

## DOUBLEIND: SIMULATION TOOL FOR CALCULATION OF FERRITE EMI SUPPRESSOR IMPEDANCE

Mirjana DAMNJANOVIĆ, Ljiljana ŽIVANOV

"Faculty of Technical Sciences" University of Novi Sad  
 Trg D. Obradovica 6, 21 000 Novi Sad, Serbia and Montenegro  
 mirad@uns.ns.ac.yu

**Abstract.** In this paper it will be described program developed for calculation of impedance of inductors. This program can be used for multilayer inductors, which consists of conductive layers in soft ferrite material. The impedance can be calculated for a few different ferrites.

**Keywords:** impedance calculations, ferrite EMI suppressor, doubleind.

### Introduction

Multilayer inductors are truly miniature components. They consists of highly conductive layer embedded in a ferrite monolithic structure, which provides a good magnetic shielding and makes inductor very suitable for high density mounting.

The size, performance and reliability make them very attractive for a wide range of applications, such as EMI suppression in universal series bus (USB), low-voltage differential signaling and in other high-speed digital interfaces incorporated in notebooks and personal computers, digital cameras and scanners. Also, ferrite suppressors have been successfully employed for attenuating EMI in switching power supplies, electronic ignition systems, garage door openers etc. [1].

They are made in EIA standard sizes: 0402, 0603, 0805, 1206, 1210 and 1812, and they have impedance between 6 and 2000Ω at 100 MHz. Multilayer inductors are specially designed to reduce noise in low impedance circuits while keeping the signal free from distortion. They function as a resistor at noise frequencies and suppress noise when they are configured in series with a noise producing circuit [2].

### Ferrite suppressor cores

Ferrite components have been used for reducing or eliminating conducted EMI on printed circuit

boards in wiring and cables for decades. The ferrite core introduces into the circuit a frequency dependent impedance.

The permeability of the ferrite material is a complex parameter consisting of a real  $\mu_r'$  and imaginary part  $\mu_r''$ ,

$$\mu_r = \mu_r' - j \cdot \mu_r'' \quad (1)$$

The real component represents the reactive portion and the imaginary component represents the losses. Both parts of the permeability are frequently dependent, as it can be seen in Fig. 1 [3].

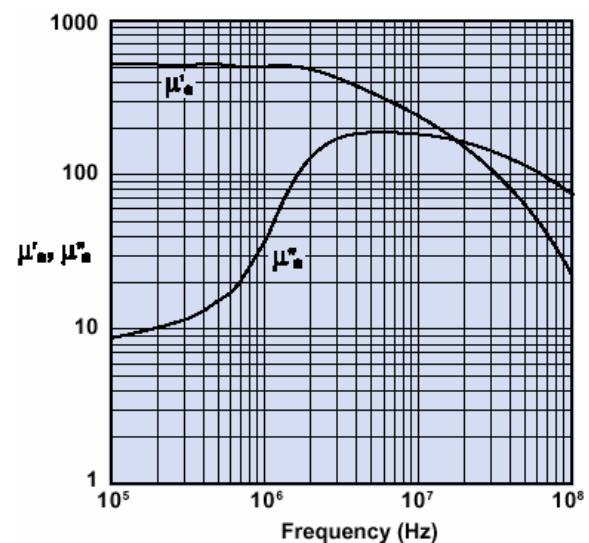


Fig. 1. Complex permeability vs. frequency for Fair-Rite material 44 [3]

The impedance of the inductor depends of the geometry of the conductive material and core, and of the permeability of the core material  $\mu$ . At low frequencies losses in inductor are low. Losses start to increase as frequency increase; at ferrimagnetic resonant frequency the material behaves as a frequency-dependent resistor and no longer as a true inductance. This is very important in elimination of conducted EMI [4]. In addition to the desired insertion loss of the inductor, parasitic effects such as inter-turn and inter-winding capacitance, self-resonance, dielectric and magnetic losses of the core, etc., play an important role in the design of such component [5].

### Equivalent circuit modelling

The impedance of the ideal inductor increases linearly with the frequency. However, in reality, there always exists a resistance in series with the inductor and the parasitic capacitance between the winding turns which appears in shunt with the inductor [6]. The equivalent circuit model of an inductor is shown in Figure 2.

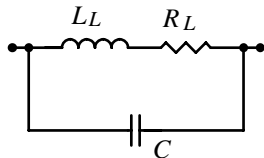


Fig. 2. The equivalent circuit model of an inductor [6]

The equivalent series resistance of the inductor  $R_L$  is caused by losses in the conductive material and magnetic losses due to the core. Usually, for ferrite-core inductors the core losses dominates at RF,

$$R_L = \omega \mu_r'' L_0, \quad (2)$$

where  $L_0$  is inductance of the coil with the core removed [7, 8].  $L_L$  is the equivalent series inductance of the inductor,

$$L_L = \mu_r' L_0. \quad (3)$$

$C$  is the equivalent lumped capacitance of the inductor that represents the parasitic effects of the winding.

Using the equivalent circuit of an inductor (Fig. 2), the total impedance can be determined as

$$Z(j\omega) = \frac{R_L + j \cdot (\omega L_L (1 - \omega^2 L_L C) - \omega R_L^2 C)}{(1 - \omega^2 L_L C)^2 + \omega^2 R_L^2 C^2} \quad (4)$$

From the expression (2), (3) and (4) it can be shown that the total impedance of the inductor  $Z$ , can be increased:

- by increasing of the  $L_0$  (e.g. by optimal design of the geometry of the conductive layer of inductor), or
- by choice of the appropriate ferrite material.

Because of that, the simulation tool *DOUBLEIND* for calculation of impedance of ferrite EMI suppressor is developed.

Characterisation of inductors using simulation is much more flexible, avoiding the need for a specific test component, relying instead on a process parameter characterisation. Because simulation adds predictive nature to the design process, changes can be made more easily to optimise and fine-tune the layout of the inductor [9].

### Design of ferrite EMI suppressor

This program is developed for simulation of characteristics of inductor, which consists of conductive layer in soft ferrite material. First step in designing of the ferrite EMI suppressor is to choose materials, which can provide the best performance of suppressor.

#### Selection of soft ferrite material

If the selection of ferrite material has to be taken, it is necessary to take care of the range of unwanted frequencies that can occur. Table 1 shows the Fair-Rite materials, their suggested operating frequency ranges and possible applications. Other important physical parameters of these materials are included in this

simulation tool, also. Those specifications can be found in [1].

Table 1. Soft ferrite materials, their suggested operating frequency ranges and applications [1]

Material	Frequency range	Test frequency	Applications
44	20-300MHz	25-100MHz	High resistivity
61	200+ MHz	100-250MHz	Wide range of parts
73	1-25 MHz	10-25 MHz	Small parts only

### Selection of conductive material

Outside the range of frequencies where conducted EMI has to be eliminated, the inductor must have low losses. To obtain that goal, for conductive layer has to be chosen material with high conductivity. In DOUBLEIND parameters for platinum and silver are included (Du Pont) [10]. The user can, also, set desired values for conductivity value of conductive paste directly.

### Selection of a structure of inductor

Besides the characteristics of materials, as it is mentioned before, the geometry of conductive layer determines the total impedance, also. Because of that it is very important to choose appropriate structure of inductor.

The proposed structures of inductors are shown in Fig. 3. Conductive layer has a meander type structure. In order to accomplish even greater suppression, one of the proposed structures with two conductive layers can be chosen.

Possible structures of inductor:

- *Single meander coil*, one layer structure (Fig. 3a),
- *Structure 1* consists of two meander coils in two layers (Fig. 3b). Distance between layers  $t_c$  can be set. In order to minimize the parasitic capacitance, two meander coils are not one above the other, but upper coil is arranged relative to lower by a half of pitch.
- *Structure 2* consists of two meander coils in two layers (Fig. 3c). Distance between layers

$t_c$  can be set. In order to minimize the parasitic capacitance, upper coil is rotated for  $90^\circ$  relatively to the lower [11].

In order to compare obtained results of calculation, analysis can be conducted for simple straight conductive line (length  $l$ , width  $w$ , thickness  $t$ ).

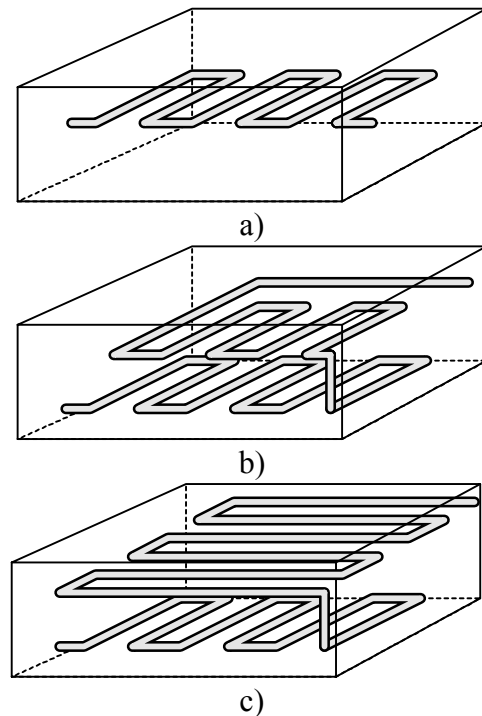


Fig. 3. Possible structures of inductor: a) single meander coil, b) structure 1 and c) structure 2.

User can choose one of the standard sizes for SMD inductor:

- 1210 (3.2 mm×2.54 mm×1.1 mm), shown in Fig. 4.
- 1206 (3.2 mm×1.6 mm×1.1 mm) or
- 0805 (2.0 mm×1.25 mm×1.1 mm).

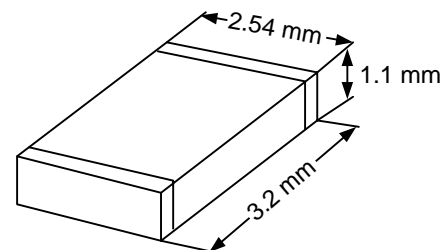


Fig. 4. Standard size 1210 of the inductor.

Once the structure and dimensions of inductor are chosen, it is necessary to set the conductors length  $l$ , width  $w$ , thickness  $t$  and the distance

between two neighbouring conductive segments  $p$ . On the basis of these initial values, the program will determine the maximal number of turns  $N_{max}$ . User can choose number of turns  $N$  not greater then  $N_{max}$ .

### Simulation tool DOUBLEIND

This simulation tool DOUBLEIND offers a lot of possibilities to design the EMI suppressor with best performance.

The calculation of impedance of inductor is very complex. Therefore, the segments of meander coil are divided into parallel filaments having small, rectangular cross sections. The self and mutual inductance were calculated using the concept of partial inductance [12,13,14].

For straight conductor of rectangular cross section self-inductance is [13]

$$L_i = 2 \cdot l \cdot \left( \ln \frac{2l}{w+t} + 0.25049 + \frac{w+t}{3l} + \frac{\mu}{4} T \right) \text{ [nH]}, \quad (5)$$

where  $L_i$  is the inductance in (nH),  $l$ ,  $w$  and  $t$  are length, width and thickness of the conductor in (cm), respectively,  $\mu$  is the conductors permeability, and  $T$  is a frequency-correction parameter.

The mutual inductance between two straight parallel conductors of rectangular cross section can be calculated as

$$L_{ij} = 2l \left[ \ln \left( \frac{l}{GMD} + \sqrt{1 + \left( \frac{l}{GMD} \right)^2} \right) - \sqrt{1 + \left( \frac{GMD}{l} \right)^2} + \frac{GMD}{l} \right], \quad (6)$$

where  $l$  is the conductors length,  $GMD$  is geometric mean distance between the conductors

$$\ln GMD = \ln d - \left( \frac{1}{12} \left( \frac{d}{w} \right)^2 + \frac{1}{60} \left( \frac{d}{w} \right)^4 + \frac{1}{168} \left( \frac{d}{w} \right)^6 + \frac{1}{360} \left( \frac{d}{w} \right)^8 + \frac{1}{660} \left( \frac{d}{w} \right)^{10} + \dots \right). \quad (7)$$

Assume that a straight conductor of the length  $l$ , having rectangular cross section is given. If the conductor cross section is divided into  $n$  parallel filaments with rectangular cross sections, then the total self-inductance of meander coil can be calculated as the sum of the partial self-inductances of all elementary filaments and the sum of all mutual inductances between all elementary filaments

$$L = \sum_{i=1}^n L_i + \sum_{i=1}^n \sum_{j=1}^n L_{ij}, \quad \text{where } i \neq j. \quad (8)$$

Similarly, for calculation of characteristics of structures 1 and 2, assume that one meander coil is divided into  $n_1$  and the other meander coil is divided into  $n_2$  elementary filaments with rectangular cross sections. Then the total mutual inductance between these two coils can be calculated as the sum of the partial mutual inductances between all elementary filaments of meander coils

$$M = \sum_{i=1}^{n_1} \sum_{j=1}^{n_2} L_{ij}. \quad (9)$$

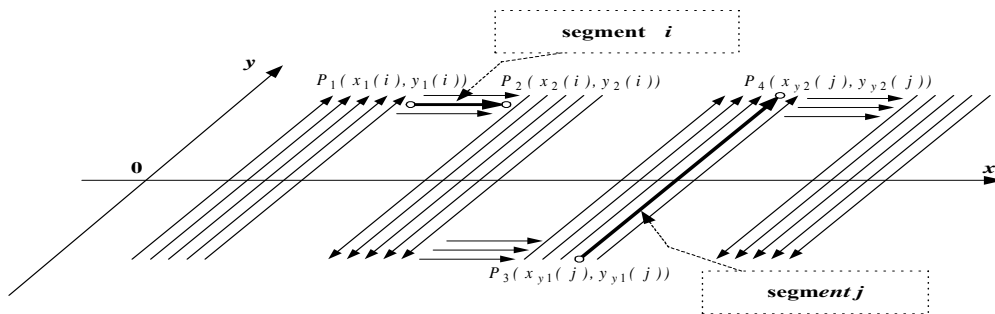


Fig. 5. Calculation of total impedance of meander coil by using the concept of partial inductance

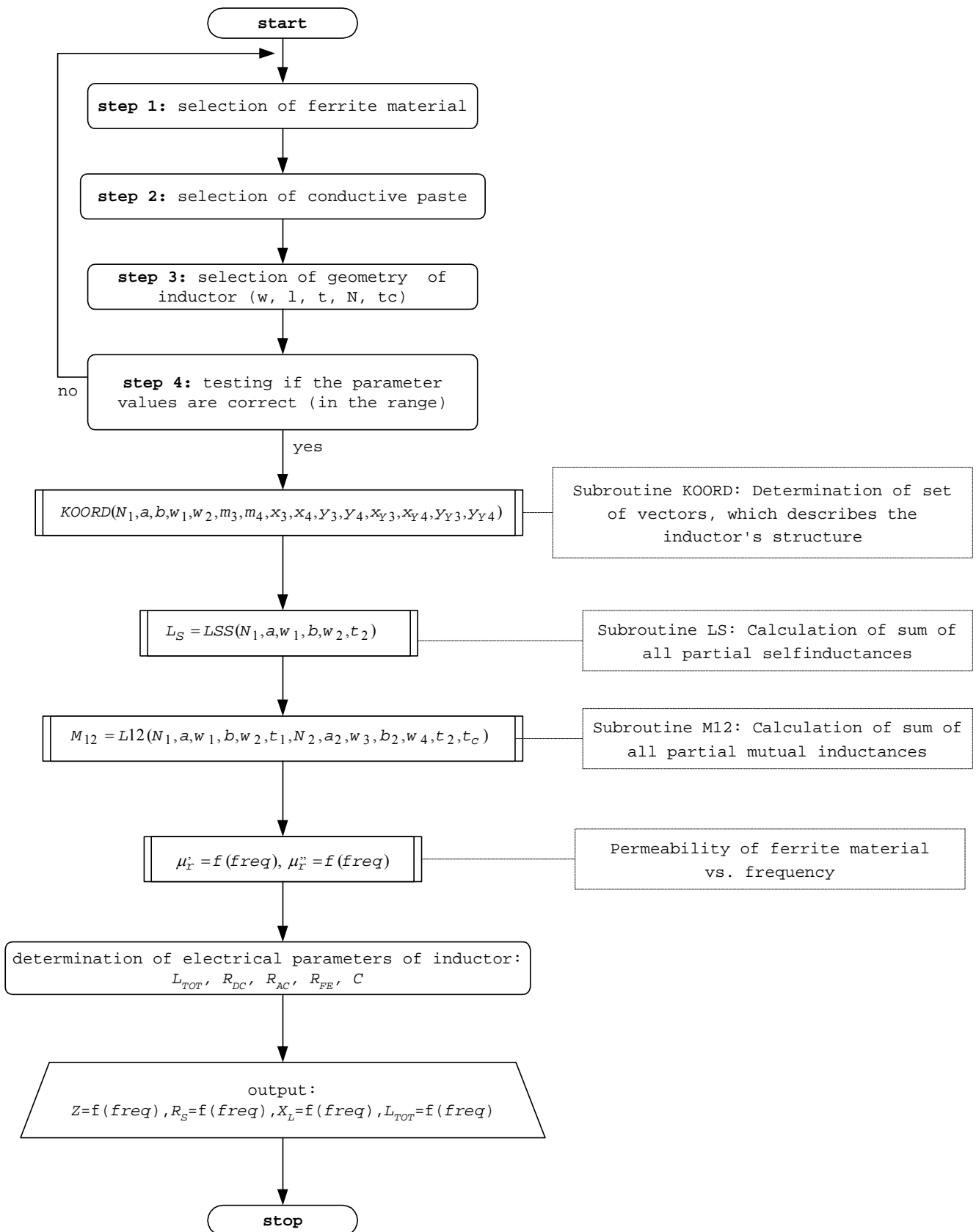


Fig. 6. Algorithm of simulation tool DOUBLEIND

Using these formulae the simulation tool DOUBLEIND was developed. The algorithm of this program is shown in Fig. 6.

### Results of simulation

In order to analyse any of these structures (Fig. 3) and calculate their total impedance, we have developed a simulation tool called *doubleind*.

As a result of the conducted simulations, calculated values can be presented:

- total impedance  $Z$  vs. frequency  $f$ ,
- series resistance  $R_S$  vs. frequency  $f$  and
- reluctance  $X_L$  vs. frequency  $f$ .

Also, comparison of these variables for different values of selected input parameter can be displayed. This option is very useful for designer to determine the optimal value of analysed parameter (e. g. width of conductive layer  $w$ , number of turns of meander coil  $N$  etc.). To demonstrate the principle of work of our simulation tool, a few simulations will be shown.

#### Example 1

The simulation result for single coil, size 1210, for Pt conductive layer ( $w=100\ \mu\text{m}$ ,  $t=10\ \mu\text{m}$ ,  $p=2w$ ,  $N=30$ ) and for ferrite core in 73 material [3] is presented on Fig. 7. As it can be seen, this ferrite can be used in EMI applications for suppression of noise frequencies above 200 MHz, when inductor behaves as a frequency-

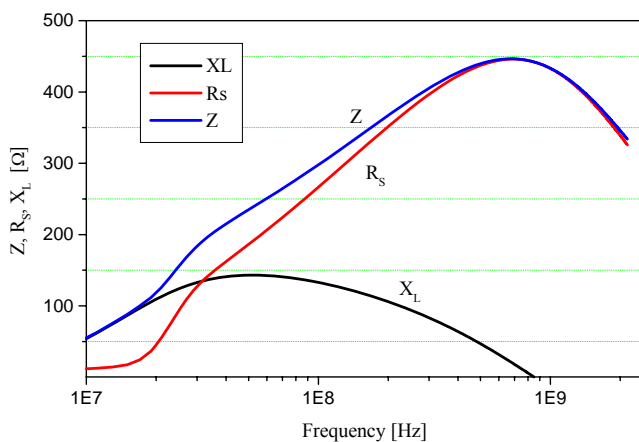


Fig. 7. Dependence of  $Z$ ,  $R_S$ ,  $X_L$  vs. frequency for single meander coil, size 1210, for  $w=100\ \mu\text{m}$ ,  $t=10\ \mu\text{m}$ ,  $N=30$ , in 61 material

dependent resistor. At low frequencies losses in inductor are low.

#### Example 2

In this example, the influence of three different conductive paste on total impedance of inductor will be shown for: platinum  $\rho_{\text{Pt}}=10.6 \cdot 10^{-6}\ \Omega\text{cm}$ , palladium  $\rho_{\text{PdAg}}=5.5 \cdot 10^{-8}\ \Omega\text{cm}$  and silver  $\rho_{\text{Ag}}=1.66 \cdot 10^{-8}\ \Omega\text{cm}$  (Fig. 8). The simulation results are obtained for structure 1, size 1210, for Pt conductive layer ( $w=150\ \mu\text{m}$ ,  $p=2w$ ,  $t=10\ \mu\text{m}$ ,  $N=18$ ), for a ferrite core in 44 material. Because the losses in conductive layer can be neglected in comparison to the losses in ferrite material, total impedance in this case is almost identical for all three pastes. This ferrite can be used for suppression in the range of 30 - 500 MHz.

#### Example 3

Total impedance of inductors with different soft materials will be presented in this example. Three soft ferrite materials are examined (see Table 1). As it is known, losses in inductor are maximal in the vicinity of ferrimagnetic resonant frequency, when the material behaves as a frequency-dependent resistor and no longer as a true inductance. Optimal selection of ferrite material will provide good elimination of conducted EMI in wanted range of frequencies (Fig. 9).

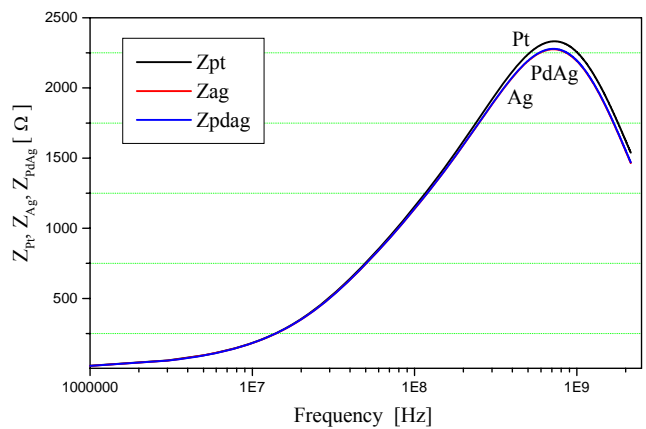


Fig. 8. Comparison of calculated values of impedance for structure 1, size 1210, in 44 material, for three different conductive paste

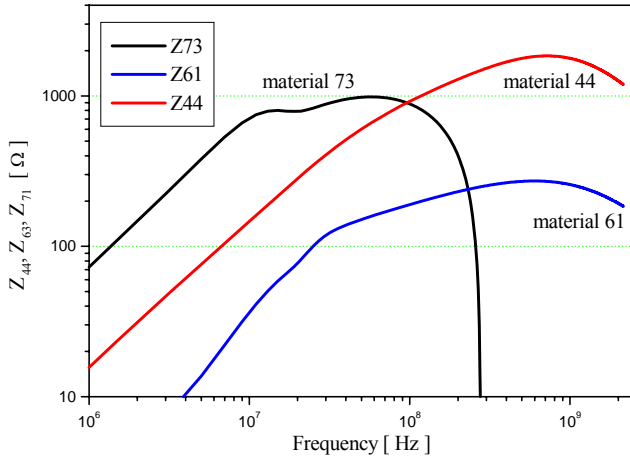


Fig. 9. Comparison of calculated values of  $Z$  for structure 2,  $w=150 \mu\text{m}$ ,  $p=2w$ ,  $t=10 \mu\text{m}$ , in three different ferrite materials

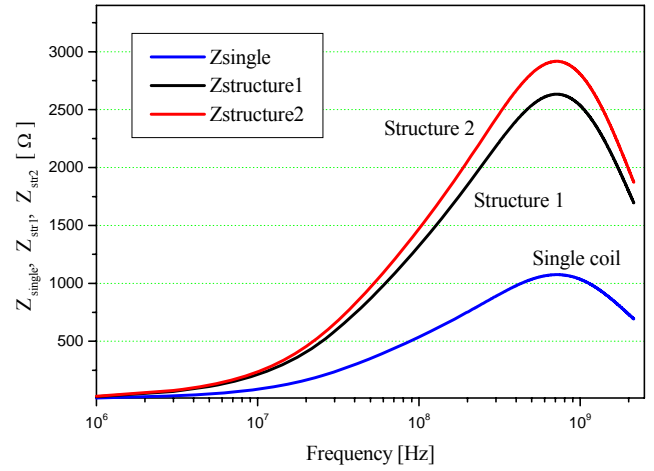


Fig. 10. Comparison of calculated values of  $Z$  for one-layer inductor and structures 1 and 2,  $w=100 \mu\text{m}$ ,  $t=10 \mu\text{m}$ , in 44 material

#### Example 4

The total impedance of the inductor depends of the permeability of the core material  $\mu$  (as it is shown in Example 3) and of the geometry of the conductive material and core.

Results of comparison of simulated values of the total impedance for one-layer meander type inductor and two proposed structures (called structure 1 and 2), would be presented in this example (Fig. 10). The size of inductor is 1210, conductive layer is Pt,  $w = 100 \mu\text{m}$ ,  $p=2w$  and  $t=10\mu\text{m}$ . Selected material is 44.

Total impedance of the inductor  $Z$ , can be decreased by decreasing of the  $L_0$  (e.g. by optimal design of the geometry of the conductive layer of inductor). To accomplish that goal, it is better to choose one of the proposed structures with two conductive layers, because their inductance is more than twice greater than inductance of single layer inductor.

#### Conclusions

In this paper is described simulation tool DOUBLEIND, which is developed for calculation of total impedance of inductor.

This simulation tool offers a lot of possibilities to design the EMI suppressor with best performance.

From the expression (2), (3) and (4) it can be shown that the total impedance of the inductor  $Z$ , can be increased:

- by increasing of the  $L_0$  (e.g. by optimal design of the geometry of the conductive layer of inductor), or
- by choice of the appropriate ferrite material.

To illustrate the advantages of this simulation tool, several parameter variation studies were made (Examples 1 -4).

First step in designing the inductor with best performances is to made the proper selection of ferrite material, in order to eliminate conducted EMI. It would be ideal to choose ferrite material, which has the ferrite resonant frequency in the range of unwanted frequencies.

Besides ferrite material, the geometry of the inductor determines the total impedance, also. Several structures of inductor are proposed. User can choose one of these structures:

- *Single meander coil*, one layer structure
- *Structure 1*, consists of two meander coils in two layers. Two meander coils are not one above the other, but upper coil is arranged relative to lower by a half of pitch.
- *Structure 2*, consists of two meander coils in two layers. In order to minimize the parasitic

capacitance, upper coil is rotated for 90° relatively to the lower.

User can choose one of the standard sizes for SMD inductor (1210, 1206, 0805).

Once the structure and dimensions of inductor are chosen (standard sizes for SMD inductor 1210, 1206 or 0805), it is necessary to set the conductors length  $l$ , width  $w$ , thickness  $t$  and pitch  $p$ .

If it is difficult to determine the optimal value of some parameter, a comparison for three different values can be performed.

The simulation results will be very useful for construction of the ferrite EMI suppressors.

## References

- [1] Technical Information from [www.fair-rite.com](http://www.fair-rite.com), *Fair-Rite Soft ferrites*, Fair-Rite Products Corp.
- [2] Technical Information from [www.ferroxcube.com](http://www.ferroxcube.com), *Multilayer Suppressors and Inductors*, Ferroxcube Products Corp.
- [3] Technical Information from [www.fair-rite.com](http://www.fair-rite.com), Fair-Rite Products Corp.
- [4] Mardiguian M. (2000) “*EMI troubleshooting techniques*”, McGraw Hill, New York.
- [5] K. Naishadham, K. (1999) *A rigorous experimental characterisation of ferrite inductors for RF noise suppression*, IEEE Trans. on Mag., pp. 271-273.
- [6] Yu Q., Holmes T.W. (2002), *RF circuit modeling of ferrite-core inductors and characterization of core materials*, IEEE Trans. on electromag. compatibility, vol. 44, No.1, pp.258-263.
- [7] Reggiani U., Grandi G., Sancineto G., Kazimierczuk M.K., Massarini A. (2000), *High-frequency behavior of laminated iron-core inductors for filtering applications*, IEEE Trans. on Mag., pp. 654-660.
- [8] Bartoli M., Reatti A., Kazimierczuk M. K. (1994), *High frequency models of ferrite core inductors*, IEEE Trans. on Mag., pp. 1670-1675.
- [9] Van Hese, J. (June 2002) *Tools and techniques for modelling spiral inductors on silicon*, Microwave Engineering, pp. 25-32
- [10] Technical Information from [www.dupont.com](http://www.dupont.com), DuPont
- [11] Damnjanović M., Živanov Lj., Stojanović G., Desnica V. (2003), *Influence of geometry of conductive layers on impedance of ferrite EMI suppressor*, 12<sup>th</sup> International Symposium on Power Electronics, Novi Sad, Paper No. T6-2.5.
- [12] Ruehli A. E. (1972), *Inductance calculations in a complex integrated circuit environment*, IBM J. res. develop. pp. 470-482.
- [13] Ruehli A., Paul C., Garret J. (1995), *Inductance calculations using partial inductances and macromodels*, Proc. Inter. Sym. on EMC. IEEE '95, Atlanta. pp. 23-27.
- [14] Greenhouse H. M. (1974), *Design of planar rectangular microelectronic inductors*, IEEE Trans. on parts, hybrids and packaging, Vol. PHP 10, pp. 101-109.