Energy Losses in Soft Magnetic Ferrites

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Soft ferrites are essential low-loss magnetic materials for high-frequency applications. This work presents a broadband experimental and theoretical analysis of magnetization dynamics and loss mechanisms in Mn-Zn and Ni-Zn ferrites from DC to the GHz range. Fluxmetric and transmission line measurements are interpreted within an extended Statistical Theory of Losses (STL), enabling quantification of the respective roles of domain wall (dw) motion and magnetization rotation and decomposition of losses into distinct components associated with eddy currents and spin damping. In Ni-Zn ferrites, eddy current losses are eliminated and a thermally activated magnetic after-effect can strongly affect the dissipation behavior. The results clarify the physical origin of broadband magnetic losses in soft ferrites.

***Index Terms*—Loss separation, magnetic losses, magnetic resonance, soft ferrites.**

I. Introduction

MORE than a century after the first studies [1] correlating chemical composition with magnetic properties of soft ferrites, these materials remain essential for power electronics and radio-frequency applications, owing to mature fabrication routes, cost-effective mass production, and intrinsically low magnetic losses. Extensive research has addressed the control of preparation conditions, magnetic anisotropy, and electrical resistivity via compositional tuning and chemical doping, together with temperature-dependent characterization. Several studies have led to a longstanding debate on the physical origin of magnetic dispersion and loss, particularly concerning the respective contributions of dw motion and magnetization rotation [2]. In this communication we discuss the quantification of these processes and their distinct dissipation mechanisms, interpreted within the physically grounded framework of the generalized STL.

II. Assessment of broadband magnetic behavior

To capture the effective magnetic response of soft ferrites over multiple frequency decades, fluxmetric measurements spanning DC to 10 MHz and peak polarizations J_p up to $\sim$ 200 mT are complemented by transmission line characterization extending into the GHz range [3]. Figure 1 presents representative magnetic loss data measured in the laboratory-grade Mn-Zn ferrite at 100 °C. The pronounced nonlinear behavior encompasses essentially the full relevant material response, which can be consistently interpreted using the complex permeability spectrum shown in Fig. 2. These spectra are obtained via a physically justified elliptical approximation of the hysteresis loop. We demonstrate how the STL, originally developed for conductive Fe-Si laminations, can be extended to nearly insulating soft ferrites [4]. The frequency-independent hysteresis loss associated with Barkhausen jumps, strongly localized dw displacements in space and time, defines the quasi-static contribution (W_hyst in Fig. 1). Classical

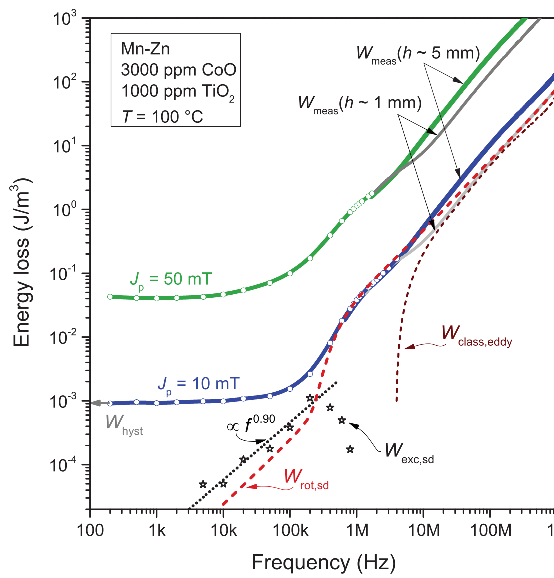

Fig. 1. Magnetic loss in Mn-Zn ferrite as a function of magnetizing frequency, showing complete loss separation at $J_\mathrm{p} = 10$ mT.

literature treatments of eddy current loss neglect the heterogeneous microstructure of ferrites, consisting of semiconductive grains separated by nanometer-scale, poorly conducting grain boundaries. This structure leads to a relaxation dispersion of electrical resistivity in Mn-Zn ferrites, with its real component decreasing from several Ωm at low frequencies to values lower by up to two orders of magnitude above the MHz range due to effective short-circuiting of grain boundaries. Such behavior can be captured by multiscale modeling of square grains separated by semi-insulating boundaries. In sufficiently thin samples (thickness $\sim$ 1 mm), the total measured loss is effectively eddy-current-free and classical eddy current loss ($W_\mathrm{class,eddy}$) becomes relevant only in thicker samples above a few MHz, as evidenced by the bifurcation between the losses

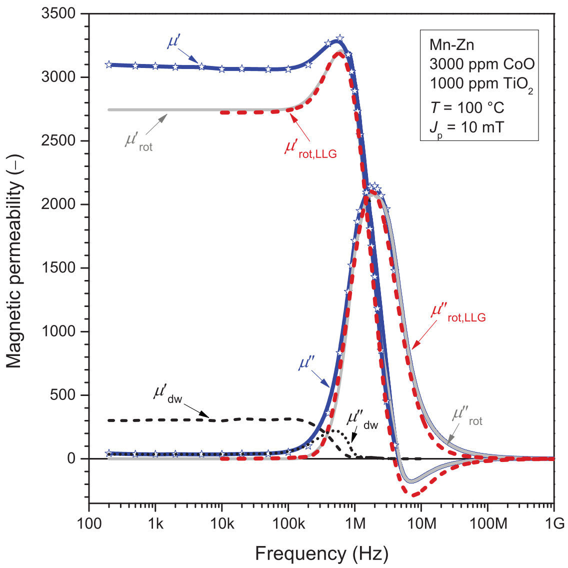

Fig. 2. Real μ' and imaginary μ'' permeability components versus frequency in Mn-Zn ferrite, decomposed into dw (μ'_{dw}, μ''_{dw}) and rotational (μ'_{rot}, μ''_{rot}) contributions. The rotational component separated from experimental data is compared with the theoretical prediction based on the LLG equation ($\mu'_{\mathrm{rot,LLG}}$, $\mu''_{\mathrm{rot,LLG}}$).

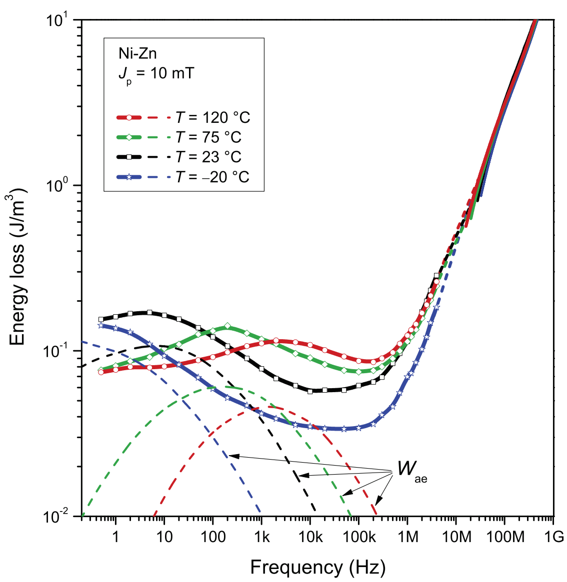

Fig. 3. Temperature evolution of magnetic losses in Ni-Zn ferrite (4C65) versus frequency, with estimated after-effect-related extra loss contribution W_{ae}.

in thin and thick sample in Fig. 1. A second eddy current-related loss term, attributed to dissipation around moving dws, can be shown to be negligible across the entire frequency range and is therefore excluded from further analysis. Once electron–lattice energy absorption is fully accounted for, the remaining dissipation mechanism is spin damping, which is intrinsically favored in insulating ferrites. Using permeability spectra measured at two different peak polarizations J_{p}, we demonstrate a physically self-consistent decomposition of real and imaginary permeability components into dw and rotational contributions, as illustrated in Fig. 2. In Mn-Zn ferrites with relatively low magnetic anisotropy, magnetization reversal exhibits a substantial contribution from rotational processes. Dws, experiencing stronger damping from eddy current counterfields and spin damping than intradomain spin rotations, are fully relaxed by frequencies around 1 MHz. In contrast, the resonant absorption of energy associated with rotational processes is accurately described by the Landau-Lifshitz-Gilbert (LLG) formalism (Fig. 2). Resonance broadening originates from the polycrystalline microstructure and the frequency-dependent distribution of effective anisotropy fields arising from the interplay between intergranular demagnetizing fields and magnetocrystalline anisotropy. The resulting complex permeability can be directly translated into the rotational spin damping loss component $W_{\mathrm{rot,sd}}$, which accounts for the high-frequency portion of the eddy-current-free loss in thin samples (Fig. 1). Subtraction of W_{hyst} and $W_{\mathrm{rot,sd}}$ from the measured loss yields the dynamic excess loss $W_{\mathrm{exc,sd}}$, attributed to spin damping related friction associated with moving dws. This contribution follows a power-law dependence $W_{\mathrm{exc,sd}} \propto f^{q}$ with $0.5 < q < 1$, reflecting the absence of eddy current counterfields and the nonuniform distribution of pinning fields [5].

In Ni-Zn ferrites, the extremely high broadband electrical resistivity exceeding 10^5 Ωm effectively eliminates eddy current losses, while the higher magnetic anisotropy shifts the ferromagnetic resonance beyond 10 MHz. We emphasize the peculiar loss behavior observed in Ni-Zn ferrite (Ferroxcube 4C65), manifested as a temperature-dependent local maximum whose central frequency shifts to higher values with increasing temperature. This feature is attributed to a thermally activated dw relaxation, introducing an additional loss component associated with atomic and electronic diffusion interacting with moving dws [3]. Using an average activation energy of $E_{\mathrm{a}} = 0.66$ eV, the temperature evolution of the after-effect-related loss component W_{ae} can be quantitatively estimated, as illustrated in Fig. 3.

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References

[1] S. Hilpert, "Correspondence as to structure and origin in magnetic properties of ferrite and iron oxide," *Ber. Dtsch. Chem. Ges.*, vol. 42, pp. 2248–2261, 1909.

[2] T. Tsutaoka, "Frequency dispersion of complex permeability in Mn-Zn and Ni-Zn spinel ferrites and their composite materials," *J. Appl. Phys.*, vol. 93, no. 5, pp. 2789–2796, 2003.

[3] S. Dobák, C. Beatrice, V. Tsakaloudi, and F. Fiorillo, "Magnetic losses in soft ferrites," *Magnetochemistry*, vol. 8, no. 6, 2022, Art. no. 60.

[4] F. Fiorillo, C. Beatrice, O. Bottauscio, A. Manzin, and M. Chiampi, "Approach to magnetic losses and their frequency dependence in Mn-Zn ferrites," *Appl. Phys. Lett.*, vol. 89, no. 12, 2006, Art. no. 122513.

[5] E. Ferrara, F. Fiorillo, C. Beatrice, S. Dobák, C. Ragusa, A. Magni, and C. Appino, "Characterization and assessment of the wideband magnetic properties of nanocrystalline alloys and soft ferrites," *J. Mater. Res.*, vol. 33, no. 15, pp. 2120–2137, 2018.