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Hysteresis loss free soft magnetic ferrites based on Larmor precession

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A big enough transverse magnetic field applied to soft magnetic ferrite toroid can magnetize the ferrite to a saturation level in transverse direction and almost completely suppresses magnetic domain structures in the ferrite, the response to the longitudinal alternating electromagnetic field changes from the original domain wall displacements and spin rotations to the precession of magnetization around the transverse field, and the hysteresis loss disappears in the ferrites. Both theoretical and experimental results indicate that the permeability and magnetic loss in the ferrite can be controlled by adjusting the transverse magnetic field. A higher Q value with relatively low permeability can be achieved by increasing the transverse field, which ensures that the ferrite can be operated at high frequencies, with magnetic loss being very low.

Keywords: ferrites, Larmor precession, magnetic losses, hysteresis loss free

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1. Introduction

Soft magnetic materials are a kind of important functional material with wide applications in electric and electronic systems, they operate in alternating electromagnetic fields and can lose energy. Their performances are largely determined by magnetic loss characteristics, and reducing the magnetic loss has become a long-term challenge for soft magnetic materials.[1,2] Magnetic loss mainly comes from the contributions of two parts: hysteresis loss and eddy current loss. Hysteresis loss occurs through magnetic material's coercivity, which is related to complex magnetic domain wall displacements and spin rotations.[3–6] It is proportional to frequency, so soft magnetic material with low coercivity become quite an energy-losing material when the frequency is higher.[2,6,7] Eddy current loss is caused by electromagnetic induction, and it is proportional to the square of frequency and becomes dominant in total loss at high frequencies.[2,6,7] The residual losses may play an important role when the operating frequency is close to the material relaxation frequency.[6] Numerous efforts have been made to reduce the energy loss in soft magnetic materials. A common method of reducing hysteresis loss is to increase the magnetic permeability of the material by reducing the magnetocrystalline anisotropy of the material,[8] which is essentially to reduce the loss by reducing the magnetic field energy stored in the material, but this method is limited by Sneck's law.[9] Hysteresis loss can also be greatly reduced by adjusting the grain size to a value lower than the single domain size.[10,11] Eddy current loss can be effectively reduced by controlling grain size and increasing material resistivity or grain boundary resistivity.[12–20] However, the frequency-dependent loss of soft magnetic material is determined by using the existing loss mechanism, and it is difficult to obtain low-loss characteristics at high frequencies. It may be necessary to completely change the loss mechanism of soft magnetic materials to achieve low-loss characteristics at high frequencies.

It is generally accepted that when a parallel bias field and vertical bias field are applied to soft magnetic ferrite toroid, this configuration can amplify the domain wall contribution and the spin rotation contribution, respectively.[21] Recently it was proposed that the application of direct current (DC) transverse magnetic field to soft magnetic composites can reduce the hysteresis loss by changing the magnetic domain structure, and it was found that the increase of the magnetic field is beneficial to the decrease of loss.[22] Now, here arises a question whether the hysteresis loss disappears when the transverse field is large enough to magnetize soft magnetic material to a saturation level and magnetic domain structures are almost suppressed in the materials. In order to answer this question, it is necessary to study the magnetic properties of soft magnetic ferrites under different DC transverse magnetic fields.

2. Theoretical consideration

If a parallel DC magnetic field is applied, the relative amplitude permeability of the soft magnetic material under an alternating current (AC) field is close to 1 when the DC field magnetizes the material to a saturation level. However, the response of the soft magnetic material to the AC longitudinal magnetic field in the saturation magnetization state magnetized by DC transverse field changes from the magnetic do-

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main evolution process to the Larmor precession of the magnetic moment around the transverse magnetic field. Theoretically, Landau–Lifshitz–Gilbert equation

$$\frac{\boldsymbol{M}_{\rm s}}{{\rm d}t} = -\gamma \boldsymbol{M}_{\rm s} \times \boldsymbol{H}_{\rm eff} + \frac{\alpha}{\boldsymbol{M}_{\rm s}} \boldsymbol{M}_{\rm s} \times \frac{{\rm d}\boldsymbol{M}_{\rm s}}{{\rm d}t} \tag{1}$$

can be used to solve this problem. Here, γ is the gyromagnetic ratio, α the damping constant, $M_{\rm s}$ the saturation magnetization of the material, and $H_{\rm eff}$ the effective magnetic field applied to the magnetic moment. Generally, equation (1) gives a tensor susceptibility, but the off-diagonal components of the tensor susceptibility are very small and can be ignored considering that the operating frequency of soft magnetic materials is much lower than the ferromagnetic resonance frequency, and the susceptibility can be approximately regarded as a scalar. The susceptibility can be obtained by solving Eq. (1), as follows:[8,23]

$$\chi = \frac{\gamma_{\rm eff} M_{\rm s}}{\gamma_{\rm eff} H_{\rm eff} - \omega + {\rm i}\alpha_{\rm eff}\omega}. \tag{2}$$

Here, $\gamma_{\rm eff}$ and $\alpha_{\rm eff}$ are the effective gyromagnetic ratio and effective damping constant because of considering the different contributions of two magnetic sublattices in ferrites are considered, and ω is the circular frequency of the AC field. It can be found from Eq. (2) that the material can have a relatively large susceptibility if ω is much less than $\gamma_{\rm eff} H_{\rm eff}$ and the effective field is much smaller than the saturation magnetization. Under the condition of $\omega \ll \gamma_{\rm eff} H_{\rm eff} < \gamma_{\rm eff} M_{\rm s}$, the real part of permeability can be expressed as

$$\mu' = \frac{M_{\rm s}}{H_{\rm eff}} + 1. \tag{3}$$

Technical magnetization theory states that the hysteresis loss of soft magnetic material originates from irreversible domain wall displacement and irreversible spin rotation.[8] The domain structure in the material almost disappears after the magnetization has reached a saturation level by DC transverse field, thus the hysteresis loss becomes zero, which can greatly reduce the magnetic loss of the soft magnetic material.

3. Experiment

MnZn and NiZn ferrite samples were prepared by solid state reaction method. Analytical grade reagents Ni_2O_3, ZnO, MnO_2, and Fe_2O_3 were taken according to the required proportion indicated in chemical formula $Ni_{0.4}Zn_{0.6}Fe_2O_4$, $Ni_{0.7}Zn_{0.3}Fe_2O_4$, and $Mn_{0.7}Zn_{0.18}Fe_{2.12}O_4$, the mixtures were milled thoroughly in agate mortar and then filled into Al_2O_3 crucible and calcined at 900 °C–1000 °C for 2 h in air, and the resulting mixtures were reground to make them become small crystallites. The obtained powders were compacted into a toroidal shape under a 200-MPa pressure with using 5% PVA as a binder. The green NiZn toroids were sintered in air at 1180 °C–1250 °C for 2 h, and MnZn samples were sintered in 0.5-L/min flow nitrogen gas at 1200 °C–1240 °C for 2 h, followed by natural cooling to room temperature.

The crystal structure of obtained MnZn and NiZn ferrite sample were investigated by x-ray diffractometer (XRD, Rigaku D/max-2550 V/PC, Cu $K\alpha$ radiation). Their magnetic hysteresis loops were measured by a vibrating sample magnetometer (VSM, Quantum Design PPMS-VSM EC II) and their soft magnetic properties were measured by BH analyzer (Iwatsu SY-8258) with the highest frequency 1 MHz and 1% tolerance. The DC transverse magnetic field was provided by $SrFe_{12}O_{19}$ or NdFeB magnet plates, and the magnitude of the field was measured by a magnetometer with a Hall probe. Because the magnetic loss angle of the ferrite is close to zero under Lamor precession, there will be a large relative error in the measurement. The experimental value was the average of the four measurements. The average of multiple measurements is stable, and the measurement accuracy can be ensured.

4. Results and discussion

Theoretical conclusions need to be confirmed by experimental results. In order to verify whether the above theoretical considerations are correct, an $Mn_{0.7}Zn_{0.18}Fe_{2.12}O_4$ (MnZn) ferrite with initial permeability $\mu_{\rm i} = 570$ and saturation magnetization $M_{\rm s} = 400$ kA/m at room temperature is used in this work. A transverse magnetic field about $H_{\rm DC} = 160$ kA/m is applied to the MnZn ferrite toroid by using two NdFeB magnet plates, and magnetic properties of ferrite with or without transverse magnetic field are measured. The comparison of measured magnetic properties of MnZn ferrite with or without transverse magnetic field is made in Fig. 1. It can be found in Fig. 1(a) that the permeability of MnZn ferrite decreases from 570 to 25 after transverse field has been applied. Magnetic losses of MnZn ferrite at different magnetic inductions with and without transverse field are measured at 500 kHz, and the results are shown in Fig. 1(b), it is found that the magnetic loss with transverse field is only about a quarter of that without transverse field. Magnetic losses in one cycle *versus* frequency with and without field, measured at $B_{\rm m} = 30$ mT, are shown in Fig. 1(c), and it is found that magnetic loss increases monotonically with frequency increasing in the case without a transverse field, but it shows a loss peak at low frequency and relatively low losses at high frequency in the case with a transverse field. The comparison between the frequency-dependent quality factor Q values in the cases without and with field, measured at $B_{\rm m} = 30$ mT, is displayed in Fig. 1(d), indicating that the Q value with DC field is about two orders of magnitude bigger than that of without the field. These experimental results shown in Fig. 1 indicate that the transverse field can largely reduce magnetic loss of MnZn ferrite, although the

permeability is also severely suppressed. It should be noted in Fig. 1(a) that the permeability increases with AC field rising in the case without transverse filed, but it becomes constant, independent of AC field in the case with a transverse field. As is well known, the permeability is approximately proportional to the magnitude of the AC field in the Rayleigh region when the permeability is dominated by domain wall displacement,[8,24] that is

$$\mu' = \mu_{\rm i} + \eta H. \tag{4}$$

Here $\mu_{\rm i}$ is the initial permeability, η is the Rayleigh constant, and $\eta = 0$ leading to zero hysteresis loss. Constant permeability with AC field implies that the hysteresis loss becomes very low in the ferrite,[25] which is consistent with the theoretical analysis of hysteresis loss disappearing in the Larmor precession. In other words, constant permeability independent of magnetic field can be used as an indicator of whether the ferrite is in Larmor precession state.

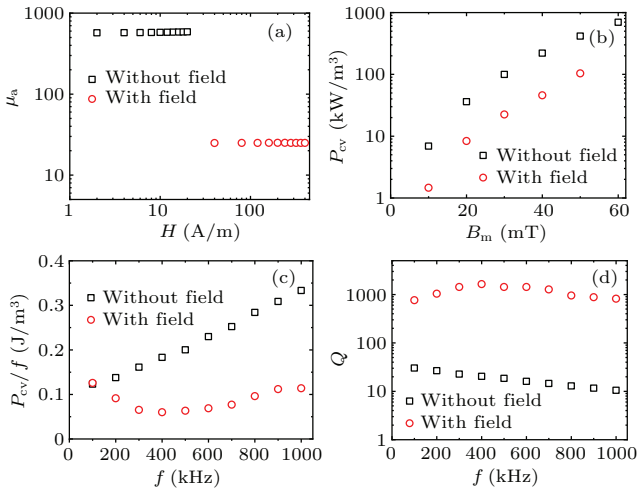


Fig. 1. Comparison between magnetic properties of Mn–Zn ferrite with and without transverse magnetic field, showing (a) variations of permeability with field, measured at 500 kHz, (b) variations of power loss with flux density $B_{\rm m}$, measured at 500 kHz, (c) variations of power loss in one cycle with frequency, measured at $B_{\rm m} = 30$ mT, and (d) variations of quality factor Q with frequency, measured at $B_{\rm m} = 30$ mT, for the cases with and without field.

In order to study the effects of different transverse magnetic fields on the magnetic properties of soft ferrites, an $Ni_{0.4}Zn_{0.6}Fe_2O_4$ (NiZn-4) ferrite with initial permeability $\mu_{\rm i} = 340$ and saturation magnetization $M_{\rm s} = 300$ kA/m and other MnZn ferrite with $\mu_{\rm i} = 590$ and $M_{\rm s} = 400$ kA/m are used to investigate the magnetic properties at different applied DC transverse magnetic fields. The transverse DC magnetic field is provided by $SrFe_{12}O_{19}$ or NdFeB magnet plates to produce different magnitudes of fields. Permeability *versus* magnitude of AC field data of NiZn-4 core, measured at $f = 200$ kHz and different DC transverse fields, are shown in Fig. 2(a). It can be found in Fig. 2(a) that the permeability of NiZn ferrite is severely suppressed by the DC field; an 110 kA/m DC transverse field reduces the permeability from about 350 to about 7.5. The larger the transverse field, the lower the permeability is, which is consistent with the result from Eq. (3). On the other hand, the permeability increases with AC field increasing when no DC field is applied, but it becomes almost constant, independent of AC field when 95 kA/m or 110 kA/m DC field is applied, which also implies that the hysteresis loss is eliminated in NiZn-4 ferrite. The magnetic losses *versus* frequency data of NiZn-4 ferrite, measured at $B_{\rm m} = 10$ mT and different DC transverse fields, are displayed in Fig. 2(b). It can be found in Fig. 2(b) that the magnetic loss of NiZn-4 ferrite is greatly reduced by DC field, for an extreme example, the magnetic loss is about 220 kW/m^3 at $f = 1$ MHz and no DC field, but it becomes about 2 kW/m^3 at $f = 1$ MHz and $H_{\rm DC} = 95$ kA/m, which is just about 1% of that of the former case. It should be noted that the magnetic loss is no longer a monotonical increase with frequency rising, but has obvious fluctuations with the frequency after a DC field has been applied. If the hysteresis loss is basically negligible in this circumstance and the magnetic loss is dominated by the eddy current loss, then the magnetic loss increases monotonically with the increase of the frequency, which is the expected result. So, the experimental result of magnetic loss fluctuates with frequency, which implies that there is a new magnetic loss mechanism plays important roles in the ferrites under transverse DC field, such as nuclear magnetic resonance. The nuclear magnetic resonance (NMR) frequency of Fe is calculated to be about 500 kHz–600 kHz in an effective magnetic field of 0.1 T, which is within the frequency range of our measurement, and NMR absorption can affect the magnetic loss of ferrite. On the other hand, it should be noted in Fig. 2(a) that the magnetic loss at $H_{\rm DC} = 110$ kA/m is larger than that at $H_{\rm DC} = 95$ kA/m, which indicates that the increase of DC magnetic field does not necessarily lead the magnetic loss to decrease further. Of course, the increase of the DC magnetic field will result in the decrease of the permeability of NiZn-4 ferrite, and the increase of the magnetic field energy stored in the material at the same magnetic flux density will also cause the magnetic loss to increase when the relative loss remains unchanged. However, only the increase of energy stored in ferrite cannot account for such a difference in magnetic loss between different DC fields. The magnetic properties of MnZn ferrite at different transverse DC fields are displayed in Fig. 3. The permeability *versus* magnitude of AC field data of an MnZn toroidal core measured at $f = 400$ kHz and different DC transverse field are shown in Fig. 3(a), and it can be noted in Fig. 3(a) that the DC transverse field can obviously suppress the permeability of MnZn ferrite, however, the permeability suppression in Fig. 3(a) is mild compared with the results in Fig. 2(a). For example, an $H_{\rm DC} = 110$ kA/m transverse field suppresses permeability to about 2.5% of that without DC field in NiZn-4

ferrite, but the same DC field only suppresses the permeability in MnZn ferrite to about 50% of that without DC field. The different levels of saturation magnetization of two ferrite samples may account for this difference according to Eq. (3). One is that a bigger saturation magnetization is beneficial to obtaining larger permeability, and the other is that the $H_{\rm eff}$ can be approximately expressed as

$$H_{\rm eff} \approx H - N_{\rm T} M_{\rm s}, \tag{5}$$

when the ferrite anisotropy field can be ignored. In Eq. (5), H is the applied DC transverse field, $N_{\rm T}$ the demagnetization factor in the transverse direction of the core, and $M_{\rm s}$ the saturation magnetization. Higher $M_{\rm s}$ results lower $H_{\rm eff}$ when H is a constant, which also leads to a larger permeability. This result is also consistent with the theoretical result obtained from Eq. (3). It can also be found in Fig. 3(a) that the permeability at $H_{\rm DC} = 110$ kA/m is proportional to the magnitude of AC field ($\eta \neq 0$), which implies that DC field is not bigger enough to magnetize MnZn ferrite to a saturation level, and some domain wall displacements and spin rotation play a role in permeability and hysteresis loss. When the DC transverse field is greater than 135 kA/m, the permeability becomes a constant independent of the AC field, it can be considered that the MnZn ferrite is magnetized to a saturation level when $H_{\rm DC} \geq 135$ kA/m, the magnetic domain structure almost disappears in the ferrite, and the hysteresis loss also approaches to zero. The cycle magnetic losses of MnZn ferrite *versus* frequency data measured at $B_{\rm m} = 20$ mT for different DC transverse fields are shown in Fig. 3(b). It can be found in Fig. 3(b) that the DC field reduces the magnetic loss and the larger the DC field, the more obvious the suppression of the magnetic loss is when the magnetic field is lower than 160 kA/m. The relation between magnetic loss and frequency becomes non-monotonical when $H_{\rm DC}$ is bigger than 135 kA/m, which also implies that there are other loss mechanisms that contribute significantly to the magnetic loss besides the eddy current loss when the core reaches saturation in the transverse direction. Comparing the results between Figs. 2(b) and 3(b), it can be found that the transverse magnetic field suppresses the magnetic loss in NiZn-4 ferrite more strongly than in MnZn, which is estimated to be related to the better electrical conductivity of MnZn and greater eddy loss. It should be pointed out that the room temperature magnetic loss of MnZn ferrite is about 80 kW/m^3 at $f = 1$ MHz, $B_{\rm m} = 20$ mT, and $H_{\rm DC} = 170$ kA/m, which is less than that of low loss MnZn ferrites as reported in Ref. [19], although the permeability of the MnZn ferrite is much smaller than the reported one.

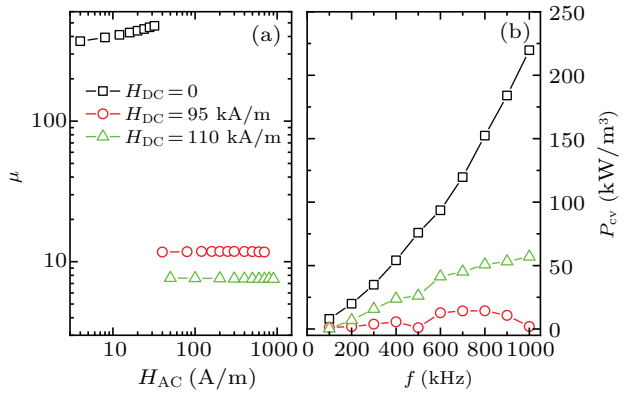


Fig. 2. (a) Variations of permeability with magnitude of AC magnetic field of NiZn ferrite, measured at 200 kHz and different DC transverse magnetic fields, and (b) variations of magnetic loss with frequency of NiZn ferrite, measured at 10 mT and different DC transverse magnetic fields.

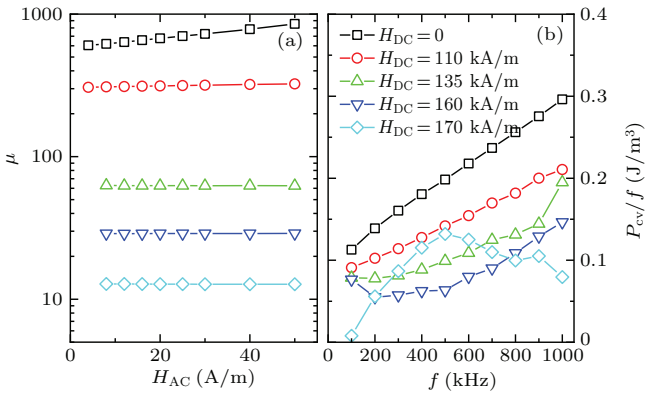


Fig. 3. (a) Variations of permeability with AC magnetic field of MnZn ferrite, measured at 400 kHz and different DC transverse magnetic fields, and (b) variations of magnetic loss in one cycle with frequency of MnZn ferrite, measured at 20 mT and different DC transverse magnetic fields.

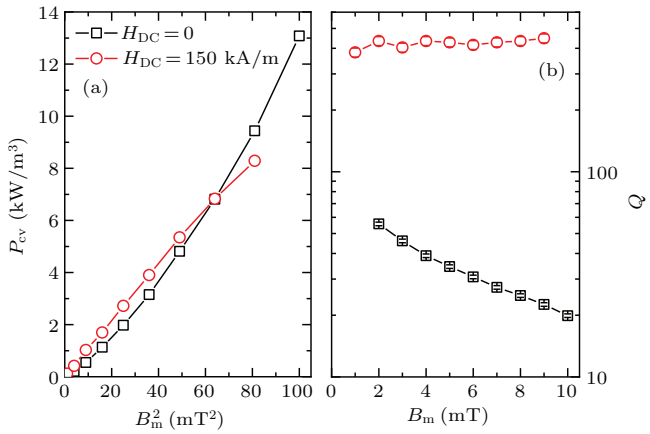


Fig. 4. (a) Variations of magnetic loss with square of magnetic flux density of NiZn ferrite, measured at 100 kHz with and without DC transvers magnetic field, and (b) variation of quality factor Q with magnetic flux density of NiZn ferrite, measured at 100 kHz with and without DC transvers magnetic field.

Regarding the conclusion that the hysteresis loss of soft magnetic materials disappears in Larmor precession, the permeability independent of AC magnetic field is given as experimental evidence in previous discussion, and more experimental evidence can be given here. Theoretical results show that when the magnetic flux density is low, the magnetization of the

soft magnetic material is in the Rayleigh region,[8,24] and the hysteresis loss is proportional to the third power of the magnetic flux density, and the eddy current loss is proportional to the square of the magnetic flux density. An $Ni_{0.7}Zn_{0.3}Fe_2O_4$ (NiZn-7) ferrite with initial permeability $\mu_i = 90$ and saturation magnetization $M_s = 380$ kA/m is used to measure magnetic loss at low magnetic flux density $B_m \leq 10$ mT, and the magnetic loss data of the ferrite *versus* the square of the magnetic flux density measured at $f = 100$ kHz are shown in Fig. 4(a). It can be found in Fig. 4(a) that the magnetic loss of NiZn-7 ferrite under DC field basically changes linearly with the square of B_m, which indicates that there is no B_m^3 component in the loss and implies that the hysteresis loss is eliminated in this circumstance. However, magnetic loss without DC field must contain the hysteresis loss component, the hysteresis loss proportional to B_m^3 leads the experimental results to deviate from the linearity and bend upwards. It should be pointed out that when the magnetic flux density is relatively small, the magnetic loss of NiZn-7 ferrite under DC field is larger than that without the field. One may argue that there is no hysteresis loss in the ferrite under DC field, so the magnetic loss of NiZn-7 under DC field should be less than that without the field. This is only true if no new losses are created in the ferrite under DC field. However, the non-monotonous variation of magnetic loss with frequency under DC field, as shown in Figs. 2 and 3, suggests some new magnetic loss processes in ferrite. The nucleus in the ferrite has a nuclear magnetic moment, which can generate NMR in an external magnetic field and also lead to magnetic loss. Like the treatment of residual losses due to magnetic resonance or magnetic relaxation, NMR-generated magnetic loss is proportional to the square of the magnetic flux density and has the same flux density dependence as eddy current loss.[6] If the loss of the ferrite in the transverse DC field is contributed by the eddy current loss and the residual loss caused by NMR, the magnetic loss at low magnetic flux density of the ferrite under DC field is greater than that without field, which is a reasonable result. On the other hand, since both the stored magnetic field energy and magnetic loss of ferrite under the transverse magnetic field are proportional to the square of the magnetic flux density, the relative loss of the material should be independent of the magnetic flux density. However, the magnetic loss of the ferrite without DC field includes the hysteresis loss, and the hysteresis loss increases faster than the storage of magnetic field energy in the material with the increase of the magnetic flux density, which causes the relative loss of the ferrite to increase with the magnetic flux density increasing. The values of quality factor Q of NiZn-7 ferrite *versus* magnetic flux density with and without DC field, measured at the same condition as in Fig. 4(a), are shown in Fig. 4(b). It can be found that Q value almost constant, independent of magnetic flux density in ferrite in the case with a DC field, while it decreases with the augmentation of magnetic flux density in ferrite in the case without transverse field, which is consistent with previous analysis. The results in Fig. 4 provide further experimental evidence that the soft magnetic material does not have hysteresis losses under Larmor precession.

5. Conclusions

Unlike general research, which is entangled in finding various methods to reduce the hysteresis loss and eddy current loss of soft magnetic materials, we propose a new method to reduce the magnetic loss of soft magnetic materials by eliminating hysteresis loss. Experimental results of ferrites under DC transverse magnetic field demonstrate that the DC magnetic field can suppress the permeability and magnetic loss of the ferrites. However, the ferrites still have relatively large permeability and low magnetic loss due to magnetic moment precession around DC field after the ferrite has been magnetized to a saturation level by the DC transverse field, which is consistent with the theoretical analysis based on the Landau–Lifshitz–Gilbert equation. Reduction of magnetic loss can be attributed to the elimination of hysteresis loss accompanied with the disappearance of the magnetic domain structure after the ferrite has been magnetized to a saturation level. The use of DC transverse field to adjust the permeability and magnetic loss offers us the possibility to tailor soft magnetic properties for applications at high frequency.

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