Modeling and Synthesis of On-chip Multi-layer Spiral Inductor for Millimeter-wave Regime Based on ANN Method

Cheng Cao[1,2], Yajing Hou[1,2], Jiangfan Liu[1,2], Xiuping Li[1,2]

[1] *School of Electronic Engineering, Beijing University of Posts and Telecommunications*
100876, Beijing, China

[2] *Beijing Key Laboratory of Work Safety Intelligent Monitoring*
xpli@bupt.edu.cn

***Abstract*—We present a multi-layer inductor implemented in 0.13 μm one-poly and seven-metal (1P7M) BiCMOS SiGe process. Self-resonance frequency (SRF) beyond 100GHz and high quality factor (Q) were obtained based on the measurement results, demonstrating that the multi-layer inductor is suitable for millimeter wave applications. Meanwhile, a modified equivalent circuit model for the multi-layer inductor is introduced. A multilayer perceptron (MLP) feedforward artificial neural networks (ANNs) is presented, which has been designed for computationally electromagnetic (EM) simulation and applied to predict the inductance characteristics.**

***Index Terms*—Multi-layer spiral inductor, equivalent circuit model, millimeter-wave, artificial neural network.**

I. Introduction

With rapid development of consumer electronics market, the development of on-chip passive devices for radio frequency integrated circuits (RFICs) has emerged as a critical issue for typical millimeter-wave applications. On-chip spiral inductors are particularly important and extensively used in RFICs such as power amplifiers, low-noise amplifiers, and oscillators to improve the performance of the systems. Unfortunately, the spiral inductors fabricated using the CMOS/BiCMOS process suffer from silicon substrate loss which degrading their Q-factors due to the the relatively low resistivity of silicon (in comparison with GaAs). Therefore, realizing high-Q on-chip spiral inductors in the silicon based process is one of the major challenges for RF researchers. Besides the Q factor, the self-resonance frequency is also an important consideration for the on-chip inductors.

Much attention has been paid in recent years to investigate multi-layer inductor achieving high Q-factor and high self-resonant frequency simultaneously. Previous studies of multi-layer inductor have been presented in [1]. However, papers rarely mentioned the inductor structure in millimeter wave regime. Millimeter-wave features of short wavelength and high frequency bandwidth. So the applications in the millimeter-wave regime can achieve higher accuracy and large bandwidth allows for higher resolution.

Artificial neural networks (ANNs) have emerged as an efficient tool in microwave modeling and design, such as antenna synthesis [2], on-chip inductor modeling [3], electromagnetic optimization [4], and dynamic modeling of nonlinear microwave circuits [5]. ANNs learn training set through the training process and the trained neural networks can generating a function to describe arbitrary and complex nonlinear relationships between the model inputs and outputs. When properly trained with reliable learning data, the artificial neural network can perform computation more efficient than an exact EM simulator. Meanwhile it can obtain higher accuracy than a model based on physics analysis.

The paper is organized in the following way. In Section II, the structure of proposed multi-layer inductor and its modified equivalent circuit model are presented. The proposed ANNs to predict the inductance characteristics is described and discussed in Section III. Finally, conclusions are drawn in Section IV.

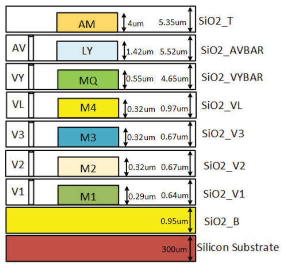
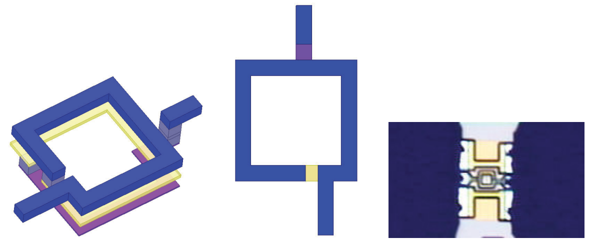


Fig. 1. metal layer structure of 0.13 μm SiGe BiCMOS.

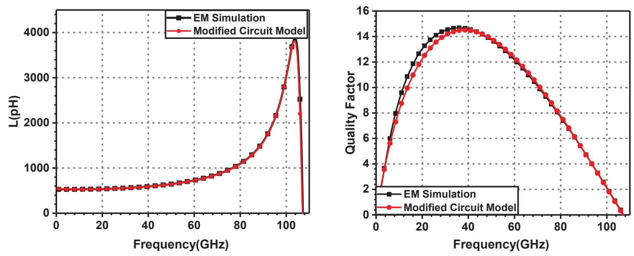
II. Multi-layer Inductor and its Equivalent Circuit Model

A novel compact on-chip multi-layer inductor is designed to achieve high self-resonance frequency and high Q-factor. The structure of multi-layer inductor is fabricated in 0.13 μm SiGe BiCMOS technology, which has seven metal layers, as illustrated in Fig.1. To simplify the design and achieve good performance, the first top three metal layers are utilized to design multi-layer inductor. The thick metal layer can minimize ohmic loss and substrate parasitic effects. The AM, LY, MQ layer thickness are 2 μm, 1.42 μm and 0.55 μm, respectively, and the top three spirals are connected by vias each other. In this structure, the electric current flows in the same direction along the spiral traces, resulting in higher mutual inductance. Thus, the proposed multi-layer inductor have a higher inductance compared with the single spiral inductor. Fig. 2 shows the top view of the inductor, where



(a) (b) (c)

Fig. 2. proposed one single spiral multi-layer inductor (a) Three dimensional view. (b) Top view. (c) Fabricated multi-layer inductor with PAD.



(a) (b)

Fig. 4. Comparison of inductance characteristics between equivalent circuit model and EM simulation.(a) Q factor. (b) L.

the metal width (W), and diameter (D) are 5 μm, and 29 μm, respectively.

The modified equivalent circuit model [6] for an on-chip multi-layer spiral inductor is shown in Fig. 3, one single-pi circuit with is connected in cascade with another enhanced single-pi equivalent circuit and M is the mutual inductance between the two spirals. Here, the upper and lower spirals are nearly identical and $M = k\sqrt{L_{s1}L_{s2}}$ denotes the coupling coefficient, with 0<k<1. In series branches of the equivalent circuit [7], L_{si} and R_{si} (i = 1,2) represent the desired inductances and series resistances, respectively. The RL ladder composed of L_i and R_i (i = 1,2) is augmented in parallel with R_{si} to capture the increase of the series resistance due to skin and proximity effects as the frequency increases. Co models the captive coupling capacitance between the input and output ports, C_{pi} (i = 1,2) represents the coupling capacitance between the adjacent metal tracks. The substrate parasitics are modeled by C_{oxi}, C_{subi} and R_{subi}, with C_{oxi} representing the capacitance between the metal spiral and substrate, whereas C_{subi} and R_{subi} representing the substrate capacitance and resistance, respectively. Fig.4 shows the validity of the proposed equivalent circuit of multi-layer. Simulations based on the equivalent circuit fit well with the EM simulation. The proposed model can characterize Q factor and L with good accuracy over a wide frequency range, where Q and L can be expressed as:

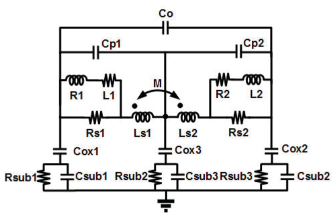


Fig. 3. Modified equivalent circuit model for multi-layer inductor

$$Q = \frac{-Im(Y_{11})}{Re(Y_{11})} \tag{1}$$

$$L = Im[1/(Y_{11})]/\omega \tag{2}$$

The S-parameters of the inductor have been measured using an Anritsu Vector network analyzer MS4647A with spread spectrum module 3743A which allows characterization up to 110GHz and Cascade Infinity ground-signal-ground probes. After de-embedding from the test pads [8], S-parameters can be obtained. The inductor characteristics such as the inductance, the quality factor, and other related parameters such as self-resonant frequency can be calculated based on the measurement data. Fig.5 shows the measured S-parameters and the core S-parameters of the multi-layer inductor after de-embedding.

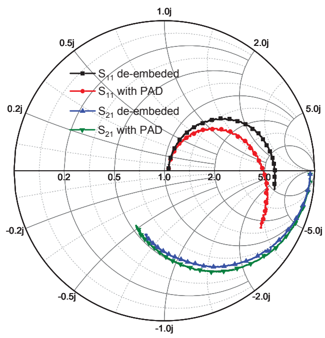


Fig. 5. Measured S-parameters.

III. Artificial Neural Networks for Multi-Layer Inductor

The multilayer perceptron (MLP) feedforward network is a widely applied neural network structure. A multilayer neural network diagram is shown in Fig. 6. The MLP structure consists of three parts: an input layer, one or more hidden layers, and an output layer. The MLP feedforward network is composed of computing nodes termed neurons. The neurons in each layer are connected to those in the next layer by weighted edges. Each neuron forms a weighted sum of its inputs which is passed through a nonlinear activation function. In general, the hidden layers can model the complex relationships between multiple inputs and multiple outputs. Typically, the more complicated the nonlinear behavior is, the more hidden layers and neurons will be need. Given the input vector $\vec{x} = (x_1, x_2, ..., x_m)^T$, the output vector $\vec{y} = (y_1, y_2, ..., y_k)^T$ of a typical three layer MLP neural network can be given by:

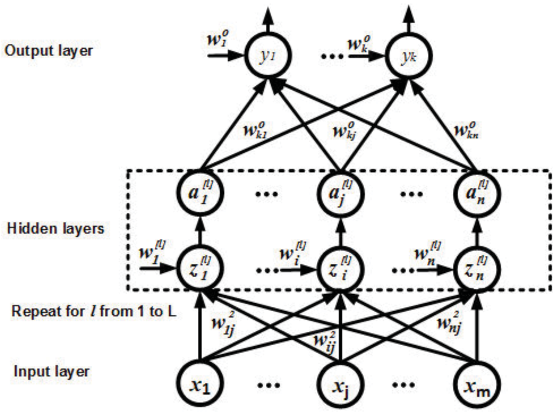


Fig. 6. The general MLP neural network structure.

$$y_k = f(w_k^o + \sum_{i=1}^{n} w_{ki}^o f(w_i^{[1]} + \sum_{j=1}^{m} w_{ij}^2 x_j)), k = 1, 2...N \quad (3)$$

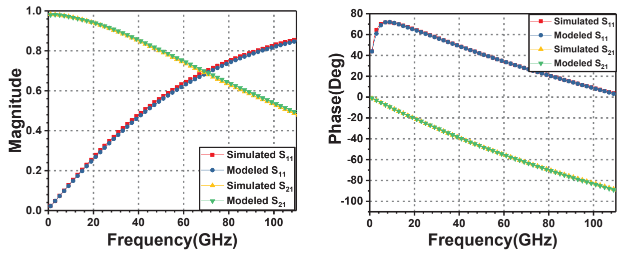
The hyperbolic tangent activation $f(\cdot)$can be expressed as:

$$tanhx = \frac{sinhx}{coshx} = \frac{e^x - e^{-x}}{e^x + e^{-x}} \quad (4)$$

Typically, when the ANNs is used for inductor design, the inductor geometry parameters are used as inputs to the ANNs. We consider two inductor-layout parameters, namely, diameter (D) and metal width (W) as the input to the neural model. The output is the set of computed S-parameters for the respective inductor at specified frequency point. We use three hidden layers with 10 neurons each, and hyperbolic tangent activation function for hidden layers and the output neurons. The training data was generated by performing ANYSYS HFSS EM simulation over a frequency range of 1GHz to 110GHz with 110 sampled points. Diameter (D) and metal width (W) varies from 3.1 μm to 15.1 μm in step value of 0.4 μm, 20.1 μm to 40.1 μm in step value of 0.4 μm respectively. This set of S-parameters constituted the training set to describe the nonlinear relationship between the inductor model.The test inductor was designed to exhibit different D and W, with values not included in the training set. Fig.7 shows the comparison between the data trained from the ANN model and the EM simulated data for the multi-layer inductor with D=29 μm, W=5 μm. Good agreement is obtained between simulated data and proposed model results over the frequency range of 1GHz to 110GHz.

IV. Conclusion

In summary, we have proposed an equivalent circuit model for on-chip multi-layer spiral inductors to characterize silicon on-chip multi-layer spiral inductors with an asymmetrical layout, which takes into account high-order parasitic effect such as skin and proximity effects and coupling effect in the substrate. Verification with measurement data from the multi-layer spiral demonstrates the validity of this model. In this paper, an ANN-based method has been proposed to predict the inductance characteristics. All the output parameters of the neural model show good matching over the entire frequency range of interest when compared with the data generated by an EM simulator. Consequently, the ANN method presented in this paper is a useful method that can be a useful tool for the design and optimization of practical on-chip multi-layer spiral inductors.



(a) (b)

Fig. 7. Comparison of S-parameters between ANNs model and EM simulation (a) Magnitude of S-parameters (b) Magnitude of S-parameters.

Acknowledgment

The authors gratefully acknowledge the support of project 61601050 from the National Natural Science Foundation of China (NSFC) and 6140518040116DZ02001 from the E-quipment Development Department of the Central Military Commission of China. The authors also extend special thanks to National Institute of Metrology (NIM) for measurement assistance.

References

[1] W. Y. Yin, S. J. Pan, L. W. Li, and Y. B. Gan, "Modelling on-chip circular double-spiral stacked inductors for RFICs," *IEEE Proceedings - Microwaves, Antennas and Propagation*, vol. 150, no. 6, p. 463, 2003.

[2] H. Aliakbari, A. Abdipour, A. Costanzo, D. Masotti, R. Mirzavand, and P. Mousavi, "ANN-based design of a versatile millimetre-wave slotted patch multi-antenna configuration for 5G scenarios," *IET Microwaves, Antennas and Propagation*, vol. 11, no. 9, pp. 1288-1295, 2017.

[3] S. K. Mandal, S. Sural, and A. Patra, "ANN- and PSO-Based Synthesis of On-Chip Spiral Inductors for RF ICs," *IEEE Transactions on Computer-Aided Design of Integrated Circuits and Systems*, vol. 27, no. 1, pp. 188-192, 2008.

[4] S. Piersanti and A. Orlandi, "Genetic Algorithm Optimization for the Total Radiated Power of a Meandered Line by Using an Artificial Neural Network," *IEEE Transactions on Electromagnetic Compatibility*, vol. 60, no. 4, pp. 1014-1017, 2018.

[5] Y. Ko et al., "Artificial Neural Network Model of SOS-MOSFETs Based on Dynamic Large-Signal Measurements," *IEEE Transactions on Microwave Theory and Techniques*, vol. 62, no. 3, pp. 491-501, 2014.

[6] F. Huang, J. Lu, N. Jiang, X. Zhang, W. Wu, and Y. Wang, "Frequency-Independent Asymmetric Double-π Equivalent Circuit for On-Chip Spiral Inductors: Physics-Based Modeling and Parameter Extraction," *IEEE Journal of Solid-State Circuits*, vol. 41, no. 10, pp. 2272-2283, 2006.

[7] C. Yu et al., "Frequency-independent equivalent-circuit model for on-chip spiral inductors," *IEEE Journal of Solid-State Circuits*, vol. 38, no. 3, pp. 419-426, 2003.

[8] B. Han, Y. Song, Z. Wang, J. Li, and X. Shi, "Verification of transmission line de-embedding method for on-chip spiral inductor based on electromagnetic simulation," *International Journal of Numerical Modelling: Electronic Networks, Devices and Fields*, vol. 29, no. 4, pp. 686-694, 2016.