Design and simulation of novel planar Micro-transformer with high quality factor

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ABSTRACT:
In this paper a novel planar micro-transformer with high quality factor is presented. Non-uniform current density distribution, especially in inner turn, increases the effective metal resistance due to skin and proximity effect .In order to overcome this problem, a novel crossover connection between turns to equal the distance current path across the turns and uniform the current distribution, has been used. With diminished current crowding effects, the effective resistance is minimized, thereby increasing the performance-parameter values. Simulation has been taken by using ADS Momentum and HFSS software. The quality factor, self-inductance, mutual inductance and coupling factor at 3.5 GHz frequency are achieved about 42.6, 4.9 nH, 3.3 nH, 0.747 respectively, and occupied structure space is 860 um×860 um. Because of the structure is symmetric, the primary and secondary characteristic is same .compare to conventional micro-transformer 17% in quality factor,5% in coupling coefficient and more than 20% in self and mutual inductance, improvement are achieved.

KEYWORDS: Planar micro-transformer, Quality factor, coupling coefficient, cross-connection, current crowding,

1. INTRODUCTION

With the increasing development of technology and demand for higher working frequency, attention to the passive components, especially micro-transformers, In order to adapt to the needs of the day, has increased. Planar micro-transformer is the geometrical arrangement of two parallel planar conductive coils which able to transport energy from one coil to the other. Energy transfers through magnetic coupling between two coils without physical contact. Wide applications of micro-transformers, especially in the energy converters, signal amplifiers, impedance matching, DC-signal isolation, low-noise feedback and in sensors such as fluxgate magnetometer, wireless pressure sensor, bio particle detector in microfluidic and wireless transmitters, shows the significance of micro-transformers.

Common planar micro-transformer have suffered from their poor performance due to the Ohmic loss of the coils in the standard CMOS technology and the substrate loss at high frequency [1].

Several studies have attempted to improve the performance of micro-transformer such as planar coils with multipath metal [2] to reduce the skin effect losses, suspended coils over the silicon trench [3] , Multiple Turn Ratio micro-tranformer [4], front-side and backside micromachining [5], porous silicon [6], patterned-ground shields (PGS) to suppress the Electromagnetic coupling induced loss in the silicon substrate [7], and substrate transfer [8], have been used to reduce the parasitic effects.

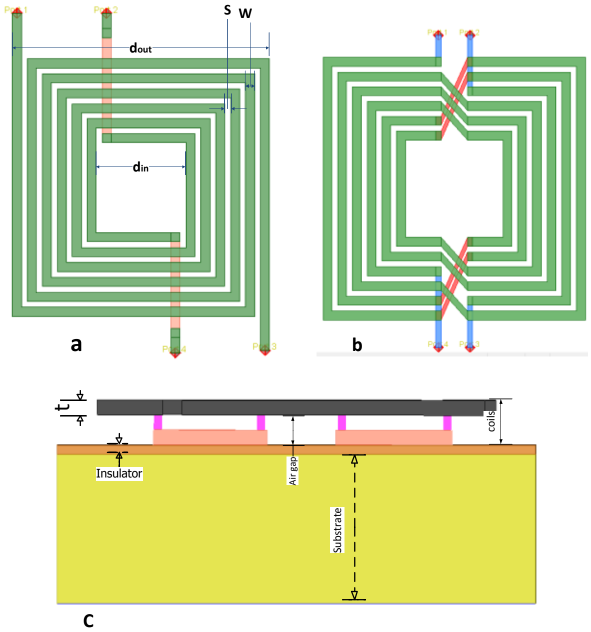

Fig. 1: Micro-transformer structure, a) conventional micro-transformer top view, b) proposed micro-

transformer top view, C) micro-transformer cross-section layout.

In spite of significant improvements are achieved in above mentioned studies, the complex process steps and high material cost and focus on improving only one or two performance parameters, become the major handicap for them.

In this paper, a novel micro-transformer that is able to overcome such challenges is proposed. All the key-performance parameters, such as, high-quality factor, high-coupling coefficient, high self-inductance, high self-resonance frequency, and chip area size have been considered. Simulation shows by uniform current distribution in order to reducing skin and proximity effects, especially in inner turns, reducing effective metal resistance therefore significant performance improvements are achieved.

2. DESIGN OF MICRO-TRANSFORMER

The micro-transformer has a planar spiral coil structure comprising of couple air isolated square inter-winding coil conductors. The two separated coils are wound parallel representing a planar inter-winding structure that called primary and secondary coil. The separated planar coils are magnetically coupled through air. The alternating current source from the primary coil produces the changing of the magnetic fields which is then coupled with the secondary coil. Induction is then created in the secondary coil via electromagnetic coupling. If the coupling is sufficiently high, transfer of electrical energy from the primary side to the secondary side will occur [9].

Figure 1-a and Figure 1-b shows the conventional and proposed micro-transformer respectively, with the same footprint size. Both of them placed on the same technology structure that shown in Figure 1-C.

The layer structure is divided in to three parts, namely, substrate, insulating layer and metal layer(coils). Metal on the top layer consists of two spiral coils having square spiral geometry. Square spiral shape is chosen because of its simple geometry to analysis and fabrication and higher inductance value relative to other shapes [10]. The underpass bottom metal layer consists of a conductor line having a role to connect the end of the coils with the output pads outside the coil.

Physically, the geometry of the coil is determined by outer dimension (dout), coil width (W), spacing between two conductor coils (S) , the inner dimension (din) and coil thickness (t). Table 1 lists the configuration of the coils design parameters and Technological parameters, such as substrate and insulator type, metal conductivity and the layer construction used in this study.

Table 1. Coils design and technological parameters of the proposed micro-transformer

W	S	din	dout	t
30 µm	20 µm	300 µm	860 µm	7 µm

Substrate: $thickness = 500\ \mu m$ $\varepsilon_r = 11.9$ $\rho = 120\Omega - m$ Coils conductor: Copper $\sigma = 5.8 \times 10^7 S/m$	Insulator(SiO2): $thickness = 0.5\ \mu m$ $\varepsilon_r = 3.9$

3. MICRO-TRANSFORMERS PERFORMANCE-PARAMERERS

Energy and impedance transmission and direct current isolation is the main objective of micro-transformer. To demonstrates the performance of the micro-transformers many parameter have been defined as figure of merit (FOM). The most important of that Characteristic parameters are quality factor (Q), coupling coefficient (K), inductance (L) and Performance-parameter can be extracted from two-port micro transformers [11].

The magnetic energy resistivity in the coil will be shown by the inductance and given by Eq. 1 [11].

$$L_P = \frac{imag\,(Z\,11)}{2\pi f} \qquad L_S = \frac{imag\,(Z\,22)}{2\pi f} \tag{1}$$

The magnetic coupling factor of two-port micro-transformer can be calculated by Eq.2 [11].

$$K = \frac{M_{12}}{\sqrt{Lp \times Ls}} \tag{2}$$

Where M_{12} is the mutual inductance; Lp and Ls are primary and secondary coil inductances, respectively.

Another important performance parameter of the two-port micro transformer is the quality-factor (Q). Based on the principle of the microwave theory, the quality factor of two-port micro transformer is the ratio of the (magnetic) energy stored in the device to the dissipated energy in a cycle and for two port structure can be expressed as Eq.3 [11].

$$Q_P = \frac{imag\,(Z\,11)}{real\,(Z\,11)} \qquad Q_S = \frac{imag\,(Z\,22)}{real\,(Z\,22)} \tag{3}$$

Where Qp and Qs denotes primary and secondary quality factor respectively.

The quality-factor represents how efficiently a signal in the primary winding is transmitted to the secondary winding. The quality-factor is determined by metal Ohmic loss, substrate dissipation, and magnetic coupling factor [12]. The metal Ohmic loss in transformer can be decreased by reducing effective metal resistance. Substrate losses can be suppressed by high resistivity substrate or high gap layers to reduce capacitance coupling between coils and substrate [13].

4. RESULT AND DISCUSSION

Figure 2 denotes the current density distribution plot of the conventional and proposed micro-transformer which is simulated by a high frequency structure simulator (HFSS). The density is increased from the outside turns to the inside coils turn, and the current density of the micro-transformer in the inner turns is compared to outer turns. In the inner turns of the conventional micro-transformers, the largest electric field density causes non-uniform current distribution [14]. This current crowding effect is due to induced eddy currents on adjacent traces in the inner turns, thus degrading the quality factor and inductance [15]. This constricts the current, increasing the effective resistance above the value that would exist for a uniform current throughout the trace width. Also the trace corners yields slightly higher fields due to proximity to the two sides that meet. Figure 2(b) shows that the proposed structure with crossover connection can effectively depress the current-crowding effect of the inner turns, as Figure 2(b) shows an increased uniformity in current density when compared with Figure 2(a).

Current density uniform distribution results that in each turns, the current path is changed to the other turns. First, current travels half the distance of outer turn then transmitted to inner turns, and after that at the midpoint of inner turn, current is transferred to middle turns, then comes back to outer turn, and this process is repeated again. As Fig 1(a) shows, at the midpoint of each turn, current path is shifted, first from outer to inner turn, then from inner to middle turn and from middle to outer turn, finally current exits from middle turn.

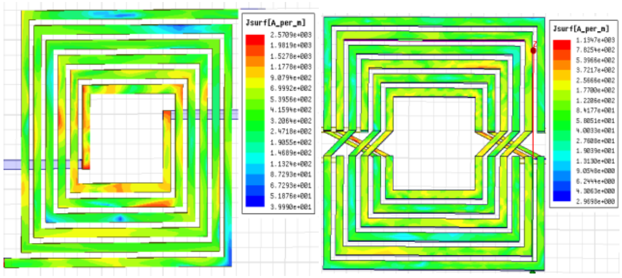

Fig. 2. Current density plots. (a) Conventional structure. (b) Proposed structure.

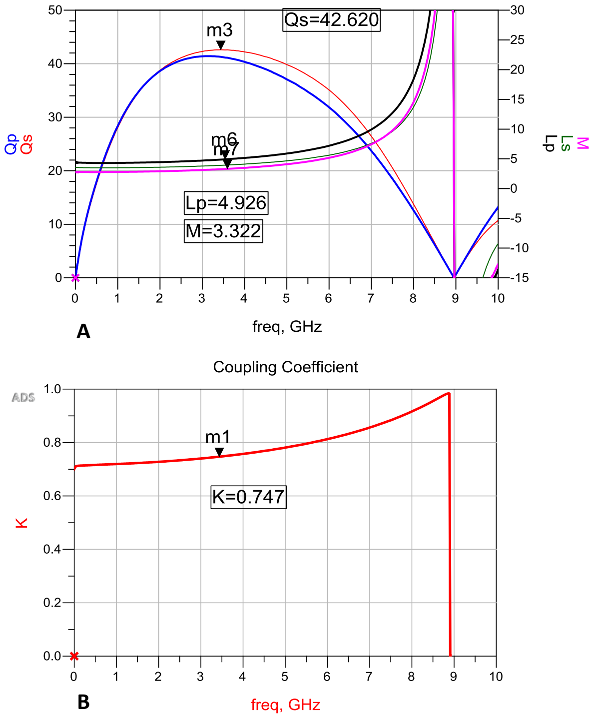

Fig. 3. Proposed micro-transformer simulation results. A) Quality factor and self and mutual inductance (nH), B) coupling coefficient.

Reduced current crowding reduces the RF resistance of the micro-transformer, thereby improving the structure performance.

Fig. 3 shows the simulated inductance, quality factor (Fig 3-A) and coupling coefficient (Fig 3-B) of the proposed micro-transformer versus frequency. As Fig. 3 shows maximum quality factor occurs at 3.5 GHz. At this frequency quality factor, self and mutual inductance and coupling Coefficient are 42.6, 4.9 nH, 3.3 nH and 0.747 respectively.

The primary and secondary coil have a symmetry structure with similar winding number and geometrical configuration, Hence self-inductance (Lp, Ls) and quality factor (Qp, Qs) of the primary and secondary coils have same value.

Resonance frequency occurs at 9 GHz that have a safe distance from operation frequency (about 3 time greater).

Near the resonance frequency, the inductances increase with the frequency until it reaches the resonance frequency region, in which the inductance and quality factor value tends to zero.

The Quality factor, inductance and coupling coefficient of the conventional micro-transformer (Fig 1-a) are shown in Fig.4.the maximum quality factor for conventional structure is achieved at 2.2GHz frequency and it is about 36.3,also self and mutual inductance and coupling coefficient is 3.7 nH, 2.6 nH and 0.71 respectively,

As Fig 4 shows, it was observed that all performance-parameters except resonance frequency Significant have been improved.

Reducing the resonance frequency value may be due to the underpass and crossover connection paths that have been added between turns that increase the total capacitance between coils and substrate.

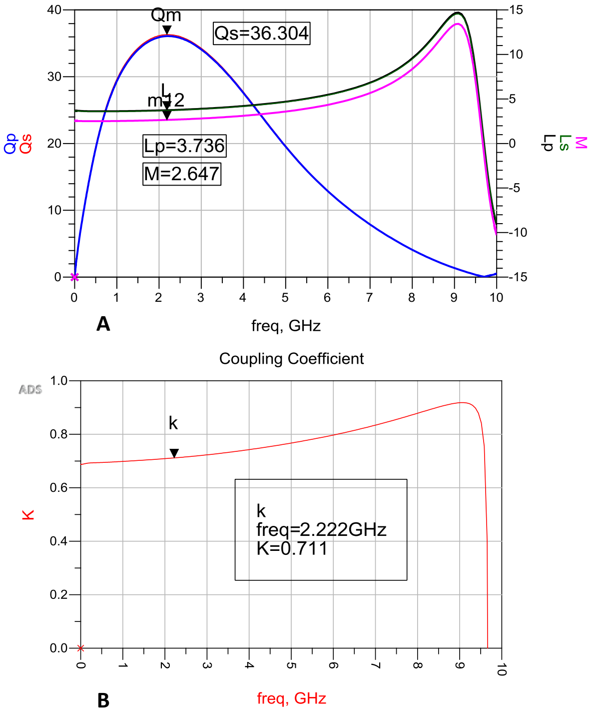

Fig. 4. Conventional micro-transformer simulation results. A) Quality factor and self and mutual inductance (nH), B) coupling coefficient.

Therefore by reducing both skin and proximity effects, especially in inner turns, significant performance improvements are achieved. Simulation results for conventional and proposed micro-transformer are compared and summarized in Table 2.

Table 2. summary of simulation results for conventional and proposed structure

W	Operation Freq.	Qp,Qs	K	Lp,Ls	M12	f_{res}
Conventional structure	2.2 GHz	36.3	0.71	3.7 nH	2.6 nH	9.8 GHz
Proposed structure	**3.5 GHz**	**42.6**	**0.747**	**3.8-4.9 nH**	**3.32 nH**	**9 GHz**

5. CONCLUTION

In this paper, a novel planar symmetrical micro transformer with crossover architecture to set up equal distance path across the turns to decrease Ohmic losses in coils, is presented.

Significant performance improvements are achieved by reducing both skin and proximity effects especially in inner turns. Proposed structure effectively depress the current-crowding effect of the inner turns and make current density distributes uniformly in all micro-transformers turns.

Simulation has been taken by using ADS Momentum and HFSS software. Simulation shows that proposed structure has uniform current density compare conventional micro-transformers.

The quality factor, self-inductance, mutual inductance and coupling factor at 3.5 GHz frequency are obtained about 42.6, 4.9 nH, 3.3 nH, 0.747 respectively

The proposed micro-transformer simulation result shows 17% in quality factor, 5% in coupling coefficient and more than 20% in inductance improvement has been achieved compare conventional structure. The cost for that performance improvement is only 8% reducing at resonance frequency.

Another property of proposed structure is that improvement has been done without increasing the structure occupy space. The proposed micro-transformer can be extremely useful in high-performance RF circuits and Sensor devices due to small size and simple structure.

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