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Composite Electromagnetic Wave Absorber Made of Soft Magnetic Material Particle and Metal Particle Dispersed in Polystyrene Resin

Kenji Sakai, Norizumi Asano, Yoichi Wada,
Yang Guan, Yuuki Sato and Shinzo Yoshikado
Doshisha University
Japan

1. Introduction

The development of an electromagnetic wave absorber suitable for frequencies higher than 1 GHz is required with the increasing use of wireless telecommunication systems. Moreover, new wireless telecommunication devices will be developed owing to the advances in the information and telecommunication field in the future. For this reason, electromagnetic wave absorber suitable for these new devices is required, especially at frequencies above 10 GHz. In this chapter, we deal with a metal-backed single-layer absorber that has a low cost and is easy to fabricate. To design a metal-backed single-layer 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 both μ_r^* and ε_r^*. In particular, μ_r', the real part of μ_r^*, must be less than unity to satisfy the non-reflective condition of electromagnetic wave for a metal-backed single-layer absorber at frequencies above 10 GHz. Therefore, the frequency dependences of μ_r^*, ε_r^*, and the absorption characteristics of a composite made of a soft magnetic material dispersed in an insulating matrix have been investigated ([a]Kasagi et.al., 1999; Lim et. al., 2005; Song et. al., 2005). However, the frequency dependences of μ_r' and μ_r'', the imaginary part of μ_r^*, has not been investigated at frequencies above 10 GHz.
Thus, for the purpose of designing electromagnetic wave absorbers with good absorption properties at frequencies above 10 GHz, the frequency dependences of μ_r^*, ε_r^*, and the return loss were investigated for the composite made of particles of soft magnetic material dispersed in polystyrene resin in the frequency range from 100 MHz to 40 GHz. Soft magnetic material used in this study is sendust (an alloy of Al 5%, Si 10%, and Fe 85%), because sendust is a low-cost material and does not contain any rare metals and sendust is suitable for use in a practical absorber. In addition, the frequency dependences of μ_r^*, ε_r^*, and the return loss of the composite made of permalloy (an alloy of Ni 45%, Fe 55%) were also investigated for the comparison. Both sendust and permalloy have high permeability values in the frequency range above 1 GHz. This characteristic makes it possible to fabricate an electromagnetic wave absorber suitable for this frequency band. Moreover, the values of μ_r' for the composite made of sendust or permalloy dispersed in polystyrene resin are expected to be less than unity because of the natural magnetic resonance and magnetic moment

	Sendust [vol%]	Aluminum [vol%]
Composite A	25	25
Composite B	12.5	37.5
Composite C	10	40

Table 1. The volume mixture ratios of the composites made of sendust and aluminum particles.

generated by the induced eddy current ([b]Kasagi et.al., 2006). This characteristic allows electromagnetic wave absorption at frequencies exceeding 10 GHz because μ_r' must be less than unity for a constant relative dielectric constant ε_r' and the composite made of soft magnetic material dispersed in polystyrene resin has constant value of ε_r'.
Furthermore, a composite electromagnetic wave absorber that can adjust the absorption characteristics by controlling μ_r' and μ_r'' are discussed in this chapter. The frequency dependence of μ_r^* for the composite made of soft magnetic material and polystyrene resin is similar to that required to satisfy the non-reflective condition. Therefore, the absorption with a wide frequency is expected if an optimum frequency dependence of μ_r^* can be obtained. However, the frequency dependence of μ_r^* is determined by the magnetic property, such as magnetic anisotropy. Thus, flexible control of the frequency dependence of μ_r^* is difficult using the composite made of a soft magnetic material and polystyrene resin.
Meanwhile, it has been reported that the composite made of metal particles, such as aluminum particles, dispersed in polystyrene resin can control the values of both μ_r' and μ_r'' by the volume mixture ratio and the size of metal particle, and can be used as an electromagnetic wave absorber (Nishikata, 2002; Sakai et. al., 2008). In particular, the value of μ_r' for the composite made of aluminum and polystyrene becomes less than unity. Thus, the frequency where the absorption of electromagnetic waves occurs can be controlled by adjusting μ_r' and μ_r''. However, the values of μ_r' and μ_r'' for this composite are almost independent of frequency, hence the non-reflective condition is satisfied in a narrow frequency range and the bandwidth of absorption is narrow. From above results, if both soft magnetic material and metal particles are dispersed in polystyrene resin, the frequency dependence of μ_r^* is expected to be controlled flexibly so that the non-reflective condition is satisfied. Therefore, the frequency dependences of μ_r^*, ε_r^*, and the absorption characteristics of a composite made of both sendust and aluminum particles dispersed in polystyrene resin were also evaluated and the flexible design of an electromagnetic wave absorber is discussed.

2. Experiment

Commercially available sendust (Al 5%, Si 10%, Fe 85%) particles and permalloy (Ni 45%, Fe 55%) particles were used. The sendust and permalloy particles were granular. The compositions of sendust and permalloy were confirmed using a 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 μm. For the composite made of both sendust and aluminum particles dispersed in polystyrene resin, commercially available aluminum particles of approximately 8 μm were used. The volume mixture ratios of sendust and aluminum particles for the composite made of both sendust and aluminum particles are shown in Table 1.

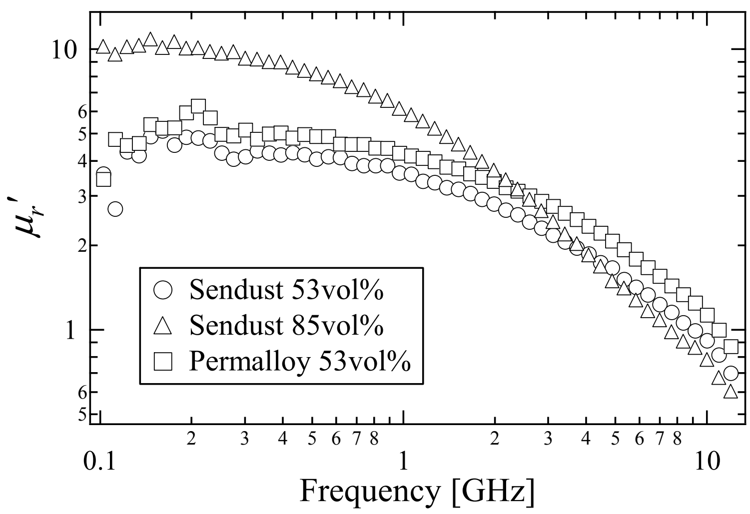
Chips of polystyrene resin were dissolved in acetone. The dissolved polystyrene resin and sendust or permalloy particles were mixed to uniformly disperse and isolate the particles. After mixing, the mixture was heated to melt the polystyrene resin and was then hot-pressed at a pressure of 5 MPa into a pellet. This was allowed to cool naturally to room temperature and was processed into a toroidal-core shape (outer diameter of approximately 7 mm, inner diameter of approximately 3 mm) for use in a 7 mm coaxial line in the frequency range 100 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 mounted inside the coaxial line or waveguide using silver past to ensure that no gap existed between the sample and the walls of the line/waveguide.

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 in the frequency range from 100 MHz to 40 GHz. The values of μ_r^* ($\mu_r^* = \mu_r' - j\mu_r''$, $j = \sqrt{-1}$) and ε_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 determined from the values of μ_r^* and ε_r^*. The return loss R for each sample thickness was calculated from Γ^* using the relation $R = 20 \log_{10}|\Gamma^*|$. R was calculated at 0.1 mm intervals in the sample thickness range 0.1 to 30 mm.

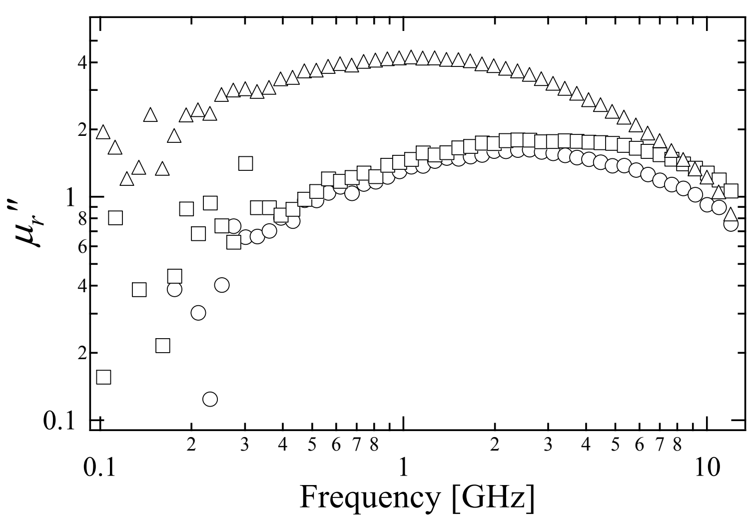
3. Results and discussion

3.1 Frequency dependences of μ_r^* and ε_r^* for the composite made of soft magnetic material dispersed in polystyrene resin

Figure 1 shows the frequency dependences of μ_r' and μ_r'' for the composite made of sendust or permalloy particles dispersed in polystyrene resin. The values of μ_r' decreased gradually with increasing frequency and became less than unity at frequencies around 10 GHz. The values of μ_r'' increased with increasing frequency, had maximum at frequencies of several GHz and decreased. As seen in Figs. 1(a) and (b), frequency dependences of μ_r' and μ_r'' for the composite made of sendust were similar to those for the composite made of permalloy. This result indicates that the magnetic property of the composite made of sendust or permalloy in the GHz range was almost the same. On the other hand, the values of both μ_r' and μ_r'' increased and the shape of frequency dependences of μ_r' and μ_r'' were different when the volume mixture ratio of sendust increased. This is because the amount of magnetic material increased and the response of the incident magnetic field changed. The variation of the frequency dependences of μ_r' and μ_r'' by the volume mixture ratio of magnetic material suggests that the absorption characteristics can be adjusted for the desired frequency range by simply changing the volume mixture ratio of magnetic material. However, when the amount of magnetic material increased or decreased, the values of ε_r' and ε_r'' increased or decreased, as shown in Fig. 2.



(a) μ_r'

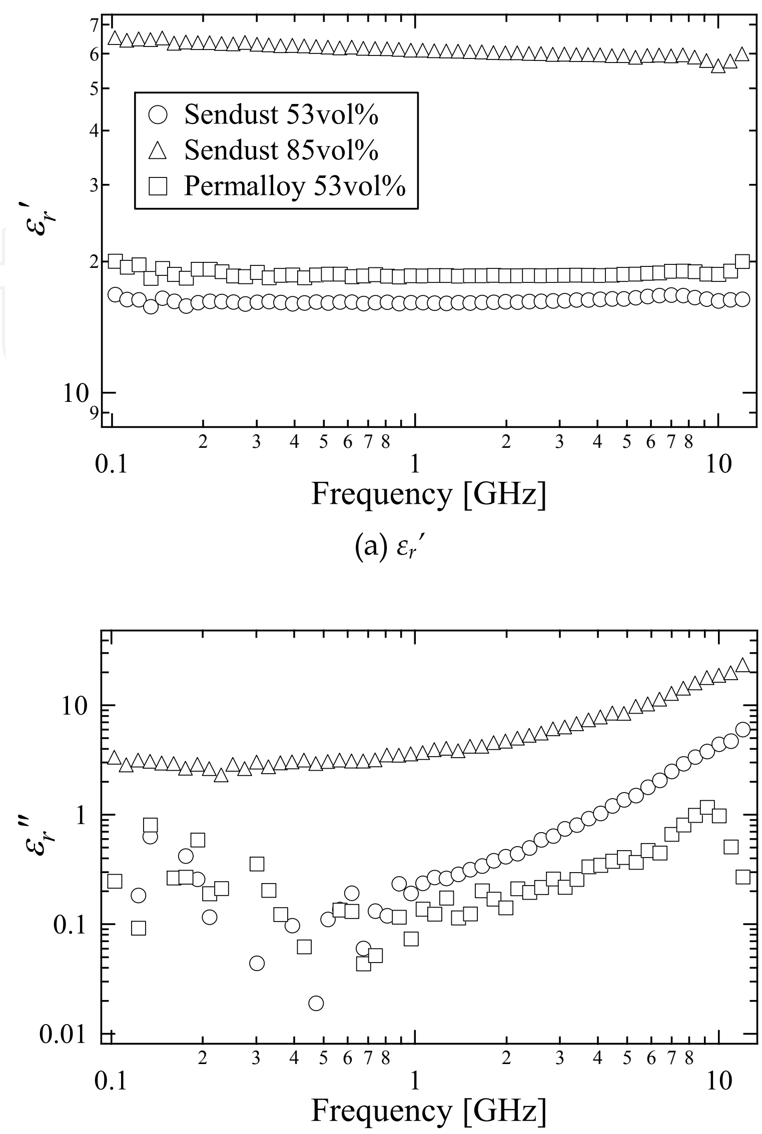


(b) μ_r''

Fig. 1. Frequency dependences of μ_r' and μ_r'' for composites made of sendust or permalloy particles dispersed in polystyrene resin.

Figure 2 shows the frequency dependences of ε_r' and ε_r'' for the composite made of sendust or permalloy particles dispersed in polystyrene resin. Although, the values of ε_r' and ε_r'' for the composite made of sendust were similar to those for the composite made of permalloy when the volume mixture ratio of sendust and permalloy is the same, both ε_r' and ε_r'' increased markedly for the composite made of 85 vol%-sendust particles. Therefore, the increase or decrease in ε_r' and ε_r'' should be considered to design an absorber when the volume mixture ratio of magnetic material is varied.

To investigate the difference of frequency dependences of μ_r^* and ε_r^* for various magnetic materials, nickel and ferrite particles were dispersed in polystyrene resin and the frequency dependences of μ_r^* and ε_r^* were evaluated in the frequency range from 100 MHz to 40 GHz.

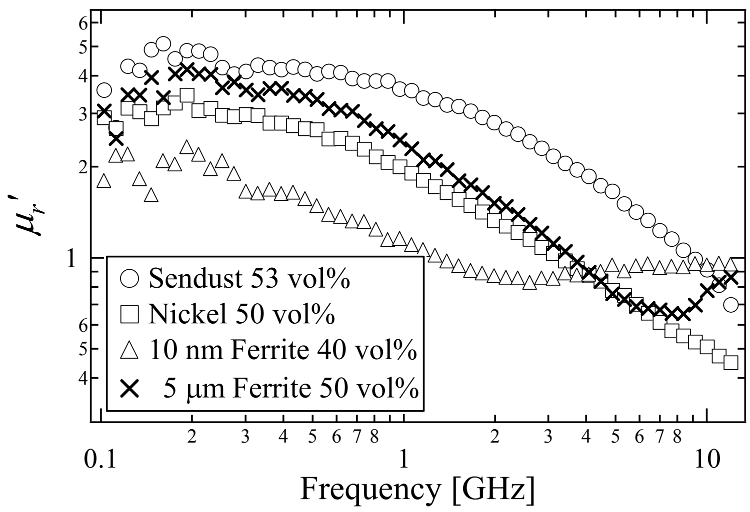


(a) ε_r'

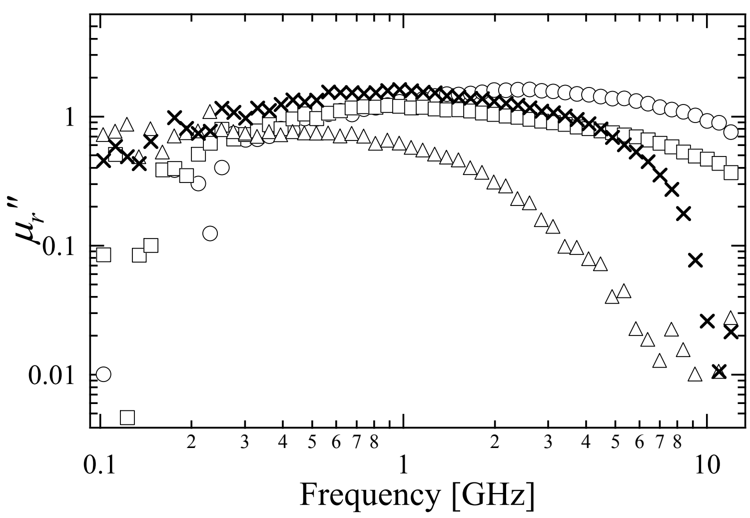
(b) ε_r''

Fig. 2. Frequency dependences of ε_r' and ε_r'' for composites made of sendust or permalloy particles dispersed in polystyrene resin.

The average particle size of nickel was between 10 and 20 μm and that of ferrite was 5 μm and 10 nm. The volume mixture ratio of nickel particles and ferrite particles of 5 μm was 50 vol%. Ferrite particles of 10 nm were difficult to disperse uniformly in polystyrene resin with increasing the amount of ferrite. Thus, the volume mixture ratio of ferrite particles of 10 nm was 40 vol% where the ferrite particles could be dispersed uniformly. Figures 3 and 4 show the frequency dependences of μ_r' and μ_r'' for the composite made of various magnetic materials. As shown in Fig. 3, the frequency dependences of μ_r' and μ_r'' for the composite made of ferrite particles of 10 nm were considerably different from those of other composite. It is speculated that the particle size of magnetic material affects the frequency dependences of μ_r' and μ_r'' because ferrite particles of 10 nm is much smaller than other magnetic material particles. The frequency dependences of μ_r' and μ_r'' for the composite made of sendust, nickel, or ferrite of 5 μm were similar. However, for the composite made of sendust, the



(a) μ_r'

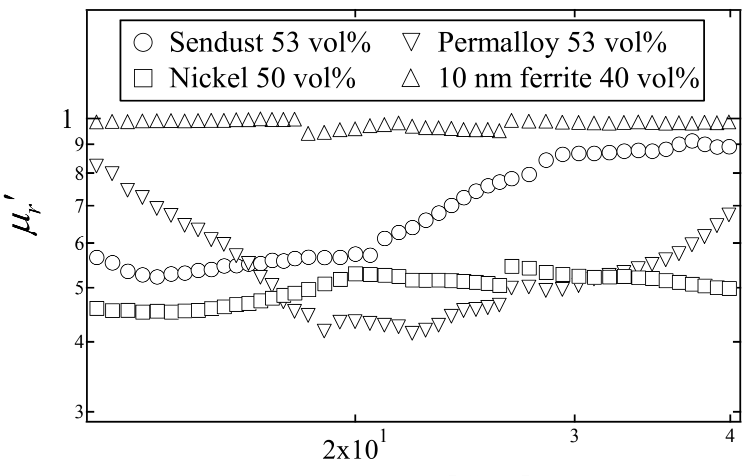


(b) μ_r''

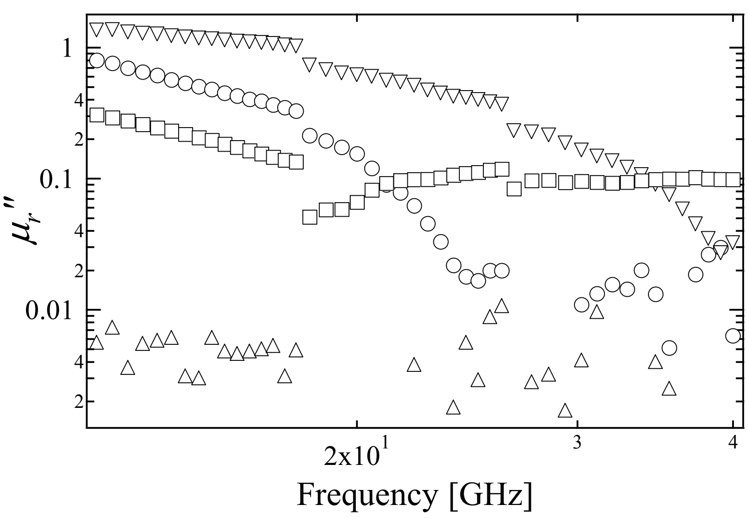
Fig. 3. Frequency dependences of μ_r' and μ_r'' for composites made of sendust, nickel or ferrite particles dispersed in polystyrene resin. The frequency range is from 100 MHz to 12.4 GHz.

frequency where μ_r' begins to decrease and μ_r'' is maximum was higher than that of other composites. This result is speculated to be the property that sendust and permalloy have high permeability values in the high frequency range.

On the other hand, in the high frequency range, the composite made of sendust, permalloy, nickel, or 10 nm-ferrite showed different frequency dependences of μ_r' and μ_r'', as shown in Figs. 4(a) and (b). For the composite made of 10 nm-ferrite, the values of μ_r' was almost 1 and μ_r'' was almost zero. This result suggests that the composite made of 10 nm-ferrite has no magnetic response to the incident electromagnetic wave of high frequency. However, the values of μ_r' for the composite made of nickel was minimum near 15 GHz and increased up to 20 GHz. Then, μ_r' decreased with increasing frequency. Moreover, the values of μ_r'' decreased up to 20 GHz and increased with increasing frequency. These frequency dependences of μ_r' and μ_r'' are different from those for the composite made of ferrite



(a) μ_r'

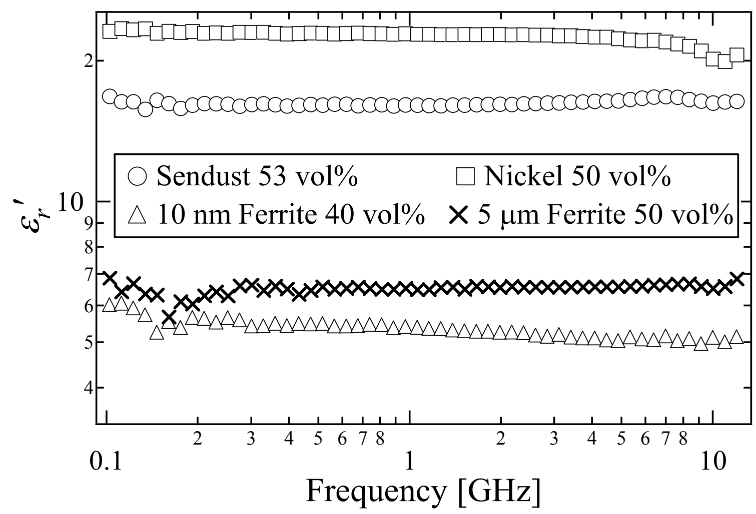


(b) μ_r''

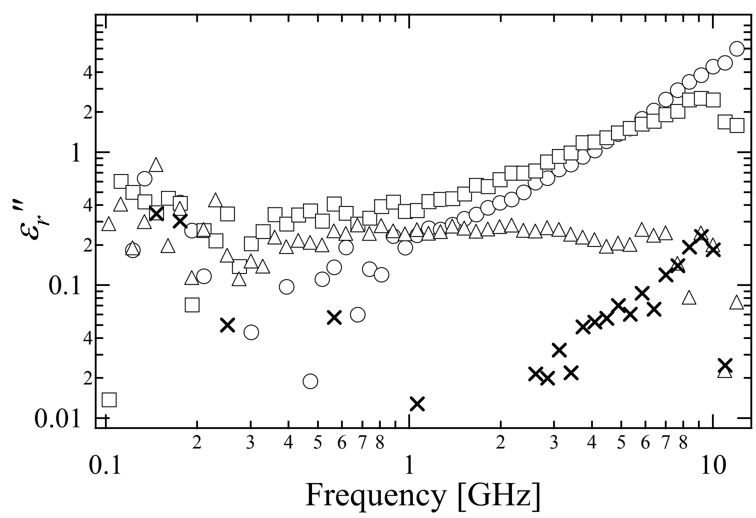
Fig. 4. Frequency dependences of μ_r' and μ_r'' for composites made of sendust, nickel or ferrite particles dispersed in polystyrene resin. The frequency range is from 12.4 to 40 GHz.

although nickel and ferrite are magnetic material. These differences are speculated to be as follows.

Nickel is a magnetic material and is conductive. The resistivity of nickel was 6.84×10^{-8} Ωm and the skin depth δ of nickel is estimated to be approximately 1.3 μm at 1 GHz. Thus, the eddy current flows on the surface of nickel particles when an electromagnetic wave of high frequency enters inside nickel particle. We have reported that this phenomenon was observed in the composite made of aluminum particles dispersed in polystyrene resin (Sakai et. al., 2008). Thus, the effects of both the natural magnetic resonance caused by the magnetism and the magnetic moments generated by the eddy current are observed in the composite made of nickel. In particular, the effect of natural magnetic resonance on μ_r' and μ_r'' caused by the magnetism of nickel decreases as the frequency increases far from the resonance frequency and the effect of magnetic moment is dominant in the high frequency



(a) ε_r'

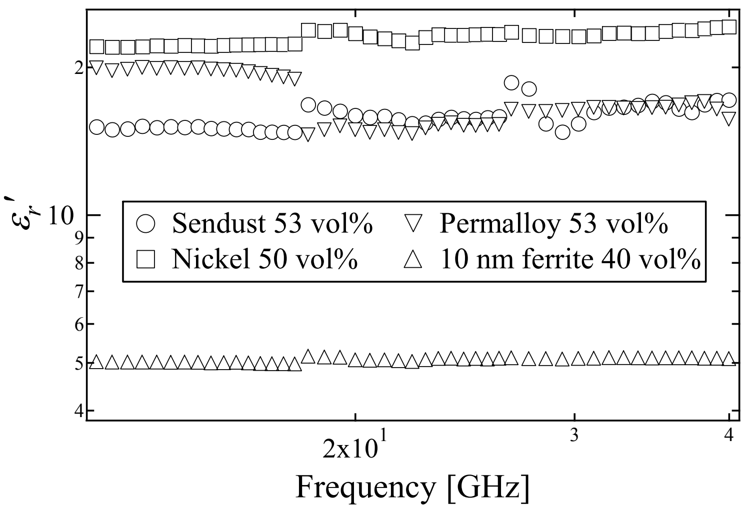


(b) ε_r''

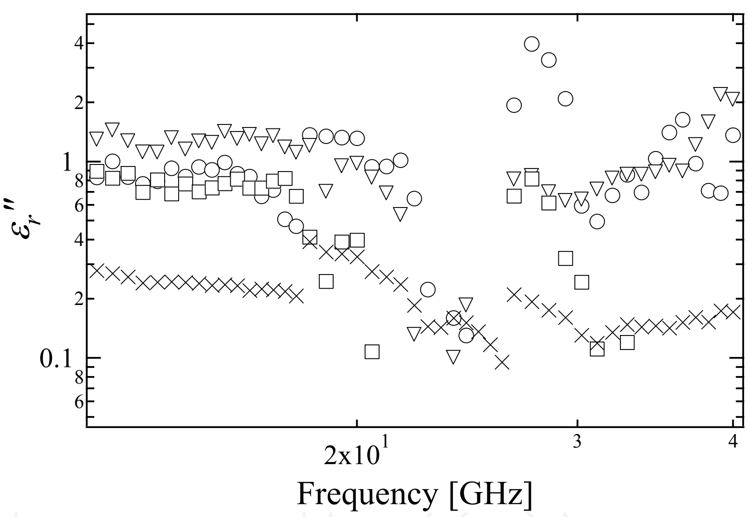
Fig. 5. Frequency dependences of ε_r' and ε_r'' for composites made of sendust, nickel or ferrite particles dispersed in polystyrene resin. The frequency range is from 100 MHz to 12.4 GHz.

range. Therefore, the composite made of nickel had different frequency dependences of μ_r' and μ_r'' in the high frequency range.

The values of μ_r' for the composite made of sendust were minimum near 13 GHz, increased gradually, and were almost a constant value of 0.9. Moreover, μ_r'' decreased with increasing frequency and was almost constant or fractional increase in the high frequency range, as shown in Fig. 4(b). A similar frequency dependences of μ_r' and μ_r'' were obtained for the composite made of permalloy. These frequency dependences for the composite made of sendust or permalloy are similar to those for the composite made of nickel and the mechanism of the frequency dependences of μ_r' and μ_r'' is speculated to be explained by the same reason as that of nickel composite because sendust and permalloy are conductive. The above results indicate that an absorber which can operate at frequencies above 10 GHz is



(a) ε_r'



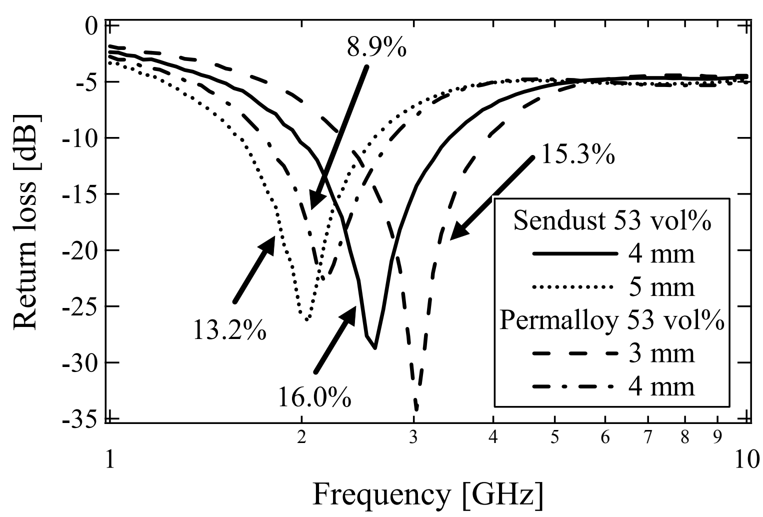
(b) ε_r''

Fig. 6. Frequency dependences of ε_r' and ε_r'' for composites made of sendust, nickel or ferrite particles dispersed in polystyrene resin. The frequency range is from 12.4 to 40 GHz.

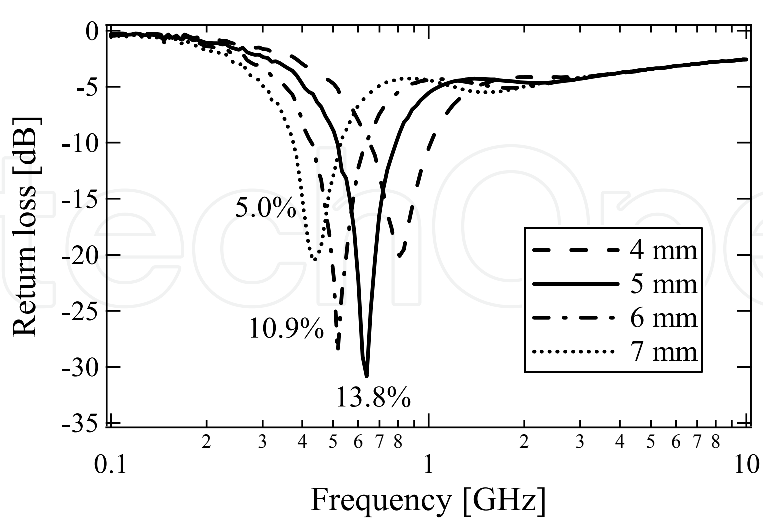
possible using a composite made of soft magnetic material particles dispersed in polystyrene resin because the values of μ_r' and μ_r'' has frequency dispersion in the high frequency range and the non-reflective condition can be satisfied in this frequency range.
Figures 5 and 6 show the frequency dependences of ε_r' and ε_r'' for the composite made of various magnetic materials. The values of ε_r' for all composite were almost constant to the frequency in spite of the difference of the magnetic material. However, the values of ε_r' and ε_r'' for the composite made of ferrite were low whereas those for the composite made of nickel were high. This is caused by the difference of the resistivity; ferrite has a high value of resistivity.

3.2 Frequency dependences of return loss for the composite made of soft magnetic material dispersed in polystyrene resin

The frequency dependence of the return loss in free space was calculated from the measured values of μ_r^* and ε_r^* to investigate the absorption characteristics of the composite. The absorber used for the calculation was a metal-backed single layer absorber and the incident electromagnetic wave was perpendicular to the surface. Figures 7 and 8 show the frequency dependences of return loss for the composite made of sendust and that made of permalloy. The percentages shown in the graphs represent the normalized −20 dB bandwidth (the bandwidth Δf corresponding to a return loss of less than −20 dB divided by the absorption center frequency f_0). A value of −20 dB corresponds to the absorption of 99% of the electromagnetic wave power.

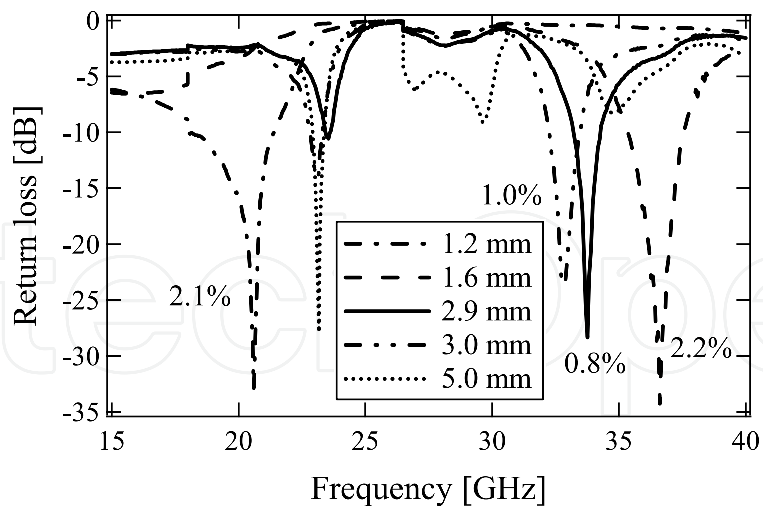


(a) 53 vol%-sendust composite and 53 vol%-permalloy composite

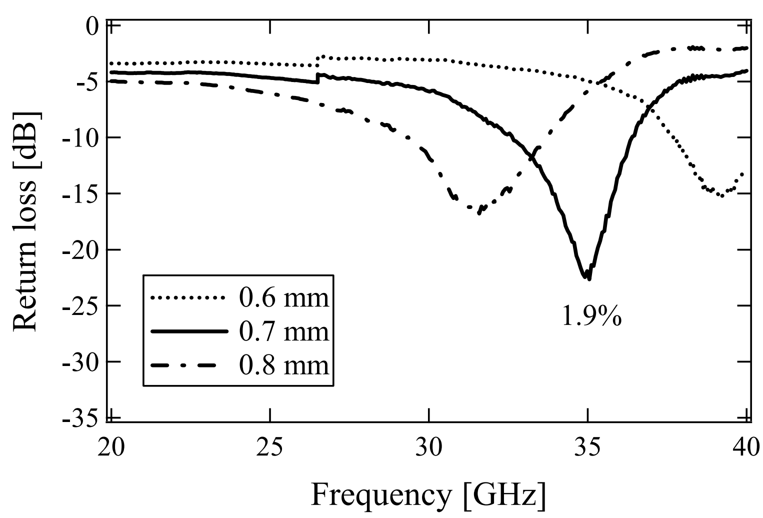


(b) 85 vol%-sendust composite

Fig. 7. Frequency dependences of return loss for composites made of sendust or permalloy particles dispersed in polystyrene resin.



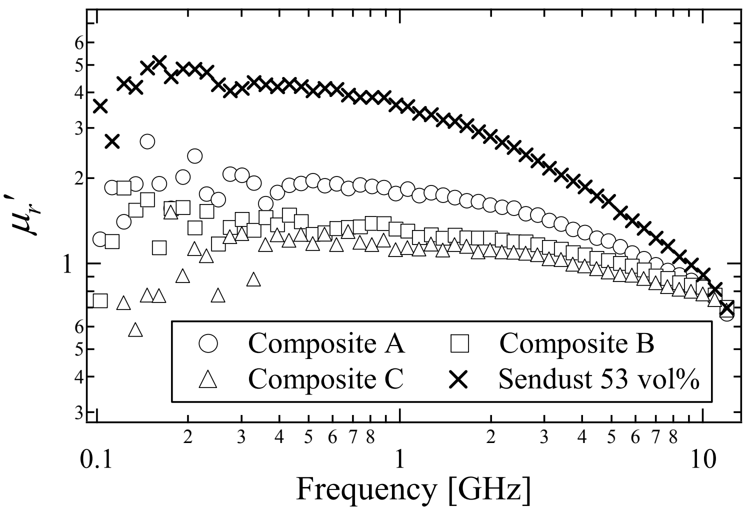
(a) 53 vol%-sendust composite



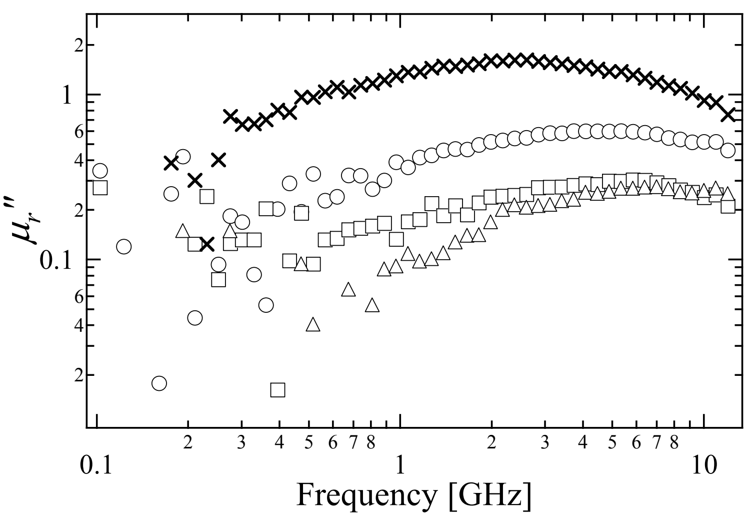
(b) 53 vol%-permalloy composite

Fig. 8. Frequency dependences of return loss for composites made of sendust or permalloy particles dispersed in polystyrene resin.

The composite made of sendust and that made of permalloy with the volume mixture ratio of 53 vol% exhibited a return loss of less than −20 dB in the frequency range of several GHz, as shown in Fig. 7(a). The sample thickness where the return loss is less than −20 dB was thin; several millimeters, and the normalized −20 dB bandwidth was over 10% (the normalized −20 dB bandwidth of commercially available absorber in the frequency range of several GHz ranges from 10 to 30%). Thus, it was found that the composite made of sendust particles dispersed in polystyrene resin can be used as a practical absorber. Moreover, as shown in Fig. 8(a), the return loss for the composite made of sendust was less than −20 dB near 20 and 36 GHz although the value of normalized −20 dB bandwidth was small. It is speculated that the absorption characteristics for the composite made of sendust can be improved in the high frequency range by selecting a suitable volume mixture ratio of sendust, because μ_r' and μ_r'' varied when the amount of sendust was changed, as discussed in section 3.1.



(a) μ_r'



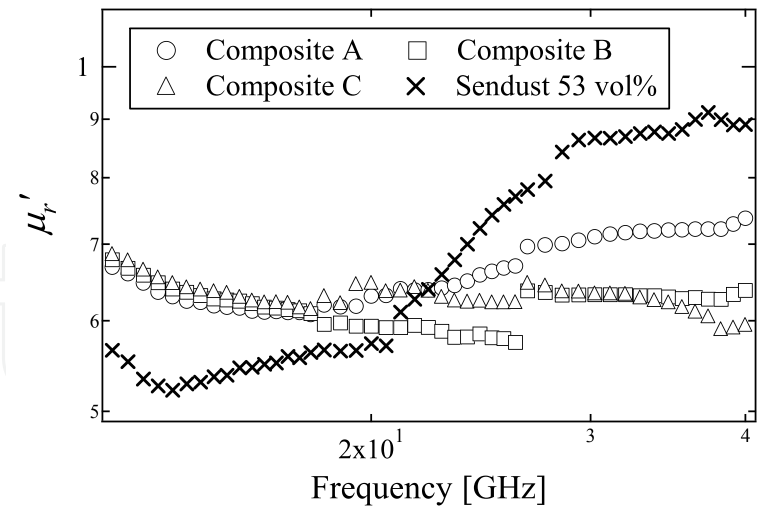
(b) μ_r''

Fig. 9. Frequency dependences of μ_r' and μ_r'' for composites made of both sendust and aluminum particles dispersed in polystyrene resin. The frequency range is from 100 MHz to 12.4 GHz.

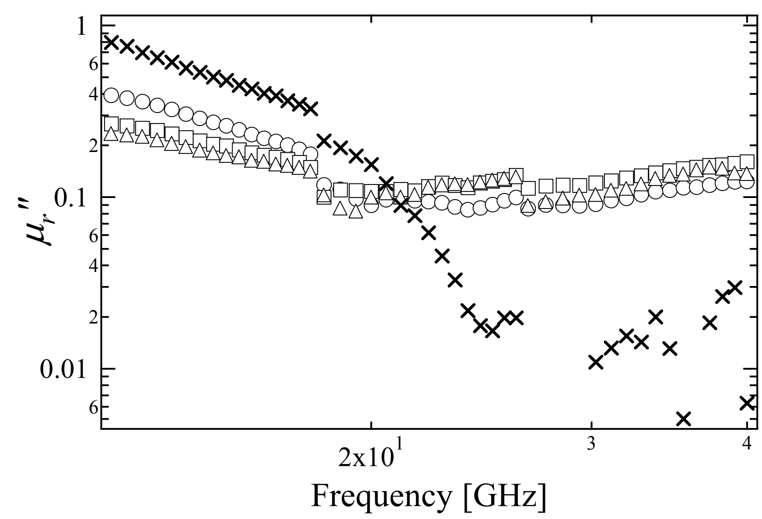
The composite made of sendust with the volume mixture ratio of 85 vol% did not have a return loss of less than −20 dB at frequencies above 1 GHz although the return loss was less than −20 dB in the frequency range of several hundred MHz. This is because the values of ε_r' and ε_r'' increased markedly with a high volume mixture ratio of sendust, as shown in section 3.1. Thus, it is speculated that good absorption characteristic can be obtained with a low volume mixture ratio of sendust.

3.3 Frequency dependences of μ_r^* and ε_r^* for the composite made of both sendust and aluminum particles dispersed in polystyrene resin

Figures 9 and 10 show the frequency dependences of μ_r' and μ_r'' for the composite made of both sendust and aluminum particles dispersed in polystyrene resin. At frequencies of below 10 GHz, the values of both μ_r' and μ_r'' were low and the shape of the frequency



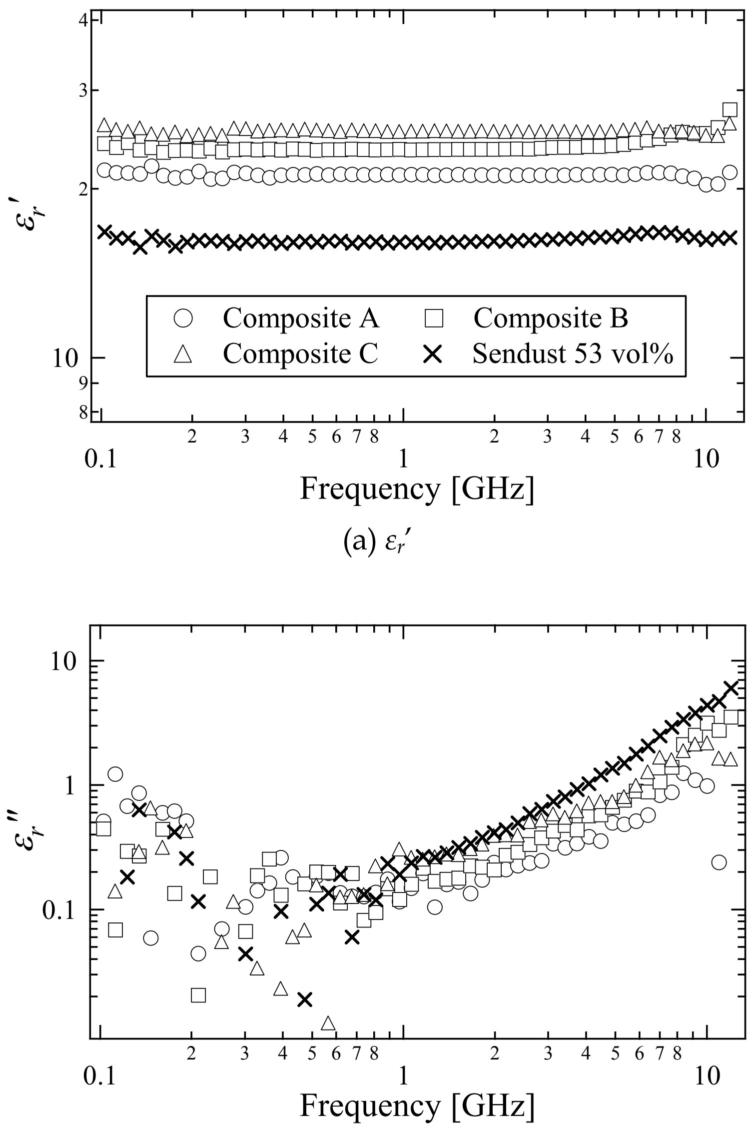
(a) μ_r'



(b) μ_r''

Fig. 10. Frequency dependences of μ_r' and μ_r'' for composites made of both sendust and aluminum particles dispersed in polystyrene resin. The frequency range is from 12.4 to 40 GHz.

dependence of μ_r' became flat with increasing the amount of aluminum particle. This result indicates that the magnetic response to the incident electromagnetic wave reduced because the magnetic material of sendust dcreased and the non-magnetic material of aluminum increased. Meanwhile, in the high frequency range, the values of μ_r' for the composite made of both sendust and aluminum were less than unity and the magnitude of μ_r' was smaller than that for the composite made of only sendust. Moreover, the values of μ_r'' for the composite made of both sendust and aluminum increased gradually at frequencies above 20 GHz. These phnomena observed in the high frequency range is considered to be that the eddy current flowed the surface of aluminum particle and the magnetic moment and magnetic loss caused by the eddy current affected the frequency dependences of μ_r' and μ_r''. From these results, it is found that the frequency dependences of μ_r' and μ_r'' that is not obtained by the composite made of only sendust can realize using the composite made of



(a) ε_r'

(b) ε_r''

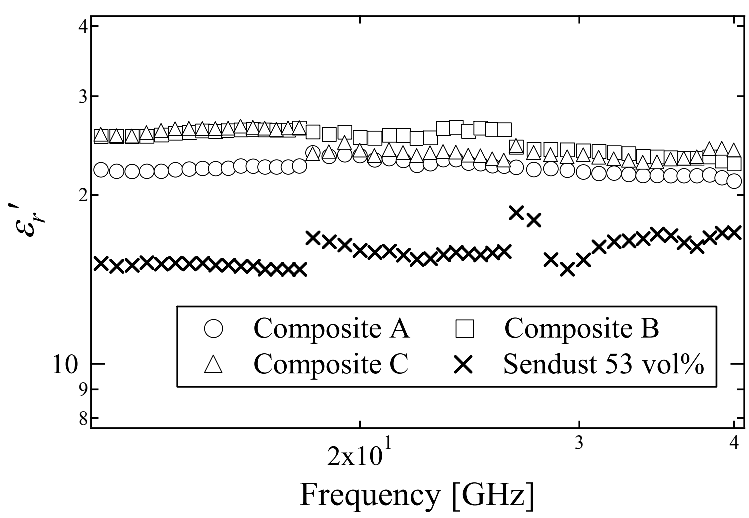
Fig. 11. Frequency dependences of ε_r' and ε_r'' for composites made of both sendust and aluminum particles dispersed in polystyrene resin. The frequency range is from 100 MHz to 12.4 GHz.

both sendust and aluminum, and the values of μ_r' and μ_r'' is changed to satisfy satisfy the non-reflective condition by simply adjusting the total volume and ratio of sendust and aluminum. Furthermore, when changing the ratio of sendust and aluminum with the same total volume of sendust and aluminum, the variation of ε_r' and ε_r'' was a little although the frequency dependences of μ_r' and μ_r'' changed considerably, as shown in Figs. 11 and 12. Figures 11 and 12 show the frequency dependences of ε_r' and ε_r'' for the composite made of both sendust and aluminum particles dispersed in polystyrene resin. Therfore, the composite made of both sendust and aluminum can control the values of μ_r' and μ_r'' reducing the increase or decrease in ε_r' and ε_r''. This leads to a flexible design of an electromagnetic wave absorber compared with the conventional method of designing an absorber.

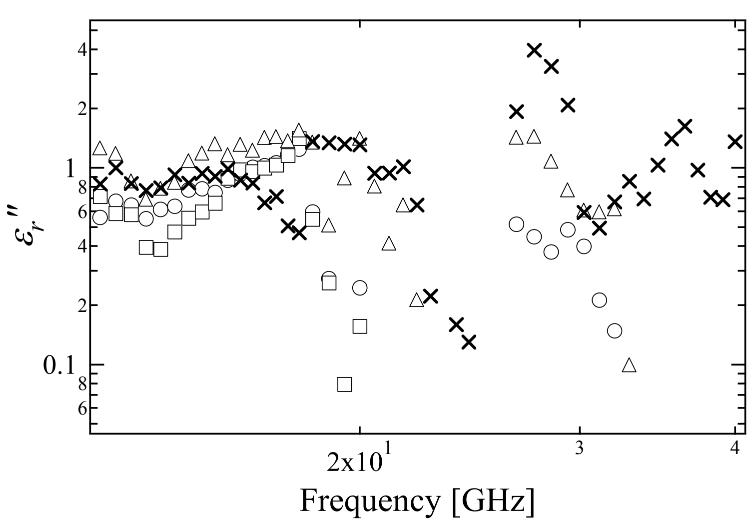
3.4 Frequency dependences of return loss for the composite made of both sendust and aluminum particles dispersed in polystyrene resin

Figure 13 show the frequency dependences of return loss for the composite made of both sendust and aluminum in the freqeuncy rage from 1 to 10 GHz. Composites A, B, and C had a return loss of less than −20 dB at a sample thickness of several millimeter. However, the value of normalized −20 dB bandwidth was small compared with that for the composite made of only sendust as shown in Fig. 7. This is because the frequency dependences of μ_r' and μ_r'' became flat and the frequency range where the non-reflective condition is satisfied was narrow.

Figure 14 show the the frequency dependences of return loss for composites B and C in the freqeuncy rage from 15 to 40 GHz. The return loss of composite A was not less than −20 dB in this frequency range. As shown in Fig. 14, composites B and C exhibited a return loss of

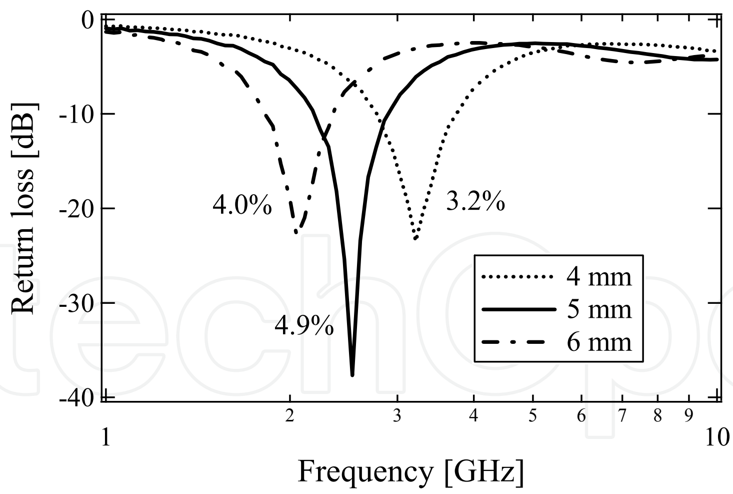


(a) ε_r'

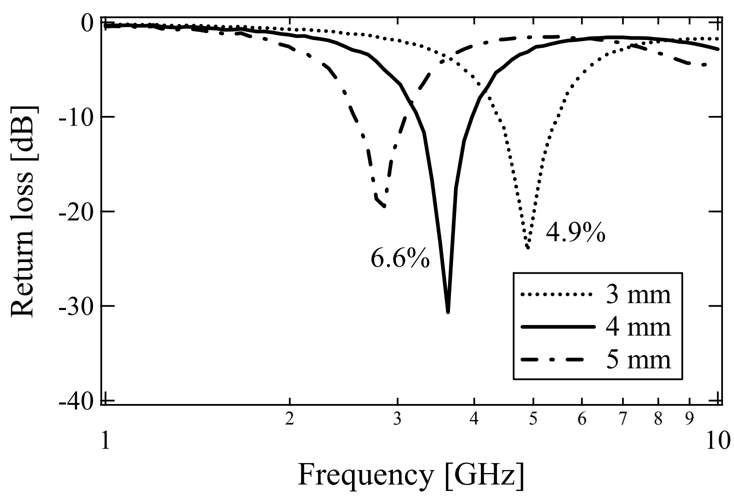


(b) ε_r''

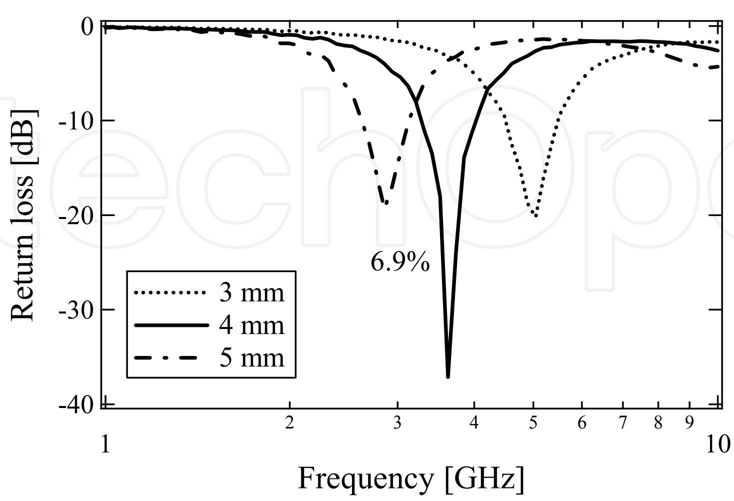
Fig. 12. Frequency dependences of ε_r' and ε_r'' for composites made of both sendust and aluminum particles dispersed in polystyrene resin. The frequency range is from 12.4 to 40 GHz.



(a) Composite A (Sendust 25 vol%, Al 25 vol%)

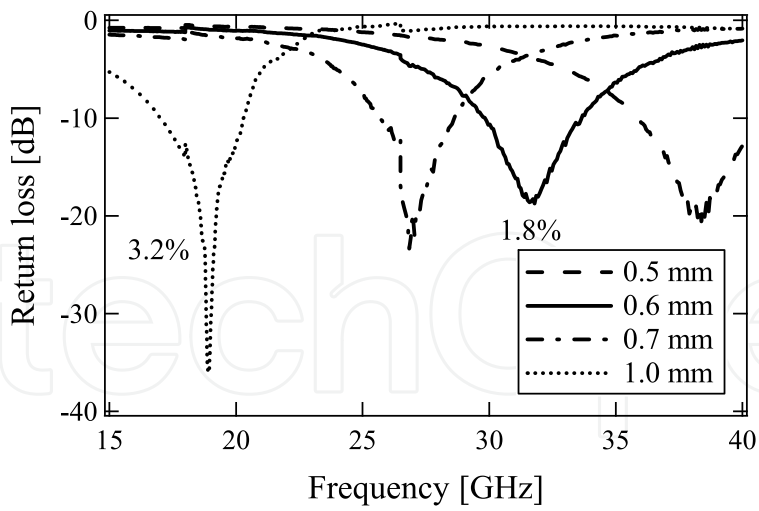


(b) Composite B (Sendust 12.5 vol%, Al 37.5 vol%)

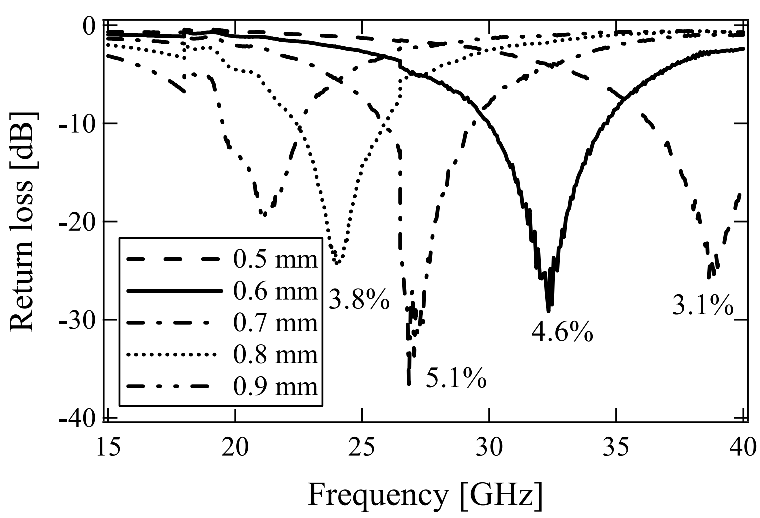


(c) Composite C (Sendust 10 vol%, Al 40 vol%)

Fig. 13. Frequency dependences of return loss for composites made of both sendust and aluminum particles dispersed in polystyrene resin. The frequency range is from 1 to 10 GHz.



(a) Composite B (Sendust 12.5 vol%, Al 37.5 vol%)



(b) Composite C (Sendust 10 vol%, Al 40 vol%)

Fig. 14. Frequency dependences of return loss for composites made of both sendust and aluminum particles dispersed in polystyrene resin. The frequency range is from 15 to 40 GHz.

less than −20 dB at frequencies above 15 GHz and the normalized −20 dB bandwidth of these two composites was broader than that for the composite made of only sendust. In addition, the sample thicknesses where the return loss is less than −20 dB were very thin. In particular, composite C had high values of normalized −20 dB bandwidth in spite of the high frequency range and the frequency where the return loss is less than −20 dB can be selected by changing the sample thickness in the range from 0.5 to 0.7 mm.

It is concluded from these results that the absorption characteristics of the composite made of sendust in the high frequency range could be improved by adding aluminum particles. Moreover, aluminum is low cost, abundant chemical element, and light wight. For example, the mass densities of composites A, B and C were approximately 2.4, 2.1, and 2.0 g / cm^3, respectively, while the mass density of the composite made of 53 vol%-sendust is approximately 3.5 g / cm^3. Therefore, a light-weight absorber can be fabricated by incorporating both sendust and aluminum.

4. Conclusion

Frequency dependences of μ_r^*, ε_r^*, and absorption characteristics for the composite made of sendust were investigated in the frequency range from 100 MHz to 40 GHz. By the comparison with the composite made of various magnetic material, the mechanism of the frequency dependences of μ_r' and μ_r'' was found to be the magnetic resonance in the low frequency range and the magnetic moment in the high frequency range. The values of μ_r' for the composite made of sendust were less than unity and the values of μ_r'' was not zero like the composite made of ferrite particles dispersed in polystyrene resin. Thus, the composite made of sendust had a return loss of less than −20 dB at frequencies above 10 GHz in addition to the absorption at frequencies of several GHz. From these result, it is concluded that a practical absorber suitable for frequencies above 10 GHz is possible using a composite made of sendust. The values of μ_r' and μ_r'' for the composite made of both sendust and aluminum particles dispersed in polystyrene resin could be controlled by changing the volume mixture ratio of sendust and aluminum. Thus, the absorption characteristics at frequencies above 10 GHz for the composite made of only sendust could be improved by using the composite made of both sendust and aluminum by selecting a suitable volume mixture ratio of sendust and aluminum, and a flexible design of an absorber was proposed.

5. Acknowledgement

This research was supported by the Japan Society for the Promotion of Science (JSPS) and Grant-in-Aid for JSPS Fellows.

6. References

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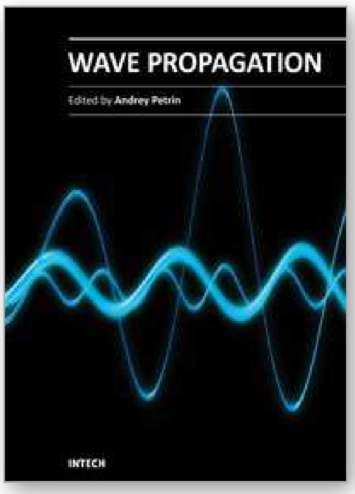

Wave Propagation

Edited by Dr. Andrey Petrin

ISBN 978-953-307-275-3
Hard cover, 570 pages
Publisher InTech
Published online 16, March, 2011
Published in print edition March, 2011

The book collects original and innovative research studies of the experienced and actively working scientists in the field of wave propagation which produced new methods in this area of research and obtained new and important results. Every chapter of this book is the result of the authors achieved in the particular field of research. The themes of the studies vary from investigation on modern applications such as metamaterials, photonic crystals and nanofocusing of light to the traditional engineering applications of electrodynamics such as antennas, waveguides and radar investigations.