Electromagnetic Modeling and Frequency Response Determination for Planar Integrated LC Structures

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Abstract *– Planar structures are considered to be constructed from a number of thin stacked layers to form hybrid integrated structures. In order to understand the functioning of this kind of structures, the starting point of this paper is a short presentation of an LC cell and its frequency response, using the transmission line model. The study is continued considering more complex structures, taking into account their number of turns and the structure's length in order to obtain and analyze their frequency response.*

Keywords – *LC structures, structure length, number of turns, frequency response.*

1. INTRODUCTION

The planar structures have a lot of advantages, among them being the equivalence with discrete components without having the same number of connections, the repeatability of the elements, the reduced conductor surface which leads to low loss values. The main advantage is considered though the small dimensions and volume [1].

At the base of a planar structure is the LC cell, made from a dielectric substrate copper platted on the upper and lower surface. An LC structure with a highlighted LC cell from this structure are represented in figure 1. Any LC structure is a resonant structure whose characteristics depend on its external connections [2].

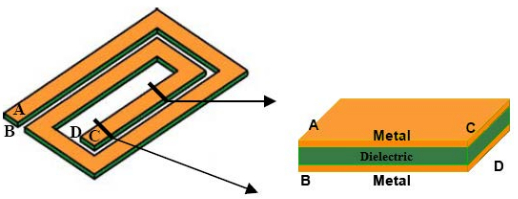


Fig. 1. LC integrated structure with an LC cell from its construction highlighted.

Although different methods were used in order to model the LC integrated structures, for this study the generalized transmission line model was used. In this paper the frequency response for a series resonator configuration is followed, beginning with a simple LC cell and reaching a multi-turn LC structure.

2. FREQUENCY RESPONSE OF AN INTEGRATED LC CELL WITH ITS PARAMETER VARIATION

The study began considering an integrated LC cell with a series resonator configuration as presented in figure 2. The variations of the impedance between the A and D ports for a frequency range between 100 kHz and 10 MHz are obtained and presented in figure 3.

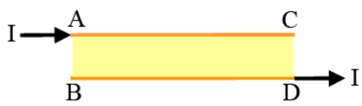
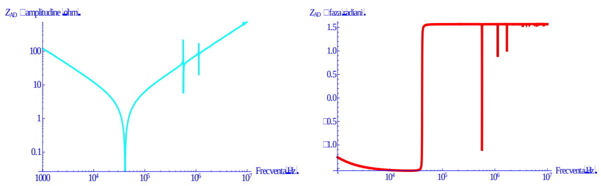


Fig. 2. Series resonator configuration of an LC cell.



a)amplitude b)phase

Fig. 3. Z_{AD} for a series resonator configuration of an LC cell.

Considering the fact that in the scientific literature the dimensions of such an LC cell aren't defined anywhere, a study was conducted considering the variation of different geometrical dimensions like its length, width, dielectric thickness and copper thickness.

For the thickness variation, 9 integrated cells were constructed with the thickness varying between 0.4 mm and 2 mm. The thickness of the copper layers (0.3 mm) and dielectric layer (0.1 mm) were maintained constant. One of the considered structures modeled in a numerical modeling software for this study is represented in figure 4. The values for the capacitance, self and mutual inductance and the resistance of this structure are obtained for all 9 cases and the frequency responses were determined for the series resonator configuration as can be observed in figure 5.

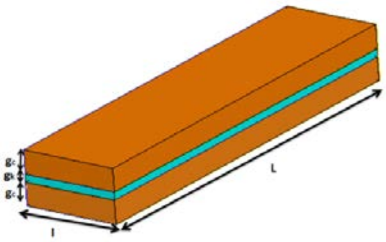
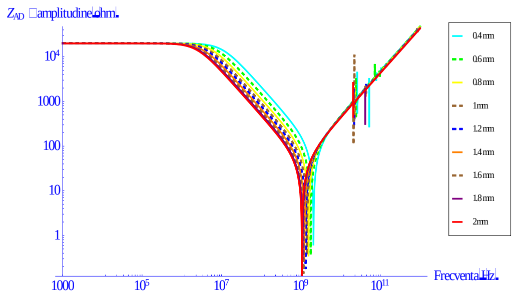
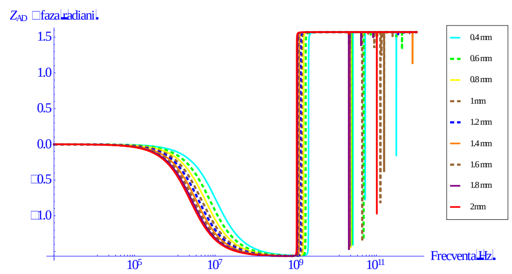


Fig. 4. Construction characteristics of an LC cell.



a)amplitude



b)phase

Fig. 5. Z_{AD} for a series resonator configuration of an LC cell with varied thickness and a 5 mm length.

It can be observed that with the increase of the LC cell the resonant frequency appears at smaller values of the analyzed frequency range. The PSpice scheme for one of the considered cases for this study is represented in figure 6 and the results are the ones from figure 7.

All the frequency responses were obtained using two programs, namely Mathematica and PSpice, always comparing the obtained results.

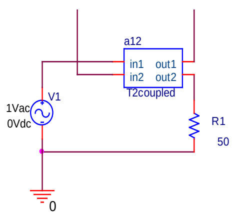
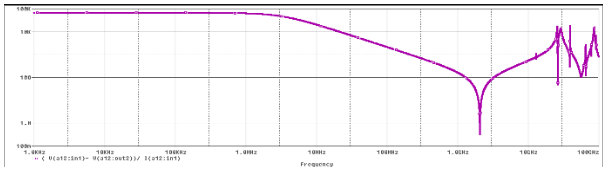
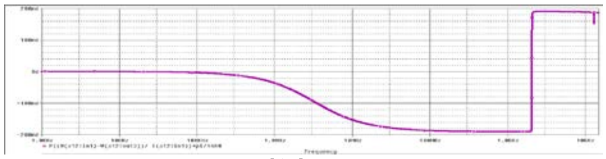


Fig. 6. PSpice scheme for the Z_{AD} simulation for a series resonator.



a)amplitude



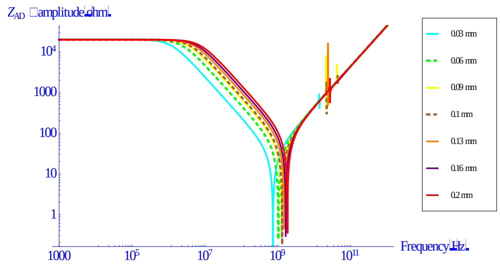
b)phase

Fig. 7. Simulation results for ZAD in the case of a series resonator.

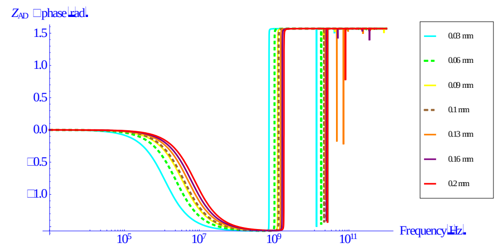
Also another length for the LC cell was considered, namely 250 mm, and it was concluded that the resonant frequency is found at lower frequency values when the length of the LC cell is increased.

The same process was followed for the determination of the dielectric thickness influence. Seven different structures were modeled in the numerical modeling software for the thickness variation between 0.03 mm and 0.2 mm. At first it was discovered that the capacitance and inductance values decrease with the increase of the dielectric value, while the resistance value remains constant. Also from the results presented in figure 8 it can be concluded that the resonant frequency is found at higher frequency values once the dielectric thickness is increased.

In the case where the copper thickness is varied between 0.005 mm and 0.3 mm and the other parameters are maintained constant, the capacitance values increase, while the inductance and resistance values decrease. The graphs for the studied cases are approximately identical, thus it can be said that the copper thickness does not influence the frequency response of an LC cell.



a)amplitude



b)phase

Fig. 8. Z_{AD} for a series resonator configuration of an 5 mm length LC cell considering the variation of the dielectric thickness.

3. FREQUENCY RESPONSE OF A LINEAR INTEGRATED LC STRUCTURE

An integrated LC structure is composed out of several integrated LC cells with the same or different parameters. A calculation formula based on the generalized transmission line theory for the LC structure constructed from cascade connected LC cells can be determined.

Figure 9 represents a linear integrated LC structure with n sections, each of them with its own parameters and lengths [3].

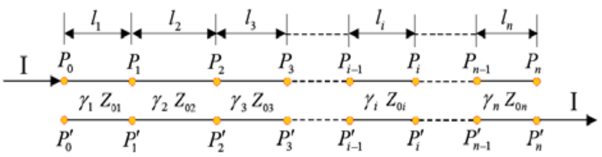


Fig. 9. LC linear integrated structure with n sections and series resonator conection.[3]

The frequency response of the LC cells connected in cascade will be determined, as previous, analytically with the help of Mathematica and through simulation with PSpice. The influence of the LC linear structure's length was determined by connecting 2 cells, and then 3 cell in cascade (figure 10). The LC cells are considered to have a length of 0.25 mm each.

It was observed that the results from the two programs are in accordance. Also, it was found that the fundamental resonant frequency is found at lower frequencies as the number of LC cells, thus the length of the structure, is increasing. The results are presented in Table 1.

It can be observed that when the number of LC cells is increased, thus the length of the structure is increased, the fundamental resonance frequency is at a lower frequency value in the frequency range considered.

Also, it was demonstrated that the result for a linear LC structure of 49.6 mm length constructed from a single cell is the same as for a linear structure with the same length but constructed from 4 LC cells.

In order to justify the use of more than one LC cell in the construction of such a linear structure, two structures were considered, one with a part embedded in a ferrite core (figure 11) and the other without a core like the ones from figure 10. Because it is known and proven with the help of a numerical modeling program that the zone where the structure is embedded in the core has different properties, this part is considered to be an LC cell. The other two parts are also different LC cells like in figure 12 [8].

Both structures have a length of 49.6 mm, with the first cell and third cell of 10.2 mm, while the middle cell has a length of 29.2 mm.

The characteristic capacitances, inductances and resistances for the considered LC cells were obtained through their modeling with the numerical modeling program. The characteristics for each of the two structures were then inserted in the model created with the help of the PSpice program presented in figure 12.

The frequency response was then obtained for the two analyzed structures. The results for the structure without the core are presented in figure 13, while the frequency response for the integrated LC structure embedded in a ferrite core can be seen in figure 14.

Analyzing the results, it can be said that in the presence of the ferrite core, the inductance for the LC cell inserted in the core is increasing. Also, it can be said that the fundamental resonant frequency is present at smaller frequency values from the studied frequency range for the core embedded structure than for the simple structure. As a final conclusion, dividing the integrated LC structures in integrated LC cells ensures a better assessment of their behavior.

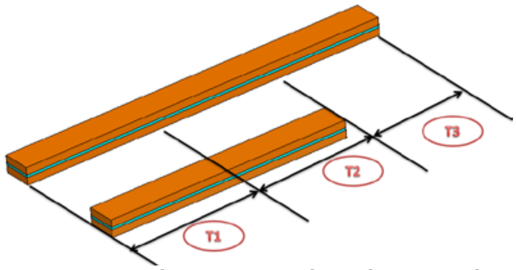


Fig. 10. Linear integrated LC structure with 2 and 3 integrated C cells connected in cascade.

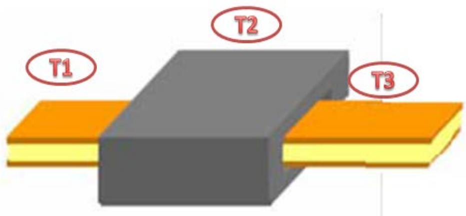


Fig. 11. Linear integrated LC structure considered to be constructed from 3 different LC cells.

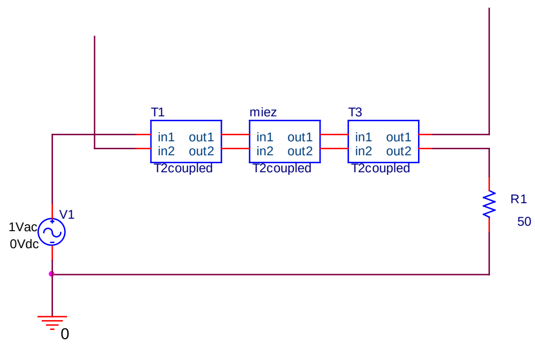
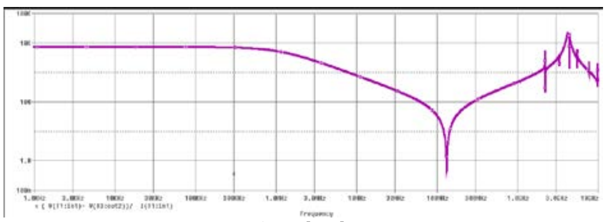
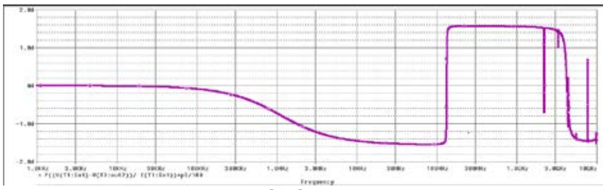


Fig. 12. PSpice scheme for Z_{AD} analysis in the case of the linear series resonator LC structure.

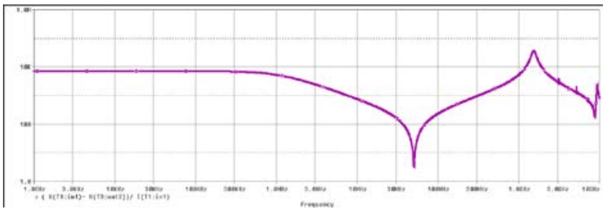


a)amplitude

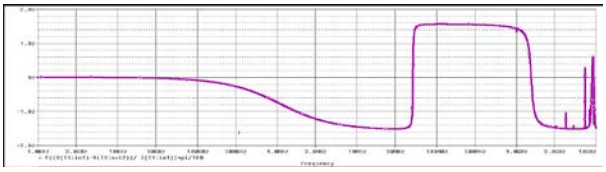


b)phase

Fig. 13. Simulation results for Z_{AD} in the case of a series resonator integrated LC structure without a core.



a)amplitude



b)phase

Fig. 14. Simulation results for Z_{AD} in the case of a series resonator integrated LC structure embedded in a ferrite core.

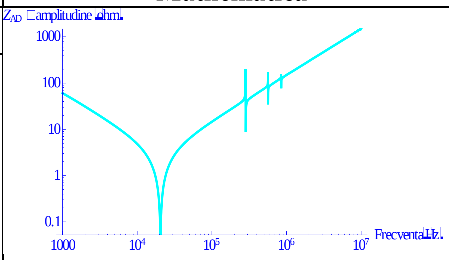
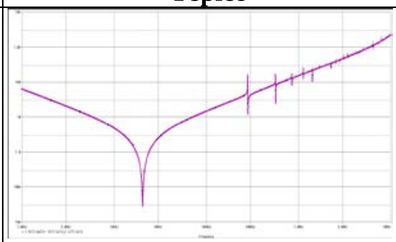
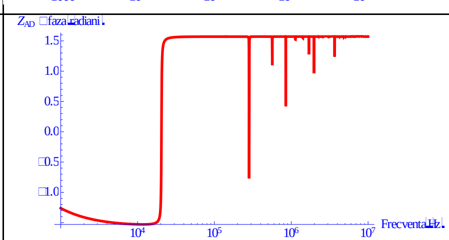
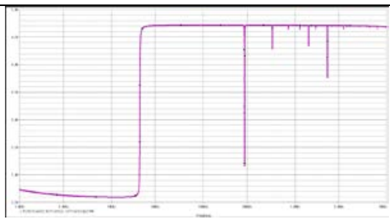
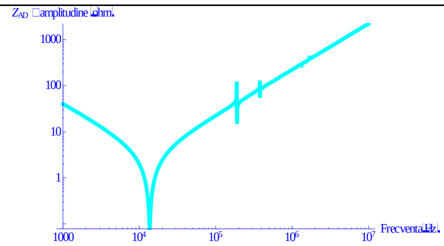
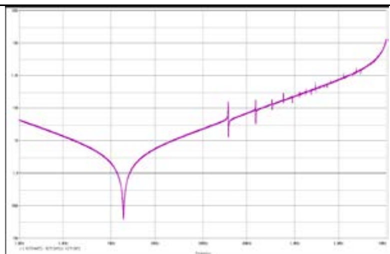
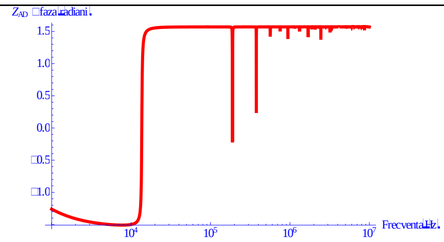
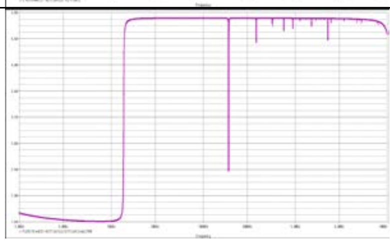
4. FREQUENCY RESPONSE OF A SPIRAL INTEGRATED LC STRUCTURE WITH ONE TURN

The integrated LC structure represents the fundamental element of a device created in planar electromagnetic technology [5].

In practical cases usually the spiral integrated LC structure is used, considered to be constructed from several LC cells connected in cascade. In the case of a spiral integrated LC structure with only one turn there are no couplings with other turns, so the analysis is simplified.

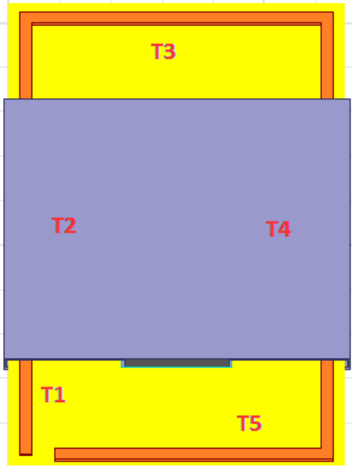
Considering the fact that this study underlies the EMI filters construction with integrated LC structure embedded in a ferrite core, the analyzed model can be observed in figure 15 [7]. In figure 15 c) the division of the considered structure into 5 different LC cells is represented. T2 and T4 cells are the cells embedded in the ferrite core, while the other 3 cells are coreless. The cell's properties are found by numerical modeling the considered structure with the help of Ansoft Maxwell 2D program, and the obtained results are inserter in the PSpice model presented in figure 16 to determine the frequency response from figure 17.

Table 1 – Impedance variation for a series resonator in the case of a linear integrated LC structure composed from several LC cells.

Number of cells	Mathematica	Pspice
With 2 cells Amplitude		
Phase		
With 3 cells Amplitude		
Phase		

a)2D model

b)transversal section of 3D model



c)3D model, top view of the structure divided in 5 LC cells

Fig. 15. The analyzed model.

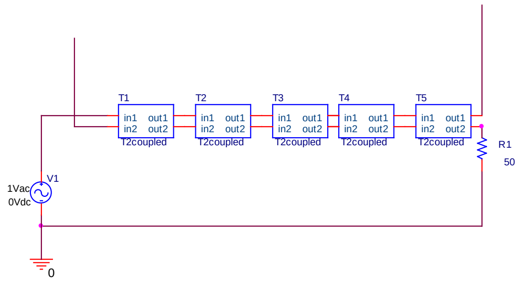


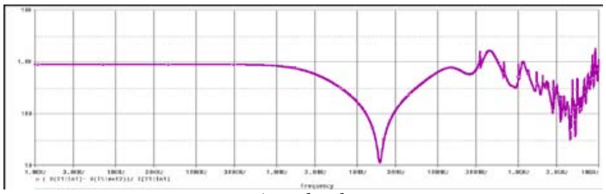
Fig. 16. PSpice scheme for Z_{AD} analysis in the case of the spiral series resonator LC structure with one turn.

The obtained values for capacitance, self and mutual inductance and resistance for the modeled spiral LC structure are presented in Table 2. T2 and T4 are the same column in the table due to the fact that they have the same geometrical dimensions and characteristics. The frequency response is presented in figure 17.

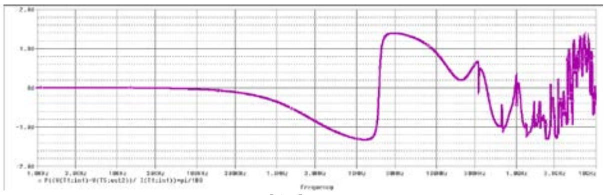
Although the graphics allure obtained for the spiral integrated LC structure with one turn remains approximately the same with the ones obtained for the linear integrated structure, the value of the fundamental resonant frequency is obtained at a lower frequency value for this case.

Table 2 –Properties of the LC cells used in the modelling of the spiral integrated LC cells with a single turn

Parameters of the considered LC cell	**T1**	**T2, T4 (Core)**	**T3**	**T5**
Inductivity per unit length, L [μH/m]	1.4814	15.874	1.4814	1.481
Capacity per unit length, C [μF/m]	0.00040	0.00040	0.0004	0.0004
Mutual inductivity per unit length,M [μH/m]	1.3776	15.75	1.3776	1.3776
Rezistence per unit length, R [Ω/m]	0.04781	0.04789	0.0478	0.0478
Conductance per unit length, G[Ωm]	0.01	0.01	0.01	0.01
Total length of the transmission line [m]	0.0102	0.0292	0.0486	0.0368



a)amplitude



b)phase

Fig. 17. Simulation results for Z_{AD} analysis in the case of the spiral series resonator LC structure with one turn.

5. FREQUENCY RESPONSE OF A SPIRAL INTEGRATED LC STRUCTURE -WITH MULTIPLE TURNS

A realistic planar integrated device is represented by more than a simple structure of a transmission line with two conductors due to the inductive and capacitive couplings between the turn sections, as it is illustrated in figure 18 [5], [6].

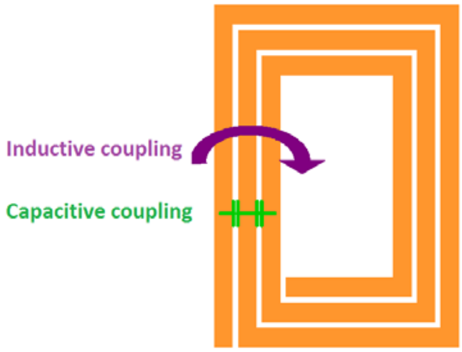


Fig.18. Inductive and capacitive couplings inside the multi-turn spiral integrated LC structure [4].

A study was conducted and it was demonstrated that the difference between the parasitic capacitance between vertical adjacent conductors and horizontal adjacent conductors is of two orders of magnitude for the structure considered in the study. This is why for obtaining the frequency response only the horizontal adjacent parasitic capacitance value was taken into account. The structure considered to be modeled has 3 turns and is embedded in a ferrite core. The parameters for the structure are presented in Table 3. The PSpice model and the frequency response of this structure are presented in figure 19 and figure 20.

The observation regarding the fundamental resonant frequency which is found at smaller frequency values if the structure is longer, is kept also for this structure. Also for the studied frequency domain a lot of resonant frequencies appear in the case of the studied structure.

Table 3 – Properties of the LC cells used in the modelling of the spiral integrated LC cells with three turns

Parameters of the considered LC cell	**a12, c12, e12**	**b12, d12 (core)**	**a34, c34, e34**	**b34,d34 (core)**	**a56, c56, e56**	**b56, d56 (core)**
Inductivity per unit length, L [μH/m]	1.9701	17.433	1.9726	16.708	1.971	17.236
Capacity per unit length, C [μF/m]	0.0001333	0.000126	0.00013173	0.0001231	0.00014294	0.00012481
Mutual inductivity per unit length,M [μH/m]	1.8691	17.342	1.5117	15.855	1.8695	17.145
Rezistence per unit length, R [Ω/m]	0.047893	0.047893	0.047893	0.047893	0.047893	0.047893
Conductance per unit length, G[Ωm]	0.01	0.01	0.01	0.01	0.01	0.01
Total length of the transmission line [m]	a12=0.0082 c12=0.0408 e12=0.0235	b12=0.0292 d12=0.0292	a34=0.0138 c34=0.0272 e34=0.0167	b34=0.0292 d34=0.0292	a56=0.0070 c56=0.0136 e56=0.0099	b56=0.0292 d56=0.0292

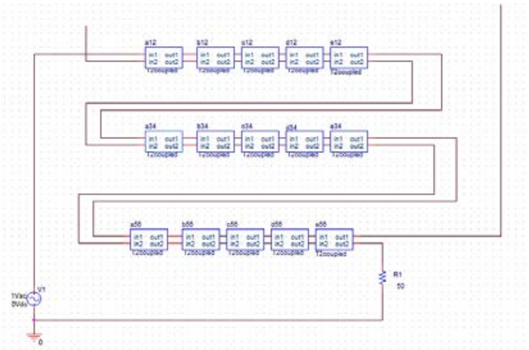
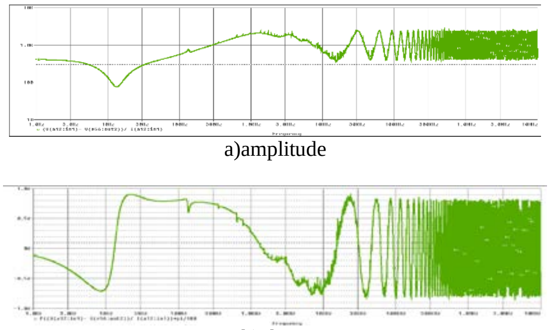


Fig. 19. PSpice scheme for Z_{AD} analysis in the case of the spiral series resonator LC structure with three turns.



a)amplitude

b)phase

Fig. 20. Simulation results for Z_{AD} analysis in the case of the spiral series resonator LC structure with three turns.

6. CONCLUSIONS

This paper presents a study regarding the frequency response of the integrated LC structures in series resonator configuration.

Considering the variation of the LC cell's geometrical dimensions, it can be observed that with the increase of the LC cell the resonant frequency appears at smaller values of the analyzed frequency range. Also the resonant frequency is found at higher frequency values once the dielectric thickness is increased and the copper thickness does not influence the frequency response of an LC cell for the studied cases.

The importance of separating a spiral integrated LC structure in LC cells was also highlighted and the conclusion that if the length of the structure is increased, the fundamental resonance frequency is at a lower frequency value from the frequency range considered was drawn for each studied case.

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