Microstrip Inductor Design and Implementation

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Abstract ─ High frequency (HF) microstrip spiral inductor design using analytical formulation with network model and numerical simulation with planar electromagnetic simulator, Sonnet, are given for high power RF application. The simplified lumped element equivalent network model parameters for the spiral inductor are used to obtain the initial dimensions of the spiral inductor for simulation. The spiral inductor is then simulated with planar electromagnetic simulator, Sonnet, using the geometry constructed with the physical dimensions obtained from the network model for the desired inductance value. The parametric study of the spiral inductor is conducted to investigate the variation on its quality factor, self resonance frequency and inductance value. The spiral inductor is implemented on a ceramic substrate and measured. The measurement, simulation, and analytical results are found to be close.

Index Terms ─ HF, inductor, microstrip, RF, spiral.

I. INTRODUCTION

Spiral type planar inductors are commonly used in communication systems as a component due to several of their benefits and practical implementation. Spiral inductor design at microwave frequencies in the literature [1-11] is extensively investigated and equivalent models have been reported when the spiral inductor is implemented on a silicon material [12-13] or gallium-arsenide (GaAs) [14-16]. However, the lack of literature in the design of spiral inductors at HF (3MHz –30MHz) range for RF applications constitutes an important problem for high power RF applications. HF is commonly used in submarine communication, semiconductor wafer processing, and plasma applications. Spiral inductors, specifically for these applications, must be able to operate under very high power conditions. Under such high power, spiral inductors should exhibit reliable thermal profile, desired inductance value and low loss. If these characteristics are not demonstrated, changes in the component value can cause catastrophic failures in the RF systems. Accurate design technique, with reliable thermal operation using thermally highly conductive and electrically low loss material, can provide optimum spiral inductor operation.

In this paper, simplified and accurate design method for the spiral inductor is presented using network model for high power RF applications. The model is used to obtain the physical dimensions of the spiral inductor for the desired inductance value. The physical dimensions are then used to construct the geometry in the planar electromagnetic simulator, Sonnet. Planar electromagnetic simulator, Sonnet, is also used to characterize the spiral inductor with the parametric study by varying the trace width and spacing between traces. The parametric study is used to understand the effect of these parameters on the quality factor, inductance value, and self resonance frequency of the inductor. Spiral inductor is then built using alumina substrate and measured. The analytical, simulation, and measurement results are found to be close. The analytical model, proposed in this paper, is, also, used to study the effect of the physical dimensions and number of turns on spiral inductance value, quality factor, and the resonant frequency. Their effects on critical spiral inductor design parameters are detailed.

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II. ANALYTICAL FORMULATION

The layout of the general microstrip rectangular spiral inductor is illustrated in Fig. 1. In this layout, w represents the width of the trace, l_1 and l_2 are the length of the outside edges, s is the spacing between the traces. It is assumed that the substrate material is alumina (Al_2O_3) with thickness h. The accurate modeling of the spiral inductor at HF range can be done using the π network shown in Fig. 2. In the π network, total inductance, coupling capacitances, substrate capacitance, are all taken into account. The capacitance of the spiral inductor is calculated using the effect of odd mode, even modes. This approach gives more realistic results for the physical representation of the spiral inductor.

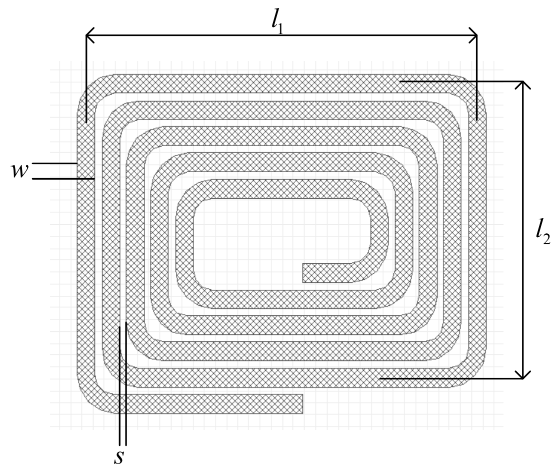

Fig. 1. Microstrip model of the spiral inductor.

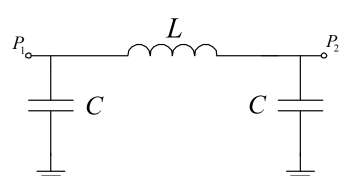

Fig. 2. Lumped-element model for spiral inductor.

In the lumped element model, L represents the total inductance value. The accurate inductance calculation at the HF range can be obtained using Greenhouse's method described in [17]. The total inductance of the spiral inductor including the effect of mutual couplings is given as

$$L = L_0 + \Sigma M \quad . \tag{1}$$

L_0 is the sum of the self inductances for each trace. ΣM takes into account of all mutual inductances in the structure. Equation given in (1) can be written more explicitly for any number of turns for a rectangular spiral inductor as

$$L_i = 0.0002 l_i \left[\ln\left(2\frac{l_i}{GMD} \right) - 1.25 + \frac{AMD}{l_i} + \frac{\mu}{4} T \right] \tag{2}$$

and

$$M_{ij} = 0.0002 l_i Q_i \, . \tag{3}$$

AMD is the arithmetic mean distance and GMD is used for the geometric distance. C is the capacitance that include the effect of odd mode, even mode and interline coupling capacitances between coupled lines of the spiral inductor. The detailed calculation of the capacitances is given in [18]. The substrate losses and conductor losses are ignored due to the low operational frequency.

One port measurement network for the spiral inductor using the model proposed in Fig. 2 is shown in Fig. 3 below

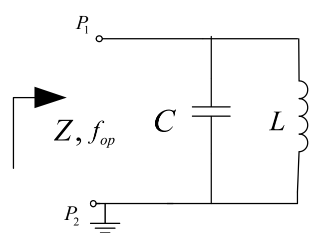

Fig. 3. One port measurement circuit.

The physical dimensions of the microstrip spiral inductor are given in Table 1. All the dimensions are given in mils.

Table 1: Physcial dimensions of the spiral inductor

Trace Width w	Spacing s	Horizontal Trace Length l_1	Vertical Trace Length l_2	Copper Thickness t	
80	30	1870	1450	4.2	
Dielectric Material	**Dielectric Permittivity** ε_r	**Dielectric Thickness** h	**Number of Turns** n	**Bridge Height** h_b	**Bridge Width** w_b
Al_2O_3	9.8	100	6.375	100	350

The inductance value of the spiral inductor using analytical model with the dimensions in Table 1 is calculated to be 590nH with the algorithm developed. In addition to the calculation of the spiral inductance value, we used our analytical model to study the effect of trace width, spacing, loop area and number of turns on inductance value, quality factor, and resonant frequency. This is accomplished by including the conductor and dielectric losses in the simplified analytical model. The conductor loss is modeled as series resistance R with inductance L and given by

$$R = \frac{2}{w}\sqrt{\frac{\pi f \mu_c}{\sigma}} \quad [\Omega / m], \tag{4}$$

where μ_c and σ are the permeability and conductivity of the conductor used as trace. The substrate loss is modeled as R_p and given by

$$R_p = \frac{\rho\, l}{wh} \quad [\Omega / m], \tag{5}$$

where h is the thickness of the substrate and ρ is given as $\rho = 0.01[\Omega \cdot m]$ for Al_2O_3. Table 2 below illustrates the calculated values of the critical spiral design parameters such as inductance, quality factor, and resonant frequency by varying trace width, outer edge dimensions signifying the change in the loop area, spacing, and number of turns.

Table 2: Study of physical dimensions

	Analytical							
	w	**s**	**l1**	**l2**	**Turns**	**L**	**Q**	**Fr**
Unit	mils	mils	mils	mils		nH		MHz
Orig. Ind	80	30	1450	1870	6.5	590.05	68.73	29.73
Mod 1	**60**	30	1450	1870	6.5	958.84	34.21	27.15
Mod 2	80	**20**	1450	1870	6.5	734.6	47.18	29.48
Mod 3	80	30	**1880**	**2411**	6.5	1243	12.87	20.27
Mod 4	80	**10**	1450	1870	**7.5**	1075	10.94	19.75

It has been seen that the higher inductance value can be obtained by reducing the width of the trace, reducing the spacing between the traces, increasing the number of turns and reducing the spacing, or increasing the loop area of the inductor by changing the outer edge dimensions. Although each of these changes increases the inductance value of the spiral inductor, it has to be noted that they have several undesired side effects. In every change, unless some other change is implemented for compensation, the quality factor and the resonant frequency of the inductor are reduced. The intensity of the reduction varies based on the change implemented. Specifically, for high power applications, the higher quality factor is needed and it guarantees better thermal management during operation. Thermally better designed spiral inductors give resonant frequencies at least three times higher than their operational frequencies. The specific spiral inductor designed in this paper is used as part of power amplifier and capable of handling more than 100W. Commercially available spiral inductors can only handle very low power levels and cannot be used for high power applications. In addition, the trace width and spacing should be designed to handle the amount of the current flow and the potential occurring between the traces. As a result, the analytical method proposed in this paper can be used to design and implement spiral inductors for high power RF applications reliably and accurately.

III. MEASUREMENT AND SIMULATION RESULTS

The spiral inductor using the dimensions in Table 1 is simulated with the method of moment based planar electromagnetic simulator Sonnet. The operational frequency is chosen to be 13.56MHz. The 3D layout of the simulated structure is illustrated in Fig. 4. The input port or port 1 is connected via bridge for inductance measurement. The bridge height and width are given in Table 1. The effect of the bridge at the frequency of the operation is minimal due to its increased width.

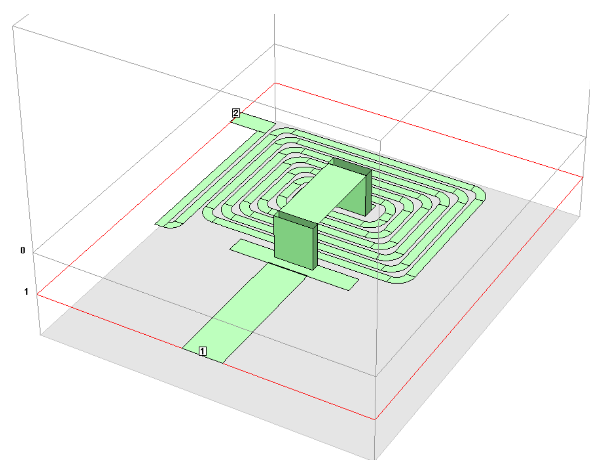

Fig. 4. 3D model of the simulated spiral inductor.

The traces as seen in Fig. 4 are segmented for parametric study to understand the effect of width and spacing on the self resonant frequency and the quality factor of the spiral inductor. One of the unique features of the planar electromagnetic simulator is the visualization of the current distribution on the spiral structure. This is specifically important for high power applications to adjust the necessary spacing between traces to prevent any possible arcs during the operation. As seen from Fig. 5, the current density on the bridge which is designed to have minimal impact on the device performance and overall inductance is lowest. The current density increases as it gets closer to the edges of each trace. It becomes maximum at the edges. This is why during the implementation of the spiral inductor the corners are rounded to increase the creepage distance to prevent potential arcs.

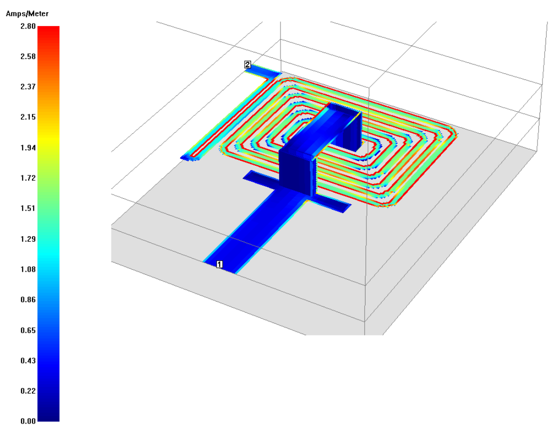

Fig. 5. Current density of the spiral inductor.

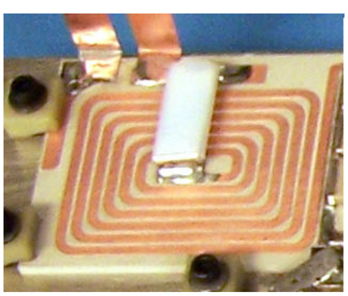

Fig. 6. Spiral inductor is constructed on 100 mil alumina substrate.

The inductance value of the spiral inductor is simulated and obtained as 588.6 nH at the operational frequency which is 13.56 MHz. The measured inductance value at this frequency is found to be 594.91 nH. The spiral inductor that is simulated and illustrated in Fig. 4 is built on 100 mil Al_2O_3 substrate as shown in Fig. 6. The higher inductance values can be obtained by increasing the number of turns, decreasing the width of the trace. The self-resonant frequency of the spiral inductor is found to be 37.8MHz. In spiral inductor design, rule of thumb is to have self resonant frequency approximately 3 times higher than the operational frequency which guarantees optimal operation. As a result, the self resonant frequency that is obtained is just below the desired value. The simulation results illustrating the inductance value and self resonant frequency is given in Fig. 7.

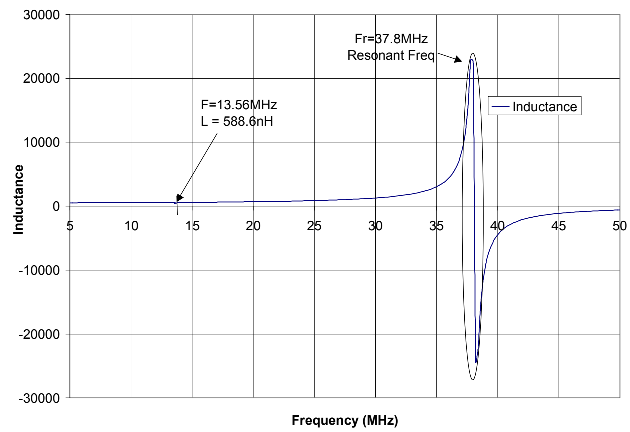

Fig. 7. Simulation results showing inductance value and resonant frequency of the spiral inductor.

The quality factor of the spiral inductor is found to be 72.6 at 13.56 MHz. As illustrated in Fig. 8, the quality factor reaches almost peak value at the operational frequency. At resonance, the quality factor is minimum as expected.

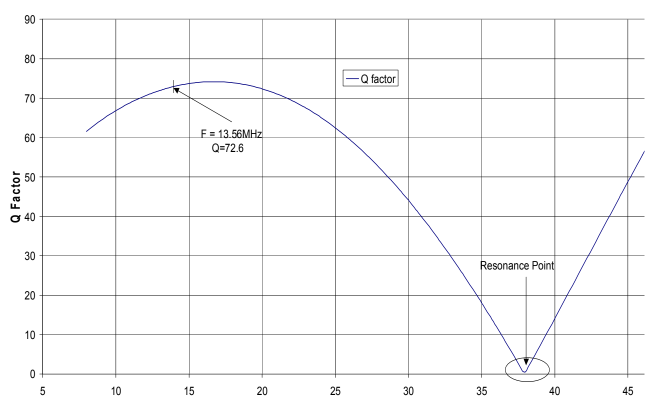

Fig. 8. Simulation results showing the quality factor of the spiral inductor.

Electromagnetic simulator, Sonnet, is used to understand the effects of spacing and width of the traces as mentioned before. It is found out that the self resonant frequency of the spiral inductor can be increased by increasing the trace width and reducing the spacing between each trace. The illustration of this is given in Fig. 9. In Fig. 9, the original width, which is 80mil, is compared with the optimized width, which is 94.32mil. The spacing in the original design is 30mils whereas the spacing in the optimized design is 15.68mil. The original self resonant frequency is increased to be greater than 50MHz with the proposed optimization.

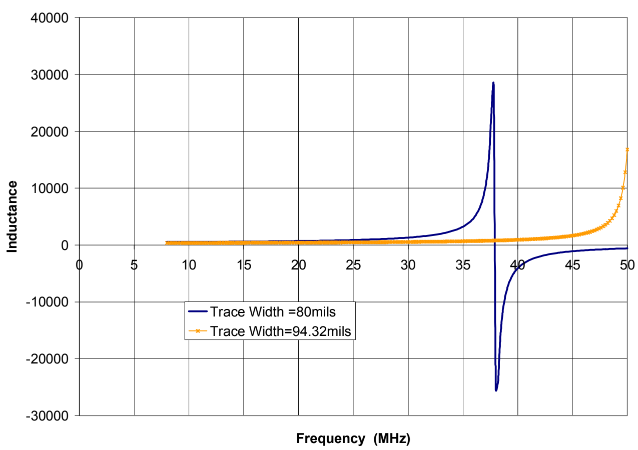

Fig. 9. Comparison of self resonant frequency of the spiral inductor.

Although, the self resonant frequency is increased to be greater than 50MHz, we need to investigate the effect of the changes that are done on the physical dimensions on the quality factor, return loss, insertion loss, and the inductance value of the spiral inductor to minimize the potential problems during operation. Figure 10 shows the comparison of the quality factor of the spiral inductor with original design and optimized design.

As shown in Fig. 10, the quality factor of the inductor is reduced to 68. This corresponds to 6.3% reduction in the quality factor value.

High quality factor is desirable to prevent any thermal problems during the operation of the device. Since, the substrate that is used has very high thermal conductivity with minimal substrate loss; the level of the reduction in the quality factor will not adversely effect the thermal profile of the spiral inductor. The change in the inductance value versus frequency when the physical dimensions are optimized to increase self resonant frequency is illustrated in Fig. 11.

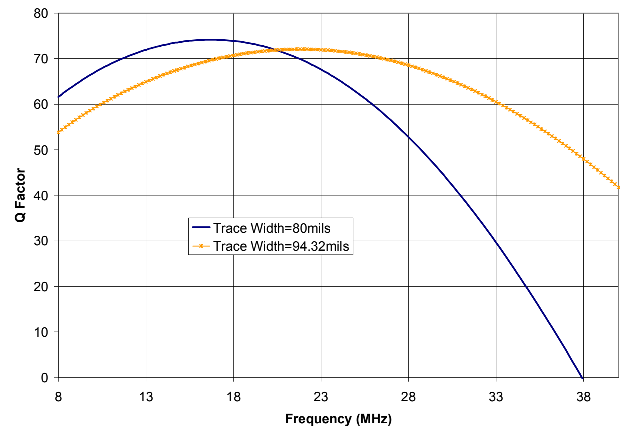

Fig. 10. Comparison of quality factor of the spiral inductor.

The changes that are implemented reduce the inductance value at the frequency of operation from 594.91nH to 390nH. This is approximately 34% reduction and is significant in comparison to the original inductance value. However, this can be compensated by a shunt capacitor that is connected

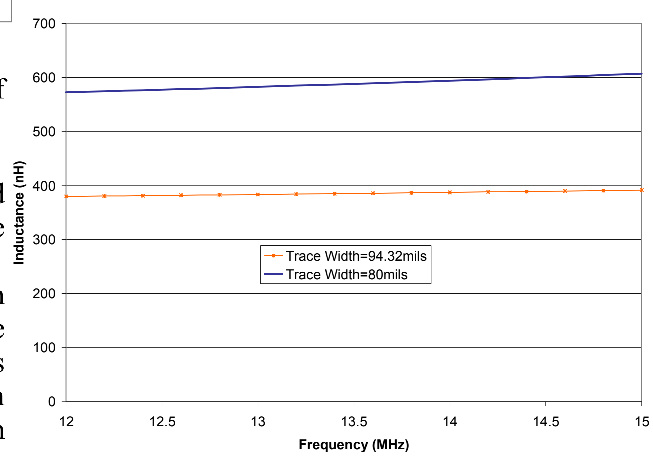

Fig. 11. Comparison of inductance value of the spiral inductor.

by a shunt capacitor that is connected between the ports of the spiral inductor. The capacitor that is required to bring 390nH up to 590.3nH is 120pF. This capacitor value is a standard value that can be easily found.

As a result, it has been shown that the spiral inductor can be optimized for the self resonant frequency using electromagnetic simulator with the proposed changes in the spacing and width of the traces without effecting the operation of the spiral inductor. The optimization on quality factor is, also, possible using the method outlined. In addition, the analytical model proposed in this paper can be used to accurately and reliably design spiral inductor for the desired inductance value, quality factor and the resonant frequency for high power RF applications at the HF range.

IV. CONCLUSION

Microstrip spiral inductors using the simplified equivalent circuit is designed, simulated, built, and measured at the HF range for high power RF applications. The measured, simulation, and analytical results are found to be very close. The parametric study of the spiral is conducted using planar electromagnetic simulator, Sonnet. It has been shown that the self resonant frequency of the spiral inductor can be increased by increasing the trace width and reducing the spacing between each trace. Increased self-resonant frequency is a very important feature for several RF applications to provide optimal operation like quality factor. The analytical method proposed in this paper is also used to study the effect of physical dimensions of the inductor including trace width, spacing, loop area, and number of turns on critical spiral inductor design parameters such as inductance value, resonant frequency, and quality factor. The results of this work can be used in RF applications at the HF range where high power is needed.

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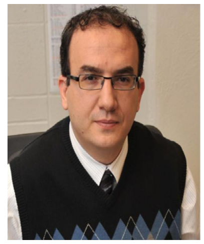

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