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Motion and Position Detection System using Mutual Inductance between Printed Spiral Inductors

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Abstract—
We make a printed spiral inductor (PS-Inductor) on a printed board. Because the PS-Inductor is flat and thinly, the PS-Inductor can be easily overlapped, therefore a mutual inductance between the PS-Inductor is used easily. In this paper, motion detection and position detection systems are developed by the mutual inductance between some primary PS-Inductors and a secondary PS-Inductor. Further, the finger position detection system is developed using the PS-Inductor.

1. Introduction

Recently, many elements of spiral structure are often used for some electronic products. A spiral inductor and a spiral antenna are one of the spiral structure elements respectively. A spiral antenna is usually used for compact communication systems. For example, the spiral antenna is used for the RFID system, using radio waves for starter of car engines, and locking or unlocking the car, and so on. A spiral inductor is used in the integrated circuits[1], and for compact inductors, and so on[2]. The spiral inductor is almost the same as the constructional spiral antenna. The spiral inductor is flat and thinly. Therefore, to overlap the spiral inductor is easy. In other words, mutual inductance between the spiral inductors can be used easily.

In this study, the spiral inductor is made on printed board. We call the spiral inductor a Printed-Spiral-Inductor(PS-Inductor). Some systems using some PS-Inductors for motion detection and position detection are developed. In Sec.2, we measured an inductance of a PS-Inductor by simulation and actual measurement.

In Sec.3, a motion detection system, which uses voltage transmission generated by mutual inductance between some primary PS-Inductors and a secondary PS-Inductor, is developed.

In Sec.4, a motion detection and a position detection system, which uses changed filter characteristics by mutual inductance between some primary PS-Inductors and a secondary PS-Inductor, is developed. In Sec.5, a position detection system, which uses changed filter characteristics by changing some PS-Inductors by finger, is developed.

2. Measurement of inductance of a PS-Inductor

2.1. Structure of the PS-Inductor

In this paper, we create only one kind of PS-Inductor as like Fig.1.

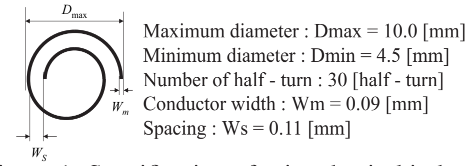

Figure 1: Specification of printed spiral inductor.

2.2. Measurements

We developed an actual measurement method [3]. In our method, the oscillator using the PS-Inductor is oscillated, and an inductance of the PS-Inductor is measured. We use a Colpitts-oscillator as the oscillator. The circuit model of the Colpitts-oscillator is shown in Fig.2. The inductance of the PS-Inductor is obtained from a oscillation frequency f and some capacitances by the circuit as follows.

$$\begin{aligned}
\alpha &= 1 - \omega^2(r_1 + r_2)R_3c_2(c_1 + C_2) - \omega^2 c_2 L', \\
\beta &= R_3(c_1 + c_2 + C_2) + c_2(r_1 + r_2) - \omega^2 L' R_3 c_2(c_1 + C_2), \\
\gamma &= R_3 - \omega^2 c_2 R_3 L', \\
\epsilon &= \frac{\alpha R_3 + \omega^2 \beta\gamma}{\alpha^2 + \omega^2\beta^2}, \\
\zeta &= -\frac{1}{\omega}\left(\frac{1}{C_1} + \frac{1}{C_3}\right) + \frac{\omega(\alpha\gamma - \beta R_3)}{\alpha^2 + \omega^2\beta^2}, \\
\eta &= \omega C_4 - \frac{\zeta}{\varepsilon^2 + \zeta^2},
\end{aligned} \tag{1}$$

and

$$L = \frac{1 + \sqrt{1 - 4\eta^2 R^2}}{2\omega\eta} \tag{2}$$

The value of inductance depends on the frequency. Therefore, we want to obtain the inductance when the frequency is 0Hz. The frequency is changed by to change capacitance, and an inductance L is estimated when the frequency is 0Hz. The inductance L is assumed as a true value. A value of inductance of the PS-Inductor is obtained as around 1.7709μH by this method.

Further, we developed a simulator using the Biot-Savart Law and the finite element method. The inductance of the PS-Inductor is around 1.8058μH.

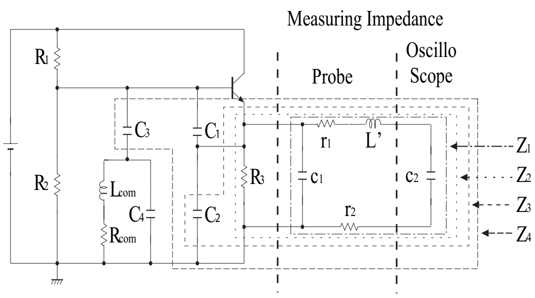

Figure 2: Circuit model.

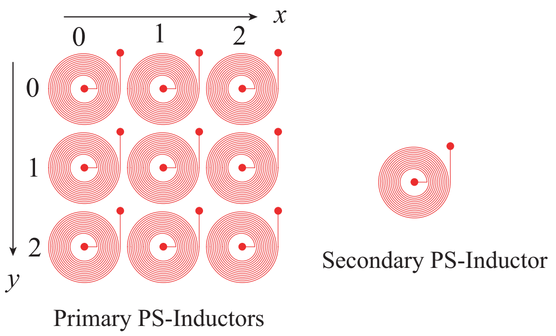

Figure 3: Printed spiral inductor(pattern1).

3. Method 1: Experiments of motion detection using PS-Inductors array

In this section, 10 PS-Inductors are used for primary and secondary circuits. In the primary circuits, 9 PS-Inductors are used as like Fig.3. We assume the x-axis and y-axis as like Fig.3. In the secondary circuits, a PS-Inductor is used as like Fig.3. The secondary PS-Inductor is overlapped with the primary PS-Inductors in the same turn direction as the primary PS-Inductors. The distance between a primary PS-Inductor and secondary PS-Inductor are fixed as 0.65mm. The secondary PS-Inductor is coupled to an arbitrary capacitor. The primary PS-Inductors array is applied alternating current voltage.
Figure.4 shows our circuit.

3.1. Measurement of frequency characteristic

Some frequency characteristics between the primary PS-Inductors and the secondary PS-Inductor are measured. Firstly, we fix some assumption.

1. The frequency is changed from 10 to 80MHz.
2. The voltage v_{in} and voltage v_{out} are measured(see Fig.4), and voltage transmission efficiencies are calculated.
3. The magnetic field must be considered, because 9 PS-Inductors is used for the primary circuit like Fig.3. Therefore, we measure at the following places:
   (a) The frequency characteristic is measured, when all primary PS-Inductors have a current and the secondary PS-Inductor is put on x and y which are 0 respectively.
   (b) The frequency characteristic is measured, when all primary PS-Inductors have a current and secondary PS-Inductor is put on (x, y)=(0, 1).
   (c) The frequency characteristic is measured, when all PS-Inductors have a current and the secondary PS-Inductor is put on x and y which are 1 respectively.
   (d) The frequency characteristic is measured, when a primary PS-Inductor has a current and the secondary PS-Inductor is put on the primary PS-Inductor.

The frequency characteristics are shown as Fig.5.
The response points are observed on around 30MHz.

3.2. Motion detection by voltage transmission between PS-Inductors

We make a motion detection system. A frequency, which a voltage transmission efficiency is changed widely, is needed for this system. Therefore, we use 33MHz by above results. The voltage transmission efficiencies between the primary PS-Inductors and the secondary PS-Inductor are measured while changing position of secondary PS-Inductor. When the secondary PS-Inductor is moved every 1mm, the voltage transmission efficiencies are obtained. The result of experiment is shown in Fig.6.
The voltage transmission efficiency is greatly changed by the secondary PS-Inductor which is slightly changed position on primary PS-Inductors. Therefore, this method is applied for motion detection. For example, we consider for one dimension. When x is fixed 13mm and y is changed by external force, the voltage transmission efficiency is shown as Fig.7. At first, it is assumed that there is secondary PS-Inductor at y=0. It is assumed that the voltage is measured every 0.1 seconds. If the voltage transmission efficiency is measured as 3.2, 3.0, and 1.2 in every 0.1 seconds, the secondary PS-Inductor is moved by 1mm in every 0.1[sec.](see Fig.7). In other words, speed of the secondary PS-inductor is 10[mm/sec.]. Therefore, we can think that if the first position can be fixed, the motion detection system can be made by this method.

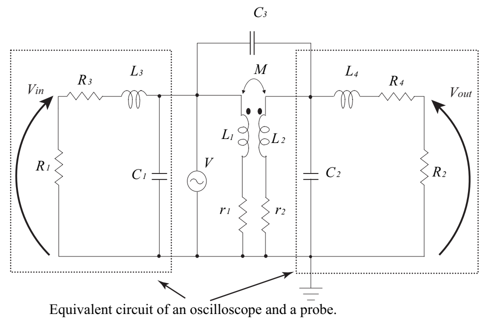

Figure 4: Measurement circuit(pattern1)
($R_1 \simeq R_2 \simeq 1$[MΩ], $R_3 \simeq R_4 \simeq 9.05$[MΩ],
$C_1 \simeq C_2 \simeq 15.55$[pF], $C_3 \simeq 0.123$[pF],
$L_3 \simeq L_4 \simeq 140[\mu$ H] and $r_1 \simeq r_2 \simeq 7.1$[Ω]).

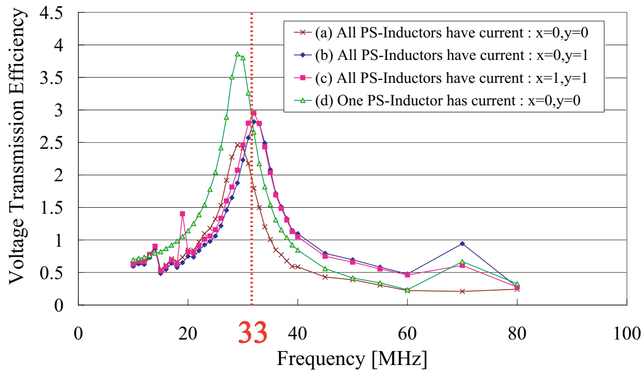

Figure 5: Frequency characteristic(pattern1).

4. Method 2: Experiments of position and motion detection using frequency characteristic of filters

In this section, we use same PS-Inductors as Sec.3. We make a measuring system as follows. 1. In the primary circuits, 4 PS-Inductors are used, and x-axis and y-axis are fixed(see Fig.8). 2. In the secondary circuits, a PS-Inductor is used. A overlapping method is the same method in Sec.3. Our circuit is shown in Fig.9.

4.1. Measurement of frequency characteristic

Some frequency characteristics between primary PS-Inductors and secondary PS-Inductor are measured. We fix some assumption as follows:

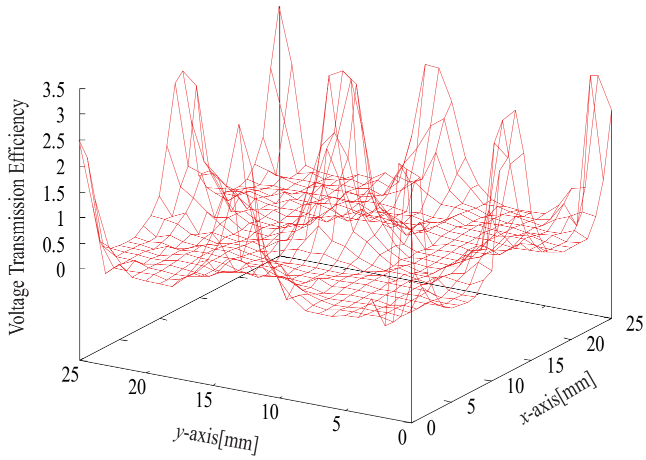

Figure 6: The voltage transmission efficiency between the primary PS-Inductors and the secondary PS-Inductor.

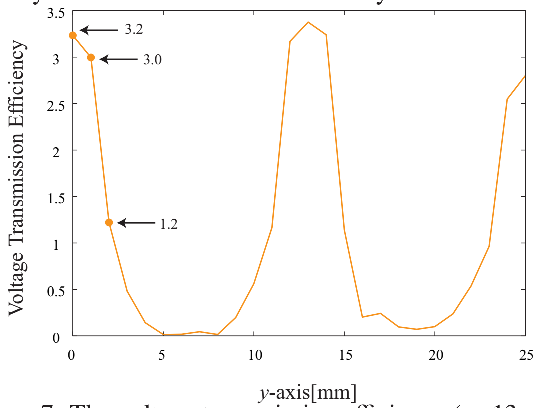

Figure 7: The voltage transmission efficiency (x=13 mm).

1. The frequency for measurement is changed from 1 to 40 MHz.
2. The v_{in} and v_{out-k}, where k = 1, 2, 3, and 4, are measured, and voltage transmission efficiencies are calculated.
3. When all primary PS-Inductors have current, and the secondary PS-Inductor is put on x and y which equal 0, the frequency characteristic is measured.
4. When all primary PS-Inductors have current, and there is not the secondary PS-Inductor, the frequency characteristic is measured.
5. When a primary PS-Inductor has current and the secondary PS-Inductor is put on the primary PS-Inductor, the frequency characteristic is measured.

The frequency characteristics are shown in Fig.10.

4.2. Motion detection and awareness of position by voltage transmission efficiency

In this section, v_{in} and v_{out-k}, where k = 1, 2, 3 and 4, are measured(see Fig.9).

If the frequency of v_{in} is fixed to 9 MHz, differential of two voltage transmission efficiencies is large when secondary PS-Inductor is put on primary PS-Inductors or not. Therefore, we fix the frequency to 9 MHz. When the secondary PS-Inductor is put on arbitrary position of primary PS-Inductors, 4 voltage transmission efficiencies are measured. If the combinations of 4 voltage transmission efficiencies is a unique combination for all combinations of 4 voltage transmission efficiencies, the position of the secondary PS-Inductor can be made clear on the primary PS-Inductors.

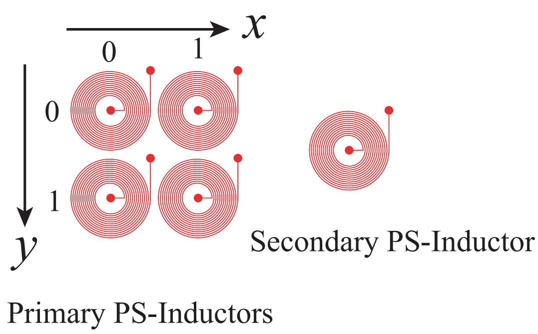

Figure 8: Printed spiral inductor(pattern2).

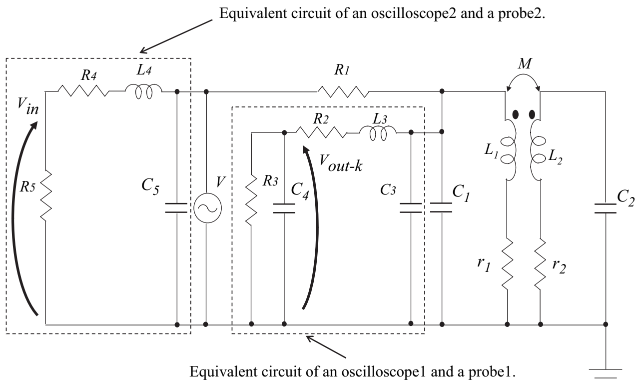

Figure 9: Measurement circuit(pattern2)
($R_1 \simeq 100[\Omega]$, $R_2 \simeq R_4 \simeq 9.05[\mathrm{M}\Omega]$, $R_3 \simeq R_5 \simeq 1[\mathrm{M}\Omega]$,
$C_1 \simeq C_2 \simeq 150$[pF],$C_3 \simeq 170$[pF], $C_4 \simeq 20$[pF],
$L_3 \simeq L_4 \simeq 140[\mu\mathrm{H}]$ and $r_1 \simeq r_2 \simeq 2.5[\Omega]$).

In this experiment, the secondary PS-Inductor is moved every 1mm. The result of this experiment is shown in Fig.11 and Table.1. Table.1 is sorted by the value of the voltage transmission efficiency. We can see that the each combination is an unique combination respectively.

5. Position detection of finger by voltage transmission efficiency

The magnetic field is affected by human body easily. When the finger is approached the PS-Inductors, the magnetic field is changed, and the inductance is changed. Therefore, the position of finger can be detected by using the PS-Inductors. A measuring system is made as like Fig.12. The v_{in} and v_{out} are measured, and voltage transmission efficiencies are calculated. The frequency is fixed as 60 MHz. The PS-Inductors are put as like Fig.13. A finger is moved every 1 cm on the PS-Inductors. The voltage transmission efficiencies are calculated while changing position of the finger. The result of experiment is shown in Table.2. Table.2 is sorted by the value of the voltage transmission efficiency. We can see that the each combination is an unique combination respectively.

Table 1: Combinations of 4 voltage transmission efficiencies.

x [mm]	y [mm]	$\frac{V_{out-1}}{V_{in}}$	$\frac{V_{out-2}}{V_{in}}$	$\frac{V_{out-3}}{V_{in}}$	$\frac{V_{out-4}}{V_{in}}$
0	1	0.746624305	1.231135822	1.18903892	1.270849881
1	1	0.750957854	1.221455939	1.164750958	1.256704981
0	2	0.756115641	1.208302446	1.165307635	1.245366938
0	0	0.784627702	1.248999199	1.192954363	1.28102482
⋮	⋮	⋮	⋮	⋮	⋮

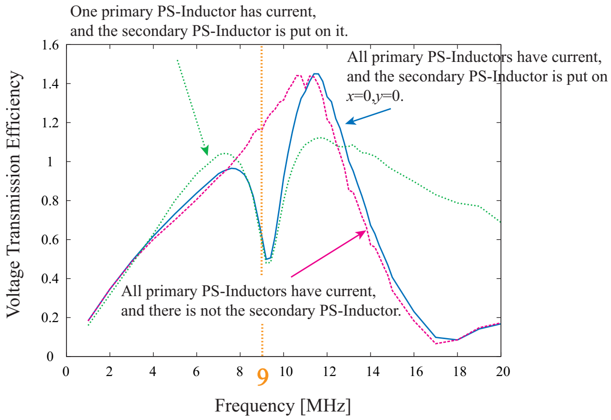

Figure 10: Frequency characteristics(pattern2).

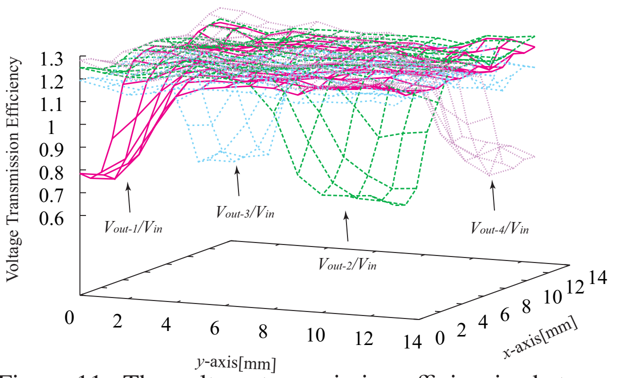

Figure 11: The voltage transmission efficiencies between v_{in} and v_{out-k} (k = 1, 2, 3, and 4).

6. Conclusion

In this study, frequency characteristics of voltage transmission efficiency between PS-Inductors was measured, and the motion detection and position detection systems were developed by using the frequency characteristics.

In Sec.3, a motion detection system was developed by using voltage transmission efficiency by mutual inductance between 9 primary PS-Inductors and a secondary PS-Inductor. The voltage transmission efficiency was greatly changed by the secondary PS-Inductor which was slightly changed position. When x was fixed as 13 mm, it was explained that the motion of secondary PS-Inductor was able to be sensed. Therefore, it was made clear that the motion detection system can be made by this method, if a first position of secondary PS-Inductor is fixed.

In Sec.4, a position detection system was developed by using a filter characteristic which is changed by a position of a secondary circuit including a PS-Inductor. When 4 voltage transmission efficiencies were measured, we can see that the combination of 4 voltage transmission efficiencies was a unique combination for all combinations of 4 voltage transmission efficiencies. Therefore, it was made clear that a position detection and motion detection system can be made by this method.

In Sec.5, a position detection system was developed by using a filter characteristic which is changed by a position of a finger. It was used for this system that the magnetic field is easily affected by human body. We measured using same method as Sec.4, and we can see that the combination of 4 voltage transmission efficiencies was a unique combination for all combinations of 4 voltage transmission efficiencies. Therefore, it was made clear that a position detection system can be made by this method.

Table 2: Measurement result.

x [mm]	y [mm]	Probe1	Probe2	Probe3	Probe4
1	1	0.439533	0.412523	0.41989	0.464088
1	2	0.440367	0.4	0.417125	0.467278
1	3	0.433558	0.394366	0.415187	0.460502
1	4	0.430845	0.372093	0.403917	0.440636
⋮	⋮	⋮	⋮	⋮	⋮

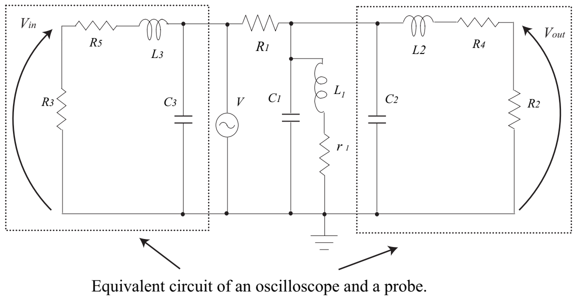

Figure 12: Measurement circuit(pattern3)
($R_1 \simeq$989[Ω], $R_2 \simeq R_3 \simeq$1[MΩ], $R_4 \simeq R_5 \simeq$9.05[MΩ],
$C_1 \simeq$957[pF],$C_2 \simeq C_3 \simeq$15.55[pF],
$L_2 \simeq L_3 \simeq$140[μH] and $r_1 \simeq$7.1[Ω]).

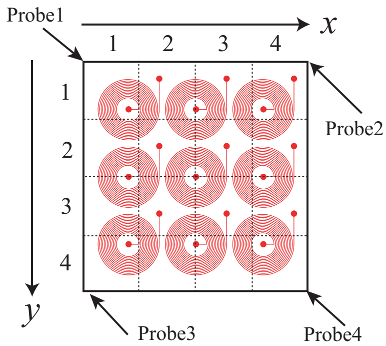

Figure 13: Printed spiral inductor(pattern3).

7. Acknowledgements

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