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Rotation Angle Measurement System using Printed Spiral Inductor and Attractor of Chua's Circuit

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Abstract—Loosening of some hidden screws in a mechanism is a big problem. Serious troubles might be induced. Therefore, a rotation angle detection system is needed. In this paper, we suggest a rotation angle measurement system with printed spiral inductor and an attractor of Chua's circuit. The shape of this printed spiral inductor is a chaos attractor. We call this Printed Spiral Inductor(PS-Inductor) Printed Chaos Spiral Inductor(PCS-Inductor).

1. Introduction

We think that a big trouble might be induced by a hidden screw which looses by vibration of a machine and so on. Therefore, we can say that automatic angle detection system of rotations is very important. A rotation angle detection method, which is cheap and good accuracy, is desired. Therefore, researches of rotation angle indicators are carried out up to now[1]–[4]. For example, there are measurement methods with resolver[1], optical rotation sensors[2], magnetic angle sensors[3], and the image recognition methods[4].

We suggest a rotation angle measurement system using two PCS-Inductors. Because, spiral inductor is very thin. Therefore, to overlap some spiral inductors is easy, and to use mutual inductances between spiral nductors is easy.

A spiral inductor, which is called a primary PCS-Inductor, is overlapped on another one, which is called secondary PCS-Inductor. If the secondary PCS-Inductor is fixed, and the primary PCS-Inductor is rotated, a mutual inductance between PCS-Inductor and the secondary PCS-Inductor is changed, and a rotation angle can be measured. An inductance is depend on a spacing between conductors of the spiral inductor[6]. Therefore, we can think that the mutual inductance between primary PCS-Inductor and secondary PCS-Inductor is depend on overlapping area. If PS-Inductor, which are made coupling semicircles, are used for the system, we can think that a variation of the mutual inductance is small because a variation of the overlapping area is small. Therefore, in this paper, a chaos attractor of Chua's Circuit is used for shape of a spiral inductor. The rotation angle measurement systems with PS-Inductors and with PCS-Inductors are actually made, and these performances are investigated. We are compared the system of PCS-Inductor to the system of PS-Inductor.

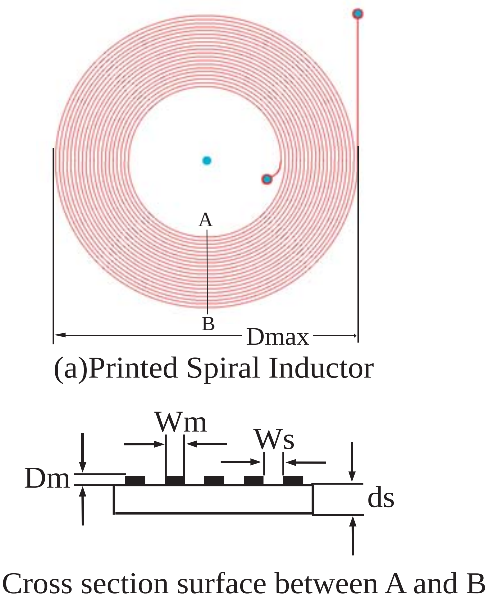


Figure 1: Printed Spiral Inductor.

2. Printed Spiral Inductor

In this study, we create two kind of spiral inductors on a printed board.

1. A spiral inductor is built up of semicircles, and is called Printed Spiral Inductor(PS-Inductor).
2. A spiral inductor is created using a chaos attractor. We name it Printed Chaos Spiral Inductor(PCS-Inductor).

2.1. PS-Inductor

Structure of the PS-Inductor is decided by six parameters(see Fig. 1). The specification of PS-Inductor are set as follows:
Maximum diameter:D_{max}=40[mm],
Conductor width:W_m=0.1[mm],
Spacing:W_s=0.1[mm],
Number of half-turn:41[half-turn],
Thickness of Conductor:D_m=35[μH],
Thickness of substrate:d_s=1.58[mm],
Material of substrate:Bakelite.

A dextral PS-Inductor is shown in Fig. 1. In this study, we make a dextral PS-Inductor and a sinistral PS-Inductor.

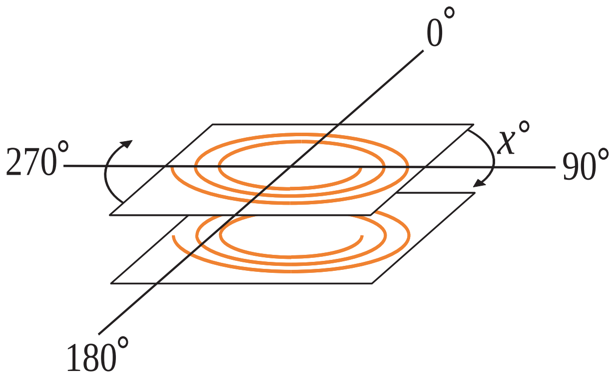
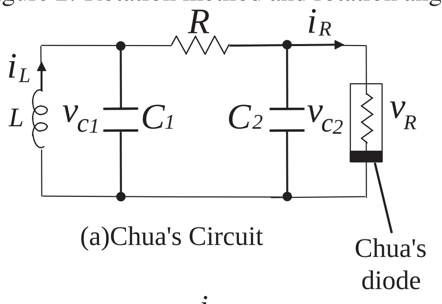
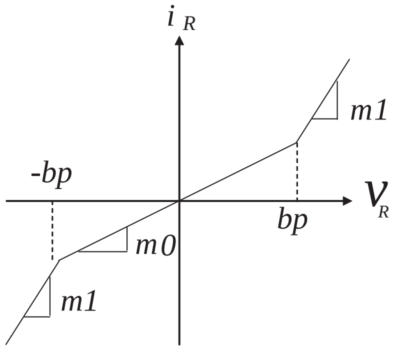


Figure 2: Rotation method and rotation angle.



(a)Chua's Circuit



(b)Chua's diode specification

Figure 3: Chua's circuit.

The each parameter of each PS-Inductor is same value. A PS-Inductor, which is called secondary PS-Inductor, is overlapped on another one, which is called primary PS-Inductor, as like Fig. 2, and a mutual inductance between PS-Inductors is measured while an secondary PS-Inductor is rotated.

A state, which two PS-Inductors are overlapped exactly, is assumed as 0 degree(see Fig. 2). Therefore, dextral and sinistral PS-Inductors are made. Measurement results of these actual PS-Inductors are as below. An inductance of dextral PS-Inductor is 17.24 μH. An inductance of sinistral PS-Inductor is 17.07 μH.

2.2. Printed Chaos Spiral Inductor

<Chua's circuit>
Figure 3(a) shows Chua's circuit model, and differential equations of Chua's circuit are shown Eqs. (1)–(3).

Table 1: Parameters of Chua's circuit.

C1	*1.0/9.0*
C2	*1.0*
L	*1.0/7.0*
G	*0.65*
m0	*-0.5*
m1	*-0.8*
bp	*1.0*

$$C_1 \frac{dv_{c_1}}{dt} = \frac{1}{R}(v_{c_2} - v_{c_1}) - g(v_{c_1}), \tag{1}$$

$$C_2 \frac{dv_{c_2}}{dt} = \frac{1}{R}(v_{c_1} - v_{c_2}) + i_L, \tag{2}$$

$$L \frac{di_L}{dt} = -v_{c_2}, \tag{3}$$

where v_{c_1} and v_{c_2} are voltages of C_1 and C_2 respectively, i_L is a current of L, and $g(v_{c_1})$ is a characteristic of Chua's diode. The characteristic of Chua's diode is shown in Fig. 3(b), and an equation of the characteristic is shown below.

$$g(v_{c_1}) = m_0 v_{c_1} + \frac{1}{2}(m_1 - m_2)|v_{c_1} + b_p| + \frac{1}{2}(m_0 - m_1)|v_{c_1} - b_p|. \tag{4}$$

These differential equations are simulated by using fourth-order Runge-Kutta method, and we get a chaos attractor. These parameters are shown in Table 1.
<Optimization of the attractor>

PCS-Inductor using the chaos attractor is needed to fulfill below conditions for our rotation angle measurement system because an inductance of the PCS-Inductor should be large value. If the inductance is too small value, we must use very high frequency, and cost of our system becomes high.

- The line must not intersect with the line when the attractor is mapped to the X-Y plane.

An inductance is depend on a spacing between conductors. We can think that the mutual inductance between primary PCS-Inductor and secondary PCS-Inductor is depend on overlapping area of the spacing. Therefore, the shape of PCS-Inductor like a circle is desired. The chaos attractor used in our system is shown in Fig. 4.

Each coordinate of the attractor is assumed as (x_k, y_k), and each coordinate of an optimization attractor is assumed as (X_k, Y_k). The "k" is changed from 0 to the number of total points of the attractor. Each coordinate of the base attractor is remap below equations.

$$X_k = 33x_k, Y_k = 99y_k \tag{5}$$

The dextral PCS-Inductor are shown in Fig. 5.
We make dextral and sinistral PCS-Inductors using the optimized chaotic attractor. Measurement results of each actual PCS-Inductor are shown below. When measurement frequency is 60 MHz, an inductance of dextral PCS-Inductor is 4.12 μH, and an inductance of sinistral PCS-Inductor is 4.32 μH. These PCS-Inductors are overlapped each other in a similar way to PS-Inductors(see Fig. 2).

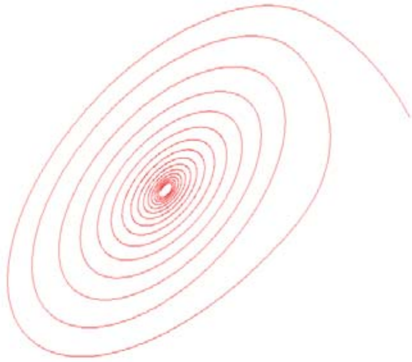


Figure 4: A chaos attractor without optimization.

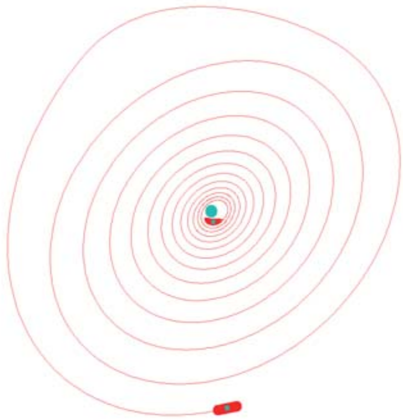


Figure 5: A dextral optimized PCS-Inductor.

3. Rotation Angle Measurement System

In our system, the secondary PS-Inductor(or PCS-Inductor) is fixed, and the primary PS-Inductor(or PCS-Inductor) is rotated. Rotation angles are measured by voltage transmission efficiency which changed by using a variation of mutual inductance between primary and secondary PS-Inductor(or PCS-Inductor).

3.1. Circuit model

Our measurement circuit model is shown in Fig. 6. The filter circuit is constructed by using two inductors, a mutual inductor, three resistors, and two capacitors.

3.2. Rotation angle measurement system with PS-Inductors

Frequency characteristics of the system with two PS-Inductors, which are exactly overlapped each other, are shown in Fig. 7. Our rotation angle measurement system needs large variation when the mutual inductance is changed a little by rotating the primary PS-Inductor. Therefore, the frequency of v_{in} is fixed 16 MHz.

When the primary PS-Inductor is rotated from 0 degree to 360 degrees, the voltages v_{in} and v_{out} are measured every 5 degrees, and the voltage transmission gains is calculated(see Fig. 8). We need large variation of voltage transmission gains, but, large variations can not be obtained by the system with PS-Inductors.

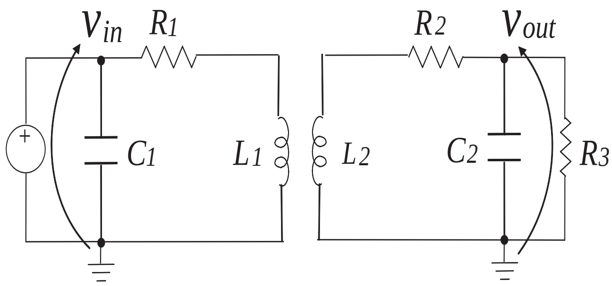


Figure 6: Rotation angle measurement system.

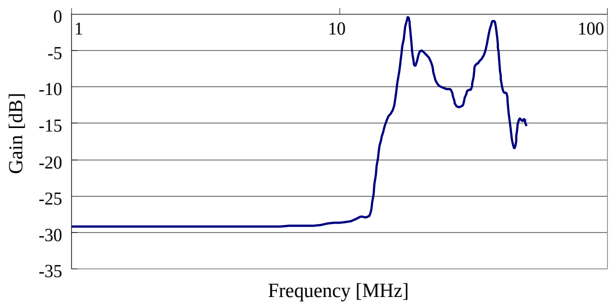


Figure 7: A frequency characteristic of the system with PS-Inductors

3.3. Rotation angle measurement system with PCS-Inductors

Frequency characteristics of the system with two PCS-Inductors, which are exactly overlapped each other, are shown in Fig. 9. A resonance frequency of our system is around 57.8 MHz.

We think that large variation can be obtained by small variation of the mutual inductance when a frequency of v_{in} is fixed as around 57.8±10 MHz. The voltage transmission gains are investigated, when the frequency of v_{in} is fixed as 1 MHz, 56 MHz, or 67 MHz. The voltage transmission gains of 1 MHz is shown in Fig. 10. The voltage transmission gains is obtained from 0 degree to 360 degrees every 10 degrees because a large variation can not be observed. We can think that detection of the rotation angle is hard if the frequency is not close to the resonance frequency. The voltage transmission gains of 56 MHz and 67 MHz are investigated from 0 degree to 360 degrees every 1 degree, and are shown in Fig. 11. The voltage transmission gains is widly changed by few rotation angles. Our system needs large variation of the voltage transmission gains, and therefore, the frequency of v_{in} fixed to around 67 MHz.

4. Conclusion

In this study, we developed a rotation angle measurement system using two PCS-Inductors. A shape of the Printed Chaos Spiral Inductor(PCS-Inductor) was used a Chua's circuit attractor. The voltage transmission gains was widely

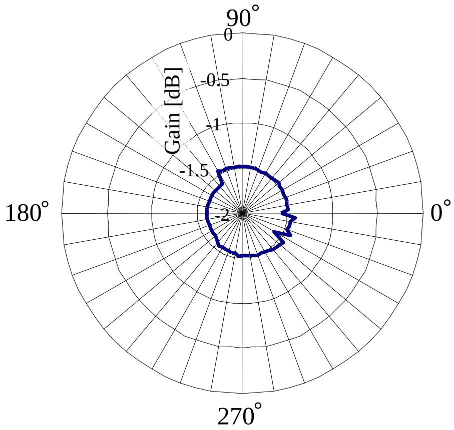


Figure 8: The voltage transmission gains of the system with PS-Inductors.

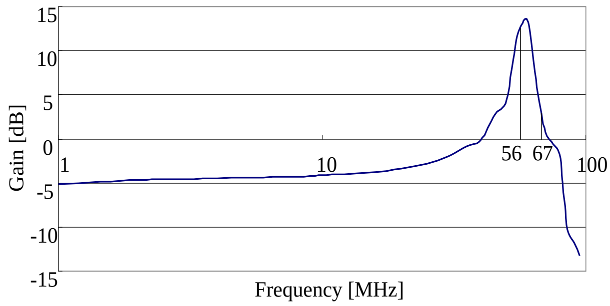


Figure 9: A frequency characteristic of the system with PCS-Inductor.

changed by rotating the primary PCS-Inductor when the frequency of the system was fixed to 56 MHz or 67 MHz. Especially, the frequency should be fixed to 67 MHz for our system. If combinations between angles and voltage transmission gains are already known and a start angle of rotation is already known, we made clear that the angle can be known by our system.

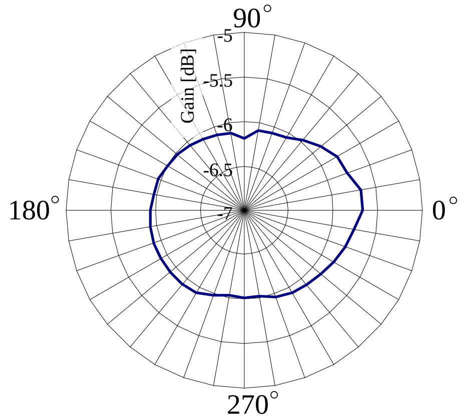


Figure 10: The voltage transmission gains of the system with PCS-Inductors(1 MHz).

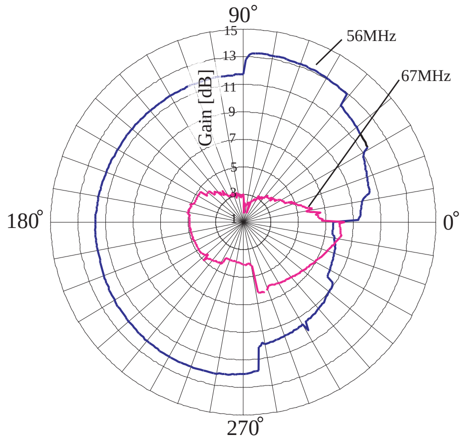


Figure 11: The voltage transmission gains of the system with PCS-Inductors(56 MHz and 67 MHz).

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