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WINDINGS LOSSES OF PLANAR COMPONENTS DETERMINATION FROM CURRENT DENSITY

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ABSTRACT
This article presents an alternative method for losses determination in planar passive components without or with magnetic layers from the distribution of current density in conductors resulting from the simulation under High Frequency Structure Simulator (HFSS). Copper losses are represented by a frequency-dependent resistance. The procedure of this method is similar to the method developed from Y12 in [1], which consists in calculating this frequency-varying resistance r(f) in three frequency ranges:

- at very low frequencies, the R_{DC} (Direct Current Resistance) resistance is calculated;
- at low frequencies (capacitive couplings are negligible), some resistance values are calculated from the current density Jvol from the HFSS simulation;
- at resonance frequencies at high frequencies.

KEYWORDS: Magnetic component; winding losses; integrated planar devices, skin and proximity effects.

1. INTRODUCTION
The miniaturization of integrated circuits leads to the miniaturization of their components, including the passive components used in low power supplies intended for the supply of several circuits. These power supplies must have high efficiency, which requires that losses of active and passive components of their constitution have to be reduced.

This article presents the determination of copper losses as a function of frequency in planar magnetic and non-magnetic components. The frequency-dependent series resistance r(f) represents the losses including those due to skin and proximity effects. Several authors have devoted their work to the determination and calculation of copper losses for windings using round wires, Litz wires or foils [1], [2], [3], [4]. Some authors have worked in the current density distribution [5], [6], [7], [8], [9], [10], [11], [12], [13].

The objective of this study is to determine the windings copper losses in planar components from the current density distribution in conductors and to compare them with measurements determined by the method of Y_{12} [1]. Our work will be carried out in the following way:

- Determine the current from the density of current obtained under HFSS;
- Determine losses and give the evolution of Rac as a function of frequency;
- Compare the results with those determined from the measurements by the Y_{12} method.

2. CURRENT IN THE CONDUCTOR

Distribution of the current density in spiral conductors
The passive component used in our study is a planar inductor with dimensions shown in Figure 1.
The current densities are extracted in complex numbers (real and imaginary) respectively along the axes OX, OY and OZ from which the different modulus can be calculated. Figure 2 is an example of the modulus of the current densities along the 3 axes J_X, J_Y and J_Z calculated and represented.

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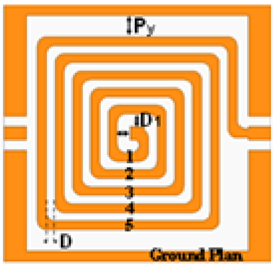

Distance between turns	D	50, 200, 400 µm
Conductor width	W	400 µm
Distance between the first coil and the central block	D1	900, 1200 µm
Distance between the last coil and the ground plane	Py	1000, 500, 2000 µm

Figure 1: Used planar inductor with its dimensions

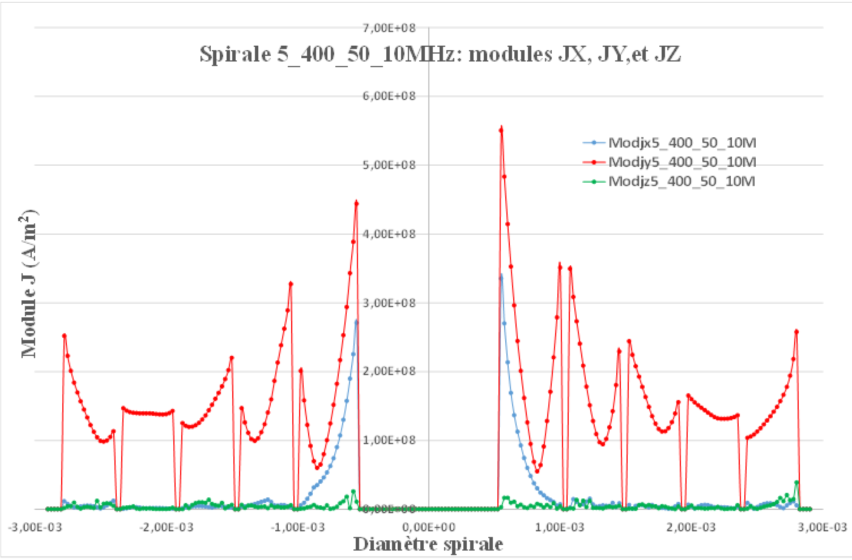

Figure 2: Modulus of current densities distribution along axes X, Y et Z

We notice that the modulus of J_X and J_Z are very low in front of the modulus of J_Y which is oriented in the same direction as the current. For this reason, we consider only the modulus of J_Y for our work (whenever the densities along the two other axes are negligible). Thus, we will represent this modulus J_Y of the current density distribution in the planar component conductors, precisely the spiral 5_400_50 at 10 MHz (5_400_50 means planar inductor with 5 turns, ribbon width of 400 µm and space width of 200 µm).

Determination of the current in conductors

As mentioned above, we will only consider the current density having the same direction as the current (Jy) to determine the latter. Knowing that the current density can be obtained in modulus and complex under HFSS and equal to the quotient of the current over the surface, we can calculate the current using the formula below:

S: cross-sectional area of the conductor*; W:* its width and *e:* its thickness

$I = \iint Jv.ds$ (i)

$S = W * e$

The current density is uniform along z-axis corresponding to the conductor's thickness and not uniform along x-axis corresponding to the conductor's width. Thus, equation (i) becomes:

$I = e. \int_{x=0}^{x=l} J_y(x).dx$ (ii)

The current density Jy(x) is given in complex form in order to take into account the phase shifts of the current in the conductor different parts.

$J_y(x) = \Re J_y(x) + \Im J_y(x)$

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So,

$$\frac{I}{e} = \int_0^l \Re J_y(x).\,dx \; + \; j\int_0^l \Im J_y(x).\,dx \qquad \text{(iii)}$$

Currents have phase shifts in each slice of the conductor, a vector sum must be performed as follows:

$$A = \Re\frac{I}{e} = \int_0^l \Re J_y(x).\,dx \; = \sum_{i=0}^{i=n-1} \frac{\Re J_{(i)} + \Re J_{(i+1)}}{2} * \Delta l \qquad \text{(iv)}$$

$$B = \Im\frac{I}{e} \; = j\int_0^l \Im J_y(x).\,dx = \sum_{i=0}^{i=n-1} \frac{\Im J_{(i)} + \Im J_{(i+1)}}{2} * \Delta l \qquad \text{(v)}$$

With n the number of steps $=l/\Delta l$. This will give us:

$$\frac{I}{e} = A + jB$$

$$I = e * \sqrt{A^2 + B^2}$$

Calculation method of the current in the conductor
Figure 3 shows the current density distribution on a spiral.

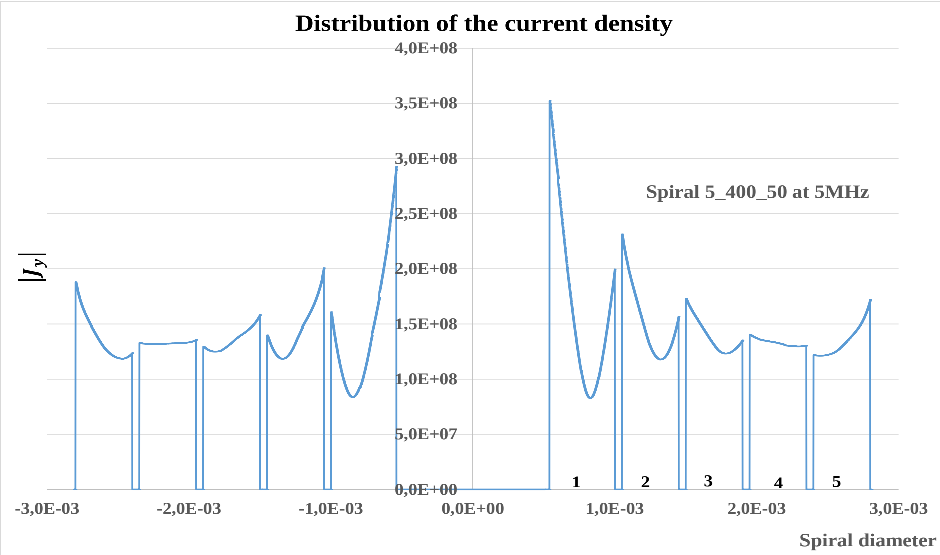

Figure 3: Distribution of the modulus of the current density of the 5_400_50 spiral at 5MHz

We calculate, in each slice of the conductor, the current that has a different amplitude and phase. Thus, the conductor is cut into sufficiently fine elements to calculate the current by the trapezoidal method. Figure 4 shows an example of a conductor cut into 15 slices.

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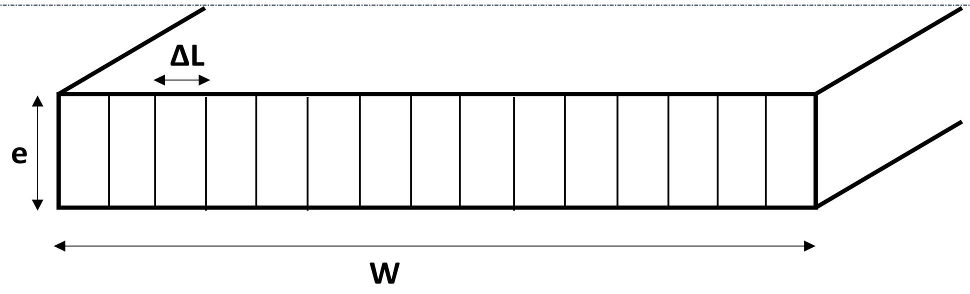

***Figure 4: Cross-section of a slice conductor*.**

For these calculations, the real (A) and imaginary (B) parts of the currents in slices are as follows:

$$A = \Re\frac{I}{e} = \sum_{i=0}^{i=399}\frac{\Re J_{(i)} + \Re J_{(i+1)}}{2} * 1\mu m \qquad \text{(vi)}$$
$$B = \Im\frac{I}{e} = \sum_{i=0}^{i=399}\frac{\Im J_{(i)} + \Im J_{(i+1)}}{2} * 1\mu m \qquad \text{(vii)}$$

It should be noted that this method consists of calculating the currents real and imaginary parts for (n) sections, taking into account their phase shifts. Real and imaginary parts are added to obtain the total current in complex form, allowing the calculation of its total value, which is equal to the modulus. It is important to avoid calculating the currents modulus in each slice before their addition, because this calculation method does not take into account the signs and phase shifts of the currents in the slices and leads to overestimation of the current. Figure 3 illustrates this method of calculation.

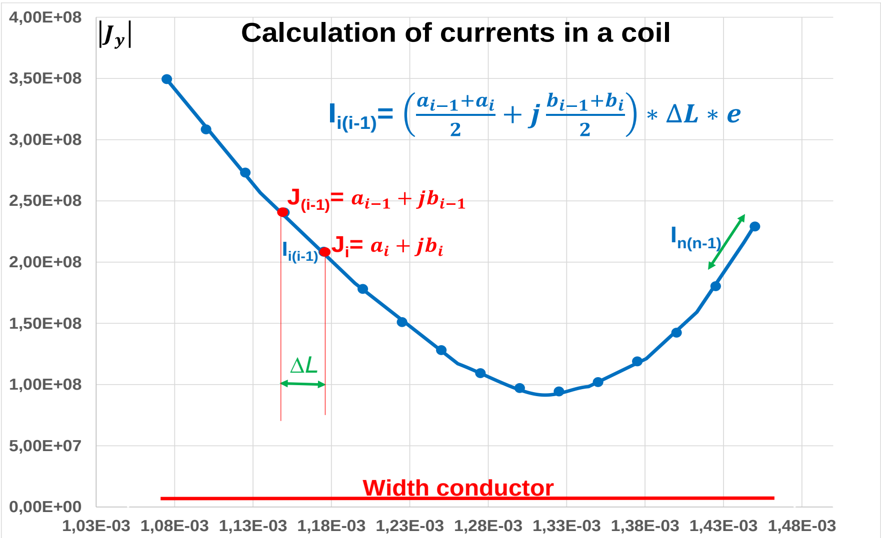

Figure 5: Calculation of the currents in a spiral conductor

Equations (vi) and (vii) are calculated in each section or interval (400 times) and their sum is made before calculating the total current of the coil:

$$\underline{I} = \underline{I_1} + \underline{I_2} + \cdots + \underline{I_j} + \underline{I_{j+1}} + \cdots$$
$$\underline{I} = (A_1 + jB_1) + (A_1 + jB_1) + \cdots + (A_j + jB_j) + (A_{j+1} + jB_{j+1}) + \cdots \qquad \text{(viii)}$$

$$\underline{I} = \sum A_i + j\sum B_i \text{ (ix)}$$
$$I = \sqrt{A^2 + B^2} \qquad \text{(x)}$$

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3. DETERMINATION OF THE RESISTANCE

The determination of the resistance from the current density is done after the current calculation in the spiral as described above. Since, losses are represented by the frequency-dependent resistance and knowing the current, we determine the resistance by using the power, which is as in equation (xi).

$$P = r.i^2 \qquad \text{(xi)}$$

Calculation of the resistance as a function of the frequency

In this part, we calculate the current and power for each interval considering constant the resistances in slices of the conductor. Thus, the total resistance of an inductor will be equal to the sum of the resistances of the different turns constituting the spiral. The power in a spiral is calculated using the following formula:

$$P_i = \rho_{cu} * L_{spire} * i_i^2/(e * \Delta L) \qquad \text{(xii)}$$
$$P_{spire} = \sum P_i \qquad \text{(xiii)}$$
$$R_{spire} = P_{spire}/I_{spire}^2 \qquad \text{(xiv)}$$

With :

ρ_{cu}: conductivity of the conductor; L_{spire}: length of a coil; i_i: current in a unit area; I_{spire}: current of the coil calculated previously; e: thickness of the conductor; ΔL: cutting step.

$$R_{Totale} = \sum R_{spire} \qquad \text{(xv)}$$

Method of determination from current density

The method consists of:

- Calculating the value of R_{DC} ($r_{DC} = \rho L/S$) at very low frequency;
- Calculating some values of the resistance from Jy as described above at medium frequencies;
- Determining the values of the resistances at the resonance frequencies by comparison.

To illustrate the two methods, we have plotted the curves of resistances representing the losses of the 5_400_50 spiral. Figures 6 and 7 represent respectively the losses in this inductor by the Jy method and those of the same inductor from the measurement by the Y_{12} method.

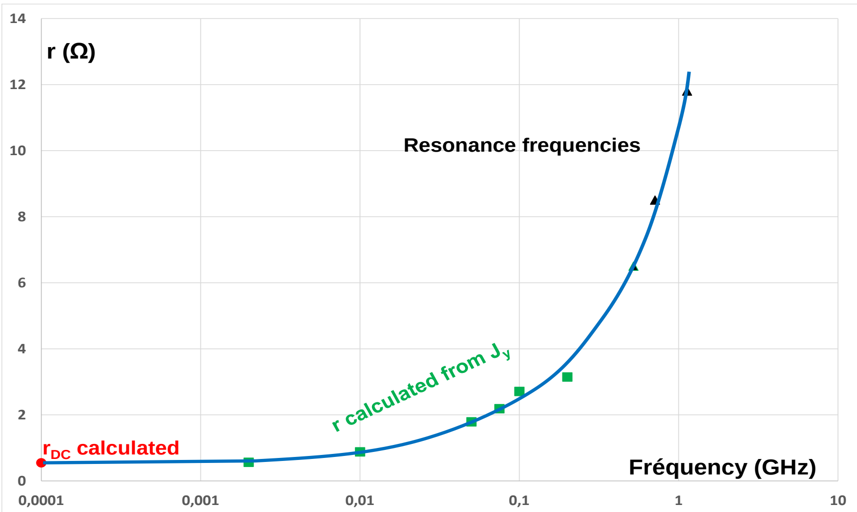

Figure 6: Losses curves in the air spiral 5_400_50 simulation: Jy method

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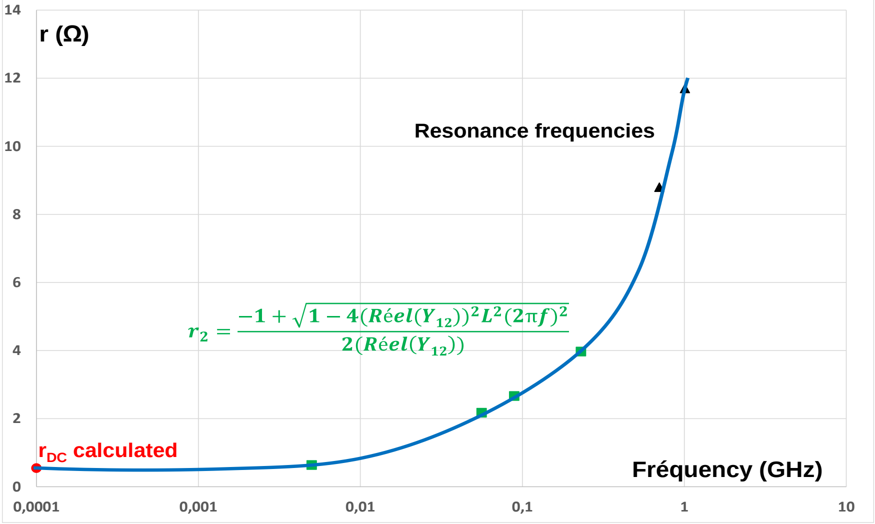

Figure 7: Losses curves in the air spiral 5_400_50 measurement: Awat method [1]

4. RESULTS AND DISCUSSION

In this section, we will compare the frequency-dependent resistances representing the losses determined from Jy with those from measurements determined by the method of Y_{12}. Figures 8, 9, and 10 show comparisons of normalized resistances between measurements and calculations from the current densities of the different spirals.

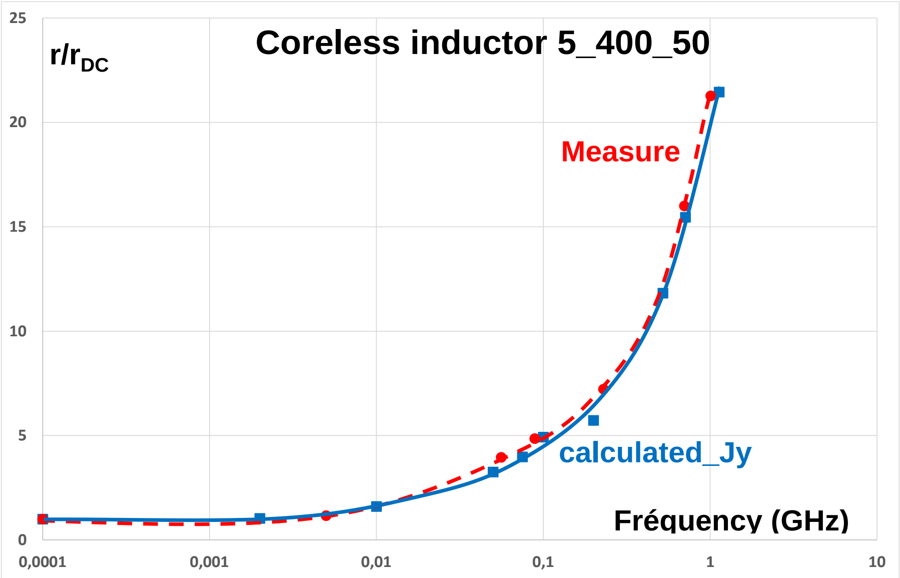

Figure 8: Comparison of r/r_{DC} ratio between measurement and calculation of the air spiral 5_400_50

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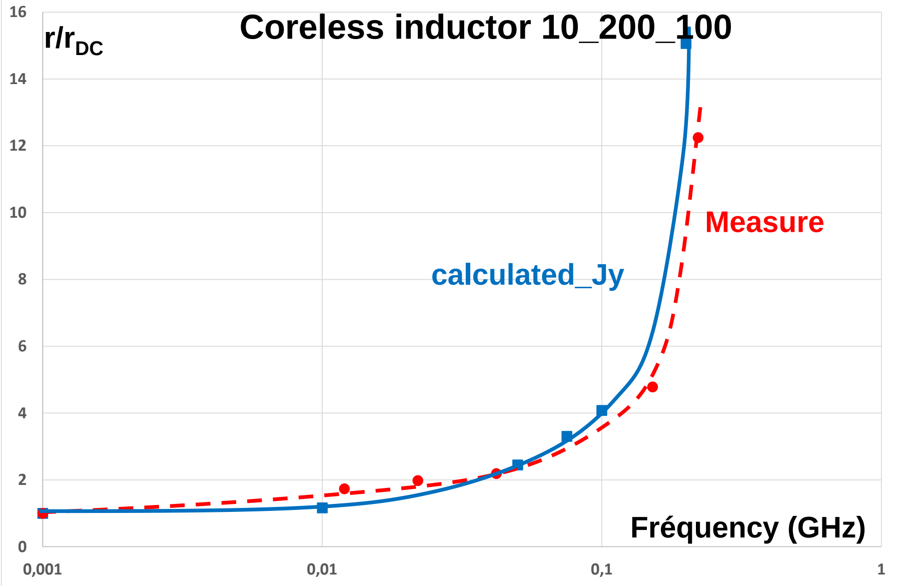

Figure 9: Comparison of r/r_{DC} ratio between measurement and calculation of the air spiral 10_200_100

Figures 8, 9 and 10 show a good correlation between the resistances calculated from the current density Jy at different frequencies and the resistances determined from measurements using the Y_{12} method.

These comparisons allowed us to validate this new method of determining the losses in passive components from the current density resulting from the simulation under HFSS.

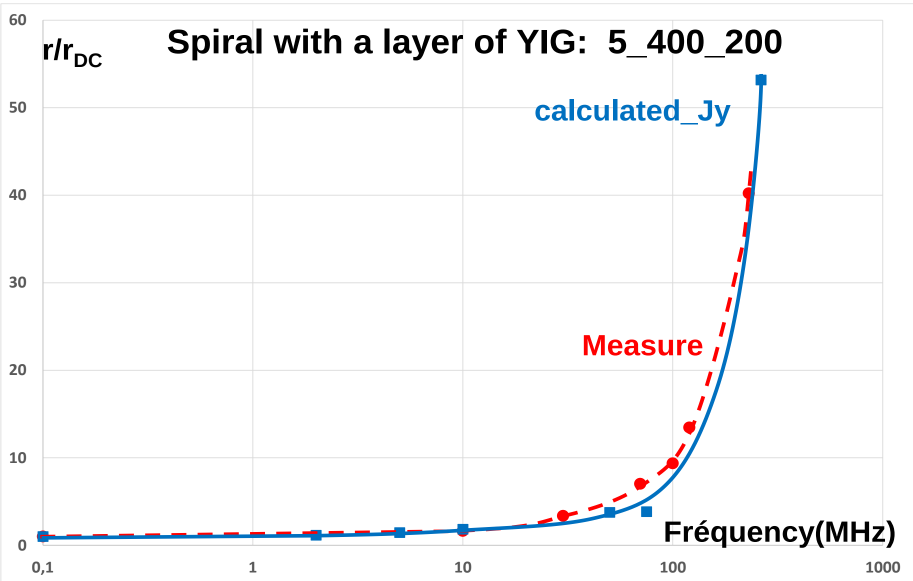

Figure 10: Comparison of r/r_{DC} ratio between measurement and calculation of the single layer spiral 5_400_200

5. CONCLUSION

A method for the calculation of winding losses in planar inductors with magnetic layer was presented in [1]. The new method presented in this paper is similar to the previous method but we introduced a new approach and a new method of winding losses calculation from the current density distribution (Jy). This new approach shows a good agreement between calculation, simulation and measurements of losses in the windings of planar components, which take into account skin and proximity effects and losses due to magnetic layer.

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