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## *Design, simulation and analysis of novel fractal integrated transformers*

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**Abstract**

This paper presents the design, simulation and analysis of novel fractal configurations of the primary and secondary coils of the integrated transformers. The performances of the proposed integrated transformers were investigated with electromagnetic simulations up to 20 GHz.

**Introduction**

Due to a growing need for wireless communication devices radio frequency and wireless market is continuing its development. The integrated transformer is an essential component in many RF and microwave integrated circuits [1-5]. Although significant efforts have been made in order to improve the characteristics of integrated transformers [6], [7], it is still a great problem to bring in piece the opposite demands for low cost, low supply voltage, low power dissipation and low distortion, but the high frequency of the operation in RF implementation of these transformers. Commonly used transformers are fabricated on lossy silicon substrate; hence they are from the start limited to a lower quality factor, coupling coefficient and high parasitic effects between the component and the substrate. Arbitrary transformer layouts also impact the transformer characteristics. Various transformers layouts including parallel winding, inter-wound winding, overlay winding and concentric spiral winding were presented in [4]. These layouts can be in planar or stacked configurations and usually have the square spiral shape. However, papers which present other geometries (apart from square spiral) of the primary and secondary coils are very rare.

The unique property of fractal curves is that, after an infinite number of iterations, their length becomes infinite although the entire curve fits into the finite area. This space-filling property can be exploited for the miniaturization of the integrated transformers. Due to the technology limitations such as a minimal line width and spacing achievable by the fabrication process and because of its degree of complexity, the ideal fractal cannot be built. Our research is limited to pre-fractals with a low degree of iteration (or low order). In this work, we present novel layouts of the primary and secondary windings in the shape of fractal curves and demonstrate a comprehensive analysis of the shape and order fractal curves influence on the inductance and quality factor of the stacked transformers for RFICs applications. The simulation has been generated using the Microwave Office software package [8].

**A brief overview of used fractal curves**

Fractals are a whole new set of geometrical objects featuring two main common properties: self-similarity and fractional dimension. There are many mathematical structures that are fractals; e.g. Sierpinski's gasket, Peano curve, von Koch's snowflake, the Mandelbrot set, the Hilbert curve, etc. [9]-[11]. In this paper, Hilbert curve, Peano curve and Koch curve have been used.

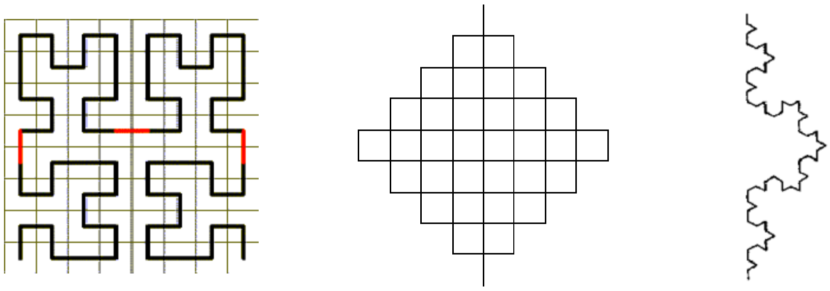


Fig. 1. Some fractal curves, (a) 3rd order Hilbert curve, (b) 2nd order Peano curve, and (c) 3rd order Koch curve.

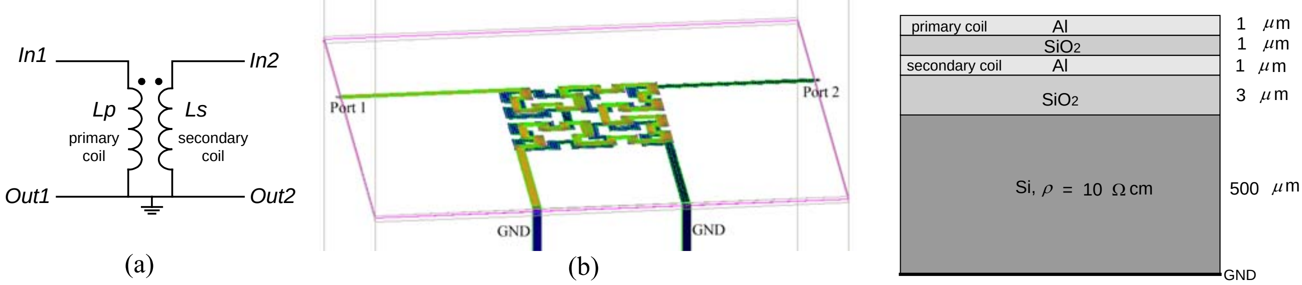
**Hilbert curve.** Hilbert curves are built through an iterative procedure that generates almost self-similar structures. The capability to pack wires in a small space following a Hilbert curve is very appealing for manufacturing winding of the integrated transformers. The construction of the 3rd order Hilbert curve is shown in Fig. 1a [9].

**Peano curve.** To generate the Peano curve, it is necessary to start with a line segment and substitute it with the basic motif. After that, every one of the 9 line segments is taken and substituted with the basic motif again. At the end, it can be obtained a square (Fig. 1b). The fractal dimension of the Peano curve is equal to 2.

**Koch curve.** Koch curve is a fractal curve characterized by such properties as - a curve that is infinitely long, contained within a finite region, not differentiable at any point (they just have corners). A geometric construction scheme for the 3rd order Koch curve is depicted in Fig. 1c.

## Design of fractal integrated transformers

We have designed novel configurations of on-chip stacked transformers, where the primary and secondary windings have shape of different fractal curves. Fig. 2a depicts a schematic symbol and Fig. 2b shows a stacked transformer model for simulation in the electromagnetic simulator Microwave Office. The main features of the transformers under study were assumed as follows. The silicon substrate was used with the thickness of 500 μm and the resistivity 10 Ω·cm (Fig. 2c). The thickness of metal layers for the primary and secondary coil is 1 μm. The oxide thickness between the silicon substrate and a metal layer for the secondary coil is 3 μm and between metal layers for the secondary (a lower layer) and the primary coil (an upper layer) is 1 μm. Aluminum is used as a conductive material, with conductivity $\sigma = 3.53 \cdot 10^7$ S/m. As the secondary winding is closer to the substrate, it is expected that its losses would be higher than those in the primary winding (and therefore quality factor of the secondary coil would be lower than for primary coil).



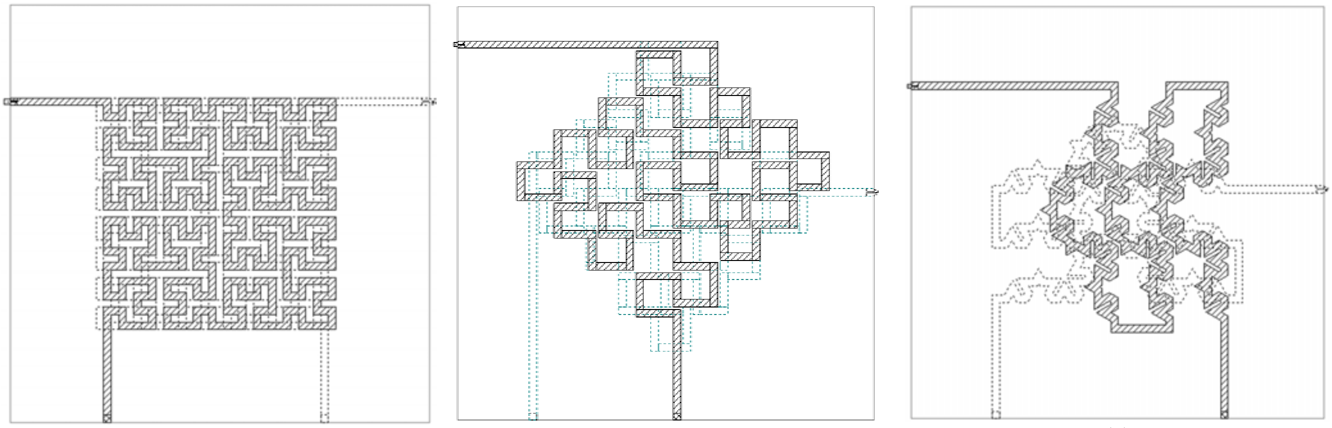

(a) (b) (c)

Fig. 2. Stacked fractal transformer: (a) schematic symbol, (b) 3D model, (c) cross section.

A stacked transformer depicted in Fig. 2b, where the primary and secondary coils have shape of 3rd order Hilbert curve, has turn ratio 1:1. Port 1 and port 2 are input and output ports, respectively.

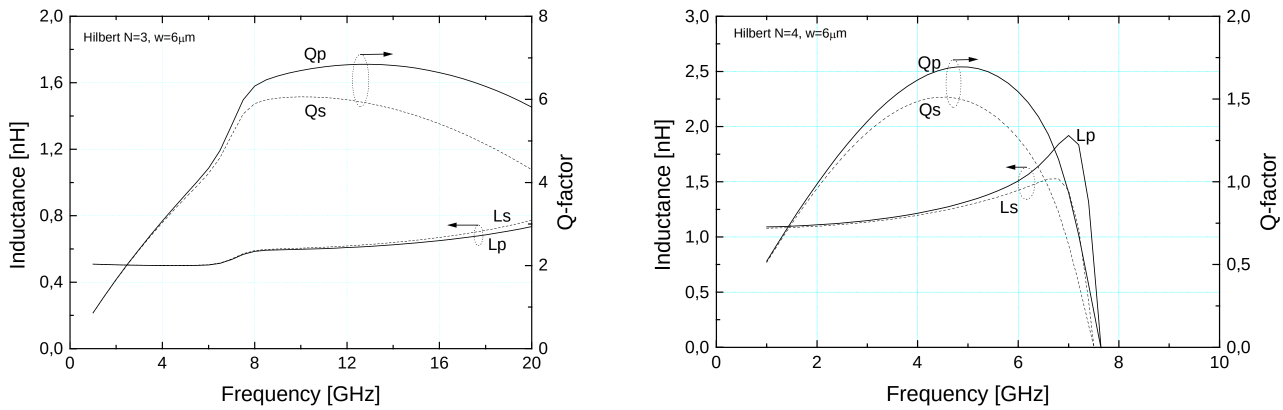
## Simulation results and discussion

In this paper, the stacked configurations of the monolithic transformers have been analyzed. The stacked configuration has the advantage of area efficiency and higher mutual coupling between the windings due to placing the primary coil on top of the secondary. Stacked transformers mainly have high coupling factor (k-factor), up to 0.9. The primary and the secondary winding are placed in adjacent metal layers causing different distances from the substrate. In order to improve its characteristics the windings have been placed in slightly offset position (horizontally or diagonally shifted), resulting in higher Q-factor and self-resonant frequency. In this section we investigate the behavior of transformer parameters with changes of various fractal curves and order of fractal curves in the primary and secondary coils of transformer. A 3D view of the stacked transformer with the primary and secondary windings in the shape of 3$^{rd}$ order Hilbert curve is depicted in Fig. 2b, whereas Fig. 3 shows a 2D view of the 4$^{th}$ order Hilbert curve transformer, 2$^{nd}$ order Peano curve transformer and three serially connected 3$^{rd}$ order Koch curves transformer, respectively. The width of aluminum layer for the primary and secondary windings has been 6μm ($w_P$= $w_S$= 6μm) for all realizations. The overall area was 336μm × 336μm. The performances of the proposed transformers were determined using EMSight, the EM simulator in Microwave Office.



(a) (b) (c)

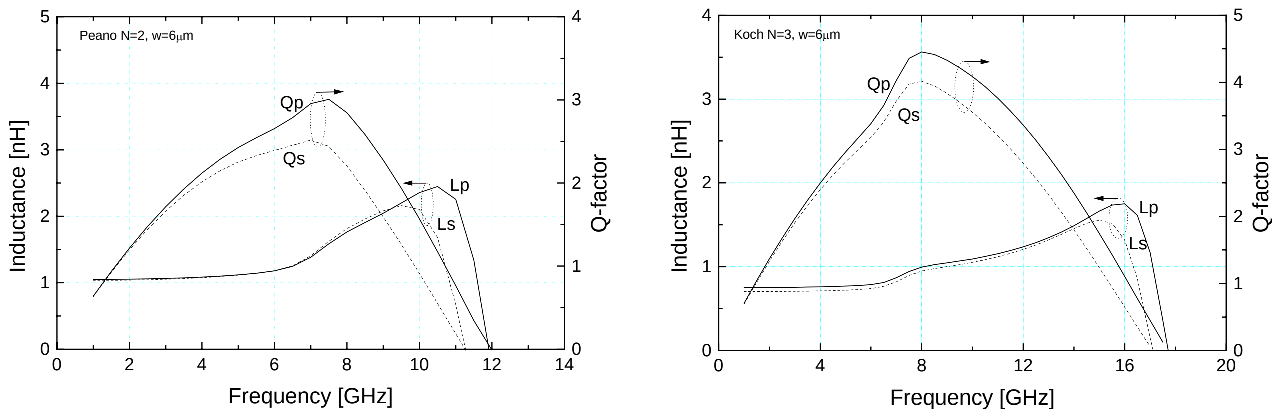
Fig. 3. Monolithic stacked transformers realized with
(a) 4$^{th}$ order Hilbert curve, (b) 2$^{nd}$ order Peano curve, and (c) three serially connected 3$^{rd}$ order Koch curves.




(a) (b)

Fig. 4. The inductance and quality factor as a function of frequency for stacked transformer with
(a) 3$^{rd}$ order Hilbert curve, (b) 4$^{th}$ order Hilbert curve.

Fig. 4 illustrates the inductance and quality factor of the transformer structures as a function of frequency. From Fig. 4 (and Fig. 5, too) it can be seen that the inductances of the primary and secondary coils are approximately the same (ratio 1:1). As shown in Fig. 4, the stacked Hilbert transformer with fractal curves of the 4$^{th}$ order achieves only inductance improvement, but Q-factor and self-resonant frequency are smaller compared to 3$^{rd}$ order curves with the same widths of the primary and secondary coil. This is a consequence of higher value of negative mutual inductance between the segments of a conductive strip with the shape of Hilbert curve and the larger area that fills 4$^{th}$ order Hilbert curve. The configuration with 3$^{rd}$ order Hilbert curve has a maximal value of the Q-factor and self-resonant frequency, afterwards realizations with Koch curves and Peano curve.




(a) (b)

Fig. 5. The inductance and quality factor as a function of frequency for stacked transformer with (a) 2nd order Peano curve, and (b) three serially connected 3rd order Koch curves.

The minimal Q-factor has the stacked transformer with 4th order Hilbert curve thanks to the largest occupied area and as a result the biggest parasitic capacitance value. As can be seen from Fig. 4a, the best Qp around 6.8, and Qs around 5.9 were achieved at approximately 12 GHz. This is better than results for a differential (Q=5.2) or interleaved (Q=5.7) transformer with the square spiral shape in open-literature [2], [3], respectively. Note that, by comparison with published results, there is also a significant increase in self-resonant frequency in the presented transformer structures.

## Conclusion

In this paper, four novel fractal stacked transformers (at the same area and the same width of conductive segments) were analyzed via full-wave EM simulations and compared in terms of the inductance and quality factor. Simulation results show that using fractal layouts for the primary and secondary windings, similar or better performances can be achieved compared to earlier published results for monolithic transformers. The realization with 3rd order Hilbert curve was shown to be superior to all the other examined configurations, after that the realization with three serially connected 3rd order Koch curves and 2nd order Peano curve. The presented results mean that transformer configurations with fractal curves are very useful for RF-IC designers to design high-performance RF and microwave integrated circuits.

## Acknowledgement

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