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Proximity Connection in Two-Dimensional Signal Transmission

Naoshi Yamahira[1] ,Yastoshi Makino[2] ,Hiroto Itai[3] and Hiroyuki Shinoda[4]

[1,2,4]Department of Information Physics and Computing, The University of Tokyo, Tokyo, Japan
[1](Tel : +81-3-5841-6893; E-mail: naoshi_ yamahira@ipc.i.u-tokyo.ac.jp)
[2,4](Tel : +81-3-5841-6926; E-mail: yastoc,shino@alab.t.u-tokyo.ac.jp)
[3]Cellcross Co., Ltd. 2-11-16 Yayoi, Bunkyo-ku, Tokyo 113-8656 Japan
(Tel : +81-3-5842-2105; E-mail: itai@cellcross.co.jp)

Abstract: This paper presents a new structure of two-dimensional signal transmission (2DST). In a 2DST system, communication nodes communicate with each other by using electromagnetic wave localized in a thin sheet (a 2DST sheet). It's also possible to supply energy to the nodes using electromagnetic wave. In this paper, we propose a basic technology of a sensor network in which sensor nodes obtain an efficient proximity connection to any positions on the 2DST sheet without electrical contacts. The sheet is composed of a conductive mesh layer, a dielectric layer, and a continuous conductive layer. The sensor nodes communicate by the evanescent waves produced around the mesh layer. We fabricated a prototype of the 2DST system. Experiments showed that communication bandwidth is at least 500 MHz. Besides, about 10 % of input energy can be transmitted through a 180-mm-by-180-mm 2DST sheet with a proximity connector.

Keywords: sensor network, two-dimensional communication, proximity connector.

1. INTRODUCTION

In room-size sensor networks on the surfaces of desks, floors, clothes, and vehicles, how to physically connect a large number of small sensor elements to the networks is an important problem.

Although radio transmission is an effective way to remove wires for communication, there are some problems in it. The permitted power to be transmitted through the air is limited, which makes wireless power supply difficult. The available frequency band for one sensor is narrow in a high density network. The consumed power for communication is large, and information leakage is often problematic.

Two-dimensional signal transmission (2DST) is an alternative to cables or radio transmission in short-distance sensor networks. As Fig. 1 shows, sensor nodes communicate through a thin 2DST sheet that traps electromagnetic wave. A 2DST sheet is composed of a dielectric layer sandwiched by two conductive layers. Since the electromagnetic radiation from the sheet to the air is small, energy transmission with electromagnetic wave is also possible.

In the preceding researches of 2DST ([1], [2], [3]), sensor nodes had to contact with two conductive layers mechanically and electrically at fixed positions. In this paper we propose a system in which the sensor nodes obtain efficient proximity connection to a 2DST sheet without electrical contacts. In addition, the nodes can ensure the connection at any positions on the sheet.

If we install 2DST sheets on a table, for example, the desk surface becomes a communication medium for personal computers and peripherals on it without wiring or intense electromagnetic radiation. The small radiation leak makes the use of our 2DST system in hospitals available and the system is preferable in the information security. A simple structure of a 2DST sheet enables us to install 2DST sheets on a large area of surfaces at low cost. It is also possible that we embed the structure in various materials of surfaces including conductive rubber and clothes. Temperature sensors on the wall for air conditioning or pressure sensors on floors for security and monitoring elder people are simply put on the surface to send high bit rate sensor signal, being supplied with power from the surfaces.

In the following section we show the principle and structure of our new connector (we call it a proximity connector) and our new 2DST sheet. We examined signal transmission with the proximity connector by numerical simulations and experiments. We confirmed in experiments that efficient power transmission is possible.

The idea of communication using two dimensional medium was originally proposed by us [4] and some other groups [5], [6] at the early 2000s. In the researches [5] and [6], however, high speed communication through the medium was out of consideration. In addition, mechanical and electrical connection between elements and the conductive layers were necessary.

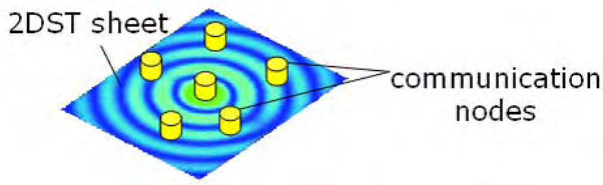


Fig. 1 An overview of 2DST. Communication nodes send and receive information through a 2DST sheet.

2. STRUCTURE 2DST SHEET

In this section, we show the principle and structure of our new 2DST sheet. As Fig. 2 shows, the 2DST sheet proposed here is composed of a conductive mesh layer, a dielectric layer, and a continuous conductive layer. It is

Table 1 The dimensions of our 2DST sheet.

	dimensions
the mesh period	5 mm
the stripe width	0.6 mm
the thickness of the sheet	1.6 mm
the thickness of the electric layer	0.035 mm

important that the mesh period and the thickness of the sheet are small enough in comparison with the electromagnetic wavelength in the sheet. The dimensions of our 2DST sheet is shown in table 1. We used a 2.4 GHz electromagnetic waves for communication and energy supply and the wavelength is about 60 mm since the relative permittivity of the dielectric layer is 4.9.

We carried out an analysis and simulations of electromagnetic waves passing through a 2DST sheet. These results showed that intense electric field exists near the mesh layer and that the intensity decreases exponentially with the distance from the surface. A sensor node with our new connector (a proximity connector) obtains the connection to the sheet by being placed in the intense field region over the surface.

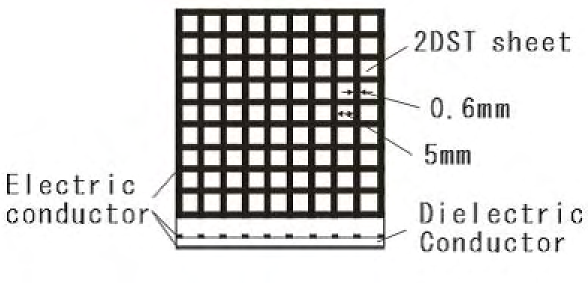


Fig. 2 The structure of the proposed 2DST sheet. The top view (upper) and the cross-section (lower) of the sheet.

2.1 ELECTROMAGNETIC ANALYSIS OF 2DST SHEET

We carry out a simple analysis of electromagnetic waves passing around our 2DST sheet. Figure 3 shows the cross-section of our 2DST sheet. It is assumed that the electromagnetic waves in the sheet is propagating along the x axis in the figure. Generally, the electromagnetic field over the periodically structured sheet ($z > 0$) can be expressed as a product of a fundamental component of the wavelenth λ_d [m] and modulation components with the period of d [m] $\ll \lambda_d$ as

$$E(x,z) = A\exp\left(\mathrm{j}\frac{2\pi}{\lambda_d}x\right)\left(\sum_{n=-\infty}^{\infty} B_n(z)\exp\left(\mathrm{j}\frac{2\pi n}{d}x\right)\right)$$

$$\left(\begin{array}{ccc} E(x,z) & : & \text{electric field at } z>0, \\ A & : & \text{constant,} \\ n & : & \text{integer,} \\ B_n(z) & : & \text{the attenuation in terms of z} \end{array}\right)$$

where $B_n(z)$ are derived from the wave equation,

$$\triangle E = -\left(\frac{2\pi}{\lambda}\right)^2 E$$

(λ [m] : the wavelength in the atmosphere).

as

$$B_n(z) = C_n \exp\left[-2\pi\sqrt{\left(\frac{1}{\lambda_d}+\frac{n}{d}\right)^2 - \left(\frac{1}{\lambda}\right)^2}\, z\right]$$

(C_n : constant).

Note that λ_d is less than λ because the relative permittivity of the dielectric layer is larger than 1. Therefore we find that $\left(\frac{1}{\lambda_d}+\frac{n}{d}\right)^2 - \left(\frac{1}{\lambda}\right)^2 > 0$. We assume that the mesh period d is much smaller than the wavelength λ_d. Then, $B_n(z)$ is approximated as followed.

$$B_n(z) \simeq \begin{cases} C_0 \exp\left[-2\pi\sqrt{\left(\frac{1}{\lambda_d}\right)^2 - \left(\frac{1}{\lambda}\right)^2}\, z\right] & (n=0) \\ C_n \exp\left(-\frac{2\pi n}{d}z\right) & (n \neq 0) \end{cases}$$

This represents the electric field forms evanescent wave being attenuated exponentially in terms of z. We find the first term has a relatively large attenuation length $1/\sqrt{\frac{1}{\lambda_d^2} - \frac{1}{\lambda^2}}$, while the second terms have small attenuation lengths of $d/2\pi|n|$. As the simulation results in the next section show, the energy of the first term is much smaller than the energy of the second terms.We find that the mesh layer makes a strong electric field in the near region over the sheet

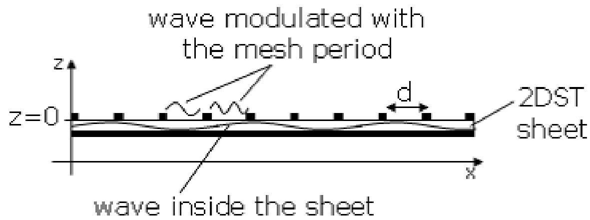


Fig. 3 The fundamental component and modulation component of the electromagnetic wave over the sheet.

2.2 SIMULATION

Figure 4 upper shows a cross-sectional view of electroenergetic density derived from the numerical simulation by CST MICROWAVE STUDIO. The lower graph shows the energy density along a certain vertical line over the sheet. The input current is impressed at the edge of the sheet and the boundary condition is set so that the electromagnetic wave is not reflected at the other three edges. In this simulation, the dimensions of the sheet are the same as the ones shown in table 1. We assumed 2.4GHz electromagnetic waves for communication.

We find that intense electric field exists near the mesh layer and that the intensity decreases with the distance from the surface as the theory expects.

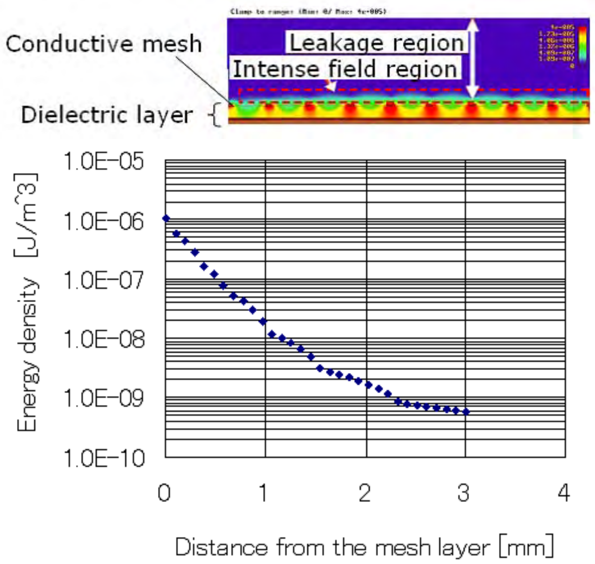


Fig. 4 The numerical simulation results of the 2.4 GHz electromagnetic wave propagation in a 2DST sheet. Energetic density of the 2DST sheet viewed from the side and a graph showing the relationship between the energetic density and the distance from the surface of the sheet.

3. PROXIMITY CONNECTOR DESIGN

Our new connector proposed in this paper is shown in Fig. 5. The axisymmetrical connector consists of metal, dielectric material with the relative permittivity of 10.5, and a SMA (sub-miniature-type-A) connector to a 50 Ω cable.

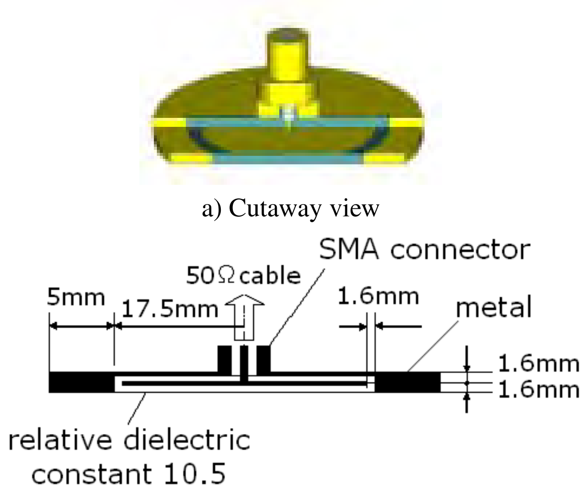
Numerical simulation results showed that this connector obtains efficient connection to any horizontal positions on the 2DST sheet without electrical contacts.

3.1 SIMULATION

We simulated an electromagnetic wave emission from a proximity connector into our 2DST sheet. We also evaluated the absorption from the sheet into the connector. Figure 6 is a model that we use in the simulation. A 0.4 mm insulating sheet is placed between the proximity connector and the 2DST sheet. The dimensios of the 2DST sheet are the same as preceding simulation. The radius of the connector was determined so that the reflection of the electromagnetic wave from the connector to a cable is minimized at the frequency of 2.4 GHz.

Figure 7 shows the amplitude reflectance at the connector as a function of frequency, where the electromagnetic wave is introduced into the SMA connector through a 50 Ω cable. We find that the reflectance is low at the frequency of 2.4 GHz

The electric field in a cross-sectional view is shown in Fig. 8. It is colored by its amplitude. This figure shows that the electromagnetic wave is emitted with resonance inside the connector. In Fig. 9, besides, it is confirmed that the emitted electromagnetic wave propagates axisymmetrically in the 2DST sheet with the rectangular mesh layer.



a) Cutaway view

b) Dimensions

Fig. 5 The structure of a proximity connector and the dimensions in the simulation.

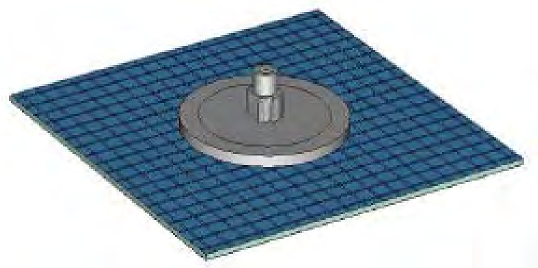


Fig. 6 A model we use in the simulation. A 0.4 mm insulating sheet is placed between the proximity connector and the 2DST sheet.

4. EXPERIMENTS

We fabricated prototypes of the proximity connector and the 2DST sheet as shown in Fig. 10 and Fig. 11. The 2DST sheet has a SMA connector on the side edge for connection to a cable. The dimensions of the proximity connector in experiments are slightly different from the ones in the numerical simulations, for obtaining the best experimental result at the frequency of 2.4 GHz.

4.1 TRANSMISSION PERFORMANCE

We used Network Analyzer for evaluation of the prototype. One port of Network Analyzer was connected to the SMA connector of the 2DST sheet and the other port to the proximity connector. A 0.4 mm insulating sheet was put on the sheet. Their performance was evaluated by measuring the parameter S12 in the frequency range from 1 GHz to 5 GHz.

Figure 12 shows an example of mesured S12. The pa-

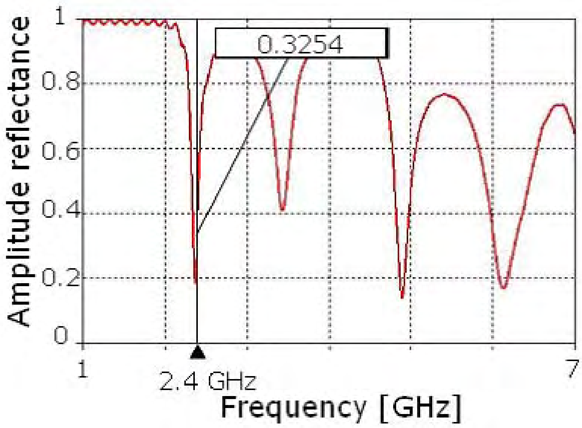


Fig. 7 The amplitude reflectance from the connector as a function of frequency, where the electromagnetic wave is impressed to the SMA connector through a 50 Ω cable.

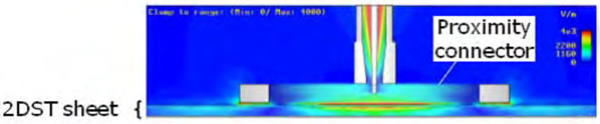


Fig. 8 The electric field in a cross-sectional view by a numerical simulation. A 2.4 GHz elecgtromagnetic wave is emitted from the connector into a 2DST sheet. This figure is captured at certain moment of one cycle.

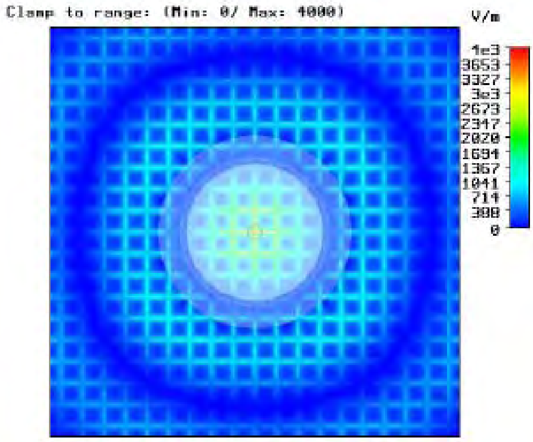
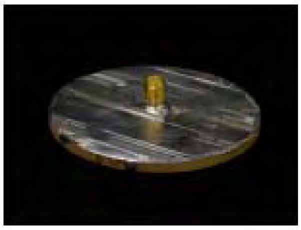
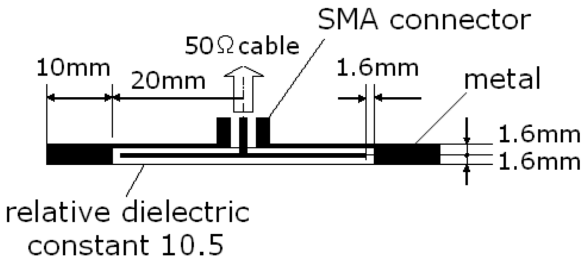


Fig. 9 Top view of the electric field inside the 2DST sheet. This figure is captured at certain moment of one cycle. The emitted electromagnetic wave propagates axisymmetrically.



(a) Perspective top view

(b) Bottom view



(c) Dimensions

Fig. 10 A prototype of the proximity connector and its dimensions. The internal structure is the same as the one shown in Fig. 5.

rameter S12 [V] at each frequency denotes the output signal amplitude received through a 50 Ω cable connected to the 2DST sheet, for 1 V input signal applied to the proximity connector through another 50Ω cable. We find that communication bandwidth is as large as 500 MHz around 2.4 GHz. Besides, it shows that 10 % of input power was received by the other port at 2.4 GHz. (The efficiency was the best case through our experiments.)

In the next experiment, we investigated the relationship between the vertical distance over the sheet and S12. The results for 2.4GHz signals are shown in Fig. 13. It shows the proximity connection rapidly decreases for $d > 0.3$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 certain horizontal straight line over the sheet. As shown in Fig. 14, S12 changed with the period of 40 mm since the standing wave was induced in the 2DST sheet.

4.2 ENERGY TRANSMISSION

We experimentally confirmed that a LED and a small motor worked with the power caught by proximity connectors. The result is shown in Fig. 15. The electromagnetic wave that the connector caught was commutated by a full-wave rectifying circuit. This experiment revealed that there was a specific region on the sheet surface where absorbed power decreased. The unevenness of the efficiency was caused by the standing wave in the 2DST sheet.

4.3 COMMUNICATION

Communication by IEEE802.11b based on 2.4 GHz signal was examined. We performed an experiment that one personal computer transmitted a video signal to another personal computer. The experimental view is shown in Fig. 16. This experiment shows that good quality of signal transmission was possible through the 2DST sheet and a couple of proximity connectors.

5. CONCLUSION

This paper proposed a new 2DST system based on proximity connection. We performed the analysis and

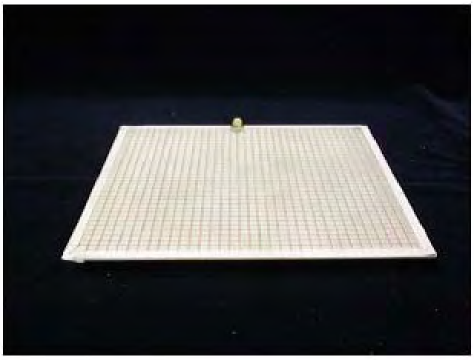


Fig. 11 A prototype of a 2DST sheet. Its dimensions are shown in table 1. The sheet is made of a double-sided board of a 180-mm-by-180-mm square and a SMA connector.

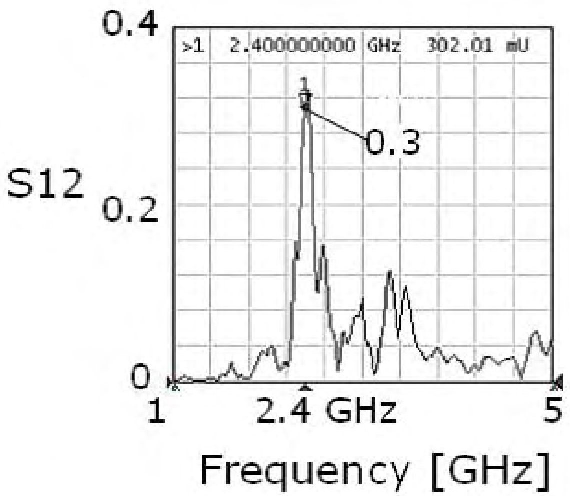


Fig. 12 The experimental result of S12 measurement between the proximity connector and the SMA connector attached to the 2DSTsheet. The definition of S12 is described in section 4.1

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 the 180-mm-by-180-mm 2DST sheet, and evaluated their performance. We experimentally confirmed that communication bandwidth is at least 500 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 in the 2DST sheet caused unevenness of the connection, which shows the necessity of non-reflective termination on the sheet edge.

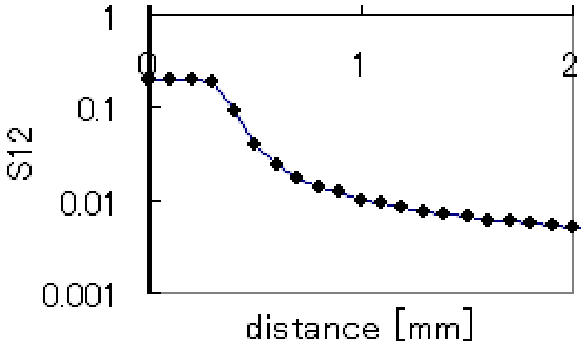


Fig. 13 Mesured S12 at 2.4 GHz versus the height of the proximity connector. The definition of S12 is described in section 4.1

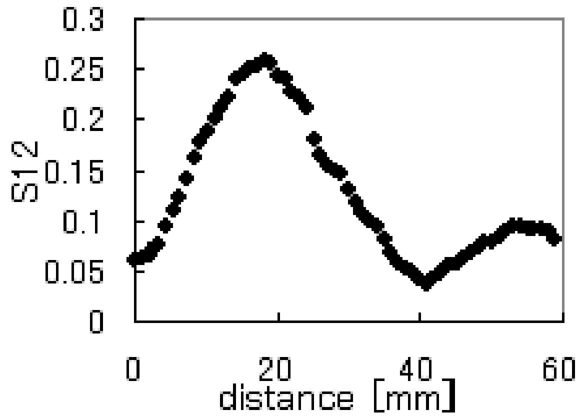


Fig. 14 Measure S12 at 2.4GHz when the proximity connector was moved along a certain horizontal straight line on the sheet.

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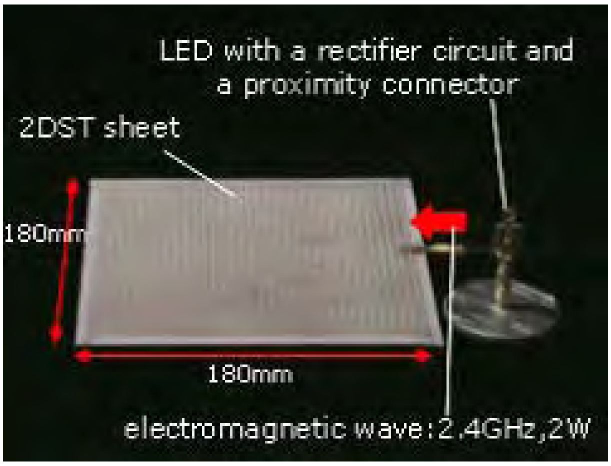

(a) Experimental setup

(c) Motor

(b) LED

Fig. 15 An experiment on energy transmission. A 2.4 GHz electromagnetic wave of 2 W was supplied into the 2DST sheet. We confirmed that the LED lighted and the motor rotated.

Fig. 16 The left personal computer were played a video transmitting the video signal to the next computer. Signal transmission through the 2DST sheet and a couple of proximity connectors was successful.