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Integrated square shape inductor with magnetic core in a buck converter DC-DC

Abstract. This paper presents the buck converter DC-DC. At first, we define the characteristics of the converter. The second, we describe our inductor; the topology of square shape inductor has been presented to extract the geometric parameters. The equivalent electrical model approved of the integrated inductor with magnetic core takes into account all the technological parameters which are illustrated by analytic expressions. Moreover, the results of different simulations concern the effect of geometrical parameters of inductor on the inductance value and quality factor. Finely, we performed simulations on the operating of our buck converter including firstly an ideal inductor and then an integrated inductor with magnetic core. Simulation results have shown that the waveforms of the current and output voltage in both cases are similar.

Keywords: inductor, magnetic core, integration, buck converter, geometric parameters.

Introduction

The always-augmenting demand for multifunctional and undersize portable electronic devices is driving the improvement of miniaturized DC-DC converters [1 – 3]. Such converters are used to shift voltage levels in electronic systems with high efficiency. There are multiple applications for such converters. For example, state-of-the-art portable smart phones and tablet PCs feature multiple components, such as the display panel, MEMS sensors, data storage devices, and cameras, which may require different operating voltage levels. Miniaturizing these converters reduces the overall size of the portable devices [4].

Passive components are the major factor in determining the overall size, cost and performance of portable products. The drive to further miniaturization and integration of portable electronic devices has recently focused on the task of passive functions [5, 6].

Integration of passive devices in the same silicon substrate is desirable in order to reduce this interconnect parasitic, reduce the size and cost of the units and increase the operating frequencies of the radio frequency circuits. Inductors are elementary and important parts in radio frequency integrated circuits [7, 8].

In this paper, the behavior of inductor 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 square shape inductor in order to attain its simulation and integrate it into a buck converter. This power inductor with magnetic core increases the quality factor value while reducing the constituent dimensions with a small manufacturing cost.

Buck converter DC-DC

The buck converter circuit is shown in figure 1. The switch $T$ has a duty cycle $D$ which ranges from 0 to 1. Figure 2 indicates relevant waveforms of the circuit when the switch $T$ is turned ON and OFF at frequency $f$, with a duty cycle $D$ [9].

The design specifications of buck converter with an output power of 0.6 W are enlisted in Table 1 and Table 2:

\[ I_{out} = \frac{P_{out}}{V_{out}} \] (1)
\[ D = \frac{V_{in}}{V_{in}} \] (2)
\[ L = \frac{V_{in} \cdot V_{out} \cdot D}{2 \cdot M_{i} \cdot f} \] (3)

The following equations then hold for the buck converter [10].

Fig. 1. Schematic of a typical DC-DC buck converter

Fig. 2. Waveforms of the voltages and currents with time in a buck converter
Table 1. Principal specification

<table>
<thead>
<tr>
<th>Specifications</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output Power</td>
<td>$P_0$</td>
<td>0.6 W</td>
</tr>
<tr>
<td>Input Voltage</td>
<td>$V_{in}$</td>
<td>7</td>
</tr>
<tr>
<td>Output Voltage</td>
<td>$V_{out}$</td>
<td>2.4</td>
</tr>
<tr>
<td>Frequency</td>
<td>$f$</td>
<td>5 MHz</td>
</tr>
</tbody>
</table>

Table 2. Material specification

<table>
<thead>
<tr>
<th>Elements</th>
<th>Material Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conductor</td>
<td>Copper (Cu) Resistivity: $\rho_{Cu} = 1.7 \times 10^{-8}$ [Ω·m] Conductivity: $\sigma_{Cu} = 5.8 \times 10^{7}$ [S/m]</td>
</tr>
<tr>
<td>Oxide</td>
<td>Silicon dioxide permittivity: $\varepsilon_{ox} = 3.97 \varepsilon_0$ $\varepsilon_0 = 8.85 \times 10^{-12}$ [F/m]</td>
</tr>
<tr>
<td>Substrate</td>
<td>Silicon (Si) Resistivity: $\rho_{Si} = 2.27 \times 10^{-1}$ [Ω·m] Permittivity: $\varepsilon_{Si} = 11.9 \varepsilon_0$</td>
</tr>
<tr>
<td>Magnetic core</td>
<td>Ferrite (NiFe) Resistivity: $\rho_{NiFe} = 20 \times 10^{-8}$ [Ω·m]</td>
</tr>
</tbody>
</table>

**Topology and dimensions inductor**

Figure 3 illustrates a power inductor in silicon with a single spiral winding layer and two electroplated magnetic core layers. From the schematic 3D view in Figure 3(a), the spiral windings are capped by two magnetic plates. From the cross-section view in Figure 3(b), the copper windings and magnetic vias are embedded into the silicon substrate [11][12][13].

![Fig. 3. (a) Schematic 3D view, (b) Cross-section view of a power inductor](image)

Table 3. The geometrical parameters of the square spiral inductor

<table>
<thead>
<tr>
<th>Geometric parameters</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of turns</td>
<td>$n$</td>
<td>3</td>
</tr>
<tr>
<td>Spacing between turns</td>
<td>$s$</td>
<td>7 µm</td>
</tr>
<tr>
<td>Width of conductor</td>
<td>$w$</td>
<td>18 µm</td>
</tr>
<tr>
<td>Thickness of conductor</td>
<td>$t$</td>
<td>1.5 µm</td>
</tr>
<tr>
<td>Inner diameter</td>
<td>$d_{in}$</td>
<td>70 µm</td>
</tr>
<tr>
<td>Outer diameter</td>
<td>$d_{out}$</td>
<td>206 µm</td>
</tr>
<tr>
<td>Total length</td>
<td>$l$</td>
<td>1.64 mm</td>
</tr>
</tbody>
</table>

**Extraction technological parameter**

The cross-section of a spiral inductor together with its equivalent $\pi$ model is illustrated in Figure 4 (a) and (b) [20]. $L_s$ consist of the self-inductance, positive mutual inductance, and negative mutual inductance. $C_s$ is the capacitance between metal lines. $R_s$ is the series resistance of the metal line. $C_{ox}$ is the capacitance of oxide layer underneath the spiral. $R_{sub}$ and $C_{sub}$ are the coupling resistance and capacitance associated with silicon substrate. $R_{mag}$ represent the ohmic losses in the magnetic core (ferrite).

Where, the thickness of substrate silicon ($t_{sub}$ = 50 µm), the thickness of ferrite NiFe ($t_{NiFe}$ = 31 µm) and thickness of the oxide of silicon SiO2 ($t_{ox}$ = 23 µm).

These technological parameters can be roughly calculated using the formulas [21][22], listed in Table 4, which would serve as starting point of simulation.
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Fig. 4. (a) Cross-section, (b) its equivalent circuit of a square inductor with magnetic core [20]

Table 4. Formulas and results for technological parameters

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Analytical equation</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ls</td>
<td>(2.34 µ Loop^2 d_mag) / (1 + 2.75 α)</td>
<td>1.55 nH</td>
</tr>
<tr>
<td>Rs</td>
<td>1 / (w α δ (1 - e^-vτ))</td>
<td>28.9 kΩ</td>
</tr>
<tr>
<td>Cs</td>
<td>n w^2 f_xy / t_xy</td>
<td>1.484 fF</td>
</tr>
<tr>
<td>Cox</td>
<td>w l f_xy / 2 t_xy</td>
<td>0.022 fF</td>
</tr>
<tr>
<td>Rmag</td>
<td>2 / (ρ_s frie l_mag)</td>
<td>0.42 mΩ</td>
</tr>
<tr>
<td>Rsub</td>
<td>2 / (ρ_s frie l_sub)</td>
<td>768.97 Ω</td>
</tr>
<tr>
<td>Csub</td>
<td>ε_d / L w / 2 t_sub</td>
<td>31.08 fF</td>
</tr>
</tbody>
</table>

Result and discussion

**Effects of the inductor geometrical parameters**

The square shape inductor has been simulated in the frequency range of 1 MHz to 10 MHz by varying the geometrical parameters such as the number of turns n, the inner diameter din, width of conductor w and space between bordering turns s. In addition, their effects on the inductance L and quality factor Q. The results using geometric parameters give some insights on the simulated results obtained from the MATLAB software.

**Number of turns**

The inductance L and quality factor Q values related to frequency are illustrated in Figure 5 and Figure 6. As number of turns of the winding n varies from 2 to 4, the inductance value increases, while the quality factor decreases with frequency.

**Inner diameter**

Figure 7 shows how the inductance L changes with respect to frequency. As inner diameter din varies at (60 µm, 70 µm and 80 µm), L improves due to the increase in the length of conductor l. However, as inner diameter decreases, Q increases gradually, as shown in Figure 8. This increase is related to the distance between opposite sides at the center of the spiral.

**Width of conductor**

The width of conductor w is varied at (16 µm, 18 µm and 20 µm). Figure 9 show that L decreases slightly as w increases. In additions, as w increases, the penalty on the resistance due to the skin effect will dominate at a given frequency, hence, the quality factor Q shifts to a lower frequency, as indicated in Figure 10.
Spacing between turns

The influences of varying the separation distance between the windings $s$, from $5 \mu m$ to $9 \mu m$. The inductance value decreases with increasing $s$. Smaller separation distances result in higher capacitive coupling between the windings and therefore a lower self-resonance frequency. The quality factor value increases with increasing the distance between windings. The simulation results are shown in Figures 11 and 12.

Application of the buck converter

In this part, we present the results of simulation of the buck converter in two cases: ideal inductor and integrated inductor with magnetic core. We used for this paper the PSIM software.

Buck converter including ideal inductor

The circuit of Figure 13 contains an ideal inductor of the buck converter; Figure 14 shows the waveform of the output voltage and current of the buck converter.
Buck converter including integrated inductor with magnetic core

Figure 15 shows the change ideal inductor of the buck converter by integrated inductor with magnetic core. The different technological parameters of the equivalent electrical models are calculated in Table 4. The Figure 16 shows the waveform of the output voltage and current of the buck converter.

Conclusion

In this paper, we have presented the design and modeling of square shape inductor integrated in buck converter. The most difficult problem is to determine the geometrical and technological parameters of the inductor with magnetic core. Next, the geometry of square shape inductor is important and gives huge impact to the performance of radio-frequency integrated circuits. Indeed, the simulation of the quality factor of a square shape inductor topology requires both weakly the width of conductor, inner diameter and the number of turns. Finally, by using a software simulation PSIM, we have compared the waveforms of the buck converter output voltages and current for the two simulations (ideal inductor, integrated inductor with magnetic core). We remark the equivalent result between two cases.

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REFERENCES


Fig. 15. buck converter with integrated inductor with magnetic core

Fig. 16. Output voltage and current of the buck converter with integrated inductor with magnetic core