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Examination and Development of a Radio Frequency Inductor

***Abstract**. Nowadays, inductors can be found in almost every electrical and electronic product. These key components are needed to store electrical energy, select frequencies, and protect agaimst overvoltage and overcurrent. In the case of the inductors, which usually work in the range of radio frequency, the one of the most important attributes is the quality factor. The aim of the project is to increase the Q-factor of an RF SMT inductor and to favour the industrial research and development about inductors by using the finite element method.*

***Streszczenie.** W wielu dziedzinach współczesnej technologii elektrycznej i elektronicznej można znaleźć induktory. Są one niezbędne w gromadzeniu elektrycznej energii, w wyborze częstotliwości, a także w ochronie przepięciowej i przetężeniowej. W przypadku induktorów, pracujących zwykle z częstotliwością radiową, istotnym ich parametrem jest współczynnik jakości (quality factor). Celem tej pracy jest wskazanie metody poprawy tego współczynnika. (**Badanie i rozwój induktorów o częstotliwości radiowej**)*

Keywords: Vector Finite Element Method, RF inductor, Q-factor.
Słowa kluczowe: wektorowa metoda elementów skńczonych, Induktor RF, współczynnik jakości..

Introduction

The object of the research is an SMT (Surface Mount Technology) inductor, which can be found in antennas amplifiers, DECT (Digital European Cordless Telecommunications) systems, mobile phones and global positioning systems (GPS). This inductor has a cubic coil with ceramic core made of Rubalit. Rubalit is a type of ceramic, which is made of 99.6 percent of Al_2O_3, which relative permittivity is 10. The diameter of the usually used winding wires are between 28 μm and 80 μm, so it is thinner than the human hair –the examined type of the component has 50 μm of its winding wire– and the material of it is made of copper and the wire has an enamel insulation. The relative permittivity of the insulation is 5. The terminals have a thick film coating made of silver, palladium and platinum to relieve the soldering of the component. The inductor is manufactured by automated machines. The dimensions of the inductor are 1.2 mm × 1.2 mm × 2 mm. The microscopic photo and the 3D CAD model of the component can be seen in Fig.1 and Fig.2.

In the first case, the effect of the modification of the winding to the quality factor was examined. The universal expression of the quality factor of an oscillating circuit is the following [4]:

$$(1)\; Q = \frac{\text{reactive power of the circuit}}{\text{real power of the circuit}} = \frac{I^2\,|\,\mathrm{Im}\{Z\}|}{I^2\,\mathrm{Re}\{Z\}} = \frac{|\,\mathrm{Im}\{Z\}|}{\mathrm{Re}\{Z\}}\,.$$

Several winding types –”closely”- and ”widely spaced” coils, and various diameters of the winding wire– have been tried out and measured to find the best arrangement of the coils on the core. The trial components were measured by an Agilent E4991A RF impedance and material analyzer. This type of analyzer provides a total solution for making accurate measurements of surface mount devices and dielectric or magnetic materials from 1 MHz to 3 GHz. To fix the small components easily, the Agilent E4991A Test Head and the Agilent 16197A SMD Test Fixture have been used.

The manufacturing and the measuring of the trial components were made in the Hungarian part of EPCOS AG, Szombathely, Hungary.

Simplified Finite Element Model and Governing Equations

First of all, towards the fast and efficient simulation, while taking care of the adequate examination of the winding, the 3D model has been simplified, and a 2D axial symmetry model has been developed. The 3D CAD model of the simplified inductor can be seen in Fig. 3. In this case, neglecting the specialties of the core does not cause significant difference between the measured and the simulated results. Fig. 4 shows the inductance as a function of the frequency in the two cases.

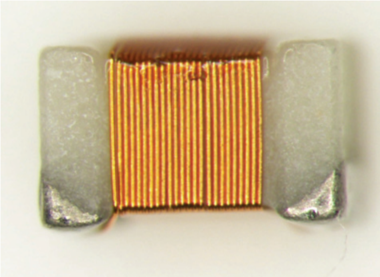

Fig.1. The microscopic photo of the inductor

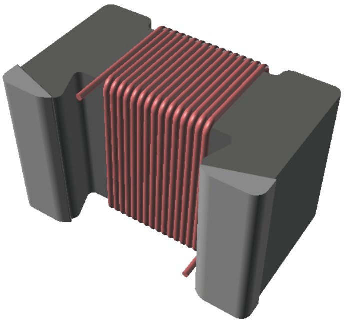

Fig. 2. The CAD model of the inductor

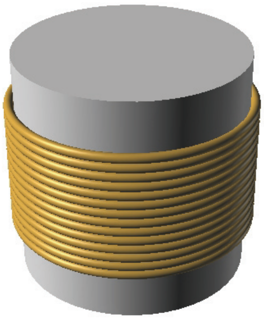

Fig.3. The CAD model of the simplified component

The dashed line represents the inductance of the model without insulation on the winding wire and the circled represents the inductor with insulated wire. It seems that the two lines are practically the same, so the insulation of the wire can be neglected.

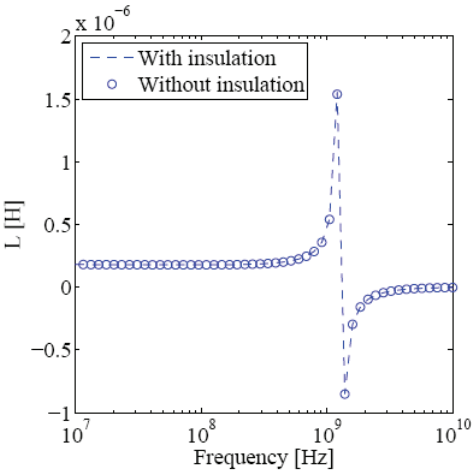

Fig.4. The inductor simulated with insulated wire and with wire without insulation

To check the results and the correctness of the simplified core, an inductor with axial symmetry core has been prepared and it has been measured in the factory. Three analyzed geometries of windings can be seen in Fig. 5. Because of the costs and the difficulties of the modification of the core or the materials of the inductor, in the first case, only the winding should be modified.

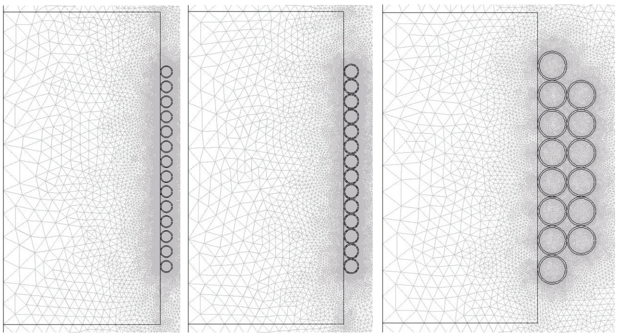

Fig.5. Finite element meshes of three different winding on the core

To solve the above problem, the full form of the Maxwell's equations have been used, because the effects of the eddy currents and the electric displacement can not be neglected at high frequencies [1,2,3],

$$(2)\quad \nabla \times \boldsymbol{H} = \boldsymbol{J_0} + \sigma \boldsymbol{E} + \varepsilon \frac{\partial \boldsymbol{E}}{\partial t},$$

$$(3)\quad \nabla \times \boldsymbol{E} = -\mu \frac{\partial \boldsymbol{H}}{\partial t},$$

$$(4)\quad \nabla \cdot \boldsymbol{B} = 0,$$

$$(5)\quad \boldsymbol{B} = \mu \boldsymbol{H},$$

where $\boldsymbol{H}$, $\boldsymbol{B}$, $\boldsymbol{E}$ and $\boldsymbol{J_0}$ are the magnetic field intensity, the magnetic flux density, the electric field intensity and the source current density of the excitation coil, σ, ε and μ are the conductivity, the permittivity and the permeability of the materials [1,2,3].

From the equations (2), (3), (4) and (5), the following partial differential equation formulated in the frequency domain can be calculated, with which the above problem can be solved:

$$(6)\quad (j\omega\sigma - \omega^2\varepsilon)\boldsymbol{A} + \nabla \times \frac{1}{\mu} \times \boldsymbol{A} = \boldsymbol{J_0},$$

where $\boldsymbol{A}$ is the magnetic vector potential and ω is the angular frequency.

The inductivity of the inductor can be calculated from the magnetic energy, i.e.

$$(7)\quad L_W = \frac{4W_m}{\hat{I}^2},$$

and from the impedance of the specimen as

$$(8)\quad L_S = \frac{\mathrm{Im}(Z)}{2\pi f},$$

where W_m, $\hat{I}$, N, Z and f are the magnetic energy of the studied region, the peak value of current flowing in the coil, the number of turns, the impedance and the frequency. The quality factor can be calculated from equation (1).

Simulation Results

To solve the above presented problem, the RF module of the COMSOL Multiphysics software package has been used [15]. At first, the problem of the manufactured component has been solved and the results –the inductance as a function of frequency and the quality factor as a function of frequency– have been compared with the measured data and they have been checked with analytical calculations (Fig. 6). In Fig. 7, the measured and the simulated inductance as a function of the frequency can be seen. The measured and the simulated quality factor as a function of the frequency can be seen in Fig. 8. The computed DC inductance, and DC resistance have been compared with the measured data and the analytical calculations to check the correctness of the model at low frequency. The measured value of the DC resistance of the inductor is 0.47 Ω, and the simulated value is 0.485 Ω.

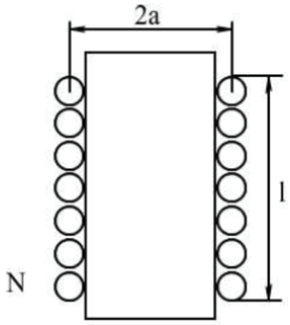

Fig.6. The schematic draw of the parameters in Nagaoka's equation

Analytically, the DC resistance is 0.463 Ω by using the following expression:

$$(9)\quad R_{DC} = N\rho \frac{l}{S},$$

where is N the number of turns, l is the length of one turn and S is the cross section of the winding wire. The measured value of the DC inductance is 183 nH, the computed value of it is 185 nH, and the analytical value of it is 178.9 nH by using the following formula:

$$(10)\quad L_{DC} = K\mu\pi a^2 \frac{N^2}{l},$$

where a is the mean radius of the coil, N is the number of turns, l is the length of coil as it can be seen in Fig. 6, and K is the Nagaoka coefficient, which is 0.6618 in this case [4], [7], [10], [11], [12], [13], [14]. It is important to note that the value of inductance can be easily modified by the increasing or decreasing of the distance between the turns in the finite element model and during the manufacturing process, too.

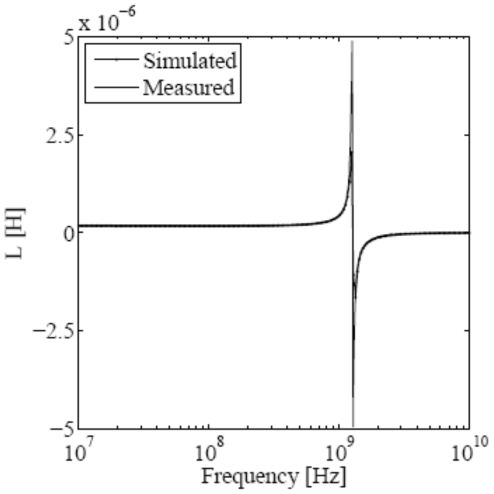

Fig.7. The measured and the simulated inductance as a function of the frequency

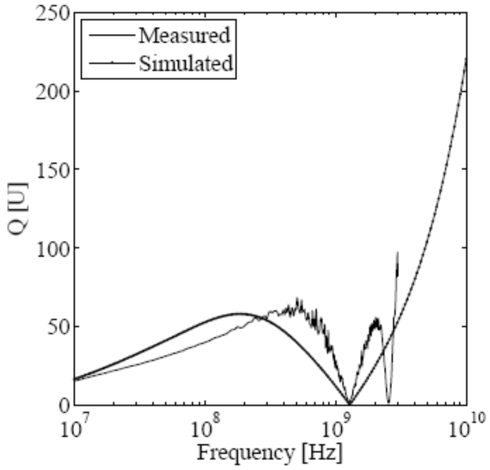

Fig.8. The measured and the simulated quality factor as a function of the frequency

Nowadays, the electronic component manufacturers need to produce smaller, faster and more efficient active and passive components. It is also true in the case of inductors. Some customer in the automotive and qualitative electronics wants to apply the presented type of inductor with super high quality factor (SHQ) in their applications. The qualification of the SHQ means higher value of it between 85 MHz and 110 MHz. The aim of this project is to find a way to increase the quality factor in the necessary rate. In the present the quality factor is about 30 in the range of the qualification SHQ.

In the first case, the increasing of the Q-factor by modifying the winding was examined by the measurements of the trial components and numerical simulations. From the expression of the quality factor, obviously the goal is to decrease the real value of the impedance Z, so the resistance of the inductor. Do not forget that the inductance has a nominal value, so the increasing of the reactive part of the impedance is not a good way.

The examination of the winding wire extends to the modification of the diameter of the winding wire, the modification of the distance between the turns and the modification of the material of the core.

The results are the following. Firstly, to decrease the serial resistance of the winding wire, the original 50 µm diameter of it was changed to 60 µm and to 80 µm.

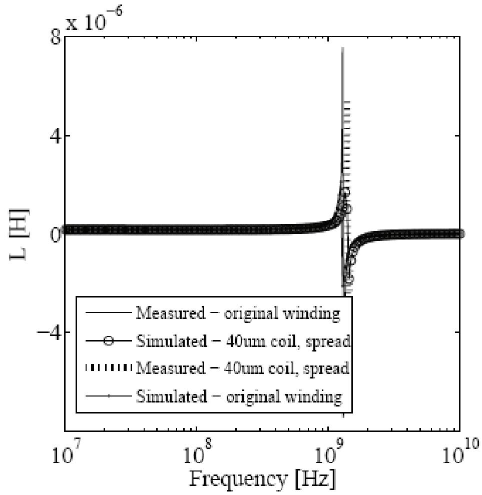

Fig.9. The measured and the simulated inductance as a function of the frequency after the modification

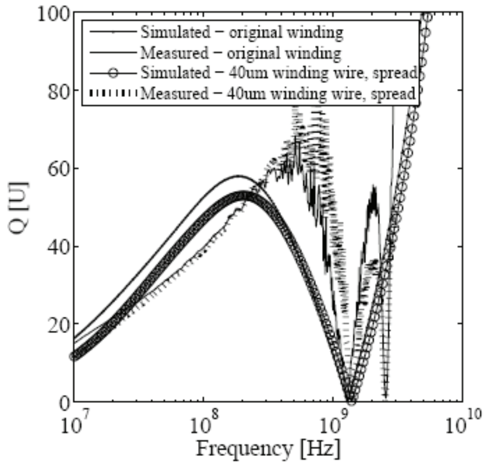

Fig.10. The measured and the simulated quality factor as a function of the frequency

In this case, the quality factor is slightly increasing, but by using thicker wire, the inductance is decreasing, moreover the space between the terminals, which length is about 1100 µm is also narrower. In conclusion, it is not possible to manufacture the inductors with thicker winding wire.

Then smaller diameter of winding wire was tried. By using thinner wire, the value of the inductance is increasing, so it is enough to use less number of turns to hold the nominal value of the inductance, additionally, in this case it is possible to increase the distance between the turns.

The measurements and the simulations show that the self resonant frequency is increasing by using spread wire and the rise of the quality factor is faster as a function of the frequency, but because of the higher resistance of the thinner wire, the quality factor is smaller than in the case of the original wire. In Fig. 9 and Fig. 11, the higher self resonant frequency is perceptible. The comparison of the quality factor of the original inductor and by using thinner wire with close and spread winding can be seen in Fig. 10.

Another attempt was the manufacturing of the inductor with ferrite core. The idea was that the nominal value of the inductance is achievable with less number of turns, so the real value of the impedance can be decreased. The experiences show that the idea is true, but the quality factor is decreased after all, because the effects of the hysteresis losses and the eddy current losses inside the core deteriorate the value of the Q-factor.

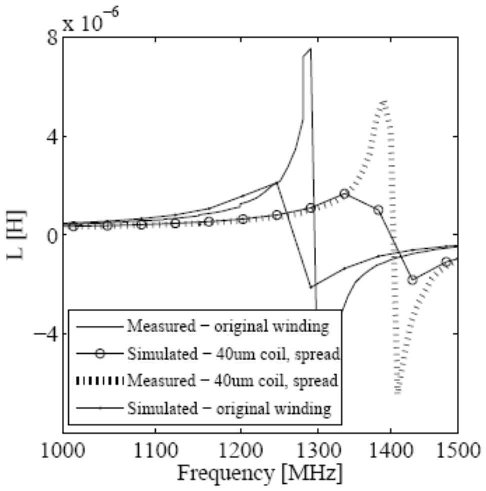

Fig.11. The measured and the simulated inductance as a function of the frequency after the modification – enlarged

The examination of different materials of the winding wire is an impossible task from the manufacturing point of view. Fortunately, in numerical solutions currently nonexistent materials can be tried out. The solutions demonstrated that by using a winding wire with higher conductivity than copper or gold, the quality factor could be increased sufficiently.

Taking it all around, thanks to the experiences of engineers the currently manufactured component is nearly the best solution for making this type of inductor. Considering the dimensions of the inductor, the nominal value of the inductance, the current manufacturing technology and the presently known materials, the quality factor is not increasable even more. There are several researches about the superconductivity and the superparamagnetism, which could solve the above problems.

Conclusions

The paper presents an actual problem of research engineers working with inductors and electronic components. To solve several problems beyond the examination of the quality factor, a finite element model has been developed by using the COMSOL Multiphysics software package. The potential formulation of the presented wave propagation problem has been implemented from the prescribed equations. The so-called scattering boundary condition has been determined and has been applied to eliminate the effect of the reflected electromagnetic waves at the artifical far boundary. The simulation of the simplified manufactured inductor has been done. To consider the capacitance and the resistance of the terminals an electric network has been implemented and the values of the parameters have been set. The built up finite element model has been tested. The measurements of the project have been executed in the hungarian factory of EPCOS AG, the results have been described and analyzed. The measured and the analyzed data have been compared with the results of the simulations. Consequently, the experiences show that by using the present materials and the present manufacturing technology, the quality factor can not be increased significantly.

The future aim of the project is to build up a 3 dimesional finite element model to simulate inductors at high frequency.

The procedure, which is under construction will be able to solve the presented problem with different materials of cores and geometries of inductances in 3D.

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