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Integrated Solenoid Inductor with Magnetic Core in a Buck Converter

Abstract: *In this paper, we discuss the design and modeling of a solenoid inductor with a magnetic core. The equivalent electrical model approved of the integrated solenoid inductor acquires into account the inductance and quality factor. The optimization of the inductance and quality factor values is based on the numerical analysis of the influence of the geometric parameters on the electrical characteristics of the solenoid inductor. The results simulation based on the MATLAB software. Finally, is discussing about the integrated solenoid inductor in a buck converter DC-DC, simulation results present by PSIM.*

Streszczenie. *Przedstawiono projekt planarnego scalonego dławika. Analizowano parametry geometryczne pod kątem najlepszej dobroci cewki. Podzespół może być zintegrowany z układem przekształtnika.* ***Scalony planarny dławik w zastosowaniu do przekształtnika***

Keywords: Solenoid Inductor, Magnetic Core, Integration, Buck Converter, Geometric Parameters.
Słowa kluczowe:

Introduction

The recent evolution in radiofrequency (RF) devices and integrated circuit technologies greatly expanded the number of wireless applications [1]. This expansion generated a growing demand for semiconductor manufacturers, requiring a higher integration in RF circuits. However, as passive device performances are directly tied to their geometry (especially for inductors), they end up being the bottleneck on radiofrequency circuitry integration.

Inductors are of utmost importance in radiofrequency integrated circuits [2]. These devices are employed in critical building blocks of radiofrequency integrated circuits such as intermediate frequency filters [2], low-noise amplifiers [3], voltage-controlled oscillators [4], and power amplifiers [5]. Current on-chip spiral inductors suffer from large parasitic and area for a meager value of inductance and quality factor [6]. The need to overcome these issues has led to the development inductors with new geometries housing magnetic cores that show an enhanced inductance compared to the air core coil.

In this paper, the behavior of solenoid inductors is systematically studied and the impact of the geometrical parameters on its inductance and quality factor. The principal object of my paper is to detail all the phases of design and modeling of a solenoid inductor in order to attain its realization and integrate it into a micro-converter [7]. This structure increases the quality factor value while reducing the constituent dimensions with a small manufacturing cost [8].

Design of solenoid inductor

A simple solenoid inductor consists of a metal wire wound around a magnetic core, as shown in figure 1 [9]. Geometric parameters used in the schematic of an integrated solenoid inductor are as follows: the number of turns of the coil N, length of the coil lc, length of the magnetic core (air core) l_m, spacing between turns s, width of the magnetic core w_m, width of the air core w_a, width of coil w_c, thickness of the coil t_c, thickness of the magnetic core t_m, thickness of the air core t_a, via overhang z_v and via size s_v.

The *NiFe* core is wrapped inside the copper winding. The magnetic core using in this work is Ferrite (*NiZn*) a relative permeability μ_r = 1400 [10]. The inductor is placed on the substrate.

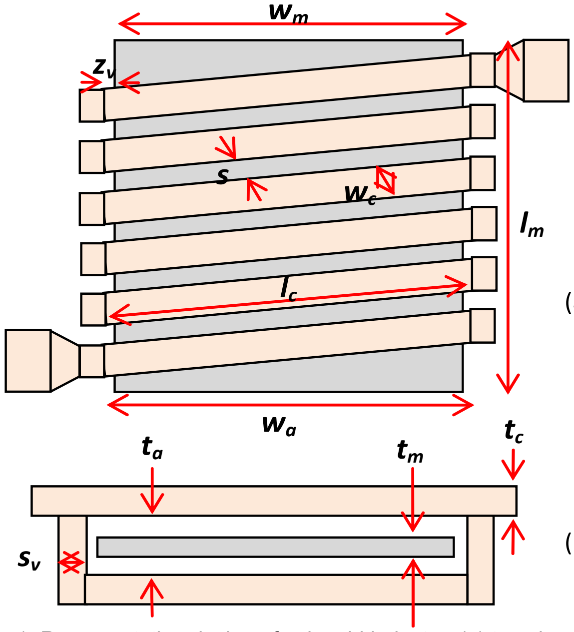

Fig. 1. Representation design of solenoid inductor: (a) top view and (b) cross section

The geometric parameters of the studied solenoid inductor are presented in Table 1. These geometric parameters of the solenoid inductor are selected for use in an integrated micro converter.

Table 1. Values of the geometrical parameters of the solenoid inductor

Parameter	Symbol	Value
Number of turns	N	5-6
Length of the coil	l_c	184 μm
Length of the magnetic core	l_m	410 μm
spacing between turns	s	18-32 μm
Width of the magnetic core	w_m	168 μm
Width of the air core	w_a	179 μm
Width of coil	w_c	28-54 μm
Thickness of coil	t_c	8 μm
Thickness of the magnetic core	t_m	8-12 μm
Thickness of the air core	t_a	11 μm
Via overhang	z_v	5 μm
Via size	s_v	10 μm

The inductance L of solenoid inductor is expressed as [11]:

$$L = \frac{\mu_0 \mu_r N^2 S_m}{l_m} \quad (1)$$

where, S_m is the cross-sectional area of the magnetic core, μ_0 and μ_r are vacuum permeability and relative permeability, respectively.

The quality factor is frequency dependent and can be written as:

$$Q = \frac{2\pi . f . \mu_0 . \mu_r . N . t_m . w_c . (1 - e^{-(t_c/\delta_c)})}{2 l_m . \rho_c} \quad (2)$$

where, *f* is the frequency, ρ_c is the electrical resistivity of the coil material and δ_c is the skin depth of the wire expressed as:

$$\delta_c = \sqrt{\frac{\rho_c}{(\pi . \mu_0 . \mu_{rc} . f)}} \quad (3)$$

where, μ_{rc} is the wire's relative magnetic permeability. For a copper conductor case, μ_{rc} = 1 and ρ_c = 17,24.10^{-9} [Ω.m] at 20 °C, σ is the conductivity of the conductor (σ_c= 5,96.10^7 S/m).

Solenoid inductor modeling

The physical layout of the solenoid inductor with air core placed on the substrate of figure 2 can be represented by the lumped element components placed into a circuit model [12]. These lumped element terms are represented in the equivalent circuit of figure 3 [13]. In this model, L_S and R_S are the series inductance and the resistance, respectively. C_s is the inter-winding capacitance, C_{ox} the capacitive coupling between the solenoid inductor and the substrate through the oxide layer, R_{sub} and C_{sub} are the losses induced in the substrate. Where t_{ox} is the thickness of oxide from the solenoid inductor to the substrate (t_{ox}=38μm), t_{sub} is the thickness of substrate (t_{sub}=75μm).

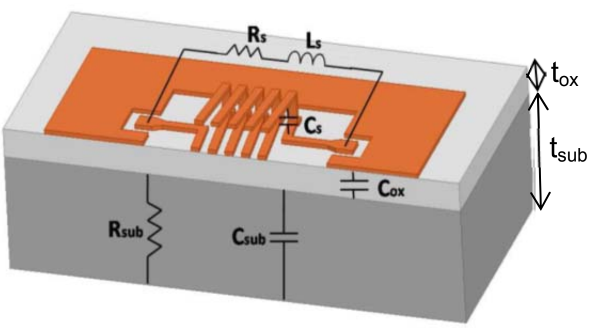

Fig. 2. Transverse section of a solenoid inductor placed on the substrate.

The performance parameters L and Q can be directly computed from the solenoid inductor Y-parameters as [13]:

$$Z_{eq} = \frac{1}{50} . \frac{(1 - S_{11})(1 + S_{22}) + S_{12} . S_{21}}{(1 + S_{11})(1 + S_{22}) - S_{12} . S_{21}} \quad (4)$$

$$L = \frac{\mathrm{Im}\left(\frac{1}{Y_{11}}\right)}{2\pi f} \quad (5)$$

$$Q = \frac{\mathrm{Im}\left(\frac{1}{Y_{12}}\right)}{\mathrm{Re}\left(\frac{1}{Y_{12}}\right)} \quad (6)$$

Results and discussion

The solenoid inductor has been simulated in the frequency range of 1MHz to 5 MHz by varying the parameters such as the sum of the width of coil and the space between bordering turns, number of turns and thickness of the magnetic core while maintaining a fixed area of the structure. The results using geometric parameters give some insights on the simulated results obtained from the *MATLAB* software. Finally using the software *PSIM* 6.0, we illustrate the waveforms of output currents and voltages of a buck converter.

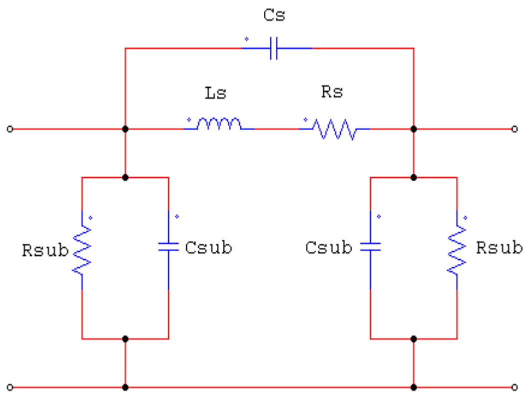

Fig. 3. Equivalent model for the solenoid inductor

Influence of the width of coil and spacing

The width of coil and the space between bordering turns can influence the inductance and quality factor of solenoid inductor. Three solenoid inductor structures are considered by care the addition of width and space at 72μm. Their width and space are 28+44μm, 40+32μm and 54+18μm, respectively.

The primary term of the two totaling numbers signify the width of coil and the next signify the space. The number of coils of these three structures of solenoid inductor is fixed at 5, width of magnetic core is 168 μm and length of magnetic core is 410 μm. Figure 4 shows the top view of these three solenoid inductors.

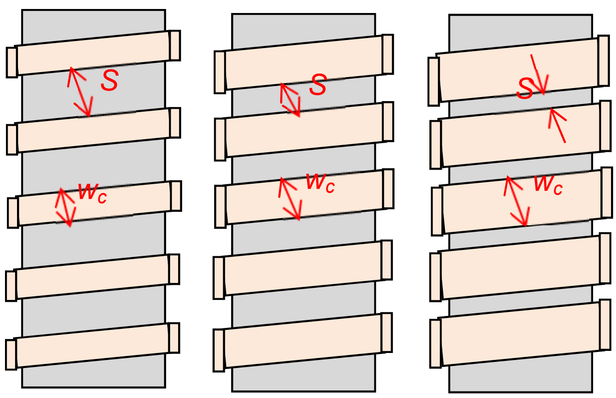

Fig. 4. The top view of solenoid inductors with width of coil plus spacing as (a) 28+44μm, (b) 40+32μm, (c) 54+18μm

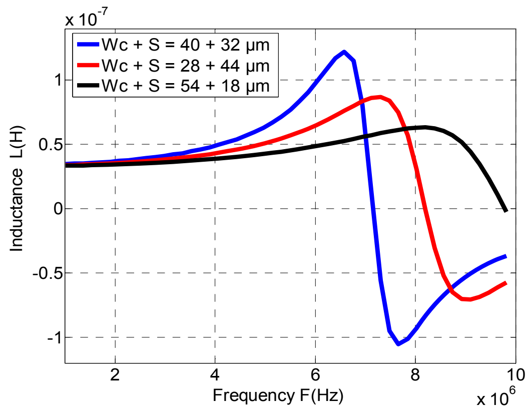

Fig. 5. Variation the inductance versus frequency for three different structures

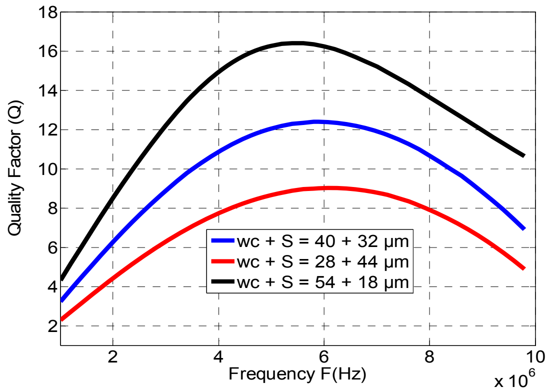

Fig. 6. Variation the quality factor versus frequency for three different structures

Figure 5 and 6 presents the inductance L and quality factor Q as function frequency of these three solenoid inductors. The inductances are about the similar of these three solenoid inductors. Over 2 MHz, the inductance curves emerge diversity because of the different parasitic capacitance. For the quality factor, it is obvious that the structure with 54 μm width of coil and 18 μm spaces acquire the maximal quality factor.

Influence of the magnetic core and air core for different number of turns

The comparison of the inductance between the magnetic core and air core devices can be seen very clearly in figure 7. As the number of turns increases, the inductance is increased with a magnetic core compared with that of an air core structure.

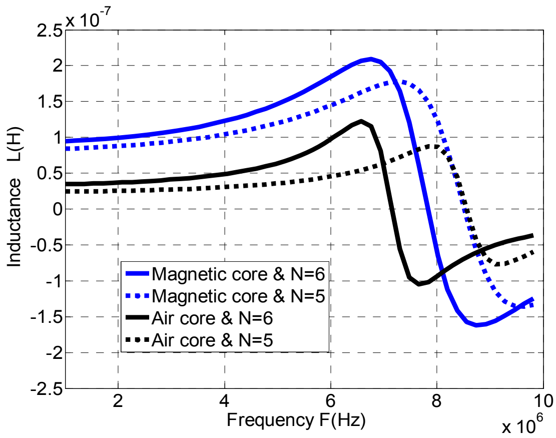

Fig. 7. Influence of magnetic core and air core on inductance for different number of turns

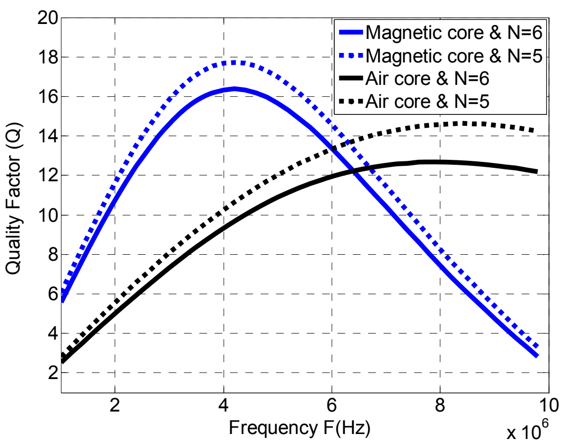

Fig. 8. influence of magnetic core and air core on quality factor for different number of turns

The influence of the magnetic core and air core on the quality factor could be seen from figure 8. Solenoid inductor with a magnetic core and air core of shows higher quality factor for cases of number of turns N=5, 6, respectively. The quality factor for the *magnetic core have a smaller slope compared to the air core* and reduce more slowly in value. The addition of the magnetic core showed an increase in inductance values and hence a better quality factor can be observed.

Influence of the gallium arsenide and silicon substrate for different thickness of magnetic core

We illustrate the simulation results of a solenoid inductor use copper for the metallic coils having GaAs as the substrate and compare it with a silicon substrate. Figure 9 illustrates that the inductance of the solenoid inductor with a gallium arsenide substrate has a higher inductance peak and smaller resonant frequency compared to the silicon substrate.

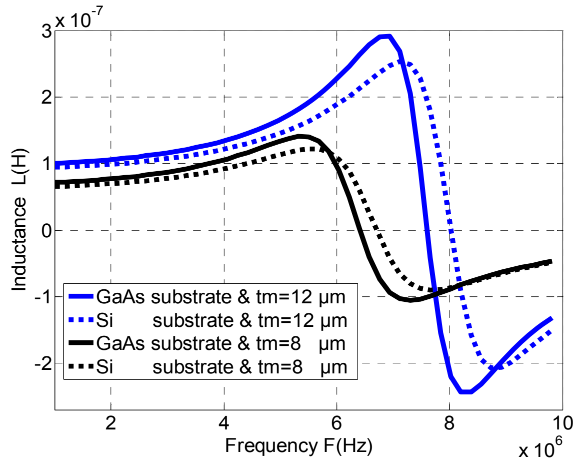

Fig. 9. Effect of GaAs and Si substrate on inductance for different thickness of magnetic core

Figure 10 shows the quality factor of GaAs being only a small part larger than that of the silicon substrate. The quality factor for GaAs was the identical as that of Si for lower frequencies but at higher frequencies, GaAs illustrated superior results for superior core thickness. At inferior core thickness, GaAs behaved very similarly compared to silicon.

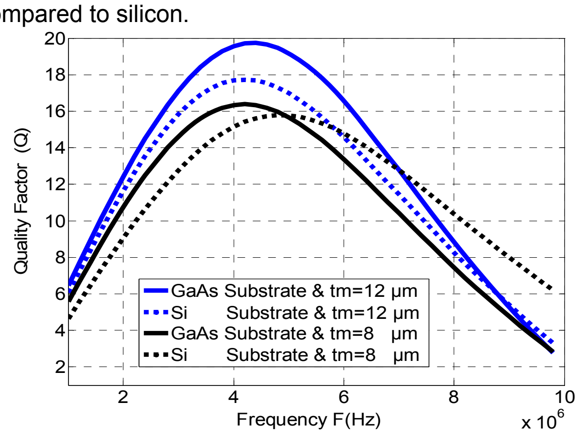

Fig. 10. Effect of GaAs and Si substrate on quality factor for different thickness of magnetic core

Buck converter application

We have selected a Buck micro converter *DC-DC* shown in figure 11. In the simulation we used *PSIM* software; the values of the micro converter electrical characteristics are enlisted in Table 2.

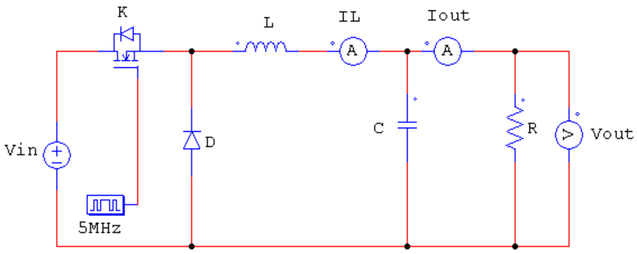

Fig. 11. Schematic diagram of Buck converter DC-DC

Table 2. Design specifications of buck micro converter DC-DC

Electrical characteristics	Symbol	Value
Input Voltage	Vin	5 V
Output voltage	Vout	1.5 V
Switching frequency of the converter	f	5 MHz
Inductance of solenoid inductor	L	150 nH

Figure 12 shows the waveform of the output voltage and current of the Buck converter with integrated solenoid inductor.

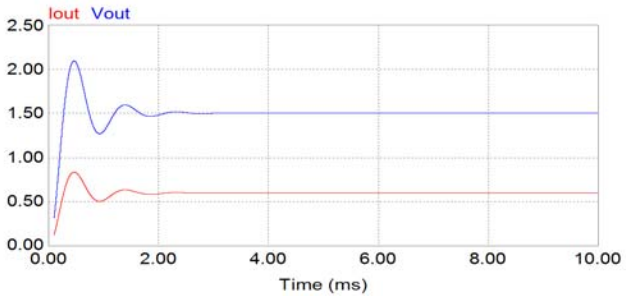

Fig. 12. Output voltage and current of the Buck converter with integrated solenoid inductor

The output current simulated at a switching frequency of 5 MHz is shown in red color. It is observed that the output current is constant; the converter delivers an output current of about 0,599 A. In addition, a similar observation is noticed for output voltage as shown in blue color. It is also important to note that the input voltage of 5 V is lowered to 1.5 V.

Conclusion

For a solenoid type inductor, the performance could be optimized by improving the core structure and adding winding turns. Add more winding turns is the most straight forward way of increasing the inductance. However, the effect of using GaAs as a substrate may show enhanced improvements once the solenoid inductor is fabricated. Increasing the width of coil helped increase the quality factor but reduced the inductance upon very large spacing. A width of coil plus space between turns of 40+32 μm showed the highest inductance for the given structure. Finally, the desired value of the output voltage was also achieved from the simulation of the DC-DC buck converter microwave. The results illustrate that the developed structure of the solenoid inductor is a very promising advance for the integration of buck converter.

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