Square Planar Spiral Inductor High Frequency Field and Parameters Analysis

Claudia Păcurar, Vasile Țopa, Adina Răcășan, Călin Munteanu, Claudia Constantinescu, Mihaela Vid

Faculty of Electric Engineering, Technical University of Cluj-Napoca, Romania

Abstract *– High frequency field and parameters analysis based on numerical modeling are of basic necessities for optimal design of the electromagnetic devices used in high frequency applications. In this article are presented the high frequency field and parameters analysis of square planar spiral inductors. There are analyzed the distributions of the electric and magnetic fields in order to highlight the effects and phenomena that occur in the spiral inductors at high frequency. It is also analyzed the inductance and quality factor variations in terms of frequency. Three square spiral inductors having only different number of turns are modeled to identify which of them have maximal value for inductance and quality factor in the considered frequency domain.*

Keywords – *field distribution, high frequency, inductance, quality factor, spiral inductor*

1. INTRODUCTION

The numerical modeling and functional simulation of the spiral inductors implemented on radiofrequency integrated circuits (RFIC) for field and parameter analysis in order to evidence the particularities of their high frequency functioning are extremely important for their optimal design.

The applicability domains of spiral inductors are very extensive, they are used in all the latest generation devices, especially those where the size, the weight and the performance are of paramount importance.

The continuous increase of the frequency to gigahertz order, together with the corresponding reduction of the dimensions of these components to microns order involves major changes both on the entire RFIC and on the elements that compose it.

Given the variety of advantages (durability, strength, reliability, possibilities for series manufacture, implementation on flexible substrate, low manufacturing cost, and so on), spiral inductors implemented on RFIC are an indispensable element in the production of advanced components and integrated circuits for high frequency applications.

We will model and functional simulate three square planar spiral inductors to highlight the effects and phenomena that occur in high frequency for understanding their functionality and to extract their inductance and quality factor.

Spiral inductors plays a crucial role in the integrated circuits that operate at frequencies of GHz order, and that have very small dimensions of nano and/or micrometer orders.

The numerical modeling were performed for square planar spiral inductors with ground ring having 3.5 turns, 9.5 turns and respectively 15.5 turns, using a commercial field solved dedicated to high frequency analysis, in order to highlight the effects and phenomena that occur at high frequency and to determined their characteristic parameters variations. The three-dimensional numerical modeling of the square spiral inductors were done in the 1-5 GHz frequency domain, for the analysis of:

- electric and magnetic field distributions, respectively current density distributions as amplitude and/or vector;
- inductance and quality factor variation versus frequency.

2. SPIRAL INDUCTORS FIELD ANALYZES

The spiral inductors filed analyzes is extremely important to predict the effects and phenomena that occur because of the frequency and because of the spiral complexity.

We model three square planar spiral inductors with 3.5 turns, 9.5 turns, respectively 15.5 turns that occupy on RFIC the same area of 0.29 mm^2.

The other dimensions of the spirals are: the exterior diameter, d_e=510 µm, the width of the turn, w=10 µm, the distance between the turns, s=5 µm, the thickness of the turn, t=2 µm. The spiral in made of copper.

The spiral in placed on an oxide layer of 6 µm thickness, made of silicon dioxide.

Under the oxide layer is the substrate, made of silicon, and having the thickness of 380 µm.

A layer of air is considered above the spiral, having the thickness of 1100 µm (Figure 1).

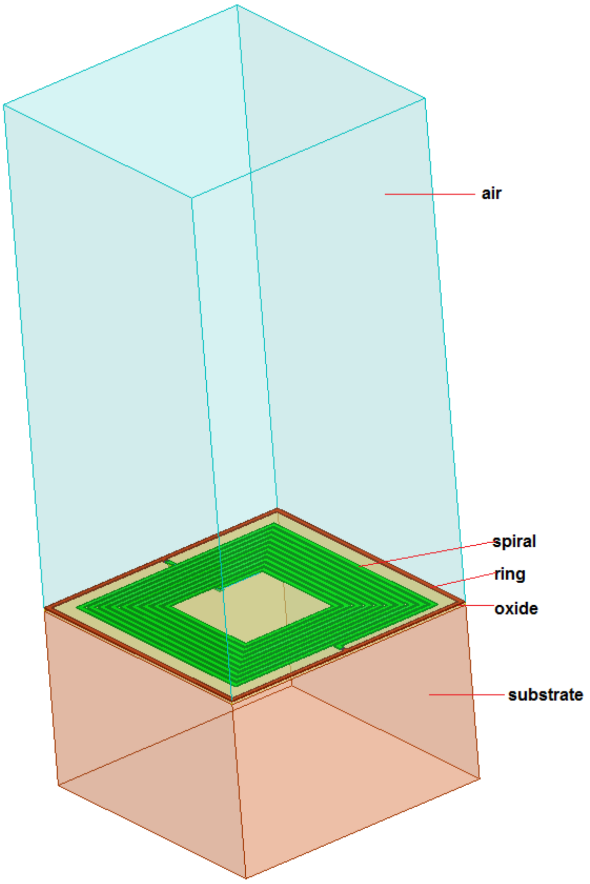


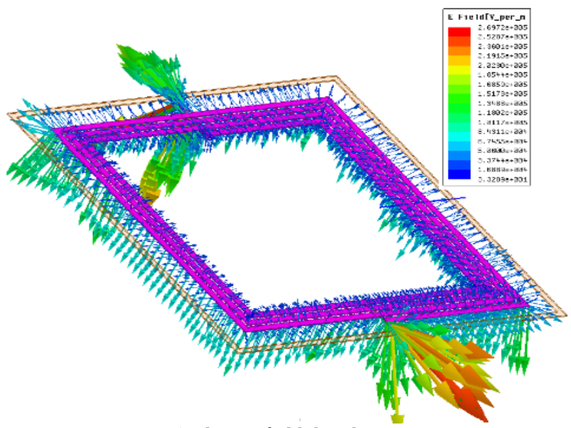
Fig. 1 – Spiral inductor 3D implementation.

The field distributions representations were done for the three spiral inductors implemented on RFIC, for each component in part: for the spiral, ground ring, oxide layer, substrate, and respectively air layer.

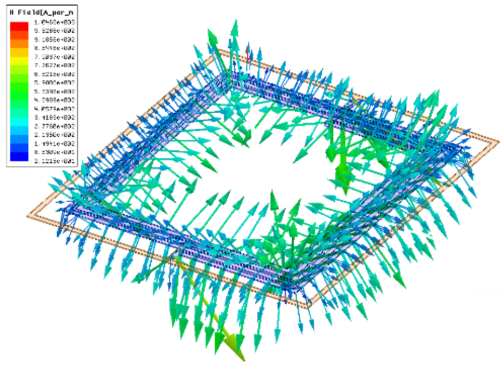
2.1. Field analysis in the spiral of the inductor

The electric and field distributions, and the surface current density distribution in the spiral of the inductor with 3.5 turns are presented in Figure 2. As can be observed in high frequency the distributions are not linier, we can say that they are chaotic.

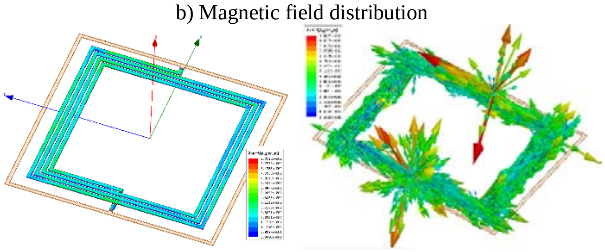
The maximal values for the electric field and for the current density distribution are in the area of the two terminals of the inductor.



a) Electric field distribution



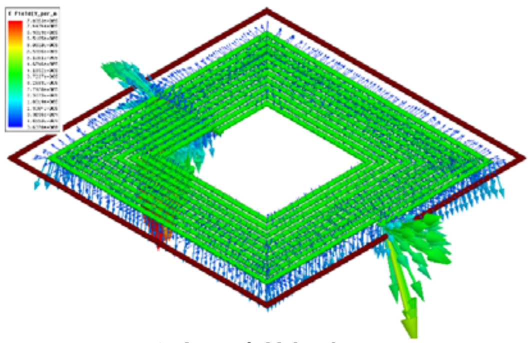
b) Magnetic field distribution



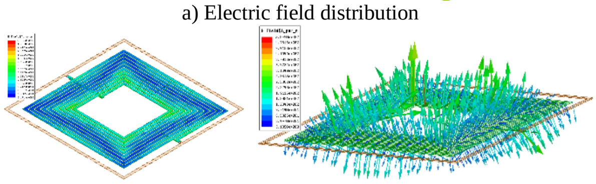
c) Surface current density distribution

Fig. 2 – Field results for the spiral inductor with 3.5 turns.

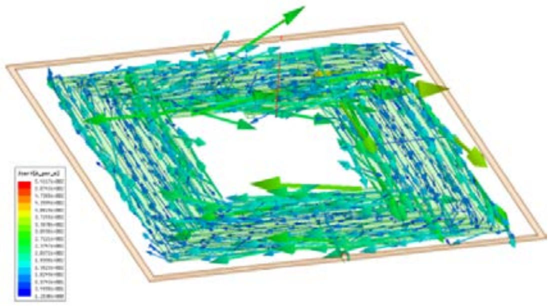
The distributions obtained for the spiral inductor with 9.5 turns are presented in Figure 3.



a) Electric field distribution



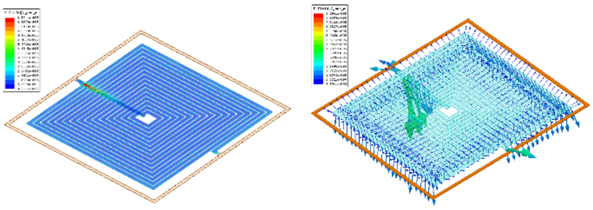
b) Magnetic field distribution



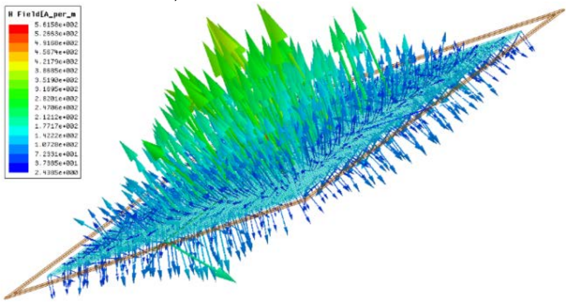
c) Surface current density distribution

Fig. 3 – Field distributions for the spiral inductor with 9.5 turns.

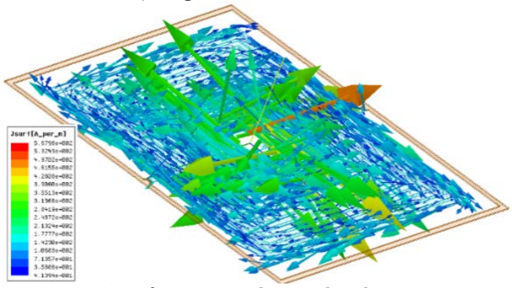
Once with the complexity of the geometry, the high frequency proximity and skin effects and phenomena are more obvious. The results obtained for the spiral inductor with 15.5 turns are presented in Figure 4.



a) Electric field distribution



b) Magnetic field distribution



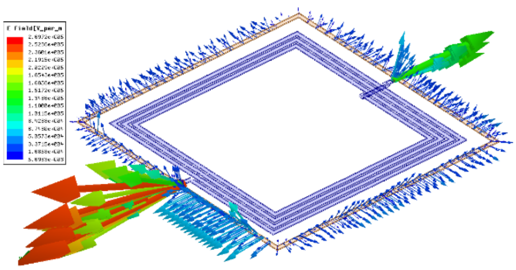
c) Surface current density distribution

Fig. 4 – Field results for the spiral inductor with 15.5 turns.

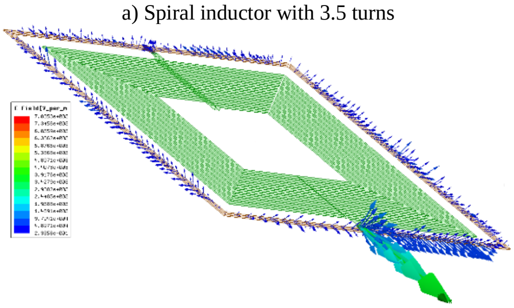
The maximal values of the field for the spiral inductor with the more complex geometry are concentrated in the center of the spiral.

2.2. Field analysis in the ring

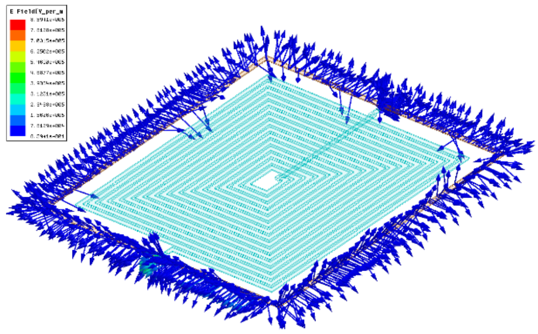
We modeled the three spiral inductor with the ground ring, so we want to see the representations of the field quantities also in the ring. In Figure 5 are the electric field distribution in the ground ring for the three spiral inductors.



a) Spiral inductor with 3.5 turns



b) Spiral inductor with 9.5 turns



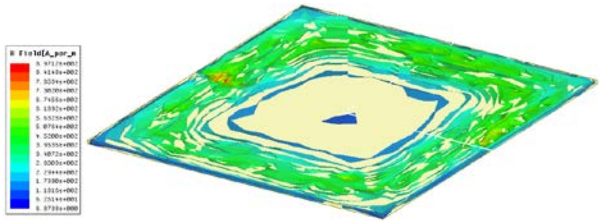
c) Spiral inductor with 15.5 turns

Fig. 5 – Electric field distributions in the ring.

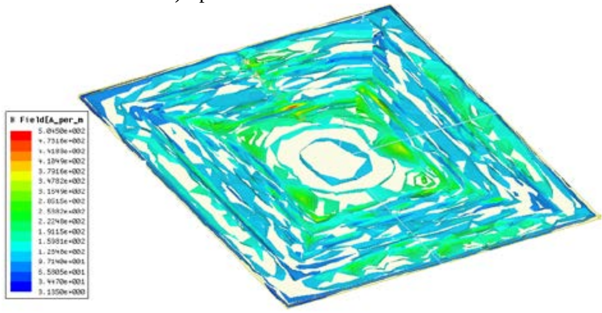
The electric field is almost constant in the ground ring, except the areas of both terminal.

2.3. Field analysis in the oxide layer

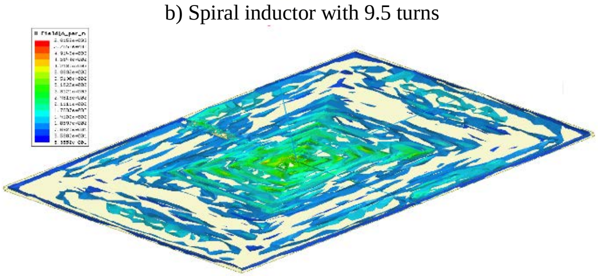
We analyzed the magnetic field distribution in the oxide layer, and we present them in Figure 6.



a) Spiral inductor with 3.5 turns



b) Spiral inductor with 9.5 turns



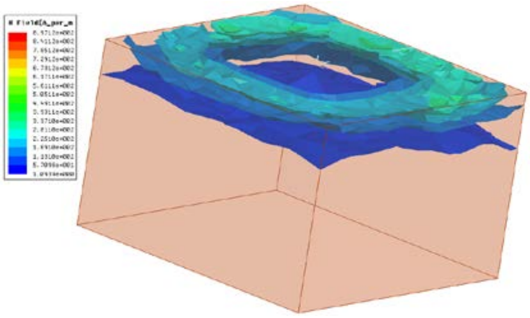
c) Spiral inductor with 15.5 turns

Fig. 6 – Magnetic field distributions in the oxide.

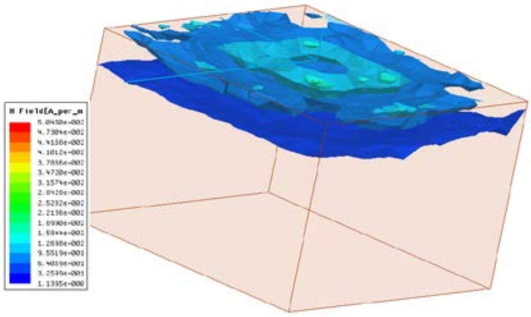
The magnetic field distributions in the oxide layer for the less complex structure, those with 3.5 turns' presents the bigger values that the other two more complex structure.

2.4. Field analysis in the substrate

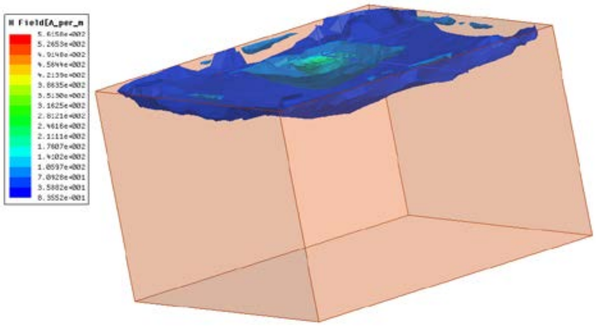
We analyzed the electric or magnetic field distribution also in the substrate, and we present them in Figure 7 for the same three square spiral inductors.



a) Spiral inductor with 3.5 turns



b) Spiral inductor with 9.5 turns



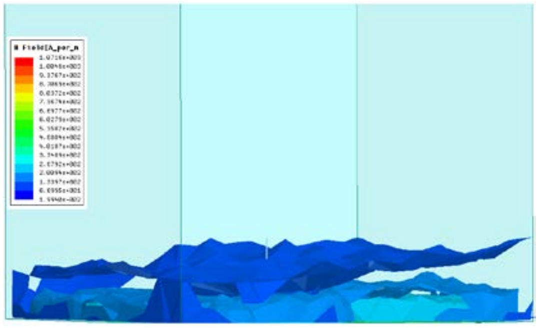
c) Spiral inductor with 15.5 turns

Fig. 7 – Magnetic field distributions in the substrate.

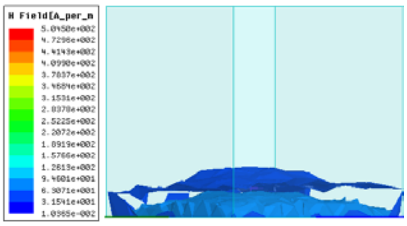
In the substrate of the spiral inductor with 3.5 turns the values of the magnetic field are bigger that for the other two modeled structures, even if it has the less complex structure.

2.5. Field analysis in the air layer

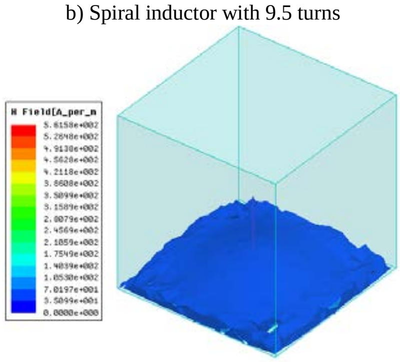
We analyzed the magnetic field distribution also in the air layer, and we present them in Figure 8. Also in the air the values of the magnetic field are bigger for the spiral inductor with 3.5 turns, even if it has the less complex structure.



a) Spiral inductor with 3.5 turns



b) Spiral inductor with 9.5 turns



c) Spiral inductor with 15.5 turns

Fig. 8 – Magnetic field distributions in the air.

3. SPIRAL INDUCTORS PARAMETERS ANALYSIS

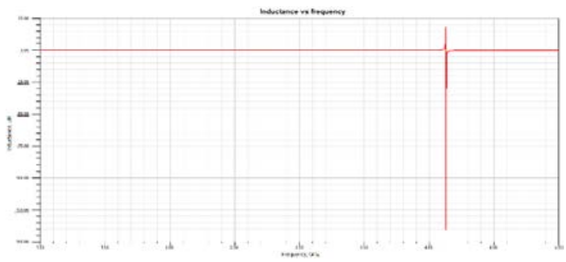
We analyze the inductance and the quality factor variation in terms of frequency for the three spiral inductors described above.

3.1. Inductance variations in terms of frequency

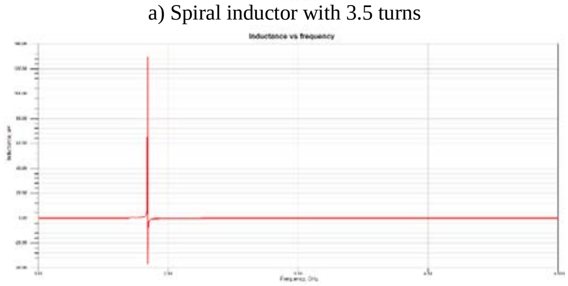
We analyze the inductance variation in 1-5 GHz frequency domain for all the spiral inductors by implementing in the program the inductance expression:

$$L = \frac{\Im m(1/Y_{11})}{2 \cdot \pi \cdot f} \qquad (1)$$

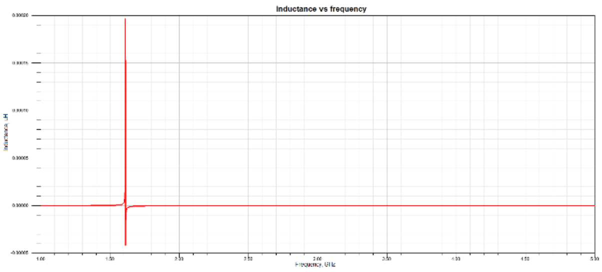
The inductance variations in terms of frequency for the three square planar spiral inductors are presented in Figure 9.



a) Spiral inductor with 3.5 turns



b) Spiral inductor with 9.5 turns



c) Spiral inductor with 15.5 turns
Fig. 9 – Inductance variations vs frequency.

The inductance has maxim value at 4.14 GHz, for the spiral inductor 3.5 turns as can be note in Figure 9a). For the spiral inductors with 9.5 turns the maxim inductance value is at 1.841 GHz, and for the one with 15.5 turns at 1.608 GHz.

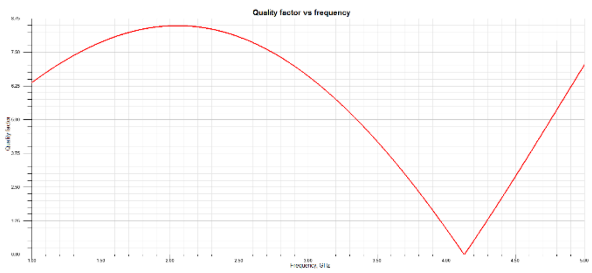
Comparing the inductance values of the three spiral inductors, the bigger value was obtained for the inductor with the maximal number of turns, knowing that inductance is directly proportional with the number of turns (1).

3.2. Quality factor variations in terms of frequency

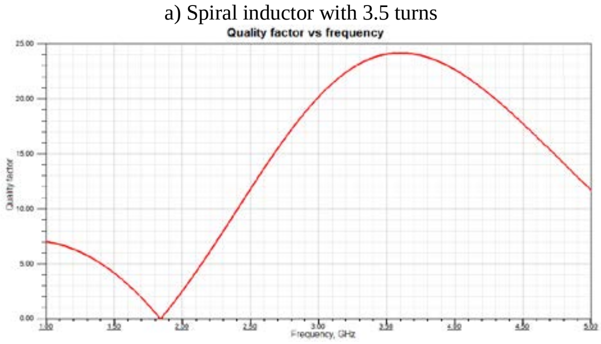
To analyze the quality factor of these three inductors we use the calculator of the program, and we implement the following expression:

$$Q = \frac{\Im m(1/Y_{11})}{\Re e(1/Y_{11})} \tag{2}$$

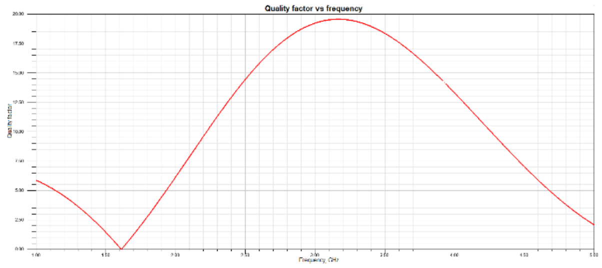
The quality factor variations in terms of frequency for the three square planar spiral inductors are presented in Figure 10. The quality factor for the spiral inductor with 3.5 turns is maxim at 2.083 GHz, as can be seen in Figure 10a) and is zero at the resonance frequency of the inductor, 4.14 GHz.



a) Spiral inductor with 3.5 turns



b) Spiral inductor with 9.5 turns



c) Spiral inductor with 15.5 turns
Fig. 10 – Quality factor variations vs frequency.

The quality factor for the spiral inductor with 9.5 turns is maxim at 3.6 GHz, as can be seen in Figure 10b) and is zero at the resonance frequency of the inductor, 1.841 GHz.

The quality factor for the spiral inductor with 15.5 turns is maxim at 3.168 GHz, as can be seen in Figure 10c) and is zero at the resonance frequency of the inductor, 1.608 GHz.

4. CONCLUSION

To improve the performances of the spiral inductors implemented in RFIC are needed the numerical modeling and parameters analyzes of each component element of the circuit. Also must be found precise numerical methods to extract their parameters. They must be also modeled and functional simulated to understand, study and analyze their behavior and functionality, to highlight the effects and phenomena that appear at high frequency and micrometer dimension. All these are needed for design and optimization of the spiral inductors in particular, and of the micrometer radiofrequency integrated circuits in general.

This paper treats the following: numerical modeling for high frequency analyzes of three spiral inductors with ground ring, inductance and quality factor variation in terms of frequency, the identification, highlight and analysis of the effects and phenomena that occur at high frequency on each part of the spiral inductor implemented on RFIC.

Synthetizing the obtained results for the three spiral inductors it is found that the inductor with 9.5 turns has maximal quality factor, proving that this structure is the most efficient one.

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S.l. dr. ing. Claudia Păcurar
Prof. dr. ing. Vasile Țopa
S.l. dr. ing. Adina Răcășan
Prof. dr. ing. Călin Munteanu
Asist. dr. ing. Claudia Hebedean
Ing. Mihaela Vid

Claudia Păcurar received the M.Sc. degree in Electrical Engineering in 2004 and the PhD Degree in Electrical Engineering in 2012, from Technical University of Cluj-Napoca. She joined the Department of Electrotechnics and Measurements from the Technical University of Cluj-Napoca in 2004. Since 2013 she is Lecturer. Her scientific work is related to electromagnetic fields, electric circuits, numerical computation, optimal design and electromagnetic compatibility.

Vasile Topa received the M.Sc. degree in electrical engineering from Technical University of Cluj-Napoca, in 1982, and the PhD. Degree in electrical engineering in 1998. He joined the Electrotechnics and Measurements Department from the Technical University of Cluj-Napoca in 1984. Since 2001 he is Professor of Electric Circuits and Electromagnetic Field Theory and head of the CAD in electrical engineering Laboratory. His scientific work is related to optimal design of electromagnetic devices and numerical computation methods in electromagnetism.

Adina Răcășan received the M.Sc. degree in electrical engineering from Technical University of Cluj-Napoca, in 2004. She joined the Electrotechnics and Measurements Department from Technical University of Cluj-Napoca in 2004 as a PhD student, receiving the PhD Degree in 2010. Since 2011 she is Lecturer. Her scientific work is related to electromagnetic fields, numerical computation, optimal design techniques and EMC.

Călin Munteanu received the M.Sc. degree in electrical engineering from Technical University of Cluj-Napoca, in 1989, and the PhD Degree in electrical engineering in 1999. He joined the Electrotechnics and Measurements Department from Technical University of Cluj- Napoca in 1991. Since 2003 he is Professor and the Head of the EMC Laboratory. His scientific work is related to EMC, electromagnetic fields, numerical computation, optimal design techniques

Claudia Hebedean received the M.Sc. degree in electrical engineering from Technical University of Cluj-Napoca, in 2009. She joined the Electrotechnics and Measurements Department from Technical University of Cluj-Napoca in 2009 as a PhD student. Her scientific work is related to electromagnetic fields, numerical computation, optimal design techniques and EMC.

Mihaela Vid received the M.Sc. degree in electrical engineering from Technical University of Cluj-Napoca, in 2014.

Claudia Păcurar
Faculty of Electrical Engineering, Technical University of Cluj-Napoca, 25-26, Barițiu st., Cluj-Napoca, Romania
Claudia.Pacurar@ethm.utcluj.ro