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Composite electromagnetic wave absorber made of soft magnetic material and polystyrene resin and control of permeability and permittivity

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Abstract

The frequency dependences of the relative complex permeability μ_r^*, the relative complex permittivity ε_r^* and the absorption characteristics for composite electromagnetic wave absorbers made of polystyrene resin and sendust particles or permalloy particles were investigated in the frequency range from 1 to 40 GHz. The size of sendust particles was varied between approximately 5 and 20 μm and the particle size dependence of μ_r^* was observed. The value of μ_r^* was shown to be controlled by adjusting the particle size of sendust, and an electromagnetic wave absorber with a flexible design was proposed. A metal-backed single-layer absorber made of sendust particles or permalloy particles absorbed more than 99% of electromagnetic wave power at frequencies above 20 GHz. In addition, a composite made of 5 μm particles exhibited a return loss of less than −20 dB in the frequency range of not only several GHz but also above 30 GHz.

Keywords: Composites; Magnetic properties; Electromagnetic wave absorber; Soft magnets; Hot pressing

1. Introduction

Electromagnetic waves with frequencies higher than 1 GHz are increasingly widely used for telecommunication devices, and the frequencies used for these devices will shift to the high-frequency range of above 10 GHz in the future. Therefore, the development of an electromagnetic wave absorber suitable for these frequency bands is necessary. To design an absorber, the control of the frequency dependences of the relative complex permeability μ_r^* and the relative complex permittivity ε_r^* is important because the absorption of an electromagnetic wave is determined by μ_r^* and ε_r^*. Therefore, the frequency dependences of μ_r^*, ε_r^* and the absorption characteristics for a composite made of a soft magnetic material such as permalloy or sendust dispersed in an insulating matrix have been investigated.[1–3] The fabrication of an absorber made of a metamaterial, for which μ_r^* and ε_r^* can be controlled, has been reported.[4] It has also been reported that a composite made of a soft magnetic material dispersed in an insulating matrix can be used as the metamaterial, and the value of μ_r', the real part of μ_r^*, for this composite was less than unity.[2] This characteristic makes it possible to absorb 99% of the power of an electromagnetic wave at frequencies above 10 GHz because μ_r' must be less than unity to satisfy the absorption condition at these frequencies. In addition, the material used for absorbers should be low-cost and available in large quantities to avoid the problem of worldwide resource depletion. Sendust is a low-cost material because it does not contain any rare metals such as Ni, hence it is more suitable for use in an absorber than other soft magnetic materials.

In this study, the frequency dependences of μ_r^*, ε_r^* and the absorption characteristics for a composite made of sendust particles or permalloy particles dispersed in polystyrene resin were evaluated in the frequency range from 1 to 40 GHz. In particular, the frequency dependence of μ_r^* and the absorption characteristics at frequencies above 10 GHz are mainly discussed. The particle size of sendust was varied, and the effects of the particle size on the frequency dependences of μ_r^*, ε_r^* and the absorption characteristics were investigated. If the values of μ_r^* and ε_r^* can be controlled by a parameter such as the particle size, it will be possible to design an absorber of electromagnetic waves of any frequency with good absorption characteristics. Therefore, the mechanism of the frequency dependence of μ_r^* is also discussed in this paper.

2. Experimental method

Commercially available sendust (Al 5%, Si 10%, Fe 85%) particles and permalloy (Ni 45%, Fe 55%) particles were used.

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The sendust and permalloy particles were spherical. The particle shapes and the compositions of sendust and permalloy were confirmed by scanning electron microscope (SEM) and energy-dispersive X-ray spectrometry (EDX). The average particle size (diameter) of the permalloy particles was approximately 10 μm and that of sendust particles was approximately 5, 10 or 20 μm. Chips of polystyrene resin were dissolved in acetone. The dissolved polystyrene resin and sendust or permalloy were mixed to uniformly disperse and isolate the soft magnetic material particles. The volume mixture ratio of sendust and permalloy was 53 vol.%. After mixing, the mixture was heated to melt the polystyrene resin and was then hot-pressed at a pressure of 5 MPa into a pellet. Then, the pellet was cooled naturally to room temperature and processed into a toroidal-core shape (with an outer diameter of approximately 7 mm and an inner diameter of approximately 3 mm) for use in a 7 mm coaxial line in the frequency range from 50 MHz to 12.4 GHz, or into a rectangular shape (P-band: 12.4–18 GHz, 15.80 mm × 7.90 mm, K-band: 18–26.5 GHz, 10.67 mm × 4.32 mm, R-band: 26.5–40 GHz, 7.11 mm × 3.56 mm) for use in a waveguide. The sample was loaded into the coaxial line or rectangular waveguide while ensuring that there was no gap between the walls of the coaxial line or the rectangular waveguide and the processed sample. To eliminate the gap, silver paste was pasted on inner and outer surface of the toroidal-core shaped sample, and both up and down sides of the rectangular shaped sample. The complex scattering matrix elements S_{11}^* (reflection coefficient) and S_{21}^* (transmission coefficient) for the TEM mode (coaxial line) or TE_{10} mode (rectangular waveguide) were measured using a vector network analyzer (Agilent Technology, 8722ES) by the full-two-port method. The values of $\mu_r^* (\mu_r^* = \mu_r' - j\mu_r'',\quad j = \sqrt{-1})$ and $\varepsilon_r^* (\varepsilon_r^* = \varepsilon_r' - j\varepsilon_r'')$ were calculated from the data of both S_{11}^* and S_{21}^*. The complex reflection coefficient Γ^* for a metal-backed single-layer absorber was then calculated from the values of μ_r^* and ε_r^*. The return loss R for each sample thickness was calculated from the complex reflection coefficient Γ^* using the relation $R = 20 \log_{10} |\Gamma^*|$.

3. Results and discussion

3.1. Frequency dependences of μ_r^* and ε_r^* for the composites made of sendust particles of various sizes or permalloy particles

Figs. 1 and 2, respectively show the frequency dependences of μ_r' and μ_r'' for the composites made of sendust particles of various sizes or permalloy particles. At frequencies below 10 GHz, the value of μ_r' for all composites decreased with increasing frequency. The value of μ_r' was largest for the composite made of sendust particles of approximately 10 μm diameter and followed by those with particles of approximately 20 and 5 μm diameter (hereafter, the word "diameter" is omitted). The values of μ_r'' for all composite increased with increasing frequency and were maximum in the frequency range from 1 to 3 GHz. As shown in Fig. 2(a), the frequency at which μ_r'' was maximum increased as the sendust particle size decreased. The same phenomena have been reported for a composite made of amorphous alloy particles, and it is considered that the difference in the frequency dependence of μ_r^* for the composites made of sendust particles of various sizes is due to the dispersion of the sendust particles.[3,5,6] The scattering of an electromagnetic wave in the composite depends on the dispersion of the sendust particles; thus, the frequency dependence of μ_r^* is different for each particle size. The frequency dependences of μ_r' and μ_r'' for the composite made of permalloy were similar to those of sendust particles, although the values of μ_r' and μ_r'' were larger as shown in Figs. 1(a) and 2(a), respectively.

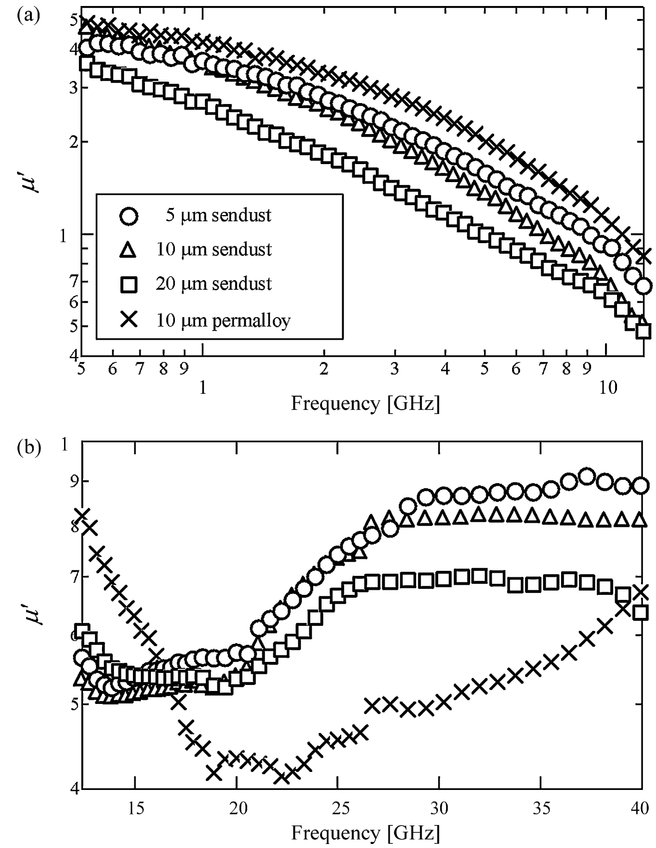

Fig. 1. Frequency dependence of μ_r' for composites made of polystyrene resin and sendust particles of various sizes or permalloy particles.

At frequencies above 10 GHz, the values of μ_r' for the composites made of sendust were minimum in the frequency range from 12 to 20 GHz then increased with increasing frequency. The minimum values of μ_r' for the composites made of 5, 10 and 20 μm particles were almost the same, approximately 0.5. However, it was found from Fig. 1(b) that the frequency at which μ_r' for the composite made of sendust particles of 20 μm was minimum was higher than that for 5 μm particles. In addition, the value of μ_r' for the composite made of sendust particles of 5 μm approached approximately 0.9 with increasing frequency, while the values of μ_r' for the composites made of sendust particles of 10 and 20 μm approached approximately 0.81 and 0.7, respectively. The values of μ_r'' for the composites made of sendust decreased with increasing frequency and were minimum in the frequency range from 20 to 25 GHz. μ_r'' for the composite made of sendust particles of 10 and 20 μm increased as the frequency increased although the value of μ_r'' for the composite made of

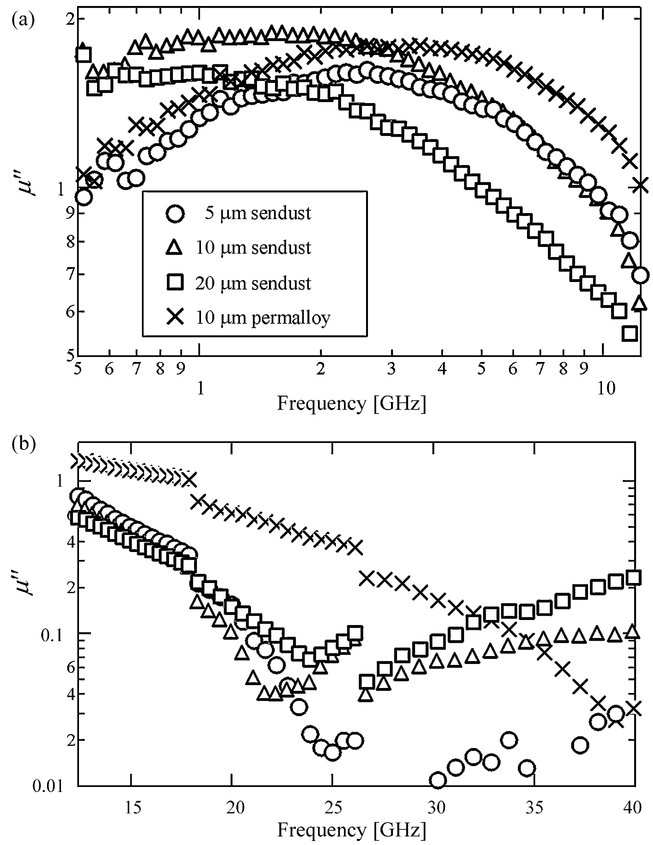

Fig. 2. Frequency dependence of μ_r'' for composites made of polystyrene resin and sendust particles of various sizes or permalloy particles.

sendust particles of 5 μm was almost zero. Meanwhile, different frequency dependences of μ_r' and μ_r'' were observed in the composite made of permalloy. Although the value of μ_r' was minimum near 22 GHz, its value was small and the frequency at which μ_r' was minimum was higher than that for the composites made of sendust. Furthermore, the value of μ_r'' decreased with increasing frequency up to 40 GHz and was larger than that for the composites made of sendust. This is because the magnetic properties of permalloy are different from those of sendust, and the response of the electromagnetic wave to the composite varies with the magnetic material. Therefore, a different frequency dependence of μ_r^* was observed for different magnetic materials. It was concluded from the above results that the frequency dependences of μ_r' and μ_r'' depend on the sendust particle size and the soft magnetic material used. This result indicates that the values of μ_r' and μ_r'' can be controlled by adjusting the particle size of sendust or by selecting a suitable soft magnetic material.

The values of ε_r' and ε_r'' decreased as the particle size of sendust decreased. This is because the sendust particles were more likely to be isolated from each other in the polystyrene resin as the particle size decreased. The values of ε_r' for all composite were fairly constant with frequency and the values of ε_r' measured at 10 GHz for composites made of sendust particles of 5, 10 and 20 μm were 16, 18 and 19, respectively. The values of ε_r' and ε_r'' for the composite made of permalloy were almost the same as those for the composite made of sendust particles of 5 μm.

3.2. Effect of magnetic moments generated by the eddy current on the complex permeability

To explain the frequency dependence of μ_r^*, two reasons can be considered. The first reason is the natural magnetic resonance of soft magnetic materials. Soft magnetic materials have a resonance frequency in the frequency range from several hundred MHz to GHz, and the resonance frequency of a composite is higher than that of a pure magnetic material. The value of μ_r' decreases rapidly near the resonance frequency, becomes less than unity then increases as the frequency increases. Thus, the values of μ_r' for the composites made of soft magnetic materials are less than unity and increase as the frequency increases far from the resonance frequency. The other reason is the generation of magnetic moments by the eddy current flowing on the surface of soft magnetic material particles, because soft magnetic materials are conductive. The phenomenon that the value of μ_r' becomes less than unity has also been observed in composites made of polystyrene resin and conductive particles such as aluminum.

Next, the effect of aluminum particles on the complex permeability is qualitatively described. The skin depth δ of a metal for an electromagnetic wave is

$$\delta = \sqrt{\frac{2}{\omega\sigma\mu_0\mu_{Mr}'}}. \tag{1}$$

Here ω is the angular frequency of the electromagnetic wave, σ is the conductivity of the metal, μ_0 is the permeability in a vacuum and μ_{Mr}' is the real part of the complex relative permeability of the metal. The skin depth of aluminum, which is from 2.6 to 0.8 μm in the frequency range from 1 to 10 GHz, is less than the diameter (approximately 8 μm) of the aluminum particles used for experiments. Therefore, the eddy current flows in the range from the surface of the aluminum particles to the skin depth and generates a magnetic field in each aluminum particle. The dimensionless magnetic susceptibility of aluminum is very small (2.1×10^{-5}) and μ_{Mr}' is approximately 1. However, in the high-frequency range, the real part of the complex relative permeability of an aluminum particle is less than unity because the magnetic field inside the aluminum particle is cancelled by the magnetic field generated by the eddy current.

To simplify the discussion, the shape of an aluminum particle is approximated as a cylinder of radius a and length $2a$. As shown in Fig. 3, a model in which current flows in the outer skin in a metal cylinder shell of thickness δ (equivalent to the skin depth) is used.[7] Here $\delta \ll a$. In a vacuum, for an incident magnetic field strength of H_0 parallel to the central axis of the cylinder, the eddy current density is defined as J. Although the length of the cylinder is finite, we assume that J is uniform in the cylindrical shell. Thus, a uniform magnetic field H' parallel to the cylindrical central axis is generated by J. H' is given by Ampere's circuital law as

$$H' = \delta J. \tag{2}$$

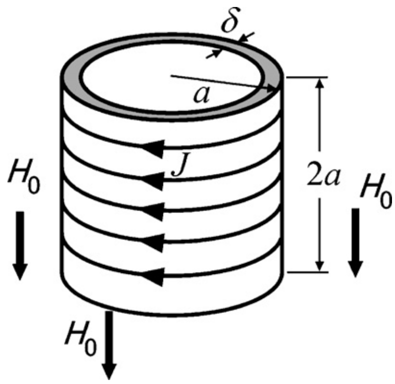

Fig. 3. Model of magnetic moment with eddy current in thin metallic cylindrical shell.

Therefore, the magnetic field H' inside the cylindrical shell is given by

$$H' = H_0 + \delta J. \tag{3}$$

Because no magnetic field exists inside the cylindrical shell owing to the skin effect, the following equation is obtained from Eq. (3).

$$H_0 + \delta J = 0. \tag{4}$$

Therefore, J is given by

$$J = -\frac{H_0}{\delta}. \tag{5}$$

Therefore, the direction of the eddy current is opposite that shown in Fig. 3. The magnetic moment m generated by J is given by

$$m = 2\pi a^3 \delta J = -2\pi a^3 H_0. \tag{6}$$

The direction of m is opposite that of H_0. If $2a$ is constant, the particle number N of aluminum particles per unit volume of the composite is given by

$$N = -\frac{V}{2\pi a^3}. \tag{7}$$

Here V is the volume mixture ratio of the aluminum particles in the composite. If it is assumed that the direction of all magnetic moments is the same and that the eddy current loss is zero, the magnetization M is given by

$$M = -VH_0. \tag{8}$$

M is independent of the frequency and the particle size of the aluminum particles according to Eq. (8). Also, the following relation holds between the average magnetic flux density B and the magnetization M in the composite when M is proportional to H_0.

$$M = \left(\frac{B}{\mu_0}\right) - H_0 = (\mu_r^* - 1)H_0 = (\mu_r' - 1 - j\mu_r'')H_0 \tag{9}$$

Here $\mu_r^* = \mu_r' - j\mu_r''$ is the complex relative permeability of the composite. μ_r'' is attributed to the eddy current loss. The following equation is obtained from Eqs. (8) and (9).

$$1 - \mu_r' = V \tag{10}$$

The value of $1 - \mu_r'$ is independent of the frequency, is proportional to V and is between 0 and 1. The Joule loss P, caused by the eddy current loss, per unit volume of the composite is

$$P = N\frac{1}{2}(4\pi a^2 \delta)\frac{J^2}{\sigma} = \frac{VH_0^2}{a}\sqrt{\frac{2\omega\mu_0}{\sigma}}. \tag{11}$$

Therefore, for small values of V, μ_r'' is given by

$$\mu_r'' = \mu_r' \frac{P}{\omega(1/2)\mu_r'\mu_0 H_0^2} = \frac{2V}{a}\sqrt{\frac{2}{\omega\sigma\mu_0}} = \frac{2V\delta}{a}. \tag{12}$$

The value of μ_r'' increases proportionally to V and is inversely proportional to a and the square root of the frequency. The above qualitative results are expected to be applicable to spherical aluminum particles.

3.3. Mechanism of the frequency dependence of μ_r^* for the composites made of sendust or permalloy

To investigate the reasons for the frequency dependence of μ_r^*, the values of μ_r' and μ_r'' for the composites made of aluminum or nickel particles dispersed in the polystyrene resin were measured. The average size of aluminum particles was approximately 8 μm and the size of nickel particles was between 10 and 20 μm. The volume mixture ratio of aluminum and nickel was 50 vol.%. The resistivities of aluminum and nickel were 2.66×10^{-8} and 6.84×10^{-8} Ω m, respectively. From these values, the skin depths δ of aluminum and nickel particles are estimated to be approximately 2.6 and 4.2 μm at 1 GHz, respectively. Thus, the eddy current flows on the surface of aluminum and nickel particles. Aluminum is a paramagnetic material and is conductive. Therefore, the effect of magnetic moments generated by the eddy current is clearly observed in the composite made of aluminum. On the other hand, the effects of both the magnetism and the magnetic moments generated by the eddy current are observed in the composite made of nickel, because nickel is a magnetic material and is conductive. Figs. 4 and 5, respectively show the frequency dependences of μ_r' and μ_r'' for the composites made of aluminum, nickel or sendust particles of 20 μm. The line in Fig. 4 shows the value of μ_r' calculated from Eq. (10) for $V = 0.5$ and that in Fig. 5 shows the value of μ_r'' calculated from Eq. (12) for the composite made of aluminum ($V = 0.5$, $\mu_{Mr}' = 1$, $a = 4$ μm). The calculated values of μ_r'' for the composites made of nickel and sendust are not shown in Fig. 5 because the values of μ_{Mr}' for pure nickel and sendust have not been obtained. The value of μ_r' for the composite made of aluminum was approximately 0.7 at 1 GHz and decreased gradually with increasing frequency. This phenomenon is explained as follows. The eddy current flows in the layer of thickness δ on an aluminum particle and generates a magnetic moment antiparallel to the incident magnetic field. Consequently, the value of μ_r' is reduced and becomes less than unity. Moreover, the value of μ_r'' decreased with increasing frequency and roughly agreed with the value calculated from Eq. (12) as shown in Fig. 5. The value

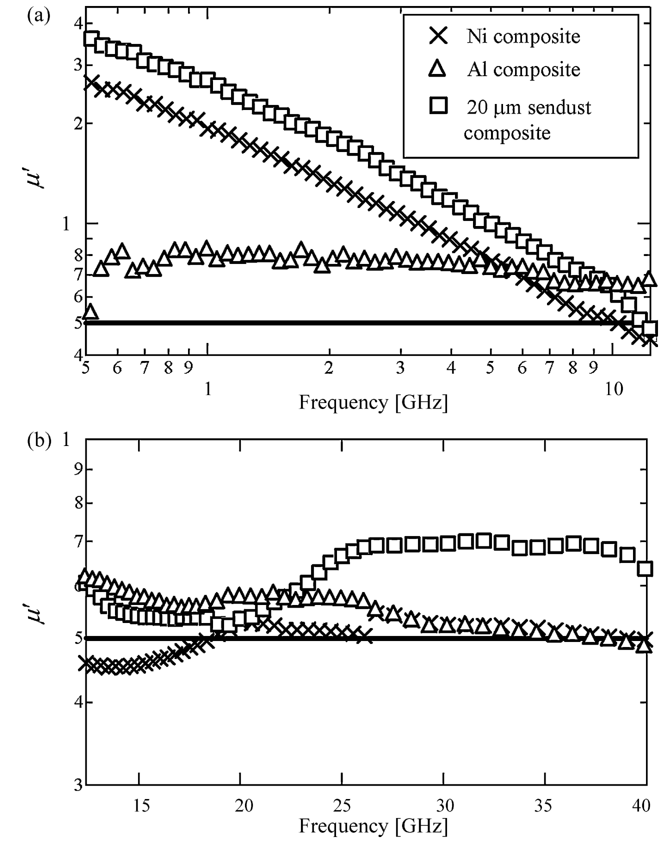

Fig. 4. Frequency dependence of μ_r' for composites made of aluminum, nickel and sendust particles of 20 μm. The line shows the values calculated from Eq. (10) for $V = 0.5$.

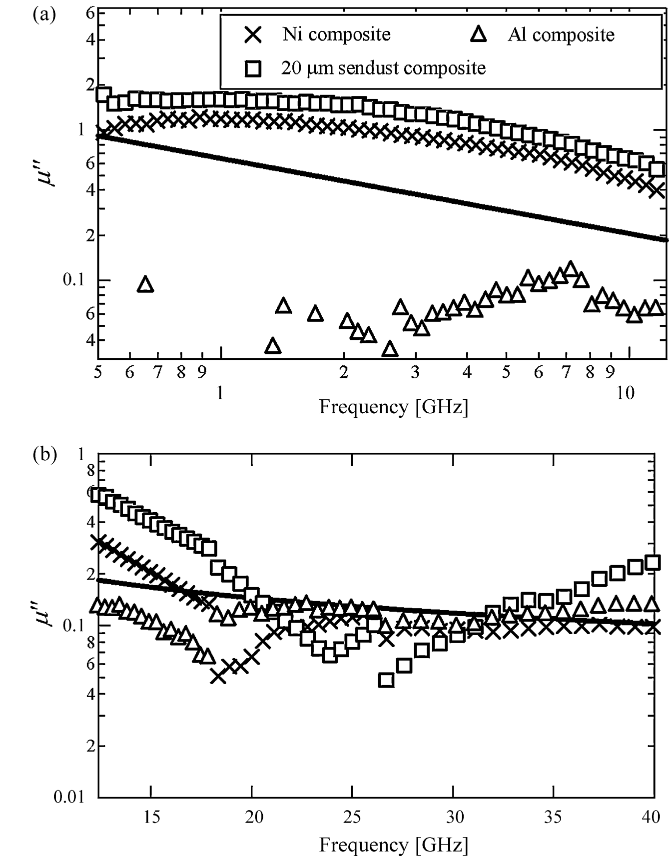

Fig. 5. Frequency dependence of μ_r'' for composites made of aluminum, nickel and sendust particles of 20 μm. The line shows the values calculated from Eq. (12) for 50 vol.% aluminum.

of μ_r' for the composite made of nickel decreased in the low-frequency range, was minimum near 14 GHz then increased with increasing frequency up to 20 GHz. μ_r'' for this composite was maximum near 1 GHz and decreased with increasing frequency. These frequency dependences of μ_r' and μ_r'' for the composite made of nickel are similar to those for the composite made of sendust as, respectively shown in Figs. 4 and 5. It is speculated that the similarity of the frequency dependence of μ_r^* between the composite made of nickel and that made of sendust is because both nickel and sendust are magnetic. Therefore, the frequency dependence of μ_r^* for the composite made of sendust can be explained by the natural magnetic resonance of sendust. However, the value of μ_r' for the composite made of nickel decreased at frequencies above 20 GHz and approached 0.5. This decrease resembles the decrease in μ_r' for the composite made of aluminum, and the value to which it approached almost agreed with that obtained from Eq. (10). In addition, the value of μ_r'' for the composite made of nickel roughly agreed with that for the composite made of aluminum at frequencies above 20 GHz. These results indicate that the effect of the magnetic moment generated by the eddy current is dominant in the high-frequency range because the effect of natural magnetic resonance is reduced as the frequency increases far from the resonance frequency. As shown in Fig. 1(a), the values of μ_r' for the composites made of sendust are less than unity and are almost constant at frequencies above 25 GHz. This frequency dependence almost agrees with that obtained for the composite made of nickel although the value of μ_r' is larger than that for the composite made of nickel. From these results, it is speculated that the frequency dependence of μ_r' for the composite made of sendust in the high-frequency range is due to the magnetic moments generated by the eddy current. Thus, the value of μ_r' in the high-frequency range can be controlled by the volume mixture ratio as given by Eq. (10). However, the values of μ_r'' for the composites made of sendust particles of 10 and 20 μm increased with increasing frequency at frequencies above 26 GHz and also increased with the particle size. These results are different from those obtained from Eq. (12). Therefore, another reason for the frequency dependence of μ_r^* in the high-frequency range must be considered in addition to the magnetic moments generated by the eddy current.

3.4. Absorption characteristics of composites made of sendust or permalloy

The frequency dependence of the return loss in free space was calculated from the measured values of μ_r^* and ε_r^* for all composites. The absorber used for the calculation was a metal-backed single-layer absorber and the incident electromagnetic wave was perpendicular to the surface. The return loss was calculated

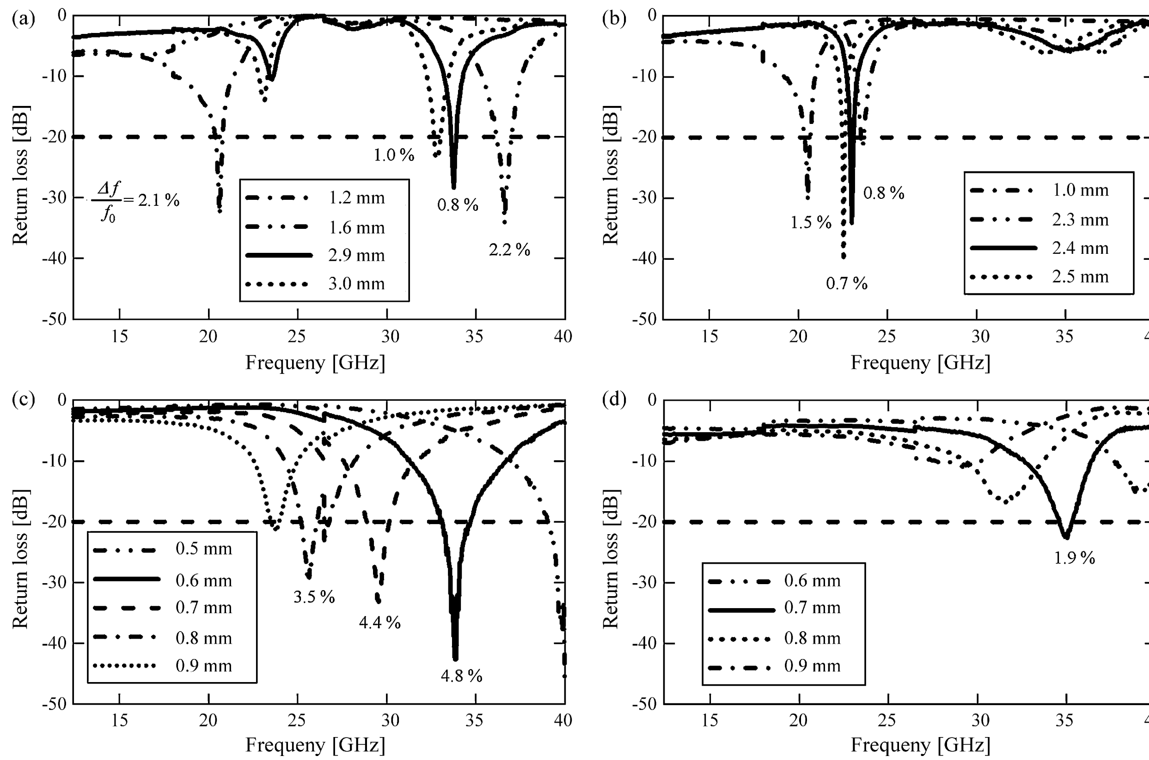

Fig. 6. Frequency dependences of return loss for composites made of sendust particles of 5, 10 or 20 μm or permalloy particles of 10 μm. (a) Sendust particles of 5 μm, (b) sendust particles of 10 μm, (c) sendust particles of 20 μm and (d) permalloy particles of 10 μm.

at 0.1 mm intervals in the sample thickness range 0.1–30 mm. Fig. 6 shows the frequency dependences of the return loss for composites made of permalloy particles or sendust particles of various sizes. The percentages shown in the graphs represent the normalized −20 dB bandwidth (the bandwidth Δf corresponding to the return loss of less than −20 dB divided by the absorption center frequency f_0). The value of −20 dB corresponds to the absorption of 99% of the electromagnetic wave power. As shown in Fig. 6(a), (b) and (c), the absorption characteristics for the composites made of sendust particles of various sizes were different. This is because the frequency dependences of μ_r^* and ε_r^* varied with the particle size of sendust as discussed previously. These four composites had a return loss of less than −20 dB in the frequency range from 20 to 40 GHz. In particular, the normalized −20 dB bandwidth for the composite made of sendust particles of 20 μm was broad, and the sample thickness for which the return loss was less than −20 dB was low compared with that for other composites. Moreover, it was found from Fig. 6(c) that the return loss for the sample thickness of 0.5 mm was less than −20 dB near 40 GHz. Thus, the absorption of a large amount of electromagnetic wave power is expected at frequencies above 40 GHz for the composite made of sendust particles of 20 μm. Furthermore, the composite made of sendust particles of 5 μm exhibited a return loss of less than −20 dB for the sample thickness of 4 mm at frequencies below 10 GHz. f_0 was 2.5 GHz and the normalized −20 dB bandwidth was approximately 15%. It was found that the composite made of sendust particles of 5 μm can operate in the frequency range of not only several GHz but also above 30 GHz.

3.5. *Comparison of the measured values of μ_r^* with the calculated values of μ_r^* that satisfy the nonreflective condition*

To examine the absorption characteristics in the frequency range from 12.4 to 40 GHz, the measured values of μ_r^* for the composite made of sendust particles of 20 μm and the calculated values of μ_r^* for different sample thicknesses that satisfy the nonreflective condition given by Eq. (13) are shown in Fig. 7.[8]

$$\sqrt{\frac{\mu_r^*}{\varepsilon_r^*}}\tanh(\gamma_0 d\sqrt{\mu_r^*\varepsilon_r^*}) = 1 \tag{13}$$

Here γ_0 is the propagation constant in free space and d is the sample thickness. The value of ε_r' used for calculation is independent of frequency and is the same as the measured value ($\varepsilon_r' = 19$). ε_r'' is assumed to be zero. As shown in Fig. 7(a), the measured values of μ_r' roughly agreed with the calculated values near 29 and 34 GHz for the sample thicknesses of 0.7 and 0.6 mm, respectively. On the other hand, the calculated lines for d = 0.7 and 0.6 mm intersected the measured values of μ_r'' near 31 and 35 GHz, respectively, as shown in Fig. 7(b). Therefore, the absorption of a large amount of electromagnetic wave power occurred at approximately 29 and 34 GHz as shown in Fig. 6(c). It was found from Fig. 7 that the values of μ_r' and μ_r'' must decrease with increasing frequency to satisfy the nonreflective condition. If these frequency dependences of μ_r' and μ_r'' can be obtained, absorption with a wide bandwidth is expected because the nonreflective condition is satisfied over a wide frequency

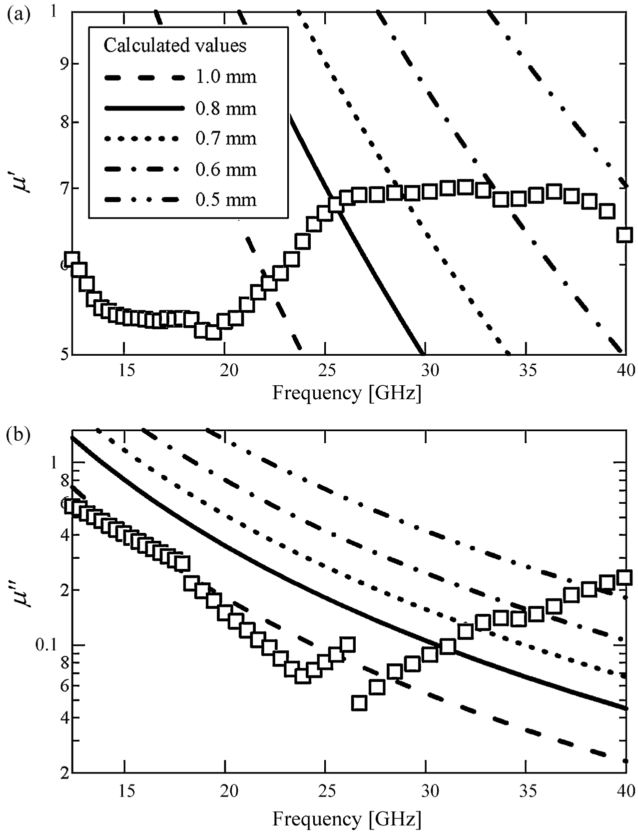

Fig. 7. Measured and calculated values of (a) μ_r' and (b) μ_r''. Plots show measured values for the composite made of sendust particles of 20 μm and lines show μ_r' and μ_r'' required for a perfectly matched absorber with metal backshort for a range of thicknesses calculated using Eq. (13). Therefore, the intersections identify the frequencies at which the absorber will give minimum return loss. (a) Real part and (b) imaginary part.

range. As shown in Fig. 2(b), the value of μ_r'' for the composites made of sendust decreased with increasing frequency below 25 GHz and that for the composite made of permalloy decreased with increasing frequency up to 40 GHz. Furthermore, it was found from Fig. 7(b) that the decreasing ratio of μ_r'' is in agreement with the calculated values. In particular, the calculated values for the sample thickness of 1 mm almost agreed with the measured values in the frequency range from 12.4 to 20 GHz. In contrast, the values of μ_r' only satisfied the nonreflective condition for the sample thickness of 1 mm near 22 GHz as shown in Fig. 7(a). Therefore, the composite made of sendust particles of 20 μm did not exhibit a return loss of less than −20 dB for the sample thickness of 1 mm. However, the value of μ_r' can be controlled by the particle size or the volume mixture ratio of sendust particles as discussed above. Therefore, we can adjust the value of μ_r' to satisfy the nonreflective condition and realize an absorber with a wide bandwidth.

4. Conclusions

The composites made of sendust or permalloy exhibited a return loss of less than −20 dB in the frequency range from 25 to 40 GHz. It was found that the frequency dependence of μ_r^* can be controlled by the particle size of sendust, the volume mixture ratio or the soft magnetic material, and an electromagnetic wave absorber with a flexible design was proposed for frequencies above 10 GHz.

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