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# **A comprehensive approach to broadband characterization of soft ferrites.**

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## Abstract

We present and discuss methods, setups, and results concerning the characterization of Mn-Zn and Ni-Zn ferrites in the frequency range DC – 1 GHz, by which we bring to light the physical mechanisms responsible for the observed frequency behavior of magnetic losses  $W$  and permeability  $\mu$  and provide thorough assessment of the broadband response of the material. A comprehensive array of polarization  $J_p$  and frequency  $f$  values is investigated. A fluxmetric approach is applied up to a few MHz, giving way to a transmission line method at higher frequencies, up to 1 GHz. The fluxmetric measurements are made at defined  $J_p$  value, typically from a few mT to some hundred mT. The waveguide characterization, centered on the use of a network analyzer, is instead made under defined exciting power. But a full experimental  $W(J_p, f)$  matrix up to 1 GHz and  $J_p$  values typically belonging to the Rayleigh region is in any case retrieved, thanks to the linear response of the material at high-frequencies. Disaccommodation measurements are the route followed in these experiments to separate the rotations from the domain wall process at all frequencies. Whatever the magnetization mode, the role of eddy currents in Mn-Zn ferrite losses is put in evidence by means of resistivity measurements and ensuing multiscale numerical modeling, the loss experiments being made on progressively thinned ring samples. It is concluded that an eddy current free  $W(J_p, f)$  behavior can always be obtained, which can be decomposed into domain wall and rotation related contributions. The latter can be calculated assuming a suitable distribution of the effective internal anisotropy fields and its introduction in the Landau-Lifshitz-Gilbert derivation of the rotational susceptibility.

## 1. Introduction

Mn-Zn and Ni-Zn sintered ferrites are the materials of choice for applications where high permeability and low losses are required in a vast range of frequencies [1, 2]. But the physical interpretation of the ferrite behaviour, namely magnetic loss and permeability, across the broad frequency domain useful for the various applications in electrical, electronic, and telecommunication devices, lags behind today's technological developments. This derives in part from lack of comprehensive magnetic characterization, typically restricted in the literature to relatively narrow ranges of frequency and polarization values [3-5]. These materials do actually display a complex magnetic phenomenology, where domain wall (dw) processes and magnetization rotations, combining in comparable proportions under DC excitation, evolve with the magnetizing frequency through different dissipation channels, descending from eddy current and spin damping phenomena. Experiments should then possibly aim at identifying and separating the different types of magnetization processes and the underlying dissipation mechanisms. In this paper we discuss an ensemble of methods and experiments we have developed for the characterization of the magnetic properties of Mn-Zn and Ni-Zn ferrites from quasi static excitation to microwave frequencies, that is, up to full relaxation of the material response. We show how fluxmetric and transmission line measuring methods seamlessly combine to provide a broad matrix of values of the complex permeability and the energy loss as a function of peak polarization  $J_p$  and frequency  $f$ . The role of eddy currents in Mn-Zn ferrites is brought to light measuring the electrical resistivity versus  $f$  and making loss measurements as a function of the sample thickness. The electrical and magnetic results are reconciled by multiscale modelling of eddy current circulation in the real heterogeneous material. The ubiquitous presence of the magnetic aftereffect is exploited to separate the dw and rotational contributions to the magnetization process. By disaccommodation experiments performed versus frequency it is verified, in particular, that the dw processes subside, in general, on entering the MHz range, and magnetization rotations prevail. These display damped resonant response, with local resonance frequencies distributed according to the distribution of the local effective anisotropy fields, the combination of magnetocrystalline anisotropy and internal demagnetizing fields.

## 2. Measurement of the electrical resistivity.

Knowledge of the electrical resistivity and its dependence on frequency is basic to the analysis of the energy losses of the Mn-Zn sintered ferrites. The typically measured resistivity values are in fact compatible, contrary to the case of the nearly insulating Ni-Zn ferrites, with the existence of eddy current generated losses [1, 5, 6, 7]. Efforts are therefore spent towards loss reduction by increasing the resistivity through addition of segregating oxides, like CaO, SiO<sub>2</sub>, Nb<sub>2</sub>O<sub>5</sub>, TiO<sub>2</sub>, and fine control of the partial pressure of oxygen during sintering [4, 8, 9]. It can be shown, however, that the eddy current loss contribution can be suppressed, at least below a few MHz, if the sample is sufficiently small [10]. This finding can be quantitatively assessed by modelling the eddy current behaviour versus frequency, where the real heterogeneous structure of the sintered material, where the semiconducting grains are separated by nearly insulating boundary layers, is taken into

68 account [11]. The capacitive properties of the nanometer-thick grain boundaries, resulting into an extremely  
 69 high value of the relative permittivity of the sintered material (a few  $10^4$ ), leads to eddy currents evolving with  
 70 increasing frequency from local, grain boundary limited, to intergrain patterns, eventually investing the whole  
 71 sample cross-section [9].

72 The real  $\rho'$  and imaginary  $\rho''$  resistivity components of the investigated Mn-Zn ferrites have been determined  
 73 by means of standard four-wire measurements of the electrical impedance of cut rings, where good voltmetric  
 74 and amperometric electrical contacts are ensured at the sample ends by sandwiching indium strips between the  
 75 freshly polished sample surface and the copper leads and applying uniform pressure. The temperature of the  
 76 sample, which was kept in a temperature controlled plastic chamber, was controlled up to  $T = 140$  °C by means  
 77 of microthermocouple stuck on it. The impedance was measured up to  $f = 15$  MHz either by an Agilent 4294A  
 78 LCR meter or a built-on-purpose setup employing an Agilent 33220A function generator and a 500 MHz  
 79 Tektronix TDS814 oscilloscope.

80 The simplest way to describe the electrical behavior of the Mn-Zn sintered ferrites consists in adopting the  
 81 equivalent RC circuit shown in Fig. 1a, where the response of the grains and their boundary layers is described  
 82 through the resistance  $R_g$  (the grains) and the parallel of a capacitance  $C_b$  and a resistance  $R_b$  (the boundary).  
 83 More complex equivalent circuits can actually be envisaged, by additionally considering the capacitance of the  
 84 grains and possible self-inductance effects [5] and by distinguishing between intrinsic and extrinsic grain  
 85 boundaries and the related resistance-capacitance equivalent circuits [9]. It appears, however, that the circuit in  
 86 Fig. 1a of impedance

$$87 \quad Z(f) = R_g + R_b / (1 + \omega^2 R_b^2 C_b^2) - j\omega R_b^2 C_b / (1 + \omega^2 R_b^2 C_b^2) \quad (1)$$

88 can satisfactorily emulate the electrical response of all the investigated Mn-Zn ferrites, as shown by the  
 89 example provided in Fig. 1, where the correspondingly predicted behaviors of  $\rho'(f)$  and  $\rho''(f)$  for an N87-type  
 90 ferrite at room temperature and at  $T = 100$  °C (dashed lines) are compared with the experiments. By  
 91 assimilating the sample as an ordered assembly of cubic grains of side equal to the measured average grain size  
 92  $\langle s \rangle$ , we can estimate, according to the predicted resistivities  $\rho'(f)$  and  $\rho''(f)$ , the resistivity of the grain  $\rho_g$  and  
 93 the parameters of the boundary layer: resistivity  $\rho_b$ , thickness  $\delta$ , and permittivity  $\epsilon = \epsilon_0 \epsilon_r$ . These quantities are  
 94 shown for the N87-type ferrite, where  $\langle s \rangle = 16$   $\mu\text{m}$ , in Table I. The estimated  $\delta$  value, of the order of the  
 95 elementary cell size, appears somewhat lower than the actual grain boundary thickness, as revealed by electron  
 96 transmission microscopy [4, 5]. One might actually consider  $\delta$  as an electrically equivalent thickness, which is  
 97 expected to attain the nanometer value in ferrites with high relative permittivity (say around  $10^5$ ) [12]. It is  
 98 observed in Table I that, according to the observed behaviour of  $\rho'(f)$  and  $\rho''(f)$  and Eq. (1), the increase of  
 99 temperature affects to considerable extent only the resistivity of the boundary layer.

100  
 101  
 102

## 103 2. Domain wall displacements versus rotational processes.

104 Soft ferrites are characterized by very low magnetocrystalline anisotropy, resulting from the mechanism of  
105 anisotropy compensation [13], and high permeability values can be obtained upon the temperature range useful  
106 for applications. Magnetization rotations and dw displacements require then comparable driving field strengths  
107 and combine all along the magnetization curve. It is widely held, that, contrary to the case of conventional Fe-  
108 based polycrystalline soft magnets [14], the rotational processes may play a dominant role at low inductions  
109 [15, 16], where most broadband applications lie, but it is difficult to quantify their contribution and the related  
110 frequency dependence. At such inductions one may indeed take advantage of the pseudoellipsoidal shape of the  
111 DC hysteresis loop and provide meaning to its evolution with frequency through the behaviour of the real  $\mu'$   
112 and imaginary  $\mu''$  permeability components. The energy loss can in such a case be expressed as

$$113 \quad W(J_p) = \pi J_p^2 \mu'' / (\mu'^2 + \mu''^2) \text{ [J/m}^3\text{]}. \quad (2)$$

114 Nakamura, et al. [17, 18] proposed to separate dw  $\mu_{dw}$  and rotational  $\mu_{rot}$  initial permeabilities and their  
115 frequency dependence in Ni-Zn sintered ferrites by postulating resonant and relaxation response for  $\mu_{dw}$  and  
116  $\mu_{rot}$ , respectively, and making best fitting of the measured  $\mu'$  and  $\mu''$  by means of five adjustable parameters.  
117 The so obtained  $\mu'_{dw}(f)$ ,  $\mu''_{dw}(f)$ ,  $\mu'_{rot}(f)$ , and  $\mu''_{rot}(f)$  behaviours are, however, highly hypothetical and basically  
118 unproved. In this work we have separately identified the complex permeabilities  $\mu_{dw}(f)$  and  $\mu_{rot}(f)$  combining  
119 the measurement of the initial magnetization curve with experiments on the time decay of the initial  
120 permeability (disaccommodation). Examples of quasi-static initial magnetization curves, limited to their low-  
121 field portion ( $J_p \leq 50 - 100$  mT) are provided in Fig. 2a. It is the induction region of actual interest for most  
122 broadband applications of soft ferrites, where, as shown in Fig. 2a, the constitutive equation  $J(H)$  closely  
123 follows the Rayleigh law  $J = aH + bH^2$  and the permeability is a linear function of the field  $\mu(H) = a + bH$  (Fig.  
124 2b). A reversible term  $aH$ , where  $a = \lim_{H \rightarrow 0} \mu(H)$  is the initial permeability, and an irreversible contribution  
125  $bH^2$  are thus identified. The irreversible magnetization is exclusively provided by the dw displacements, while  
126 both rotations and dw motion combine to provide the reversible term. Assuming a uniform distribution of the  
127 easy axes of the polycrystalline material, it is obtained that the rotational permeability is to good approximation  
128 constant in a large part of the Rayleigh region.

129 Permeability and energy losses have been measured in Mn-Zn and Ni-Zn ring samples at different  $J_p$  values,  
130 starting from  $J_p = 1$  mT, from a few hundred Hz (quasi-static regime) up to about 10 MHz by means of a  
131 calibrated hysteresisgraph/wattmeter. These measurements remarkably show that within the previous restricted  
132  $J_p$  limits the  $\mu'(f)$  and  $\mu''(f)$  curves (and, *a fortiori*, the  $W(f)$  curves) all collapse onto a single curve [19], as  
133 illustrated for two  $J_p$  values in the example given in Fig. 3. This permits us to extend the experimental  
134 frequency band towards the GHz range by relaxing the requirement of a defined measuring value of  $J_p$ . We  
135 have applied for this a transmission line method, using a Vector Network Analyzer (Agilent 8753A), where the  
136 complex permeability is obtained between about 1 MHz and 1 GHz by measuring the impedance of the ferrite  
137 ring sample, placed at the bottom of a shorted coaxial line, in reflection mode under constant incident power  $P$

138 = 10 mW [20]. Fig. 3 provides some important piece of information. Based on our previous analysis of the  
 139 Rayleigh diagram, we can state first that any difference  $\mu'_{\text{diff}} = \mu'(J_{p2}) - \mu'(J_{p1})$ , with  $J_{p2} > J_{p1}$ , is entirely  
 140 associated with the dw processes and can be written as  $\mu'_{\text{diff}} = \mu'_{\text{dw}}(J_{p2}) - \mu'_{\text{dw}}(J_{p1})$ . From the observed  
 141 frequency dependence of  $\mu'_{\text{diff}}(f)$  it is recognized that the dw dynamics is of relaxation type. The hump on the  
 142  $\mu'(f)$  curve, the landmark trait of ferromagnetic resonance, thus originates in the rotational process. It tends to  
 143 drown into the increasing contribution by the relaxation-type dw term  $\mu'_{\text{dw}}$  with increasing  $J_p$ . Coalescing of  
 144 the different  $\mu'(J_p)$  curves at high frequencies is thus simply understood as a consequence of the decrease and  
 145 disappearance of  $\mu'_{\text{dw}}(f)$  beyond the relaxation frequency, the surviving rotational term  $\mu'_{\text{rot}}(f)$  being, as  
 146 previously remarked, quite independent of  $J_p$  in the Rayleigh region. The relaxation character of the dw  
 147 dynamics is confirmed by disaccommodation experiments, where the decay of the initial permeability versus  
 148 time under a weak AC field is measured immediately after the demagnetization process. Disaccommodation is  
 149 exclusively related to the dws, whose oscillatory motion slightly shrinks with time under the stabilizing action  
 150 of diffusing cations. We have shown in a previous work [11] that the rate of decay of  $\mu'$  (of logarithmic type)  
 151 in Mn-Zn ferrites decreases with increasing the frequency of the exciting field in a way totally consistent with a  
 152 relaxation dispersion of the dw permeability, eventually tending to revert, according to the theory, to a slight  
 153 increase beyond the cutoff frequency. This equally happens in Ni-Zn ferrites, as demonstrated in Fig. 4 by the  
 154 time dependence of the reduced permeability  $\mu'(t)/\mu'(t_0)$ , with  $t_0 = 2$  s, measured at field frequencies ranging  
 155 between 500 kHz and 2 MHz.

156 Having clarified the nature of the dispersion of  $\mu_{r,\text{dw}}(J_p)$ , we can turn to quantitative discrimination between  
 157 the dw and rotational permeabilities, again exploiting disaccommodation. The idea is one of comparing the  
 158 permeability decays starting from the demagnetized state and from remanence (major loop). The former  
 159 condition is attained by conventional demagnetization procedure at 50 Hz, the latter by sudden release of a  
 160 saturating DC field. The strength of the weak AC exciting field is such as to engender a quasi-reversible  
 161 polarization swing, typically  $\Delta J = \pm 2$  mT. In the limit of small oscillations the rotational susceptibility can be  
 162 written, for easy axes of anisotropy constant  $K$  distributed according to an angular function  $g(\theta)$ ,

$$163 \quad \chi_{\text{rot}} = \int_{-\pi/2}^{\pi/2} (\mu_0 M_s^2 / 2K) \cdot \sin^2 \theta g(\theta) d\theta, \quad (3)$$

164 where  $M_s$  is the saturation magnetization. Since  $\sin^2 \theta = \sin^2(\pi - \theta)$ , all quadrants are equivalent and  $\chi_{\text{rot}}$  is the  
 165 same for small moment rotations occurring either at remanence ( $J = J_r$ ) or in the demagnetized state ( $J = 0$ ).  
 166 The difference  $\Delta\mu$  between the small amplitude permeabilities observed in these two states is therefore entirely  
 167 ascribed to the lower domain wall contribution at remanence  $\Delta\mu(t) = \mu_{\text{dw}}(J = 0, t) - \mu_{\text{dw}}(J = J_r, t)$ . Fig. 5  
 168 shows that the permeability, taken at  $f = 10$  kHz, decays slightly faster in the demagnetized state. Since the  
 169 derivative  $D = d\mu/d(\log t)$  can be taken approximately proportional to  $\mu_{\text{dw}}$  at any time  $t$  [21], we can also write

$$170 \quad \mu_{\text{dw}}(J = 0, t) / \mu_{\text{dw}}(J = J_r, t) = D(J = 0, t) / D(J = J_r, t), \quad (4)$$

171

172 where the time  $t$  of interest is the one where the loss measurement is performed after demagnetization, typically  
 173 around  $10^3$  s. Combining at this time the previous equations and further taking into account that with  $f = 10$   
 174 kHz  $\mu(t) \cong \mu'(t)$  and  $\mu'(f) \cong \mu'_{DC}$ , we obtain the dw contribution to the real permeability component under  
 175 quasi-static excitation

$$176 \quad \mu'_{dw,DC}(J=0) = \frac{\Delta\mu}{1 - D(J=J_r)/D(J=0)}, \quad (5)$$

177 at the low  $J_p$  level impressed by the AC field ( $J_p = 2$  mT for the case of Fig. 5). We estimate for such a case the  
 178 relative permeabilities  $\mu'_{r,dw,DC} = 445$  versus  $\mu'_{r,DC} = 2040$  (N87 ferrite) and  $\mu'_{r,dw,DC} = 695$  versus  $\mu'_{r,DC} = 4540$   
 179 (N30 ferrite). Having thus estimated  $\mu'_{dw,DC}(J_p = 2$  mT), it is an easy matter to retrieve the whole  $\mu'_{dw}(f)$   
 180 behaviours at the different  $J_p$  values exploiting the previously introduced experimental quantities  $\mu'_{diff}(f, J_{pi}) =$   
 181  $\mu'(f, J_{pi}) - \mu'(f, J_p = 2$  mT)  $= \mu'_{dw}(f, J_{pi}) - \mu'_{dw}(f, J_p = 2$  mT). We can in fact estimate  $\mu'_{dw}(f, J_p = 2$  mT)  
 182 assuming it replicates the frequency dependence of the experimental  $\mu'_{diff}(f, J_{pi} = 5$  mT), while tending to the  
 183 calculated  $\mu'_{dw,DC}(J_p = 2$  mT) at low frequencies. It is then immediate to calculate  $\mu'_{dw}(f, J_{pi})$  at all  $J_{pi}$  values,  
 184 till an upper limit roughly identified by the Rayleigh law. Quite a similar procedure, passing through the  
 185 etermination of the experimental quantity  $\mu''_{diff}(f, J_{pi}) = \mu''(f, J_{pi}) - \mu''(f, J_p = 2$  mT)  $= \mu''_{dw}(f, J_{pi}) - \mu''_{dw}(f, J_p =$   
 186  $2$  mT), can be applied in order to retrieve the imaginary component  $\mu''_{dw}(f, J_{pi})$ . Now the low-frequency limit  
 187 is given by the condition  $\mu''_{dw,DC}(J_p = 2$  mT)  $\cong \mu''(J_p = 2$  mT), because the quasi-static energy loss is  
 188 exclusively generated by the dw processes. Fig. 6 compares the so-extracted  $\mu'_{dw}(f, J_{pi})$  and  $\mu''_{dw}(f, J_{pi})$   
 189 behaviours with the measured permeability components  $\mu'(f, J_{pi})$  and  $\mu''(f, J_{pi})$ , in the  $J_p$  range 2 mT – 50 mT  
 190 (Mn-Zn ferrite N87). The relaxation character of the dw dynamics leads to vanishing of  $\mu'_{r,dw}(f)$  and  $\mu''_{r,dw}(f)$   
 191 on entering the MHz range, where they are completely superseded by the rotational terms. These are associated  
 192 with the resonant response of the material, as illustrated by the peaked behaviour  $\mu'_{r,rot}(f) = \mu'_r(f) - \mu'_{r,dw}(f)$  in  
 193 Fig. 7.

194

### 195 **3. Energy losses.**

196 We have remarked that the phenomenology of energy losses can be viewed in terms of complex magnetic  
 197 permeability, as synthetically shown by Eq. (1). The previous analysis gives then us the opportunity to  
 198 discriminate between the loss contributions originating from the dw and the rotational processes.

199 Writing the expression for the energy loss at a given  $J_p$  value as

$$200 \quad W(J_p) = \pi J_p^2 (\mu''_{dw} + \mu''_{rot}) / (\mu'^2 + \mu''^2) = W_{dw}(J_p) + W_{rot}(J_p), \quad [\text{J/m}^3] \quad (6)$$

201 and taking the  $\mu''_{dw}$  and  $\mu''_{rot}$  dependence on frequency obtained through the previously discussed procedure  
 202 (see Fig. 7), we arrive at the decomposition of the loss in its dw and rotational components. Fig. 8 provides an  
 203 example of the so-obtained  $W_{dw}(f)$  and  $W_{rot}(f)$  behaviours at two different  $J_p$  values in a Mn-Zn N87-type ring  
 204 sample (outside diameter 15 mm, inside diameter 10.4 mm, thickness 5.09 mm). It is noted that  $W_{dw}(f)$  and  
 205  $W_{rot}(f)$  comparably contribute to  $W(f)$  in a relatively narrow intermediate frequency interval only. It is also



206 observed that, according to Eq. (6),  $W_{\text{rot}}(f)$  strictly follows a  $J_p^2$  law, being  $\mu''_{\text{rot}}$  independent of  $J_p$ , while  $W_{\text{dw}}(f)$   
 207 grows faster, because  $\mu''_{\text{dw}}$  increases with  $J_p$  (see Fig. 6). Consequently, overlapping between the fluxmetric  
 208 and transmission line measurements occurs over a shrinking region on increasing  $J_p$ . In this region, a relatively  
 209 sharp transition of the slope of the  $W(f)$  curve occurs. It might be argued that such a transition could be related  
 210 in some way to the concurring drop of the electrical resistivity (see Fig.1), thereby implying an important  
 211 contribution to the losses by the eddy currents. This is not the case. A same  $W(f)$  behaviour is in fact observed  
 212 in the insulating Ni-Zn ferrites [22] and in sufficiently small Mn-Zn samples, like the ones considered in Fig. 8.  
 213 Eddy current losses in the sintered Mn-Zn ferrites have important practical implications, as demonstrated by  
 214 the constant efforts devoted to the development of materials with increased grain boundary resistivity [4], but  
 215 their calculation is difficult, because of the electrically heterogeneous structure of the material. Their role is in  
 216 any case apparent when measuring the losses in differently sized Mn-Zn samples. The general literature  
 217 approach to the calculation of eddy current losses is one of applying the conventional formulation for a  
 218 homogeneous material (classical loss  $W_{\text{class}}(J_p, f)$ ), which, for a circular sample of diameter  $d$  is simply  
 219 expressed as

$$220 \quad W_{\text{class}}(J_p, f) = \frac{\pi^2}{16\rho'(f)} \cdot d^2 J_p^2 f, \quad (7)$$

221 where  $\rho'(f)$  is the real resistivity component, as obtained with the measurements reported in Fig. 1. It has been  
 222 shown, however, that Eq. (7) can largely overestimate the actual eddy current losses and can be reconciled with  
 223 a correct formulation only at very high frequencies in [11]. Because of the insulating character of the grain  
 224 boundary layer, eddy currents at low frequencies circulate inside the grains and the ensuing energy dissipation  
 225 is much lower than the one predicted using the measured  $\rho'(f)$  in Eq. (7), which amounts to assume eddy  
 226 current patterns freely investing the sample cross-section. The general problem of calculating the eddy current  
 227 losses in the sintered Mn-Zn ferrites has been discussed in [11], where the electromagnetic field equations in  
 228 the heterogeneous material are formulated under a variational multiscale approach and numerically  
 229 implemented by means of finite element method, by which the evolution of the eddy current patterns from  
 230 grain limited to global upon increasing frequency can be described. It is obtained, in particular, that the  
 231 numerical results can be fitted by the closed expression

$$232 \quad W_{\text{eddy}}^{(\text{cl})}(J_p, f) = \left\{ \frac{(k_0 - k_\infty)A}{1 + \exp[m \log_{10}(f/f_0)]} + k_\infty A \right\} J_p^2 f, \quad [\text{J/m}^3] \quad (8)$$

233 where  $k_0 A J_p^2$  and  $k_\infty A J_p^2$  are the calculated limits of  $W_{\text{eddy}}^{(\text{cl})}(J_p, f)/f$  for  $f \rightarrow 0$  (eddy currents confined in a  
 234 single grain, typically below a few kHz) and  $f \rightarrow \infty$  (eddy currents circulating across the whole sample cross-  
 235 section, typically beyond a few MHz), respectively. Eq. (8) provides a “classical contribution” (it will actually  
 236 tend to  $W_{\text{class}}(J_p, f)$  at high frequencies), because the calculation does not take into account the role of the moving  
 237 domain walls and the ensuing local eddy currents. The related contribution (the excess eddy current loss) has  
 238

239 been estimated [10, 11] and found to be always negligible with respect to  $W_{\text{eddy}}^{(\text{cl})}$ , which then accounts for the  
 240 whole of the eddy current losses. The quantity  $A$  is an effective area, depending on the width-to-thickness ratio  
 241  $w/h$ . It is related to the actual cross-sectional area  $S$  as  $A = gS$ , where  $g$  is geometrical constant given by  
 242  $g = 1 - 0.0923(p-1)^{1.63}$  and  $p = w/h$  if  $w > h$  and  $p = h/w$  if  $h > w$ . Each material is associated with a defined set  
 243 of parameters  $k_0$ ,  $k_\infty$ ,  $m$ , and  $f_0$ , where the constants  $m$  and  $f_0$  are obtained from best fitting of the curves  
 244 calculated with the numerical method. Eq. (8) has been applied to differently sized Mn-Zn ring samples, as  
 245 illustrated in the example given in Fig. 9, where  $m = 4.68$  and  $f_0 = 3.2 \cdot 10^6$ . It is noted here that only in the largest  
 246 sample (cross-section of width  $w = 5.25$  mm and height  $h = 9.72$  mm) eddy currents appreciably contribute to  
 247  $W(f)$  (at least below  $f = 10$  MHz). By subtracting the calculated  $W_{\text{eddy}}^{(\text{cl})}(f)$  from the measured loss, we obtain the  
 248 eddy current free  $W_{\text{sd}}(f)$  behavior (thick solid curves in Fig. 9). The large and the small N30-type ring samples  
 249 have not the very same structure, resulting into an about 30% different quasi-static loss. But at high frequencies  
 250 all eddy current free curves merge into a single curve, as expected for a rotations dominated magnetization  
 251 process. This finding permits us, with little loss of accuracy, to dispense from the complications of the numerical  
 252 procedure. One can either adjust the value of the constants  $m$  and  $f_0$  for best fitting of the eddy current free curve  
 253 after subtraction of  $W_{\text{eddy}}^{(\text{cl})}(f)$  from the measured  $W(f)$  or exploit the general empirical finding that the ratio of  
 254 the conventional to the actual classical eddy current losses  $R(f) = W_{\text{class}}(f)/W_{\text{eddy}}^{(\text{cl})}(f)$  is a relaxation-type  
 255 function. At low frequencies this ratio is a precisely known quantity  $R_0$  and we can pose  $R(f) = 1 + \frac{R_0 - 1}{1 + (f/f_1)^2}$ ,  
 256 where the parameter  $f_1$  is again obtained by best fitting of the  $W_{\text{sd}}(f)$  curve. In this way we are finally left to  
 257 justify the  $W_{\text{sd}}(f)$  behaviour, which, in many practical samples (as in the example given in Fig. 8), is coincident  
 258 with the  $W(f)$  behavior. The physical mechanism lying behind the energy dissipation is the damping of the  
 259 precessional motion of the spin moments, taking place both inside the moving domain walls and inside the  
 260 domains. The energy loss in the sample of Fig. 8 all originates from spin damping and is decomposed into dw  
 261 and rotational contributions. The former can be lumped in the coercivity and the additional dynamic dw effects  
 262 and we can write  $W_{\text{dw}}(f) = W_{\text{h}} + W_{\text{dw,dyn}}(f)$ , where  $W_{\text{h}}$  is the hysteresis (quasi-static) loss and  $W_{\text{dw,dyn}}(f)$  can be  
 263 expressed in a way analogous to the standard derivation of the excess loss in metallic alloys [10, 22], the starting  
 264 point in both cases being an identical equation for the damped motion of the dw [23]. The spin damping  
 265 coefficient  $\beta_{\text{sd}}$  appearing in this equation is related to the Landau-Lifshitz damping constant  $\alpha_{\text{LL}}$  by the  
 266 expression  $\beta_{\text{sd}} = (2J_s / \mu_0 \gamma \delta) \cdot \alpha_{\text{LL}}$ , where  $J_s$  is the saturation polarization,  $\mu_0$  is the magnetic constant,  $\gamma$  is the  
 267 electron gyromagnetic ratio, and  $\delta$  is the dw thickness. The viscous response to the applied AC field of the spin  
 268 moments inside the domains is described by the linear Landau-Lifshitz-Gilbert equation, by which we can obtain  
 269 analytical formulations for  $\mu'_{\text{rot}}$  and  $\mu''_{\text{rot}}$ . The pretty low values of the magnetocrystalline anisotropy of the soft  
 270 ferrites makes the intergrain demagnetizing fields to interfere with the magnetocrystalline anisotropy fields,

271 resulting in a distribution of the effective internal anisotropy fields  $H_{k,eff}$ , that is a continuous spectrum of  
 272 resonance frequencies. The theoretical  $\mu'_{rot}$  and  $\mu''_{rot}$  behaviours are obtained assuming that  $H_{k,eff}$  is distributed  
 273 according to a lognormal function  $g(H_{k,eff}) = \frac{1}{\sqrt{2\pi}\sigma H_{k,eff}} \cdot \exp[-\frac{(\ln(H_{k,eff}) - h)^2}{2\sigma^2}]$ , where  $h = \langle \ln(H_{k,eff}) \rangle$  and  $\sigma$ ,  
 274 the standard deviation of  $\ln(H_{k,eff})$ , are adjusted for best fitting of the experimental rotational permeabilities, once  
 275 further integration is made over the isotropic distribution of the easy axes in the sample plane. An example of  
 276 predictive capability provided by this approach is shown in Fig. 7, regarding the Mn-Zn ferrite type N87, for  
 277 which where  $\alpha_{LL} = 0.04$ ,  $h = 5.3$ ,  $\sigma = 1.2$  have been used. The rotational loss can then be immediately predicted  
 278 through Eq. (6), resulting in the fitting lines shown in Fig. 10 for three different  $J_p$  values.

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#### 280 4. Conclusions.

281 We have presented and discussed the broadband magnetic behaviour of Mn-Zn and Ni-Zn sintered ferrites,  
 282 clarifying the respective roles of domain wall displacements and rotational processes in providing the material  
 283 response from DC to 1 GHz. With the help of permeability disaccommodation measurements, we have been  
 284 able to quantitatively identify and separate the real and complex permeability components  $\mu'_{dw}$ ,  $\mu'_{rot}$ ,  $\mu''_{dw}$ , and  
 285  $\mu''_{rot}$  and, a fortiori, dw  $W_{dw}$  and rotational  $W_{rot}$  energy losses across the whole broad range of frequencies.  
 286 Evidence is offered for the relaxation character of the dw dynamics, which is completely thwarted by the  
 287 dissipating mechanisms on entering the MHz range and fully overcome by the rotations. It has been shown that  
 288 eddy currents can contribute to the magnetic losses in Mn-Zn ferrites, provided the frequency is sufficiently  
 289 high and the samples are large, as quantitatively predicted by a specific multiscale model relying on the  
 290 measurement of the electrical resistivity of the material as a function of frequency. It is concluded that, for any  
 291 defined peak polarization value, an eddy current free  $W_{sd}(f) = W_{sd,dw}(f) + W_{sd,rot}(f)$  curve, independent of sample  
 292 size, can be recovered for any material, where spin damping is the associated dissipation mechanism. The  
 293 rotational permeability  $\mu'_{rot}(f)$  and  $\mu''_{rot}(f)$  curves are predicted as solutions of the Landau-Lifshitz-Gilbert  
 294 equation, under assumed lognormal distribution of the internal effective anisotropy fields, and the associated  
 295  $W_{sd,rot}(f)$  behaviour is correspondingly obtained, resulting in good agreement with the experimental results.

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