A Study of Multilayer Spiral Inductor Using Metamaterial Substrate for 5.8GHz WiMAX Application

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***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-dimensinal structure. The results was then exported to Microsoft excel and Matlab to extract the dielectric value. 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 research used 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, losses and effective dielectric constant are described in this paper.

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 research [2], this new research improves the quality factor by using MTML as a substrate and multilayer spiral at WiMAX frequency of 5.8GHz. Section 2 will explain the concepts of material chosen, describe the optimization of MTML in an existing inductors in order to achieve higher quality. Methodology is discussed in section 3 and the justification of results discussions and conclusion are presented in section 4.

II. DESIGN CONCEPT AND OPTIMIZATION

A. Metamaterial Design Concept

The idea to study the MTML is basically from its permittivity, ε and permeability, μ character. The material can be classified in Group II, III and IV of the ε- μ diagram as shown in fig. 1 below.

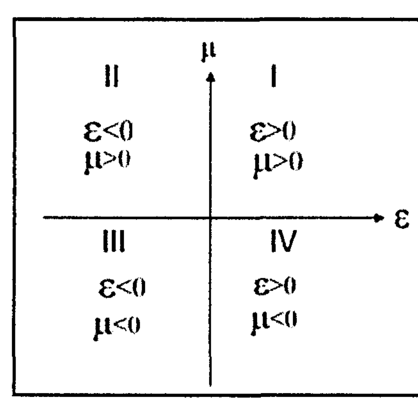


Fig. 1. Permittivity (ε) - permeability (μ) diagram.

From the diagram, almost all materials are categorized in Group I where the ε and μ are both positive. Second quadrant or Group II obtained as a metal at the optical frequencies evanescent wave which has Negative Refractive Index (NRI). Forth quadrant was quiet similar to second quadrant but the material was ferromagnetic material when the μ is negative. Backward Wave (BW) propagation was the attribute found in Group III when the material has Double Negative properties (DNG) or also called as LH MTML [3].

Previous researchers from all over the world [3, 6-11] designed MTML with several slabs and layers. It is different with this project, whereby MTML was designed only for one unit cell structure. In this case, the thickness of this substrate is 1 of 20 of its original size [11]. This was to reduce the size of substrate as well as low cost approaches. High expectation on MTML potential from previous researcher inspired this research to study the performance of inductor technology using one unit cell of MTML. There are a number of structures that have been invented by previous researchers [5, 6, 8-12]. Some structures used for this project are omega structure, split ring structure, symmetry structure and s structure. Only one structure was chosen to be used in this study. Since this research is an improvement from the previous project [2], therefore GaAs material was chosen as a substrate for MTML structure. The structure was chosen based on its permittivity and permeability performance. To get these DNG parameters is the most important factor in this study. It is highly needed to identify how the material that contradicted to a lot of physic laws affects the inductor.

The value of DNG has been calculated using the Nicholson-Ross-Weir (NRW) formula [4]. The simplified formula to measure permittivity (ε) and permeability (μ) properties can be defined by the following equation:

$$\varepsilon_r = \frac{\lambda_0^2}{\mu_r}\left\{\frac{1}{\lambda_c^2} - \left[\frac{1}{2\pi L}\ln\left(\frac{1}{T}\right)\right]^2\right\} \quad (1)$$

$$\mu_r = \frac{1+\Gamma_1}{\Lambda(1-\Gamma)\sqrt{\left(\frac{1}{\lambda_0^2} - \frac{1}{\lambda_c^2}\right)}} \quad (2)$$

Basic geometric parameters for dielectric measurement is defined by reflection coefficient (Γ), cutoff wavelength (λ_0), free space wavelength (λ_c), length of material used (L), transmission coefficient (T) and is a simplified form of relationship between angular frequency and transmission coefficient that is (Λ). There are several other techniques available for measurement and conversion for different material [4]. GaAs is one of the materials that are suitable to use the NRW conversion technique since it is a lossy and non magnetic material.

B. Inductor Design Concept

In this research, it will discuss 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 research 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. 2 below show the basic structure of spiral inductor used

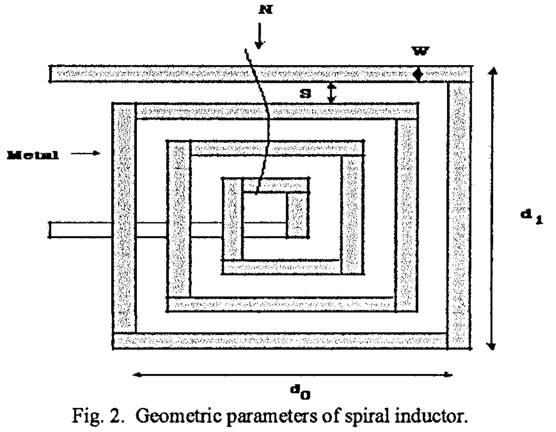


Fig. 2. Geometric parameters of spiral inductor.

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].

III. METHODOLOGY

A. *Metamaterial Substrate*

In this paper, left handed MTML designed rely on the paper from [4].By using existing parameter, MTML was designed and simulated. Subsequently, using S parameter obtained, they were export to commercial software to calculate the permittivity value by utilize NRW approach. Four different structures was used and the structures was designed using Perfect Electric Conductor (PEC) and have embedded to GaAs substrate to become MTML. MTML has chosen Base on its negative permittivity performance at operating frequency 5.8GHz. Study on miniaturization substrate size also done when design MTML substrate using previous parameters [2].

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. 4. The utilized of polyimide used on the first layer also studied this paper.

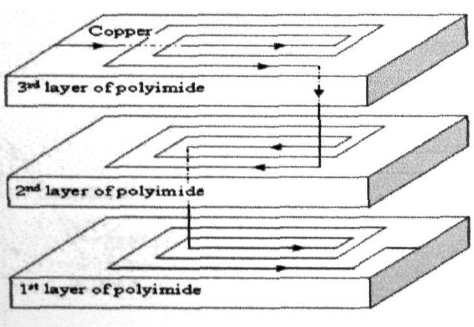


Fig. 3. The illustration of the multilayer spiral inductor

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. 4 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.

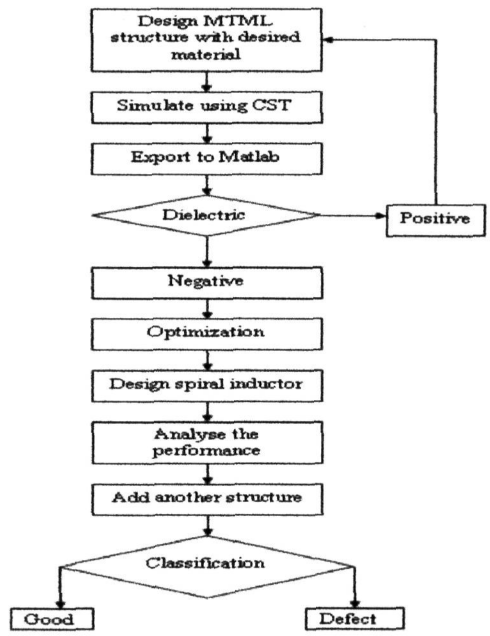
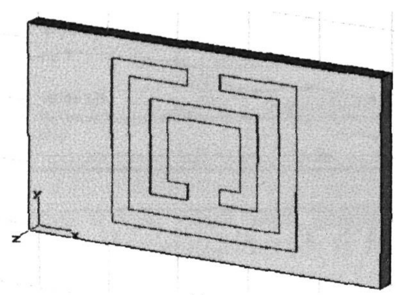


Fig. 4. Flow chart of design multilayer spiral inductors using MTML structures

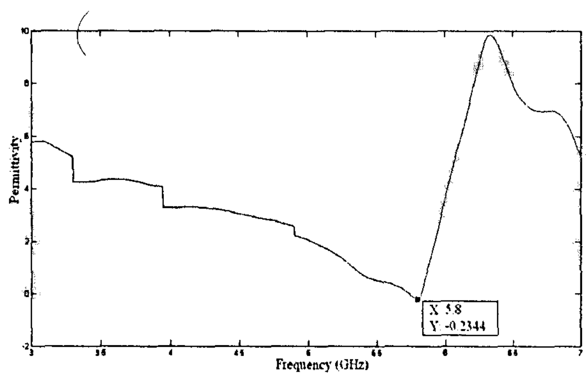
IV. Result and Discussion

A. *Metamaterial*

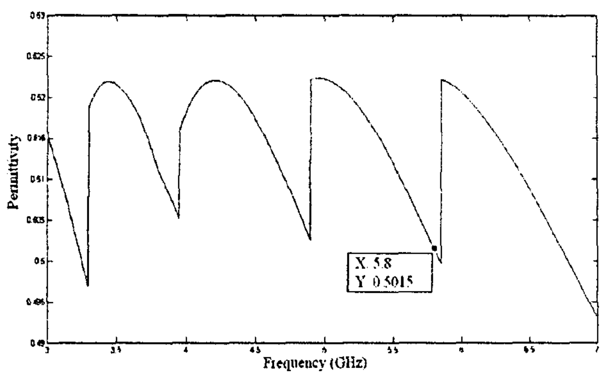
From simulations on different structures, split ring structure was choose as MTML structure shown in fig. 5(a). In referring to the fig. 5(b), the optimization to get the best performance in negative value has been done. It is known that permittivity easily affected by the size of waveguide port used and difficult to move the negative value of the graph to the lower frequency, but not to the higher frequency. With that problem understood, this type of structure has its own characteristic and the minimum limit frequency that each can achieve. Regarding to miniaturize the size of substrate, permittivity also affects that changed as shown in fig. 5(c).



(a)



(b)

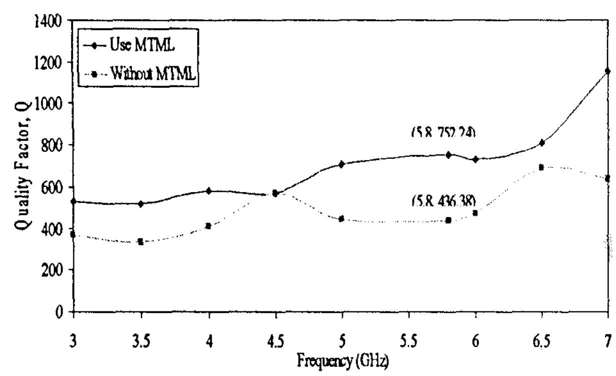


(c)

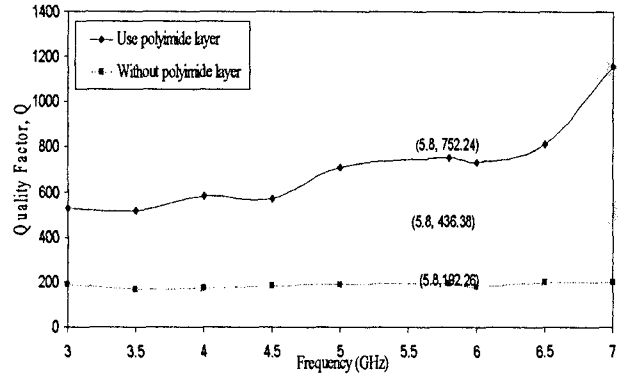
Fig. 5. (a) MTML substrate (b) MTML permittivity on 5 mm x 3.33 mm x 0.25 mm substrate size and (c) MTML permittivity on 600 μm x 380 μm x 670 μm substrate size.

C. Quality Factor

The potential of MTML has been proven as shown in fig. 6(a) It shows the higher Q factor as compared to [2]. Therefore, discovery of MTML to be applied on spiral inductor is definitely worthwhile. Fig. 6(b) 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.



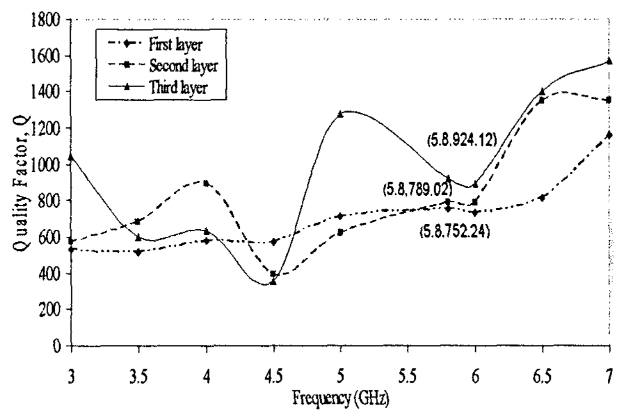
(a)



(b)

Fig. 6. (a) Comparison the utilization of MTML structure on the first layer and (b) The different between use polyimide layer and without use polyimide layer.

The performance of Q factor is the most important feature to be determined in designing an inductor. Referring fig. 7(a), 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. 7(b) 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.



(a)

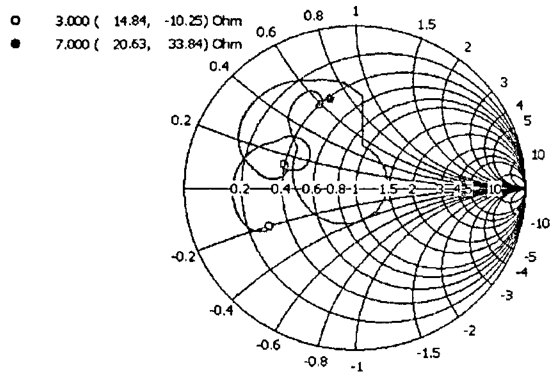


Fig. 7. (a) The performance of Q-factor for three layer and (b) Loop in the impedance locus on a smith chart at third layer.

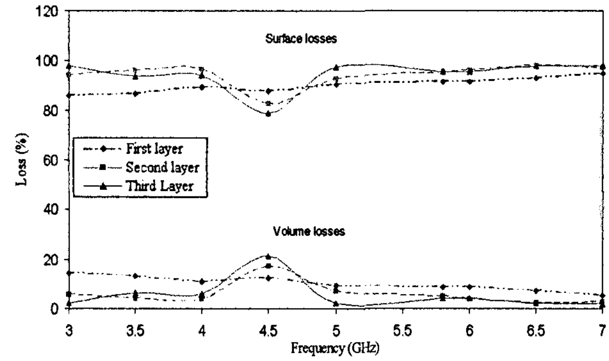
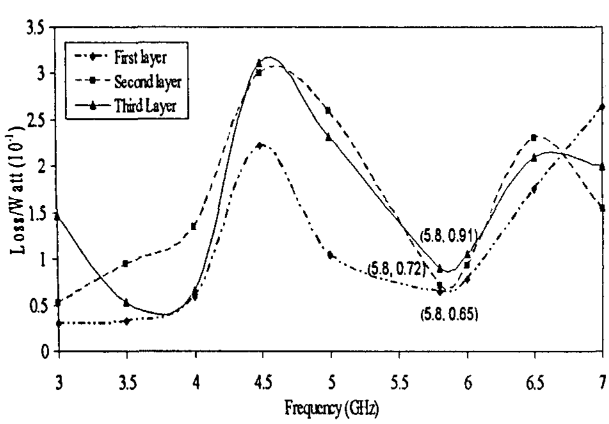


Fig. 8. (a) Loss occur at three layer of spiral inductor and (b) Comparison between losses (%) occur at the surface and volume of integrated structure spiral inductor

C. 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. 8(a) to the fig. 7(a) 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(b) 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.



(a)

D. Effective Dielectric Constant

Fig. 9 below showed the graph of effective dielectric constant at the first layer. The effective dielectric constant for three layers of spiral inductor has generated same pattern of graph which is have summarize in table I. In the multilayer structures, polyimide thickness has strong effect to the effective dielectric constant. This concept is strongly supported and proved by [1, 2] thicker polyimide layer causes lower dielectric constant and thus trigger longer wavelength and higher centre of frequency [2].

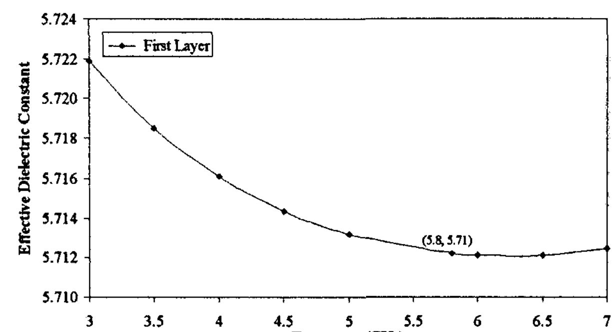


Fig. 9. Effective dielectric constant for first layer spiral inductor

TABLE I
EFFECTIVE DIELECTRIC CONSTANT DIFFERENT LAYER OF SPIRAL INDUCTOR

Properties	Operating frequency 5.8 GHz		
	First layer	Second layer	Third layer
Effective Dielectric Constant	5.71	5.36	4.32

This happen due to effect from properties of the polyimide itself as mentioned in section II. Refer to fig. 7(b), there was the increasing size of loop from lower to higher frequency which is strong relationship to the decreasing in effective dielectric constant. Therefore, narrow bandwidth will not have to this integrated circuit and easy to meet the bandwidth requirement for some other broadband wireless communication systems.

V. CONCLUSION

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. This design is able to achieve a lower effective dielectric constant when polyimide layers are added to the structure. 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.

VI. FUTURE DEVELOPMENT

Although MTML have already been utilized in this project, in order to improve the Q-factor of spiral inductor there are some challenges for further researchers in this project. They have to oversee the performance of Q-factor by increase more number of layers and also add dielectric layer to cover the highest metal.

Subsequently, future researchers will have to discover a smaller unit cell of MTML structure. The miniaturization of inductors can be widely used in MMICs technology which will result in a more efficient uses of chip areas and a lower cost while maintaining the same performance. This also can be done using other material such as Silicon Germanium (SiGe). Nowadays, SiGe is one of the big performance materials which has rapidly grow especially in CMOS technology. This research will open the door to future researcher to study the effect of this material to produce a spiral inductor using MTML.

ACKNOWLEDGMENT

I would like to express my deepest gratitude, appreciation and thanks to my supervisor, Pn. Zuhani Ismail Khan for her guidance, comment, advices, supervision, encouragement and faith in me in accomplishing this project. My appreciation goes to En Asari Sulaiman, Pn Hashimah Baba and En Huzaimy Jusoh for helping me understand the concept of metamaterial. I would also like to say thank you to Hanisah Bte Muhamed Nadzar for her comment and helping me to understand the concept of inductor and how to choose suitable materials. Finally I would love to say thank you to my family and my friends for encouraging me to completing this project.

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