e$, and loss tangent$_u$. Those properties of Ni-Zn spinel ferrite were approximately 7.0, 8.4, 0.01 and 0.1 MHz to 150 MHz, respectively; loss tangent$_u$, in particular, increased nearly exponentially with frequency above 80 MHz. Increase of loss tangent$_u$ was overcome by composite with polymer. The 40 wt. % loaded composite material changed these properties (approximately 3.8, 2.2, 0.003 and 0.1 at 161 MHz.); therefore, a higher frequency can be used. This material was optimized by particle size distribution. Composite material with smaller particle size is most useful because it shows similar magnetic loss of up to 211 MHz. Magneto-dielectric composite materials are more useful for antenna because they have lower values of complex permittivity and permeability, and higher application frequency. These results are certificated by simulation of antennas.

Keyword: composite material, ferrite, permittivity, permeability, antenna.

1. INTRODUCTION

Recently, the miniaturization and wide bandwidth of antennas are major issues in the RF (radio frequency) industry. These issues revolve around the physical dimensions of antennas for the latest compact and smart phones. The antenna size is decided by the wavelength with the electromagnetic properties of the base frame material for the antennas, such as permittivity (ε_r) and permeability (μ_r).[1,2]

In general, dielectric material (DM) of high permittivity was used for the miniaturization of antennas. The material was prepared as a composite with polymer and ceramic of high permittivity. Thus, high dielectric material (HDM) is composite material (HDCM) for the miniaturization of antennas. It is interpreted in the following Eq. 1 about the miniaturization of antennas.

$$\lambda = \frac{\lambda_0}{\sqrt{\varepsilon_r}} \tag{1}$$

λ is the effective wavelength determined by the permittivity of material, and λ_0 is the wavelength in a vacuum. The effective wavelength can be derived from Eq. 1 i.e. related to the miniaturization of antennas. Thus, the material of high permittivity was studied for the miniaturization of antennas; however, the efficiency and bandwidth of antennas are complicated by excessive miniaturization.

These complications are construed in the following equations; Eq. 2 deals with the gain of dipole antenna and equation 3 deals with the bandwidth of patch antenna.

$$Gain = \left(\frac{\pi h_e}{\lambda}\right)^2 \frac{73}{R_r} \tag{2}$$

h_e and R_r denote the length and resistance of the radiator. Thus, gain was improved through the increase of h_e and the decrease of R_r and λ. h_e and λ were decided from electromagnetic properties of base frame material of the antennas; therefore, their properties should be optimized for the gain of the antennas.

Eq. 1 is modified by the addition of permeability, as follows

$$\lambda = \frac{\lambda_0}{\sqrt{\varepsilon_r \mu_r}} \tag{3}$$

In Eq. 3, magneto dielectric material (MDM) shows the same effect on the miniaturization of the antennas if the square of permittivity, and the multiplication of permittivity and permeability, show equal values. From Eq. 4, the bandwidth of MDM is wider than that of the HDCM. Thus, MDM is more useful than a HDCM for miniaturization and a broad bandwidth of antenna.

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$$Bandwidth \approx \frac{96\sqrt{\frac{\mu_r}{\varepsilon_r}}\frac{t}{\lambda_0}}{\sqrt{2\left|4+17\sqrt{\mu_r\varepsilon_r}\right|}} \tag{4}$$

In general, MDM type is ferrite, it shows promise for technical applications, such as transformer cores, magnetic memories, noise filters, isolators, circulators, and so forth.[1-5] Recently, they are particularly in the spotlight for microwave communications.

However, it has low mechanical properties and high manufacturing temperature, and is limited for preparing complicated shapes.[3-9] Thus, these problems are overcome composite with dielectric material (magneto dielectric composite material: MDCM). The MDCM has the dielectric and magnetic properties of ferrite plus the high strength mechanical properties and simple manufacturing method (injection molding) of polymer.

We studied about MDCM with the ferrite (Ni-Zn spinel type, filler) and polymer (silicon elastomer, matrix) under various weight fractions and particle sizes.

2. EXPERIMENTAL PROCEDURE

2.1. Simulation of antennas

We simulated antennas by high frequency structuring simulation (HFSS, Ver. 11.0, Ansoft Co., Ltd.). Properties of base frame material were permittivity of 4, 8, 16, and permeability of 1, 2. Antennas were designed as a simple patch type for 100 MHz. These conditions are shown in Table 1.

2.2. Preparation of composite material

Composite materials were prepared by mix of filler (Ni-Zn ferrite) and matrix (Si-elastomer). Preparation conditions were different weight loadings and particle size distribution of Ni-Zn ferrite (loading percent is 10 wt. %, 20 wt. %, 30 wt. % and 40 wt. %). The filler was synthesized by co-precipitation method and sintered at 1,000`C. Then, it was reduced to ferrite powder, was granulized and sieved through three meshes (250 μm, 150 μm, and 53 μm) for the homogeneity.

2.3. Characterization of Dielectric and Magnetic Properties

The complex permeability and permittivity of the samples were measured using RF Impedance / Materials Analyzer (E4991A, Agilent) over 1 MHz –1 GHz, with test fixtures (16453 A and 16454 A). Measurement samples were prepared in two types of disk (diameter is 18 mm) and toroidal (outer diameter and inner diameter were 18 mm and 11 mm).

3. RESULT AND DISCUSSION

3.1. Simulation results of antennas

We simulated two types of material: DCM (A,B,C) and MDCM (D,E). The simulated results are summarized in Table 2. All of the simulated materials show the effect of the miniaturization of the antennas. The antenna's patch sizes decrease with the increase of the multiplication of permittivity and permeability; therefore, radiator size of the antenna is also decreased. The C and E antennas show the most miniaturized results because their base frame materials have the highest value of multiplication of permittivity and permeability. However, the bandwidth and efficiency show the lowest results because the radiator size of the antenna was decreased by an excessively high value of multiplication of permittivity and permeability. The B and D antennas show similar results with C and E antennas. However, D antenna shows more useful results than any other antennas in bandwidth and efficiency. These results suggest that MDCM is more useful and it must be used for low values of permittivity and permeability. These results were understood from Eqs. 3 and 4. We designed MDCM for antennas from simulated results.

3.2. Dielectric and Magnetic Properties

For MDCM, the complex permittivity and permeability of the matrix and the filler material are illustrated in Fig. 1. The real parts of permittivity and permeability of the matrix were 2.5 and 1.0, and the imaginary parts were close to zero until 1 GHz. The real parts of permittivity and permeability of the filler were approximately 7.1 - 7.2 and 7.5 – 7.8 MHz until 80 MHz. The loss tangent$_e$ and loss tangent$_u$ of the filler were approximately 0.02 and 0.03 at 80 MHz. The permeability of the filler increased from 80 MHz to 240 MHz, and then decreased as frequency increased. This slop movement is called "Snoek's limit" [10]. It is the limited frequency of the filler for mobile device, because magnetic loss is increased like exponential. Thus, it should be overcome to use higher frequencies through composite with polymer.

Table 1. Conditions of simulation

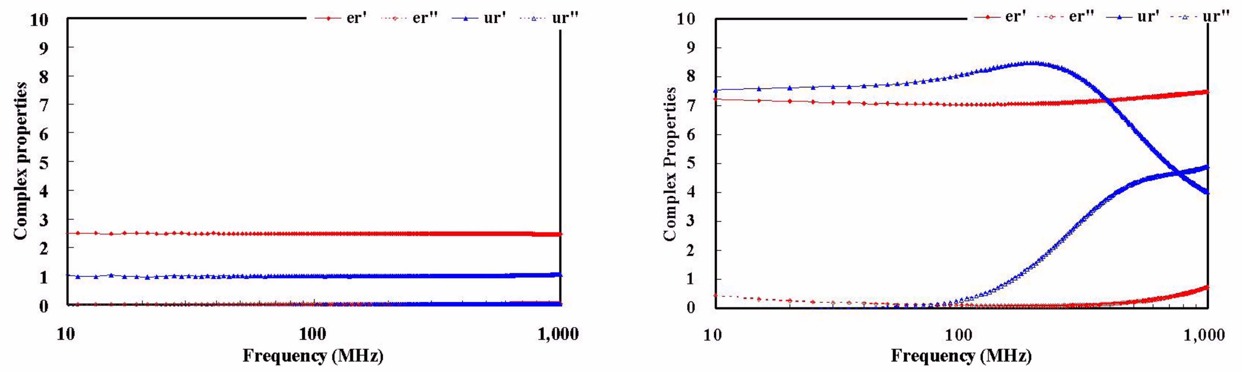
Name	Permittivity	Permeability	Permeability × Permittivity	Permeability/ Permittivity
A	4	1	4	0.25
B	8	1	8	0.125
C	16	1	16	0.063
D	4	2	8	0.5
E	8	2	16	0.25

Table 2. Results of simulation

Sample name	A	B	C	D	E
Patch size in wave length (λ_0)	25/100	18/100	13/100	18/100	13/100
Relative bandwidth (Basis condition A, %)	100.0	83.8	85.2	109.0	86.2
Relative efficiency (Basis condition A, %)	100.0	67.0	40.9	128.6	86.9

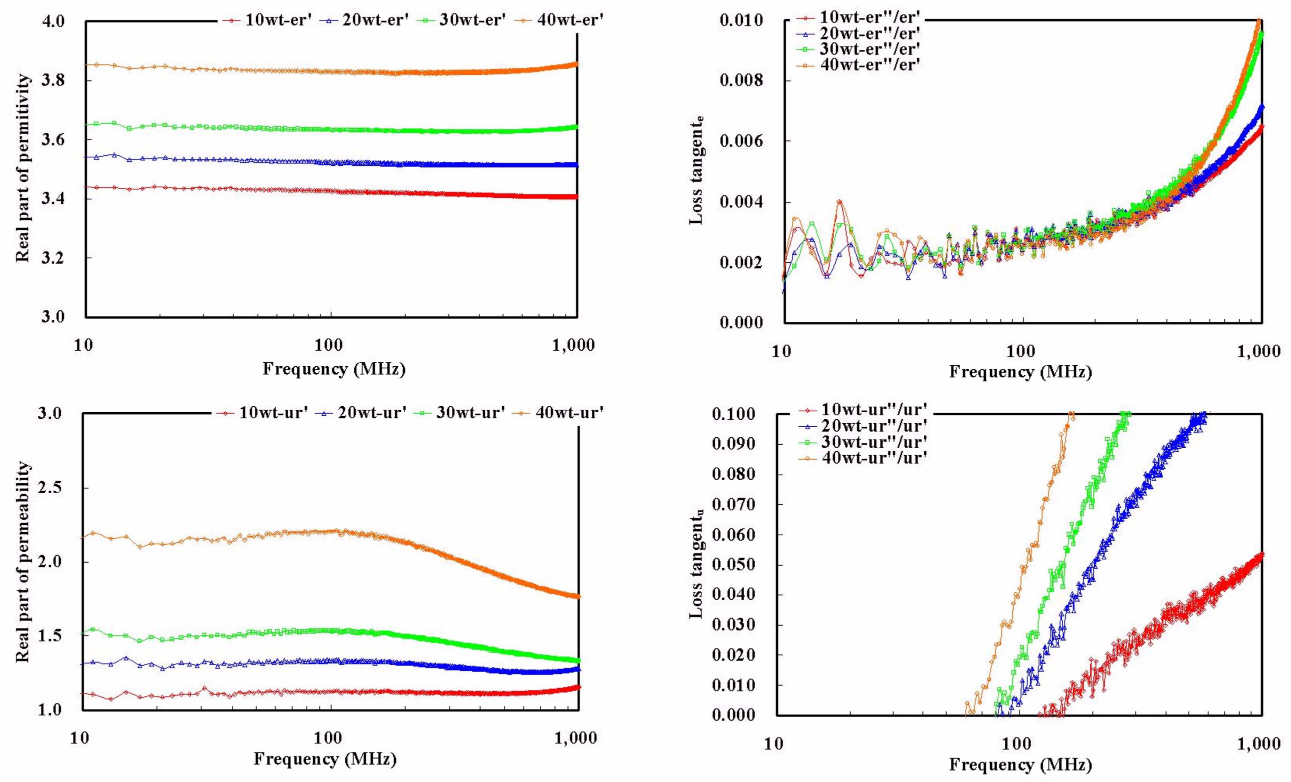
Figure 2 shows the real parts of permittivity and permeability, as well as loss tangent$_e$ and loss tangent$_u$ of the composite material with different weight loadings of Ni-Zn ferrite. The complex permittivity and permeability of MDCM and their ratio (permeability/permittivity) increase with increases in the ferrite's loading fraction; however, loss tangent$_e$ and loss tangent$_u$ also increase. The real parts of permittivity and permeability, loss tangent$_e$ and loss tangent$_u$ of the 40 wt. % loaded sample, are 3.83, 2.16, 0.003 and 0.1 at 161 MHz. The application frequency was moved to a higher frequency through composite. These results suggest that the MDCM is more useful than either single material for microwave applications.

Increase of loss tangent was optimized by particle size distribution of the filler. Figure 3 shows the complex permittivity and permeability of the MDCM at different particle sizes (< 53, 53 - 150, 150 - 250 μm) distribution of Ni-Zn ferrite. The complex permittivity and permeability of the



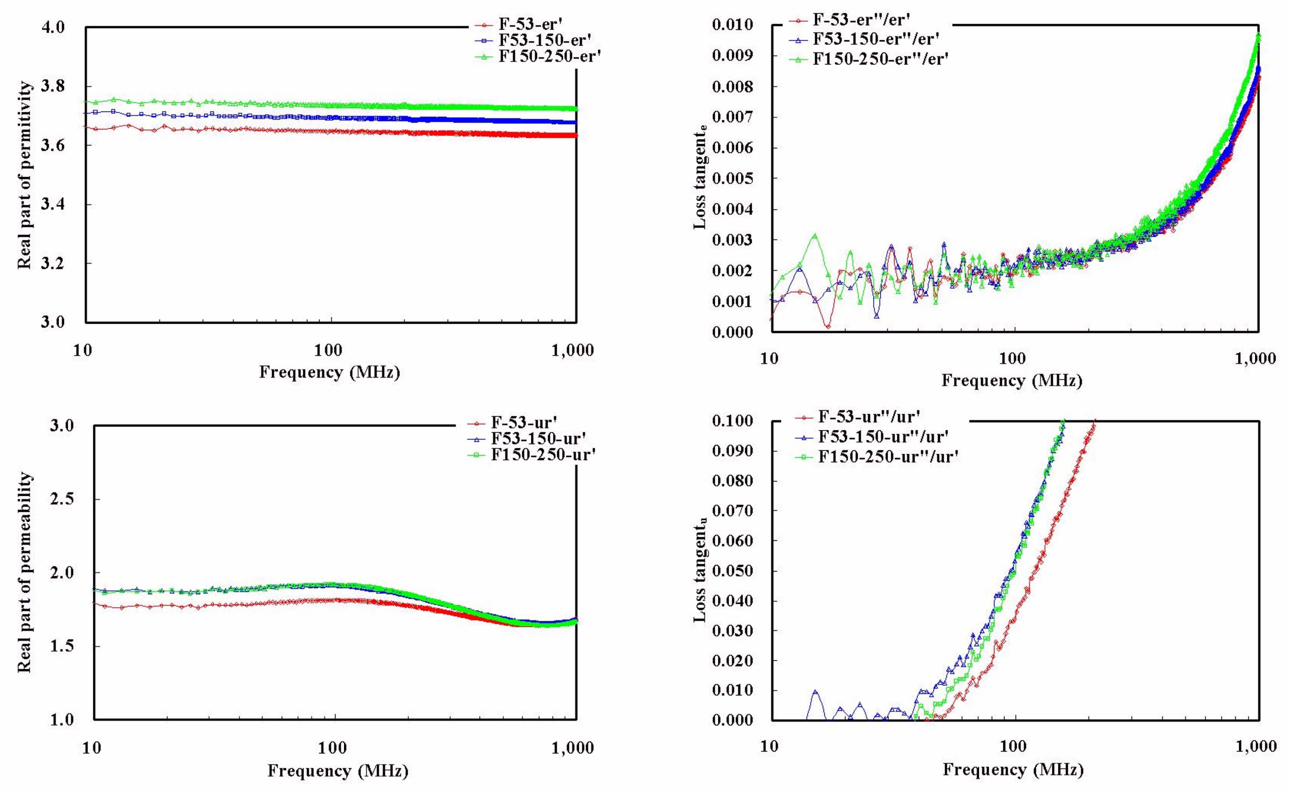
(a) (b)

Fig. 1. Complex permittivity and permeability of matrix (Si-elastomer) and filler (Ni-Zn ferrite) material: (a) Matrix material and (b) Filler material.



(a) (b)

Fig. 2. Dielectric and magnetic properties of MDCMs with containing ferrite wt. %: (a) Real part of permittivity and permeability and (b) Loss tangent$_e$ and loss tangent$_u$.



(a) (b)

Fig. 3. Dielectric and magnetic properties of MDCMs with particle size distribution: (a) Real part of permittivity and permeability and (b) Loss tangent$_e$ and loss tangent$_u$.

samples decrease with decreases in particle sizes. In particular, samples of below 53 μm are shown to be more useful than others in both dielectric and magnetic loss tangent, because small particle size affects homogeneity and distribution in the matrix. Through the use of under 53 μm filler and 40 wt. % ferrite loading conditions, the ratio of permittivity and permeability, loss tangent$_e$, loss tangent$_u$, and their ratios were modified close to the simulation results (experimental results are 3.64, 1.77, 0.003, 0.096 and 0.49 at 211 MHz.).

3.3. Measured vs Calculated Properties

For illustration and comparison, experimental results and the calculated results from the mixing rule (Eq. 5) are shown in Fig. 4.

$$\log \varepsilon_{composite} = w_{filler} \log \varepsilon_{filler} + w_{matrix} \log \varepsilon_{matrix} \qquad (5)$$

Where w_{filler}, $\varepsilon_{composite}$, ε_{filler}, and $\varepsilon_{matrixr}$ are the weight fraction of the filler, the real part of permittivity of MDCM, of the filler, and of the matrix. This equation is also for the effective permeability of the composite system ($\mu_{composite}$).[5-10] The measured and calculated values of the real part of permittivity and permeability (ferrite 40 wt. %) are shown in Fig. 4. The discrepancy of these properties was approximately 0 to 0.2.

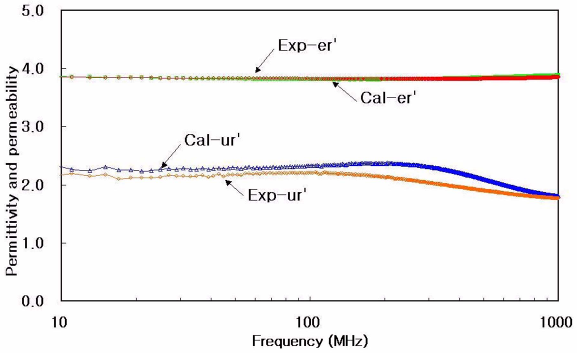


Fig. 4. Measured and calculated properties of MDCM (ferrite 40 wt. %).

These results suggest that a composite of the two constituents is in good agreement. Thus, we should be able to predict the properties of the composites by correlating equations and measurements.

4. CONCLUSIONS

Low values of magneto-dielectric composite materials were studied with various weight fractions and ferrite particle sizes. We found these to be useful for antenna in low values of electromagnetic properties through simulation. Ni-Zn spinel ferrite has an application frequency of 150 MHz for antennas. Its loss tangent$_u$, in particular, increases nearly exponentially from 80 MHz. The problem of magnetic loss was overcome by creating a polymer composite (silicon elastomer). The composite material (ferrite 40 wt. % loaded sample) demonstrated higher operating frequencies. Then, this material was modified by particle size distribution. The magneto-dielectric composite material with smaller particle sizes was more useful in antennas because of its lower values of permittivity and permeability, loss tangent$_e$ and loss tangent$_u$, plus its higher operating frequency.

ACKNOWLEDGMENT

This work was supported by the ATC center program of MKE. (10031490, Design of a compact antenna using magnetic and dielectric composite materials for mobile handset applications).

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