Experimental Study on Spiral Inductors

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ABSTRACT

An experimental study of spiral inductor loss is described quantitatively. For the evaluation of the loss, over one hundred types of spiral inductors with different figures (square, circle, octagon) and line/space widths are fabricated, then π-network equivalent circuits are extracted from measured s-parameters. The results show that the resistance R of circular and octagonal shaped inductors is smaller by 10% than that of a square shaped inductor with the same inductance value. They also indicate that minimization of the line space is more effective for reducing the loss of the inductor with the same inductance value than maximization of the line width.

INTRODUCTION

It is very important to reduce loss of spiral inductors in order to obtain higher performance of high power, high efficiency amplifiers and low noise amplifiers. To reduce the loss of spiral inductors, the spiral inductor must be accurately characterized. Existing commercial electromagnetic field simulators lack sufficient accuracy, because it is difficult to estimate the conductor loss, dielectric loss of GaAs and skin effect.

In this paper, to evaluate the loss, over one hundred different spiral inductors are fabricated and measured changing their figures and line/space widths as parameters. To estimate the loss, the π-network equivalent circuits are used to extract the resistive and inductive elements. The simplified π-network equivalent circuit is used for the extraction because it extracts the circuit parameters uniquely and it is easy to incorporate in circuit simulators[1]. The applicable frequency range of this equivalent circuit has been investigated. Some important conclusions regarding spiral inductor loss have been derived.

MEASUREMENT AND EXTRACTION

We measured the s-parameters of the spiral inductors with a method of on-wafer probing. The measured frequency range is from 0.1 GHz to 30.1 GHz.

Figure 1 shows the measured patterns of the spiral inductors which are fabricated on a 100 μm thick GaAs substrate. Some portions of the spiral conductor are formed as air bridges to avoid short circuits with the straight line as shown in Fig.1. Table I shows the dimensions of the square shaped spiral inductors for the evaluation of loss. The spiral inductors except for the square type have a conductor thickness of 7.4 μm and line/space=10/10 μm.

Figure 2 shows a π-network equivalent circuit used for the evaluation of the loss. The equivalent circuit

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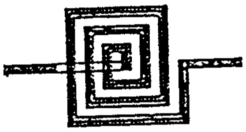
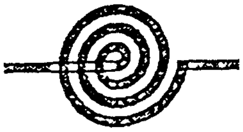
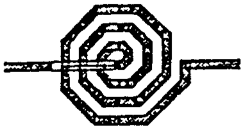


(a) Square



(b) Circle



(c) Octagon

Fig. 1: Measured patterns of the spiral inductors.(a) Square, (b) Circle, (c) Octagon.

Table I: The dimensions of the square spiral inductors evaluated for loss.

Thickness t [μm]	Line/Space (w/s) [μm]
2.0	5/5, 5/10, 10/10, 20/10, 40/10,50/10, 10/5, 10/20
3.8	10/10
4.8	10/10
6.4	10/10
7.4	10/10

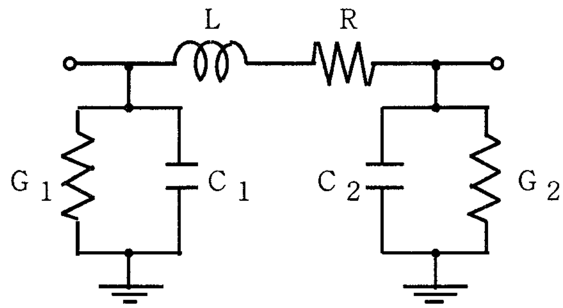


Fig. 2: Π-network equivalent circuit used for the evaluation of the loss.

parameters are extracted analytically using equations (1)-(3) with the Y-parameters transformed from the measured s-parameters[1-4].

$$R + j\omega L = -1 / Y_{12} = -1 / Y_{21} \quad (1)$$

$$G_1 + j\omega C_1 = Y_{11} + Y_{12} \quad (2)$$

$$G_2 + j\omega C_2 = Y_{22} + Y_{12} \quad (3)$$

The equivalent circuit parameters are extracted at each frequency.

RESULTS

Before the comparison of the extracted parameters, an upper limit of frequency for the equivalent circuit (Fig.2) should be verified assuming that the extracted inductance L is constant. To investigate the applicable frequency range, $Im(-1/Y_{12})$ in eq.(1) is calculated both with the measured s-parameters for each frequency and with the equivalent circuit (L=7.1 nH, coupling capacitance between the spiral conductors C=-0.01pF, -0.005 pF, 0 pF, 0.005 pF).

Figure 3 shows a comparison of $Im(-1/Y_{12})$, which is calculated using measured s-parameters, with $Im(-1/Y_{12})$, which is calculated using constant inductance (L=7.1 nH) and the coupling capacitance. The simple equivalent circuit employed in this paper (C=0 pF) is valid up to 5 GHz which is one third of the first resonant frequency. When using the coupling capacitance (C =-0.005pF), the equivalent circuit is valid up to 10 GHz which is two thirds of the first resonant frequency. In this paper, the equivalent circuit has been used at a

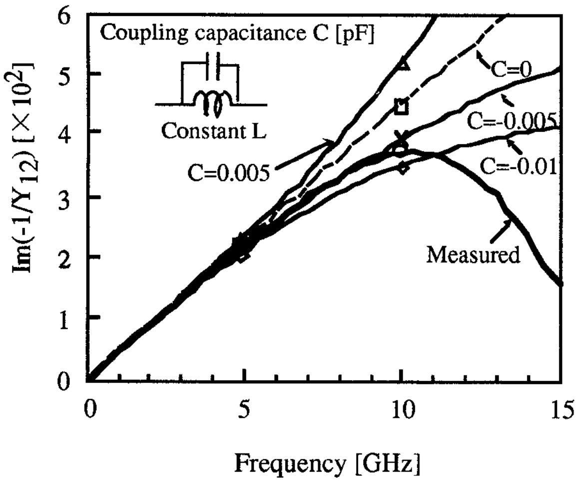


Fig. 3: Comparison of measured $Im(-1/Y_{12})$ with $Im(-1/Y_{12})$ calculated with constant inductance (L=7.1 nH) and the coupling capacitance (C=-0.01 pF, -0.005pF, 0pF and 0.005pF).

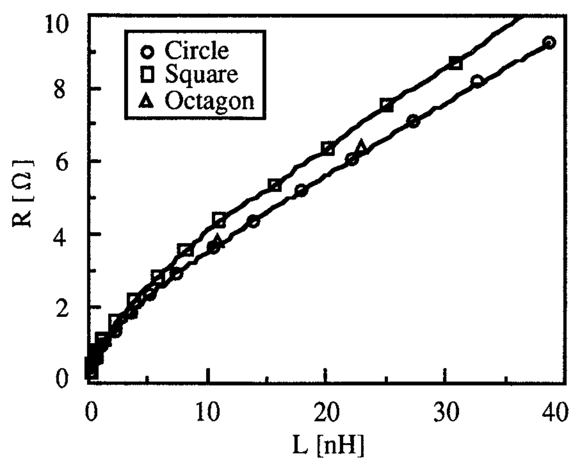
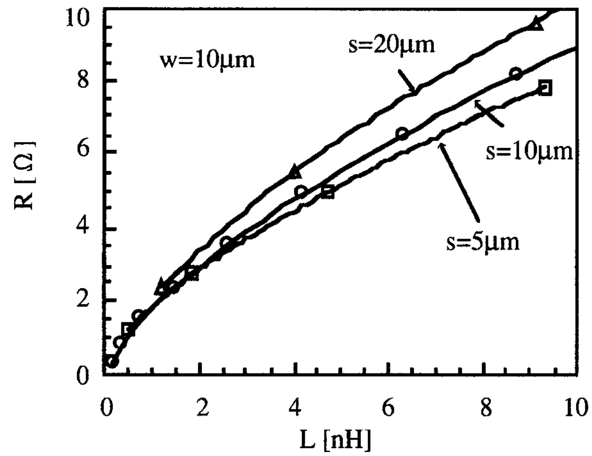
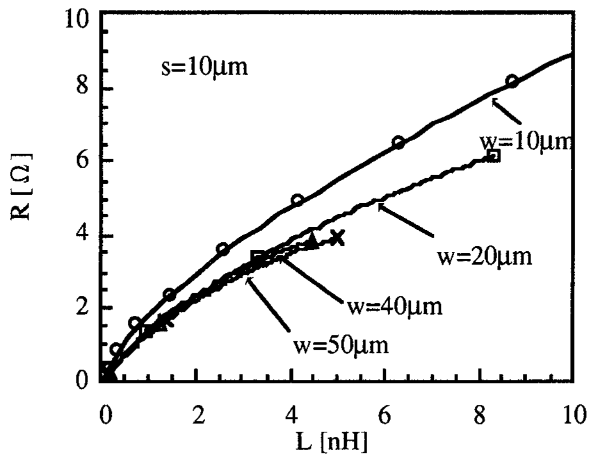


Fig. 4: Comparison of resistance R of the spiral inductors with the different figures and turns extracted at 1 GHz . (Conductor thickness t=7.4um)



(a) Constant width



(b) Constant space

Fig. 5: Comparison of resistance R of square spiral inductors with the different w/s and turns extracted at 1 GHz (Conductor thickness t=2.0 μ m). (a) Constant width, (b) Constant space.

frequency less than one third of the first resonant frequency. In practice, spiral inductors integrated in MMICs for mobile communications are generally used for such low frequencies. So, the simple equivalent circuit without coupling capacitance makes it easy to extract the circuit parameters uniquely. However, the resistance R depends on frequency because of skin effect. So resistance R at 1 GHz has been used for the comparison in this paper.

Figure 4 shows a plot of resistance R and inductance L for the comparison of the different figures. Many spiral inductors with different turns have been fabricated, and from which the equivalent parameters R and L have been extracted at 1 GHz. It can be found that the resistance R of circular and octagonal shaped inductors is smaller by 10% than that of a square shaped inductor at the same inductance L.

Figure 5(a) shows a lot of same resistance R and inductance L of the rectangle shaped spiral inductors but using the line space s as a parameter. When the line space s becomes narrow, resistance R decreases at the same inductance L.

Figure 5(b) shows the same plot but using the line width w as a parameter. When the line width becomes wide, resistance R decreases at the same inductance L. However, when the width is larger than 40 μm, the resistance R does not decrease any more and reaches saturation. This is because the line length increases to keep the inductance L, so that the resistance R increases according to the line length. These results indicate that to narrow the space is more effective for reducing the loss than to widen the line. The demerit of widening the line is that the resonant frequency becomes lower according to the increase of the capacitance C_1 and C_2, which are the capacitances between the line metal and the ground plane.

CONCLUSION

The applicable frequency range of the simple π-network equivalent circuit for the analysis of spiral inductors has been investigated. For the analysis the equivalent circuit parameters of over one hundred types of spiral inductors have been extracted. The results show that the resistance of circular and octagonal shaped inductors is smaller by 10% than that of a square shaped inductor with the same inductance L. They also indicate that to narrow the space is more effective for reducing the loss of the inductor than to widen the line.

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