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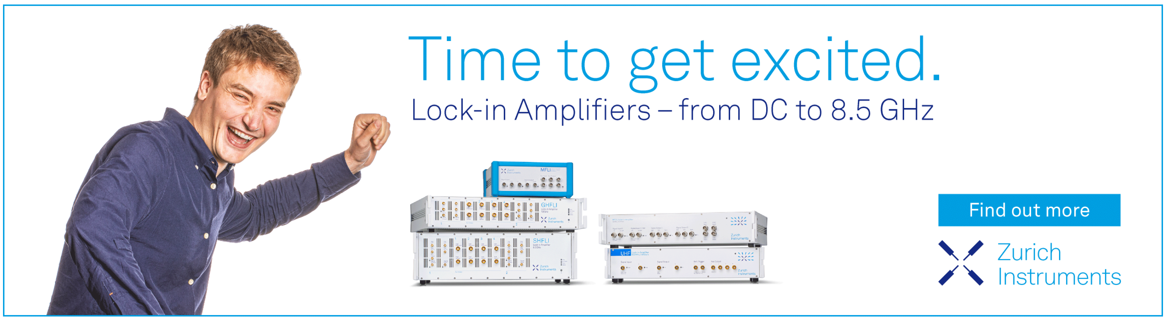

Magnetic field effect on the complex permeability spectra in a Ni–Zn ferrite

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Complex permeability spectra $\mu^*(=\mu'-i\mu'')$ in a Ni–Zn ferrite was studied in the frequency range from 10 kHz to 3 GHz under dc magnetic field up to 1000 Oe. In the absence of a dc magnetic field, the μ' spectrum has a frequency dispersion above 1 MHz; the μ'' spectrum has a maximum at about 2 MHz. This feature can be described by the superposition of the two types of magnetic resonance, domain wall motion with a resonance frequency $\omega_{\mathrm{dw}}^{r}=3.5$ MHz and spin rotation with a resonance frequency $\omega_{\mathrm{spin}}^{r}=8.0$ MHz. Under dc magnetic field, low frequency permeability μ' decreases with increasing static field bias. On the other hand, the μ'' spectrum is broadened and two distinct peaks appear in the external field of 606 Oe. Under about 900 Oe external field, this ferrite becomes to have single-domain structure and the dispersion of domain wall motion in the permeability spectra disappears. In the above 700 Oe external field, high frequency dispersion of μ^* shows ferromagnetic resonance characteristics. © *1997 American Institute of Physics.* [S0021-8979(97)07218-6]

I. INTRODUCTION

For high frequency (hf) devices such as electromagnetic wave absorbers, converters or inductors, initial permeability of the ferrite materials in hf region is an important factor. Thus, many experimental and theoretical investigations on the frequency dispersion of complex permeability in ferrite materials have been performed. However, hf permeability of ferrite materials, without the ferrox–planas type hexagonal ferrite, are restricted by the Snoek's limit. Therefore, several methods to improve the high frequency permeability have been intended. We have studied the hf permeability for the composite structure of ferrite particles and resin, and found that the permeability in rf frequency region can be improved in the ferrite composite material.[1–3] External magnetic field effect on the complex permeability of ferrite materials has also been studied to improve the hf permeability. Verweel *et al.* investigated the dc magnetic field effect on the permeability in a Ni–Zn ferrite. They reported that both μ' and μ'' decrease with increasing magnetic field, and magnetic loss μ'' is reduced with application of a dc magnetic field.[4] Kotsuka made a theoretical treatment of the microwave attenuation characteristics of the sintered ferrite in the static magnetic field between 100 and 500 MHz; and concluded that the attenuation characteristics of electromagnetic wave absorber can be improved by applying the static magnetic field.[5] Bush has carried out the studies of the dc magnetic field effect on the complex permeability for several ferrites and garnets in rf frequency region, and made a generalization of Snoek's limit.[6–8] It was found that μ' increases with increasing magnetic field and has a maximum at several hundred Oe in the rf frequency region. They treated this feature as the magnetic field effect on the domain wall resonance in the ferrite materials.[7]

In general, since the permeability of polycrystalline ferrites can be described as the superposition of two different magnetization mechanisms: spin rotation and domain wall motion, it is worth studying the change of complex permeability spectra in the external magnetic field for sintered ferrites and ferrite composite materials, with the goal of the improvement of hf permeability. In this study, we have measured the complex permeability spectra in a sintered Ni–Zn ferrite under dc magnetic field. The change of frequency dispersion characteristics of the complex permeability under external magnetic field will be discussed.

II. EXPERIMENT

A Ni–Zn sintered ferrite $Ni_{0.24}Zn_{0.65}Cu_{0.07}Fe_{2.04}O_4$ was prepared by the conventional sintering method. In order to measure permeability, obtained samples were cut into a toroidal from with an inner diameter of 3.03 mm, and with an outer diameter of 7.0 mm. The complex permeability ($\mu^*=\mu'-i\mu''$) of the samples were measured with a coaxial transmission line connected to an impedance analyzer (HP4194A from 10 kHz to 100 MHz), or a network analyzer (HP8753C from 10 MHz to 3 GHz). The coaxial line cell was inserted into a solenoid type electromagnet with an inner diameter of 5.2 cm, an outer diameter of 10.86 cm and a height of 7.43 cm, which can generate a dc magnetic field H_{dc} up to about 1 kOe. Schematic diagram of the experimental apparatus is shown in Fig. 1. Measurement system with the coaxial line apparatus is further described in Ref. 2. In this apparatus, the dc magnetic field is applied perpendicular to the measuring alternative magnetic field h_{rf} (inset of Fig.

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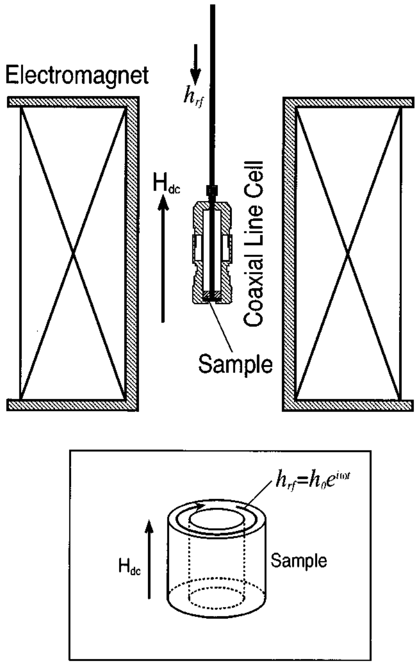

FIG. 1. Schematic diagram of experimental setup for the dc magnetic field effect. Inset shows the configuration of hf field and dc magnetic field.

1). The μ' and μ'' were calculated from the impedance Z_{in} for low frequency region, or from the reflection coefficient Γ for high frequency region.[2]

III. RESULTS AND DISCUSSION

Figures 2 and 3 show the complex permeability spectra of a Ni–Zn ferrite sample [(a) real part μ' and (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 1 MHz and the μ'' has a maximum at around 2 MHz. When the external dc field is applied, the μ' at low frequencies decrease with increasing H_{dc}. However, the μ' at high frequencies increases with increasing H_{dc} above several 10 MHz. In the μ'' spectrum, the frequency at which μ'' becomes maximum increases and spectrum is broadened with increase of H_{dc}. Further, we can see two peaks in the external field of 455, 606, and 758 Oe; only one peak remains under 909 Oe. This feature an be clearly seen in Fig. 3(b).

The μ^* spectra of ferrite are described by two types of magnetizing processes: spin rotation and domain wall motion. Therefore, zero dc field permeability spectra consist of the two types of resonance components. Assuming that the spin resonance has a relaxation type frequency dispersion, and domain wall resonance has a resonance type one, we can separate the two components in the μ^* spectra, considering their frequency dependence.[9] Each component of permeability $\mu=1+\chi_{spin}+\chi_{dw}$ can be shown as

$$\chi_{spin}=\frac{K_{spin}}{1+i\omega/\omega_{spin}^{r}}, \tag{1}$$

$$\chi_{dw}=\frac{K_{dw}\omega_{dw}^{r\,2}}{\omega_{dw}^{r\,2}-\omega^2+i\beta\omega}, \tag{2}$$

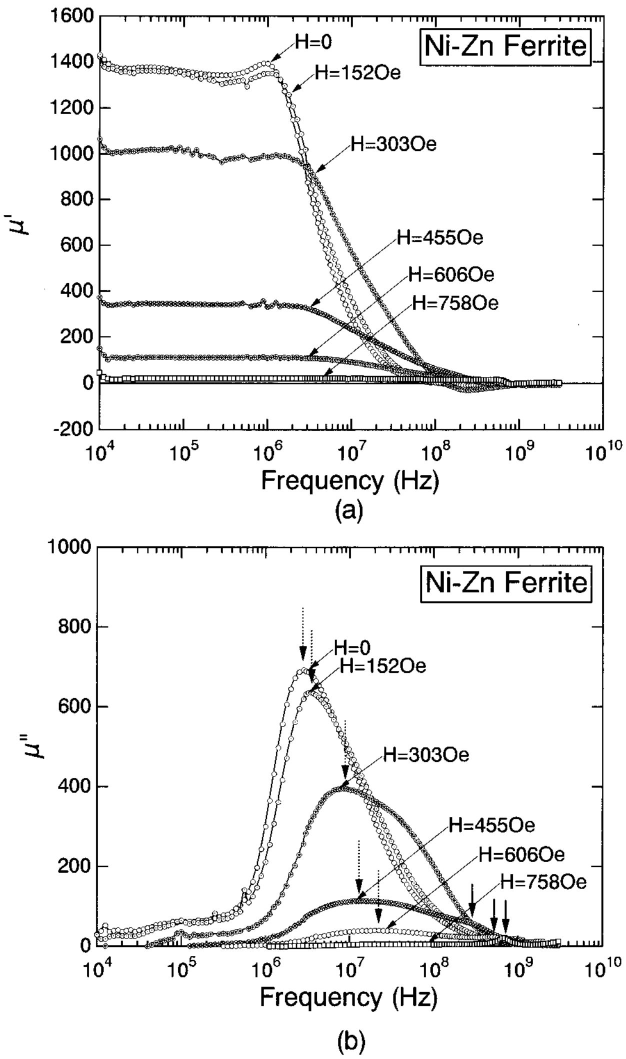

FIG. 2. Real (a) and imaginary (b) parts of permeability (μ' and μ'') for Ni–Zn sintered ferrite in various external dc magnetic field.

with ω the rf magnetic field frequency, K_{spin} the static spin susceptibility, K_{dw} static susceptibility of domain wall motion, and β the damping factor of the domain wall motion. Dispersion parameters were determined by numerical fitting of the obtained μ' and μ'' spectra to Eqs. (1) and (2). Figure 4 shows the separated two components of the permeability spectra under zero bias field. It is found that the domain wall permeability is dominant in low frequency region. Estimated resonance frequencies ω_{dw}^{r} and ω_{spin}^{r} are 3.47 and 7.97 MHz, respectively. By applying external dc magnetic field, domain walls move and magnetic domains, in which magnetization direction is along the H_{dc}, become larger. Accordingly, the decrease of domain walls attributes the decrease of low frequency permeability. Simultaneously, spin resonance frequency increases due to increase of the effective field applied to the magnetic moment; low frequency spin components also decreases due to Snoek's law. Therefore, two peaks in μ'' spectra in the $H_{dc}=455-758$ Oe correspond to the two types of resonance frequencies ω_{dw}^{r} and ω_{spin}^{r}. Furthermore, dispersion character of μ^* spectra in 909 Oe external field indicates the ferromagnetic or ferrimagnetic resonance. Since

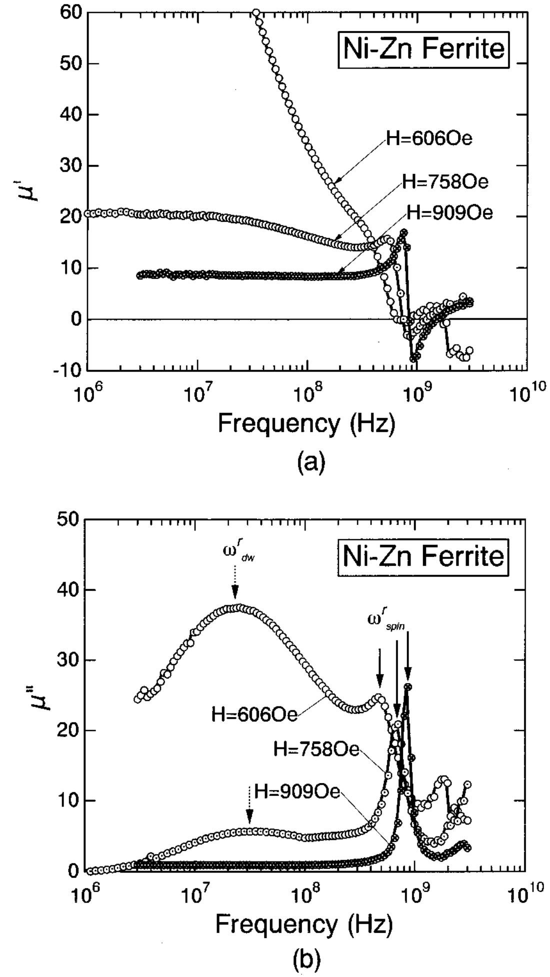

FIG. 3. Real (a) and imaginary (b) parts of permeability (μ' and μ'') for Ni–Zn sintered ferrite in high external dc magnetic field.

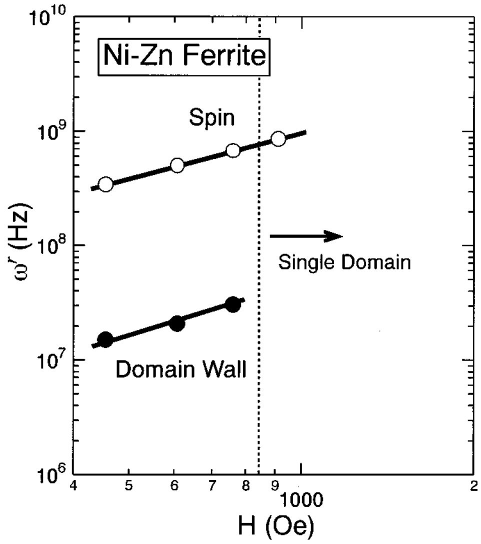

FIG. 5. Magnetic field dependence of spin rotation and domain wall resonance frequencies for sintered Ni–Zn ferrite.

the dc magnetization almost saturates under 2 kOe external field and only one sharp peak at hf can be seen in the μ'' spectrum under 909 Oe, this ferrite sample is considered to have a single-domain structure under 909 Oe. A magnetic field variation of resonance frequencies, which are determined from the two peaks in the μ'' spectra, are shown in Fig. 5. The spin resonance frequency can be expressed as a function of an equivalent anisotropy field H_a, and an external field H_{dc}, $\omega^r_{spin} = (\gamma/2\pi)(H_a + H_{dc})$, where γ is the gyromagnetic ratio. Both ω^r_{dw} and ω^r_{spin} increase, linearly with increasing magnetic field. The spin resonance frequency shift

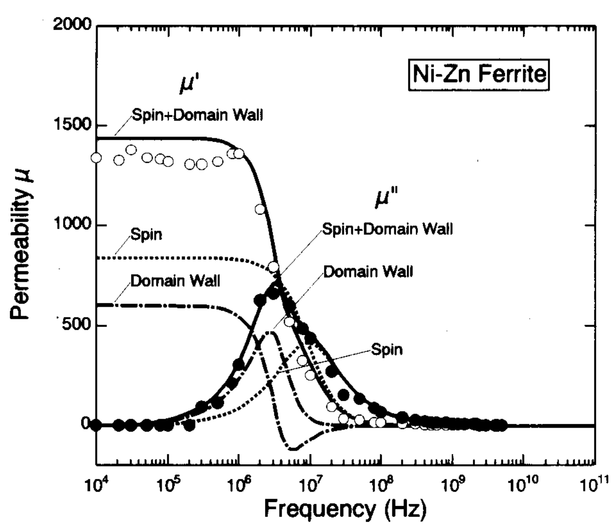

FIG. 4. Permeability spectra of a sintered Ni–Zn ferrite which are quoted in Ref. 2. Experimental values are denoted by the open circles for μ' and solid circles for μ''. Solid lines show total calculated permeability, which is obtained by combining the spin rotation component (broken line) and domain wall component (dashed-dotted lines).

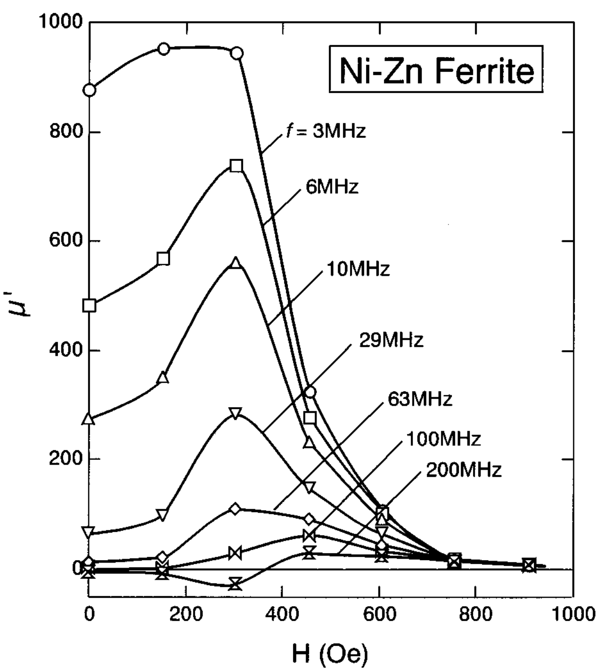

FIG. 6. Magnetic field variation of real part of permeability μ' in the middle frequency region.

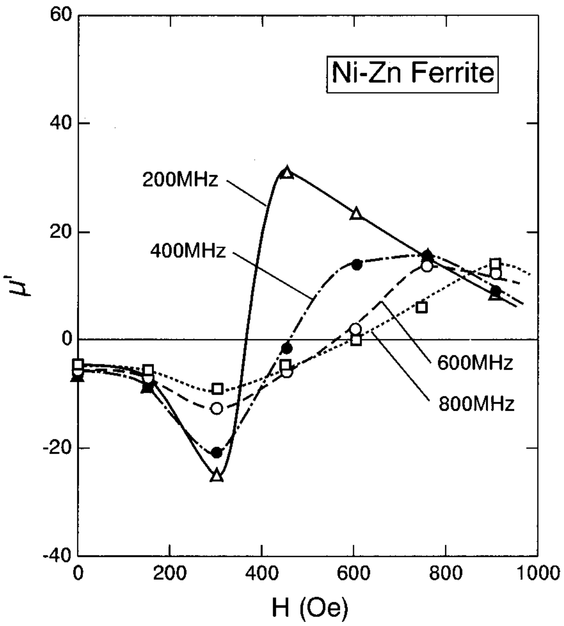

FIG. 7. Magnetic field variation of real part of permeability μ' in the hf region.

per the unit increase of external dc field is 1.16×10^8 Hz/Oe. An increase of the domain wall resonance frequency can be attributed to the increase of the domain wall stiffness by the external dc field.

Figures 6 and 7 show the variation of the real part permeability μ' with external dc magnetic field at various frequencies. The effect of the dc magnetic field on the μ' can be divided into three regions: low, middle, and hf ranges. In the low frequency region below 1 MHz, μ' decreases with the external dc field as seen in Fig. 2(a). In the middle frequency region from 3 to 200 MHz, μ' has a maximum at about 300 Oe external dc field due to the increase of both resonance frequencies. This feature is almost the same as $Mg_{0.35}Zn_{0.65}Fe_2O_4$ in Bush's data.[6] Further, in the hf region above 100 MHz μ' shows a ferromagnetic resonancelike variation as shown in Fig. 7. The external dc magnetic field at which μ' crosses 0 increases with increasing frequency. This is similar to the yttrium aluminum garnet data.[7]

VI. CONCLUSION

The dc magnetic field effect on the complex permeability spectra in a Ni–Zn ferrite has been studied. In the absence of the dc magnetic field, there exist two types of magnetic resonances: spin rotation and domain wall motion in the complex permeability. These two components can be separated by the dc magnetic field due to the increase of magnetic domains. Above an external dc magnetic field of 900 kOe, Ni–Zn ferrite has a single-domain structure; a ferromagnetic resonance can be seen with the resonance frequency of about 1 GHz. The Ni–Zn ferrite is useful to make hf devices. Therefore, further improvement of the permeability above 100 MHz is required. At this point, ferrite composite materials which have higher permeability values, than that of sintered ferrites in hf region are useful for investigating the dc magnetic field effect. The dc magnetic field effect studies for ferrite composite materials are now in progress.

ACKNOWLEDGMENT

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