High Performance 3-D Helical RF Transformers

Dae-Hee Weon and Saeed Mohammadi

School of Electrical and Computer Engineering, Purdue University, West Lafayette, IN 47907

Abstract – **We have designed, fabricated, and tested 3-dimensional helical RF transformers on high-resistivity Si substrate using stressed metal technology [1]. The technology for these transformers is based on one step Cr/Au metal deposition and electroplating. These transformers exhibit high coupling coefficient and high power efficiency over an extended frequency range. A 4:4 turn ratio transformer in this work achieves a coupling coefficient k of 0.84 at 5 GHz, with k over 0.7 for frequencies from 1.6 to 6.6 GHz and with P_{out}/P_{in} over 75% up to 20GHz.**

Index Terms – **High coupling coefficient, high power efficiency, high frequency, RF transformers, stressed metal technology, three dimensional fabrication.**

I. INTRODUCTION

With the continuously increasing demand for low-cost, low-power, and low-noise radio-frequency integrated circuits (RFICs), high-performance passive components have become an essential part of circuit design. On-chip transformers have been employed in many microwave and RF circuits to provide impedance matching, impedance transformation, signal coupling, and phase splitting. The use of on-chip transformers has been widely demonstrated to enhance the performance of RFIC circuits such as voltage-controlled oscillators (VCO), low-noise amplifiers (LNA), power amplifiers (PA), and mixers [2-4]. To help with the circuit design, analysis and design of on-chip spiral transformers have been explored in details [5-6].

The operation of a passive transformer is based upon mutual inductances among two or more conductors, or windings. The transformer is designed to couple alternating current from one winding to the other without a significant loss of power. The impedance levels between the windings are transformed in the process *i.e.* the ratio of terminal voltage to current flow changes between windings. In addition, direct current flow is blocked by the transformer, allowing the windings to be biased at different DC potentials.

The performance of an inductor with regard to its losses can be well described by its quality factor, *i.e.*, the ratio of the (magnetic) energy stored in the device to the dissipated energy in a cycle. For transformers, however, no such simple figure-of-merit exists. The mutual inductance (M) between the two inter-wound coils and the magnetic coupling coefficient (k) can be calculated from the two-port Z-parameters.

$$M = \frac{1}{\omega}\mathrm{Im}(Z_{21}) \ , \quad k = \frac{M}{\sqrt{L_p L_s}} \tag{1}$$

where ω is the angular frequency, L_p and L_s are the imaginary parts of Z_{11} and Z_{22} divided by ω, respectively. The coupling coefficient is one of the most important figures of merit for transformer performance. If the magnetic coupling between windings is perfect (i.e., no leakage of the magnetic flux), the coupling coefficient is unity. The concept of coupling coefficient and mutual inductance collapses as the transformer dimensions become significant compared to the wavelength resulting in distributed effects.

In applications where the transfer of power is the primary objective, the transformer efficiency can be defined as the ratio of the power delivered to the load to the input power [7]. P_{out}/P_{in} is evaluated as

$$\frac{P_{out}}{P_{in}} = \frac{|S_{21}|^2 / 50}{\mathrm{Re}\left[|S_{11}+1|^2 / Z_{in} \right]} \tag{2}$$

when port 1 is the input port to the transformer and port 2 (transformer output) is terminated with 50Ω.

On chip transformers in RF circuits are typically implemented using two planar spiral inductors that are interweaved together. There are some variations in terms of how the two spiral inductors are laid out. For instance, by cutting one spiral from the middle, a tapped transformer is achieved, while if when two spirals run parallel to each other, a Parallel (Shibata) structure is achieved. Other implementations include intertwined, symmetric, step up and stacked [8]. All these implementations suffer from loss associated with Si substrate, relatively small bandwidth, and requirement for multi-layer thick metallization. Losses in the substrate of a transformer results in lower coupling coefficient and power efficiency in which part of the stored energy is wasted to heat in the same manner the quality factor is degraded in spiral inductors. As the frequency increases the coupling coefficient of spiral transformers degrade due to the dominant substrate loss.

In three dimensional transformers such as those implemented here, magnetic flux is mostly above the substrate, resulting in less flux penetration into the lossy substrate, thus less loss. Therefore, substantially lower eddy currents are generated resulting in an increase in the coupling coefficient and power efficiency of the 3-D transformer. Due to insignificant substrate loss in these devices, as the frequency increases, the coupling between the adjacent turns is enforced, resulting in an increasing coupling coefficient with frequency.

In this work, we have designed, fabricated, and characterized helical RF transformers on high-resistivity (10 KΩ·cm) Si substrate which exhibit high coupling coefficient and high power efficiency using a three-dimensional (3-D) processing technology [9].

II. TECHNOLOGY

The transformers presented herein are based on a recently developed stressed metal technology [9] in which a Cr/Au metal layered combination is deposited to create a metal with a built-in stress. This built-in stress is used to create 3-D transformers printed on silicon substrate. Our fabrication technology is based on depositing Cr and Au, which are both compatible with integrated circuit fabrication. After depositing a sacrificial layer and the stressed metal combination and etching the metal fingers, the sacrificial layer is removed. As a result of stress, the metal structure bends upward. A final Au electroplating step is performed to improve the metal contact resistance and the rigidity of the structure. By alternating the fingers between two windings, we have designed transformers without a need for additional processing steps such as vias. To better demonstrate our design of 3-D helical RF transformer, schematic diagram of a 3:4 turn ratio transformer is shown in Fig. 1. Fig. 2 shows the SEM pictures of a 1:1 and 4:4 turn ratio transformers fabricated in this technology.

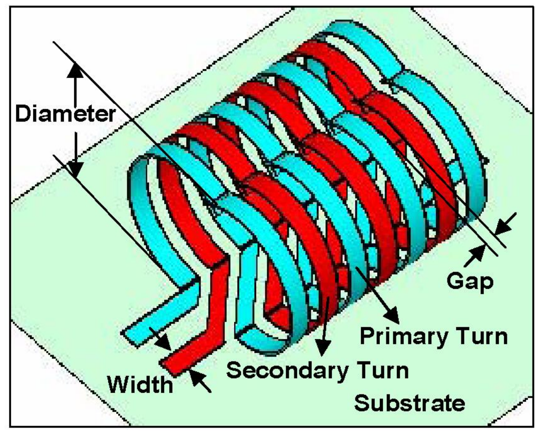
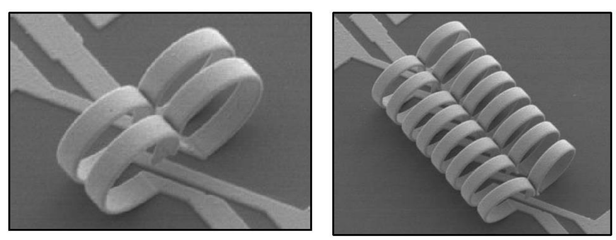


Fig. 1. Schematic diagram of 3-dimensional RF transformer with 3:4 turn ratio by alternating the fingers between two windings.



(a) (b)

Fig. 2. SEM images of 3-D transformers fabricated on high resistivity Si substrate. (a) 1:1 turn ratio transformer and (b) 4:4 turn ratio transformer.

In this work, we have fabricated and characterized transformers on high-resistivity (10 KΩ·cm) Si substrate with 1:1, 1:2, 2:2, 2:3, 3:3, 3:4, and 4:4 turn ratios. These transformers have metal width of 45 μm, diameter of 350 μm, metal thickness of 5 μm, and turn-to-turn gap of 15 μm.

III. RF CHARACTERIZATION

The S-parameters of the fabricated transformers are measured using Agilent 8722 network analyzer calibrated using SOLT up to 20 GHz. Cascade Microtech coplanar GSG probes were used for on-wafer measurement. To perform accurate coupling coefficient (k-factor) measurements, herein, several transformers of the same geometry have been measured to ensure repeatability in the measurements. The deviation of the measurement values is within 5%. Fig. 3 shows the measured coupling coefficient, k, extracted from the measured S-parameters for n:n (n=1,2,3,and 4) turn ratio transformers fabricated on high resistivity Si substrate. As can be seen from this figure, a 4:4 turn ratio transformer achieves a coupling coefficient, k of 0.84 at 5 GHz, with k over 0.7 for frequencies from 1.6 to 6.6 GHz. For 1:1 turn ratio transformer, a coupling coefficient, k is 0.65 at 5 GHz, with k over 0.7 for frequencies from 8.6 to 17 GHz. As mentioned earlier, a distinctive characteristic of three dimensional transformers is that its coupling coefficient increases with frequency due to insignificant substrate loss in these devices.

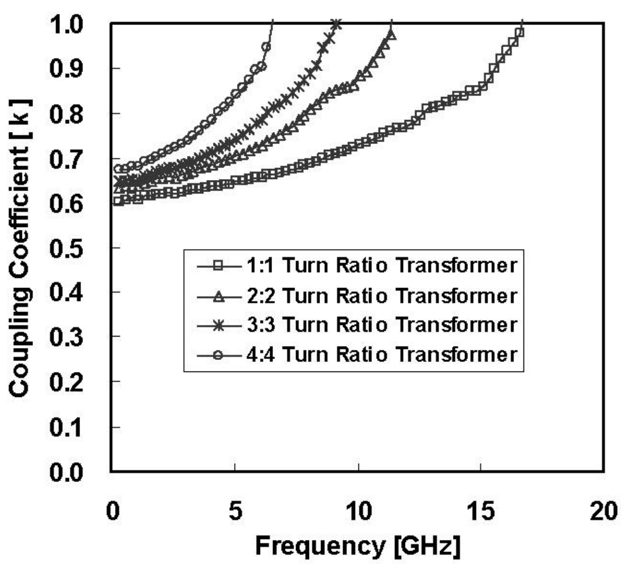


Fig. 3. Measured coupling coefficient, k-factors of 3-D transformers with n:n (n=1,2,3,and 4) turn ratio. Transformers in this table have 350μm diameter, 45um metal width and 4.0μm electroplated Au thickness.

Coupling coefficient is merely defined for a lumped transformer where the mutual inductance is a single element connecting two lumped inductors. An actual 3-D transformer is a distributed device with distributed mutual inductance. Therefore, the concept of coupling coefficient at high frequency is not valid for 3-D transformers. A better performance indicative especially for 3-D RF transformers would be the transformer power efficiency P_{out}/P_{in} (see eq. (2)). Fig. 4 shows the measured power efficiency, P_{out}/P_{in}, extracted from the S-parameters for n:n (n=1,2,3,and 4) turn ratio transformers fabricated on high resistivity Si substrate. As can be seen from this figure, A 1:1 turn ratio transformer with coupling factor, k of higher than 0.6 has a power efficiency, P_{out}/P_{in} over 70% up to 20GHz. For 4:4 turn ratio transformer, a coupling coefficient, k is 0.84 at 5 GHz, with P_{out}/P_{in} over 75% up to 20GHz.

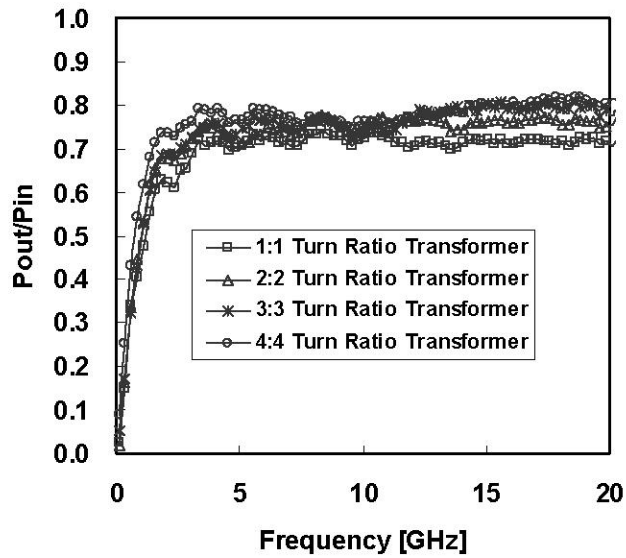


Fig. 4. Measured power efficiency, P_{out}/P_{in} of 3-D transformers with n:n turn ratio (n=1,2,3,and 4). Transformers in this table have 350μm diameter, 45um metal width and 4.0μm electroplated Au thickness.

Table 1 summarizes the coupling coefficient and power efficiency of several transformers fabricated on high-resistivity Si substrate using this technology. The data is extracted from the S-parameter measurement according to eqs. (1) and (2).

We have also employed Ansoft HFSS to simulate 3-D helical RF transformers with various turn ratios. The simulation verifies the trend observed in measurement. Fig 5 shows the results of simulated and measured coupling coefficient and power efficiency of 2:3 turn ratio transformers on high-resistivity Si substrate. As can be seen from the figure simulated data matched well with measured data.

Table 1. Coupling coefficient and power efficiency of 3-dimensional transformers calculated from S-parameters measurement. Transformers in this table have 350μm diameter, 45um metal width and 4.0μm electroplated Au.

Turn Ratio	k-factor @5GHz	P_{out}/P_{in} @5GHz
1:1	0.65	70.7 %
1:2	0.70	71.0 %
2:2	0.71	71.3 %
2:3	0.74	71.6 %
3:3	0.76	71.8 %
3:4	0.81	73.0 %
4:4	0.84	76.6 %

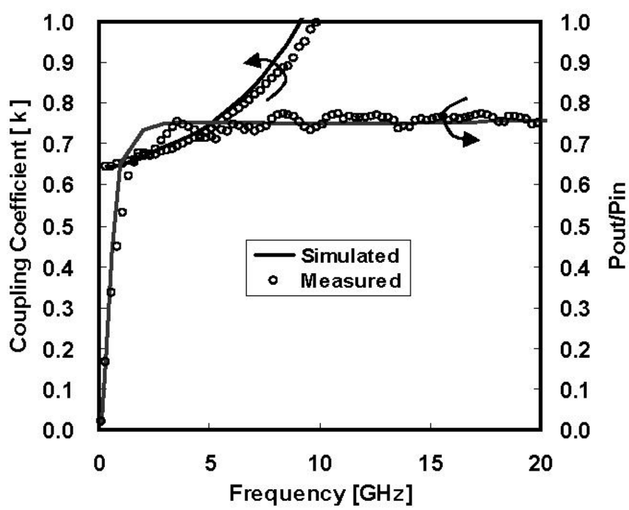


Fig. 5.Simulated and measured coupling coefficient and power efficiency of a 2:3 turn ratio transformer. Transformers in this table have 350μm diameter, 45um metal width and 4.0μm electroplated Au thickness.

IV. CONCLUSION

Various three-dimensional RF transformers were fabricated on high-resistivity (10 KΩ·cm) Si substrate. These transformers exhibited high coupling coefficient, k-factor and high power efficiency, P_{out}/P_{in} up to very high frequencies. Unlike planar transformers reported in literature, 3-D transformers achieve very wideband operation (up to 20GHz for transformers with dimensions reported here). The availability of integrated 3-D RF transformers with high k-factor and high power efficiency will open up new design directions for RF and microwave integrated circuits.

ACKNOWLEDGEMENT

This work is supported by DARPA Technology for Efficient and Agile Microsystems (TEAM) DAAB07-02-1-L430.

REFERENCES

[1] Christopher L. Chua, et al. "Out-of-plane high-Q inductors on low-resistance silicon" *J. Microelectromech. Syst.*, vol. 12, pp. 989-995, Dec. 2003.

[2] J.J. Zhou and D.J. Allstot, "Monolithic transformers and their application in a differential CMOS RF low-noise amplifier" *IEEE Journal of Solid-State Circuits,* Volume 33, Issue 12, Dec. 1998, pp. 2020 – 2027.

[3] J.R. Long and M.A. Copeland, "A 1.9 GHz low-voltage silicon bipolar receiver front-end for wireless personal communications systems", *IEEE Journal of Solid-State Circuits* Volume 30, Issue 12, Dec. 1995, pp.1438 – 1448.

[4] L. Selmi and B. Ricco, "Design of an X-band transformer-coupled amplifier with improved stability and layout" , *IEEE Journal of Solid-State Circuits*, Volume 28, Issue 6, June 1993, pp. 701 – 703.

[5] J.R. Long, "Monolithic transformers for silicon RF IC design" , *IEEE Journal of Solid-State Circuits,* Volume 35, Issue 9, Sept. 2000, pp. 1368 – 1382.

[6] S.S. Mohan, C.P. Yue, M.D.M. Hershenson, S.S. Wong, and T.H. Lee, "Modeling and characterization of on-chip transformers" *IEEE Int. Electron Devices Meet. Tech. Dig.* Dec. 1998, pp.531 – 534.

[7] R. Smith, Circuit, Devices & Systems, Wiley & Sons,1971

[8] Haitao Gan, "On-chip transformer modeling, characterization, and applications in power and low noise amplifiers," Ph.D. Thesis, Stanford University, 2006.

[9] Dae-Hee Weon, Jeong-Il Kim, Jong-Hyeok Jeon, Saeed Mohammadi, and Linda P. B. Katehi, "High Performance 3-D Micro-Machined Inductors on CMOS Substrate," *Microwave Symposium Digest, 2005 IEEE MTT-S International,* Volume 2, 12-17 June 2005 pp.701 – 704.