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Resonant Proximity Connector for Two-Dimensional Sensor Implantation

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Abstract: In this paper, we propose a stable proximity connector RPC (Resonant Proximity Connector) to TDC (Two-Dimensional Communication) sheet. RPC is an electrode whose length is a quarter of the electromagnetic wavelength. The induced resonance around the electrode reduces the impedance between the connector and TDC sheet, which allows sensor chips to communicate with TDC sheet stably. Since the resonance depends on only the length of the electrode, this connector realizes stable connection of the sensor chip to TDC sheet for the variable gap distance between them. Using this technology, we can construct high density sensor networks on surfaces of clothes, desks, vehicles, and rooms without complicated wiring. The communication sheet can be made of flexible materials like fabric or rubber. We demonstrate the principle of RPC and simulation and experimental results.

Keywords: Two-Dimensional Communication, sensor network, proximity connection, resonance, impedance matching

1. INTRODUCTION

Recently, developing a method to implant large number of sensor elements in various materials is becoming a major problem of sensing as the sensor elements become smaller and the price of them becomes lower. In the future, flexible sensor network will be required for the ubiquitous network society.

For sensor network systems, there are two major methods that sensors communicate each other. First, it is to connect each sensor with something line-form media (e.g. optical fiber, electric wire, cable, etc). In this method, the sensor can transmit signals with the minimal energy. However, as the number of sensors increases, the effort of wiring increases and it becomes difficult to construct sensor network. The physical flexibility of the device is lost by wiring, which makes high density implantation of sensors into clothes difficult.

Another method is to construct sensor network with electromagnetic wave which transmits through the air. In this method, sensors communicate each other without wiring. However, electromagnetic wave can transmit to the undesired place. Power transmission is limited within a small power. In addition, electromagnetic wave is not preferable in the place such as hospital.

We proposed Two-Dimensional Communication (TDC) method to realize wireless sensor networks in two-dimension [1,4]. Fig.1 shows the Schematic illustration of TDC sheet. TDC sheet is composed of two conductive layers and a dielectric layer. In this system, each sensor chip communicates with omni directional microwave traveling in the sheet. Using TDC method, we can construct high density sensor network without complicated wires. Furthermore, we can make TDC sheet with flexible and elastic materials as rubber or fabric, which enables us to realize sensor networks on surfaces of clothes, desks, vehicles, and rooms, etc.

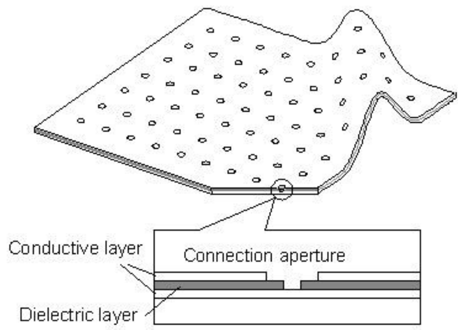

Fig.1 Illustration of two-dimensional communication sheet [4].

In this paper, we propose a method of stable non-contact connection between sensor chips and a TDC sheet. In the methods of [1,4], the connection needed mechanical and electrical contact to the TDC sheet, which made production process complex and caused stress concentration around the connection that made the device fragile. In this paper we solve the problems by the proximity connection.

The idea of communication using two dimensional medium was originally proposed by us [1] and some other groups [2-3] at the early 2000s. In the researches [2] and [3], however, high speed communication through the medium was out of consideration. Mechanical and electrical connections of elements to the conductive layers were also necessary. Our method provides high-speed connection using microwaves with no electrical contact at each sensor.

2. RESONANT PROXIMITY CONNECTOR

The most primitive method of the connection between sensor chips and a TDC sheet is to connect them with solid conductor. However, a hard connector existing in a soft sheet causes physical fragility by stress concentration around it. Moreover, production process connecting a large number of sensors is complex. Therefore, it is desirable to connect sensor chips and TDC sheet without electrical contact.

An easy method to connect sensor chips and TDC sheet without electrical contact is to utilize the capacitive coupling existing between them. Let the radiation impedance of TDC sheet Z_0. In this case, the impedance seen from the terminal of sensor chips is a total of the impedance Z_0 and the reactance $1/j\omega C$ from the capacitance C between the connector and the TDC sheet.

One problem in using capacitive coupling C is that it highly depends on the variation of the gap d between the connector and the TDC sheet as shown in Fig. 2. The reactance X from C is written as

$$X = \frac{1}{\omega C} = \frac{d}{2\pi f \varepsilon_0 \varepsilon_r S}, \tag{1}$$

where S, ε_0 and ε_r denote respectively the area of the connector, the dielectric constant in the air, and the relative permittivity of the dielectric layer. For f = 2.4GHz, $S = 2.5\times2.5\times\pi$ mm^2, d = 0.5 mm, and ε_r = 4.9, the reactance X is 38.9 Ω. Since Re[Z_0] for a TDC sheet with 1 mm thickness is as small as 5 Ω at 2.4 GHz, the reactance X causes serious loss of connection. Therefore we have to prepare variable inductance L to satisfy

$$\omega L = \frac{1}{\omega C}, \tag{2}$$

that follows the capacitance change by the gap d, which makes the circuit design of the sensor chip complex. (Fig.2).

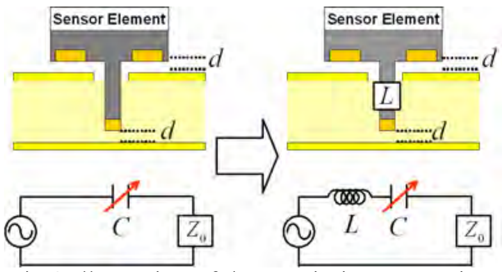

Fig.2 Illustration of the proximity connection.

Fig.3 shows the illustration of the proximity connector we propose here. The connector is an electrode whose length is a quarter of the wavelength λ. When we apply voltage between A and B, the voltage V and the current I are respectively the minimum and the maximum at feeding point A on the $\lambda/4$ resonant electrode. Then the impedance Z_1 between A and B

$$Z_1 = V / I, \tag{3}$$

becomes the minimum.

The condition of the resonance depends on the length of the electrode and hardly depends on the gap distance d. We can use various shapes of electrodes with their length of $\lambda/4$ that are parallel to the TDC sheet. We conducted simulation analysis to examine our theory. In next section, we describe the simulation model and the results.

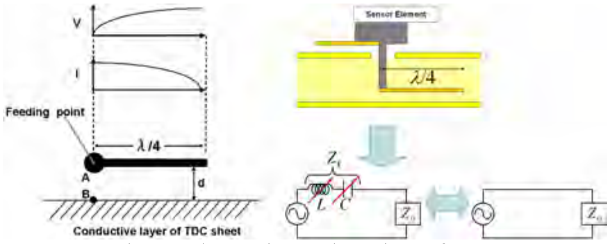

Fig.3 Schematic explanation of RPC

3. NUMERICAL SIMULATION

We conducted simulation analysis using the software MW-Studio (AET Japan, Inc) considering metallic resistance. Fig.4 shows the illustration of the simulation model. The simulation model consists of a SMA connector, TDC sheet, and the electrode we propose. In this simulation, we set copper foil whose thickness is 35 μm as conductive layer and a glass epoxy board whose thickness and relative permittivity are 2.1 mm and 4.9, respectively. Although we will not use SMA connectors and a glass epoxy board for sensor implantation, we assume them for experimental confirmation.

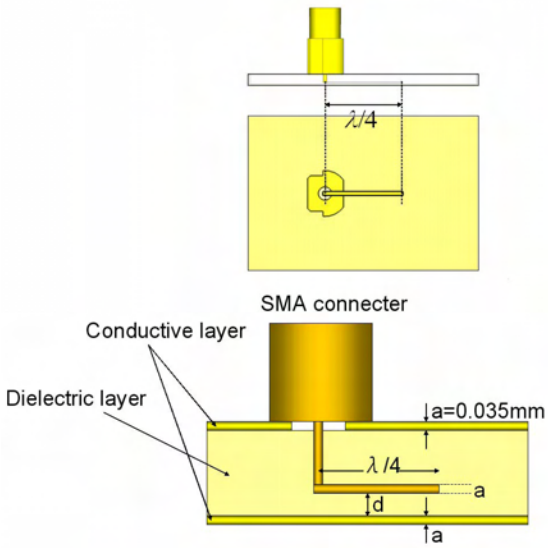

Fig.4 RPC model for simulation analysis

The wavelength λ of electromagnetic wave which travels in TDC sheet is written as

$$\lambda = \frac{c}{f\sqrt{\varepsilon_r}}, \tag{4}$$

where c is the velocity of the electromagnetic wave. For f = 2.4GHz, λ is 56.5mm. Although the exact length of $\lambda/4$ is 14.1 mm, we set the electrode length 15.3 mm to obtain the best result considering the open-end correction and the effect of the size of the feeding point. The width of the electrode is 0.8mm.

The software gives the impedance Z at the SMA connector that is the sum of the radiation impedance Z_0 of the TDC sheet and the connection impedance Z_1. In order to obtain Z_1, we first obtain the value of Z_0 for d = 0 mm (electrically shorted). Then we calculate Z for various gaps d. We show final results of Z_1, obtained by

$$Z_1 = Z - Z_0, \tag{5}$$

Table 1 shows the impedance Z_1 for various gaps d. The reactance is less than 2Ω, which shows our theory is effective to make the connection stable irrespective of the distance between the electrode and TDC sheet. The reason why the real parts of Z_1 are negative is that they were calculated mechanically by equation (5). We show the results at other frequencies for comparisons (Table 1, Fig.5).

Table 1 The impedance Z_1 for various gaps d

d [mm]	Impedance Z_1 [Ω]		
	2.4GHz	1.0GHz	3.0GHz
0.1	-2.14+j1.96	-1.30-j20.92	50.0+j50.9
0.2	-3.60+j0.82	-2.64-j29.57	120.0+j86.7
0.3	-6.67-j0.17	-2.23-j36.56	159.0+j124.3
0.4	-8.89-j0.97	-2.15-j40.59	191.8+j155.9
0.5	-11.0-j1.95	-2.21-j42.94	211.4+j186.2

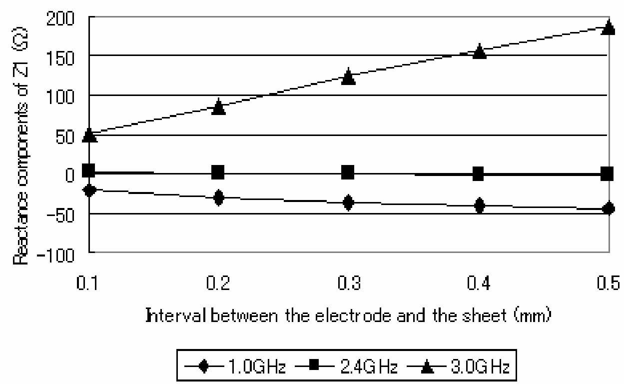

Fig.5 Reactance components of Z_1 for various d of the straight electrode

Since the resonance only depends on the length of the electrode, the form of the electrode can be circular or spiral to make connector smaller. We also conducted simulation analysis about a circular electrode and a spiral electrode.

We show the simulation model of a circular electrode in Fig.6. The size of TDC sheet is infinite, and the diameter of the electrode is 5.6mm. As shown in Table 2 and Fig.7, the reactance of Z_1 is less than 5Ω at 2.4GHz.

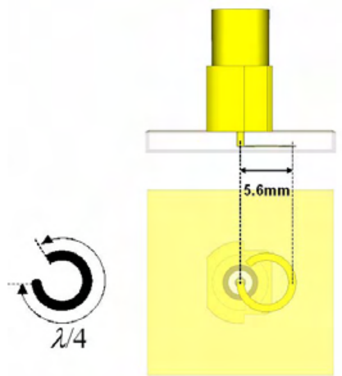

Fig.6 Circular model of the RPC connector

Table 2 The calculated impedance Z_1 of the circular electrode for various gaps d

d [mm]	Impedance Z_1 [Ω]		
	2.4GHz	1.0GHz	3.0GHz
0.1	-5.07+j1.69	0.81-j17.88	34.6+j54.2
0.2	-5.64+j4.67	6.45+j32.03	76.2+j97.4
0.3	-6.89+j2.16	-2.64-j32.87	117.2+j123.5
0.4	-9.56-j2.07	-0.47-j36.92	123.6+j128.9
0.5	-11.66-j4.54	-1.07-j40.76	17.4+j149.7

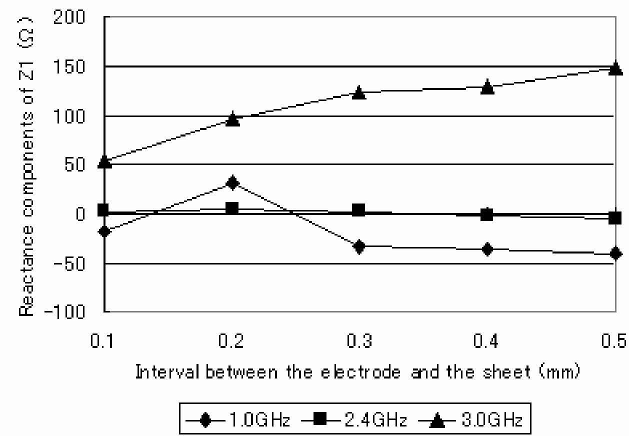

Fig.7 Reactance components of Z_1 for various d of the circular electrode

Fig.8 shows the spiral electrode model. The diameter of the electrode is 2.8mm. Table3 and Fig.9 show the impedance Z_1 of the spiral model for various gaps d. The reactance is less than 5Ω, hence we can say that our theory is effective also for such a very small spiral electrode.

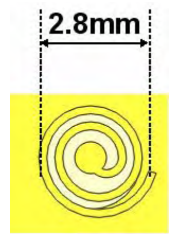

Fig.8 Spiral electrode model of RPC.

Table 3 The calculated impedance Z_1 of the spiral electrode for various gaps d

d [mm]	Impedance Z_1 [Ω]		
	2.4GHz	1.0GHz	3.0GHz
0.1	-2.44+j4.75	1.286-j45.29	449.2-j114.1
0.2	-1.68+j4.18	-0.844-j61.78	29.4-j360.9
0.3	-3.1-j0.77	-1.804-j74.84	-22.3-j306.0
0.4	-3.5+j1.35	-1.278-j85.10	-47.8-j268.7
0.5	-5.75-j1.62	-1.732-j98.71	-53.3-j257.7

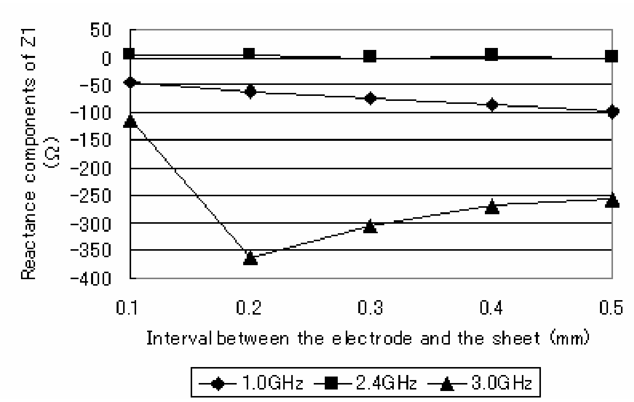

Fig.9 Reactance components of Z_1 for various d of the spiral electrode

4. DISCUSSION ON POWER SUPPLY

We supply each sensor chip with power from the edge of TDC sheet. In this section, we discuss the effective frequency of power supply. First, consider the power is supplied by a low frequency signal source whose wavelength is much longer than the size of the TDC sheet. Then we can deal with TDC sheet as a large area of condenser.

The efficiency of supplying power is deteriorated when sensors are put in low density. To consider this problem, we cut out a unit area including a single sensor from the TDC sheet as shown in Fig.10 (left). We also show the equivalent circuit in Fig.10 (right). In Fig.10, C_1 is the capacitance between a sensor and the TDC sheet, and C_0 is the capacitance between two layers of the unit TDC sheet for one sensor, excluding the contribution of the sensor area.

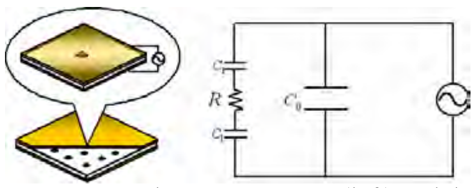

Fig.10 An area where a sensor put (left) and the equivalent circuit (right).

We compare the power W_R consumed at R with the power W_C consumed at C_0. In order to maximize W_R, we should attach L_1 to cancel C_1 as Fig.11 shows. The current into C_0 supplied by the power source is also minimized by the inductance L_0. If we can realize the perfect resonance, the influences of both capacitances can be canceled. However, the quality factors of the resonances are finite, which are denoted by residual resistances R_0 and R_1 as shown in Fig.12

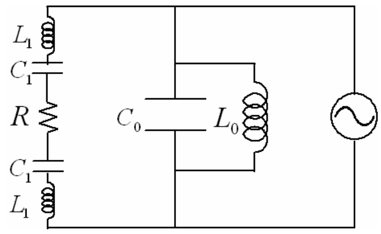

Fig.11 Illustration of circuit canceling C_0 and C_1

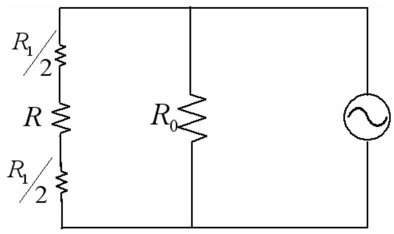

Fig.12 Equivalent circuit of residual resistances.

These resistances are written as

$$R_0 = Q_0 \frac{1}{\omega C_0}, \tag{6}$$

$$R_1 = \frac{1}{Q_1}\frac{1}{\omega C_1}, \tag{7}$$

where Q_0 and Q_1 are quality factors of the resonances.

Then the ratio of W_C to W_R is given as

$$\frac{W_C}{W_R} > \frac{R_1 + R}{R_0} = \frac{C_0}{C_1}\frac{1}{Q_0 Q_1} + \frac{\omega C_0 R}{Q_0} = \frac{d_1 S_0}{d_0 S_1}\frac{1}{Q_0 Q_1} + \frac{\varepsilon_0 \varepsilon_r \omega R S_0}{d_0 Q_0}, \tag{8}$$

where d_0 and d_1 are the thickness of the TDC sheet and the distance between the sensor and the TDC sheet, respectively, and S_0 and S_1 are the area of the sensor and the area of the unit TDC sheet for one sensor, respectively.

If we assume that d_0 = 2 mm, d_1 = 0.5 mm, $Q_0 = Q_1$ =30, R = 100 Ω, and $\omega = 2\pi \times 50 \times 10^6$, the equation can be written as

$$\frac{R_1 + R}{R_0} \approx \frac{1}{1800}\frac{S_0}{S_1}, \tag{9}$$

This equation means that the power W_C wasted at C_0 exceeds W_R for a large value of S_0/S_1. For example, if we put a sensor whose area is 1×1 mm^2 in a TDC sheet whose area is 4×4 cm^2, more than half of supplied current is wasted. Therefore, non-contact power supply by capacitive coupling at a low frequency becomes inefficient for a low density of sensor implantation.

Meanwhile, microwaves whose wavelength is much shorter than the size of TDC sheet can be effective for power supply for low density sensors.

5. EXPERIMENT ON POWER SUPPLY

We conducted experiment on microwave power supply in TDC sheet. The sheet consists of aluminum foil as conductive layer and a flexible poly olefin sheet as dielectric layer. The thickness of this sheet is 6 mm. We show the photograph of the TDC sheet in Fig.13

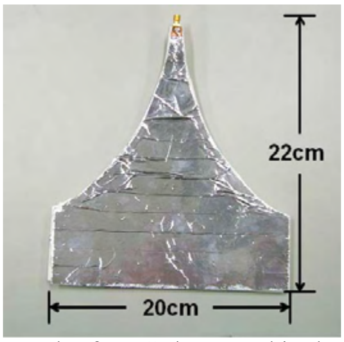

Fig.13 Photograph of TDC sheet used in the experiment.

To evaluate the supplied power to a sensor, we made a rectification circuit put on the $\lambda/4$ electrode. We show the photograph of circuit with the electrode in Fig. 14.

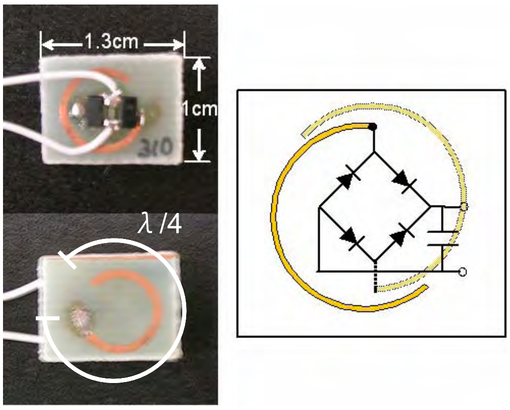

Fig.14 Photograph of the electrode (left) and illustration of rectification circuit (right).

We supplied power from the edge of TDC sheet with a 2W-2.4GHz power amplifier, and put the electrode with the rectification circuit and a LED into the TDC sheet. The location of the rectification circuit is 17cm from feeding point. As shown in Fig.15, the LED shone by the power that the electrode acquired. The consumed power was about 20 mW for 110 mW input power.

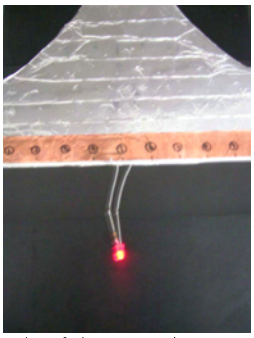

Fig.15 Photograph of the experiment of power supply. The LED is shinning by power the electrode acquired.

6. CONCLUSION

In this paper, we proposed a stable proximity connector RPC (Resonant Proximity Connector) to TDC (Two-Dimensional Communication) sheet. RPC is an electrode whose length is a quarter of the electromagnetic wavelength. The induced resonance around the electrode reduces the impedance between the connector and TDC sheet, which allows sensor chips to communicate with TDC sheet stably. Simulation results on straight, ring, spiral RPCs showed that the concept is effective.

We also discussed the power supply for distributed sensors. When sensor's density is low, microwave power supply becomes effective. By the experiment in power supply with a RPC and a LED, we confirmed that power can be supplied to the sensor element in TDC sheet.

Fabricating a sensor chip equipped with a sensor, RPC, and communication functions, is a future work.

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