Design of Composite Electromagnetic Wave Absorber Made of Soft Magnetic Materials Dispersed and Isolated in Polystyrene Resin

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Abstract—Composite electromagnetic wave absorbers made of a soft magnetic material (permalloy or sendust) and polystyrene resin were investigated. The volume mixture ratio of magnetic material was varied in the range from 18 vol% to 75 vol%. The composites with the low volume mixture ratio of soft magnetic material absorbed more than 99% of electromagnetic wave power in the frequency range from 1 GHz to 12 GHz. The values of the real part $\mu_r'$ of the relative complex permeability $\mu_r^*$ for both magnetic materials were less than unity at frequencies above approximately 6 GHz as the volume mixture ratio of magnetic material increased. This result suggests the possible realization of an electromagnetic wave absorber that can operate above 10 GHz.

1. INTRODUCTION
Electromagnetic waves with frequencies higher than 1 GHz are now more widely used for communication with the increasing use of telecommunication devices such as mobile phones. In the case of electric toll collection (ETC) systems, their operating frequency will increase from 5.8 GHz to more than 10 GHz in the future. Therefore, the development of an electromagnetic wave absorber suitable for these frequency bands is required.

The purpose of this study is to investigate the design of a practical composite absorber that operates in a wide frequency range above 1 GHz. The composite absorber consists of soft magnetic material particles, such as permalloy or sendust, and polystyrene resin. Both permalloy and sendust satisfy Snoek's limit at high frequencies [1] and have high permeability values in the frequency range above 1 GHz. These characteristics make it possible to fabricate an electromagnetic wave absorber suitable for this frequency band [2, 3]. In addition, it is expected that the composite materials have values of $\mu_r'$, the real part of the relative complex permeability $\mu_r^*$, of less than unity, because in qualitative theoretical calculations it has been predicted that the $\mu_r'$ has to be less than unity for a constant relative dielectric constant $\varepsilon_r'$. This characteristic allows electromagnetic wave absorption above 10 GHz. These soft magnetic materials, however, have high electric conductivity. Thus, if the number of particles of such a magnetic material dispersed in the resin, such as polystyrene, exceeds the percolation threshold, magnetic particles will be in direct contact with each other and the average conductivity $\sigma$ of the composite will increase markedly. Eventually, the reflection coefficient of the electromagnetic wave reflected by the composite will increase and the absorption characteristics will be degraded [4]. To prevent the increase in $\sigma$, we attempt to disperse and isolate the magnetic particles in the polystyrene resin so that they are not in contact with each other. To isolate the magnetic particles, the surface of each magnetic particle is coated with very fine polystyrene particles of less than approximately 1 $\mu$m diameter, which is less than that (approximately 20 $\mu$m diameter) of the magnetic particles.

2. EXPERIMENTS
Chips of polystyrene resin of approximately 200 $\mu$m diameter were ground with ethanol by mechanical milling (MM) (Fritsch, P7) using a zirconia pot and zirconia balls of 1 mm diameter for 1.5 h. The rotation speed of the turntable was 600 rpm. The ratio of the rotation speeds of the milling pot to the turntable was 2:1. Permalloy (Ni 45%, Fe 55%) particles (grain type, average grain size of approximately 10 $\mu$m) or sendust (Al 5%, Si 10%, Fe 85%) particles (flake type, average grain size of approximately 20 $\mu$m) and ground polystyrene particles (average grain size of approximately 1 $\mu$m) were then mixed by MM for 30 min to coat the particles of the magnetic material with the polystyrene particles. After mixing, the powder mixture was heated to melt the polystyrene resin then hot-pressed at a pressure of 5 MPa into a pellet shape. Then, the pellet was cooled naturally.
to room temperature and processed to a toroidal-core shape (outer diameter of 7 mm and inner diameter of 3.04 mm) for use in a 7 mm coaxial line or to a rectangular shape (22.8 mm × 10.16 mm) for use in a waveguide at the X-band (8.2 GHz to 12.4 GHz). The sample was loaded into a coaxial line or rectangular waveguide while ensuring that there was no gap between the coaxial line or rectangular waveguide and the toroidal-core sample. The complex scattering matrix elements, $S_{11}^*$ (reflection coefficient) and $S_{21}^*$ (transmission coefficient) were measured using a vector network analyzer (Agilent Technology 8722ES) by the full-two-port or one-port reflection method. The values of $\mu_r^*$ ($\mu_r^* = \mu_e' - j\mu_e''$, $j = \sqrt{-1}$) and the relative complex permittivity ($\varepsilon_r^* = \varepsilon_e' - j\varepsilon_e''$) were calculated from the data of both $S_{11}^*$ and $S_{21}^*$. The return loss $R$ for various sample thicknesses was calculated from the complex reflection coefficients $\Gamma^*$ using the relation $R = 20 \log_{10} |\Gamma^*|$.  

3. RESULTS AND DISCUSSION

3.1. Dispersion State of Magnetic Material Particles and the Conductivity of Composite Materials

Surface optical microphotographs of the composites made of permalloy or sendust are shown in Fig. 1. Each particle of the magnetic material was surrounded by polystyrene resin even if the volume mixture ratio of the magnetic material exceeded the percolation threshold of 33 vol%, as shown in Fig. 1. This is because very fine polystyrene particles coated the surface of each particle of the magnetic material and melted polystyrene resin entered between the particles of the magnetic material. The values of $\varepsilon_r''$ increased gradually for both composite with the volume mixture of the magnetic material, even when it exceeded the percolation threshold. These results show that the particles of the magnetic material are isolated from each other and that the composites have a low value of $\sigma$.

![Surface optical micro-photographs of composites: (a) 75 vol% permalloy and (b) 57 vol% sendust.](image)

3.2. Frequency Dependence of $\mu_e'$ and Absorption Characteristics

Figures 2 and 3 show the frequency dependences of $\mu_e'$ and $\mu_e''$ for the composites made of permalloy or sendust, respectively. In this study, a qualitative theoretical calculation was performed to investigate the absorption in the frequency range above 1 GHz. The measured values of $\mu_r^*$ for the composites made of permalloy or sendust and the calculated values of $\mu_r^*$ that satisfy the non-reflective condition Equation (1) are shown in Figs. 4 and 5, respectively [5].

$$1 = \sqrt{\mu_r^*/\varepsilon_r^*} \tanh \left( \gamma_0 d \sqrt{\mu_r^*/\varepsilon_r^*} \right) \tag{1}$$

Here, $\gamma_0$ is the propagation constant in free space and $d$ is the sample thickness. The value of $\varepsilon_e'$ used for calculation was independent of frequency and the same as the measured value. $\varepsilon_e''$ was assumed to be zero. The measured values of $\mu_e'$ for the composite made of 33 vol% permalloy roughly agreed with the calculated values for $d = 3$ and 4 mm, as shown in Fig. 4, and those for the composite made of 25 vol% sendust almost agreed with the calculated values for $d = 4$ mm, as shown in Fig. 5, in the frequency range from 1 GHz to 10 GHz. On the other hand, the plots of the measured values of $\mu_e''$ for the the composite made of 33 vol% permalloy intersected the calculated line near 6 GHz for $\varepsilon_e' = 10$ and $d = 3$ mm, and those for the composite made of 25 vol% sendust intersected the calculated line near 5 GHz for $\varepsilon_e' = 10$ and $d = 4$ mm, as shown in Figs. 4 and 5. Therefore, it is expected that the absorption of a large amount of electromagnetic wave power occurs at approximately 6 GHz and $d = 3$ mm for the composite made of 33 vol% permalloy and
at approximately 5 GHz and \( d = 4 \) mm for the composite made of 25 vol% sendust, as shown in Fig. 6. Fig. 6 shows the absorption center frequency \( f_0 \) and the normalized \(-20\) dB bandwidth (the bandwidth corresponding to the return loss of \(-20\) dB is divided by \( f_0 \)) of each composite. The value of \(-20\) dB corresponds to the absorption of 99% of the electromagnetic wave power. The composites made of permalloy or sendust showed a return loss of less than \(-20\) dB for the optimum \( d \) value and the bandwidth was approximately 10%. Furthermore, the sample thickness for which the return loss becomes less than \(-20\) dB was relatively thin compared with that of commercial absorbers. In particular, the composites made of sendust have some advantages over those made of permalloy because sendust contains no rare metals such as Ni and the mass density of the composites made of sendust is very small. For example, the mass density is approximately 1.5 for the composite made of 18 vol% sendust and approximately 1.8 that of 33 vol% sendust.

To investigate the absorption at frequencies near 10 GHz, the values of \( \mu^r \) and \( \varepsilon^r \) for the composite made of 25 vol% sendust were measured by the reflection method using the rectangular waveguide at X-band frequencies because the accuracy of measurement was poor using the coaxial line due to the generation of higher-order modes. The frequency dependences of the return loss at X-band frequencies for the composite made of 25 vol% sendust are shown in Fig. 7. The absorbing center frequency \( f_0 \) increases from 8.5 GHz to 11.6 GHz as the sample thickness decreases from 2 mm to 1.5 mm. \( f_0 \) varies markedly over the narrow range of sample thickness as the frequency becomes higher than 8 GHz. The return loss was less than \(-20\) dB near 11.6 GHz for the sample thickness of 1.5 mm, as shown in Fig. 7, and the bandwidth was approximately 6%. Therefore, the composite made of 25 vol% sendust can also be used as an electromagnetic wave absorber in the frequency range above 10 GHz.

The composites made of permalloy or sendust showed values of \( \mu^r \) of less than unity at frequencies above approximately 6 GHz as the volume mixture ratio of magnetic material increased, as shown in Figs. 2 and 3. It is speculated that this phenomenon is due to magnetic moments generated by
an eddy current flowing on the surface of the particles of the magnetic material. Soft magnetic material is generally conductive and the skin depth $\delta$ of soft magnetic material, which is given by Equation (2), is less than the radius of the soft magnetic material particles at frequencies above approximately 5 GHz.

$$\delta = \sqrt{\frac{2\rho}{\omega\mu_0\mu_r}} \quad (2)$$

Here, $\omega$ is the angular frequency and $\rho$ is the resistivity. For example, $\delta$ for this permalloy is
estimated to be 3.1 μm at 5 GHz because the resistivity of the permalloy is $2 \times 10^{-7}$ Ωm [6] and it decreases in proportion to $1/\sqrt{\omega}$. The eddy current flows in the layer of skin depth $\delta$ on a magnetic material particle and generates a magnetic moment antiparallel to incident magnetic field. Consequently, the value of $\mu'_r$ is reduced and sometimes becomes less than unity. This result suggests the possibility of electromagnetic wave absorption above 10 GHz, because Equation (1) indicates that the values of $\mu'_r$ should be less than unity in the high-frequency region. The values of $1 - \mu'_r$ for various volume mixture ratios of permalloy and sendust are shown in Fig. 8. $1 - \mu'_r$ increased with the increase in the volume mixture ratio of magnetic material. In particular, $1 - \mu'_r$ for sendust was roughly proportional to the volume mixture ratio above 25 vol%. This result indicates that the effect of the magnetic moments generated by the eddy current becomes dominant as the amount of magnetic material increases. To examine this phenomenon, composites made of aluminum particles having a grain size of approximately 80 μm and polystyrene resin were prepared. Fig. 9 shows the values of $1 - \mu'_r$ for various volume mixture ratios of aluminum. $1 - \mu'_r$ increased proportional to the volume mixture ratio of aluminum particles. Although the grain size and skin depth of the aluminum particles are different from those of the magnetic material particles, a similar result to the composites made of permalloy or sendust was observed in the composites made of aluminum. Therefore, it is speculated that the reason why the values of $\mu'_r$ become less than unity may be qualitatively explained by magnetic moment generated by the eddy current.

For the composite with a volume mixture ratio of 75 vol% permalloy, the measured values of $\mu'_r$ almost agreed with the calculated values at frequencies from approximately 8 GHz to 20 GHz for $\varepsilon'_r = 60$ and $d = 1$ mm, as shown in Fig. 4(a). On the other hand, the measured values of $\mu''_r$ agreed with the calculated values only at approximately 3.5 GHz. Therefore, the composites with a high volume mixture ratio of permalloy did not show a return loss of less than $-20$ dB in the measured frequency range. A similar result was obtained for the composites with a high volume mixture ratio of sendust. However, it is speculated from Figs. 4 and 5 that the lines showing the frequency dependence of the measured values of $\mu''_r$ may intersect the calculated lines at a frequency above 10 GHz, which is outside the range of the measurement, because $\mu''_r$ rapidly decrease in the high-frequency range. Therefore, it may be possible to show a return loss of less than $-20$ dB at frequencies above 10 GHz. Investigations of the absorption in this high-frequency range is now in progress.
4. CONCLUSIONS

Composites with a low volume mixture ratio of soft magnetic material showed a return loss of less than $-20\,\text{dB}$ in the frequency range from 1 GHz to 12 GHz. It is concluded that these composites are suitable for use in practical electromagnetic wave absorbers in the frequency range used for ETC systems or mobile phones.

The values of $\mu'_r$ for composites with a high volume mixture ratio of soft magnetic material were less than unity in the frequency range above approximately 6 GHz, and the absorption of electromagnetic wave power at frequency range above 10 GHz is expected.

REFERENCES