Q-Factor Evaluation of Spiral Inductor for 5.8GHz WiMAX Application

Kama Azura Othman, *Member, IAENG;* Zuhani Ismail Khan, Siti Aminah Kadri, Norhayati Hamzah

Abstract— **New discovery material which contradicted in physic law known as metamaterial has been designed. It is the combination of the normal material (GaAs) with the unique structure. Computer Simulation Technology (CST) software has been used to design and simulate three-dimensional structure. Negative permittivity of material with split ring structure embedded in it has been used as a substrate for an inductor design. In a typical amplifier MMIC, up to 80% of chip area is occupied by inductors. Eagerness and inspired toward miniaturization, compact spiral inductors has been developed. These miniaturized inductors are constructed using a combination of three metal and three polyimide layers on a metamaterial substrate alternately. The area of multilayer inductor is almost four times smaller than planar design while maintaining same performance. The increasing number of layer, the performance of the inductor also improved. High performance of quality factor is the paramount desired with the consideration of losses.**

Index Terms **—Metamaterial, spiral inductor, permittivity, quality factor**

I. Introduction

PLANAR spiral inductors are widely used in monolithic microwave integrated circuits (MMICs) for commercial wireless communications. However, these inductors often take up a large portion of the chip area, occupying far more space than the active devices. In a typical amplifier MMIC up to 80% of chip area is occupied by inductors[1]. Based on this reason, an invention and development of low-cost and highly integrated MMICs is highly needed. Multilayer MMICs technology employing multilevel of dielectrics and metals are finding increasing applications in compact and high-performance circuits [1, 2].

These layers used Metamaterials (MTML) as a substrate. MTML is also known as left-handed (LH) material. This material is said to have simultaneous negative parameters or double negative parameters (DNG Parameters) of the permittivity and permeability that lead to the reversal of multiple theories and laws [3]. In order to get negative permittivity, the structure was designed based on [4] parameter and a few type of lossy material. This paper will described the used of the combination of the Split Ring structure embedded in Gallium Arsenide (GaAs) substrate. MTML substrate acts as a substrate to the layers of stacked spiral inductor metal on the top and is separated by the polyimide dielectric layers. These layers are joined in the centre by a hole through the polyimide layers [1]. The performance of the combination of MTML with the multilayer of spiral inductor effect to quality factor, and losses are evaluated.

From a previous research [2], a study on multilayer spiral inductor did not contribute to increasing quality factor (Q factor) when one by one of polyimide layer was added. As an improvement from the previous work [2], this research work improves the quality factor by using MTML as a substrate and multilayer spiral at WiMAX frequency of 5.8GHz. Section II will explain the concepts of material chosen, and also describe the optimization of MTML in an existing inductors in order to achieve higher quality. Results and discussions are presented in section III and section IV is the conclusion.

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II. Design concept and optimization

A. Inductor Design Concept

In this research work, discussion falls on the inductor as a radio frequency (RF) passive component with predominant inductive behavior which at the same time still considers the existing parasitic capacitance.

Polyimide has been chosen in this work because of its characteristic as a good insulator. Compared to Silicon Oxide (SiO_2), polyimide is a better insulator. The main factor is because polyimide has a lower dielectric constant than SiO_2, which could provide a major reduction in power consumption on integrated circuit [13].Low permittivity dielectric makes this insulator dissipates less power in field effect transistors (FET) that is used in semiconductor industry.

Gold or it scientific name Aurum (Au) is widely used in Micro-electro Mechanicals (MEMs) field and used in the previous research paper [2],as a metal. It has an advantage property as a high conductivity and better electric conductor, which is a vital factor that can be used in MEMs field. Fairly inert material has given an added value to Au since the surface of the structure cannot oxide in the atmosphere. This property helps to maintain conductivity in atmospheric application.

However in this design copper is used instead of Au. The important paramount is that it has higher conductivity than Au. This property gives advantage to this integrated circuit to have a low dissipated amount of heat and to reduce waste of power. The unique properties possessed by copper make it worthy to be used in integrated circuit and becomes a niche in MEMs component. Since copper will largely hinge upon the strength of the adhesive bond in the MEMs community, it is highly preferred to be used in this research. By using copper as a metal, Fig. 1 below show the basic structure of spiral inductor used

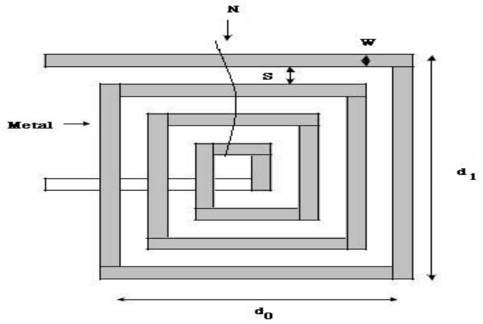

Fig. 1 Basic structure of spiral inductor

The basic geometric parameters of inductor structure is defined by the number of turns (N), the width of tracks (W) and space (S), and total area covered (d_0 x d_1) [14].

B. Multilayer Spiral Inductor

The inductor has been designed with three layers of metal and sandwiched with three layers of polyimide alternately on MTML substrate. There are a few types of stacked inductors that were studied [1] but in this research off stacked patch antenna is used. More than one metal layer design has to be connected together to reduce resistance and to minimize area.

A spiral inductor was built with 6.5 turns on each multilevel and connected to polyimide and GaAs. Their spacing is widened to 0.036mm in order to reduce the interspiral capacitor [1]. Similar width that is 0.08mm applied to every layer. This multilayer structure uses 0.25mm-thick GaAs as MTML substrate and was stacked with layers of polyimide on it. Each polyimide is 0.0128mm thick. The illustration of the multilayer spiral inductor is shown in fig. 2. The utilized of polyimide used on the first layer also studied this paper.

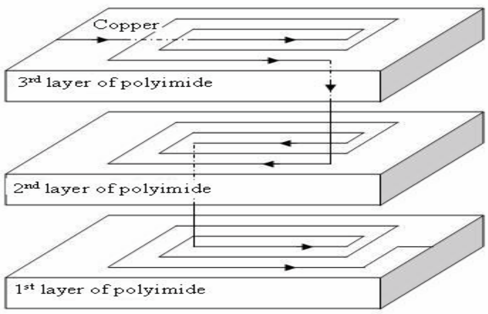

Fig. 2. The illustration of the multilayer spiral inductor

The design parameters for the lateral structure of an inductor are really important. The optimization to achieve high quality factor is affected by these parameters. Fig. 3 shows the flow chart in designing the structure of multilayer spiral inductor using MTML substrate. Simulation was done layer by layer to see the comparative on Q factor. The potential of MTML also proof by compared the simulation of the first layer without use MTML structure which is only use GaAs as a substrate.

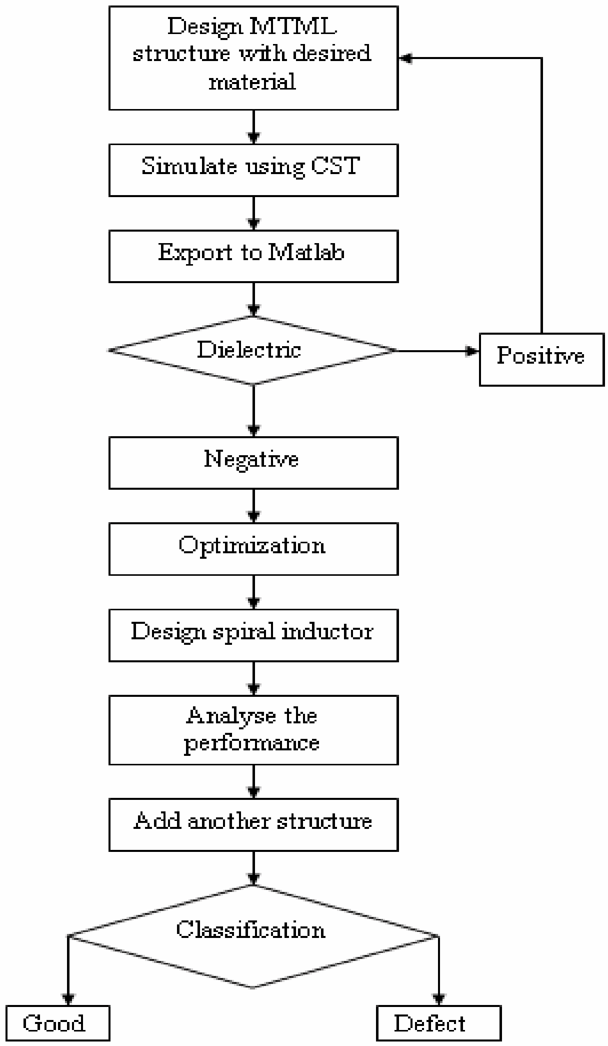

Fig. 3 Design flow of multilayer spiral inductor using MTML

C. Q Factor

Due to the fact that there are added parasitic capacitances to the model, stored electrical energy becomes an unwelcome addition to the inductor, negatively affecting the inductor's quality [7]. For a conventional spiral inductor, the quality factor can be defined as in equation (1) using lumped physical model.

The Q factor is the ratio of the stored to dissipated energy per RF cycle at a given frequency. Ideally, reactive components have no dissipation. However, their metal leads have resistance, make it worse by skin effect, and there are additional losses associated with their operation due to radiation, insulation, shielding, magnetic core losses in

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inductors, and dielectric losses in capacitors [7]. In addition, the effect of parasitic reactance reduces the component Q factor.

$$Q = \frac{L_s}{R_F} \cdot \frac{R_F}{R_F - [(\omega^2 \frac{L_S}{R_F})^2 - 1] R_S}$$

$$= [1 - \frac{R_s^2 (C_s + C_p)}{L_s} - \omega^2 L_s (C_s + C_p)] \qquad (1)$$

III. RESULTS

A. Q Factor

The Q-factor is the ratio of the stored to dissipated energy per RF cycle at a given frequency which is the important paramount need to be considered in inductor design. For first layer to this project, there were varied a few thing to get the best performance. Operating frequency 5.8GHz become as a reference point. Then, two layers more was added on it.

During the first layer, a few things were varied in different aspect to get the best performance. First of all, spiral inductor was design and patch directly on the MTML substrate. Then, polyimide layer was patched between the MTML substrate and spiral inductor. Design and simulation for the first layer without MTML structure was done to see the different use and not use MTML.

The potential of MTML has been proven and thus MTML to be applied on spiral inductor is definitely worthwhile. Fig. 4(a) shows the usage of polyimide between MTML substrate and copper at the first layer is an accurate and worthy action since the value of Q factor is higher compared to the copper which was directly stacked on MTML substrate.

The performance of Q factor is the most important feature to be determined in designing an inductor. Referring fig. 5(c), first layer of Q factor is around 752.24 at frequency 5.8GHz. The increasing value of Q factor can be seen after the 2nd and 3rd layer design of polyimide and spiral inductor is stacked on it. However, Q factor slightly decreases and then increase towards high frequency during 5.8GHz. This occurs since current value start to fall because of the skin effect and crowding to reach higher resonant frequency. Q factor and its resonant frequency will decrease when loss occur. Eddy current and some fringing capacitances also contributed to these losses. Fig. 6 proved that inductor design was not able to avoid from the capacitance existence. In this case, losses occur during substrates contact due to the parasitic capacitances that take place between of the substrates and inductors.

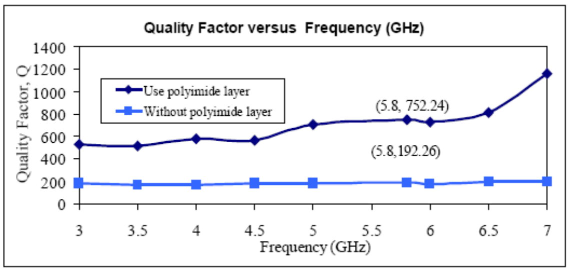

Fig.4(a) Quality factor for using and without using polyimide

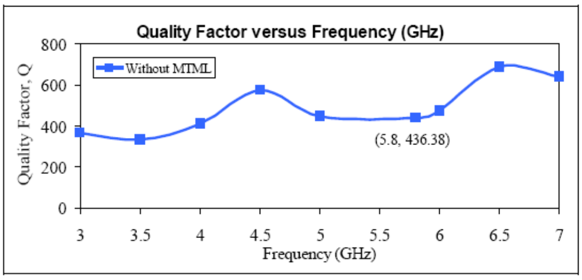

Fig.4(b) Q factor without using MTML as a substrate

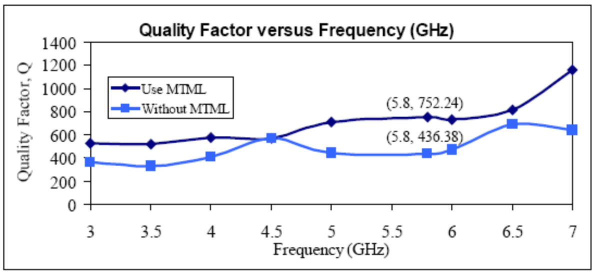

Fig.4 (c) Comparisons for using and without using MTML as a substrate

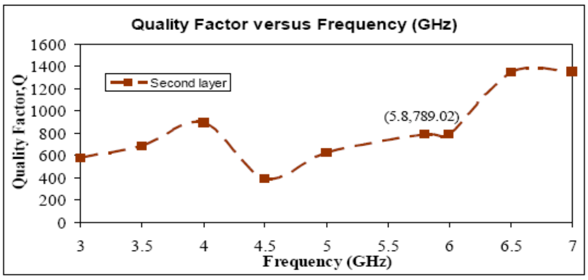

Fig 5(a) Q factor performance for the second layer

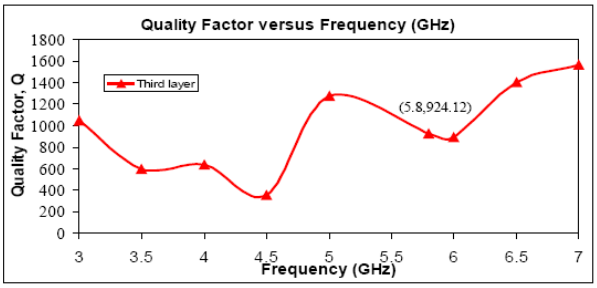

Fig. 5(b) Q factor performances for the third layer

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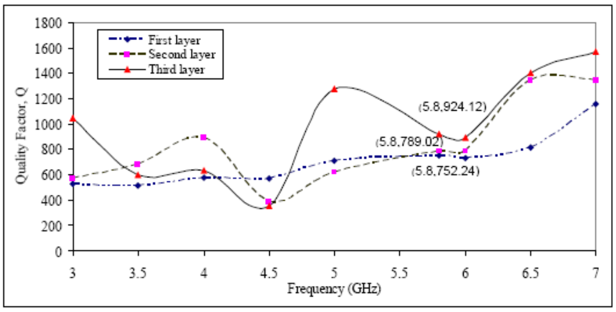

Fig. 5(c) Q factor performances for different layer of spiral inductor

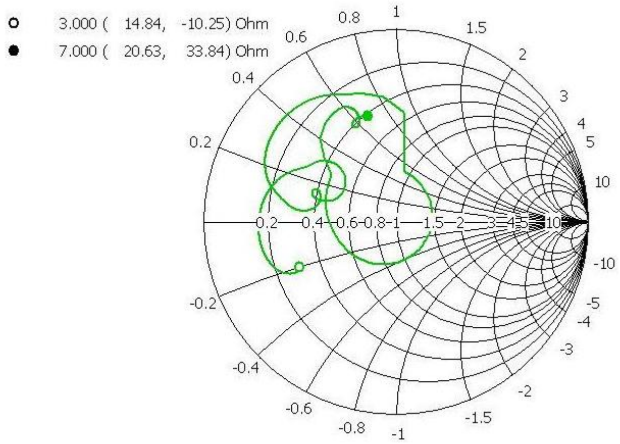

Fig. 6 Loop in the impedance locus on a Smith chart at third layer

B. Loss of Materials

Using frequency solver on CST microwave studio, total loss energy can be determined. In this research, loss of materials has strong effect on the Q- factor. This is shown comparatively between fig. 7 to the fig. 8 However, since the value of loss is too small, less effect can be seen to the value of Q-factor. When multilayer structures of polyimide thickness increases, loss was not proportionally increased. Thus, the increasing number of layer does not effect to the loss occurred. Fig.8 showed the comparison between surface losses and volume losses in percentage for three different layers. These losses exist from the material used in this design. Referring to the concept on how the materials in this integrated circuit were chosen, probabilities for loss to occur is has been predicted. Surface has higher losses than volume due to oxide to atmospheric. Skin effect also contributed from position of spiral inductor to substrate did not in λ/4 gap.

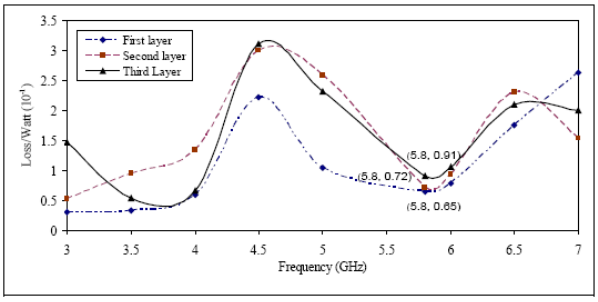

Fig. 7 Loss occur at three layer of spiral inductor

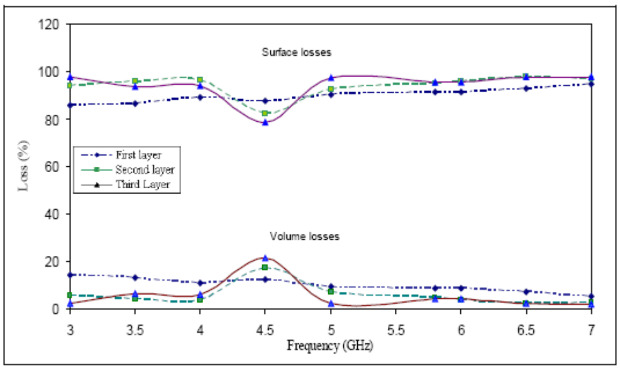

Fig. 8.Comparison between losses (%) occur at the surface and volume of integrated structure spiral inductor

IV. CONCLUSIONS

Improvement of inductors using MTML is newly designed, optimized, analyzed, and compared in this project. MTML is the perfect match to enhance compact inductor technology when the layer of spiral inductor is proportional to the Q factor performance. The layer of polyimide between MTML and metal contributed to the high Q factor. There is no major effect on Q factor due to small value of losses occurred. However, the thicker layers generate higher surface losses. Meticulous design is needed since permittivity of MTML substrate is strongly affected by the size of substrate, waveguide port and type of material used. Focusing on MTML, it is believed that this structure has enormous potential to lead in all high frequency electronics technology for tomorrow's application, compared to other structures.

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