

## Effect of differently shaped spiral inductors on micro power integrated circuit

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**Abstract.** *This paper investigates the impact of parasitic effects on the performance of on-chip planar spiral inductors for DC-DC converter applications, focusing on three geometries: square, hexagonal, and octagonal. Detailed electromagnetic simulations in MATLAB are employed to analyze the frequency-dependent behavior of key parasitic components, including ohmic resistance ( $R_s$ ), substrate resistance ( $R_{sub}$ ), oxide capacitance ( $C_{ox}$ ), and substrate capacitance ( $C_{sub}$ ) across a frequency range of 1 GHz to 10 GHz. The study reveals that the octagonal spiral inductor outperforms the others, demonstrating a 29% reduction in ohmic resistance at 1.5 GHz compared to the square geometry and achieving the highest substrate resistance, which helps reduce current leakage. Additionally, the octagonal inductor exhibits the lowest parasitic capacitance and a high-quality factor, peaking at 30 at 4.2 GHz. These results underscore the significant impact of inductor geometry on minimizing energy dissipation and electromagnetic interference, positioning the octagonal spiral inductor as a compelling choice for enhancing efficiency and miniaturization in DC-DC converter designs.*

**Keywords:** Spiral inductor, integration, integrated circuit, micro converter

### 1. INTRODUCTION

The miniaturization trend pervasive in modern portable electronics demands significant advancements in power management circuit design, prioritizing both high efficiency and increased power density [1][2][3]. DC-DC converters are essential components in these systems, tasked with the efficient conversion and regulation of voltage levels to power various integrated circuits [4][5][6]. Planar spiral inductors, as fundamental energy storage elements within DC-DC converters, exert a significant influence on critical performance metrics such as overall efficiency and power delivery capability [7][8]. However, their inherent susceptibility to parasitic effects primarily manifested as unwanted resistances and capacitances due to their fabrication on silicon substrates presents a significant design challenge. These parasitic elements contribute to energy losses, dissipated as heat, thereby degrading converter efficiency and increasing the required circuit footprint to manage thermal constraints [9]. Additionally, parasitic effects can contribute to electromagnetic interference, potentially

affecting the performance of adjacent sensitive circuitry [10].

Extensive research efforts have focused on mitigating these detrimental effects, primarily through optimization strategies applied to conventional square and circular planar inductor geometries [11]. While these endeavors have yielded incremental improvements, they are often limited by the inherent characteristics of these established designs and necessitate complex fabrication techniques, leading to increased manufacturing complexity and cost [12]. This limitation underscores the necessity to explore alternative inductor geometries that intrinsically offer enhanced parasitic mitigation characteristics. Emerging research suggests that non-conventional geometries, particularly hexagonal and octagonal spirals, hold promise in this regard due to their unique structural characteristics, which potentially reduce parasitic capacitance and resistance [13]. However, a comprehensive analysis of their performance, specifically within the context of on-chip DC-DC converters and across a frequency range relevant to these applications, is lacking.

To address this critical gap, we present a rigorous comparative analysis of parasitic effects in three distinct planar spiral inductor designs: square, hexagonal, and octagonal. Utilizing accurate electromagnetic simulations in MATLAB, we systematically characterize the frequency-dependent behavior of each geometry over a range of 1 GHz to 10 GHz, focusing on four key parasitic elements: ohmic resistance ( $R_s$ ), substrate resistance ( $R_{sub}$ ), oxide capacitance ( $C_{ox}$ ), and substrate capacitance ( $C_{sub}$ ).

Our investigation reveals that the octagonal spiral inductor demonstrates a distinct performance advantage compared to the traditional square and hexagonal geometries, particularly in its ability to minimize parasitic effects and maintain a high quality factor across the studied frequency range. These findings underscore the significant influence of inductor geometry on DC-DC converter performance and highlight the octagonal spiral as a promising candidate for achieving high

efficiency and miniaturization in on-chip power management solutions for future electronic devices.

## 2. PLANAR SPIRAL INDUCTOR DESIGN AND MODELING

### 2.1 Design of planar spiral inductor.

Planar spiral inductors exhibit various structural configurations, including square, hexagonal, and octagonal geometries, as illustrated in Figure 1 [14][15]. Table 1 provides a summary of five critical geometric dimensions: turn width  $w$ , spacing between turns  $s$ , number of turns  $n$ , inner diameter  $d_{in}$ , and outer diameter  $d_{out}$ . These geometric parameters significantly influence the inductance of the planar inductor. Specifically, increasing the number of turns and the outer diameter enhances the inductance [16][17].

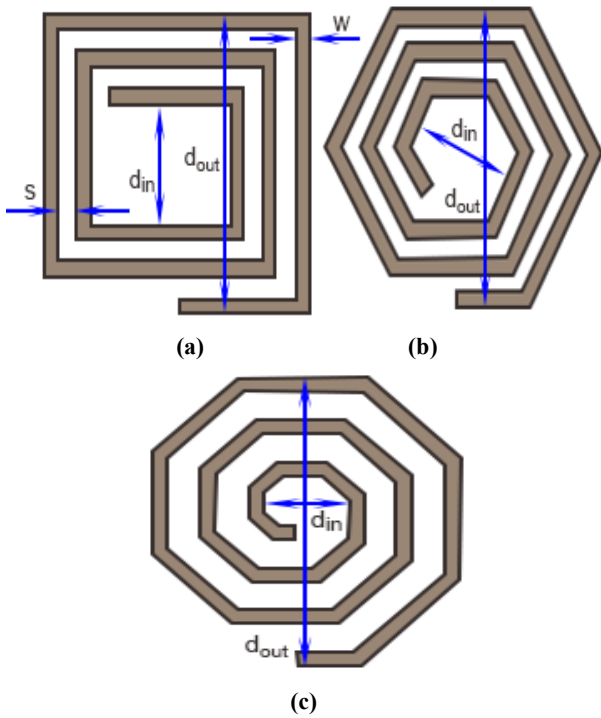


Figure 1. Three types of planar spiral inductors (a) Square, (b) Hexagonal, and (c) Octagonal

To accurately reflect practical implementations, and based on the dimensioning results presented in Table 1, the geometry of the spiral inductor model has been developed in a three-dimensional representation, as depicted in Figure 2.

Table 1. Equal geometric parameter values for three different spiral inductor structures.

| Parameter | $w$                     | $s$                     | $n$ | $d_{in}$                | $d_{out}$                |
|-----------|-------------------------|-------------------------|-----|-------------------------|--------------------------|
| Value     | 20<br>[ $\mu\text{m}$ ] | 10<br>[ $\mu\text{m}$ ] | 3   | 60<br>[ $\mu\text{m}$ ] | 220<br>[ $\mu\text{m}$ ] |

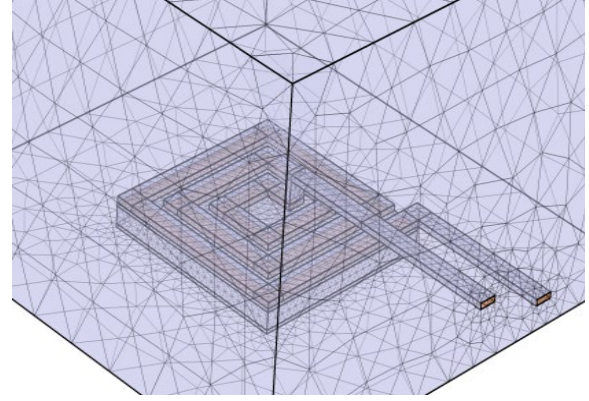


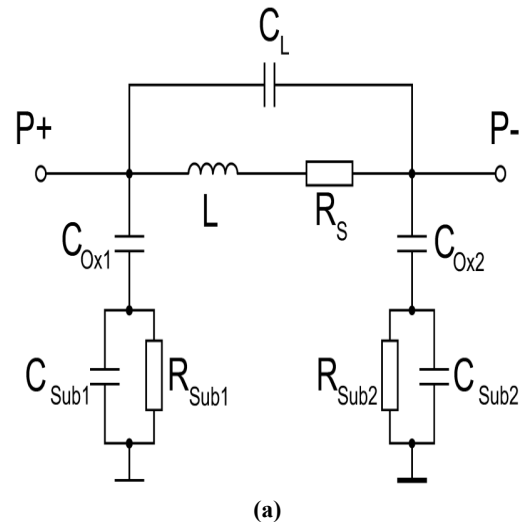
Figure 2. Structure of the spiral inductor simulated with the mesh of the field of study

### 2.2 Modeling of planar inductor

Despite ongoing research, the application of planar spiral inductors is constrained by the absence of a precise model. Simplifying the electrical model of a planar spiral inductor on a substrate is essential to identify the minimal set of electrical parameters necessary for accurate representation. Figure 3 demonstrate the  $\pi$  equivalent model resulting from a two-outlet inductor ( $P+$ ,  $P-$ ) [18][19]. The main parameter of this circuit electric is the inductance  $L$ . As for the remaining parameters of equivalent circuit, they are caused by the parasitic phenomena of structure a integrated planar spiral inductor [20].

Thus,  $R_s$  is the series resistance of the inductor metal,  $C_L$  is the fringing capacitance between the inductor coils,  $C_{ox}$  is the shunt capacitances of the oxide layer,  $R_{sub}$  and  $C_{sub}$  are the ohmic losses and capacitance in the substrate [21].

Using this circuit model, the dispersion parameters of the planar inductor can be easily derived. we can group together electrical parameters from figure 3 in the method indicated in figure 4(a) [22]. This permits us to envision the planar inductor as a  $\pi$ -network [23].



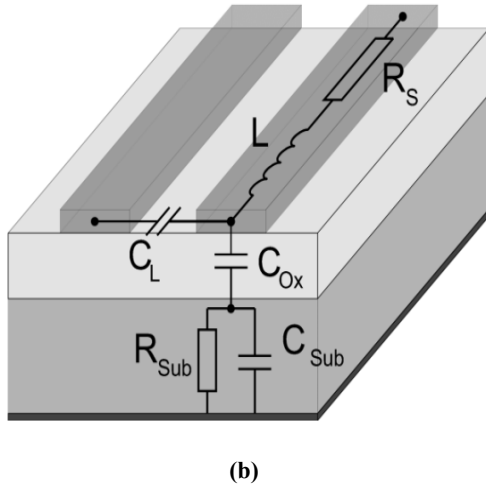
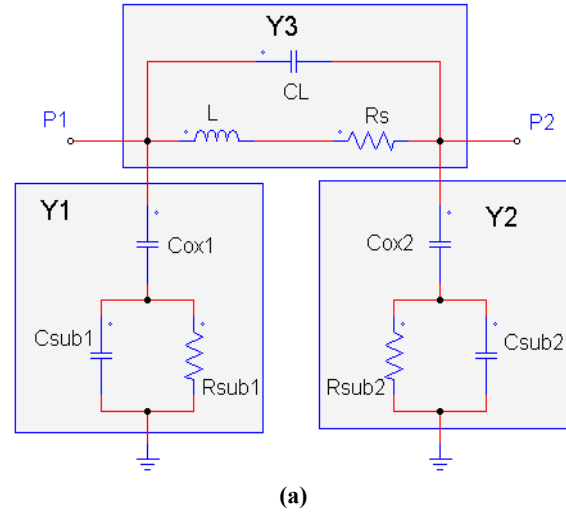


Figure 3. (a) Cross-section, (b) its equivalent circuit of a planar inductor



Based on this figure, the reactance's (Y1), (Y2) and (Y3) can be calculated as follows [24][25]:

$$Y_1 = Y_2 = \frac{1}{\frac{1}{j\omega C_{ox}} + \frac{R_{sub}}{1 + R_{sub}(j\omega C_{sub})}}} \quad (1)$$

$$Y_3 = j\omega C_L + \frac{1}{j\omega L + R_s} \quad (2)$$

The Y-parameters of the scheme are given as follows

$$\begin{bmatrix} Y_{11} & Y_{12} \\ Y_{21} & Y_{22} \end{bmatrix} = \begin{bmatrix} Y_1 + Y_3 & -Y_3 \\ -Y_3 & Y_2 + Y_3 \end{bmatrix} \quad (3)$$

After development

$$\begin{cases} Y_1 = Y_{11} + Y_{12} \\ Y_2 = Y_{22} + Y_{21} \\ Y_3 = -Y_{12} = -Y_{21} \end{cases} \quad (4)$$

The electrical model, coupled with the S-parameters profile, enables the estimation of the inductor's electrical parameters. In practice, the S-parameters are converted into admittance (Y) parameters using the  $\pi$  equivalent model, as depicted in Figure 4(b). The conversion from Y-parameters to S-parameters is performed using the following procedure:

$$S_{11} = \frac{(Y_0 - Y_{11})(Y_0 + Y_{22}) + (Y_{12} \cdot Y_{21})}{(Y_{11} + Y_0)(Y_{22} + Y_0) - (Y_{12} \cdot Y_{21})} \quad (5)$$

$$S_{12} = \frac{(-2) \cdot Y_{12} \cdot Y_0}{(Y_{11} + Y_0)(Y_{22} + Y_0) - (Y_{12} \cdot Y_{21})} \quad (6)$$

$$S_{21} = \frac{(-2) \cdot Y_{21} \cdot Y_0}{(Y_{11} + Y_0)(Y_{22} + Y_0) - (Y_{12} \cdot Y_{21})} \quad (7)$$

$$S_{22} = \frac{(Y_0 + Y_{11})(Y_0 - Y_{22}) + (Y_{12} \cdot Y_{21})}{(Y_{11} + Y_0)(Y_{22} + Y_0) - (Y_{12} \cdot Y_{21})} \quad (8)$$

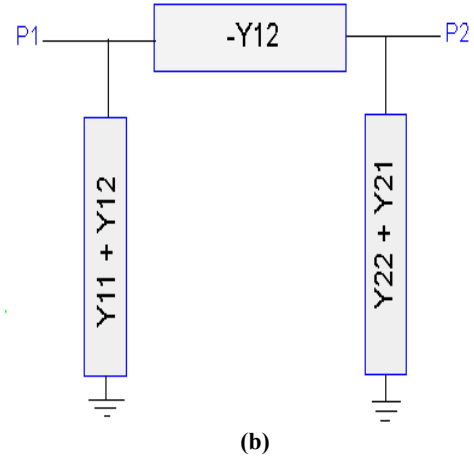


Figure 4. (a) Nine elements of the equivalent circuit (b) Y-parameters  $\pi$  model

The electrical parameters of the equivalent circuit of the spiral inductor are extracted using the Y- parameters [26]:

$$L = \frac{\text{Im}\left(\frac{1}{Y_{11}}\right)}{2 \cdot \pi \cdot f} \quad (9)$$

$$R_s = \text{Re}\left(\frac{1}{Y_{11}}\right) \quad (10)$$

$$Q = \frac{\text{Im}\left(\frac{1}{Y_{11}}\right)}{\text{Re}\left(\frac{1}{Y_{11}}\right)} \quad (11)$$

$$C_{ox1} = \frac{-1}{2 \cdot \pi \cdot f \cdot \text{Im}\left(\frac{1}{Y_{11} + Y_{12}}\right)} \quad (12)$$

$$C_{ox2} = \frac{-1}{2 \cdot \pi \cdot f \cdot \text{Im}\left(\frac{1}{Y_{22} + Y_{21}}\right)} \quad (13)$$

$$C_{sub1} = \frac{Im(Y_{11}+Y_{12})}{2.\pi.f} \quad (14)$$

$$C_{sub2} = \frac{Im(Y_{22}+Y_{21})}{2.\pi.f} \quad (15)$$

$$R_{sub1} = \frac{1}{Re(Y_{11}+Y_{12})} \quad (16)$$

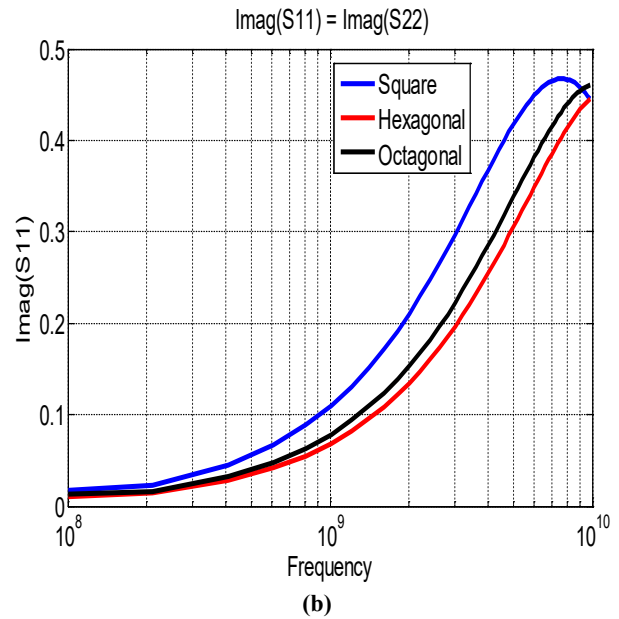
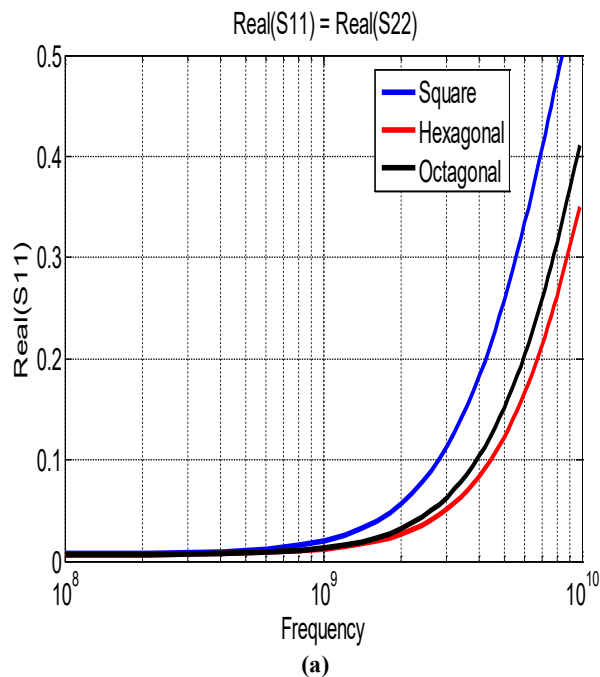
$$R_{sub2} = \frac{1}{Re(Y_{22}+Y_{21})} \quad (17)$$

### 3. RESULT AND ANALYSIS

#### 3.1 S-Parameter.

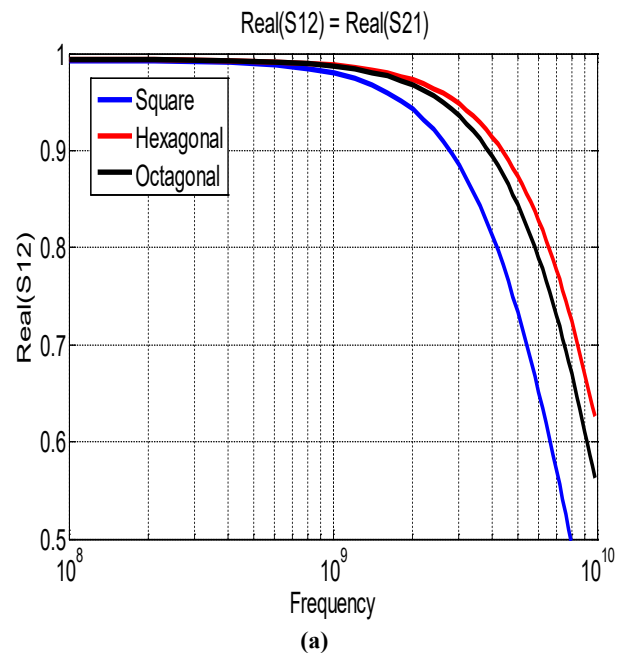
The figures below show the effect of different shapes of a planar spiral inductor on the values for the S-parameters versus frequency, which are obtained from the equivalent circuit modeling of the inductor. Given the symmetry of the model, it is observed that  $S_{11} = S_{22}$  and  $S_{12} = S_{21}$ .

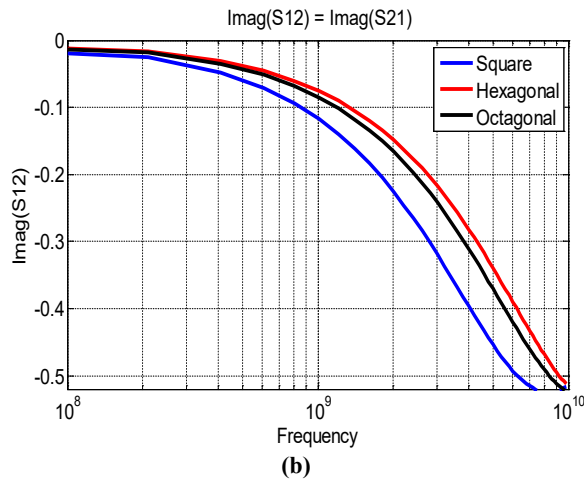
Figures 5(a) and 5(b) show the real and the imaginary values of  $S_{11}$ , over a range of 100 MHz to 100 [GHz]. At lower frequencies, the values of  $S_{11}$  are nearly the same for all shape of inductors and are approximately equal to 0. But as the frequency increases, these values increase more rapidly for each of these different shapes with the square taking the lead, the hexagonal, and finally the octagonal.



**Figures 5. Show the effect of different shapes of the spiral inductor on the ( $S_{11}$ ) values, (a) the real and (b) the imaginary.**

The results for  $S_{12}$  are shown in Figures 6(a) and 6(b) across the same frequency range as before. At lower frequencies,  $S_{12}$  values are similar for all inductor shapes, with the real part near 1 and the imaginary part near 0. As frequency increases, both real and imaginary components of  $S_{12}$  decline, reflecting increased impedance mismatch and parasitic effects. The square inductor exhibits a more rapid decrease in  $S_{12}$  values compared to the hexagonal and octagonal inductors, due to its geometric configuration which introduces greater parasitic capacitance and resistance at higher frequencies.





Figures 6. Show the effect of different shapes of the spiral inductor on the (S12) values, (a) the real and (b) the imaginary.

### 3.2 Electrical parameter

A simulation of three coils with different shapes and with the same geometric parameters was prepared in order to find out their effect on all the six electrical parameters shown in figure 4(a), using the MATLAB software.

Figures 7 to 12 show the extracted electrical parameters for wave frequency from 1 GHz to 10 [GHz].

#### 3.2.1 Inductance

Despite the identical geometric parameters of the three differently shaped inductors, a noticeable variation in inductance values is observed across the frequency range of 1 to 10 GHz, as illustrated in Figure 7. Within the frequency range of 1 to 4.5 GHz, the hexagonal and octagonal inductors exhibit nearly equivalent inductance values. However, a significant difference in the self-resonant frequency (SRF) is observed between these two inductors, with a disparity of approximately 0.8 GHz.

Notably, the square inductor demonstrates higher inductance and SRF values compared to the other geometries. This behavior can be attributed to the longer length of the spiral coil in the square design, which inherently increases the inductance. The higher inductance in the square inductor results from the increased magnetic flux linkage due to the extended path of the current-carrying conductor.

The reduction in resonant frequency observed across different inductor shapes can be explained by the widening angle of the coil, particularly evident in the octagonal inductor. As the coil angle increases, the effective inductance decreases, leading to a lower resonant frequency. This indicates that the inductance value is predominantly influenced by the geometry of the planar inductor, with the shape playing a critical role in determining both the inductance and the self-resonant frequency.

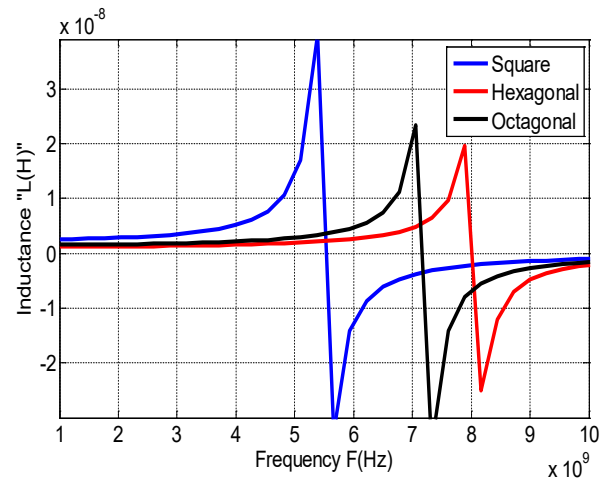


Figure 7. Effect of different shapes of spiral inductor on inductance with frequency change

#### 3.2.2 Quality factor

Using formula (11), Figure 8 illustrates the variation in the quality factor (Q) as influenced by the geometric shapes of the three inductors. The analysis reveals that the octagonal inductor achieves the highest quality factor, with a peak value of 30 at a frequency of 4.2 GHz. In comparison, the hexagonal inductor reaches a maximum quality factor of 27.5 at the same frequency of 4.2 GHz, while the square spiral inductor exhibits a Qmax of 26.5 at a slightly lower frequency of 3.5 GHz.

The superior quality factor of the octagonal inductor can be attributed to the reduction in the length of the coil conductor, which directly results in a decrease in its ohmic resistance. The quality factor is a measure of the inductor's efficiency, defined as the ratio of its inductive reactance to its series resistance. As the resistance of the inductor decreases, the quality factor increases, indicating lower energy losses in the form of heat. The shorter conductor length in the octagonal design minimizes resistive losses, thereby enhancing the overall efficiency of the inductor and leading to the observed peak in the quality factor.

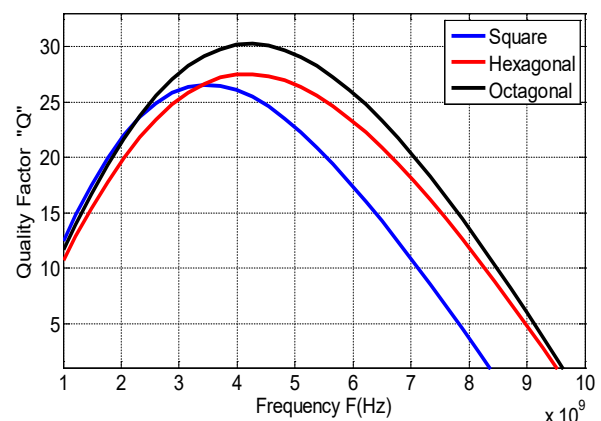


Figure 8. Variation the quality factor as function frequency of the square, hexagonal and octagonal spiral inductor.

### 3.2.3 Resistance

Figure 9 presents the simulation results illustrating the frequency-dependent behavior of the conductor metal resistance losses for the three inductors with different geometrical structures. At a frequency of 1.5 GHz, the results indicate that the octagonal inductor exhibits lower resistance compared to the hexagonal and square inductors, with reductions of 3.7% and 29%, respectively.

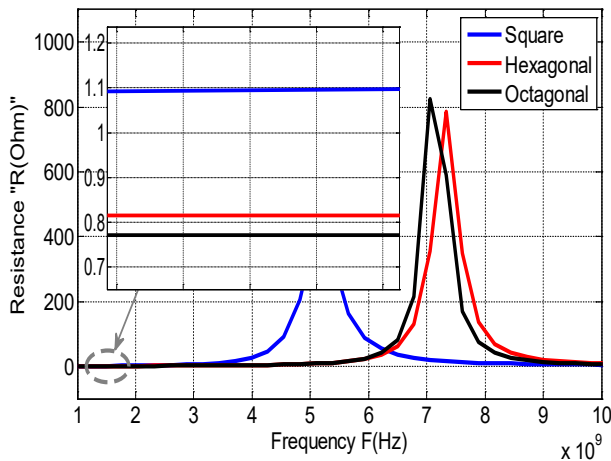


Figure 9. Effect of different shape of spiral inductors on resistance versus frequency

The observed reduction in resistance for the octagonal inductor can be attributed to the direct proportionality between resistance and the length of the conductor ribbon in the spiral. A shorter conductor length results in lower ohmic resistance, thereby minimizing energy losses within the inductor. Additionally, the design of the octagonal inductor lacks sharp corners, which helps to mitigate current crowding effects.

In contrast, the square inductor experiences higher resistance due to the presence of sharp edges. The sharp corners in the square geometry exacerbate current crowding at the edges, where the current density increases significantly. This increased current density leads to higher resistive losses, thereby elevating the overall resistance of the square inductor.

The octagonal inductor, by avoiding sharp angles and optimizing the distribution of current flow, effectively reduces resistive losses and demonstrates superior performance in terms of lower resistance compared to the other structures.

### 3.2.4 Capacitance of oxide

Figure 10 illustrates the variation of oxide capacitance as a function of frequency for different spiral inductor geometries. The curves representing the parasitic capacitance of oxide exhibit a noticeable transient regime between 0 and 1 GHz, which can be attributed to

the effects of low-frequency behavior. This transient response highlights the sensitivity of oxide capacitance to low-frequency variations.

At higher frequencies, the influence of different coil structures on the oxide capacitance diminishes, suggesting that the effect of geometric shape becomes less pronounced. However, the impact of coil geometry cannot be entirely disregarded, as evidenced by the notably higher capacitance values observed for the square coil when compared to the hexagonal and octagonal inductors.

Among the three geometries, the square inductor consistently exhibits the highest oxide capacitance. This can be explained by the larger area of overlap between the coil turns in the square geometry, which increases the effective capacitance. The hexagonal inductor ranks second in terms of oxide capacitance, while the octagonal inductor shows the lowest capacitance values.

The differences in oxide capacitance among the inductor shapes underscore the importance of geometric design in determining the parasitic capacitance. These capacitance variations can have significant implications for the performance of integrated circuits, particularly in terms of their capacitive coupling and overall efficiency.

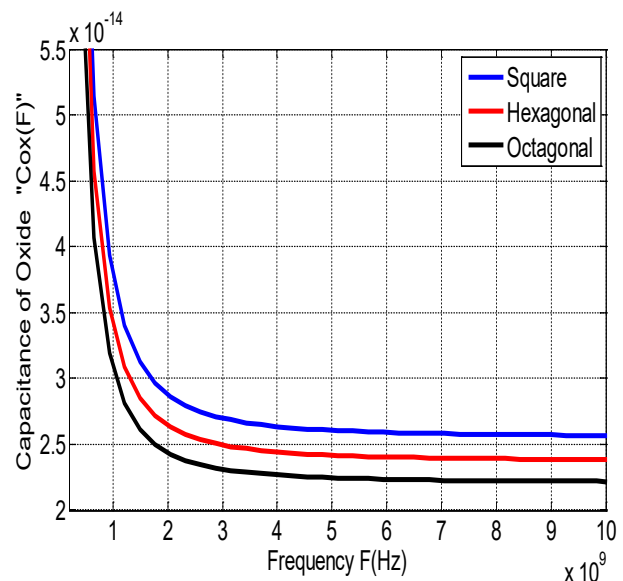


Figure 10. Evolution of the capacitance of oxide for spiral inductor of different shapes versus frequency

### 3.2.5 Resistance of substrate

Figure 11 illustrates the impact of different spiral inductor geometries on substrate resistance. At high frequencies, the results reveal distinct resistance values for each inductor shape, with substrate resistance measured at 1.9 k $\Omega$  for the square inductor, 2.2 k $\Omega$  for the hexagonal inductor, and 3.3 k $\Omega$  for the octagonal inductor. This progression indicates that resistance increases from square to hexagonal to octagonal configurations. The lower substrate resistance observed

in square inductors suggests a higher susceptibility to parasitic effects, as a reduced substrate resistance facilitates the infiltration of parasitic currents, leading to increased power losses and diminished circuit efficiency.

In contrast, the hexagonal and octagonal inductors, which exhibit higher substrate resistance, are more effective in mitigating parasitic current infiltration. The elevated resistance in these geometries acts as a barrier, reducing the likelihood of parasitic losses and improving overall performance. The octagonal inductor, in particular, with the highest substrate resistance, demonstrates superior suppression of parasitic currents, making it the most favorable option for applications requiring high efficiency and minimal parasitic interference.

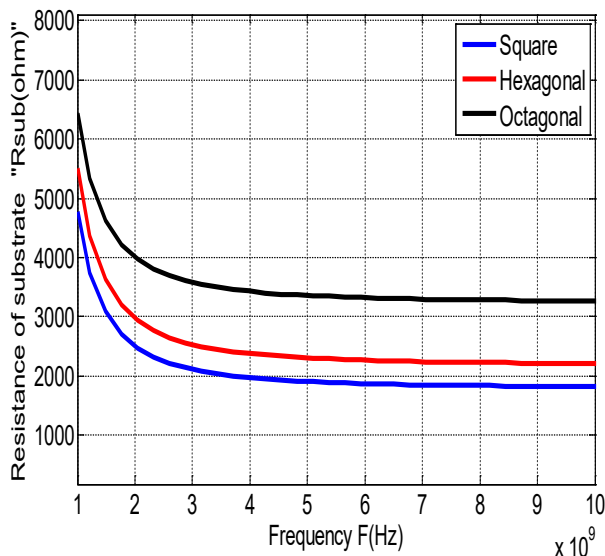


Figure 11. Variation the resistance of substrate for three inductors of different shapes as function frequency

### 3.2.6 Capacitance of substrate

The figure 12 presents the frequency evolution of the parasitic capacitance effects on the substrate for the three inductors: square, hexagonal and octagonal.

We note that the shapes of the parasitic capacitance take on almost similar shapes for the three structures. We observe that there are two distinct zones:

For the frequencies below 1 GHz, the variation in parasitic capacitance among the different inductor shapes—square, hexagonal, and octagonal—is minimal and does not show significant differences. This similarity in parasitic capacitance at lower frequencies indicates that the impact of geometric shape on substrate capacitance is relatively uniform in this frequency range.

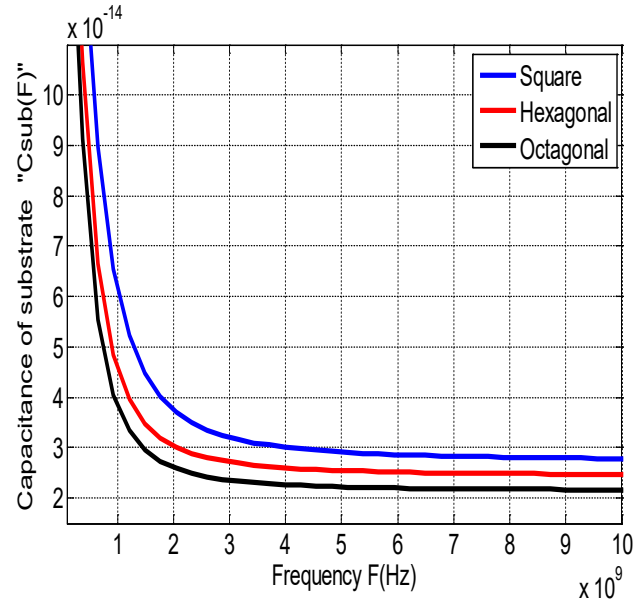


Figure 12. Variation the capacitance of substrate for three inductors of different shapes versus frequency

As for frequencies that exceed 2 GHz, the parasitic capacitance has constant and varying values according to the type of inductor shape.

We find it high for the square file compared to the hexagonal and octagonal file, respectively.

## 4. CONCLUSION

The geometric shape of a planar inductor significantly affects the parasitic effects resulting from current flow. These parasitic effects have a significant impact on the converter, as parasitic resistances lead to additional power losses, resulting in excessive thermal dissipation. This reduces the overall efficiency of the converter. Parasitic effects also introduce electromagnetic disturbances that can result in interference with other electronic components and deterioration of the overall system performance.

The work presented in this article is a comparative study of the different parasitic effects from three spiral inductors: square, octagonal, and hexagonal spirals. The studied parasitic effects are resistive and capacitive effects.

The results have shown that the octagonal geometry, which is the closest to the spiral, yields the best results. Considering the resistive parasitic effects, the octagonal inductor exhibits the lowest ohmic resistance over a frequency range beyond 6 GHz. It also benefits from the highest substrate resistance ( $R_{sub}$ ), which prevents the infiltration of parasitic currents into the substrate and avoids its heating. Similarly, the octagonal inductor shows the lowest values of parasitic capacitances (substrate capacitance  $C_{sub}$  and oxide capacitance  $C_{ox}$ ). The octagonal geometry has an inductance value very close to the square and hexagonal geometries, with a relatively high resonance frequency (7 GHz), and it exhibits the highest quality factor.

In conclusion, the comparative study of the three planar spiral inductors, square, hexagonal, and octagonal, has demonstrated the importance of the geometric shape in reducing parasitic effects and improving the overall efficiency of converters. The results have revealed that the octagonal geometry offers the best results.

## 5. ACKNOWLEDGMENT

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