2005 International Symposium on Nonlinear
Theory and its Applications (NOLTA2005)
Bruges, Belgium, October 18-21, 2005

Position detection by Voltage Transmission between Two Printed Spiral Inductors

Yoshiei Tanaka†, Mizuki Motoyoshi‡, Masayuki Yamauchi†, and Mamoru Tanaka†

†Department of Electrical and Electronics Engineering, Sophia University
7-1, Kioi-cho, Chiyoda-ku, Tokyo 102-8554, Japan
‡Department of Electronics Engineering, School of Engineering, The University of Tokyo
Email: yoshiei@tlab.ee.sophia.ac.jp, motoyoshi@m.ieice.org

Abstract— In this paper, we present a new position detection system with two printed spiral inductors(PS-Inductors). When the voltage transmission efficiency between first PS-Inductor and second PS-Inductor, which are not same PS-Inductor, is measured, value of the voltage transmission efficiency are observed with changing position. Position can be detected by using the characteristic values. We make clear to be able to construct the position detection system.

1. introduction

Recently, spiral inductor is used for chip inductor, on-chip inductor and so on. Therefore, a spiral antenna is used for RFID etc.. The spiral inductors and spiral antennas are developed rapidly. Especially, spiral antennas are used to RFID etc[1]-[3]. However, mutual inductance between two or more spiral inductors is not often used.

In this study, voltage transmission efficiencies between two printed spiral inductors (PS-Inductors) are investigated. If an alternate current of an arbitrary frequency is given to the primary PS-Inductor, an alternate current which has the same cycle of primary PS-Inductor is generated at the secondary PS-Inductor by the electromagnetic induction[4],[5]. Transmission efficiency is obtained from voltages of primary PS-Inductor and secondary PS-Inductor.

Firstly, voltage transmission efficiency between two same PS-Inductors is investigated as changing frequency. Next, by shape, size and the location of the secondary PS-Inductor is changed, transmission efficiencies are investigated. Finally, the new position detection system is constructed based on the above-mentioned measurement result. When secondary inductor at an arbitrary coordinate is existed, the voltage transmission efficiency($v1_{ik}$) is measured. The secondary inductor is rotated by an arbitrary angle. and the voltage transmission efficiency($v2_{ij}$) is measured. If a combination of $v1_{ik}$ and $v2_{ik}$ differs from combinations of $v1_{lm}$ and $v2_{lm}$ of all coordinates, position of secondary inductor can be determined by using $v1$ and $v2$, It is made clear that an angle, which the combination of $v1_{ik}$ and $v2_{ik}$ is unique value, exists. We make clear to be able to construct the position detection system.

2. Measurement of Inductance

The inductance of the PS-Inductor is given from following circuit (see Fig.1). This circuit shows the Colpitts oscillator. In setting up the circuit equation in this circuit, and assuming imaginary part =0, the following equations (1) are given.

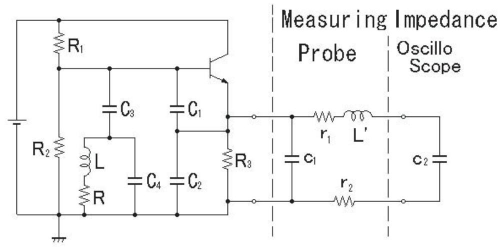


Figure 1: Circuit of inductance measurement

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

where

$$\eta = (\omega C_4 + \frac{-\zeta}{\epsilon + \zeta})$$

$$\alpha = 1 - \omega^2(r_1 + r_2)R_3 c_2(c_1 + C_2) - \omega^2 c_2 L'$$

$$\beta = R_3(c_1 + c_2 + C_2) + c_2(r_1 + r_2) - \omega^2 L' R_3 c_2(c_1 + C_2)$$

$$\gamma = R_3 - \omega^2 c_2 R_3 L'$$

$$\delta = (r_1 + r_2)c_2 R_3$$

$$\epsilon = \frac{\alpha R_3 + \omega^2 \beta\gamma}{\alpha^2 + \omega^2\beta^2}$$

$$\zeta = -\frac{1}{\omega}(\frac{1}{C_1} + \frac{1}{C_3}) + \frac{\omega(\alpha\gamma - \beta R_3)}{\alpha^2 + \omega^2\beta^2} .$$

3. Experiment

3.1. Transmission Efficiency of Same Inductors

Two PS-Inductors which have same characteristics are overlapped at a distance of 1.6[mm]. Voltage transmission efficiency between the primary and the secondary PS-Inductors is observed by using a circuit of Fig.2. The parameter is each $L1 = L2 = 11.0[\mu H], and C2 = 109[nF]$. The voltage transmission efficiency is obtained as follows.

$$Voltage\ Transmission\ Efficiency = \frac{V_2}{V_1}. \qquad (2)$$

An observed phenomenon is shown in Fig.3. Vertical axis means voltage transmission efficiency, and horizontal axis means frequency. Maximum voltage transmission efficiency is observed when frequency is around 11.8[MHz]. Although two PS-Inductors are same parameters, maximum output voltage can be generated seven times of input voltage.

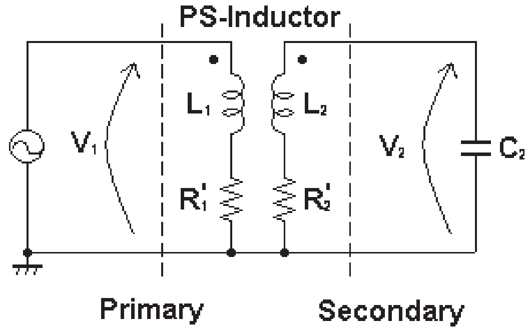


Figure 2: Circuit of measurement (same inductors).

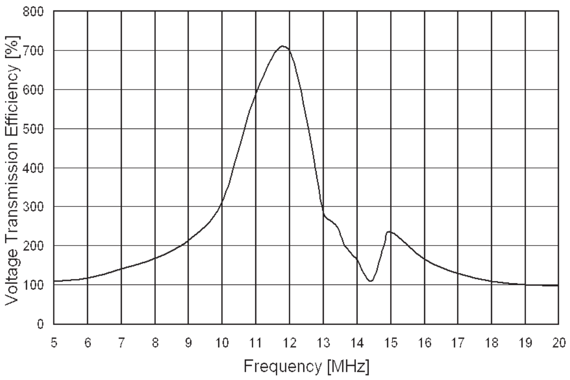


Figure 3: Voltage transmission efficiency between two same PS-Inductors.

3.2. Resonance Frequency

We prepare the PS-Inductors of the following specifications.

1. Primary inductor (see Fig.4)

   Maximum diameter(D_{max}) = 92.0[mm]
   Minimum diameter(D_{min}) = 4.0[mm]
   Number of half turns = 89[turns]
   Width of conductor = 0.2[mm]
   Distance between conductors = 0.8[mm]

2. Secondary inductor (see Fig.5)

As the secondary inductors, some half-circles which diameters respectively differ are prepared. The diameters (D) of half-circles are shown in Table 1.

C_2 is coupled to the secondary inductor (see Fig.2). The capacity of C_2 is set 106[nF] which is much larger than capacitance of a probe because of disregarding the influence of the capacitance of the probe. Centers of the primary inductor and secondary inductor are set to same location and proportion of secondary voltage to primary voltage is investigated changing frequency of input signal. Fig.6 shows the results. Theoretical resonance frequency is given by this equation.

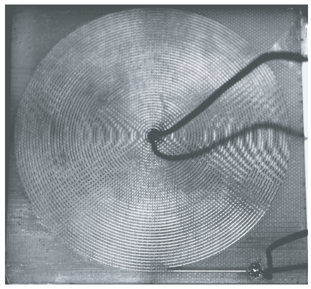


Figure 4: Primary inductor.

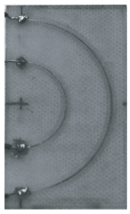


Figure 5: Sample of secondary inductor.

Table 1: Diameters of half circle.

Diameter (D) [mm]	Proportion to D_{max} [%]
23.0	25
46.0	50
69.0	75
92.0	100

$$f = \frac{1}{2\pi\sqrt{LC}}. \qquad (3)$$

Table2 shows the theoretical value and the experimental result of resonance frequency.

We can observe that experimental results resemble to values of theory. The following measurements are used resonance frequencies of experimental result of Table 2.

3.3. Transmission Efficiency

3.3.1. Method of measurement

The transmission efficiency between primary and secondary is measured changing position of secondary half

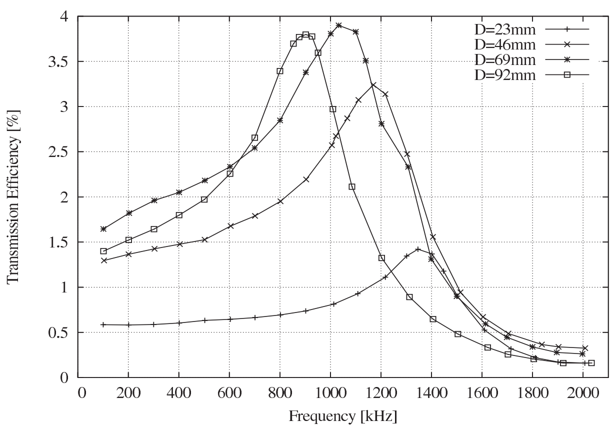


Figure 6: Frequency characteristic

Table 2: Resonance frequency of each inductor

Diameter	Measurements	Theoretically value
23.0	1.4	1.4
46.0	1.2	1.1
69.0	1.1	0.99
92.0	0.90	0.88
[mm]	[MHz]	[MHz]

circle inductor. The methods of changing the position is as follows:

1. The center of primary inductor and the center of secondary inductor are matched, and the center of primary is set as original point, and, x-axis and y-axis are provided.
2. The secondary inductor is moved at intervals of 5.0[mm] along x-axis and y-axis respectively.

3.3.2. Measurement result

The measurement results of Sec.3.3.1 are shown in Figs.8-11. The (a) of each Figs.8-11 expresses result of mapping to xz-plane.

When y=0, voltage proportions of each secondary inductor to primary inductor are shown in Fig.7. We can observe that voltage proportion depends on diameter of the secondary inductor.

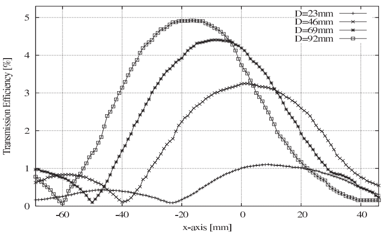
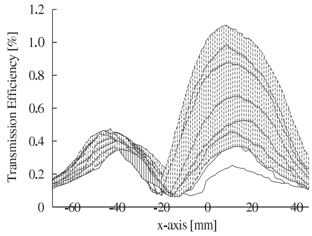


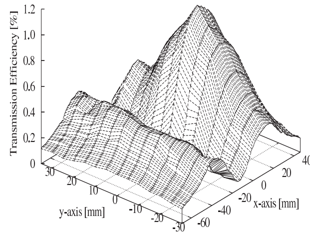
Figure 7: Voltage proportion of secondary to primary (y=0).

Six phenomena are observed as follows:

1. Maximum proportion of voltage exists on y-axis without influence of diameter of secondary PS-Inductor.
2. The second heights of local maximum are almost same.
3. A coordinate of maximum voltage proportion is changed to depend on diameter of secondary PS-Inductor.
4. A line where the voltage proportion is around zero existed.
5. Value of voltage proportion depend on the diameter of secondary PS-Inductor very much.
6. When D=23[mm] and y=-25[mm], line of minimum value is observed. We can not observe minimum value as other diameter of secondary PS-Inductors.

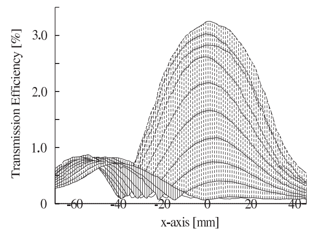


(a) Voltage proportion of secondary to primary (mapping to xz-plane).

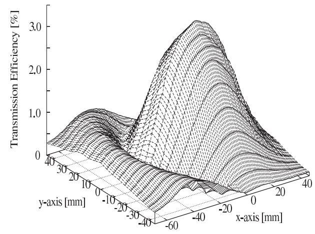


(b) Voltage proportion of secondary to primary.

Figure 8: D=23.0(25%) [mm].

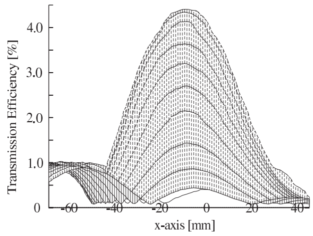


(a) Voltage proportion of secondary to primary (mapping to xz-plane).

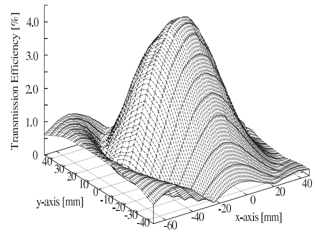


(b) Voltage proportion of secondary to primary.

Figure 9: D=46.0 (50%) [mm].

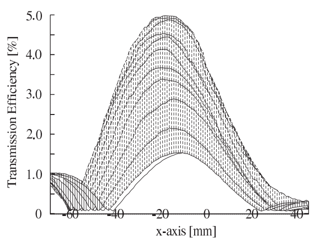


(a) Voltage proportion of secondary to primary (mapping to xz-plane).

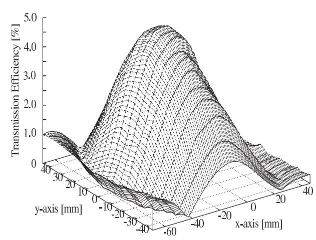


(b) Voltage proportion of secondary to primary.

Figure 10: D=69.0 (75%) [mm].



(a) Voltage proportion of secondary to primary (mapping to xz-plane).



(b) Voltage proportion of secondary to primary.

Figure 11: D=92.0 (100%) [mm].

3.4. Position detection

A system of position detection is constructed by using the results of the Sec.3.3.2. A voltage transmission efficiency of arbitrary coordinates (x, y) is expressed $v_1(x, y)$ A voltage transmission efficiency at (x, y) is expressed $v_2(x, y)$ when the secondary inductor is rotated an arbitrary angle. If a combination of $v_1(i, k)$ and $v_2(i, k)$ is unique for combinations at all other positions, the system of position detection can be constructed. We consider v_1v_2-plane which is mapped from xy-plane. When $(v_1(0, 0), v_2(0, 0))$ is the reference point, the vectors are expressed as follows:

$$(v1_{ik}, v2_{ik}) = (v_1(i, k) - v_1(0, 0), v_2(i, k) - v_2(0, 0)) \quad (4)$$

where

$$-\frac{D_{max}}{2} \leq i \leq \frac{D_{max}}{2}, \quad -\frac{D_{max}}{2} \leq k \leq \frac{D_{max}}{2}. \quad (5)$$

When Eq.6 is satisfied, a combination of $v1_{ik}$ and $v2_{ik}$ is unique.

$$v1_{ik} \neq v1_{lm} \quad \text{or} \quad v2_{ik} \neq v2_{lm} \quad (i \neq l \ \text{or} \ k \neq m)\,. \quad (6)$$

We investigate the arbitrary angle which satisfies these requirements. These requirements are satisfied when the secondary inductor is rotated 180 degrees and the diameter of secondary inductor equals 46[mm](see Fig.12).

4. Conclusion

In this study, voltage transmission between two PS-Inductors were investigated and we made clear to be able to construct the position detection system.

When two same PS-Inductors were matched and frequency was changed, very interesting phenomenon of voltage transmission efficiency was observed. When frequency was around 11.7[MHz], maximum voltage transmission efficiency was able to be generated. The maximum output voltage of the input voltage was generated seven times.

Further, voltage transmission efficiency between primary and secondary PS-Inductors was investigated when each diameter was $D = 23[mm],\ 46[mm],\ 69[mm]\ and\ 92[mm]$. Six phenomena were observed.

When the secondary inductor is rotated 180 degrees and the diameter of secondary inductor equals 46[mm], a position of secondary PS-Inductor was able to be detected by measuring $v_1(i, k)$ and $v_2(i, k)$.

Acknowledgments

This research is supported by the fund of Open Research Center Project from MEXT of Japanese Government (2002-2006).

x [mm]	y [mm]	v1 [%]	v2 [%]
-45	-45	0.6925	0.103
-40	-45	0.728	0.1095
-35	-45	0.6905	0.1115
-30	-45	0.625	0.1155
-25	-45	0.519	0.103
-20	-45	0.4185	0.1065
-15	-45	0.303	0.097
-10	-45	0.2	0.0875
-5	-45	0.1065	0.103
0	-45	0.0655	0.1565
5	-45	0.094	0.228
10	-45	0.122	0.3125
15	-45	0.1175	0.403
20	-45	0.103	0.5125
25	-45	0.094	0.6125
30	-45	0.0845	0.7
35	-45	0.0845	0.7375
40	-45	0.0815	0.7405
45	-45	0.0875	0.7065
-45	-40	0.7375	0.0905
-40	-40	0.7125	0.0815
-35	-40	0.64	0.0845
-30	-40	0.522	0.1
-25	-40	0.378	0.1405
-20	-40	0.219	0.175
-15	-40	0.072	0.222
-10	-40	0.225	0.2415
-5	-40	0.2875	0.2375
0	-40	0.3625	0.203
5	-40	0.403	0.1315
10	-40	0.397	0.135
15	-40	0.3625	0.25
20	-40	0.3065	0.385
25	-40	0.247	0.53
30	-40	0.203	0.655
35	-40	0.169	0.76
40	-40	0.1375	0.815
45	-40	0.1125	0.815
-45	-35	0.7405	0.1
-40	-35	0.6905	0.14
-35	-35	0.597	0.17
-30	-35	0.447	0.235
-25	-35	0.2565	0.315
-20	-35	0.1345	0.405
-15	-35	0.3405	0.515
-10	-35	0.5125	0.595
-5	-35	0.647	0.61
0	-35	0.722	0.585
5	-35	0.7405	0.51
10	-35	0.708	0.36
15	-35	0.6405	0.21
20	-35	0.5345	0.14
25	-35	0.425	0.315
30	-35	0.3315	0.5
35	-35	0.2565	0.67
40	-35	0.1875	0.765
45	-35	0.147	0.82
-45	-30	0.71	0.17
-40	-30	0.6	0.225
-35	-30	0.43	0.32
-30	-30	0.225	0.44
-25	-30	0.18	0.58
-20	-30	0.445	0.705
-15	-30	0.68	0.82
-10	-30	0.9	1
-5	-30	1.065	1.08
0	-30	1.15	1.085
1	-30	1.155	0.985
2	-30	1.165	0.815
3	-30	1.165	0.58
4	-30	1.17	0.335
5	-30	1.18	0.115
6	-30	1.165	0.315
7	-30	1.155	0.525
8	-30	1.135	0.705
9	-30	1.115	0.805
10	-30	1.1	0.25
15	-30	0.96	0.335
20	-30	0.805	0.46
25	-30	0.65	0.635
30	-30	0.49	0.835
35	-30	0.35	1.04
40	-30	0.28	1.25
45	-30	0.205	1.445
-45	-25	0.68	1.52
-40	-25	0.49	1.54
-35	-25	0.28	1.42
-30	-25	0.15	1.235
-25	-25	0.47	0.885
-20	-25	0.805	0.65
-15	-25	1.135	0.33
-10	-25	1.385	0.1
-5	-25	1.565	0.365
0	-25	1.655	0.6
5	-25	1.635	0.75
10	-25	1.515	0.295
15	-25	1.32	0.42
20	-25	1.1	0.545
25	-25	0.86	0.795
30	-25	0.68	1.065
35	-25	0.475	1.405
40	-25	0.345	1.705
45	-25	0.25	1.97
-45	-20	0.603	2.085
-40	-20	0.3815	2.08
-35	-20	0.15	1.915
-30	-20	0.42	1.71
-25	-20	0.795	1.405
-20	-20	1.19	1.085
-15	-20	1.565	0.67
-10	-20	1.875	0.315
-5	-20	2.065	0.169
0	-20	2.15	0.472
5	-20	2.11	0.628
10	-20	1.97	0.36
15	-20	1.705	0.5
20	-20	1.455	0.69
25	-20	1.125	0.97
30	-20	0.83	1.33
35	-20	0.61	1.69
40	-20	0.455	2.045
45	-20	0.33	2.345
-45	-15	0.515	2.47
-40	-15	0.295	2.5
-35	-15	0.28	2.39
-30	-15	0.655	2.22
-25	-15	1.08	1.905
-20	-15	1.595	1.485
-15	-15	1.985	1.03
-10	-15	2.375	0.61
-5	-15	2.565	0.22
0	-15	2.615	0.375
5	-15	2.515	0.64
10	-15	2.315	0.42
15	-15	2.08	0.595
20	-15	1.725	0.845
25	-15	1.335	1.17
30	-15	0.99	1.595
35	-15	0.695	2.03
40	-15	0.515	2.36
45	-15	0.375	2.58
-45	-10	0.478	2.705
-40	-10	0.1655	2.735
-35	-10	0.3	2.69
-30	-10	0.79	2.47
-25	-10	1.285	2.205
-20	-10	1.85	1.705
-15	-10	2.315	1.155
-10	-10	2.61	0.69
-5	-10	2.75	0.26
0	-10	2.825	0.26
5	-10	2.805	0.545
10	-10	2.705	0.455
15	-10	2.47	0.625
20	-10	2.14	0.94
25	-10	1.67	1.345
30	-10	1.265	1.765
35	-10	0.875	2.235
40	-10	0.625	2.595
45	-10	0.405	2.815
-45	-5	0.405	2.955
-40	-5	0.135	3
-35	-5	0.51	2.905
-30	-5	0.985	2.75
-25	-5	1.515	2.455
-20	-5	2.095	1.955
-15	-5	2.515	1.42
-10	-5	2.78	0.875
-5	-5	2.945	0.397
0	-5	3.03	0.18
5	-5	2.955	0.51
10	-5	2.795	0.575
15	-5	2.565	0.765
20	-5	2.25	1.095
25	-5	1.75	1.625
30	-5	1.28	2.14
35	-5	0.875	2.595
40	-5	0.58	2.89
45	-5	0.405	3.11
-45	0	0.445	3.205
-40	0	0.11	3.24
-35	0	0.43	3.11
-30	0	1.055	2.945
-25	0	1.635	2.655
-20	0	2.235	2.235
-15	0	2.655	1.635
-10	0	2.945	1.055
-5	0	3.11	0.43
0	0	3.24	0.11
5	0	3.205	0.445
10	0	3.11	0.405
15	0	2.89	0.58
20	0	2.595	0.875
25	0	2.14	1.28
30	0	1.625	1.75
35	0	1.095	2.25
40	0	0.765	2.565
45	0	0.575	2.795
-45	5	0.51	2.955
-40	5	0.18	3.03
-35	5	0.397	2.945
-30	5	0.875	2.78
-25	5	1.42	2.515
-20	5	1.955	2.095
-15	5	2.455	1.515
-10	5	2.75	0.985
-5	5	2.905	0.51
0	5	3	0.135
5	5	2.955	0.405
10	5	2.815	0.405
15	5	2.595	0.625
20	5	2.235	0.875
25	5	1.765	1.265
30	5	1.345	1.67
35	5	0.94	2.14
40	5	0.625	2.47
45	5	0.455	2.705
-45	10	0.545	2.805
-40	10	0.26	2.825
-35	10	0.26	2.75
-30	10	0.69	2.61
-25	10	1.155	2.315
-20	10	1.705	1.85
-15	10	2.205	1.285
-10	10	2.47	0.79
-5	10	2.69	0.3
0	10	2.735	0.1655
5	10	2.705	0.478
10	10	2.58	0.375
15	10	2.36	0.515
20	10	2.03	0.695
25	10	1.595	0.99
30	10	1.17	1.335
35	10	0.845	1.725
40	10	0.595	2.08
45	10	0.42	2.315
-45	15	0.64	2.515
-40	15	0.375	2.615
-35	15	0.22	2.565
-30	15	0.61	2.375
-25	15	1.03	1.985
-20	15	1.485	1.595
-15	15	1.905	1.08
-10	15	2.22	0.655
-5	15	2.39	0.28
0	15	2.5	0.295
5	15	2.47	0.515
10	15	2.345	0.33
15	15	2.045	0.455
20	15	1.69	0.61
25	15	1.33	0.83
30	15	0.97	1.125
35	15	0.69	1.455
40	15	0.5	1.705
45	15	0.36	1.97
-45	20	0.628	2.11
-40	20	0.472	2.15
-35	20	0.169	2.065
-30	20	0.315	1.875
-25	20	0.67	1.565
-20	20	1.085	1.19
-15	20	1.405	0.795
-10	20	1.71	0.42
-5	20	1.915	0.15
0	20	2.08	0.3815
5	20	2.085	0.603
10	20	1.97	0.25
15	20	1.705	0.345
20	20	1.405	0.475
25	20	1.065	0.68
30	20	0.795	0.86
35	20	0.545	1.1
40	20	0.42	1.32
45	20	0.295	1.515
-45	25	0.75	1.635
-40	25	0.6	1.655
-35	25	0.365	1.565
-30	25	0.1	1.385
-25	25	0.33	1.135
-20	25	0.65	0.805
-15	25	0.885	0.47
-10	25	1.235	0.15
-5	25	1.42	0.28
0	25	1.54	0.49
5	25	1.52	0.68
10	25	1.445	0.205
15	25	1.25	0.28
20	25	1.04	0.35
25	25	0.835	0.49
30	25	0.635	0.65
35	25	0.46	0.805
40	25	0.335	0.96
45	25	0.25	1.1
-45	30	0.805	1.115
-40	30	0.705	1.135
-35	30	0.525	1.155
-30	30	0.315	1.165
-25	30	0.115	1.18
-20	30	0.335	1.17
-15	30	0.58	1.165
-10	30	0.815	1.165
-5	30	0.985	1.155
0	30	1.085	1.15
5	30	1.08	1.065
10	30	1	0.9
15	30	0.82	0.68
20	30	0.705	0.445
25	30	0.58	0.18
30	30	0.44	0.225
35	30	0.32	0.43
40	30	0.225	0.6
45	30	0.17	0.71
-45	35	0.82	0.147
-40	35	0.765	0.1875
-35	35	0.67	0.2565
-30	35	0.5	0.3315
-25	35	0.315	0.425
-20	35	0.14	0.5345
-15	35	0.21	0.6405
-10	35	0.36	0.708
-5	35	0.51	0.7405
0	35	0.585	0.722
5	35	0.61	0.647
10	35	0.595	0.5125
15	35	0.515	0.3405
20	35	0.405	0.1345
25	35	0.315	0.2565
30	35	0.235	0.447
35	35	0.17	0.597
40	35	0.14	0.6905
45	35	0.1	0.7405
-45	40	0.815	0.1125
-40	40	0.815	0.1375
-35	40	0.76	0.169
-30	40	0.655	0.203
-25	40	0.53	0.247
-20	40	0.385	0.3065
-15	40	0.25	0.3625
-10	40	0.135	0.397
-5	40	0.1315	0.403
0	40	0.203	0.3625
5	40	0.2375	0.2875
10	40	0.2415	0.225
15	40	0.222	0.072
20	40	0.175	0.219
25	40	0.1405	0.378
30	40	0.1	0.522
35	40	0.0845	0.64
40	40	0.0815	0.7125
45	40	0.0905	0.7375
-45	45	0.7065	0.0875
-40	45	0.7405	0.0815
-35	45	0.7375	0.0845
-30	45	0.7	0.0845
-25	45	0.6125	0.094
-20	45	0.5125	0.103
-15	45	0.403	0.1175
-10	45	0.3125	0.122
-5	45	0.228	0.094
0	45	0.1565	0.0655
5	45	0.103	0.1065
10	45	0.0875	0.2
15	45	0.097	0.303
20	45	0.1065	0.4185
25	45	0.103	0.519
30	45	0.1155	0.625
35	45	0.1115	0.6905
40	45	0.1095	0.728
45	45	0.103	0.6925

Figure 12: Combination of $v_1(x, y)$ and $v_2(x, y)$.

References

[1] Schmuckle, F.J., "The method of lines for the analysis of rectangular spiral inductors [in MMICs]," Microwave Theory and Techniques, IEEE Transactions on , Vol.41 , Issue6, pp.1183–1186, June-July 1993.

[2] MIng Hsiang Chiou, "A new wideband modeling technique for spiral inductors," Semiconductor Device Research Symposium, 2003 International, pp.290–291, 10-12 Dec 2003.

[3] Lutz, R.D., "Modeling of spiral inductors on lossy substrates for RFIC applications," Radio Frequency Integrated Circuits (RFIC) Symposium, 1998 IEEE, pp.313–316, 7-9 June 1998 ,

[4] Eiji SUZUKI, "Optical Magnetic Field Probe with a Loop Antenna Element Doubly Loaded with LiNbO3 Crystals," Ieice Trans. Electron., Vol.E87-C, No.11, pp.1989–1996, Nov. 2004.

[5] Atsushi KUROKAWA, "Approximation Formula Approach for the Efficient Extraction of On-Chip Mutual Inductances," Ieice Trans. Fundamentals, Vol.E86-A, No.12, pp.2933-2941, Dec. 2003.