EFFECT OF METAL USED IN RESISTOR AND INDUCTOR DESIGN FOR MONOLITHIC MICROWAVE INTEGRATED CIRCUITS (MMIC) APPLICATIONS

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Abstract— **The work highlights the design, development and fabrication of passive element for MMIC application. Different type of metals such as Aurum (Au), Platinum (Pt), and Copper (Cu) were used in the design to confer the basic characteristic of inductor (L) and resistor (R) that have been used in MMIC. The design of inductor (L) and resistor (R) were in a single turn meander inductor of 4nH and thin film resistor of 50 Ω respectively, based on microstrip theory in order to explore their performances. Analysis of the prototype using vector network analyzer of meander inductor showed that the used of various conductor strip does not affect the values of inductance. Miniaturization of the inductor and resistor were achieved with the use of high-k substrate.**

I. INTRODUCTION

IN electronics, an integrated circuit that is also known as IC, microchip, silicon chip, or chip is a miniaturized electronic circuit which is consisting mainly of semiconductor devices, as well as passive components that has been manufactured in the surface of a thin substrate of semiconductor material. Microwaves monolithic integrated circuit (MMIC) is a microwave circuit in which one or more discrete microwave devices are mounted on a substrate and operate at microwave frequencies of 300 MHz to 300 GHz. MMIC device contains all of the active and passive circuit elements such as resistors, inductors and capacitors are fabricated in monolithic form on any substrates which is high dielectric and low dielectric [1].

In MIC technology, a thin film resistor is realized as a thin strip of lossy conductor on top of the dielectric substrate. The exposed resistive area defines the resistance of the structure. The resistive layer is a metal conductor which is depends on metal conductivity. In attendance, several types of inductors used commonly in MMIC such as circular spiral inductor, meander inductor, and rectangular spiral inductor. The choice of one or other type and number of turns depends on the inductance values which desired. Since the rectangular spiral inductor involves a more complicate process, therefore we choose to design a single turn meander inductor on top of the dielectric substrate.

This paper presents a design of a 50 Ω thin film resistor and 4nH single turn meander inductor using CAD tools. By using simulation the metal is changed as well as the dielectric substrate. To verify the 50 Ω thin resistor and 4nH single turn meander inductor is fabricated using Roger Duroid substrate. The measurement is demonstrated to compare with the simulation.

A. *Scope of Work*

This work highlights the design, development and certain fabrication of passive devices. In this project, the thin film resistor R and meander inductor L will be designed based on the basic equation of the respective model mentioned in the microstrip theory. Then the model will be designed and simulated using CAD tools and different types of metal and high substrate are introduced to investigate their performance at high frequency. The design were fabricate based on design structure of Rogers Duroid substrate. Fig.1 shows the flow chart of the overall process that involved in completing the task.

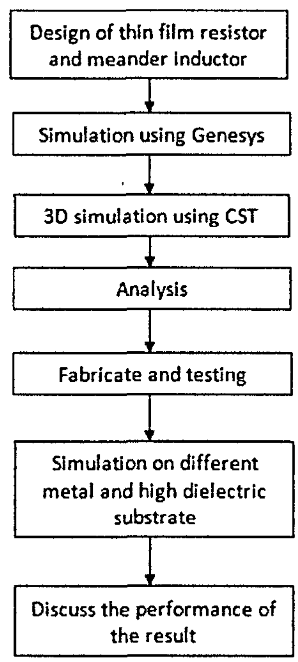


Fig. 1: Flow chart of the project

II. PASSIVE DEVICES MICROSTRIP THEORY

A. Thin Film Resistor

Basic geometry of thin film resistor is defined by sheet resistivity (Rs), length (L) and width (W) where the sheet resistivity is defined in unit ohm per square. Fig. 2 depicts the top view and equivalent circuit of thin film resistor.
Thin film resistor is represented by equation

$$R = Rs\ \frac{L}{W}$$

where Rs is sheet resistivity that calculates in ohms per square, L is the length of metal and W is width of metal. The sheet resistivity can be adjusted by controlling the thickness of the resistive layer. Therefore, the desired resistance of thin film resistor can be adjusted by controlling the length and width of the resistive layer to achieve the accurate thin film value [2].

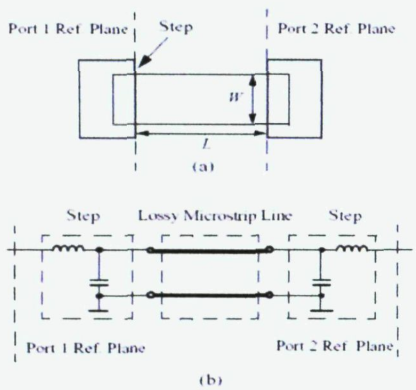


Fig.2 (a) Top view of thin film resistor, (b) Equivalent circuit of thin film resistor

B. Meander Inductor

Basic geometry inductor can be defined by length (*l*), thickness (t), strip spacing (s), width (w), and also the covered area. Fig. 2 illustrates the basic structure of meander inductor with geometric parameters and a simple equivalent lumped element circuit that involved in describing the meander line inductor devices characteristic where the RC represent the result of dielectric loss. For C represents the capacitance between 2 metals, L and Rl represent the ideal series inductor and series resistance [3]. Basic inductor is represented by equation

$$L = \frac{\mu o\ \mu r\ N^2\ A}{l}$$

where μo is permeability of free space, μr is permeability of relative material, N is the number of turns, A is the area of inductor and *l* is the total length of the inductor. Quality factor is calculated to determine the quality of an inductor. Higher quality factor will give the pure inductances. Quality factor or Q of a passive circuit element can be defined as

$$Q = \frac{\mathrm{Im}\,[Z_{\mathrm{in}}]}{\mathrm{Re}\,[Z_{\mathrm{in}}]} = \frac{X}{R} = \frac{\omega L}{R}$$

where Re [*Z*in] and Im [*Z*in] are the real and imaginary parts of the input impedance of the inductor, respectively [4].

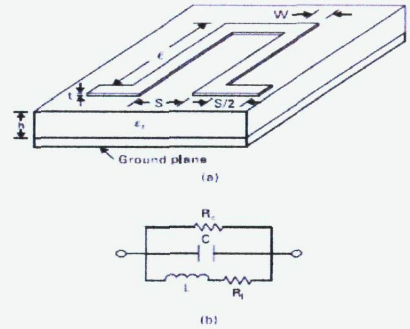


Fig.3 (a) Overview of meander inductor, (b) Equivalent circuit of meander inductor

III. DESIGN AND OPTIMIZATION

A. Simulation using CAD

Simulation of the thin film resistor and meander inductor are done by commercially CAD tools namely, *Genesys* and *CST*. The simulation is done for Roger Duroid substrate with different metal. Also, high-k substrate is introduced to observe the effect on the device.

a) Genesys Software

Fig. 4 (a), (b) and Fig. 5 (a), (b) depict the lumped element and geometric shapes of thin film resistor and meander inductor by using *Genesys* software respectively. The simulation is done to confer their characteristic by the circuit and the layout. 2D simulation is divided into two group of simulation based on different substrate material, namely low-k and high-k.

i. Low-k Simulation

Genesys software provides 2D simulation on thin film resistor and meander inductor on Rogers Duroid substrate. The dimension of the layout is obtained and tabulated in Table1 and Table 2. The layout is illustrated in Fig 4 (b) and Fig 5 (b) respectively.

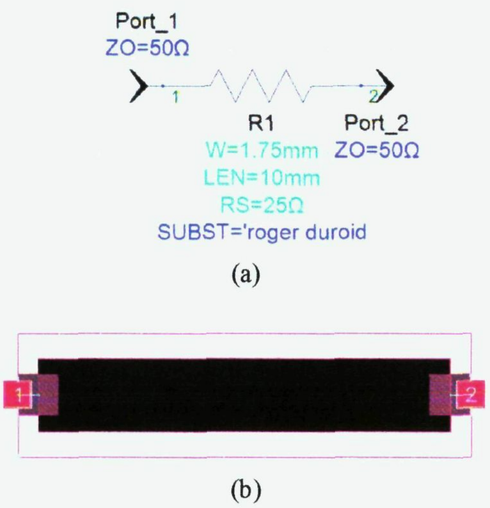
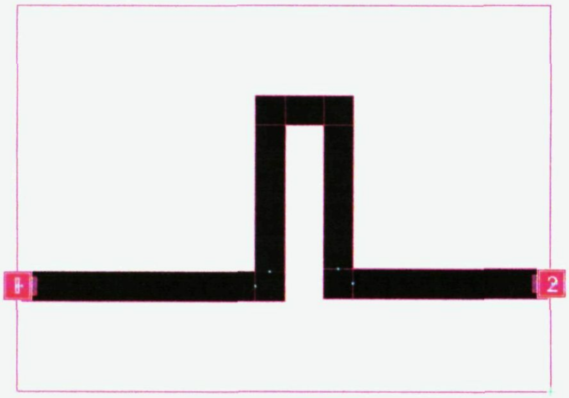


Fig. 4: Thin film resistor: (a) lumped element (b) layout of resistive layer

(a)

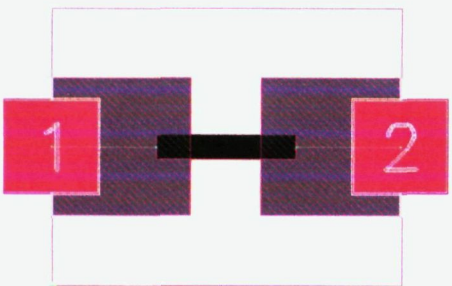


(b)

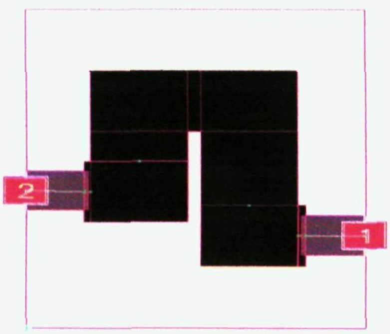
Fig. 5: Meander inductor (a) lumped element, (b) layout of metal on substrate

ii. High-k Simulation

High-k simulation is done by reducing the dimension to 90%. As tabulated in Table 1 and Table 2, the length is reduced to 90% compared to the Roger Duroid's dimension while maintaining the specification of resistor and inductor. The layout is illustrated in Fig 6 (a) and (b).



(a)



(b)

Fig 6: Layout of metal on substrate (a) Thin film resistor, (b) Meander inductor.

	Rogers Duroid Substrate (er=2.33)	High dielectric Substrate (er=100)
Sheet Resistivity	25 Ω per square	25 Ω per square
Length	10 mm	1 mm
Width	1.75 mm	0.175 mm

Table 1: Dimension of thin film resistor

	Rogers Duroid Substrate (er=2.33)	High dielectric Substrate (er=100)
Width	1.52 mm	1.52 mm
L1	12 mm	1.2 mm
L2	8 mm	0.8 mm
L3	7.5 mm	0.75 mm
L4	10 mm	1 mm
Strip Spacing	2 mm	0.2 mm

Table 2: Dimension of meander inductor

b) CST Software

CST software provides 3D simulation and also divided into two groups of simulation based on different substrate material, namely low-k and high-k.

i. Low-k Substrate

CST software provides 3D simulation on thin film resistor and meander inductor on Rogers Duroid substrate. Fig. 7 and Fig. 8 depict the 3D layout of thin film resistor and single turn meander inductor that is used in the simulation for low-k substrate. The dimension employed in *CST* software is based on the *Genesys* dimension using Roger Duroid substrate.

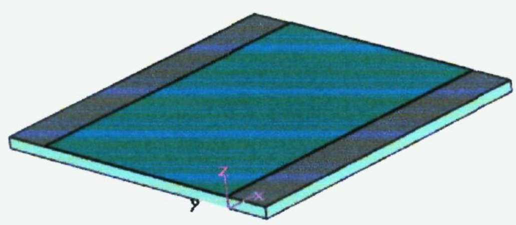


Fig.7: Thin film resistor in 3D

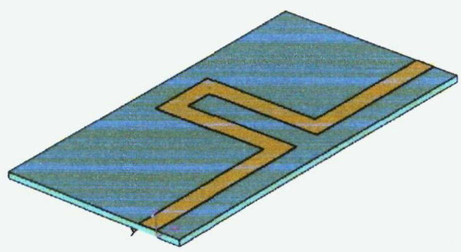
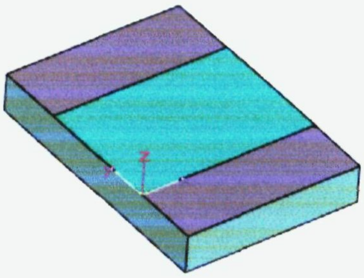


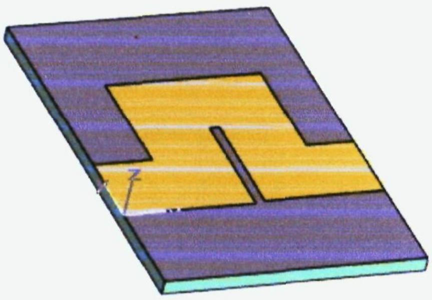
Fig.8: Meander inductor in 3D

ii. High-k Substrate

High-k simulation is done by reducing the dimension to 90%. As expected, the length is reduced to 90% compared to the Roger Duroid's dimension while maintaining the specification of resistor and inductor. The layout is illustrated in Fig 9.



(a)



(b)

Fig 9: Layout of passive devices in 3D on high dielectric substrate (a) thin film resistor, (b) meander inductor

IV. FABRICATION AND MEASUREMENT

Only the meander inductor is fabricated on Rogers Duroid substrate. Thin film resistor cannot be fabricated because of the sheet resistivity which required specific thickness of resistive layer in order to avoid maximum length and width. Meander inductor is fabricated by etching the Rogers Duroid substrate, then platting the aluminium for grounding, soldering the SMA connector for measuring with vector network analyzer (VNA). Fig.10 depicts the fabricated meander inductor.

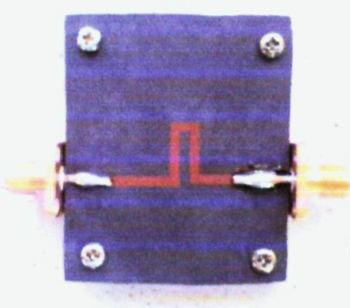
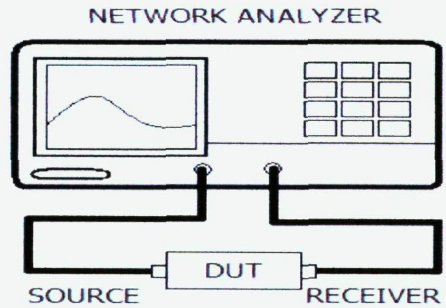


Fig. 10: Top view of fabricated meander inductor

The fabricated meander inductor is measured by using *Wiltron* vector network analyzer. The vector network analyzer is used to measure the S-parameters and impedance for the inductor. The vector network analyzer is calibrated in order to obtain an accurate measured value [5]. Fig.11 (a) and (b) depicts vector network analyzer (VNA) and the connection of device under testing (DUT) in measuring process.

(a)



(b)

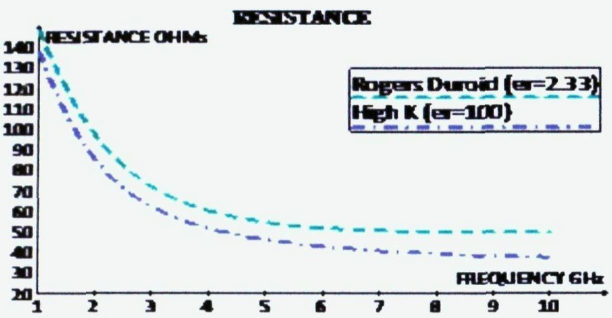
Fig. 11: (a) Wiltron vector network analyzer, (b) Connection device under test (DUT).

V. RESULTS AND DISCUSSION

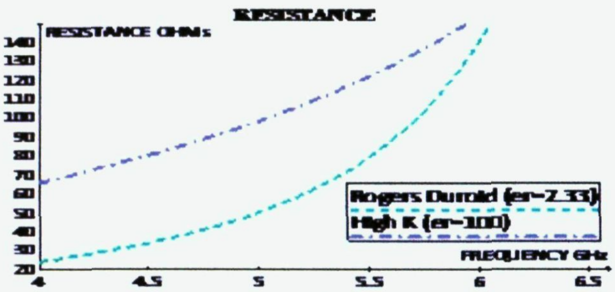
A. Thin Film Resistor

Based on the simulation result using *Genesys* software, the design of thin film resistor was expected to achieve 50 Ω constant from 1 GHz to 10 GHz. Conversely, the design and optimized thin film resistor has shown that the resistance decreased and remain constant as the frequency of operation is increased. For this reason, the constant value of 50 Ω can be obtained from 5 GHz to 10 GHz. The effects of resistivity behavior and skin depth are the cause of the changes value of resistance over frequency [6]. The lowest sheet resistivity also affected the resistance and the loads as the thin resistor begins to exhibit the behavior of a transmission line rather than a lumped element [1]. From the work of Zhenwen Wang and M. Jamal Deen, by introducing an empirical self-capacitance parameter too will give some effects in order to make an accurate and constant resistance over the frequency [7]. Otherwise, by changing the electrical resistivity (rho) and sheet resistivity (Rs) also, may cause the major effect to the resistance value [8].

On the other hand, high dielectric such as piezoelectric substrate (er=100) produce a different response in resistivity compared to the Rogers Duroid (er=2.33) substrate as illustrated in Fig.12. After optimizing the geometric shape such as length and width of resistive layer, the size were reduced about 90% in order to confer similar response of resistivity values.



(a)



(b)

Fig. 12 (a) Resistance over frequency by *Genesys* simulation, (b) Resistance over frequency by *CST* simulation.

B. Meander Inductor

Fig.13 shows the result of inductance based on measurement and simulation by *Genesys* and *CST*. The design of an inductor is expected to produce an inductor of 4nH at frequency of 4 GHz.

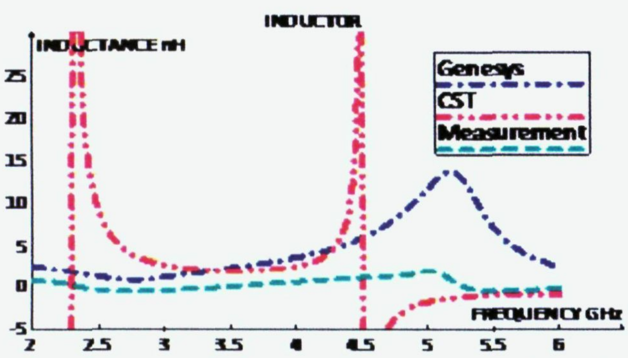


Fig.13: Inductance value based on measurement and simulation using CAD tools.

Q-factor of an inductance is extracted based on the equation mentioned in Section 2.0. Fig.14 depicts the result of the extracted Q-factor from the simulation and the measurement. As result, there are some losses occur between the simulation and measurement.

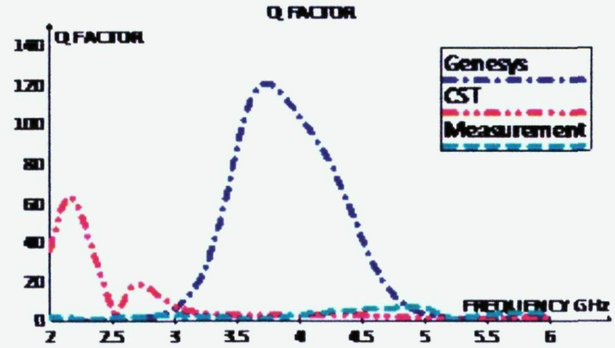


Fig.14: Q factor value based on measurement and simulation using CST

The measurement result of meander inductor is differed between the simulations and measurement. The reduction inductance values are caused by lack of packaging in fabrication process and the parasitic effect occurred in soldering and grounding. The prediction of L and Q is very complex due to interaction of magnetic fields with the structure of width, spacing, and number of turns. In short, the L and Q of meander inductor will produce lowest inductance and quality factor [3]. In this work, the design is one turn meander inductor; hence it is expected to produce lower inductance. Therefore, in order to design an inductor with best performance is by increasing the number of turns and the area of inductor which gives higher quality factor [1].

C. Effects of Different Metals on Substrate

Figure 14 depicts the result of CST simulation of meander inductor and Q factor with different metal on Rogers Duroid substrate. As a result, the resonance frequency of meander inductor is changed due to the different metals. The changes in inductance are expected because of the skin effect of the metal due to metal conductivity. Different conductivity affects the inductance value and its resonant frequency [3].

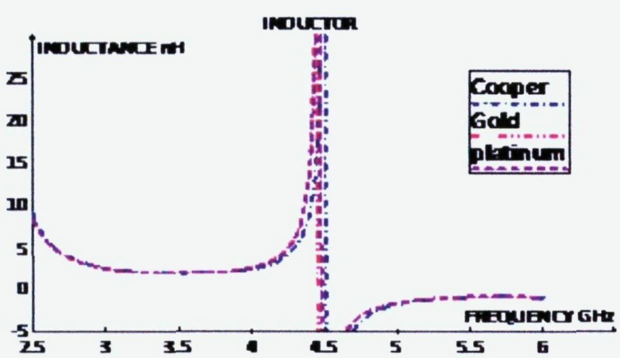


Fig.14: Inductance value due to different metals.

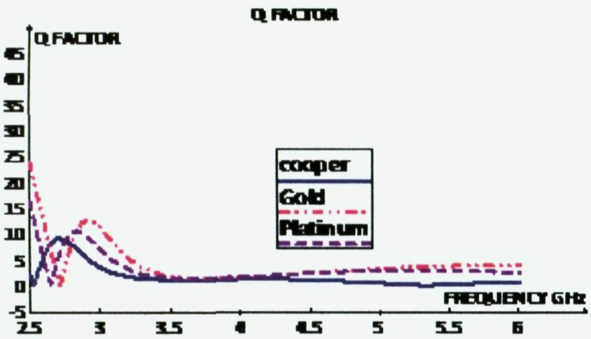


Fig.15: Quality factor value due to different metals.

By introducing different metals on meander inductor, the quality factor of inductor also affected as shown in Fig.15. In view of the fact that there are skin effect and parasitic effect due to fringing capacitance between the inductor metal and conductivity, it is the reason of the changes in quality factor and frequency resonance [4]. Therefore, the quality factor of inductors can be increased by reducing magnetically induced currents in the trace width by narrowing the line width [3].

D. Effects on Different Substrate

As the high dielectric substrate is introduced, the geometric shapes were expected to be miniaturized. From the optimized design, the physical shape of meander inductor is reduced about 90% in order to acquire the same inductance value as mentioned in Sec. III. Figure 16 shows the value of inductance and quality factor when introducing high dielectric substrate by simulation.

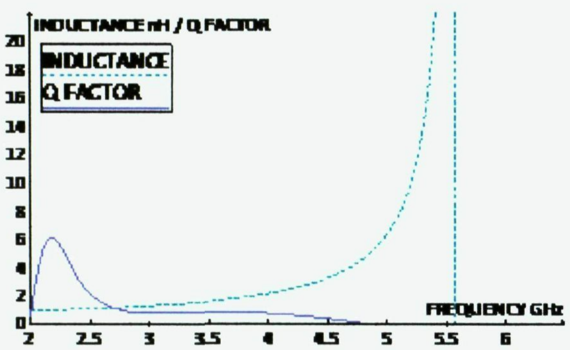


Fig.16: Value of inductance and Q factor in high dielectric substrate.

VI. CONCLUSION

To sum, 50 Ω thin film resistor and 4nH meander inductor was designed, developed and analyzed. By using simulation the metal is changed as well as the dielectric substrate. To verify the 50Ω thin resistor and 4nH single turn meander inductor is fabricated using Roger Duroid substrate. The measurement is demonstrated to compare with the simulation and discussed. The results have shown that there are some parasitic effects that occurred during measurement. This is because of the error in packaging during fabrication processes which caused high series resistance and it limits the passive devices performance. By employing high-k substrate, the design is achieved to be miniaturized and performed correspond to the characteristic of passive elements.

VII. FUTURE DEVELOPMENT

The resistor could be further miniaturized by using compound conductor strip as resistive layer which is have high electrical resistivity (rho). The values of the meander line inductor could be increased by increasing its number of turns (N). In order to increase the quality factor (Q) of meander inductor is by multilayer inductor. Otherwise, reducing the area of inductor can be done by using spiral inductor. The realization of the high-k passive devices could be done by using high-k substrates such as PZT.

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