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# Design of LTCC-based high-Q coil for 2 GHz active magnetic field probe.

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*Abstract*—A high-Q coil based on LTCC process has been designed. The coil is to be applied for high sensitivity magnetic field probe at 2 GHz. The probe is going to be used for magnetic near field measurement on LTE-based IC chip
**Keyword Magnetic field probe, High-Q coil, LTCC**

## I. Introduction

Need for high frequency and high spatial resolution magnetic-field probes is increased recently to investigate the noise source and noise flow path inside the highly complex and densely integrated LTE-based IC chips of the present and upcoming generations. Proper understanding of the sources and paths of noise propagation is necessary to countermeasure it in terms of electromagnetic compatibility (EMC) [1].

The miniaturized shielded-loop probe is a known probe used to measure the distribution of the magnetic near-field of a large-scale integration (LSI) chip on a printed circuit board (PCB). A planar thin-film-type shielded-loop probe made by pattern plating is usable in the frequency range up to 7 GHz, and offers 10-μm class spatial resolution simultaneously [2] – [5].But the coil on the top of probe to measure the noise signal is very small. Therefore output signal level to be observed when measuring is weak and noisy. High sensitivity probe is needed.

Objective of this research is to design a high-Q coil for high sensitivity active magnetic field probe at 2 GHz. The idea is to employ thick metal line to reduce the resistance of the coil, and to use narrow line width to achieve a high spatial resolution. LTCC (Low Temperature Co-fired Ceramic) processing technique is chosen for the fabrication of the coil with 5 μm line thickness and 5 μm line width.

## II. Active Magnetic Field Probe

### A. Constitute of the probe

Fig. 1 shows the structure of active magnetic probe. The probe is built up with coil and amplifier. According to Faraday's law of electromagnetic induction, alternating weak noise through the coil will induce a voltage at the ends of the coil. The voltage will be amplified by the amplifier and then be measured by a spectrum analyzer. The noise level, then, can be observed as the output of the probe in dBm.

### B. Sensitivity

To measure weak noise signal, high sensitivity is needed. The way to increase sensitivity is reducing the noise from coil and amplifier. So high SNR (Signal-to-Noise Ratio) is needed. The equation of SNR is

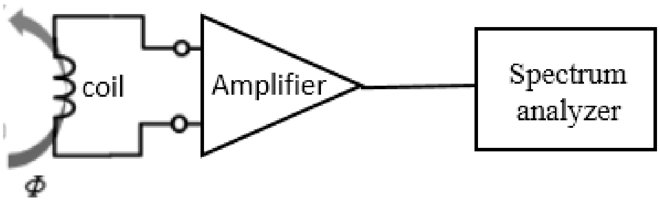



Figure 1. Active probe with measuring tools

$$SNR = \left(\frac{A_S}{A_N}\right)^2 \qquad (1)$$

In the equation $A_S$ is the value of detected voltage from coil. $A_N$ is the value of noise in probe circuit.

The noise of the probe ($P_x$) is made up of thermal noise of the coil ($P_i$) and internal noise of the amplifier and is given by:

$$P_x = P_i + NF \qquad (2)$$

NF is the noise figure of the entire amplifier circuit. In addition, thermal noise $A_{NC}$ from the coil is

$$A_{NC} = \sqrt{4kTRB} \qquad (3)$$

Here, k is the Boltzmann constant, T is temperature in K, R is the loop coil resistance, and B is the bandwidth. At this time, the input thermal noise power $P_i$ is

$$P_i = 10\log\left(\frac{A_{NC}^2}{4R}\right) = 10\log(kTB) \qquad (4)$$

Noise voltage $A_N$ is using the equivalent input noise power $P_X$,

$$A_N = \sqrt{4N_x R} \qquad (5)$$

$$N_X = 10^{\left(\frac{P_X}{10}\right)} \qquad (6)$$

Detection voltage is the voltage induced in the loop coil of the probe. According to Faraday's law of electromagnetic induction, induced voltage is given by:

$$A_S = -\frac{d\Phi}{dt} \tag{7}$$

The Φ is the flux through the loop coil. Here, when the induced voltage is assumed to the voltage from mutual induction by sources and the loop coils of the magnetic field, the flux linkage Φ is

$$\Phi = k_C\sqrt{L_1L_2}I_1 + L_2I_2 \cong k_C\sqrt{L_1L_2}I_1 \tag{8}$$

$k_C$ is binding constants, $L_1$ is self-inductance of the source, $L_2$ is the self-inductance of the loop coil, the $I_1$ current through the origin, $I_2$ is the current through the loop coils. $L_2I_1$ means the flux of coil-self is very small can be ignored. Therefore, the effective value $A_S$ of the signal voltage is

$$A_S = \omega k_C\sqrt{L_1L_2}I_1 \tag{9}$$

SNR of the active magnetic field probe is (1), using (5) and (9) [6],

$$SNR = \frac{\omega^2 k_C^{\,2} L_1 L_2 I_1^{\,2}}{4N_X R} = \left(\frac{k_C^{\,2} L_1 I_1}{4N_X}\cdot\omega\right)\cdot Q \tag{10}$$

$$Q = \frac{\omega L_2}{R} \tag{11}$$

Q is the Q value of the loop coil. From equation (10), it is found that the sensitivity of the active magnetic field probe is proportional to the Q value of the loop coil. Accordingly, it was a design guideline to increase Q of the loop coils in this work.

## C. *Spatial resolution*

Another important parameter of the probe is spatial resolution, which means distance the probe moved when output reduced by 6 dB like fig. 2 shows. Spatial resolution shows the ability to distinguish the lines in circuit. It mainly depends on the distance between coil inner side and circuit that called lift-off. Reduce line width can reduce the lift-off because it can set the probe more closely to the circuit and then increase spatial resolution.

# III. DESIGN ELEMENTS OF COIL

## A. *Quality factor of coil*

From equation (11) Q is depend on L R and ω. To calculate L, Greenhouse's one turn spiral inductance equation at direct-current is used as given by: [7]

$$L=0.002s\left\{\ln\left(\frac{2s}{w+t}\right)+0.5+\frac{w+t}{3s}\right\} \tag{12}$$

In the equation, s is the total length of coil's line, and w is the width of coil's line, and t is the thickness of coil's line. Because $\ln\left(\frac{2s}{w+t}\right)$ has small influence to L, so a larger s can contribute to a large L. To avoid influencing the spatial resolution, increase coil's length instead of coil's width is the best way.

## B. *Resistance*

At 2 GHz because of skin effect shown in Fig. 3 the current will only pass the surface of line (dark part). So at high frequency resistance will become larger because the area which current passes, Skin depth can be used to calculate the effective area and then calculate resistance.

$$\delta=\sqrt{\frac{2\rho}{\omega\mu_r\mu_0}} \tag{13}$$

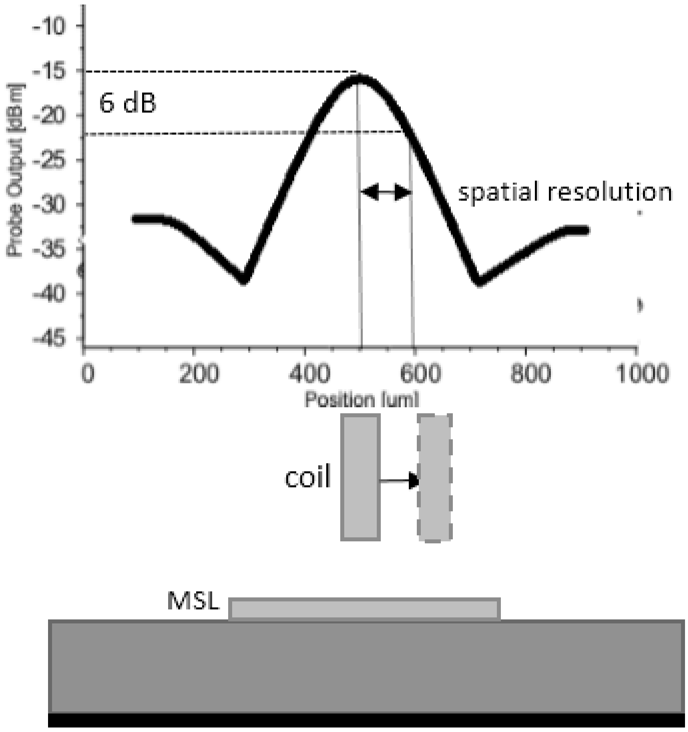



Figure 2. Coil scanning the MSL and get the output.

In the equation ρ is the resistivity of the conductor, ω is angular frequency of current, $\mu_0$ is the permeability of free space. $\mu_r$ *is* Magnetic permeability of the conductor. At 2 GHz the copper's skin depth is 1.5 μm. The way to calculate R is

$$R=\frac{\rho l}{wt-(w-2\delta)(t-2\delta)} \tag{14}$$

In the equation w is the width of coil's line, and t is the thickness of coil's line. When line thickness is less than two times of skin depts. (3μm), increase can reduce resistance very effectively because at this time current passes though everywhere of the line. When w and t is larger than 3μm, increasing w and t is not an effective way to reduce resistance because in the middle of line current is nearly zero. However the area is still increasing so the resistance will be reducing.

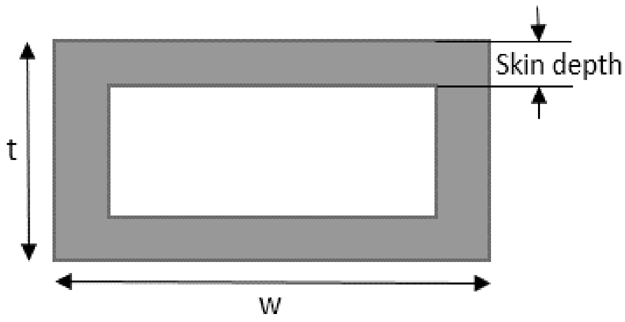



Figure 3. Sectional view of coil's line with 2 GHz current

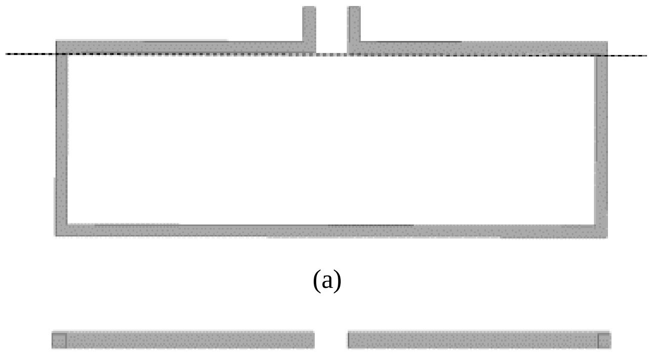
### C. LTCC(Low temperature co-fired ceramic)

We designed coil based on LTCC process. Since the thickness of line in LTCC can be much larger than that in the CMOS process. This will result in the reduction of the resistance of coil, which in turn enhance the Q of the coil. In this design the coil will fabricated on the surface of LTCC board to avoid the influence of via resistance. .

## IV. DESIGN AND SIMULATION OF COIL

### A. design of the coil

According to the (12) (14) and design rules from LTCC company, Fig 4 shows the general shape of coil designed.



(a)

(b)

Figure 4. Top view (a) and sectional view (b) of the coil.

Line thickness and line width is 5μm, which is larger than 2 times of skin depth (3 μm), and it is also larger than the line in CMOS process. But not too large to degrade the spatial resolution of the coil. .

The coil will be terminated to two pads which are also placed on the surface of LTCC. These coil pads on the LTCC will be connect to the pads on the amplifier's chip, to complete the probe.

### B. Simulation of the coil

Three-dimensional electromagnetic simulation software (HFSS- Ansoft) has been used to simulate the coil model to get the Y parameters and using a π-type equivalent circuit calculate resistance inductance and Q-factor.

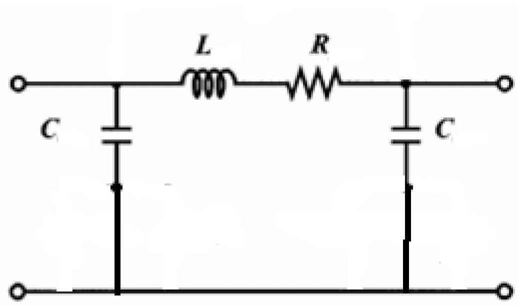
Fig.5 shows the equivalent circuit of the coil and coil model in HFSS. L is the inductance of the coil. R is the resistance of the coil, and C is the capacitance between coil and LTCC board. The coil is on the surface of LTCC board and two ports connect with the both sides of coil and PEC (perfect electrical conductor) as the ground is around the coil.

The HFSS will simulate the model and calculate Y parameters. Using Y parameters. L R and Q of the coil are calculated and given as

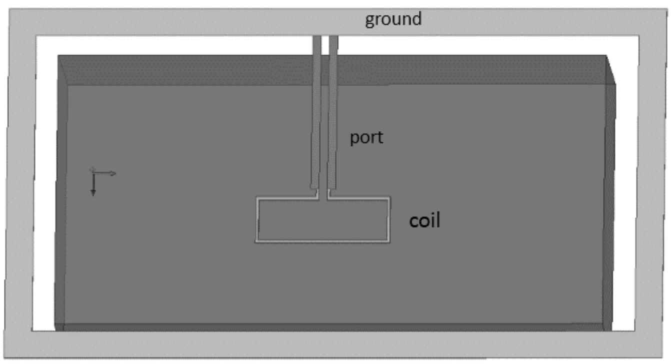
$$Q=\frac{im(Y_{11})}{re(Y_{11})} \tag{15}$$

$$R= re(\frac{1}{Y_{12}}) \tag{16}$$

$$L=\frac{im(\frac{1}{Y_{12}})}{\omega} \tag{17}$$




(a)




(b)

Figure 5. Equivalent circuit (a) and the Simulation model in HFSS (b)

Table.1 shows the designed coil's L R and Q, compare with our lab's fabricated coil in CMOS process. The resistance become much less because CMOS process cannot provide large line thickness. The Q 11.2 for LTCC coil that will reduce the coil's noise and have a good SNR of the coil.

TABLE I. COIL'S ELCCTRICAL CHARACTERISTICS AT 2 GHZ

| **Simulate item** | **Table Column Head** | | |
|---|---|---|---|
| | ***LTCC coil (design)*** | ***CMOS coil (fabricated)*** | ***unit*** |
| L | 0.61 | 0.97 | nH |
| R | 0.68 | 4.84 | Ω |
| Q | 11.2 | 2.47 | - |
| size | 75*375 | 100*50 | μm |

## V. SUMMARY

In this research, the target is to design a high-Q coil based-on LTCC process for magnetic field probe at 2 GHz. The designed coil has a larger line thickness than CMOS process that will reduce resistance of coil. The simulated value of the Q-factor of LTCC coil is 11.2, which is much larger than CMOS coil fabricated in our lab before. A high SNR is be expected from this near field magnetic probe once this LTCC-based coil is connected with the amplifier.

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