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DESIGN AND SIMULATION OF NOVEL FRACTAL INTEGRATED TRANSFORMER STRUCTURES

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ABSTRACT

Silicon based radio frequency integrated circuits (IC) are becoming more and more competitive in wide band frequency range. An essential component of these IC is on-chip (integrated) transformer. They are widely used in mobile communications, microwave integrated circuits, low noise amplifiers, active mixers, and baluns. In this paper, for the first time, we present different configurations of fractal-integrated transformers. Monolithic transformers using fractals (von Koch fractal, and Hilbert fractal) are investigated. In this way, a number of lithographic processes are decreased, which simplifies production technology. We analyzed clarify the influence of substrate conductivity, mutual coupling, symmetry and process parameters on transformer behavior.

1. INTRODUCTION

Constant growth of wireless applications brought to an intensive need for mobile communications and mobile communication devices. Due to growing need for wireless communication devices radio frequency and wireless market is continuing its development. An essential component of these IC is integrated transformer. They are widely used in mobile communications, microwave integrated circuits, low noise amplifiers (LNA), active mixers, baluns (give balanced output for unbalanced input). Transformers are proved effective for miniaturized sensors, actuators, filters and power converters that should be integrated on chip modules and installed in various electronic systems [1]-[3].

Although significant efforts have been made in order to improve the characteristics of integrated transformers [4], [5], 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 high frequency of 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.

In this paper, for the first time, we present different configurations of fractal integrated transformers. The influence of substrate conductivity, mutual coupling, symmetry and process parameters on transformer behaviour are investigated. We analyze transformer performances using simulation results by commercial 3D electromagnetic simulator Ansoft HFSS [6].

2. OVERVIEW OF FRACTAL STRUCTURES

Benoit B. Mandelbrot investigated the relationship between fractals and nature [7]. Most fractal objects have self-similar shapes, although some fractal objects exist that are hardly self-similar at all [8].

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.

2.1 THE VON KOCH FRACTALS

The geometric construction of the basic von Koch curve is shown in Fig. 1. The geometric construction of the standard Koch curve is fairly simple [8].

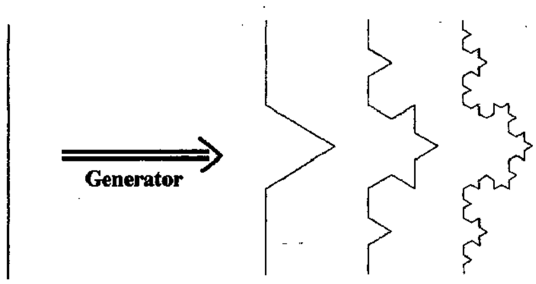


Fig. 1. *Geometrical construction of standard Koch curves*

2.2 HILBERT FRACTALS

The space-filling properties of the Hilbert curve and related curves make them attractive candidates for use in the design of fractal transformer. The first three steps in the construction of the Hilbert curve are shown in Fig. 2 [9].

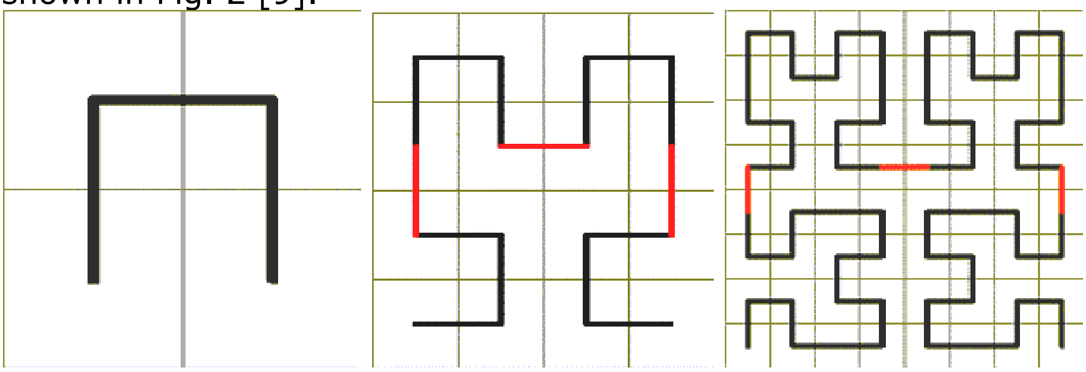
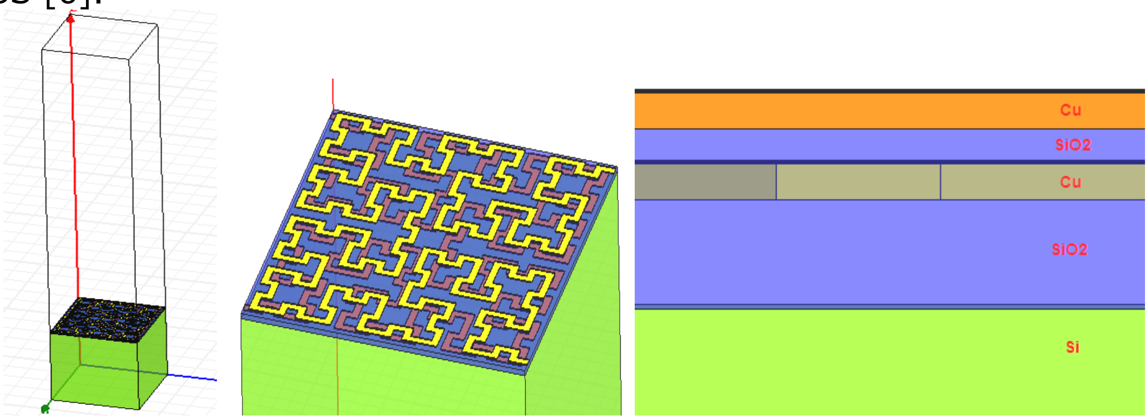


Fig. 2. *Hilbert curve (iteration 0, iteration 1, iteration 2)*

3. FRACTAL TRANSFORMERS

The parasitic effects, dominating transformers, are depending from a way of their realization and configuration [10]. By fractal analysis, we concluded that they are impossible to make interleaved transformer, and even a tapped transformer would be very hard to realize. This means that only remaining solution is in design of stacked transformer. Two fractal curves will represent primary and secondary windings (coils). They are placed in a substrate, being separated by a layer of SiO_2. Fig. 3a shows a transformer model for simulation in 3D electromagnetic simulator Ansoft HFSS [6].



a) b) c)

Fig. 3. *Fractal transformer: a) model, b) model without air box, c) cross section*

Transparent box is an air box, necessary to define ports. Enlarged model, without air box, where the substrate (green), SiO_2 (blue), and transparent layers of Cu (orange and gray color) are visible, is shown in Fig. 3b. Air box will be omitted in next models, due to better visibility. Fig. 3c shows an enlarged part of cross section where layer sequence is visible. Conductive material at the top, marked orange, is a copper layer 1μm thick, used as primary windings. Second conductive layer, also 1μm thick, marked gray, is secondary winding. It is practically placed into SiO_2. Distance between primary and secondary windings is 1μm. As secondary winding is closer to substrate, it is expected that its losses would be higher than those in the primary winding.

4. DESIGN AND SIMULATION OF FRACTAL TRANSFORMERS

In this section we investigate behavior of transformer parameters with changes of various fractal curves and their levels in primary and secondary part of transformer. First we tried with some simpler fractal curves, i.e. with low level of fractal curve. Primary and secondary windings are made of copper in the form of Hilbert's fractal third level (N=3). Width of copper layer for primary and secondary windings is 6μm (w_P= w_S=6μm), and it is 1μm thick (t_{Cu} = 1μm). Thickness of SiO_2 is 5μm, and Si is 380μm. Width and length of Si and SiO_2 layers for this transformer is 125x125μm. Fig. 4 shows a model of this transformer for simulation in Ansoft HFSS, and Fig. 5 shows simulation results as the quality factor (Q-factor) and inductance depending from frequency. On the basis of simulation results we can see that primary inductance is Lp=0.6nH, and the secondary inductance is Ls=0.3nH.

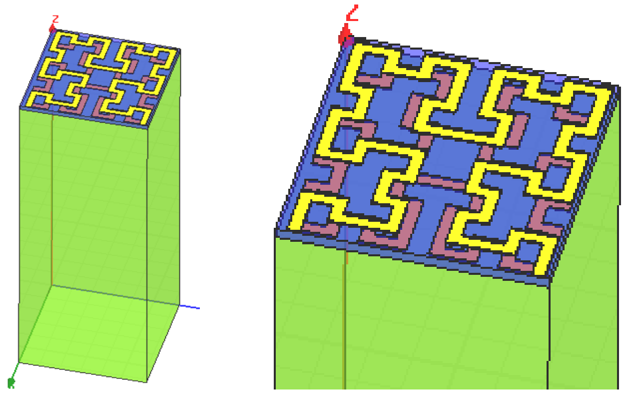


Fig. 4. *Monolithic fractal transformer realized with two Hilbert curve N=3, t_{Cu}=1µm.*

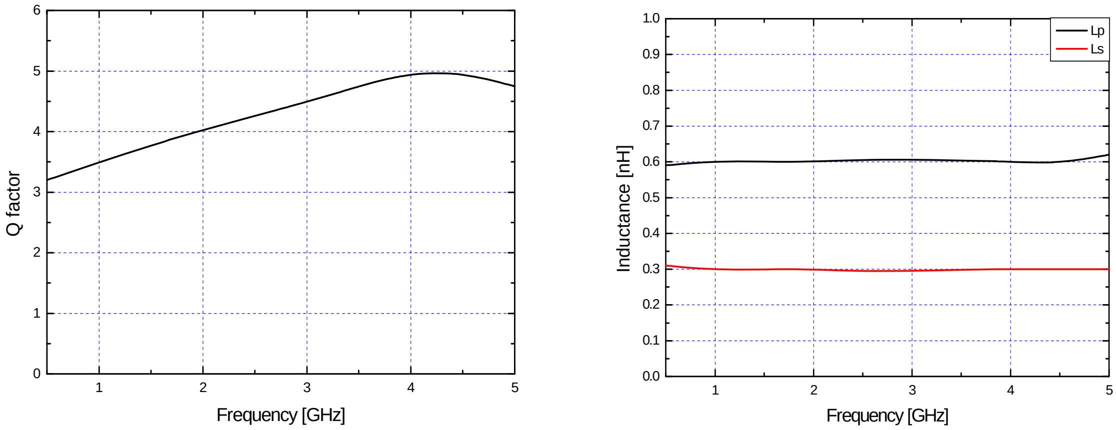


Fig. 5. *Q-factor and inductance versus frequency (two Hilbert curve N=3, w_P= w_S=6µm, t_{Cu}=1µm).*

Transformer turns ratio $n = \sqrt{\frac{Lp}{Ls}}$ is about 1.41. We may see that inductance is changed very little with frequency change, in considered range of frequency (from 0.5GHz to 5GHz, i.e. RF range). Maximal value of the Q-factor is obtained at frequency of 4.2 GHz.

In the next simulation we have increased level of fractal curve. Primary and secondary winding are realized using Hilbert's fractal of fourth level (N=4).

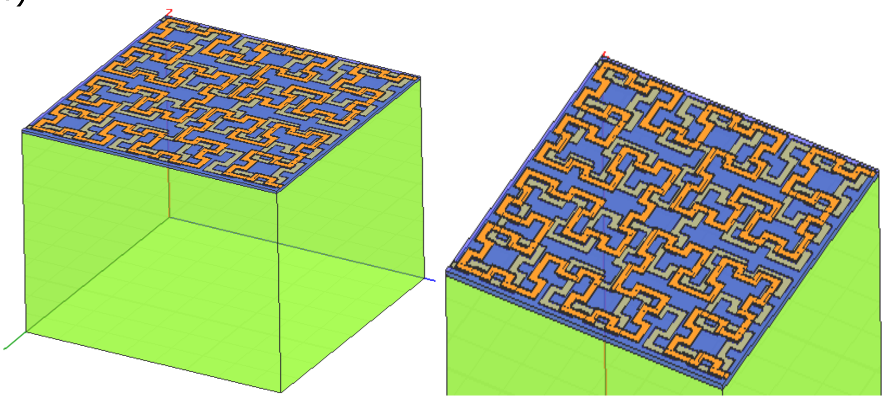


Fig. 6. *Monolithic fractal transformer realized with two Hilbert curve N=4,w_P=10µm, w_S=10µm, t_{Cu}=1µm.*

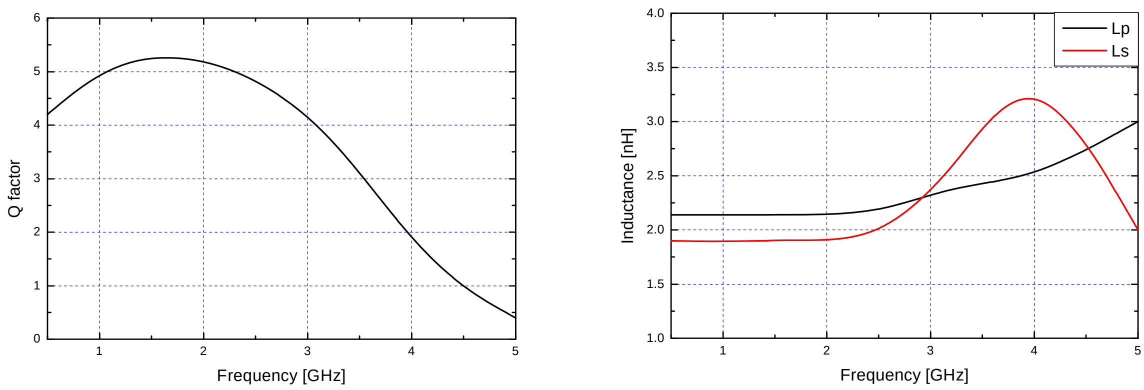
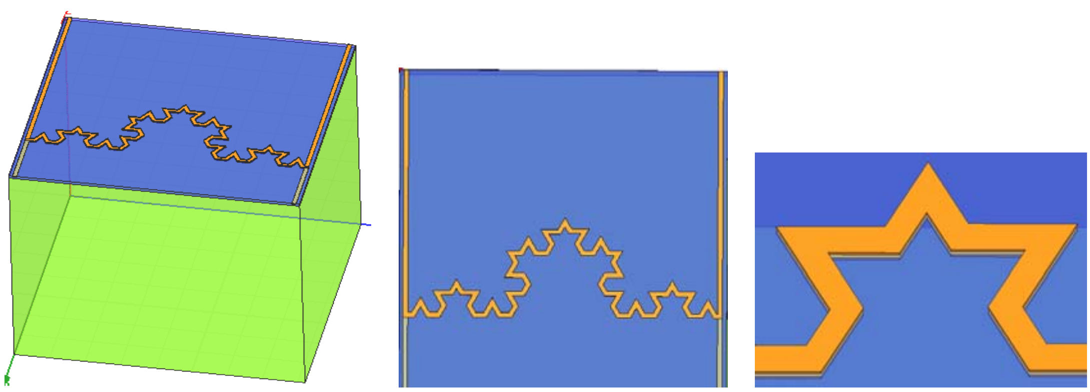


Fig. 7. *Q-factor and inductance versus frequency (Hilbert fractal N=4, w_P= w_S=10μm, t_{Cu}=1μm)*

Technological parameters remain the same: thickness of Si layer is 380μm, of SiO_2 is 5μm, and of Cu is 1μm. Width and length of Si and SiO_2 layers is 400x400μm. Width of copper layer, which makes primary and secondary winding of transformer, is 10μm. Transformer model is shown in Fig. 6, and simulation results in Fig. 7, as Q-factor and inductance.

By increasing the level of fractal curve level, by which primary and secondary windings of transformer were realized, their inductance is also increased. Transformer turns ratio n is about 1.08, which is very low. The Q-factor is not changed significantly. Maximal value of the Q-factor has moved to lower frequencies and is placed about 1.75GHz. At higher frequencies (above 2GHz) a large change of inductance occurs with frequency changes.

Similar simulations were repeated for the Koch fractal of third level. The primary and secondary windings were also made from this fractal. Thickness of the copper, Si and SiO_2 layers, as well as their width, still remains unchanged. Transformer is designed that primary and secondary windings are parallel. Model (in HFSS) of this transformer is shown in Fig. 8a. Fig. 8b shows a view from above, and Fig. 8c shows only conductive layers. Fig. 9 shows results of simulation as the Q-factor and inductance depending from frequency.



a) b) c)

Fig. 8. *Monolithic fractal transformer: a) model for simulation (Koch fractal N=3) b) zooming model c) more zooming model.*

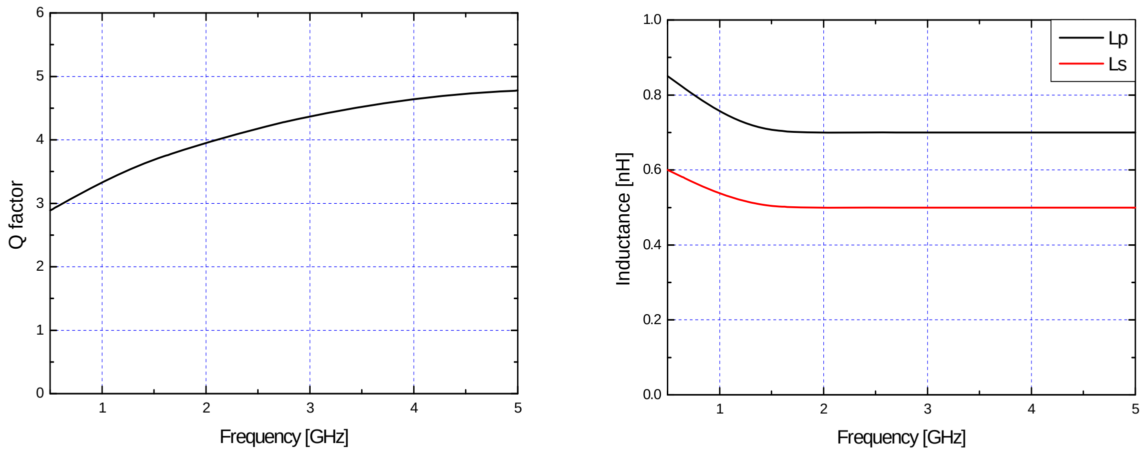
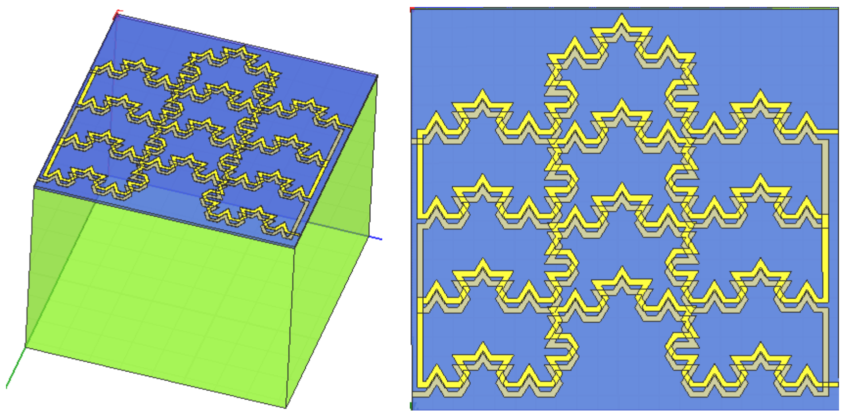


Fig. 9. *Q-factor and inductance versus frequency (Koch fractal N=3, $w_P= w_S=6\mu m$, $t_{Cu}=1\mu m$).*

Finally, complexity of this structure is increased in order to maximal utilization of the area on chip. We connected four Koch fractals in sequence, as shown in Fig. 10b. Two of these connections are used as primary and secondary windings for the transformer. Geometrical and technological parameters are the same as in previous simulation. Model of this transformer is shown in Fig 10a. Results of simulation are shown in Fig. 11.



a) *b)*

Fig. 10. *Monolithic fractal transformer: a) model for simulation (four serial linked Koch fractal N=3) b) zooming model.*

After comparison of previous two simulation results, we can see that sequential connection of fractal structures enables considerably higher inductance for both primary and secondary windings. The Q-factor is not changed significantly, but maximal value is obtained at considerably lower frequencies in sequential connection of fractal curves (because of higher occupied area and parasitic capacitance and lower self-resonace frequency).

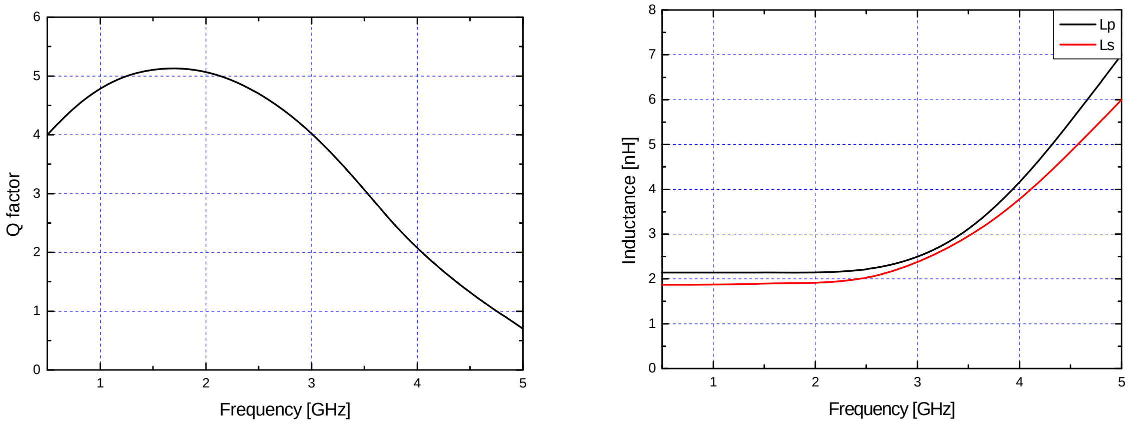


Fig. 11. *Q-factor and inductance versus frequency (four serial linked Koch fractal N=3, $w_P= w_S=6\mu m$, $d_{Cu}=1\mu m$)*.

5. CONCLUSION

In this paper, for the first time, we will present monolithic transformers using fractals. In this way, a number of lithographic processes are decreased, which simplifies production technology.

We have shown presentation of monolithic fractal transformers, their division and ways of realization. Their models have been realized and simulated in Ansoft HFSS, as well.

The level of fractals used in them, as well as the width of conductive layer of the primary one has been changed. Primary winding has been moved in regard to secondary winding in order to monitoring the change of Q-factor and inductance. Based on the obtained simulation results, adequate conclusions about these novel monolithic fractal transformers have been made.

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