Complex Permeability Spectra of Permendur Composite Materials

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Abstract. Complex permeability $\mu'$ and permittivity $\varepsilon'$ spectra of permendur (Co₅₀Fe₅₀) composite materials have been studied in the microwave frequency range considering the application to the left-handed meta-materials and EMC devices. High surface electrical resistance of the permendur particles was achieved by the heat-treatment in order to suppress the eddy current effect in the high particle content composites. For the 82.6 vol.% composite, the $\mu'$ is 11 and less than 1 at 100 MHz and 6 GHz, respectively; the $\mu''$ shows the two peaks around 700 MHz and 3 GHz due to the domain wall and gyromagnetic spin resonance. On the other hand, the $\varepsilon'$ is almost constant value of 28 and the $\varepsilon''$ is almost zero in the frequency range from 100 MHz to 6 GHz. The calculated reflection loss of a single-layer electromagnetic wave absorber (EM absorber) designed by using permendur composites indicates less than -20 dB around the matching frequency of 1 GHz.

1. Introduction

The left-handed meta-materials (LHM), which have simultaneously negative permeability and permittivity (DNG) in the microwave frequency range, have been the subject of considerable interest [1, 2]. We have been studying the possibility of the LHM using the frequency dispersion of permeability in ferromagnetic metal composite materials combined with the permittivity spectrum of the metal wire array composite structure (WAC) [3, 4]. Though soft ferromagnetic metal composites have relatively high permeability in the low frequency region, the permeability rapidly decreases with increasing frequency due to the eddy current effect [5]. We have shown that a heat-treatment of particles is effective to suppress the eddy current effect in the complex permeability spectra of Permalloy (Ni₈₀Fe₂₀) composite materials and a negative permeability was observed in the microwave frequency range [4].

In this work, we have studied the complex permeability and permittivity spectra of permendur composite materials having heat-treated particles in the microwave frequency range with and without the external DC magnetic field. The possibility of the LHM and the microwave absorption characteristics of the single layer EM absorber using permendur composites will be discussed.
2. Experimental
Commercially available Co_{50}Fe_{50} spherical powder was used for permendur composite materials. Particle diameter was examined by a scanning electron microscopic (SEM); the mean particle diameter $d_m$ was 2.08 $\mu$m. Permendur particles were heat-treated in air using an electric furnace at the 300 ºC for 5 hours in order to make the oxidized surface layer and suppress the eddy current effect in the composite structure.

Permendur composite materials were prepared by mixing permendur powder with Polyphenylene Sulfide (PPS) resin powder. This mixture was heated at 300 ºC for 30 minutes to melt the resin then pressed at a pressure of about 32 MPa in the cooling process down to room temperature. Obtained samples were cut into a toroidal form with 3 mm inner diameter and 7 mm outer diameter. The sample thickness was controlled about 1 mm in order to avoid the dimensional resonance of the electromagnetic wave in a coaxial line. The electrical resistance of the heat-treated powder was measured by a two terminal method using a coaxial electrode and an impedance analyzer.

Complex permeability and permittivity spectra were measured by the S-parameter method in the frequency range from 100 MHz to 6 GHz using a network analyzer. Complex permeability spectra under the external DC magnetic field were obtained by the coaxial line technique in the frequency range from 100 kHz to 3.8 GHz using a network analyzer. The external DC magnetic field was generated by an electromagnet up to 14.1 kOe, and the static field was applied perpendicular to the measuring alternative magnetic field.

3. Results and Discussion
Figure 1 shows the complex permeability spectra ((a) real and (b) imaginary parts) of permendur composite materials at the several particle contents. The real part $\mu'$ of the 82.6 vol.% composite is about 11 at 100 MHz and decreases with increasing frequency and has the value of less than 1 at 6 GHz. The $\mu'$ at 100 MHz decreases with decreasing particle content. In each composite, negative permeability was not observed in the measurement frequency range. On the other hand, the $\mu''$ of the 82.6 vol.% composite shows the two peaks around 700 MHz and 3 GHz. These peaks shift to higher frequency with decreasing particle content.

Complex permeability spectra ((a) real and (b) imaginary parts) of the 82.6 vol.% composite

![Figure 1](image-url)
material under the external DC magnetic field are shown in Fig. 2. When the external magnetic field increases, the $\mu'$ value at 100 MHz decreases and the $\mu''$ peak around 700 MHz also decreases and vanishes. On the other hand, the $\mu''$ peak around 3 GHz shifts to higher frequency and becomes sharp with increasing the external magnetic field. In the previous study, we reported complex permeability for permalloy (Ni$_{45}$Fe$_{55}$) composites as a function of applied the external magnetic field [5]. In generally, the frequency dispersion of permeability can be characterized by the superposition of the domain wall and the gyro-magnetic spin resonance. For permeability of permalloy composites under the external magnetic field, the domain wall contribution decreases and finally vanishes with increasing the external magnetic field. In contrast, the spin contribution becomes dominant and dispersion character of permeability becomes the resonance type, which has a steep frequency dispersion of permeability, under high magnetic field. Considering this behavior of permeability for permalloy composites, the two peaks around 700 MHz and 3 GHz in the $\mu''$ of permendur composites correspond to the domain wall and the gyro-magnetic spin resonance, respectively, and the decrease of the $\mu'$ value with increasing the external magnetic field is attributed to the decrease of domain wall contribution. Further, permalloy composite with high particle content has negative permeability above 5 GHz [4]. This is attributed to that permalloy has comparatively large magnetic anisotropy field [5].

In Mn-Zn ferrite, the domain wall contribution in permeability vanishes and a resonance type frequency dispersion of permeability appears under the external magnetic field below 1 kOe [6]. On the other hand, in permeability of the 82.6 vol.% permendur composites under the external field, the domain wall contribution is maintained at 3.7 kOe as shown in Figure 2. This suggests that permendur has comparatively large anisotropy field and high particle content composites can make a negative permeability in microwave frequency range. From above results, investigations for the permeability dispersion in higher frequency region are required.

Figure 3 shows complex permittivity spectra of permendur composites having the different particle content in the frequency range from 100 MHz to 6 GHz. At each content, the $\varepsilon'$ is almost constant and the $\varepsilon''$ is almost zero in the measurement frequency range. This indicates that these composites have insulating property; the eddy current effect in composite structure can be suppressed by heat-treatment of permendur particles. The value of the $\mu'$ at 100 MHz is 28 in 82.6 vol.% composite and decreases with decreasing particle content in composites.
Figure 4 shows the calculated reflection loss of the single-layer microwave absorber using permendur composites as a function of frequency. The solid line indicates the -20 dB i.e. the absorption of 99% of the microwave power. A matching frequency $f_m$ and a matching thickness $d$ were determined in the condition that the reflection loss indicated the minimum value. For the 67.0 vol.% composite, the $f_m$ locates at 0.8 GHz with the $d$ of 7.6 mm. On the other hand, the 45.6 vol.% composite shows the matching at 1.6 GHz with the $d$ of 7.6 mm. Thus permendur composite absorbers show the microwave absorption characteristics around 1 GHz.

4. Conclusions

Complex permeability and permittivity spectra of permendur composite materials containing heat-treated particles have been studied in the microwave frequency range with and without the external DC magnetic field. For the 82.6 vol.% composite, the frequency dispersion of permeability by the domain wall and the gyro-magnetic spin resonance was observed around 700 MHz and 3 GHz, respectively. The negative permeability was not obtained up to 6 GHz in all composites. Complex permittivity spectra of permendur composites indicated the insulating property. In the single-layer EM wave absorbers using permendur composites, impedance matching can be obtained in the frequency range from 0.8 to 1.6 GHz. For further investigations, the study of complex permeability and permittivity spectra of permendur composites in higher frequency region are now in progress.

References

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