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Thermal Modeling of an Integrated Circular Inductor

Y. Benhadda[1,*], A. Hamid[1], T. Lebey[2]

[1] *University of Sciences and Technology of Oran (USTO- MB) 31000, Algeria*
[2] *University of Paul Sabatier, LAPLACE Laboratory, Toulouse, France*

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We present in this paper a study on the thermal behavior of an integrated circular inductor. We determinate a mathematical expression giving the evolution of temperatures in an integrated inductor using the separation of variables method and a visualization of the thermal behavior is determined in 3D space dimension using the finite element method.

Keywords: Thermal, Integrated circular inductor, Separation of variables, Finite element.

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1. INTRODUCTION

In power electronics, modeling of passive components constitute a particularly important issue. Indeed, the magnetic components, inductors and transformers are mainly used to transmit or store energy. The passive elements volume reduction leads to a mounted in operating frequency, but this increase in frequency causes an increase in losses [1-3]. If the behavior of some components is relatively insensitive to temperature changes, it is not the same thing for magnetic components whose characteristics depend strongly on the temperature. The losses freed in the form of heat are become a major concern due to the reduction of trade with the outside surfaces and increasing the density of losses. Under these conditions, the inclusion of temperature and its influence on the magnetic and electrical characteristics of the component is essential.

The purpose of this work is the thermal modeling of an integrated circular inductor. We have developed mathematical models that allowed us to determine the thermal behavior of our component. The Solving of mathematical equations by the method of separation of variables and the finite element method [4-5] has allowed us to see the evolution of the temperature in the different parts that make up the inductor in 3D.

2. GEOMETRICAL AND ELECTRICAL PARAMETERS OF AN INTEGRATED CIRCULAR INDUCTOR

The geometry parameters characterizing the integrated inductor (Fig. 1) are the number of turns n, the width of the conductor w, thickness of the conductor t, the spacing between conductor s, length of the conductor l, the outer diameter d_{out} and input diameter d_{in}.

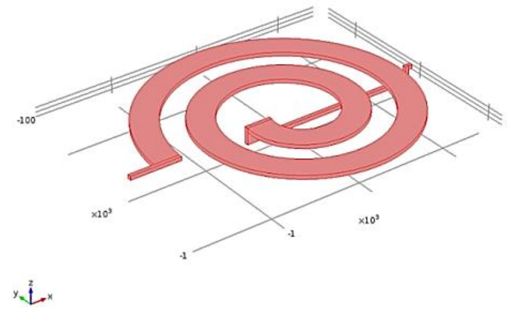


Fig. 1 – Geometry of integrated circular spiral inductor

Table 1 contains the specifications and the design results of the circular spiral integrated inductor [6].

Table 2 presents electrical parameters of the integrated inductor [6].

Table 1 – Design results of the circular spiral integrated inductor

Parameter	Value
Inductance, L (μH)	0.5
External diameter, d_{out} (mm)	3
Internal diameter, d_{in} (mm)	0.9
Number of turns, n	2
Thickness of the conductor, t (μm)	40
Width of the conductor, w (μm)	280
Spacing between conductor, s (μm)	245
Length of the conductor, l (mm)	15.9

The geometry of a circular spiral integrated inductor on substrate is shown in Figure 2.

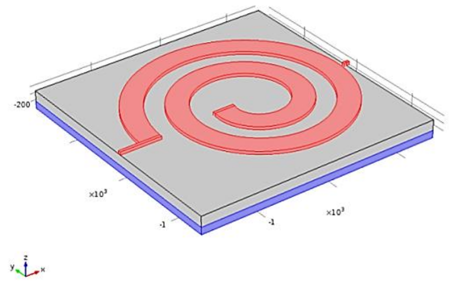


Fig. 2 – Geometry of integrated circular spiral inductor on substrate

3. THERMAL MODELING OF A CIRCULAR INDUCTOR

In this section we will predict the evolution of the temperature in an integrated circular spiral inductor using:

– Mathematical model based of the separation of variables method [7-8].

– Visualization of the thermal behavior based of the finite element method [9].

* benhadda_yamina@yahoo.fr

Table 2 – Electricals Parameters of the Integrated Circular Spiral Inductor

Electricals parameters	Values
$R_s(\Omega)$	0.0241
$R_{sub}(\Omega)$	0.002
$C_s(pF)$	0.023
$C_{ox}(pF)$	15.37
$C_{sub}(pF)$	2.03
Q	58

We present an integrated inductor in the air, with thickness L (Figure 3). We consider also an integrated circular spiral inductor on substrate. k_1, k_2 and k_3 be the thermal conductivities for the first layer in $0 \le y \le L_1$, second in $L_1 \le y \le L_2$ and third in $L_2 \le y \le L_3$. q is the heat source. Initially, the three layers are at temperature T_0. The boundary surface at y=0 is kept at temperature T_0 and the boundary at $y = L_1 + L_2 + L_3$, dissipate heat by convection with h constant (Figure 4).

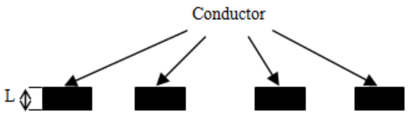


Fig. 3 – Transversal cup of an integrated inductor in the air

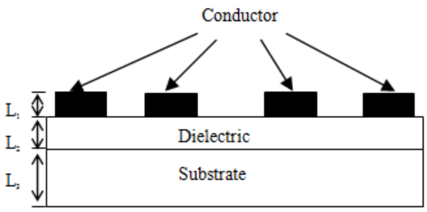


Fig. 4 – Transversal cup of an integrated inductor

The heat source [10] q can be expressed as (1)

$$q = \frac{P_c}{V} \tag{1}$$

where, V is the volume of our component.

The loss [11] P_c can be expressed as (2)

$$P_c = R_s.I^2 + R_{AC}.I_L^2 \tag{2}$$

where, R_{AC} is the resistance at alternative current (3).

$$R_{AC} = \frac{\rho l}{\delta(1 - e^{-(t/\delta)})} \tag{3}$$

3.1 Mathematical Model

The mathematical formulation of an integrated circular spiral inductor in the air is given as (4)

$$\frac{\partial^2 T}{\partial y^2} + \frac{1}{k} q = \frac{1}{\alpha}\frac{\partial T}{\partial t} \tag{4}$$

For solve this equation, we can determinate the solution analytical for homogeneous problem $T_h(y,t)$, and the solution of steady-state problem $T_s(y)$. The solution for the original problem (4) is determined from (5).

$$T(y,t) = T_h(y,t) + T_s(y) \tag{5}$$

The analytical solution 1D for equation (4) is given as (6)

$$T_h(y,t) = \sum_{m=1}^{\infty} \frac{e^{-\beta_n^2.t}}{N(\beta_m)}.Y(\beta_m, y).\int_{y'=0}^{L} Y(\beta_m, y').T_0 dy' \tag{6}$$

With, $Y(\beta_m, y) = \sin\beta_m y$, $\frac{1}{N(\beta_m)} = \frac{2}{L}$ and $\sin\beta_m y = 0$.

$\beta_m = m\pi/a$, m=1,2,3,…

$T_s(y)$ is the solution of the steady-state.

The mathematical formulation of an integrated circular spiral inductor on substrate is given as (7), for i = 1, 2, 3.

$$\frac{\partial^2 T_i}{\partial y^2} + \frac{q}{k_i} = \frac{1}{\alpha_i}\frac{\partial T_i}{\partial t} \tag{7}$$

For solve this equation, we can determinate the solution analytical for homogeneous problem $\theta_i(y,t)$, and the solution of steady-state problem $T_i(y)$. We use the Green's function of heat conduction problems with heat source. The solution is determined from (8).

$$T_i(y,t) = \theta_i(y,t) + T_i(y) \tag{8}$$

The temperature boundary conditions are determined from (9)

$$\begin{aligned} &\theta_1 = 0, at: y = 0 \\ &\left.\begin{aligned} &\lambda_i \frac{\partial \theta_i}{\partial y} = \lambda_{i+1}\frac{\partial \theta_{i+1}}{\partial y} \\ &\theta_i = \theta_{i+1} \end{aligned}\right\}, \text{at interface}, i = 1,2 \\ &\lambda_3 \frac{\partial \theta_3}{\partial y} + h\theta_3, at: y = L_1 + L_2 + L_3 \end{aligned} \tag{9}$$

h represent the convective heat transfer coefficient. The initial condition is (10).

$$\theta_1(y,t) = T_0 \tag{10}$$

We determinate $\theta_i(y,t)$ with following equation (11)

$$\theta_i(y,t) = \sum_{n=1}^{\infty} \frac{1}{N_n} e^{-\beta_n^2.t}\left(A_{in}\sin\frac{\beta_n.y}{\sqrt{\alpha_i}} + B_{in}\cos\frac{\beta_n.y}{\sqrt{\alpha_i}}\right)G \tag{11}$$

The solution $T_s(y)$ is determined from (12)

$$T_s(y) = \varphi_i(y).T_0 + \Psi_i(y).T_0 \tag{12}$$

The functions $\varphi_i(y)$ and $\Psi_i(y)$ are the solutions of the steady-state. The solution of the heat equation with heat source is given by Green's function $G_{ij}(y,t\,|\,x',\tau)$ (13).

$$T_i(y,t)=\sum_{j=1}^{M}\left\{\begin{array}{l}\int_{y_j}^{y_{j+1}} y'\left|G_{ij}y,t\right|y',\tau)\Big|_{\tau=0}T_0dy'+\int_{\tau=0}^{t}d\tau.\\ \int_{y_j}^{y_{i+1}} y'G_{ij}(y,t\left|y',\tau\right)\left[\dfrac{\alpha_j}{k_j}q\right]dy'\end{array}\right\} \tag{13}$$

3.2 Results

In this section, we present the temperature profile of our integrated circular inductor in the air and on substrate.

Figure 5 shows the temperature profile in our component on the air. We note that the temperature distribution is constant in the conductor, it stabilize at a value of 25 °C corresponding to the ambient temperature (boundary conditions).

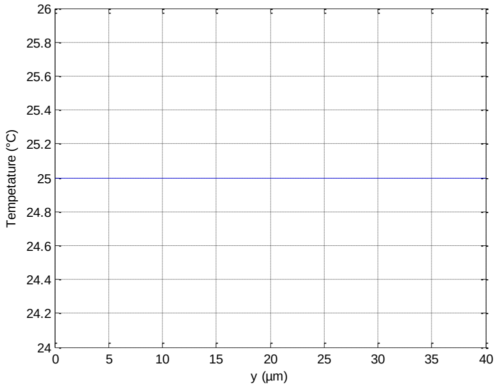
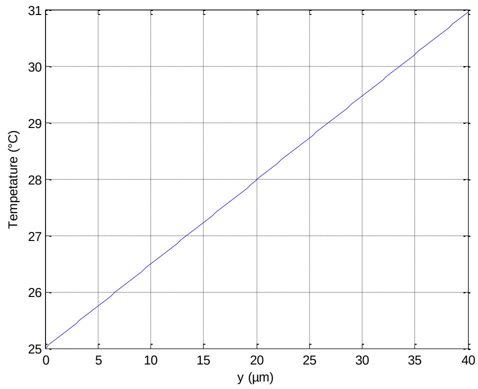


Fig. 5 – Temperature profile in an integrated inductor on the air



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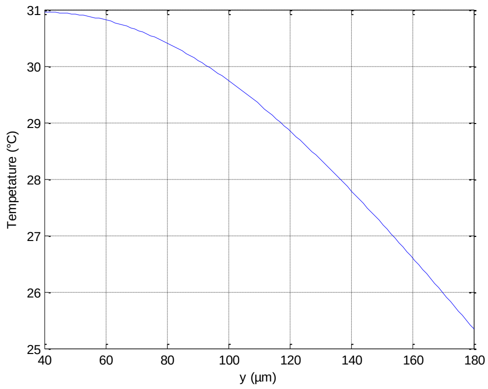

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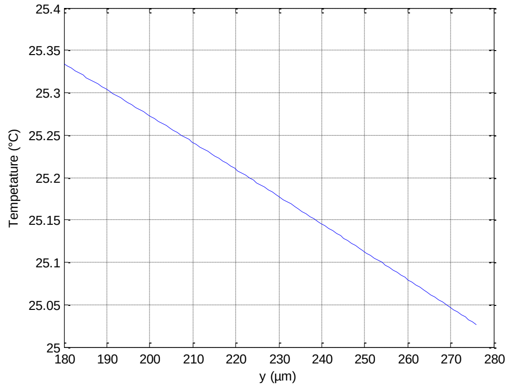


c

Fig. 6 – Evolution of temperature in an integrated inductor on substrate in a, (a) conductor, (b) dielectric and (c) substrate

In Figure 6 (a), (b) and (c), we observe the evolution of temperature in an integrated inductor on substrate in a conductor, dielectric and in a substrate, respectively. The temperature distribution increase in the copper and it decreases in the silicon oxide layers, and the substrate. Our results were compared with those from the literature [5]. We notice the same evolutions therefore quite acceptable and in very good agreement.

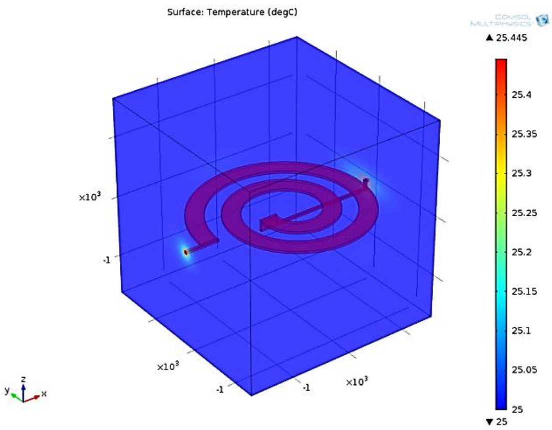
3.3 Visualization of the Thermal Behavior

In this section, we present the temperature distribution in our integrated inductor, based on the finite element method.

Geometry of this study is created in 3D space dimension. This distribution is obtained by solving the equation (32) of heat taking into account certain boundary conditions.

$$\rho.C_p\frac{\partial T}{\partial t}-\nabla\left(k\nabla T\right)=q \tag{32}$$

In Figure 7, we observe the temperature distribution in the inductor on the air. We see from these figures that the temperature attained is from 25 °C.



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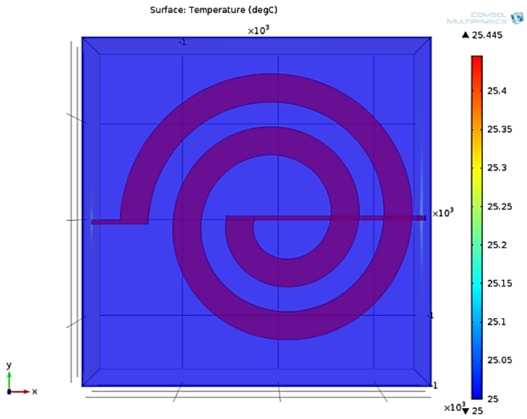

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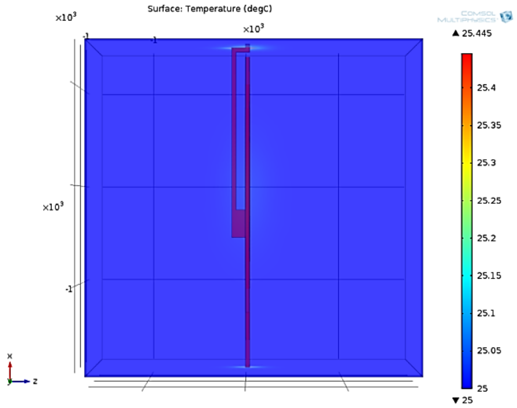

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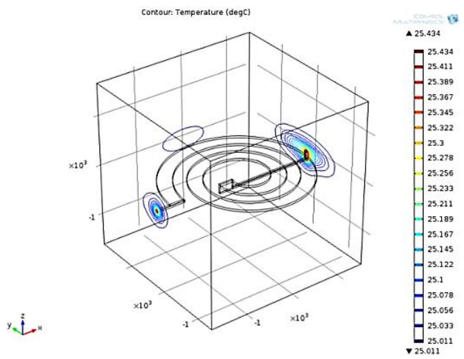


d

Fig. 7 – Temperature distribution in the inductor on the air, (a) general view, (b) view dessu, (c) front view, (d) on contour

In figure 8, we observe the total heat flux distribution in the inductor on the air.

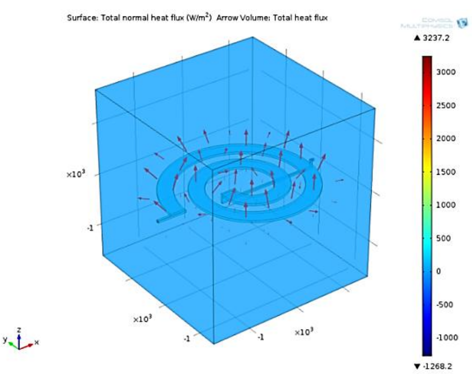
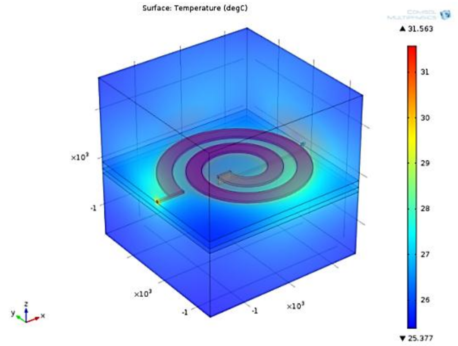


Fig. 8 – Total heat flux distribution in the inductor on the air

In Figure 9, we observe the temperature distribution in the inductor on substrate. We see from these figures that the temperature is about 31 °C. Our results were compared with those from the literature [5]. We notice the same evolutions therefore quite acceptable and in very good agreement.



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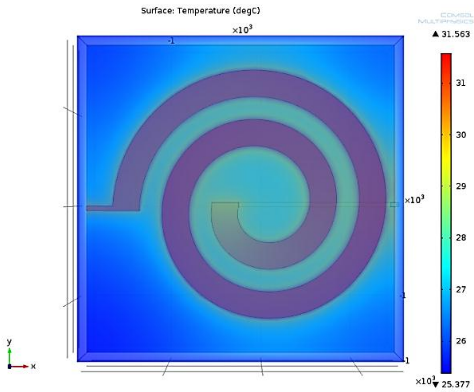

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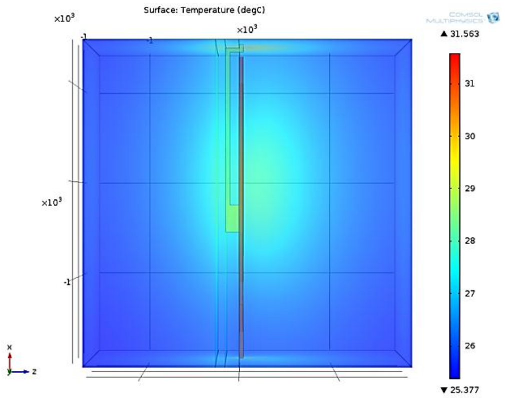

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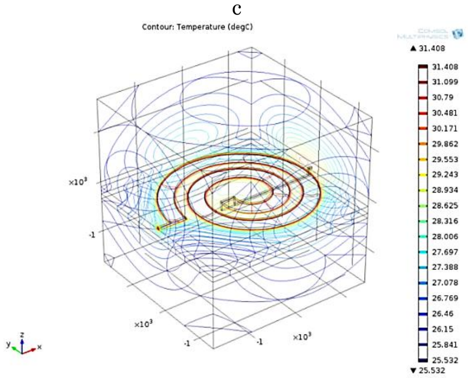

d

Fig. 9 – Temperature distribution in the inductor on substrate, (a) general view, (b) view dessu, (c) front view, (d) on contour

In Figure 10, we observe the total heat flux distribution in the inductor on substrate.

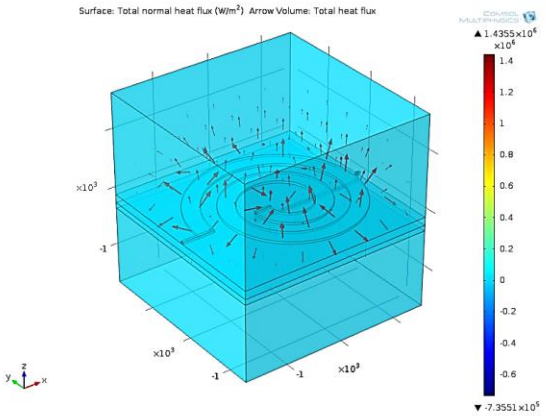

Fig. 10 – Total heat flux distribution in the inductor on substrate

4. CONCLUSION

The integrated inductor is a very important element in the power electronics. For its design, the determination of its geometrical and electrical parameters must be complemented by the study of the thermal behavior. In this paper we addressed the problem of thermal modeling in integrated passive components, in our case, an integrated inductor. We have implemented the literature methods for the design of our integrated inductor and the calculation of the heat losse. We have also developed mathematical models that allowed us to determine the thermal behavior of our component. The results concerning the temperature distribution in the different layers of our component in the transient regimes. These results are useful for understanding the operation of our integrated inductor.

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