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.

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 $l_c$, 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 $\mu_r = 1400$ [10]. The inductor is placed on the substrate.

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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of turns</td>
<td>$N$</td>
<td>5-6</td>
</tr>
<tr>
<td>Length of the coil</td>
<td>$l_c$</td>
<td>184 $\mu$m</td>
</tr>
<tr>
<td>Length of the magnetic core</td>
<td>$l_m$</td>
<td>410 $\mu$m</td>
</tr>
<tr>
<td>spacing between turns</td>
<td>$s$</td>
<td>18-32 $\mu$m</td>
</tr>
<tr>
<td>Width of the magnetic core</td>
<td>$w_m$</td>
<td>168 $\mu$m</td>
</tr>
<tr>
<td>Width of the air core</td>
<td>$w_a$</td>
<td>179 $\mu$m</td>
</tr>
<tr>
<td>Width of coil</td>
<td>$w_c$</td>
<td>28-54 $\mu$m</td>
</tr>
<tr>
<td>Thickness of coil</td>
<td>$t_c$</td>
<td>8 $\mu$m</td>
</tr>
<tr>
<td>Thickness of the magnetic core</td>
<td>$t_m$</td>
<td>8-12 $\mu$m</td>
</tr>
<tr>
<td>Thickness of the air core</td>
<td>$t_a$</td>
<td>11 $\mu$m</td>
</tr>
<tr>
<td>Via overhang</td>
<td>$z_v$</td>
<td>5 $\mu$m</td>
</tr>
<tr>
<td>Via size</td>
<td>$s_v$</td>
<td>10 $\mu$m</td>
</tr>
</tbody>
</table>
The inductance $L$ of solenoid inductor is expressed as [11]:

$$L = \frac{\mu_0 N^2 S_m}{l_m}$$

where, $S_m$ is the cross-sectional area of the magnetic core, $\mu_0$ and $\mu_r$ are vacuum permeability and relative permeability, respectively.

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

$$Q = \frac{2 \pi f \mu_0 \mu_r N l_m W_c (1 - e^{-2\delta_c / \delta})}{2 \delta \rho_c}$$

where, $f$ is the frequency, $\rho_c$ is the electrical resistivity of the coil material and $\delta$ is the skin depth of the wire expressed as:

$$\delta_c = \frac{\rho_c}{\sigma (\mu_0 \mu_r f)}$$

where, $\mu_0$ is the wire’s relative magnetic permeability. For a copper conductor case, $\mu_0 = 1$ and $\rho_c = 17.24 \times 10^{-8} \Omega \cdot m$ at 20 °C, $\sigma$ is the conductivity of the conductor ($\sigma = 5.96 \times 10^7$ 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 $\delta_{ox}$ is the thickness of oxide from the solenoid inductor to the substrate ($t_{ox} = 38 \mu m$), $t_{sub}$ is the thickness of substrate ($t_{sub} = 75 \mu m$).

**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.

**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**
Figure 5 and 6 presents the inductance L and quality factor Q as functions of 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.

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.

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

<table>
<thead>
<tr>
<th>Electrical characteristics</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input Voltage</td>
<td>Vin</td>
<td>5 V</td>
</tr>
<tr>
<td>Output voltage</td>
<td>Vout</td>
<td>1.5 V</td>
</tr>
<tr>
<td>Switching frequency of the converter</td>
<td>f</td>
<td>5 MHz</td>
</tr>
<tr>
<td>Inductance of solenoid inductor</td>
<td>L</td>
<td>150 nH</td>
</tr>
</tbody>
</table>

Figure 12 shows the waveform of the 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 straightforward 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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