DOMAIN WALL RESONANCE AND ITS EFFECT ON LOSSES IN FERRITES[†]

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ABSTRACT

The core loss characterization in ferrites under strong magnetic fields is studied for high frequency power converter applications. The measurements show strong dependence of core loss on the magnitude of dc or ac magnetic fields. An induced anisotropy field, due to material composition or applied bias field, causes multiple peaks in permeability and core loss characteristics at certain frequencies due to domain wall resonances. The characteristics of certain nickel-zinc ferrites, such as 4C4, degrade permanently after they are exposed to a strong magnetic field, which results in an irreversible alteration of the local magnetic anisotropies and their corresponding domain wall resonances.

1. INTRODUCTION

Ferrites are commonly used in high-frequency power conversion because of their low losses. In single-ended topologies, such as flyback or forward, the power transformer is subjected to a dc bias. In other topologies the core is unbiased under steady state operation. However, the core can be momentarily biased during start-up, line or load transients. Since manufacturers of ferrites do not provide core loss data under dc bias conditions, it is important to study the effect of a dc bias on ferrite characteristics, such as permeability and core loss, at high frequencies.

This paper provides measurement data illustrating the effect of the strong magnetic field on the core loss and permeability in commercial ferrites. The following core loss characterization technique was aimed at measurement of a core loss under dc bias condition. Manganese-zinc and nickel-zinc ferrites were chosen for testing since they are commonly used in high-frequency power application. The recent advancement of high-frequency converter topologies has enabled them to operate above 1 MHz. This has prompted designers to use nickel-zinc ferrites for power inductors and power transformers [1, 2].

In literature, a significant increase in permeability and loss at certain excitation frequencies was shown in a magnesium ferrite [3] and nickel ferrite [4] in a 10 to 100 MHz range and it was attributed to domain wall resonance. When the high-frequency magnetic field is applied parallel to the domain wall it exerts a pressure which causes the walls to oscillate. If the frequency of the excitation coincides with the natural frequency of the domain wall resonance (determined by the wall elasticity and associated mass) the amplitude of the oscillation increases dramatically [5]. The oscillating domain wall dissipates its energy through the interaction with magnetic domains and the magnetic particle grain boundary. The effect is noticeable only if a large number of domain walls resonate simultaneously. This is possible when domain walls are stabilized (stiffened) by a large anisotropy field. Such field can be created either externally by applying a dc current or can exist in the ferrite itself, such as, a remanence field. In some materials the stiffness of the domain wall is introduced by with the intent to minimize the domain wall movement in order to reduce the hysteresis loss. In nickel-zinc ferrites with excess iron and a small concentrations of cobalt, the domain walls are stabilized by uniaxial (magnetized in one easy direction) anisotropies induced locally within the magnetic domains during thermal annealing. The presence of Co^{2+} ions introduces a high orbital contribution to the ionic magnetic moment, which produces local anisotropy field and small displacements in domain walls in order to minimize the wall movement and thus minimize the loss. In such ferrites no external bias field is necessary to create an anisotropy field. However, if an external field is applied, it realigns the anisotropy field, and if an external field is large enough, it can irreversibly alter local anisotropy fields leading to an increase in the core loss and widening B-H loop [6, 7]. On the other hand, the manganese-zinc ferrites do not contain additives for domain wall stabilization. Therefore, an external dc magnetic field is necessary to create anisotropy.

The following section uncovers the role of magnetic wall resonance and its contribution to a core loss and permeability in certain ferrites used in high-frequency power conversion.

2. EXPERIMENTAL DATA

In order to find how a domain wall resonance affects the permeability and loss, the number of measured data points has to be very large, up to 10,000 per decade of frequency. Such an effort was possible only due to automated testing and computerized data acquisition and processing. The characterization of core loss was performed using the measurement setup in Fig. 1.

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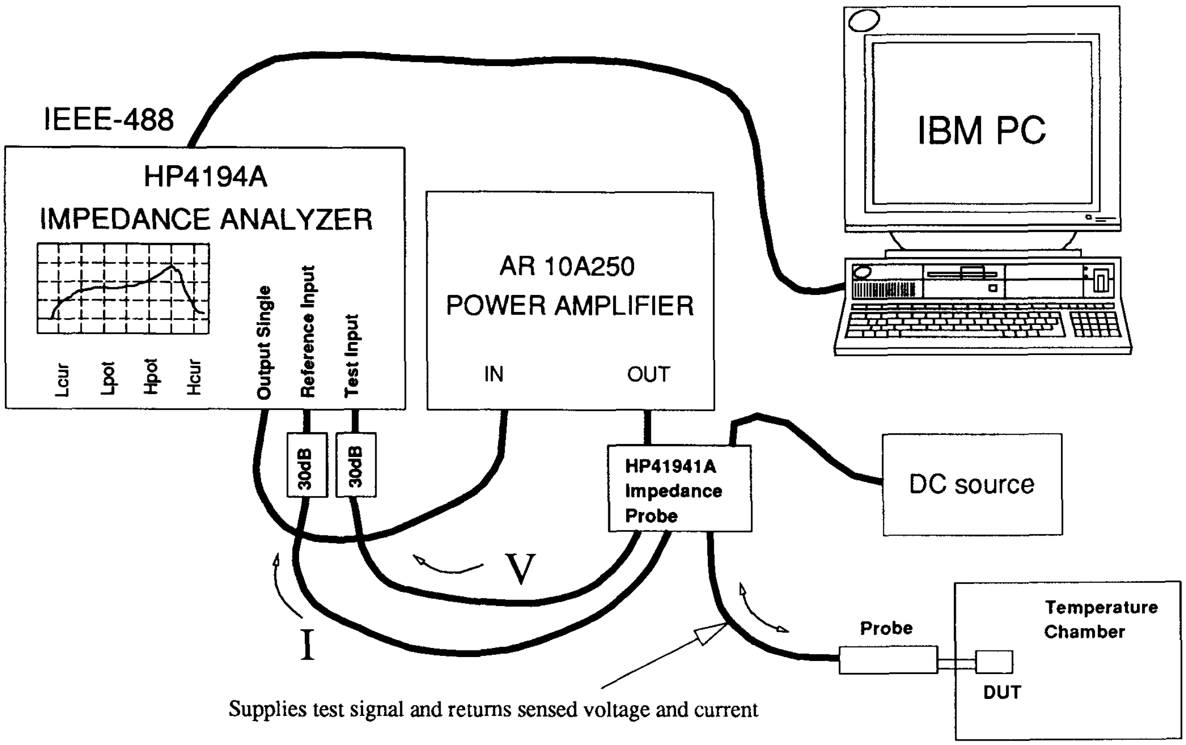

Fig. 1. Core loss measurement setup.

The HP4194A impedance analyzer with an HP41941A impedance probe together with a wide-band power amplifier were used to characterize magnetic materials in the frequency range from 100 kHz to 100 MHz. In order to measure core loss accurately, the winding losses were offset during the calibration procedure when the same winding coil without magnetic core was used as the 0 Ω reference. The impedance analyzer was controlled with an IBM PS/2 computer through IEEE-488 interface to maintain constant peak ac flux density during measurement [8].

Two grades of ferrites were tested: 4C4 (nickel-zinc) in the form of a toroid (Philips part no. 213T050) and 3F3 (manganese-zinc) in the form of a toroid (Philips part no. 768T188). 3F3 material was also tested in the form of an EE core (Philips part no. 814E250). The 4C4 ferrite was characterized at 10 mT ac flux density under different dc bias conditions. Bias current was applied through the impedance probe. The measured permeability of the 4C4 ferrite is shown in Fig. 2 and core loss in Fig. 3. Even without dc bias the characteristics contain a large number of strong peaks, causing the core loss to increase up to thirty times compared to the base line, contrary to the typical smooth curves given in the manufacturer data books. External dc bias field increases both the baseline and the peaks of the core loss characteristics. In stronger fields, new peaks occur and some old disappear due to the change of the domain structure and anisotropy field in the ferrite. The largest peaks increase core loss up to thirty times over the corresponding value before a dc bias is applied. The base line core loss doubles at the largest bias. After the bias is removed, the base line core loss remains permanently about 50% larger then the initial loss before a bias is applied. Since the peaks on loss and permeability characteristics are very narrow they can not be caused by relaxation. The spin resonance can not explain a phenomenon of multiple peaks because their resonant frequencies do not change proportionally to the applied field. Therefore, it is believed that the domain wall resonance is the cause of the multiple narrow peaks in ferrite characteristics. The width of the resonant peaks is shown in Figs. 4 and 5, which show expanded small part of the characteristics in Figs. 2 and 3. The 4C4 ferrite was also tested under a strong high-frequency ac magnetic field. The permeability is plotted in Fig. 6 and core loss in Fig. 7. The first set of characteristics was obtained from a core never before exposed to the magnetic field. The core was measured with a flux density of 10 mT.

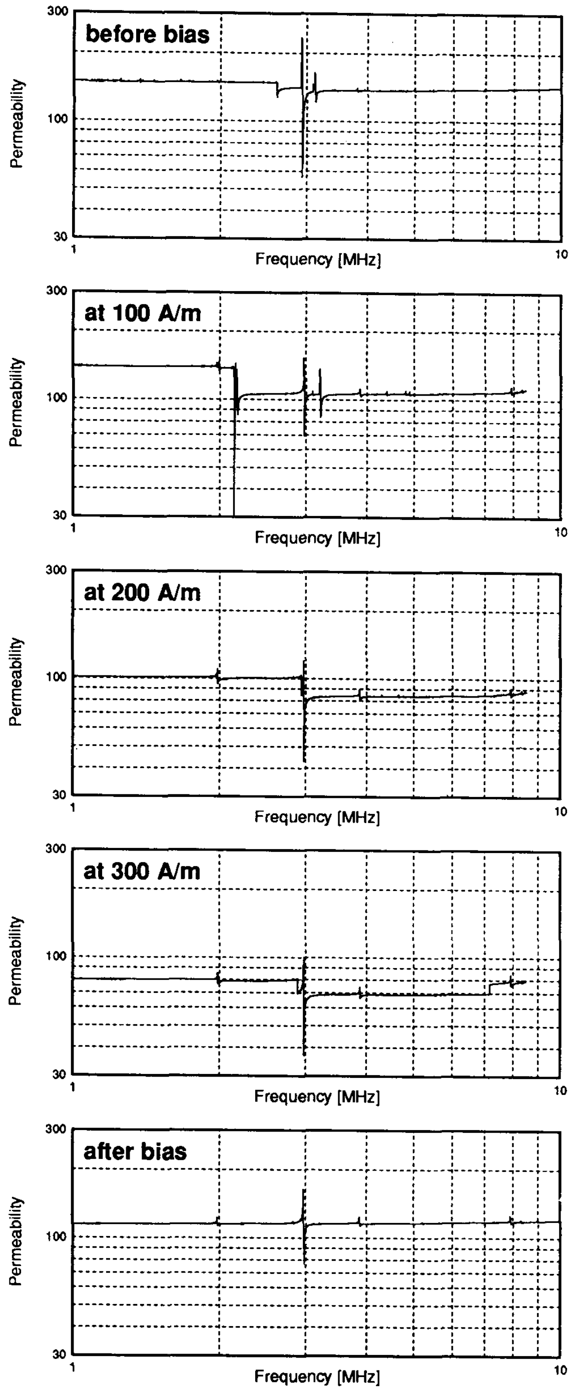

Fig. 2. Permeability of 4C4 ferrite at 10 mT ac flux density before dc bias, with dc bias, and after dc bias.

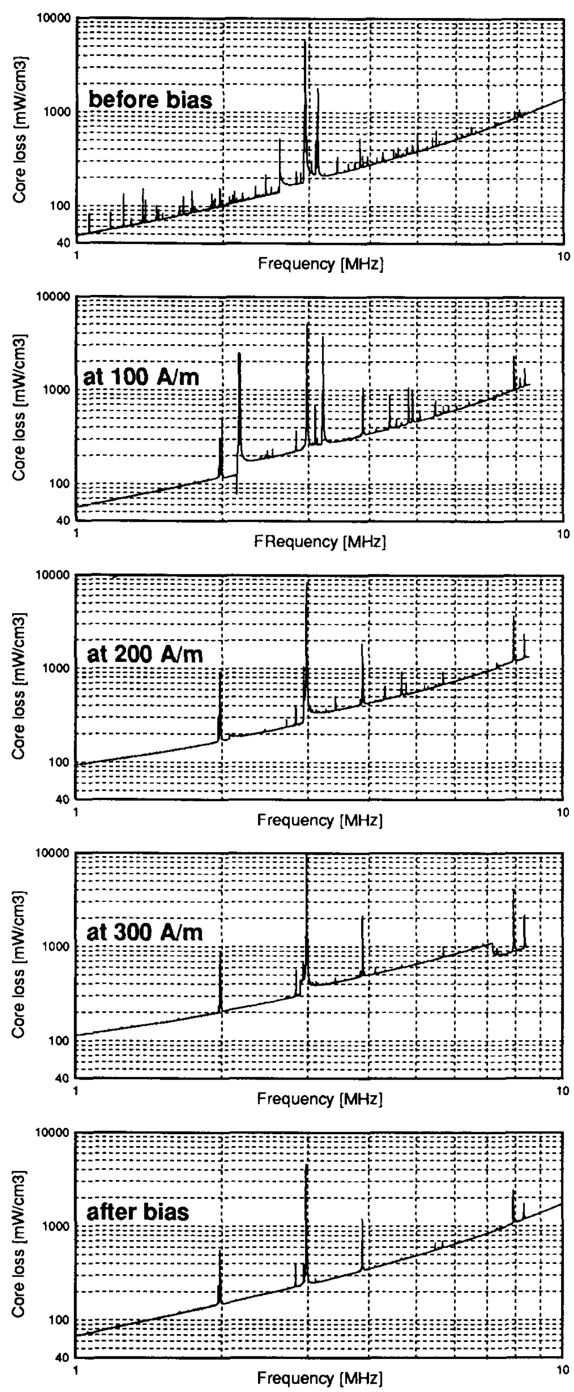

Fig. 3. Core loss of 4C4 ferrite at 10 mT ac flux density before dc bias, with dc bias, and after dc bias.

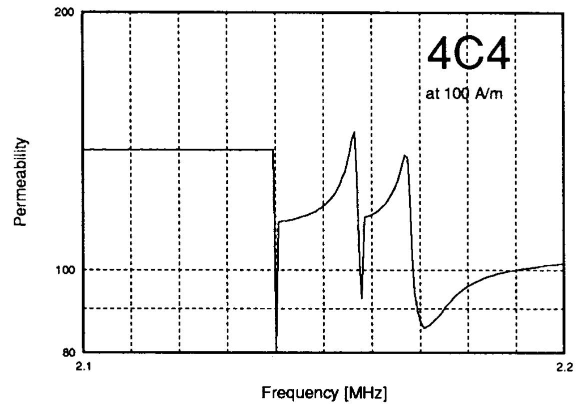

Fig. 4. Permeability of 4C4 ferrite at 10 mT ac flux density with 100 A/m dc bias field.

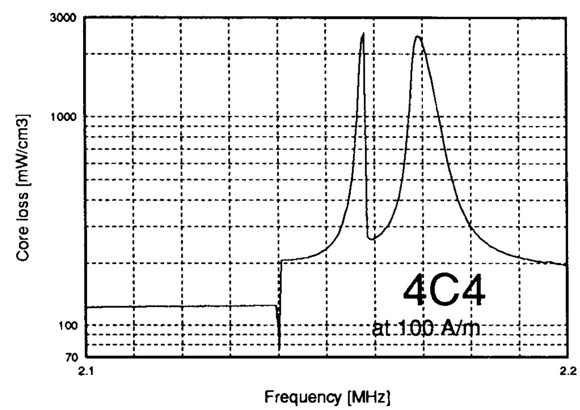

Fig. 5. Core loss of 4C4 ferrite at 10 mT ac flux density with 100 A/m dc bias field.

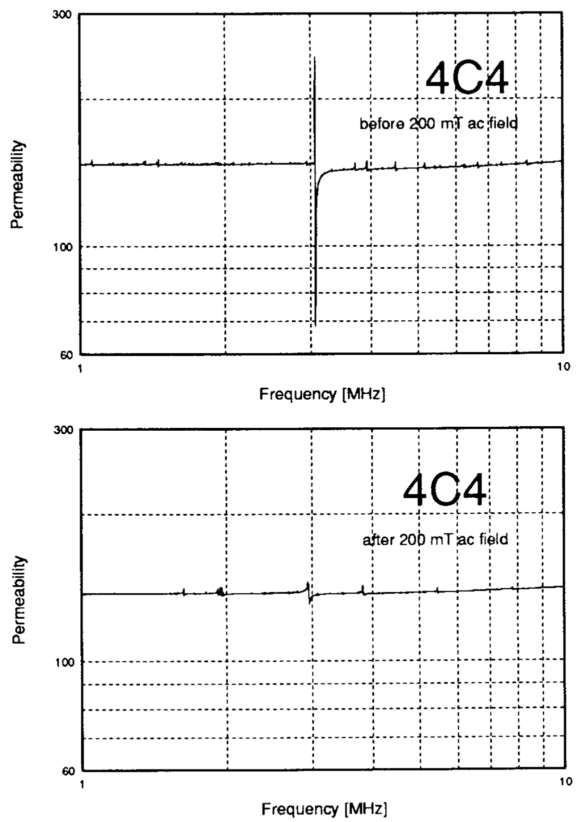

Fig. 6. Permeability of 4C4 ferrite at 10 mT ac flux density before and after treatment with 200 mT, 1 MHz magnetic field.

The same test was repeated on the same core after it was exposed to a magnetic field with peak flux density of 200 mT and frequency of 1 MHz. As shown in Figs. 6 and 7, when 4C4 ferrite was exposed to a strong high-frequency ac magnetic field, an increase in core loss, accompanied by a slight drop in the permeability, occurred similar to the previous case when a dc field was applied. About 20% increase of base line core loss was observed. The number of resonant peaks due to the domain wall resonance decreased because the large external ac field alters the local anisotropy fields of the virgin core. Therefore, the domain wall resonances are altered permanently after treatment with a strong ac magnetic field.

Another ferrite tested, 3F3 made by Philips, is a low-loss ferrite for high-frequency power conversion applications. Since it is a manganese-zinc ferrite, it does not have local anisotropy fields. The only field that can exist in this ferrite without an external dc bias field is a small magnetic remanence. However, when a large external dc bias field is applied, the magnetic domain wall resonance can be induced. The 3F3 ferrite was characterized at 50 mT ac flux density under different dc bias. The permeability and core loss characteristics for a toroid are shown in Figs. 8 and 9, respectively .

Since the anisotropy field in 3F3 ferrite is induced by the external field and this ferrite does not have local anisotropies, the magnetization of the core is much more uniform than that of 4C4 in the previous tests. Therefore, the characteristics of 3F3 ferrite shown in Figs. 8 and 9 have far fewer peaks due to the magnetic domain wall resonance. Also many smaller resonances might have been masked by the eddy current losses which are substantial in manganese-zinc ferrites. The core loss characteristic almost returns to the original shape after dc bias is removed because of low coercivity of the manganese-zinc ferrite. When 100 A/m bias field was applied, the core loss increased up to twenty times in the peaks of the core loss due to the domain wall resonance over the corresponding values without a bias. The base line core loss increased up to fifteen times.

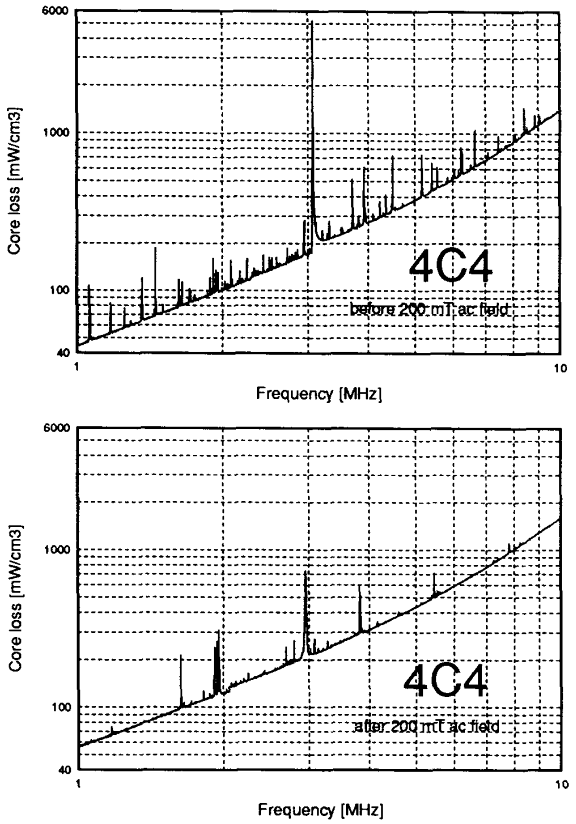

Fig. 7. Core loss of 4C4 ferrite at 10 mT ac flux density before and after treatment with 200 mT, 1 MHz magnetic field.

If the core has other then toroid shape, the field distribution in the core is much less uniform. The domain walls associated with different grains are no longer subjected to the same applied dc or ac magnetic field. Therefore, the permeability and core loss characteristics for the EE core, shown in Figs. 10 and 11, have smaller and broader peaks compared to the toroid core.

The magnetic domain properties are very sensitive to slight changes in chemical composition and sintering conditions during ferrite manufacturing. The characteristics presented here may be unique to the particular batch of ferrite and probably the size and shape of the core. The magnetic domain wall resonance can have adverse effects on the ferrite components used in the power supply. When the core is operated at a frequency coinciding with the domain wall resonance the core loss is significantly increased. The transformers and inductors using manganese-zinc ferrite cores, which operate with large ac flux density, are less likely to suffer a significant increase of core loss due to the domain wall resonance because a large ac field weakens induced anisotropy due to dc bias. However, in high-

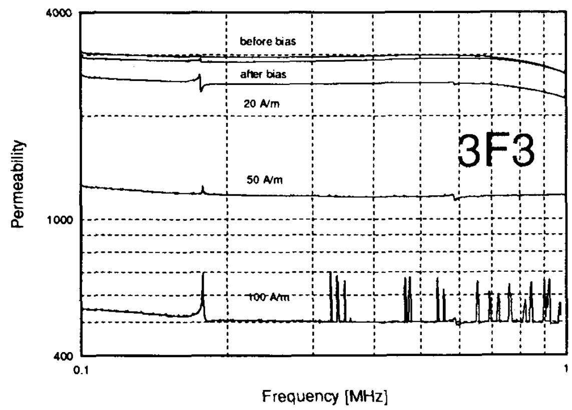

Fig. 8. Permeability of 3F3 ferrite in toroidal form at 50 mT ac flux density before dc bias, with dc bias, and after dc bias.

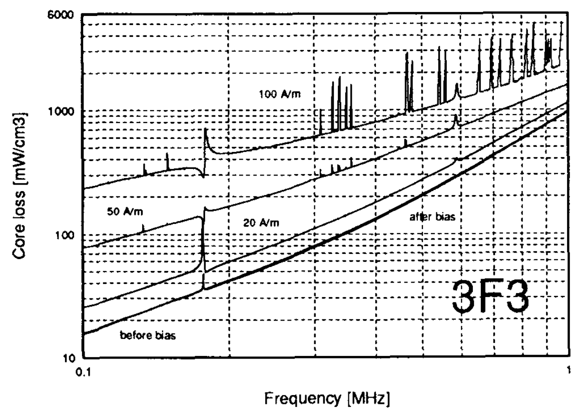

Fig. 9. Core loss of 3F3 ferrite in toroidal form at 50 mT ac flux density before dc bias, with dc bias, and after dc bias.

frequency applications, where the core is usually operated under low ac flux density levels and dc bias, it is much more susceptible to domain wall resonance, resulting in excessive loss and overheating. Therefore, special attention must be paid when designing high-frequency magnetic components with ferrite cores operating with a dc bias.

3. CONCLUSIONS

The core loss of ferrite materials increases substantially under a dc bias field. The magnetic domains oriented in one direction under a dc bias require more energy to change their orientation and thus cause more core loss.

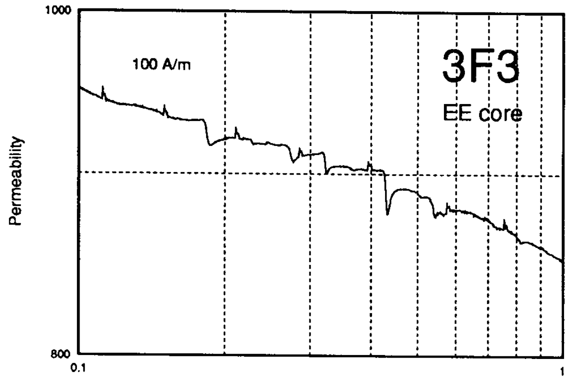

Fig. 10. Permeability and core loss characteristics of 3F3 ferrite in EE core form at 50 mT ac flux density with 100 A/m dc bias field.

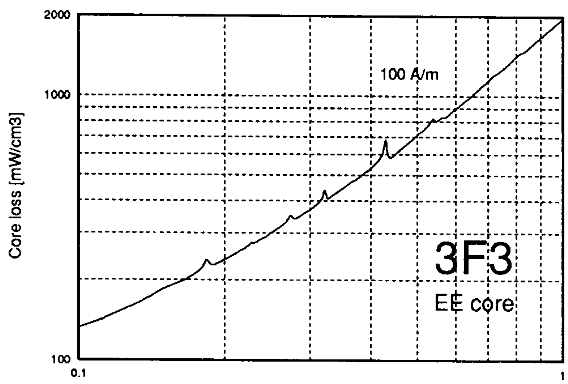

Fig. 11. Permeability and core loss characteristics of 3F3 ferrite in EE core form at 50 mT ac flux density with 100 A/m dc bias field.

Under a dc bias field high peaks occur on permeability and core loss characteristics at numerous discrete frequencies. The amplitude and number of peaks varies with the magnitude of the dc bias. It is believed that this phenomenon is due to the domain wall resonance. The dc bias induces anisotropy in the ferrite and stiffens the magnetic domain walls. The stiffened walls oscillate when are subjected to an excitation whose frequency coincides with the natural frequency of the domain walls. The larger the amplitude of the oscillations, the higher the peaks on the permeability and loss characteristics. The domain wall resonance occurs in manganese-zinc ferrites only when a dc bias is applied. However, in nickel-zinc ferrites with excess iron and a small addition of cobalt, such as 4C4, there exist internal anisotropy fields, which are sufficient to cause domain wall resonance under high frequency excitation even without a dc bias. A permanent change in permeability and core loss characteristics occur after the 4C4 nickel-zinc ferrite is exposed to a strong magnetic field, either dc or ac, because the local anisotropy is altered. This process is irreversible. If such ferrites are used in power transformers or inductors, special care must be taken to prevent the ferrite from excessive magnetic fields due to turn-on and turn-off transients, overvoltage, or overload conditions. Since both manganese-zinc and nickel-zinc ferrites exhibit excessive resonant losses due to magnetic domain wall resonance in the presence of a strong magnetic field, it is very important to carefully characterize the permeability and core losses and identify the resonances which result in significant losses. More research is necessary to quantify the effects of the domain wall resonance and to determine and control the amplitude and frequency of the resonant peaks through an improved manufacturing process.

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