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Design and Modeling of Small Solenoid Inductor for Radio frequency Circuits

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Abstract. Design and modeling of solenoid inductor is presented. The effect of thickness of magnetic cores, number of turns, width of magnetic cores and width of coils of solenoid inductor on inductance, quality factor and Self-resonant frequency are considered. Development in percentage increase of quality factor is due to increase in width of magnetic cores. It can be found that ~32% of solenoid area reduction is observed when compared with conventional solenoid inductor design. The effective inductance and quality factor is checked by simulation for dynamic variation of various parameters over the desired frequency range. The dimension of solenoid inductor considered for asnalysis is 100 µm ×100 µm, suitable for better solenoid inductor design in high frequency radio frequency circuits.

Keywords: *solenoid inductor, quality factor, radio frequency, magnetic cores, spiral inductor*

1. Introduction

Integrated circuits in radio frequency, including mixers, switches, low noise amplifiers and voltage controlled oscillators, have begun to restore separate and hybrid components in wireless portable communication applications. Inductors play an important role in radio frequency integrated circuits, inspiring general work on the advance of structures to attain optimized performance. On-chip inductors are critical for permitting integrated wireless communication systems since the use of separate components introduce parasitic, creating the system integration and miniaturization intricate. Vertical, three-dimensional (3-D) structures have been proposed previously [1], with results illustrating advanced inductance and quality factor as compared to planar structures. In new times, integrated inductors manufactured utilizing magnetic cores [2] and thin films [3], have established a performance development of 30 times more than that of an air core inductor of an identical geometry.

A high quality factor can be obtained by the use of a magnetic core with a small iron loss at high frequencies. Thin film micro inductors [4] were prepared using multilayered CoNbZr/AIN film. The optimum conditions for a high Q were explored by varying the size of the magnetic core and the structure of the solenoid inductor. The inductance L and quality factor Q were observed to have higher values with decreasing thickness of magnetic core and with increasing thickness of metal coil [5].

This paper comprises of as follows Section 2 discuss about design and modeling, Section 3 about results and discussion and Section 4 about conclusion.

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2. Design and Modelling

The schematic of an inductor with magnetic core listing various parameters used in the representative model are shown in Fig. 1.

L_m is the length of magnetic cores (air core), n is the number of turns, w_m is the width of magnetic cores, t_m is the thickness of magnetic cores, l is the length of the coils, w is the width of coils, t is the thickness of coils, t_a is the thickness of the air core, s is the space between turns, s_V is the via size and w_V is the width of the via.

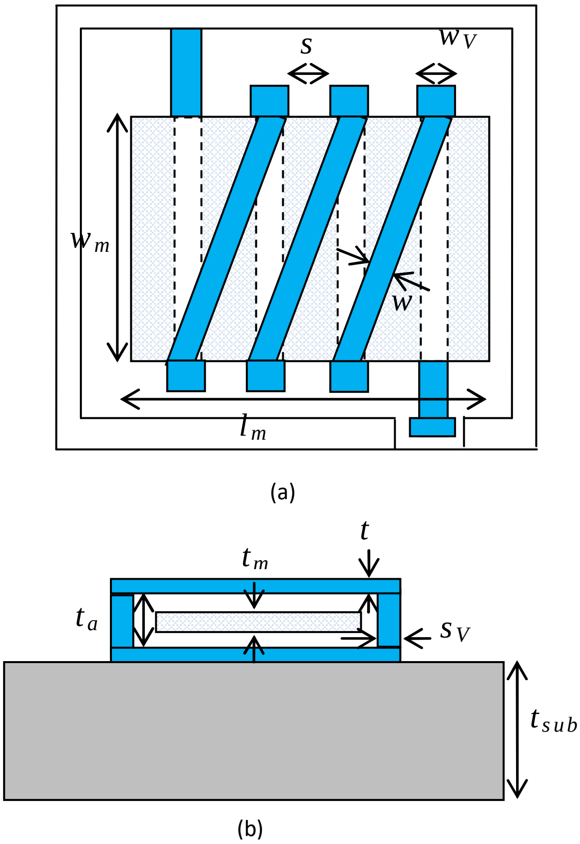

Fig. 1: Integrated solenoid inductor with magnetic core: (a) top view and (b) cross-sectional view

The model for a solenoid inductor is shown in Fig. 2 [6]. The spiral π model includes the series inductance *Ls*, the series resistance *Rs*, the feed-forward capacitance *Cs*, the inductor to substrate capacitance *Cox*, and the substrate resistance *Rsub* and capacitance *Csub*. The expression for the inductance of the integrated solenoid inductor can be approximate by [7]:

$$\boldsymbol{L_s = \frac{\mu_0 \mu_r n^2 w_m t_m}{l_m}} \qquad (1)$$

where n is the total number of turns; w_m, t_m and l_m are the width, the thickness and the length of magnetic core, respectively. μ_r is the relative permeability of the core and μ_0 is the permeability of free space.

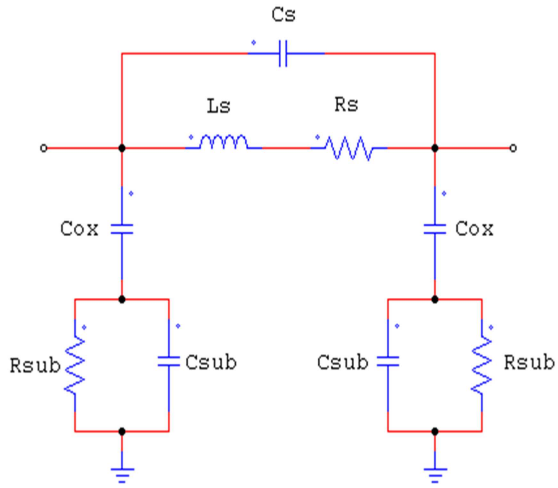

Fig. 2: Electrical model for the solenoid inductor

The expression for series resistance is expressed as [8]:

$$R_s = \frac{2n\rho w_m}{w\delta(1-e^{-t/\delta})} \tag{2}$$

where, ρ is the electrical resistivity of the coil material, w is the width, t is thickness and δ is the skin depth of the coil.

The skin depth is a function of the frequency and is written as [9]:

$$\delta = \sqrt{\frac{2}{\omega\sigma\mu_0}} \tag{3}$$

where, ω is the angular frequency, σ is the conductivity of the coil and μ_0 is the permeability of free space.

Another important parameter that decides the usefulness of a solenoid inductor is the quality factor. It is defined as the ratio of the energy stored to the energy dissipated in the circuit.

According to $Q = \omega L/R$, the expressions for the quality factor of an integrated solenoid inductor can be expressed as follows [10]:

$$Q = \frac{\omega\mu_0\mu_r n t_m w\delta(1-e^{-t/\delta})}{2\rho l_m} \tag{4}$$

3. Results and Discussion

The simulation process followed for the analysis of solenoid inductor is meshing and porting of the device. After porting S-parameters are obtained to calculate inductance and quality factor. Now from S-parameters, Y-Parameters are obtained. Using Y-Parameters the inductance and quality factor values are calculated using the expressions shown in 5 and 6 respectively [11].

$$L = \frac{Img\left(\frac{1}{Y_{11}}\right)}{2.\pi.f} \tag{5}$$

$$\boldsymbol{Q} = \frac{\boldsymbol{Img}\left(\frac{1}{Y_{11}}\right)}{\boldsymbol{Real}\left(\frac{1}{Y_{11}}\right)} \tag{6}$$

The only mean to enhance the performances of an integrated inductor is to optimize its physical parameters. This section describes the different inductor parameters that could be changed and the results which are obtained by simulation with *MATLAB*.

3.1. Effect of thickness of magnetic cores

Thickness of magnetic cores is varied from 2 µm to 4 µm. As thicknesses of magnetic cores increase, inductance and quality factor of solenoid inductor increase. But there is insignificant shift in the self resonant frequency and the value of inductance. Fig. 3 and Fig. 4 show the effect of increasing thickness of magnetic cores on inductance and quality factor respectively.

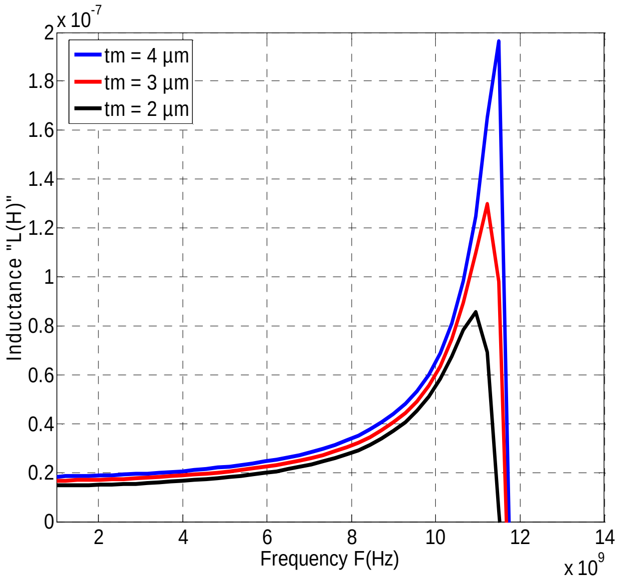

Fig. 3: Inductance for different thickness of magnetic cores.

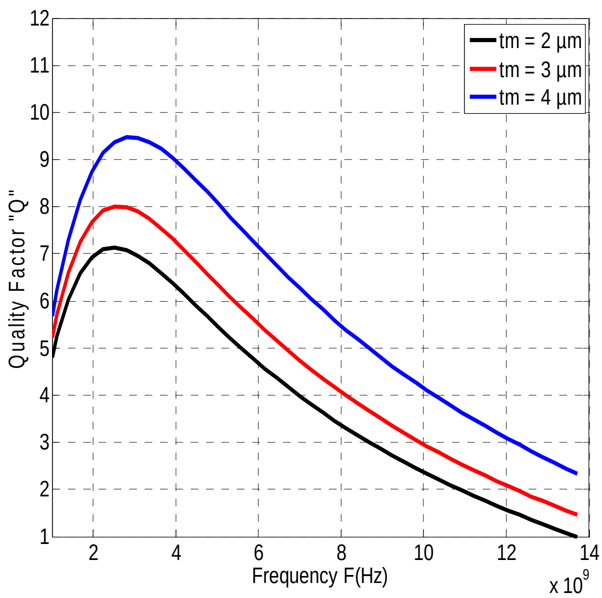

Fig. 4: Quality factor for different thickness of magnetic cores.

3.2.Effect of number of turns

As the number of turns is increased from 3 to 5, self resonant frequency of solenoid inductor decreases significantly. Fig. 5 and Fig. 6 show the results of solenoid inductor with increased number of turns. Inductance and quality factor increase with number of turns.

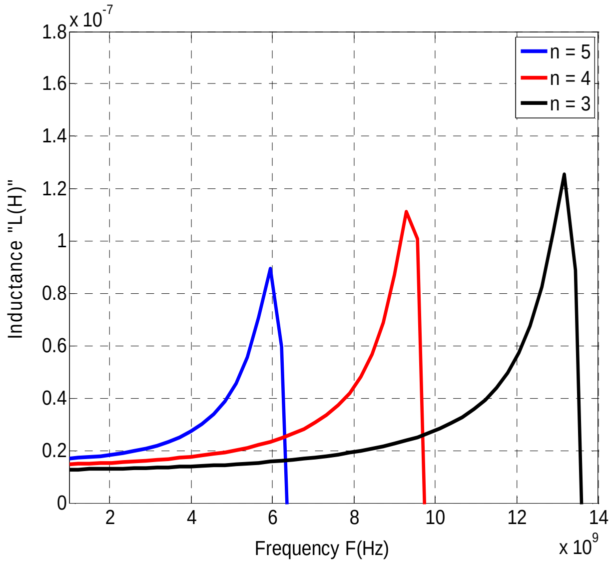

Fig. 5: Inductance for different number of turns

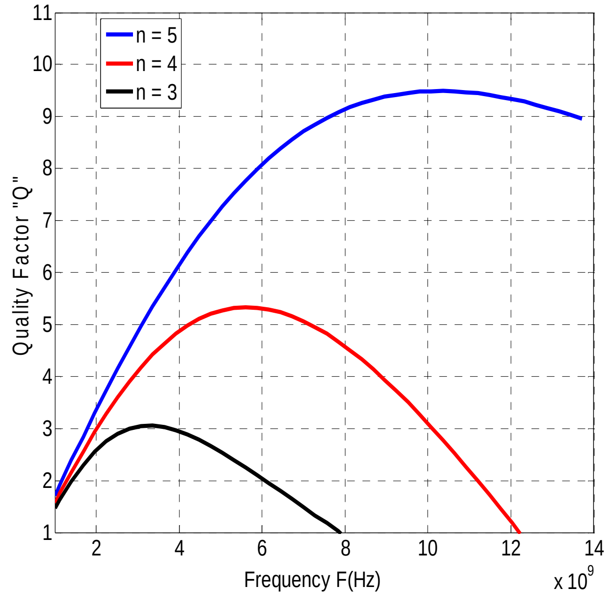

Fig. 6: Quality Factor for different number of turns

3.3.Effect of Width of Coils and Width of Magnetic Cores

This investigation is done in two parts: (I) increasing width of magnetic cores with constant width of coils and (II) increasing width of coils with constant width of magnetic cores. Though these investigations are done on a wide range of data, only two cases are shown: (a) width of magnetic cores varied from 10 µm to 20 µm with a constant width of coils of 3 µm Fig. 7 and Fig. 8, (b) width of coils of solenoid inductor varied from 2 µm to 4 µm with a constant width of magnetic cores of 15 µm Fig. 9 and Fig. 10.

For a constant width of coils, as the width of magnetic cores is increased, it is observed that the self resonant frequency of solenoid inductor decreases. Wider width of magnetic cores has the highest inductance till its resonant frequency compared to others. If the width of coils is increased then the shift in self resonant frequency towards lower frequencies is observed. Higher inductance and quality factor till self resonant frequency are achieved at an optimal value of magnetic cores.

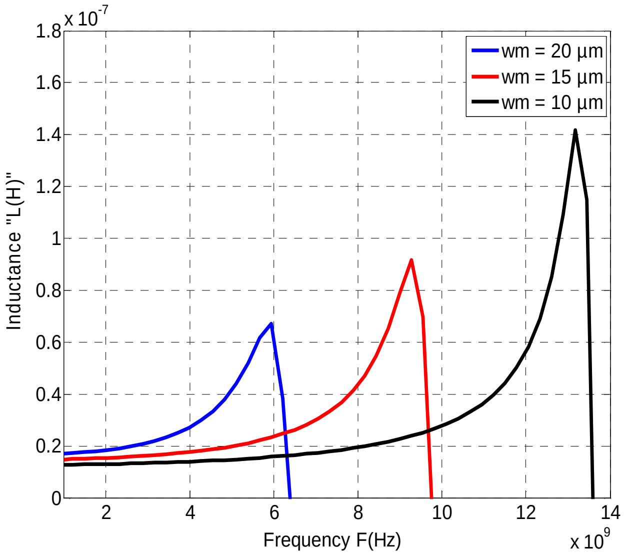

Fig. 7: Inductance for different width of magnetic cores

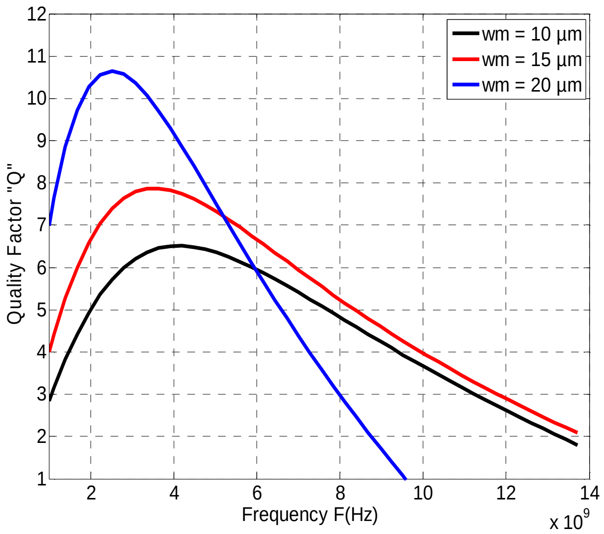

Fig. 8: Quality factor for different width of magnetic cores

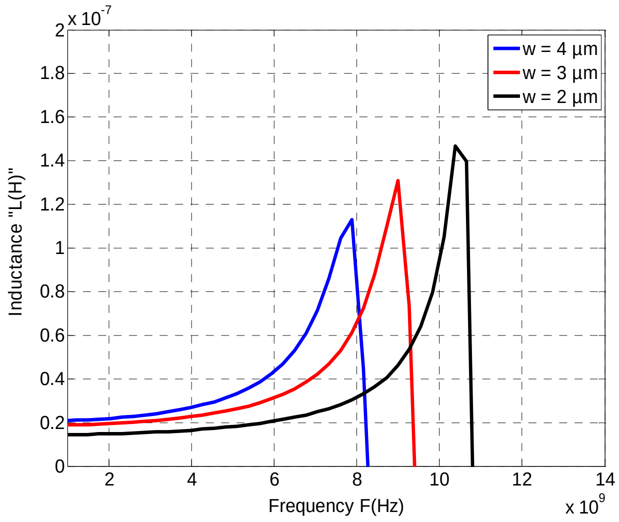

Fig. 9: Inductance for different width of coils

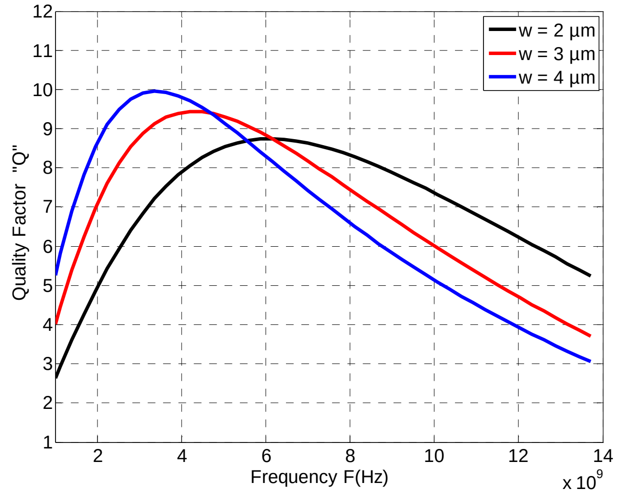

Fig. 10: Quality factor for different width of coils

Comparison between previous works and my design is shown in Table 1. The values mentioned in the table under my work are the maximum inductance, quality factor and self resonant frequency obtained by the parametric analysis. The area of solenoid inductor for the entire analysis process is same as mentioned.

Table 1: Comparison of different inductors

Works	**Size**	**Frequency**	Q_{max}	**Réf**
Spiral inductor	250 x 250 (μm^2)	100-10^3 (MHz)	8	12
Spiral inductor	180 x 180 (μm^2)	0,1-100 (MHz)	7	13
Solenoid inductor	150 x 150 (μm^2)	10-20 (MHz)	4	14
Solenoid inductor	100 x 100 (μm^2)	1-14 (GHz)	9,5	My work

4. Conclusion

Thorough investigation of miniaturized solenoid inductor for radio frequency circuits is concluded in this paper. The parametric characteristic of this design was presented and the design procedure outlines its performance in terms inductance and quality factor. Better performance of the design is obtained with the optimized parameters from different iterations. Maximum value of quality factor obtained in the analysis is 2 at 8 GHz; Inductance is 140nH at 11GHz. Size reductions of ~32% is obtained for the design when compared to conventional solenoid inductors.

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