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Surface Sensor Network Using Inductive Signal Transmission Layer

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***Abstract*—In this paper, we report the latest results of our two-dimensional communication project. In the system we show here, the sensor node that touches the surface of a Two-Dimensional Signal Transmission sheet (2DST sheet) establishes the connection. The system allows free location of the sensor node, and proximity (non-contact) connection is realized stably. The structure of 2DST sheet is simple and realized with various materials at low cost. Since the sensor nodes communicate with electromagnetic waves confined in two-dimensional medium, they are free from the interference from the nodes apart from the sheet. Powering with microwave through the sheet is also possible.**

***Keywords*—sensor network; surface LAN; two-dimensional communication**

I. Introduction

Physical connection of a large number of sensors is one of key issues in sensor networking in rooms, vehicles, and clothes. Radio connection is often the method that minimizes the cost of the sensor placement, and in some cases, the only way to distribute sensors over a large area of farmland and mountainous field. In those applications, the main research theme of sensor network is communication protocols to extremely save the energy consumptions under limited batteries.

In communication within a room-size or smaller area, we can suppose preferable physical forms of connection other than wireless communication. Surface LAN realized by two-dimensional signal transmission (2DST [6][7][8][9]) is a reasonable communication form that realizes high density placement of sensors enjoying wide band communication. In this paper, we report the latest results of our 2DST project. In the proposed system, the sensor node that touches the surface of a 2DST sheet establishes the connection. The system allows free location of the sensor node where proximity (non-contact) connection is realized stably.

In communication of 2DST, the sensor nodes communicate using microwave which propagates in two-dimensional sheet. The first merit of 2DST is that the communication is free from the interference [1] from unexpected signals outside of the room. The sensors belonging to a 2DST sheet is also harmless to the sensors apart from the sheet. The second important merit

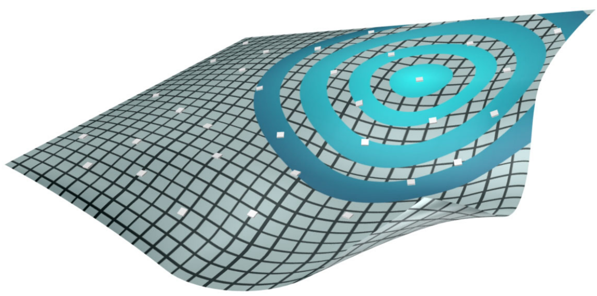


Fig. 1. The concept of two-dimensional signal transmission (2DST). Sensor nodes send/receive packets through the 2DST sheet.

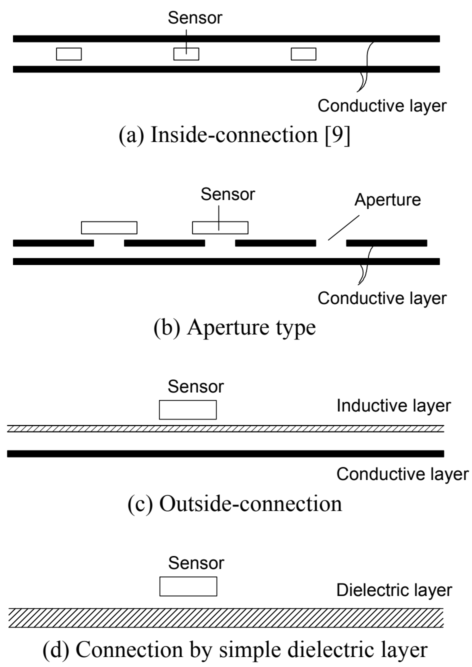


Fig. 2. Cross-sections of possible types of 2DST. In this paper, types (c) is studied.

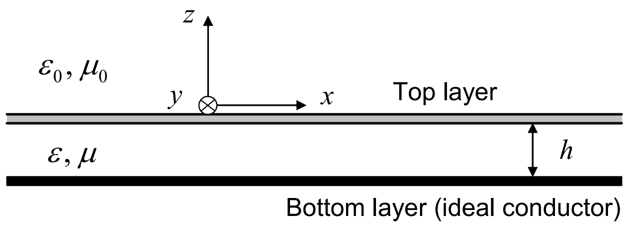


Fig. 3. Coordinate system and sheet parameters.

is that sensor nodes can receive the power for operation from the sheet that enables wide band communication without batteries. The third merit is that the required energy for signal transmission is smaller than usual radio. In addition, it is easy to avoid the multi-path problem by termination at the sheet edge.

The sheet structure is simple, and the simplicity enables us to form the 2DST structure on the surfaces of various materials of walls, desks, floors, and even clothing. The drawback of 2DST compared with usual radio connection is that we have to prepare special surfaces for signal transmission. However, when we produce desks with the 2DST structure, the additional cost is low and becomes negligible in mass production.

The idea of communication using two dimensional medium was originally proposed by Lifton et al. [3], Laerhoven et al. [4] and us [2] at the early 2000s. In research [3], however, the 2D plane was used for DC power supply and radio was used for the communication. Also in research [4], high speed communication through the medium was out of consideration, since a pair of parallel large conductors makes a huge condenser. In addition, mechanical and electrical contacts of elements to the conductive layers were necessary in the preceding researches. Networked surfaces [5] proposed by Scott et al. was also based on a concept similar to two-dimensional communication. But their device was not a continuous medium and required a complex structure of surface with multiple electrodes combined by wires.

II. Non-Contact Connection to 2DST Sheet

We can suppose at least four types of 2DST as shown in Fig. 2. In the first form of figure (a), the sensors are sandwiched by two conductive layers. In this structure the electromagnetic wave can be strictly confined within the sheet. TEM mode with the electric field vertical to the surface conveys the signals in this case. A method to make the proximity connector on the sensor chip much smaller than the wavelength using resonance is described in [9]. The second type as shown in Fig. 2 (b) allows the sensor chips to be attached on the sheet after the sheet production. Electro-magnetic waves are sent/received through apertures on the sheet. The structure is effective in the case that the sensor location is decided in advance. Fig. 2 (c) realizes free location of the sensors on the sheet. The sensor can even move on the surface keeping the connection. In this paper we show how to realize the communication in the form of Fig. 2 (c). Parts of the results described here were already published in a Japanese domestic conference [8]. In this paper, we show the details of the theory and the results.

A. Electromagnetic wave around 2DST sheet

Under the coordinate system shown in Fig. 3, the z component of electric field above the surface is written as

$$E_z = \frac{k_2{}^2}{k_1} V \exp(-k_1 z)\exp(-jkx)\exp(j\omega t) \quad (z > 0) \qquad (1)$$

$$\left[\begin{array}{l} k_1^2 = (\mu\varepsilon - \mu_0\varepsilon_0)\omega^2 - \dfrac{j\sigma\varepsilon\omega}{h} \\ k_2^2 = \dfrac{j\sigma\varepsilon\omega}{h} \\ k^2 = \mu\varepsilon\omega^2 - \dfrac{j\sigma\varepsilon\omega}{h} \end{array}\right]$$

for the wave traveling toward $+x$, where μ and ε denote respectively the magnetic permeability and dielectric constant of the sheet, and μ_0 and ε_0 are those of the atmosphere. The parameter V is the voltage between the top layer, S, and the bottom layer, B, at $x = t = 0$. The equation is an approximation based on the assumption $|k_1 h| << 1$ and $|k_2 h| << 1$, where h is the dielectric layer thickness. The parameter σ is the sheet impedance of the top layer defined as

$$\sigma \equiv R + jX \equiv \frac{E_x}{i_x} \qquad [\Omega] \qquad (2)$$

where E_x is the electric field along the x axis at the top layer and i_x is the current density [A/m] along x axis. We assume that the bottom layer is an ideal conductor and that the top layer is sufficiently thin. If the top layer is ideal continuous conductor, σ is equal to 0, which results in $E_x = 0$. We call a top layer whose sheet impedance is inductive as $X > 0$ an "inductive layer." An inductive layer can be realized by a mesh of well conductive material with the period shorter than the wavelength. When S is a mesh whose period is smaller than the wavelength, E_x and i_x denote their averages in the period.

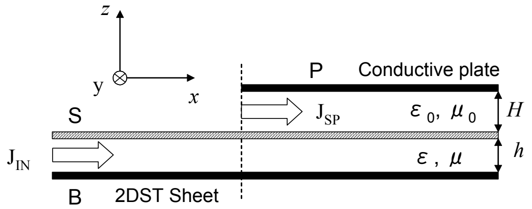
Based on the equation (1), we can calculate leakage ratio r that is defined as the ratio of the electromagnetic energy flow J_1 running along $+x$ direction outside of the sheet to the energy flow J_2 inside the sheet. The calculation result is

$$r \equiv \frac{J_1}{J_2} = \frac{\pi\varepsilon_0}{\varepsilon}\frac{\gamma^2}{\sqrt{1+\gamma}^3} h \sqrt{\frac{1}{\lambda^2} - \frac{1}{\lambda_0^2}} \qquad (3)$$

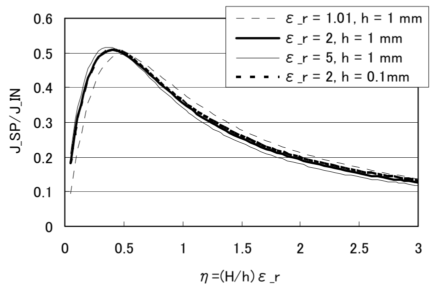
where λ_0 and λ are respectively equal to the electromagnetic wave length in the air and the one in a medium with ε and μ. Dimensionless parameter γ is defined as

$$\gamma \equiv X \frac{\varepsilon}{h(\varepsilon\mu - \varepsilon_0\mu_0)\omega}, \qquad (4)$$

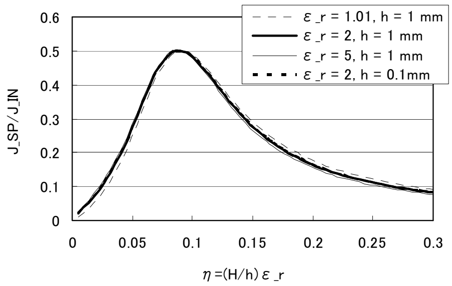
which is a normalized sheet inductance that determines the electromagnetic leakage and the connection property. In a case when $\varepsilon/\varepsilon_0 = 1.4$, $\mu = \mu_0$, $h = 1$ mm, and $\gamma = 1.0$, r is as small as 0.4 % at 2.4 GHz. Electromagnetic wave can be sent/absorbed to/from the 2DST sheet by placing a conductive plate near S as explained later, while the electro-magnetic energy outside of the sheet remains small without the proximate conductive plate.



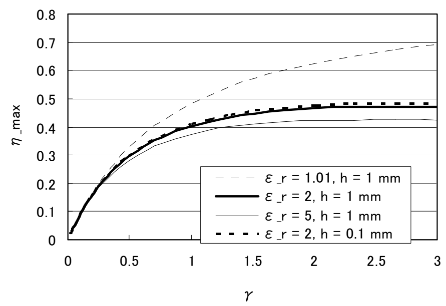
(a) Definitions of parameters. Conductive plate P is put close to inductive surface S.



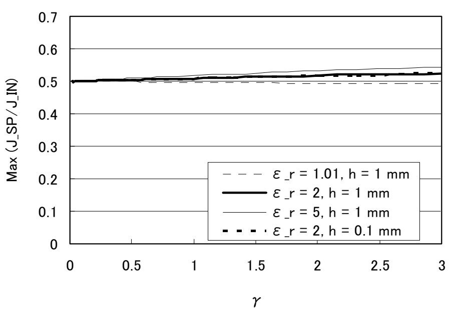
(b) J_{SP}/J_{IN} versus η for $\gamma = 1$.



(c) J_{SP}/J_{IN} versus η for $\gamma = 0.1$.

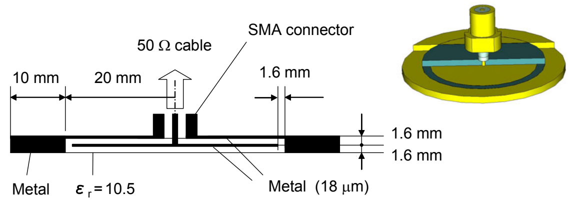


(d) η to maximize J_{SP}/J_{IN} versus γ.

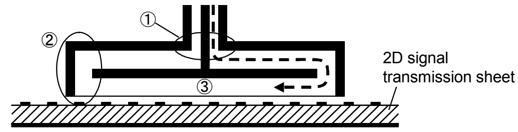


(e) Maximal J_{SP}/J_{IN} versus γ.

Fig. 4. Explanation of proximity connection by a conductor. The electromagnetic energy running between S and B is absorbed into the space between S and P.



(a)



(b)

Fig. 5. An example of proximity connector design. The detail of the axisymmetric connector (a) and an illustration of the principle.

B. Proximity connection

Consider a situation in which a sufficiently large conductor, P, is put parallel and close to S as shown in Fig. 4. In order to understand proximity connection, the following normalized height from S

$$\eta \equiv H \frac{\varepsilon}{h\varepsilon_0}, \tag{5}$$

and γ gien in equation (4) are useful.

Let electromagnetic wave run in x direction from the left with power density J_{IN} [W/m]. Fig. 4 (b) shows calculation results of J_{SP} for $\gamma = 1$. Parameter J_{SP} is the electromagnetic power running in the space between P and S. The graph is plotted as a function of normalized height η for various dielectric constant of the sheet material. This figure shows that electromagnetic power as large as 50 % of incident power is lifted up into the S-P gap when $\eta = 0.5$. The plots in Fig. 4 (c) are for $\gamma = 0.1$. In this case, the maximum of J_{SP}/J_{IN} is still about 50 % while η to maximize J_{SP}/J_{IN} becomes as small as 0.1. These calculation results tell us that a simple plate put close to the sheet can absorb the electromagnetic energy out of the sheet. Fig. 4 (d) shows the maximum of J_{SP}/J_{IN} versus γ. This graph shows that the maximum is about 50 % independent of the normalized sheet reactance γ. Instead the η to give the maximum becomes small when we decrease γ in the region $\gamma < 1$.

Therefore, if we add some structure that guides the energy absorbed into the S-P space to a cable, we can realize a proximity connector. If we optimize the structure as a receiver, it is optimum also as a transmitter by the reciprocity theorem.

C. Design of proximity connector

In this section, we show an example of proximity connector based on the theory explained in the preceding section. The design concept is qualitatively explained in Fig. 5. When we put the connector on the surface of the 2DST sheet, the micro wave impressed from the coaxial cable follows the winding axisymmetric path shown by the arrow of the broken line. Then reflections occur at three parts in the connector due to the discontinuous change of the impedances. Those positions are illustrated as ①, ② and ③ in the figure. As a result, reflected signal back to the coaxial cable is the mixture of the reflected

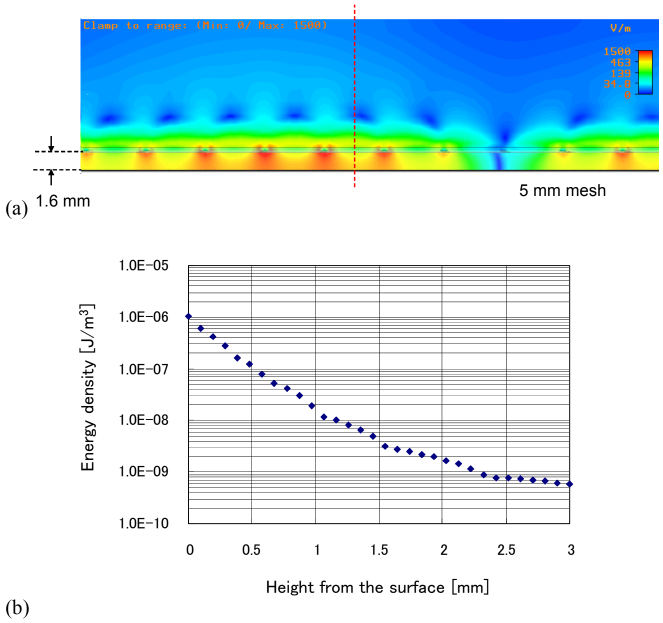


Fig. 6. Simulation results. Electric field around the 2DST sheet (a), and electromagnetic energy density along the red dashed line of the upper figure (b).

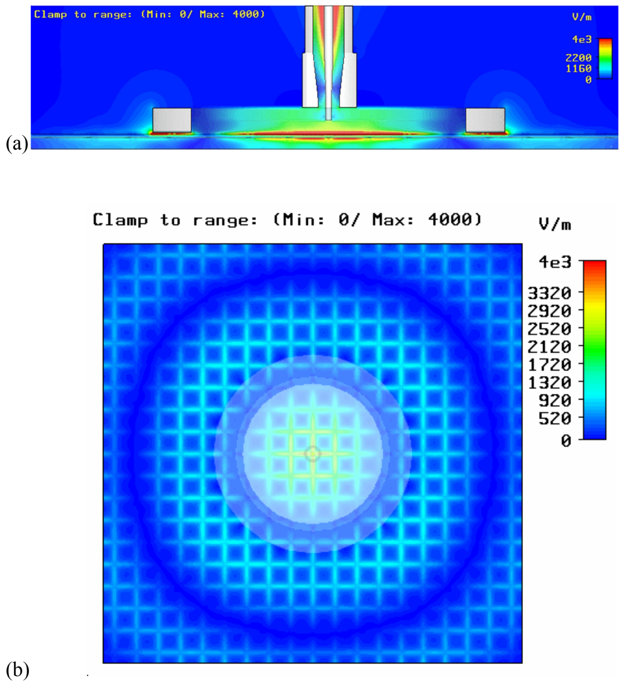


Fig. 7. Simulation results. The cross-section view of electric field intensity around the proximity connector (a), and the top view (b).

signals at each point. By choosing connector radius R so that the reflected signals from ② and ③ counteract the reflection at ①, we can reduce the reflected power. In an ideal case, the input signal is fed in the sheet without reflection back to the cable.

III. Simulations and Results

We confirmed the above discussions by simulation analyses using a software MW-STUDIO (AET Japan Inc.). The 2DST sheet was modeled as follows. The thickness of conductive layer B was 35 μm. The insulator layer was with the relative permittivity ε_r = 4.9 and the thickness of 1.6 mm. Inductive layer S is a rectangular mesh of conductive material 35 μm thick. The period of the mesh lattice was 5 mm and the line width of the lattice was 0.6 mm. Though the total size of the sheet was modeled as 55 mm by 55 mm, we assumed no reflection occurs at the sheet edge.

Figure 6 shows the simulation results of the electromagnetic fields induced around the 2DST sheet. The electric field intensity is graphically shown in (a). Fig. 6 (b) shows that the energy density decreases by 30 dB at 3 mm from the S layer. The reason why the decreasing curve of Fig. 6 is not exponential is that the detail of the electromagnetic field is written in the form as

$$f(x,z) = A\exp(-jkx)\left(\sum_{n=-\infty}^{\infty} B_n(z)\exp\left(j\frac{2\pi n}{d}x\right)\right)$$
$$\approx AC_0\exp(-jkx)\exp(-k_1 z)$$
$$+A\sum_{n\neq 0} C_n\exp\left(j\frac{2\pi n}{d}x\right)\exp\left(-\frac{2\pi n}{d}z\right)$$

where $d << 2\pi/k$. In equation (1) we omitted the term of $n \neq 0$ by averaging the electromagnetic field in the mesh period. The attenuation constant k_1 along z axis is 1.0 [1/cm].

The phenomenon in the proximity connector was also simulated. The proximity connector model was put on the surface of the 2DST sheet. Then 2.4 GHz microwave was impressed through the SMA connector as shown in Fig. 7 (a). The dimensions of the connector are optimized so that it can work at 2.4 GHz. Figure 7 (a) shows the cross-section of electric field in the connector. Figure (b) shows the top view of electric field in the 2DST sheet. The impressed energy propagated concentrically in the sheet even with the rectangular mesh layer.

IV. Experiments

We fabricated prototypes of 2DST sheet and proximity connector (Fig. 8). The 2DST sheet was 180 mm by 180 mm with the same parameters as those in the simulation. The detail of the prototype connector is shown in Fig. 5 (a). As an insulator between the sheet and the connector, we put a paper whose thickness was 0.1 mm. Using these prototypes, we conducted following experiments.

A. *Observation of S-parameter*

As shown in Fig. 8, the 2DST sheet has a SMA connector on the side edge for connection to a 50 Ω cable. One port of our network analyzer was connected to the SMA connector of the 2DST sheet and the other port to the proximity connector. Their performance was evaluated by measuring transmission coefficient S12 in the frequency range from 1 GHz to 5 GHz.

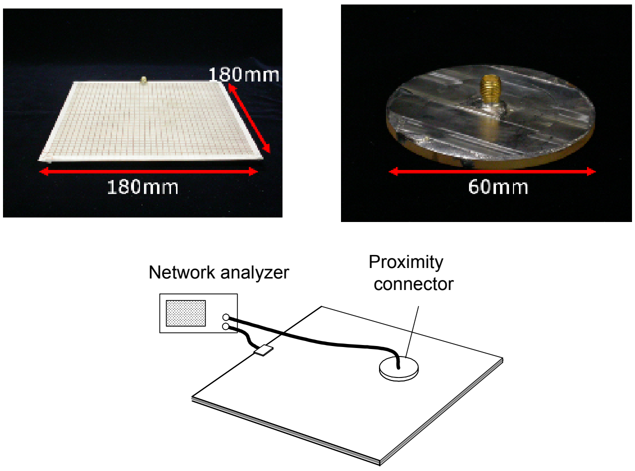


Fig. 8. The 2DST sheet used in the experiment (left side) and the proximity connector (right side). The connector size is 60 mm in diameter for 2.4 GHz signals. The internal structure is shown in Fig. 5.

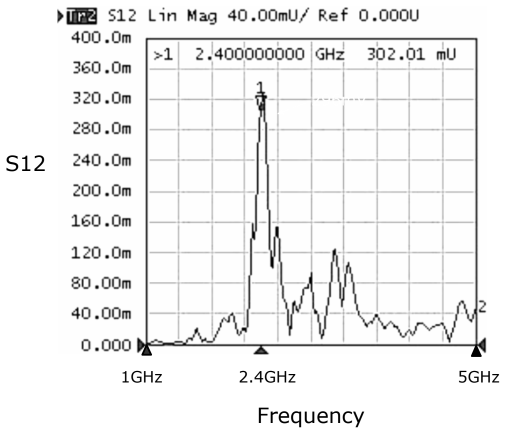
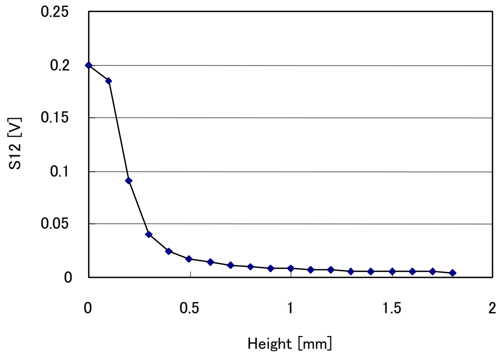


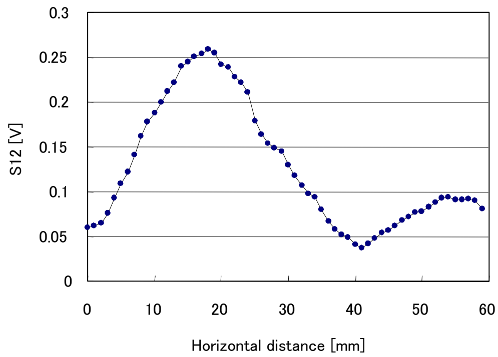
Fig. 9. Result of S12 measurement by a network analyzer. Transmission coefficient S12 was measured between the proximity connector and the SMA connector attached to the 2DST sheet. The definition of S12 is described in section IV.

Figure 9 shows an example of measured S12. The parameter S12 [mV] at each frequency denotes the output signal amplitude received through the 50 Ω cable connected to the 2DST sheet, for 1 [V] input signal applied to the proximity connector through the other 50 Ω cable. We find that the communication bandwidth is as large as 300 MHz around 2.4 GHz. Besides, it shows that 10 % of input power was received by the other port at 2.4 GHz in the best case.

In the next experiment, we investigated the relationship between the vertical distance above the sheet and S12. The results for 2.4 GHz signals are shown in Fig. 10 (a). It shows the proximity connection rapidly decreases for $d > 0.1$ mm. We also investigated the relationship between the horizontal position on the sheet and S12. We measured S12 at 2.4 GHz moving the proximity connector along a horizontal straight line on the sheet. As shown in Fig. 10 (b), S12 changed with the period of 4 cm reflecting the standing wave induced in the 2DST sheet. The data of Fig. 9 is the result obtained at the peak



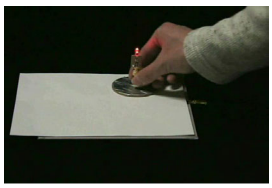
(a)



(b)

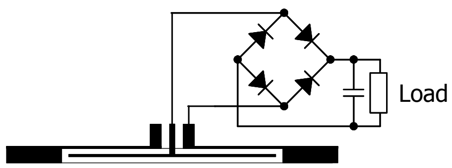
Fig. 10. Measured S12 versus connector position. S12 versus vertical displacement of the connector (a), and S12 versus horizontal displacement of the connector (b).

(a) Demonstration of high-speed video transmission.



(b) LED

(c) Motor



(d) Circuit used in experiments (b) and (c).

Fig. 11. Views of demonstrations. (a): Movie transmission using IEEE 802.11b. The left PC playes a video transmitting the video signal to the next computer. (b) and (c): Power transmission to light a LED and a motor. (d): Full-wave rectifying circuit for power reception.

position in the standing wave. In order to avoid the standing wave, we have to terminate the sheet edge.

B. Demonstration

Communication by IEEE 802.11b based on 2.4 GHz signal was demonstrated. We performed an experiment that one personal computer transmitted a video signal to another personal computer. In the experimental setup, commercially available wireless LAN cards were used. The antennas of them were replaced by the proximity connectors explained in the previous subsection, which was the only difference from the usual wireless peer-to-peer communication. The experimental view is shown in Fig. 11 (a). This experiment shows that good quality of signal transmission was possible through the 2DST sheet and a couple of proximity connectors. Since the size of the 2DST sheet was finite, standing waves in the sheet are induced, which degrades the communication quality. However, it was harmless to 11 Mbps connection.

We also confirmed experimentally that a LED and a small motor worked with the power caught by proximity connectors. The view is shown in Fig. 11 (b) and (c). We supplied 2 W microwave at 2.4 GHz to the 2DST sheet. The electromagnetic wave that the connector caught was commutated by a full-wave rectifying circuit as shown in Fig. 11 (d). Also in power supply, the unevenness of the efficiency was seen, which was caused by the standing wave in the 2DST sheet. For a 50 Ω resister as the load in Fig. 11 (d), instead of the LED or the motor, the maximum of the consumed power was 80 mW for the 2 W microwave input.

V. Conclusion

This paper proposed a new 2DST system based on proximity connection. We performed analyses and simulations of the signal transmission in a mesh-surface 2DST sheet, which clarified an evanescent wave trapped around the 2DST sheet can propagate over/in the sheet. We designed a proximity connector to the 2DST sheet by numerical simulation. We fabricated prototypes of the proximity connector and a 180 mm $\times$180 mm 2DST sheet, and evaluated their performance. We experimentally confirmed that the communication bandwidth is at least 300 MHz around 2.4 GHz and 10 % of supplied power to the 2DST sheet was absorbed by the proximity connector through the sheet in the best case.

It was also revealed that the standing waves in the 2DST sheet caused unevenness of the connection, which shows the necessity of non-reflective termination on the sheet edge.

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