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Modelling of electrical properties of Mn-Zn ferrites taking into account the frequency of the occurrence of the dimensional resonance

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Besides their magnetic properties, Mn-Zn ferrites are also characterized by appreciable electrical properties. This electromagnetic nature of Mn-Zn ferrites material properties causes a dimensional resonance to occur in samples. The latter hinders measurements of the frequency dependences of intrinsic permittivity and electrical conductivity. In the paper, we present a sign in measurement results that shows the frequency range in which dimensional resonance has already occurred. Above this range, properties extracted from measurements are not intrinsic any longer. We refer to the sign to determine the last point of the measurement data set that is used as an input for an equivalent circuit modelling of the electrical properties. This "last point" criterion helps to exclude the possibility of modelling apparent properties instead of intrinsic ones. The results obtained show that the frequency dependent electrical properties may be well modeled even if the upper limit of the input frequency range to the curve fitting is below the frequency range in which the dimensional resonance occurs.

K e y w o r d s: Mn-Zn ferrite, dimensional resonance, electrical conductivity, relative permittivity, ferrite core modelling, equivalent electrical circuit modelling, N87, N97

1 Introduction

It is known, that, apart from the contribution of the magnetic properties, the power loss in Mn-Zn ferrite cores is also influenced by their electrical properties [1–3]. In this regard, for the analysis of this power loss, an approach is to make use of an electrical equivalent circuit model of the core [4–6]. However, prior to obtaining an equivalent model, measurements of the electrical properties of the particular ferrite have to be carried out.

A way to measure electrical properties of Mn-Zn ferrites in the frequency range below 1 GHz is the parallel plate capacitor method [7]. The sample is placed in between two electrodes and the impedance of it is measured. Unlike other solid materials, however, with Mn-Zn ferrites these measurements are hindered by a dimensional effect occurring in samples. Mn-Zn ferrites are characterized by giant permittivity and finite electrical conductivity [8] as well as high permeability. This electromagnetic nature of the material properties causes a dimensional resonance to occur in samples [9]. For instance, when an electrical field is applied across a Mn-Zn ferrite sample, with the increase of the frequency of the signal the wavelength in the material shortens. As a consequence, depending on the dimensions of the sample contact surfaces, above a given frequency in its volume the magnetic field is not negligible [10, 11]. Then, the measured impedance response is influenced by both the electrical and magnetic properties.

In the literature, methods are proposed for the extraction of intrinsic properties from measurements done with samples that have large contact surfaces [11, 12]. These methods involve calculations in accordance with the particular sample geometry in order to eliminate the influence of the dimensional resonance. On the other hand, for the direct measurements of the intrinsic electrical properties, one may shift the occurrence of the dimensional resonance to higher frequencies by testing a sample, which contact surfaces have a small dimension. For a wide band measurement, a thickness of about 1 mm is used [9, 13]. Then again, even in such thin samples the dimensional resonance still would occur in the MHz range. Moreover, though the dimensional resonance could be well visible in the impedance responses of samples with large contact surfaces, it could be hardly detected with samples that have small surfaces [11]. For example, in [14] it was recognized that the dimensional resonance occurred, however, the frequency of its occurrence was not justified. In this respect, there is a need of a clue to inform the researcher that the dimensional resonance already occurred.

In the paper, we regard equivalent circuit modelling of intrinsic electrical properties of Mn-Zn ferrites based on impedance measurements of samples. Firstly, we suggest how to establish which frequencies are influenced by the dimensional resonance phenomenon. The suggested sign provides information about the upper limit of the frequency range to be considered when aimed at modelling of only intrinsic electrical properties. Then, two types of equivalent circuit models of the latter are regarded, by which it is demonstrated that simple RC branches do not properly model the tested Mn-Zn ferrites' electrical prop-

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Table 1. Samples under test

sample	magnetic material	sample shape	contact surface dimensions (mm)	distance between contact surfaces (mm)
*side*50	N87	extruded banana-like surface	(9.25 to 3) × 32	25
*mid*50	N87	cylinder	diameter=20	25
*plate*N87	N87	I planar	2 × 18	10
*plate*N97	N97	I planar	3 × 32	20

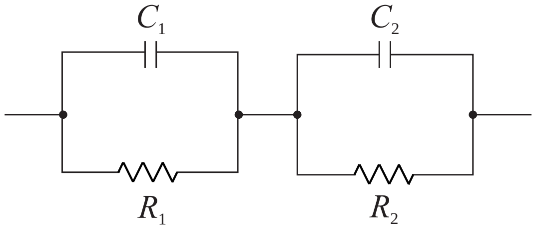


Fig. 1. Equivalent electrical circuit of a Mn-Zn ferrite

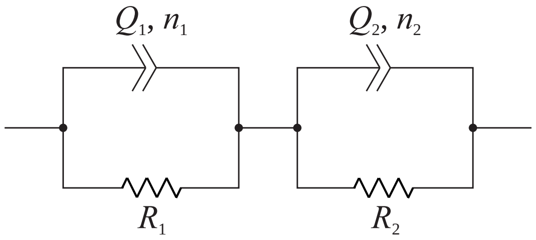


Fig. 2. Equivalent electrical circuit of a Mn-Zn ferrite with constant phase elements in place of constant valued capacitances

erties in the considered frequency range. On the other hand, the use of constant phase elements instead proves a successful modelling. In addition, obtained results suggest that some extrapolation of the modeled dependencies beyond the frequency of the dimensional resonance occurrence could still reflect intrinsic properties.

2 Description of the experiments and the equivalent circuit models considered

2.1 Measurements

Impedance measurements were carried out at room temperature in the frequency range 40 Hz to 5 MHz with an Agilent 4294A impedance analyzer and a 42941 A impedance probe kit(clip leaded). Samples were hold with a plastic clamp between thin copper foils. For the "open" compensation of the impedance probe kit, the latter was loaded with the plastic clamp opened as an "open circuit" condition. For the "short" compensation, the thin copper foils were connected to the clip leads and shortened at the far end.

In order to search for a sign in measurement results that shows the dimensional resonance occurrence, the impedances of a side and a middle leg cut from commercially available PQ 50 core halves [15] were firstly measured (samples *side*50 and *mid*50 in Tab. 1). The impedances of planar cores of I shape [16, 17] were then measured (samples *plate*N87 and*plate* N97 in Tab. 1), for the modelling of measured electrical properties. The contact surfaces of the samples were metalized with silver conductive paint.

2.2 Electrical equivalent circuit models

For the modelling of the electrical properties, curve fitting of measured impedance spectra was performed by the use of the EIS Spectrum Analyzer program [18]. To fit experimental data, it applies a minimization algorithm for the determination of the elements' values of the equivalent circuit model, which is assembled by the user beforehand.

Two types of electrical equivalent circuit models were considered. Mn-Zn ferrites have a heterogeneous grain-grain boundaries structure, which may be represented by two parallel RC pairs connected in series, as shown in Fig. 1 — one reflecting the electrical nature of the grains and the other — that of the grain boundaries [1, 19]. This was the firstly considered equivalent circuit.

The second circuit considered is shown in Fig. 2. The $R||C+R||C$ structure of the circuit in Fig. 1 is kept, however there are constant phase elements (CPEs) in place of the constant valued capacitances. The CPE is an element that is applicable in the equivalent circuit modelling of imperfect dielectrics. It is characterized by two parameters — $Q, \big(s^n/(\Omega\text{cm}^2)\big)$ and $n, (-)$ [20]. The impedance of a CPE has the form $Z_{\text{CPE}}(\omega) = 1/[(j\omega)^n Q]$, where j is the imaginary unit and ω is the angular frequency in rad/s; when $n = 1$, the CPE corresponds to a pure capacitor, *ie* the constant phase element parameter Q is identical to a constant valued capacitance C [21]. The impedance of a parallel RQ circuit(where "RQ" is used to denote a circuit comprised of a resistor and a CPE)has the form

$$Z = \frac{R}{1 + (j\omega)^n QR}\,. \tag{1}$$

2.3 Calculation of the electrical properties

The calculation of the electrical properties based on either impedance measurements or equivalent circuit models, is performed by substituting the respective admittances and dimensions of the samples under test in the

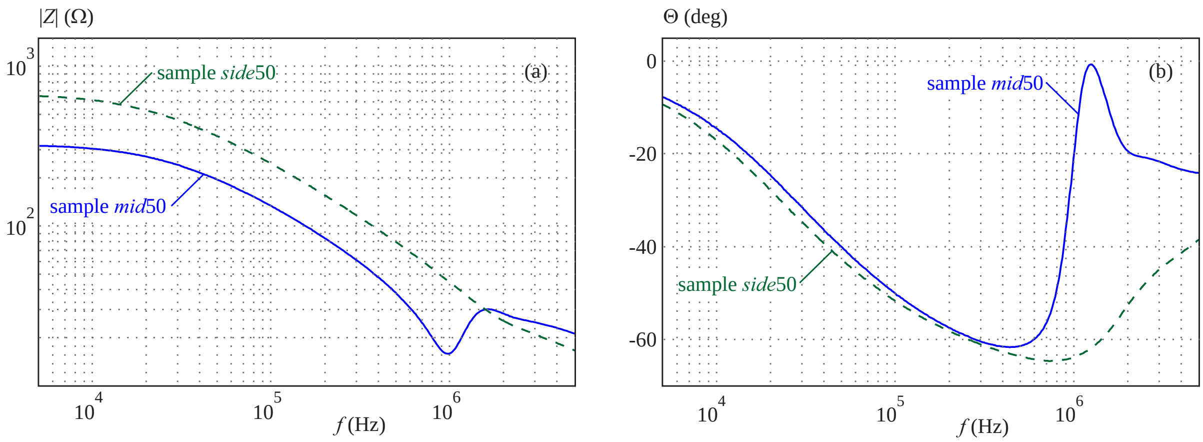


Fig. 3. Results of impedance measurements of a middle and a side legs cut from a PQ 50/50 core half (sample *mid*50 and sample *side*50, respectively): (a) – magnitude, (b) – phase angle

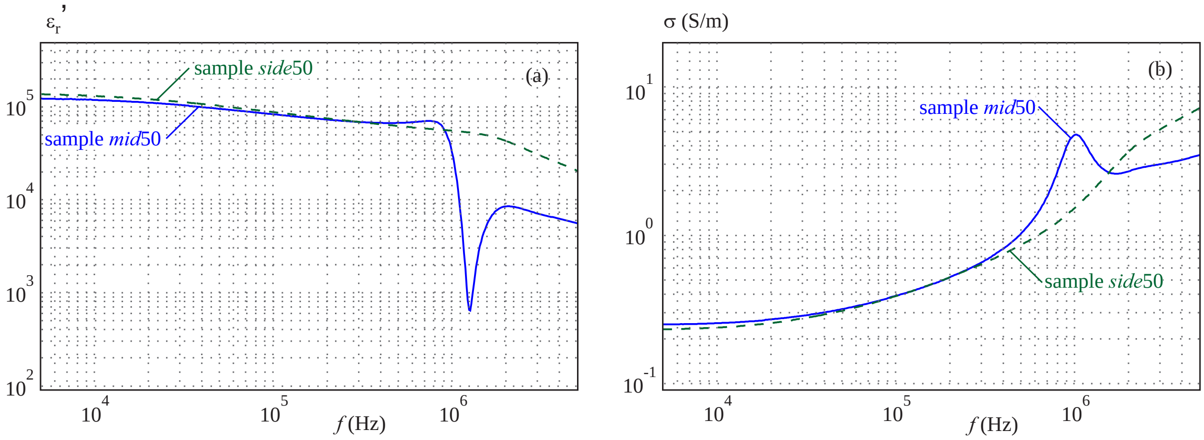


Fig. 4. Electrical properties extracted from the impedance measurements of the *mid*50 and *side*50 samples, presented in Fig. 3: (a) – relative permittivity, (b) – electrical conductivity

following expressions

$$\sigma = \frac{Y'h}{A}, \quad \varepsilon_{\mathrm{r}}' = \frac{Y''h}{\omega\varepsilon_0 A}, \tag{2,3}$$

where σ is the electrical conductivity of the material, ε_r is relative permittivity of the material, Y' and Y'' are real and imaginary parts of the measured/modeled admittance, ε_0 is the permittivity of free space, A is the contact surface area of the sample and h is the height of the sample (distance between the electrodes).

3 Results and discussion

3.1 Detection of the dimensional resonance occurrence in measurement results

Figure 3 depicts the measured impedance responses of the *side*50 and *mid*50 samples. As it has been discussed [22], the impedance of the *mid*50 sample clearly demonstrates a dimensional effect, most apparent in the magnitude response where a resonance behavior is noticeable at about 1 MHz, Fig. 3(a). On the other hand, while there is a fold in the magnitude response of the *side*50 sample near 2 MHz, Fig. 3(a), it cannot be categorized as a resonance.

In Fig. 4 are given the electrical properties extracted from the measured impedances of the *side*50 and *mid*50 samples, depicted in Fig. 3. The two samples originated from two different core halves. However, the production lot is expected to be the same, as the cores were the same delivery. In this regard, it is accepted that the samples share same material properties. Such an assumption is proved by the results in Fig. 4 where to a certain frequency there is a good overlap between the properties extracted from the two samples. Based on this assumption, we may conclude the middle leg sample exhibits intrinsic properties up to about 300 kHz. The deviation above this point is influenced by a magnetic field due to the dimensional resonance. However, from the same plots we cannot directly determine whether the properties of the side leg are intrinsic in the whole frequency range observed, and if not — to which point are.

Here we demonstrate the existence of a sign that shows the frequency range in which the dimensional resonance has already occurred. For the purpose, we make use of the imaginary part of the relative complex permittivity, which is related to the electrical conductivity by the dependence

$$\varepsilon_{\mathrm{r}}'' = \frac{\sigma}{\omega\varepsilon_0}. \tag{4}$$

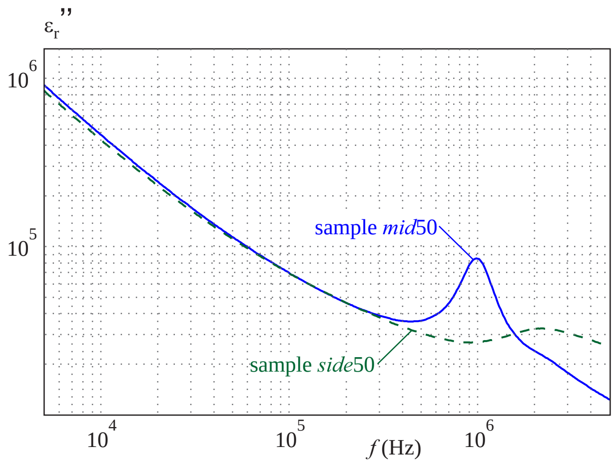


Fig. 5. Imaginary part of the complex relative permittivity extracted from the measured impedances of the *mid*50 and *side*50 samples, presented in Fig. 3

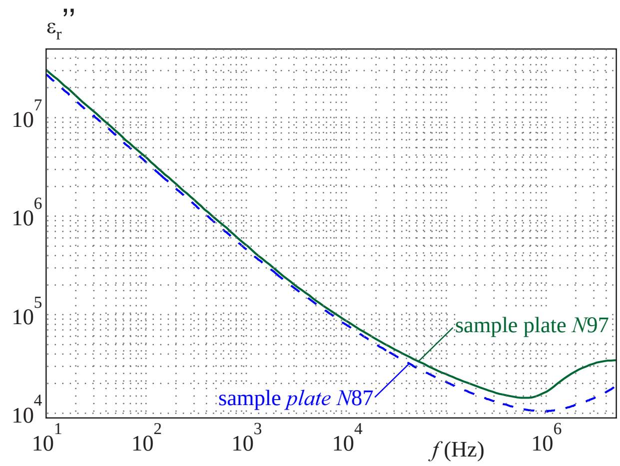
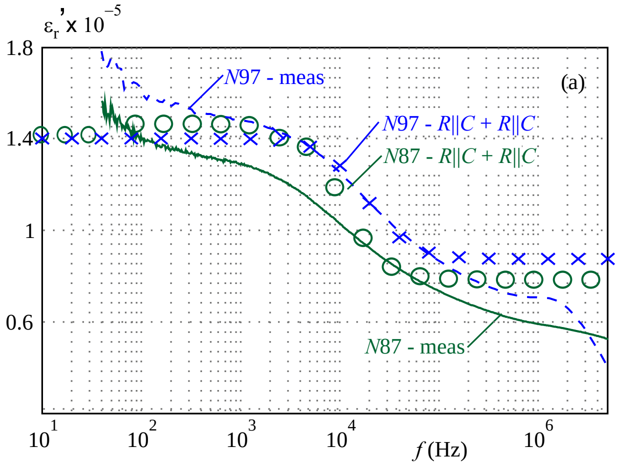


Fig. 6. Imaginary part of the complex relative permittivity extracted from the measured impedances of samples *plate*N87 and *plate*N97



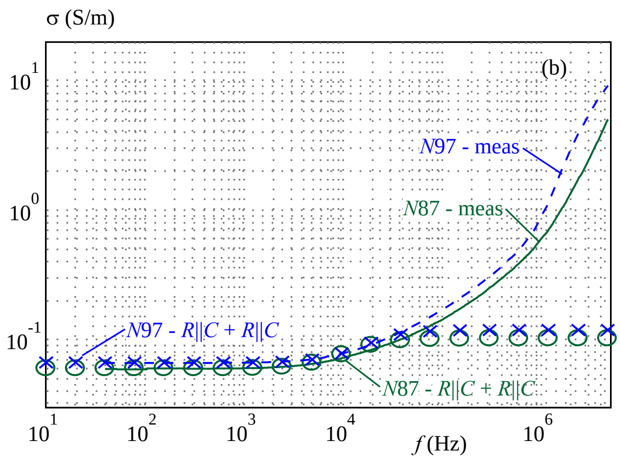


Fig. 7. Electrical properties of N87 and N97 ferrites extracted from measurements of the samples *plate*N87 and *plate*N97 and corresponding properties modeled by a $R||C + R||C$ circuit (values given in Tab. 2): (a) – relative permittivity, (b) – electrical conductivity

Table 2. Values of the $R||C + R||C$ equivalent circuit elements regarding the tested samples *plate*N87 and *plate*N97

sample	input frequency	$R_1(\Omega)$	C_1(F)	$R_2(\Omega)$	C_2(F)
*plate*N87	40 Hz to 1 MHz	2995.7	8.1194×10^{-9}	1547	3.3607×10^{-9}
*plate*N97	40 Hz to 700 kHz	2351.5	9.5753×10^{-9}	716.47	6.0863×10^{-9}

Figure 5 illustrates the imaginary part of the relative complex permittivity extracted from the measurements of the *side*50 and *mid*50 samples. Under the assumption that the samples share same properties, in comparing the two curves in Fig. 5, we again may name the frequency of 300 kHz up to which the middle leg exhibits intrinsic electrical properties. This result corresponds to what has been obtained in [22]. Furthermore, still looking at the curve of the imaginary part of permittivity of the *mid*50 sample, we notice that in the frequency range 300 kHz to 600 kHz there is a local minimum. With the side leg, although less pronounced, we again see such a behavior, however within a higher frequency range. This local minimum we deem a sign of an occurred dimensional resonance. Using this sign, in terms of the *side*50 sample we may conclude that beyond the local minimum at about 850 kHz the exhibited electrical properties are already influenced by the dimensional resonance. In [22], it has been shown that in another same-size, same-delivery side leg sample, dimensional resonance started taking place at about 700 kHz.

As an alternative, if we go back and look at the phase response of the measured impedances, given in Fig. 3, we shall see that the information provided from the just considered plot of the imaginary part of complex permittivity was already available there. The approximate frequencies of the dimensional resonance occurrence are indicated by the first bend of the phase response that from there on takes an opposite direction.

Table 3. Values of the $R||Q+R||Q$ equivalent circuit elements regarding the tested samples *plate*N87 and *plate*N97

sample	input frequency (kHz)	R_1 (Ω)	Q_1 ($s^n/\Omega\text{cm}^2$)	n_1 ($-$)	R_2 (Ω)	Q_2 ($s^n/\Omega\text{cm}^2$)	n_2 ($-$)
*plate*N87	0.04 to 1000	2866.2	1.1267×10^{-8}	86.8968/90	1681.1	1.6226×10^{-8}	79.4682/90
	1 to 500	3279.4	1.3343×10^{-8}	83.6415/90	1285.6	1.971×10^{-8}	79.5618/90
	30 to 500	3793.4	9.8289×10^{-9}	80.4672/90	8.9264×10^{-13}	43.017×10^{-5}	22.2453/90
*plate*N97	0.04 to 700	2327.6	1.2477×10^{-8}	87.3963/90	768.7	4.1306×10^{-8}	77.2272/90
	1 to 340	2343	1.3852×10^{-8}	86.4261/90	771.78	4.6761×10^{-8}	76.6737/90
	30 to 340	2806.3	1.5293×10^{-8}	82.5606/90	247.32	7.5765×10^{-8}	77.7132/90

3.2 Modeling of the electrical properties

For the modelling of the electrical properties, the measured impedances are of the *plate*N87 and *plate*N97 samples (see Tab. 1). In Fig. 6 are presented the frequency dependences of the imaginary part of permittivity extracted from these measurements. Based on the comments in the previous section, from Fig. 6 we deduce the approximate frequencies at which dimensional resonance occurred within the samples. With the *plate*N87 we consider it to be the frequency point of 1 MHz and with the *plate*N97 — 700 kHz. Then, for the equivalent circuit modelling of the intrinsic properties of the two materials, these points are the last to be used as an input data to the curve fitting of the measured impedances.

Now, by the use of the fitting software [18] we model the measured impedances by the $R||C+R||C$ equivalent electrical circuit, which is given Fig. 1. Obtained values of the respective elements are reported in Tab. 2. The corresponding frequency dependences with regard to electrical properties are given in Fig. 7, where a comparison is made between modeled and measured relative permittivity and ac electrical conductivity of the tested ferrites. As can be seen from the plots, in terms of conductivity a good overlap between modeled and measured dependences is achieved only up to 40 kHz. In terms of permittivity, only the one of N97 ferrite is well modelled in the range 5 kHz to 80 kHz. Moreover, it may be seen from the plots that both modeled permittivity and conductivity dependences are characterized with two stable levels at low and high frequencies. However, the experimental spectra show a continuous change of the electrical properties with frequency, which points that a $R||C+R||C$ circuit does not properly model the measured samples' impedances. Thereon, the next approach is for the modelling to make use of the $R||Q+R||Q$ circuit, presented in Fig. 2.

With the $R||Q+R||Q$ equivalent circuit we use different frequency ranges as an input to the program for an impedance spectrum analysis. In Table 3 are given obtained values of the respective equivalent circuit elements related to the considered input frequency ranges. Figures 8 and 9 depict the corresponding dependences of the electrical properties obtained.

From Table 3 it may be deduced that the values of the equivalent circuit elements are dependent upon the input frequency range. Furthermore, in case of *plate*N87, input range 30 kHz to 500 kHz, extreme results are obtained in terms of the second RQ pair — extremely low resistance accompanied by very large value of the constant phase element parameter Q and too low value of the constant phase exponent n. From Fig. 8, it may be seen that with these values an improper modelling of both the permittivity and conductivity below 30 kHz is achieved. In the case of 1 kHz to 500 kHz input range, only accuracy in permittivity suffers below 1 kHz.

On the other hand, in terms of the *plate*N87, best fit is obtained when the input frequency range to the curve fitting spans the whole measurement range up to the considered point of the dimensional resonance occurrence at 1 MHz. Beyond 1 MHz, the conductivity already deviates from measured data, as expected to be, and permittivity starts to deviate even at some 700 kHz to 800 kHz. Notwithstanding, it is noticeable that, independently of the input frequency range, in all cases obtained values lead to quite same electrical properties above 30 kHz. This lower limit of 30 kHz depends on the lowest input frequency point available for the curve fitting. However, in the high frequency end, results obtained are quite alike. Thus, it may be inferred that electrical properties may safely be modeled taking an upper frequency limit to the curve fitting that is below the frequency point considered to be the one of the dimensional resonance occurrence.

Results obtained with the tested sample *plate*N97, given in Fig. 9, confirm what has been said so far. The goodness of the fit at the low frequency end depends upon the lowest input frequency point available to the curve fitting, whereas at the high frequency end the modeled properties are quite insensitive to the input frequency range to the curve fit. Parenthetically, compared to the N87, it seems the N97 ferrite is easier to be modeled, for even in the case of 30 kHz to 340 kHz input range, a good fit is obtained in terms conductivity down to the lowest frequency point of the observed frequency range.

In general, whereas the whole frequency range as an input leads to best fit, a frequency range of 1 kHz to half the frequency of the dimensional resonance occurrence is still reasonable for the equivalent circuit modelling of the considered N87 and N97 ferrites. For power inductors and transformers, Mn-Zn ferrites are used mostly above 20 kHz, so the fit below 1 kHz is less important. On the other hand, taking the upper limit of the frequency range to the modelling to be below the local minimum of the

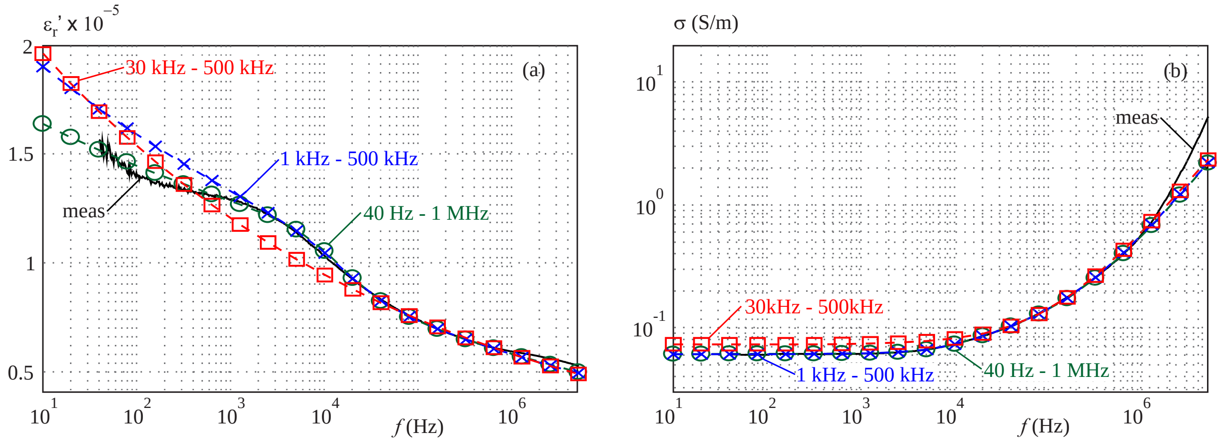


Fig. 8. (a) – relative permittivity, and (b) – electrical conductivity, extracted from both measurements and $R||Q + R||Q$ equivalent circuit modelling of the *plate*N87 impedance: solid line — experimental data; lines with markers — results obtained by modelling with different input frequency ranges to the curve fitting (according to Tab. 3

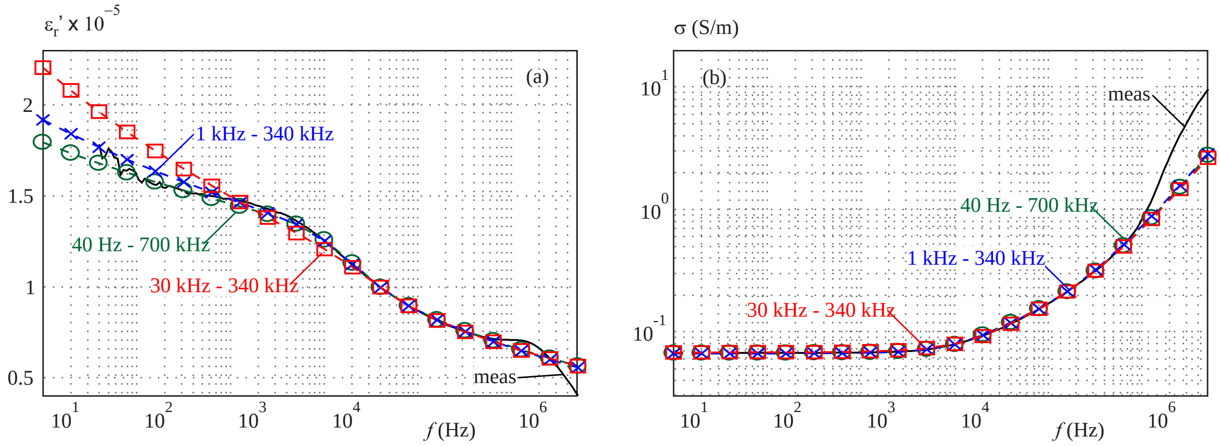


Fig. 9. (a) – relative permittivity, and (b) – electrical conductivity, extracted from both measurements and $R||Q + R||Q$ equivalent circuit modelling of the *plate*N97 impedance: solid line — experimental data; lines with markers — results obtained by modelling with different input frequency ranges to the curve fitting, according to Tab. 3

imaginary part of the complex relative permittivity helps to exclude the possibility of approaching to model apparent properties instead of intrinsic ones.

3 Conclusion

In the paper, it was presented an identified sign by which it can directly be established the approximate frequency of the dimensional resonance occurrence when the impedance of a Mn-Zn ferrite sample is measured. This sign is a local minimum, which may be noticed in both the calculated frequency dependence of the imaginary part of the complex relative permittivity and the measured frequency phase response of the sample. Taking this frequency as a last input point to the modelling of measured impedances, the electrical properties of N87 and N97 Mn-Zn ferrites were modeled by the use of a series connection of two parallel RC pairs and a series connection of two parallel RQ pairs. The second approach only proved to lead to satisfactory results.

It was demonstrated the importance of the frequency range that is cut from the measurement results and used as an input data to the modelling. It became clear that input frequency range of different width leads to different values of the equivalent circuit parameters. The lower end of the input frequency range determines the goodness of the fit of the measured properties below this lower frequency point, however, the goodness of the fit at high frequencies is not so sensitive to the considered input frequency ranges. Based on these observations, it may be expected that some extrapolation of the modeled properties beyond the frequency of dimensional resonance still could reflect true electrical properties. For example, it was shown that from the impedance measurements of 2 mm and 3 mm thick plates, the extraction of the intrinsic electrical properties of N87 and N97 Mn-Zn ferrites could be done in the frequency range up to approximately 1 MHz. Above it, the dimensional resonance already hides true electrical properties. However, with the $R||Q + R||Q$ models, the different input frequency ranges hardly affect the modeled properties in the range from 30 kHz up to 5 MHz.

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