MODELING AND ANALYSIS OF CPW BASED MULTI-LAYER ON-CHIP INDUCTORS AND DESIGN OF MULTI-RESONATOR FOR RF SIGNATURE SENSOR

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ABSTRACT

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CPW based multi-layer inductors which can provide higher frequency bandwidth and Quality factor (Q) values are studied and characterized so that a new microwave equivalent circuit model may be obtained. In order to study the correlation between the inductance and the length, width and thickness of the conductor, electromagnetic (EM) structures of multi-layer inductors are designed and compared to electrical models. Simulated data and test data were compared and analyzed. Results showed that conductor length change causes major inductance change; conductor width change causes major capacitance change. Detailed results and analysis are shown in this thesis work.
On the second step, a passive multi-resonator based RF signature sensor has been developed. Based on research result from part I, some improvement has been made to the designed RFSS has a working frequency at 7.5GHz frequency with about 20dB insertion loss at the fundamental resonance frequency.
Dedicated to my family

Jinshu, Zhao and Xiaohui
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INTRODUCTION

1.1 Introduction of On-chip Inductors

Due to the rapid development of mobile communication and wireless communication, the demand for low cost, high integration level, small volume radio frequency (RF) receiver and transmitter components has been significantly increased. As one of the most important elements of voltage control oscillators, low noise amplifiers and source-free microwave filters, inductors have become a popular and necessary research area.

Usually, inductors are made with a magnetic core and loops of wire. Different from the normal inductor, on-chip inductor is a type of inductor which is used in radio frequency applications. At higher frequencies, normal inductors have higher loss and resistance. These effects causes power loss, and can reduce the Quality factor (Q-factor) of the electric circuit. On-chip inductors can reduce the skin effect and power loss at higher frequency, because of this they have been widely used in the microwave engineering field.
In the design of on-chip inductors, how to improve the Q-factor and reduce inductor volume have become two major issues. New findings of on-chip inductors are constantly emerging, but there is still inadequate understanding of the inductor’s characteristics and how it relates to the Q-factor [1]. It has been shown that at high frequency, the electrical model of inductors based on mathematical calculations could not provide strong theoretical support for optimal design of inductors. There is a lot of research based on inductor modeling, but a limited number of them are based on multi-layer and CPW substrate on-chip inductors. An electrical model with more accuracy needs to be built. My research presents electrical models of CPW based multi-layer on-chip inductors.

The objective of my research is to find the correlation between inductor value and conductor dimensions for CPW based BST thin-film double layer on-chip inductors. Our lab has designed a lot of microwave devices including Barium Strontium Titanate (BST) thin-film varactors, bowtie antenna integrated with varactors, and high frequency band pass filters. Most of these devices are CPW based multi-layer structures with BST thin-film between metal layers. Inductance is a basic characteristic in each of those devices. My research focuses on design and modeling of double layer CPW based circuits to analyze their inductance characteristics. Since there was no research focused on inductor’s characteristics in our lab, this will help us to have better understanding of the inductance affect in any CPW based design.
Barium Strontium Titanate (BST) thin-film plays a very important role for voltage-tunable feature. BST (Ba$_{1-x}$Sr$_x$TiO$_3$) is a solid solution of barium titanate (BaTiO$_3$ or BTO) and strontium titanate (SrTiO$_3$ or STO). BST has both paraelectric and ferroelectric behavior because of its specific composition and temperature. BST exhibits properties of high dielectric constant, small loss tangent and voltage tunable permittivity [2]. According to these characteristics, BST becomes a good choice of tunable microwave devices. The dielectric constant ranges from 120-500 on silicon substrates depending on thickness and bias voltage level. The zero-voltage dielectric constant is as high as 1000 on sapphire substrates and reduces to 250 at an electric field of approximately 400 kV/cm [3].

1.2 Introduction of RFID System & Application

Currently, more and more scientific research focuses on tracking, monitoring or state-changing of certain object. The state-changing progress could be a very long process, or there could be very tiny change so that it is hard for human eyes to observe the change. In some other condition, the object may need an extreme environment that will harm the human health.

Under this circumstance, a special kind of device needs to be designed with certain requirements in order to monitor different kind of objects. This monitoring system requires several special features:

1. Sustained supervision
Since the research could be a very long progress, sustained monitoring is needed to make sure important research data won’t be missing

2. **Accurate sensor**

   Under some condition, the very small amount of change could lead to a huge difference of research result. The accuracy of the sensor needs to suit different research requirements.

3. **Wireless sensor & data transmit**

   Some experiments, such as compression strength or impact capability test, need a high pressure or dangerous environment that may be harmful for human health. In such experiments, the sensor and data transmission must be wireless so that the experiment could be done in a relatively isolated environment.

4. **Different control range**

   Depending on different kinds of research, the control range of system could vary.

   A simple and low-cost method of doing this monitor system is by using the Radio Frequency Identification (RFID) system. RFID is a contactless data-capturing technique, which uses radio frequency waves for automatic identification. The basic construction of a RFID system includes: a data carrying device called the RFID
transponder (often known as tag), and the interrogator, which is also known as the RFID reader. The RFID transponder usually contains a transmission antenna, a receiving antenna and an integrated circuit [4].

RFID technique has been widely used in low-cost object tracking system such as tracking of certain devices in buildings and tracking of animals in large fields. A research group in University of Utah has designed an RFID tracking system, sponsored by L-3 Communication Inc., which focuses on tracking medical devices in a hospital environment [5]. Tags are placed on devices and locations of each tag are monitored by the base station. The signal transmitted between the tags and the RFID reader is captured and analyzed. Different from the RFID tracking system, the RFID monitoring system focus on observing and reporting the state or environment change of a motionless or slow-moving object. This kind of monitoring system will be found very useful in experiment such as pressure test.
CHAPTER II

LITERATURE REVIEW OF RELATED RESEARCH

Ferroelectric materials have a wide range of applications because of its special features. This type of material possesses a spontaneous electric polarization which is can be reversed, resulting in applications such as non-volatile memory. Application of ferroelectric devices will be introduced during this chapter.

2.1 Ferroelectric Varactors

Some applications using BST thin-films in the field of microwave engineering include varactors, tunable filters, antennas, etc. The invention of BST thin-film brings huge change to tunable microwave devices. BST films exhibits an excellent tunable behavior at room temperature. In the field of ferroelectric devices, ferroelectric varactors play a very important role.

Guru Subramanyam and his team [2] developed a ferroelectric varactor shunt switch which can be useful for microwave switching. The BST thin-film layer is in between two metal layers with a parallel plate configuration. This varactor has
experimental performance at 41GHz frequency and insertion loss lower than -7dB. After inserting the BST layer, the varactor has voltage dependent tunability.

BST thin film varactors are used in tuning other ferroelectric devices. By using BST thin-film tunable behavior, Pan, K [6] has developed a bowtie antenna which can shift resonance frequency point over a broadband. The size of designed bowtie antenna is around 6mm * 6mm with three varactors attached at feed line of the antenna. When applying different DC bias, the antenna could tune from 5.75 GHz at 0V to 6.2GHz at 8V.

Other applications based on BST thin film varactor is designed by H. Jiang and his team member [7]. In this application, BST thin film varactor technology is applied to CPW square-ring slot antenna, which used on antenna miniaturization and reconfiguration. In the paper, the testing result of antennas with and without integrated BST varactors was shown. The comparison shows the size of miniaturized antenna is reduced by 31% at 0.12λ0 × 0.12λ0. Working frequency of the miniaturized antenna with BST varactors is from 5.8 to 6.1GHz at 3V. This device is useful at low-power, small size environment.

2.2 Interdigitated Ferroelectric Capacitors

Interdigitated ferroelectric capacitor is another important ferroelectric device research area. Yoon [8] has developed a ferroelectric capacitor, which has 33% to 45% tunability. The device focuses on finger shaped structures with BST thin-film
filled between conductor and sapphire substrate. The single finger structure has tunability of 33% at 10V and 45% at 30V, at 100 kHz frequency.

A 102-finger interdigitated capacitor has been fabricated and tested. With capacitance increase of 6%, the tunability has decreased by 2~3% at the frequency of 1GHz. When frequency goes from 100 kHz to 1GHz, more loss is generated. The decrease of tunability is acceptable with increase in capacitor value.

The ferroelectric capacitor is an important element of other ferroelectric devices. Z. Zhao [9] designs a ferroelectric 360-degree phase shifter, which is also based on BST thin-film material and high conductivity RF electrodes. Different from Yoon’s research, this ferroelectric 360-degree phase shifter has working frequency from 20GHz to 30GHz. At such high frequency, it is hard to keep the tunability and low insertion loss. Zhao tested the designed device under different voltage and frequency range in order to find the best working frequency and insertion loss. At 21.7GHz frequency, the device has 330-degree phase shift and 6.1dB insertion loss. At 32GHz, the device have 360-degree phase shift, while insertion loss is 7dB. Zhao’s design achieved high frequency tunability with less than 1mm square size. Due to the small size and less power consumption, these phase shifters are well suited for phased-array applications.

2.3 Inductor Modeling

In the inductor modeling area, a lot of different research has been done. Aoki, Y and Honjo, K [10] have developed a new electrical model for multi-layer inductors
which is suitable for wide frequency range. The design is a low loss, high Q spiral inductor which is fabricated by wafer level packing (WLP) on silicon substrates. A conventional evaluation method is used to determine inductance and Q-factor. This method provides Q-factor evaluation from 2-5nH inductance. In the modeling process, maximum available power gain is used to evaluate the energy loss and provides unique insertion loss of passive inductor devices. The electrical model has been confirmed from 2.7 to 8.2nH inductors.

Hong, T and team members [11] designed an electrical model for low temperature cofired-ceramic (LTCC) embedded inductors. The model includes a core circuit, a new T-model circuit and several resonators. After combining the above elements together, the electrical model covers the transmission line effects and coil coupling between lines. The electrical model could model LTCC inductors efficiently because the reactive element could be extracted from S-parameters.

2.4 RFID and RFSS

RFID system has been widely used in many areas because of its advantages. Design of components for RFID tag varies. RFID tag could be either active or passive. Many kinds of RFID tags have been designed in ferroelectric field.

S, Preradovic and N, Karmakar [12] designed a multi-resonators based chipless tag integrated with temperature sensor. They choose UWB monopole antenna as receiving and transmitting antenna; and use cascaded spiral EBGs as the resonators. Electromagnetic band-gap (EBG) structured material is a kind material
which is designed to prevent the propagation of frequencies bandwidth. The designed chipless RFID tag features on small size, less sensitive to tag orientation. With integration of the temperature sensor, the RFID tag could changes the radar cross-section of the tag antenna. This RFID tag has working frequency from 2GHz to 2.6GHz and it is suitable for low cost sensing applications.

BST material could also been useful for its tunable feature, other than using the tuning feature based on bias voltage, BST material could also been used based on temperature tuning feature. C. Mandel and his/her team members [13] designed a passive sensor with RFID capabilities. This wireless sensor is based on phase modulation scheme and is also used for temperature monitoring. The approach utilizes the temperature-sensitive feature for BST thick film capacitances, which are integrated into a phase modulation circuit. Designed RFID sensor use backscatter technique and is based on meta-material transmission lines.
CHAPTER III

MODELING AND ANALYSIS OF CPW BASED MULTI-LAYER ON-CHIP INDUCTORS

The objective of this section of research is to find the correlation between inductor value and conductor dimensions for CPW based BST thin-film double layer on-chip inductors. In our lab, the main research focus is on characteristics of BST varactors and we have limited research results for CPW inductors. This will cause some design difficulties. In order to understand the coupling effect for inductors under certain design structure, research focus in this thesis is only on design and modeling CPW based double layer inductors. The effect of BST layer will also be considered in this research.

3.1 Software Simulation and Hardware Setup

Our lab provided advanced equipment and environment for microwave devices design. Here are the general steps for design a certain microwave devices.

1. Objectives and requirement of device
2. Draw the device in simulation software
3. Select different material type for each layer and simulated the device
4. Assess the simulation results and revise the device design

In the fabrication and testing process, there are three steps:

1. Device fabrication in clean room

2. Device testing using an on-wafer probe station and a network analyzer

3. Export test data from network analyzer and analyze the test results.

We are using AWR Design Environment developed by National Instruments and Advanced Design System (ADS) developed by Agilent as main simulation tools. Figure 3.1-1 shows the main interface of AWR design environment software.

![Figure 3.1-1 Interface of AWR design environment](image)
Devices are fabricated by our group in Wright-Patterson Air Force Base clean room. After receiving the fabricated devices, the testing of the devices are done using the on-wafer probe station available in our laboratory.

Scattering parameters (S parameters, such as S11, S12) are obtained from the testing. S-parameters are imported from Agilent’s vector network analyzer and converted into excel format and saved in the connected PC. Then we could import the test data file into AWR and analyze the test results. For proposed multi-layer inductor, an electrical model has been developed to help analyze the test result.

3.2 CPW Based Multi-layer Inductors

In order to study the coupling effect and correlation between conductor shape and inductor value, a set of single port multi-layer inductors has been developed.

The conductor dimensions include length, width and thickness. Changing the thickness is easy by using the simulation software, it will be hard to fabricate different device thickness because that would require changing the fabrication steps for each particular thickness. Since the thickness will remain the same for each device, conductor length and width are the two variables that can be changed to determine their effects on the inductor performance. For each designed EM structure, the conductor width and length are incremented by a certain value. After testing all the structures, a complete data list of inductor values based on conductor length and width will be provided. For changing the conductor length, additional turns were added to the conductor line. For the multi-layer inductors, 1 turn, 2 turns,
4 turns and 8 turns structures were designed. For each turn number, inductors with three different conductor widths were designed: 10µm, 20µm and 50µm, there are also a few structures tested with width of 100µm.

The designed EM structure of on-chip inductors are shown in Figure 3.2-1. Part (a) of Figure 3.2-2 is 1 turn, 700µm length inductor, and part (b) of Figure 3.2-1 shows 8 turns, 5000µm length inductor. Both of the two structures use 10µm conductor width. These inductor structures are based on 50 ohm transmission line. All of the EM structures are double layered, with the top and bottom metal layers shown in Figure 3.2-2.

![EM Structure](image)

(a) (b)

Figure 3.2-1  EM structure of different kinds of on-chip inductors
Figure 3.2-2 represents the two layers of an example structure. The bottom layer metal is similar to the top layer metal, but is missing the feed line due to the goal of maximizing the coupling effect between the two layers. Due to no power input for bottom metal layer, all voltage on this layer comes from coupling effect between two layers. In AWR software, we could also look at the EM structure in 3D view. Figure 3.2-3 shows 4 Turn, 20µm width structures in 3D view.
The thickness between two layers is 0.25µm. Figure 3.2-4 shows the layout of different layers.

3.3 Simulation & Test Results

After designing the inductor structures, it is necessary to simulate them and look at the result. The simulation process is done by AWR software. By giving the
required data, such as permittivity, thickness and grids, AWR calculates S-
parameters of designed structures accurately. These calculations are based on an
ideal situation; it eliminates environmental effects and loss during fabrication or
testing process.

During the fabrication process, the structure uses sapphire as substrate, gold as
conductor and BST material between two conductor layers. Sapphire substrate has a
relative dielectric constant of 9.7, and the loss tangent of <0.005, which is 2 times
smaller than loss tangent of silicon. Gold has very high conductivity at 2x10⁷ S/m
which will provide good electrical conductivity of the structures. Because the
microwave device is tiny, large numbers of devices are fabricated together on the
same wafer.

The inductor structures were test after fabrication. Figure 2.3-1 is a picture of a
fabricated inductor. The sample inductor has two layers, 8 conductor turns, and
20µm width. There is a 10µm gap at the feed line. CPW probe can be seen on the
left of the picture at the feed line.
Figure 3.3-1  Picture of fabricated wafer

Figure 3.3-2  Inductor structure in testing
3.3.1 Simulation Results

Simulation results could be shown in different forms, such as S-parameter and Y-parameter. First we focus on S-parameters. For general two-port microwave devices, S-parameters are listed below:

- \( S_{11} \) is the input port voltage reflection coefficient
- \( S_{12} \) is the reverse voltage gain
- \( S_{21} \) is the forward voltage gain
- \( S_{22} \) is the output port voltage reflection coefficient [5]

For a one port device, such as the designed inductor, the only S-parameter is \( S_{11} \), the return loss of the port. One of the inductor structures under test is shown in Figure 3.3-3.

(a) 1 turn 10\( \mu \)m width  (b) 1 turn 20\( \mu \)m width
(a) 1 turn 50µm width

Figure 3.3-3  Designed inductors of 1 turn, different width
Figure 3.3-4 (a) shows $S_{11}$ curves versus different frequency points. For X axis, the simulated frequency range is 1GHz-20GHz. For Y axis, the unit is dB. The brown, red and pink curve represents three inductor structures having the same conductor length but different width. Since the resonance frequency point is beyond 20GHz, which exceed our test limit, we couldn’t see the resonance frequency point from this figure.

In Figure 3.3-4 (b), we look at the simulation results through Smith chart. As the marker shows, r represents real value of S11 while x represents imaginary number of S11. Comparing the results, all three samples have similar real parts, so
the only difference comes from the imaginary, or x value. This difference between the samples represents the difference in inductance value by the following equation.

\[ X_{\text{diff}} = j\omega L_{\text{diff}} \]  

Equation 1

Figure 3.3-5 shows four inductors which all have same conductor width (10µm) but different conductor length (turn number).

The simulation results of devices showing above are in figure 3.3-6. The red line indicates 1 turn structure; the pink, blue and brown line indicates 2 turns, 4
turns and 8 turns’ inductor structures. As the conductor length increases, the resonance frequency point shifts from higher to lower frequency. This could be explained by Equation 1:

\[ f = \frac{1}{2\pi\sqrt{LC}} \]  
Equation 2

\( f \) indicates the resonance frequency point. In Figure 3.3-6, the resonance frequency points are around 16GHz, 11GHz and 5.5GHz. For the red line, resonance frequency point goes beyond 20GHz, which won’t be tested. Equation 1 shows that when frequency points goes down, \( \sqrt{LC} \) should increase. In order to understand detailed changing of \( L \) and \( C \), more research result will be shown.

![S11 curve, same width, diff length](image)

Figure 3.3-6  Simulation results 10\( \mu \)m width diff length
3.3.2 Comparison of Results

All the figures shown above are all based on software simulation. In the microwave research area, research results won’t be accepted without real testing. There could be large differences between simulation and test results because of fabrication environment, test environment, the purity of conductor material and other loss conditions.

Figure 3.3-7 shows comparisons between simulation results and test results. Designed inductors have 8 turns, and 20µm conductor width. The test result is shown as the green line in the figure; the pink, blue and red lines are shown as the test results. The label of the figure could be hard to understand because the name came from fabrication process. For the pink line, the label shows “8T20WTOP”, this indicates only top layer of the inductor was tested. The label means that there are 8 turns of 20 µm wide conductor lines, and the inductor is based on single metal layer (top metal layer). For the blue line, label shows “8T20WNoFEED”, this indicates that the inductor is a two layer inductor. Due to noise and other loss condition, simulation and test results have some difference. The two results all have resonance frequency points at around 15.5 GHz; it proves that the design and simulation results were right.
3.4 Formulas of Inductance Calculation

In electrical circuits, when current passes through conductors, electromagnetic fields will be generated. The value of magnetic field divided by the value of current equals the inductance. Inductors only work for alternating current (AC) circuits. For normal inductors, a voltage across it and current passing through it could be represented by the following equation:

$$v(t) = L \frac{di(t)}{dt}$$  \hspace{1cm} \text{Equation 3}

Where $v(t)$ is a time-varying voltage and $i(t)$ is the time-varying current [8]. From the equation we could understand the effect of an inductor in an electrical circuit. In order to resist the current change, a voltage value is developed from the inductor.
For normal inductors, inductance value could be calculated by formulas.

Because the type of inductor varies, there are different kinds of inductor calculation formulas. For air-coil inductors, inductance value could be calculated by:

\[
L \text{ (mH)} = \frac{(0.08D.D.N.N)}{(3D+9W+10H)}
\text{ Equation 4}
\]

Where D is the diameter of the coil, N is the number of turns of the coil, d is diameter of the conductor wire, H represents coil height, and W represents coil width.

Some of the inductors only have experience formulas. [9] For straight wire conductor inductors, inductance value equals to:

\[
L = 0.2l \left( \ln \frac{4l}{d} - 1 \right) + 0.3\% 
\text{ Equation 5}
\]

Or

\[
L = 0.2l \left( \ln \frac{4l}{d} - \frac{3}{4} \right) + 0.3\% 
\text{ Equation 6}
\]

Equations variances depend on material, frequency and diameter of conductor. In Equation 4 and 5, l is the length of conductor, d is the diameter of the conductor, and f the frequency.

Another experience formula is introduced; the set of formula includes straight wire conductor and turning condition:

\[
L = 0.002 * l \left[ \ln \left( \frac{2l}{r} \right) - 0.75 \right] \text{nH} 
\text{ Equation 7}
\]
Where $l$ is conductor length, $r$ is conductor width. At every turn, the self-inductance is approximately [5]:

$$L_{\text{turn}} = \frac{\mu t l}{\pi} \ln\left(\frac{W - \omega t}{\omega t}\right), \quad \text{Equation 8}$$

Where $\omega t = 1/\sqrt{(\pi f \mu \sigma)}$

$\mu$ represents permeability of conductor, $\sigma$ is conductivity of conductor, $f$ is frequency point, and $l_i$ is length of the turning conductor. The above formulas could only give us approximate inductance values. These formulas work only for single layer, straight wire conductors. For spiral shape and multi-layered inductors, it is very hard to find formula for inductance value. But different shape of conductor could be transferred into different electrical circuit structure. If the electrical circuit has similar performance (such as $S$-parameter or $Q$-factor) as the EM structure, the circuit becomes the “electric model” of the EM structure. With the help of an electrical model, it is easy to calculate circuit components’ values.

3.5 Electrical Model of Designed Inductors

Based on inductor structures that have been tested, an electrical model has been built and simulated. AWR design environment software has an embedded tool which lets you build all kinds of electrical model circuits. The advantage of using AWR is the specialty of electrical model builder. It allows user to choose from large selection of basic circuit components, transmission lines, substrates, etc. The
electrical model will also be simulated and the simulation results will be compared with EM structure.

3.5.1 Electrical Model of Top Layer Structure

When building an electrical model, a conductor line must have resistors; the value of resistors depends on the size and material of conductors, shown in figure 3.5-1. In the meantime, there will also be inductance value to oppose the current change passing through the conductor. Capacitors usually exist between two conductor lines or layers.

Following these rules, electrical model has been designed for the first layer of the EM structure; model as shown in Figure 3.5-2. The electrical circuit connects to a transmission line module. The transmission line module simulates the real transmission line by providing the physical width, length and thickness. The transmission line module then connects to a 50 Ohm port.
On the bottom of the figure there is a substrate module, which simulates the inductor substrates by a list of parameters.

Figure 3.5-2  Electric model of single layer inductor structure

3.5.2 Electrical Model of Double Layer Structure

Double layer inductor modeling could be achieved by combining two signal layer inductor models together. In order to maximize the coupling effect, the bottom layer doesn’t have a feed line. Between two layers, the coupling effect could be expressed by mutual inductance and capacitance. The mutual inductance is hard to find based on calculation, a sufficient way is to use an electrical model. Figure 3.5-3 shows the designed electrical model of the multi-layer inductor structure.
3.6 Electrical Model Analysis

3.6.1 Electrical Model Matching

As mentioned, mathematical calculation isn’t accurate enough so the electrical model based on a mathematical calculation didn’t match the EM structure very well. Since mathematical calculation is not accurate enough for our research, an alternate method of calculating the right value of circuit elements needs to be determined. The “tuner” in the AWR software has become a helpful tool. The elements’ value is tuned so that the S11 curve of electrical model matches S11 curve of inductor structures. Figure 3.6-1 through 3.6-4 showing the matching result for double layer inductor model. At some frequency range, two lines have some difference; this may be due to parasitic losses in the lines. But overall, the results of electrical model match the result of real inductor structure.
Figure 3.6-1  1 turn 10µm width

Electrical model vs. EM structure (blue vs. red)

Figure 3.6-2  2 turn 10µm width

Electrical model vs. EM structure (blue vs. red)
Figure 3.6-3  4 turn 10µm width

Electrical model vs. EM structure (blue vs. red)

Figure 3.6-4  8 turn 10µm width

Electrical model vs. EM structure (brown vs. red)
The inductance values of the electrical model are given in Table 1. By increasing the conductor turns (conductor length), the inductance value also has a major increase. For the same conductor length but different conductor width, the inductance values have minor changes.

<table>
<thead>
<tr>
<th>Length (µm)</th>
<th>1 Turn (680µm)</th>
<th>2 Turns (1300µm)</th>
<th>4 Turns (1600µm)</th>
<th>8 Turns (2900µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>0.09</td>
<td>0.88</td>
<td>0.09</td>
<td>0.09</td>
</tr>
<tr>
<td>20</td>
<td>0.09</td>
<td>0.1</td>
<td>0.8</td>
<td>0.10</td>
</tr>
</tbody>
</table>

Table 1 Inductance value derived from electrical model for different conductor dimensions
3.6.2 Q-Factor Calculation

Quality factor (Q-factor) is one of the most important characteristics of inductors. Calculation and analysis of Q-factor is important and necessary for the research. There are many ways to calculate the Q-factor, such as using bandwidth, phase stability and Y parameters. In AWR Design Environment software, it is easy to plot the real part and imaginary part of Y11 parameter.

\[ Q = \frac{|\text{Im}(Y_{11})|}{|\text{Re}(Y_{11})|} \]  

Equation 9

Using the 4 turn 10µm conductor width inductor as an example, the plot of imaginary and real part of Y11 is shown in Figure 3.6-6. At the resonance frequency point (f=11GHz), the Q-factor reaches its peak of 1.8 and the Q-factor decrease at other frequency range.

![Real and imaginary part of Y11](image)

Figure 3.6-6 Real and imaginary part of Y11
After comparing the Q-factor for different types of on-chip inductors, a regular pattern of Q-factor distribution could be found.

For 10µm conductor width, but different number of turns, the Q-factor increases from 1.6 (1 turn) to 1.952 (8 turns). For the same turn number but different conductor width, the Q-factor didn’t have a large impact.

3.7 Summary of CPW Based Multi-layer On-Chip Inductor Results

Based on the simulation results and electrical model results, several conclusions can be made. First, inductance value not only comes from conductor length, coupling effect could also generate coupled inductance value which is mutual inductance. Second, the inductance value increases when conductor layer increases. The mutual inductance and capacitance between two layers affect the total inductance value. Third, the inductance value increases when conductor dimensions changes. The length increase gives inductance value a major increase, and the width increase will cause small inductance decrease, and large capacitor change [2].
CHAPTER IV

DESIGN OF MULTI-RESONATOR BASED ZERO-POWERED RF SIGNATURE SENSORS (RFSS)

4.1 Introduction and Significance of Research

Although RFID has found application in many areas, there’s no particular RFID system that satisfies criteria for every application. Depending on different research/application environment, different criteria are needed. Some applications, such as mine ventilation safety system, required an accurate CO\textsubscript{2} concentration measurement sensor. When the CO\textsubscript{2} concentration exceeds the acceptable level, an alarm system needs to be triggered. For other applications, different kinds of sensor maybe need. Some applications will trigger an alarm system; some others only need data capture process [14].

For the RFID wireless monitoring system, several design difficulties are present.

How to design an appropriate antenna and resonator?

For a chip-less RFID tag, antennas and multi-resonators are important. The design of the antenna directly influences the data transmitted quality and monitoring
range. Also, the multi-resonator circuit is needed to encode the multi-frequency interrogation signal from the RFID reader. How to achieve encoding of multi-frequency signals becomes another important question.

How does this system rely on RF signal?

Even through an accurate sensor is attached to the tag, a simple and accurate measurement method is still needed for the proposed system. Simple control methods make the code package size smaller, and at the same time, accuracy of the result need to be ensured.

4.2 Operation Principle of RFID System

4.2.1 Whole Picture of RFID System

The proposed monitoring system generally works like Figure 4.2-1, [14]:

RFID Transponder consists of two antennas, one transmitting and one receiving antenna, and a multi-resonator section. The tag receiving antenna accepts the interrogation signal from the RFID reader. The frequency spectrum signal is encoded by the multi-resonator. The encoded data will be retransmitted to the RFID reader by the tag transmitting antenna, also in frequency spectrum form. By comparing the interrogation signal and encoding signal, the environment change could be observed.
Considering special criteria of the monitoring system, an Ultra Wide-Band (UWB) antenna is chosen as the transmitting and receiving antennas. UWB could provide high-bandwidth and RF spectrum during communication. The bandwidth of UWB antenna could achieve 2GHz-10GHz, which is reasonably high compared to other antennas. Another advantage of this antenna is it requires very low energy level, which is suitable for small tag and control system. One of the drawbacks of an UWB antenna is it only works for short-range transmission (about 40cm), [15] [16]. UWB antennas could fulfill the criteria for some short-range monitoring system.

For future improvement, a spiral antenna, fed by CPW may be tested and designed to the proposed system. The two spiral elements are simultaneously coupled to a single feed line and produce a circular polarization. For a CPW fed antenna, the spiral antenna and the feeding structure are fabricated on the same plane of the substrate so that the circuit process and the position alignment could be simplified.
4.2.2 Frequency Encoding

In the RFID system, we measure the change in the system by comparing the gain and insertion loss of the interrogation signal and encoding signal. Figure 2 shows the sketch of the frequency shifting before and after encoding. The black solid curve represents insertion loss of the receiving RF, which is before frequency encoding. We can see from the figure that there are three “grooves” at different frequencies for the insertion loss. If we mark the three peaks of the grooves as a binary signal “1” and others as “0”, we get a binary sequence which contains several 0s and three 1s. The RF signal then goes through the multi-resonator, if the monitored property of an object, such as temperature or pressure, changed, it will cause some change to the encoding RF signal [17]. The encoding insertion loss is the red broken line in Figure 4.2-2. In ideal conditions, there will be a frequency shift that can be observed from Figure 4.2-2. If we create a new binary sequence, the position of 1s will be shifted. The amount of frequency shifting is the amount of property change. One of the applications to be studied is the use of such devices for wireless monitoring of chem-bio sensors. Since it uses the RF signature, we can also call this as RF signature sensor (RFSS) [18].
4.3 Objectives of Research

RFID system includes both software and hardware design. In the EM design field, several components are required. First of all, two antennas, transmitting and receiving, are doing the communication work for the whole system. Second, a multi-resonator sensor is needed to develop multi-resonance signature for EM signals. With the help of the previous chapter, the research focus is on designing a multi-resonator sensor and builds the electrical model of the multi-resonator sensor. This sensor could receive the signal from the base station; generate the resonance and send the signal back to the RFID reader.
4.4 Design of the RFSS

Several requirements need to be researched for designed resonator.

1. The device should be designed on CPW base.

2. The size of the device should be small enough.

3. The resonance of the device should be deep and narrow (high Q quality factor).

Based on above requirements, a slot spiral resonator has been designed:

Figure 4.4-1 part (a) and (b) shows the design of a single slot spiral resonator.

There are two edge ports and a slot spiral shape on the transmission line. In the previous chapter, the objective focuses on the relationship of the conductor
dimension and inductance value, the resonance of designed inductor doesn’t need to be as good as other published devices, but in the real resonator design, small resonance depth is not acceptable.

After doing research, we found that slot spiral shape creates larger coupling effect. The spiral slot can be seen as an inductor and the more laps the spiral slot has, the bigger the inductor will be.

4.5 Test Results and Improvement

4.5.1 Simulation Result of Single Slot Spiral Resonator

Figure 4.5-1 is the simulation result of the resonator. A resonance can be observed around 8.3 GHz frequencies with 8.5dB power loss. According to figure 4.5-1, we could use a -3dB cutoff frequency method to calculate the Q-factor.

\[ Q = \frac{f_0}{f_2 - f_1} \]  

Equation 10

F0 is center frequency point, which equals to 8.3GHz. F1 and f2 are the two cutoff frequencies at -3dB. In figure 4.5-1, f1=8.22GHz, f2=8.38GHz. The Q-factor of this device is approximately 26.7. This is a high Q-factor and has large improvement compared to the previous chapter. But for design requirement, the center frequency 8.3GHz is a bit high. Some improvement needs to be done to lower the center frequency while keeping the resonance depth.
4.5.2 Attempts to Improve Single Slot Spiral Design

If we look back to Figure 3.3-6, it shows when the number of the turns increases, the center frequency of resonance shifts to left, which is smaller. A attempt has been make to verify whether this relationship also work on slot spiral inductors.

In Figure 4.5-2, we change the slot shape by adding one and half laps more of the spiral slot, expecting to shift the resonance center frequency to left and deeper peak and the certain frequency point. The result is shown in figure 4.5-2 and 4.5-3. At figure 4.5-3, the resonance frequency shifts to 7.3GHz, this agrees with the previous chapter’s research result.
In the RFID system, 10dB loss can’t fulfill the requirement. Due to size and shape limit, a resonator with several loops could not design. In previous chapter, a two layer design was utilized to increase the inductor value. Another attempt has been made to verify if put several slot spirals in series, which could increase the coupling effect and improve the insertion loss.
Another attempt was made, the design of serial slot spiral resonator is shown in figure 4.5-4. Figure 4.5-5 shows the simulation result of serial slot spiral resonator.

Resonance center frequency has increased to 7.55GHz, but resonance point has significantly changed to -20.32dB.

Figure 4.5-4   Multi-resonator RFSS
4.6 Summary of Multi-resonator Sensor Results

In conclusion, slot spiral is an acceptable method to generate resonance in a RFID tag. In order to make the resonator tunable, a BST material will be added under the top layer. Following the conclusion in Chapter 3, we are able to change the shape of spiral device to meet our requirement. This also proves that the result from Chapter 3 is correct.
While attempting to design a resonator for RFID tag, some difficulties were encountered on how to change the resonance frequency. After a lot of failed attempts, a new idea to investigate multi-layer resonators was conceived. Our lab has done a lot of work on coupling capacitors, such as varactor with BST thin films design [19]. There was no related research which focuses on coupled inductance. In order to understand the coupling effect, both capacitor and inductors need to be studied. With this as motivation, we began the thesis research on finding correlation between inductance value and conductor dimension.

For the first part of this thesis a simple electric circuit model was obtained from inductor structures; by turning the lumped element value in the electric circuit, S11 curve of electric circuit matches S11 curve of EM structure simulation. By looking at the inductance value of the circuit, it proves the assumptions that were made at the beginning of Chapter 2.

1. Increase of conductor length (turns) will cause inductance value to increase.
2. Increase of conductor width will cause inductance value to decrease, but mainly capacitor change.

Following the inductor study, a multi-resonator based rf signature sensor (RFSS) was designed by adding multiple slot resonators. The resonance frequency has been shift down for 0.8 GHz, which was expected. On the second stage, by putting three slot spirals in a series, the result got about 0.6GHz frequency shifting, but significantly changed the Q factor (26.7~ 50).

Some future work needs to be done to make the slot spiral design a working RFID tag. In order to transmitting and receiving the signal, antennas need to be adding into the design. We have attempted to put two patch antennas one in vertical position and one in horizontal position. This will improve the isolation between each antenna. Due to the limited size of test room and noisy environment, the test result didn’t show as we expected. More research needs to be done include analysis of noise and loss, filter design and amplifier design.
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APPENDIX

APPLICATION OF CPW BASED CIRCUIT IN OPTICAL MODULE –
INTRODUCTION OF INTERNSHIP JOB IN FINISAR CO.

1 Introduction of Finisar

Finisar is one of the most prosperous companies in the world which research
and produce optical communication modules. In 1992, Finisar release the first 850nm
multi-mode transceiver module in the world. During the next decade, Finisar
continues there first position in optical communication business. They developed the
first transceiver with digital diagnostic function; SFP module, and CFP module which
works at 100GHz frequency. Until now, Finisar Co. owns 39 patents in United States,
and there are 319 patents are during application process. Finisar has developed
number of innovative technologies in optical communication area; the company stays
in top position of the related business.

2 SFP Module

A SFP hot pluggable optical module is shown in Figure 3-1. The component
structure is Figure 3-2. In this module, signal is send by Transmitter Optical Sub-
Assembly (TOSA). TOSA is drive by diode laser chip, the function of this chip is to
keep the bias current on TOSA, and drive laser diode in order to transmit the optical pulse. As the receiver, Receiver Optical Sub-Assembly (ROSA) is constituted by PIN diode and TIA. TIA could convert optical signal into electrical signal.

When optical link is low long or laser power is too low, TIA output signal on ROSA is unstable. At this condition, a post amplifier is added after TIA, which amplifies the TIA signal predictably. The main function of post amplifier is to use amplify small signal with low noise, at the meantime, provide standard logic current level. The high speed parallel chip could decode the amplified signal.

There are different kinds of electric circuits inside an optical module; it includes driver for laser diode, digital circuit for LVPECL and TTL I/O buffer; also
the post amplifier simulation circuit which amplifies small signal. These electric circuit works at the microwave frequency larger than 4GHz, and being arranged in a very limit space. At such high frequency, any electric wire in the PCB board could generate and receive RF signal as antenna, which cause serious harassment.

In order to eliminate the interference between electric circuits, the design of source circuit becomes very important. RF circuits are very sensitive to source noise, especially for burr voltage and other high frequency harmonic waves. If the source circuit doesn’t have decoupling process, the burr voltage will cause signal distortion.

One of the effective solutions for distortion between each circuit level is to use star wiring. Star wiring supplies voltage to each module on the board directly. In PCB board of the optical module, the transmitting and receiving parts are divided and each part has separate source pin. Inside of transmitting and receiving parts, star wiring is used to make sure the digital part and analog part has separate electrical source, and decouple at the source wire pin. At last, the filter will eliminate the distortion from digital circuit.