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Magnetic Field Effect on the Complex Permeability for a Mn–Zn Ferrite and its Composite Materials

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Abstract

Complex permeability spectra ($\mu^* = \mu' - i\mu''$) in Mn–Zn ferrite and its composite materials have been studied in the frequency range from 10 kHz to 2 GHz under magnetic fields up to 1000 Oe. In the sintered ferrite, the μ' spectrum has a resonance type frequency dispersion above 100 kHz which is originated mainly by the domain wall vibration and μ'' shows a maximum at about 800 kHz in the absence of a dc magnetic field. Under dc magnetic field, dispersion character changes from resonance type to relaxation type spin resonance with the disappearance of the magnetic domain wall. High frequency permeability can be suppressed by the skin depth effect of eddy current above 1 MHz. In the composite materials, the permeability dispersion frequencies locate above 100 MHz and resonance type dispersion, which is mainly attributed to the spin resonance, is stabilized by the demagnetizing field in the embedded particles. Spin resonance character is enhanced by the external dc magnetic field.

Keywords: magnetic permeability, composites, magnetic properties, ferrites, soft magnets.

1 Introduction

For high frequency electromagnetic devices such as electromagnetic wave absorbers, converters or inductors, initial permeability of the ferrite materials in radio frequency (RF) region is an important factor. Thus, many investigations have been carried out in experimental and theoretical bases.[1–3] For instance, though Mn–Zn ferrites have a large permeability in the low frequency region, their permeability decreases rapidly in the high frequency region above 1 MHz. Therefore, several methods to improve the high frequency permeability have been intended. We have examined the high frequency permeability for the ferrite composite materials and found that the permeability in the RF region can be improved by composite structure of ferrite and resin.[4–6] Complex permeability of such ferrite composite materials , in which ferrite particles are embedded in a binder matrix, have also been the subject of considerable interest.[7–9] We also studied the dc magnetic field effect on the complex permeability spectra in a sintered Ni–Zn ferrite.[10] It is found that the frequency dispersion is separated into two parts; two distinct peaks of μ'' corresponding to the domain wall and spin rotation resonances can be identified under several hundred Oe. The domain wall resonance disappears under about 900 Oe and the ferrimagnetic resonance like spin resonance is stabilized.

On the other hand, a ferrite antenna based on the concept of integration has been developed using a Mn–Zn ferrite over several MHz range and considerable improvement in sensitivity over the conventional ferrite antennas has been obtained.[11] In this antenna, parametric amplification is used and non-linear dispersion of complex permeability is an important factor for ferrite materials. From the view point of ferrite antenna for RF region, studies for high frequency permeability dispersion of ferrite materials are necessary. In this study, we have measured the complex permeability spectra of a Mn–Zn ferrite and its composite materials under dc magnetic field, with the goal as the improvement

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of high frequency permeability and the investigation of non-linear dispersion of complex permeability. The change of the complex permeability under external magnetic field will be discussed.

2 Experimental

Mn–Zn ferrite particles were prepared by mechanical grinding of a commercially available sintered ferrite core. The composition of this Mn–Zn ferrite determined by an EPMA method is $Mn_{0.53}Zn_{0.41}Fe_{2.06}O_4$. Particle size was controlled under 75 μm. Ferrite composite materials were prepared by mixing ferrite particles with PPS (polyphenylene sulfide) resin powder, melting the resin at 300 °C and pressing the mixture at a pressure of 1000 kg cm^{-2} in the cooling process down to the room temperature. Complex permeability spectra were measured with a coaxial transmission line connected to an impedance analyzer (HP4194A from 10 kHz to 100 MHz), or a network analyzer (HP 8409A from 100 MHz to 2 GHz). The coaxial line cell was inserted into a solenoid type electromagnet which can generate a dc magnetic field H up to about 1000 Oe. The measurement system with the coaxial line apparatus is further described in Refs. 5 and 10. In this apparatus, the dc magnetic field is applied perpendicular to the measuring alternative magnetic field. The ac resistivity was measured by a two probe method in the frequency range from 100 Hz to 40 MHz using an impedance analyzer.

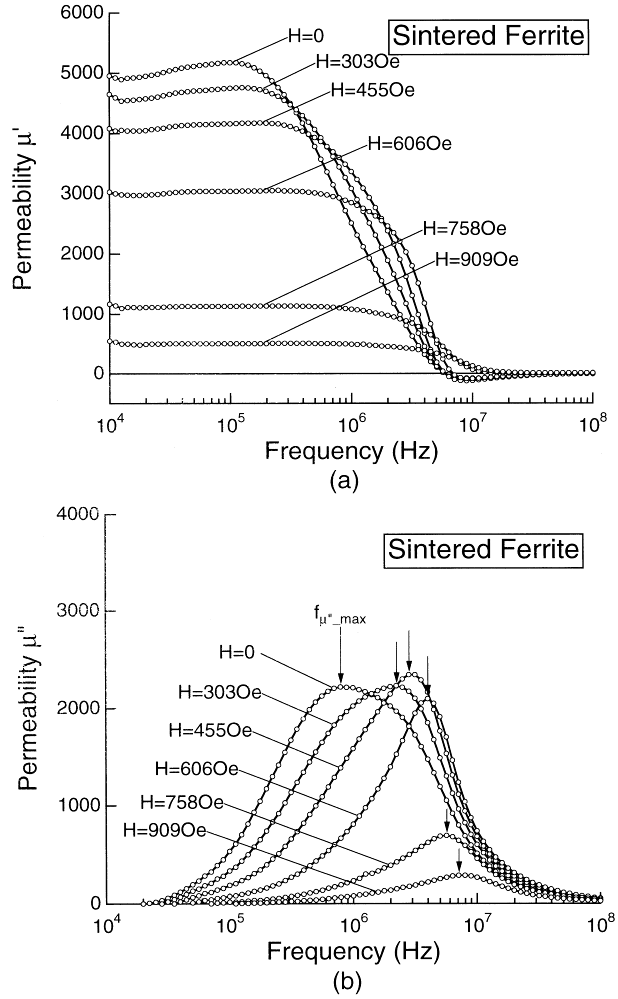

Fig. 1. (a) Real and (b) imaginary parts of permeability (μ' and μ'') for Mn–Zn sintered ferrite in various external dc magnetic field.

3 Results and Discussion

Figure 1 shows the complex relative permeability spectra of a Mn–Zn ferrite [(a) real part μ' (b) imaginary part μ''] with and without the external dc magnetic field. In the absence of a dc magnetic field, μ' begins to decrease at about 200 kHz and μ' has a maximum at around 1 MHz. Dispersion character is of a resonance type. This is mainly attributed to the magnetic domain wall resonance. When the external dc field is applied, μ' at low frequencies decreases with increasing H and the maximum of μ'' shifts to higher frequencies. The dispersion character under 758 Oe external field is of a relaxation type. Since the magnetization of this Mn–Zn ferrite almost saturates at about 1000 Oe, this Mn–Zn ferrite is considered to have a single domain structure under 758 Oe external field. Therefore, this dispersion is originated by the relaxation type spin resonance due to high spin damping factor; high permeability of Mn–Zn ferrite at low frequencies is mainly attributed to the magnetic domain wall vibration. Considering the results of sintered Ni–Zn ferrite,[10] in which the resonance type permeability dispersion is observed for a single domain structure under dc field, the damping factor of spin rotation is larger in Mn–Zn ferrite than that in Ni–Zn ferrite. Accordingly, it is considered that a higher dc magnetic field over 1000 Oe is necessary to make the resonance type frequency dispersion in this Mn–Zn ferrite. We denote $f_{\mu''-\max}$ as the frequency where μ'' has a maximum. Variation of angular frequency $\omega_{\mu''-\max} = 2\pi f_{\mu''-\max}$ with dc magnetic field H is shown in Fig. 2. It is found that the slope of $\omega_{\mu''-\max}$ versus H curve changes at about 700 Oe. Below about 700 Oe external field, $\omega_{\mu''-\max}$ is determined by the superposition of two peaks originated by domain wall and spin resonance, but contribution of spin resonance can be small due to suppression of the high frequency permeability by eddy current effect.[6] Above 700 Oe, maximum frequency of μ'' is determined by $\omega_{\mu''-\max} = \gamma\ (H_a + H)$, with γ the gyromagnetic ratio and H_{a} the anisotropy field. It is considered that the eddy current causes a

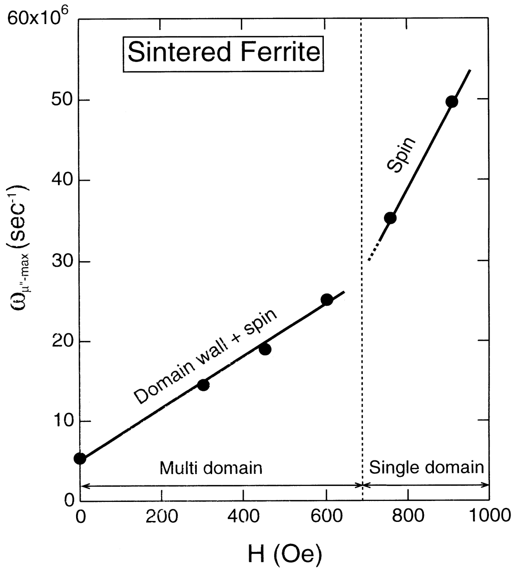

Fig. 2. Magnetic field dependence of the angular frequency with the maximum of $\mu''(\omega_{\mu''-\max})$ for sintered Mn–Zn ferrite. Solid lines are guides for the eyes.

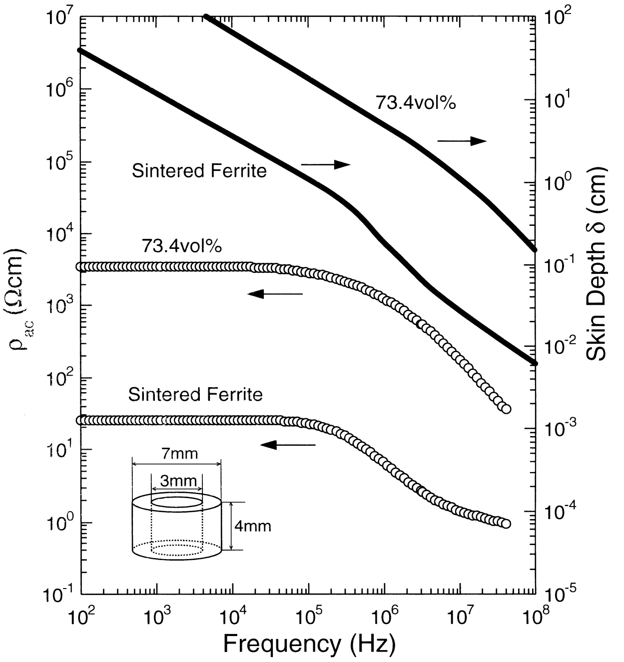

Fig. 3. The variation of ac resistivity ρ_{ac} and the skin depth δ with frequency for sintered ferrite and the 73·4 vol% composite material.

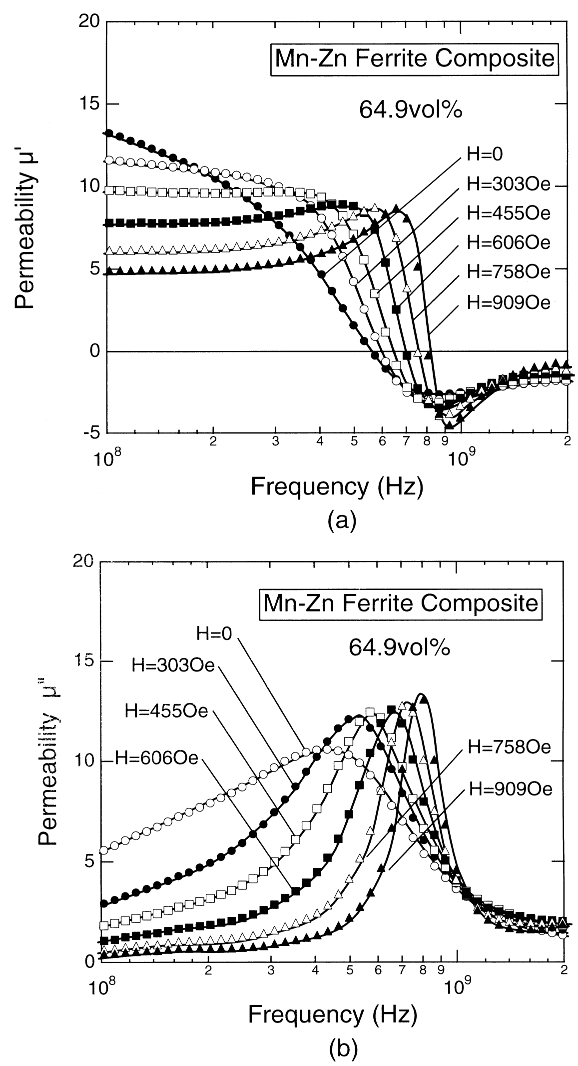

Fig. 4. (a) Real and (b) imaginary parts of permeability (μ' and μ'') for the 64·9 vol% Mn–Zn ferrite composite in various external dc magnetic fields.

decrease of effective volume which contributes the permeability of samples due to skin depth effect. Therefore, ac resistivity ρ_{ac} was also measured to roughly estimate the frequency variation of the skin depth δ. Frequency dependence of ρ_{ac} and δ for the sintered ferrite and composite materials are shown in Fig. 3. The skin depth δ is estimated by $\delta = (2/\omega\mu\sigma)^{1/2}$ as in the case of high conductivity materials, where the absolute values of permeability and extrapolated ρ_{ac} values are used. The inset shows the sample geometry of the sintered ferrite. In low frequency region, δ is large enough and electromagnetic waves can penetrate into the whole sample. However, with increasing frequency, the eddy current starts to affect the permeability when the skin depth is smaller than the sample thickness. Considering the sample geometry, the skin depth which affects the effective volume of samples is a few mm. Therefore, the skin depth effect can occur from about 1 MHz with increasing frequency in sintered ferrite. For composite materials, ρ_{ac} increases in order of over three in the 73·4 vol% sample. However, since frequency dispersion locates about 200 MHz, there can exist the skin depth effect in the permeability spectra, but it is considered to be small. With decreasing ferrite content, the eddy current effect is rapidly suppressed by the decrease of conductivity. Thus, the skin depth effect can be negligible in low ferrite content composite materials. We also measured the ρ_{ac} under dc magnetic field but no pronounced change was observed in ρ_{ac} curves.

Figures 4 and 5 show the complex permeability spectra of Mn–Zn ferrite composite materials of 64·9 and 48·4 vol%, [(a) real part μ' (b) imaginary part μ''] with and without the external dc magnetic field. In composite materials, dispersion character is a resonance type and dispersion frequencies locate over 100 MHz in the absence of a dc magnetic field; the $f_{\mu''-\max}$ is about 550 MHz for the 64·9 vol% and about 1 GHz for the 48·4 vol% samples, respectively. This feature can be realized as follows. The number of magnetic domains in embedded ferrite particles are less than in the sintered ferrite and domain wall size is also small. Thus, the domain wall resonance frequency can be higher than that in the sintered ferrite due to the small size of domain walls. Further, spin resonance frequency can be increased by the demagnetizing field generated by the magnetic poles on the embedded ferrite particles.[4] When the external dc magnetic field is applied, dispersion curves become steep in the μ' spectra and peaks become sharp in the μ'' spectra. It should be noted that no discontinuity is observed between multidomain and single domain structures. This feature shows that frequency dispersion in the zero dc bias field can be mainly attributable to

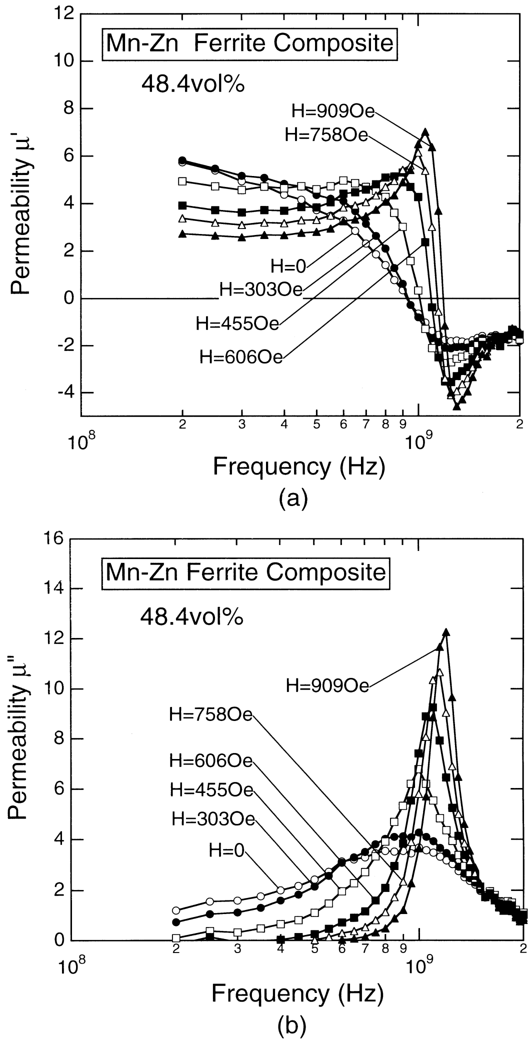

Fig. 5. (a) Real and (b) imaginary parts of permeability (μ' and μ'') for the 48·4 vol% Mn–Zn ferrite composite in various external dc magnetic field.

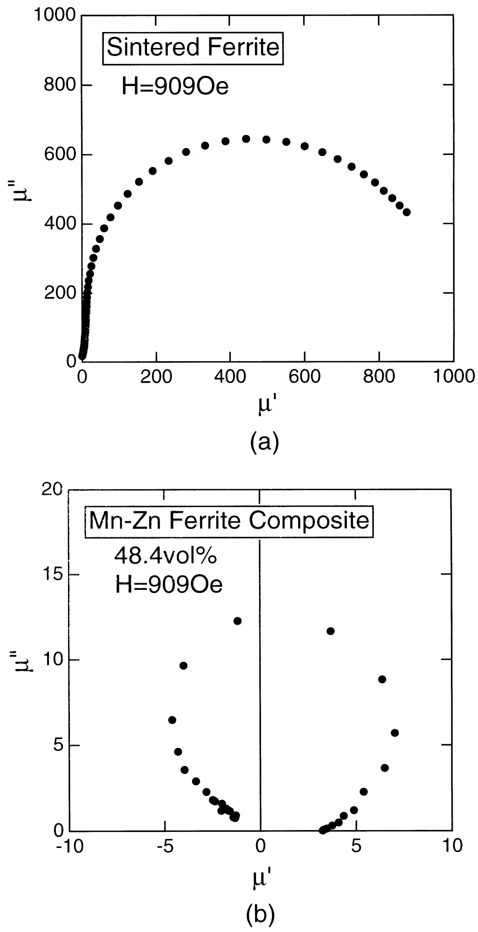

Fig. 6. The μ'' versus μ' plots for the sintered ferrite (a) and 48·4 vol% composite material (b) under 909 Oe external magnetic field.

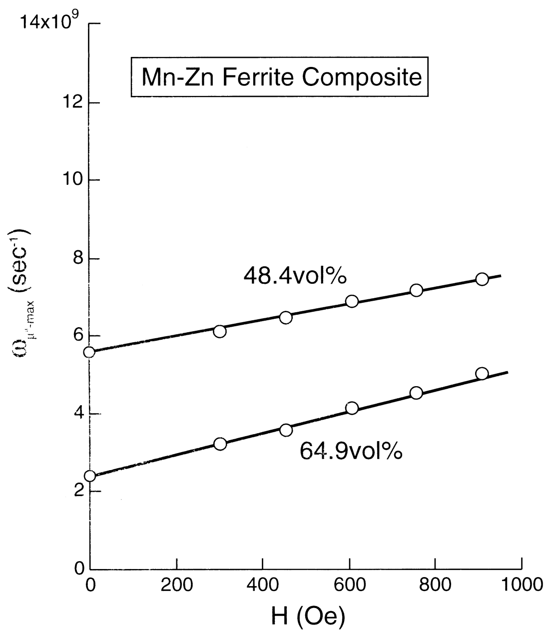

Fig. 7. Magnetic field dependence of the angular frequency with the maximum of $\mu''(\omega_{\mu''-\max})$ for Mn–Zn ferrite composite materials. Solid lines are guides for the eyes.

the spin resonance in composite structures. Figure 6 shows the μ'' versus μ'' curves for the sintered Mn–Zn ferrite (a) and 48·4 vol% ferrite composite material (b) under 909 Oe external magnetic field. In this magnetic field, both samples have a single domain structure. It is clearly found that the sintered ferrite shows a relaxation type dispersion and the ferrite composite shows resonance type one. Therefore, the demagnetizing field changes of the dispersion character for spin resonance from relaxation type in sintered ferrite to resonance one in composite materials. In both composite materials, distinct non-linear dispersion in the RF region up to several GHz can be achieved by applying about 1000 Oe bias field; these materials are a good candidate for the RF ferrite antenna. Figure 7 shows the variation of $\omega_{\mu''-\max}$ with dc magnetic field H. The $\omega_{\mu''-\max}$ increases linearly with increasing dc bias field in both composite samples and the slope of the curves are almost the same. Therefore, in composite materials, the relation between resonance frequency and external bias field can be presented by $\omega_{\mu''-\max} = \gamma(H_a + H_d + H)$ with H_d the demagnetizing field.

For further investigations, studies for the controllability of non-linear permeability dispersion by external magnetic fields are now in progress.

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