

Position Sensing based on Electric Field Measurement on Two-Dimensional Signal Transmission Sheet

Kei Nakatsuma, Yasutoshi Makino and Hiroyuki Shinoda
Department of Information Physics and Computing
The University of Tokyo
Tokyo, Japan
e-mail: {tsuna, yasutoc, shino}@alab.t.u-tokyo.ac.jp

Abstract— Our group has proposed a new communication technology named “Two-Dimensional Communication” for high-density indoor sensor networks. In this paper, we propose a method to detect the positions and orientations of sensor nodes placed on the Two-Dimensional Signal Transmission sheet (2DST sheet). First, we introduce the scheme of encoding the position information on the 2DST sheet. Next, we analyze the electromagnetic field modulation by the conductive mesh pattern on the 2DST sheet, and describe the proposed method that determines the sensor locations from the measured electric field pattern. Finally, we show the results of several fundamental experiments to confirm this principle.

Keywords—Two-Dimensional Communication; Sensor Network; Node-Localization; Ubiquitous Computing;

I. INTRODUCTION

Our group has proposed a novel communication technology named “Two-Dimensional Communication” for high-density sensor networks used in living rooms, offices, and factories, and also used in cars, air planes, and robots as an alternative communication technology to WiFi, CAN, and so on [1]. On the Two-Dimensional Signal Transmission sheet (2DST sheet), the sensor nodes can communicate with each other and acquire electricity anywhere on the sheet without any direct electrical connections to it. This technology achieves wireless and batteryless ubiquitous infrastructures.

One general problem in sensor networks is to identify the positions of the distributed sensor nodes. It is difficult to specify the positions of large numbers of nodes in installing them in the facility. Even for relatively small numbers of nodes, if they are placed at arbitrary positions or their positions are time-varying, some positioning mechanism is required to relate each node to its position.

In this paper, we propose a method for detecting the positions and orientations of sensor nodes arbitrarily placed on the 2DST sheet. The position detection of the sensor nodes is useful not only for acquiring location specific information, but also for efficient electricity supply to targeted nodes. In addition, by detecting the positions of various devices, as displays,

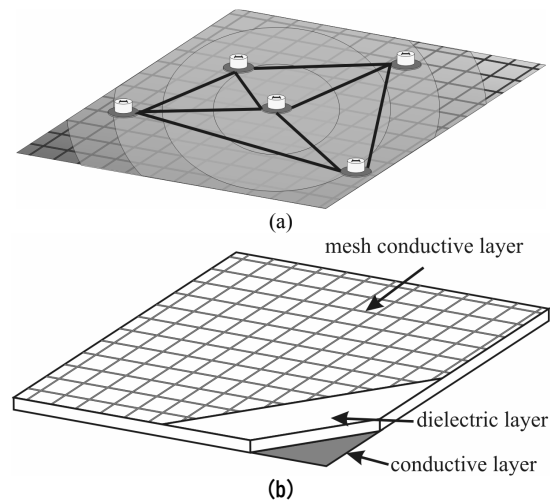


Figure 1. (a): The concept of the Two-Dimensional Signal Transmission (2DST). Sensor nodes can send/receive packets through the 2DST sheet. (b): The structure of the 2DST sheet. Two conductive layers sandwich a dielectric layer. The top conductive layer has a meshed structure, and the bottom is a continuous conductive layer.

PDAs, cell phones, laptops, etc. on the 2DST sheet, it is possible to provide location-specific functions or information to the devices (e.g. Microsoft Surface [3], DataTiles [4]).

There are several possible methods to detect the positions of the sensor nodes placed on a two-dimensional surface. For example, Pin&Play system [5] utilizes images captured with an external camera. Microsoft Surface [3] also uses a camera placed at the backside of the display to detect the positions and orientations of 2D barcode-like tags. The problem in practical use of the vision-based system like Pin&Play is that an external camera should be placed for one surface. Also it can be a drawback that it usually suffers from the occlusion problem. DataTiles [4] use RFID tags and identify the positions of Tiles by RFID readers distributed on the surface. Although we can follow this method for positioning on the 2DST sheet, it makes the structure of the 2DST sheet complicated. MAGIC-Surface [6] is a flat array of small components which enable communication, electricity supply,

and positioning functions without direct physical connection. The component uses the magnetic field to detect the positions and orientations of objects placed on it. Networked Surfaces [7] also detect the positions and orientations of objects using conductive pads.

We employ the method which utilizes the electromagnetic field in close proximity to the 2DST sheet, which is produced by the propagation of microwaves. The structure of the 2DST sheet is still simple. This method requires only a small modification to the pattern of the mesh layer of the existing 2DST sheet. Nevertheless the sensor nodes obtain precise position in 1 mm accuracy easily. In addition, thin obstacles like a piece of paper can be placed between the 2DST sheet and the nodes. The method does not suffer from the occlusion problem in visual positioning systems.

We have already reported the concept of this method in the Japanese domestic conference [2]. In [2], we measured the magnetic field generated above the 2DST sheet with a micro coil array. Though the simulation analysis showed the magnetic-field-based method is effective for precise positioning, it also showed that the sensor node should have a magnetic pattern detector with very high density. In this paper, we propose a more practical method based on the electric field sensing and report the results of the experiments.

This paper begins with a description of our approach and design goals. Then, in Section 3, the method for encoding the position information on the 2DST sheet is explained. In Section 4, the results of the electromagnetic field simulations are shown, and the new method for physical encoding and detecting the position on the 2DST sheet are discussed. Based on the analyses, we conducted a fundamental experiment to confirm the feasibility of the proposed method. The results are shown in Section 5.

II. POSITIONING SYSTEM OVERVIEW

The basic idea of the proposed method is inspired by a pen-positioning system by Anoto [8]. Anoto's pen identifies its position on a special paper by capturing the fine pattern printed on it with an optical device embedded into the pen. The printed pattern at each location is unique so that the pen can identify the location.

In our system, we use the electromagnetic field pattern produced by the mesh layer of the 2DST sheet. The 2DST sheet has three layers. Two conductive layers sandwich the dielectric layer (Fig. 1). Microwaves for communication and power supply can propagate in the dielectric layer. The top conductive layer has a meshed structure which forms an evanescent wave immediately above the surface of the sheet. Thus, sensor nodes on the sheet can communicate and acquire electricity through the proximal connection to the evanescent wave. The spatial pattern of the evanescent wave depends on the mesh shape of the top conductive layer, while the pattern of the mesh does not affect the propagation of the electromagnetic wave if it is designed under the constraint that the macroscopic sheet inductance is kept constant [1]. Therefore it is possible to assign a unique mesh pattern to each location on the 2DST sheet without obstructing the propagation of the electromagnetic wave. By detecting the pattern of the evanescent wave generated on the 2DST sheet, it is possible for sensor nodes to identify their location on the 2DST sheet.

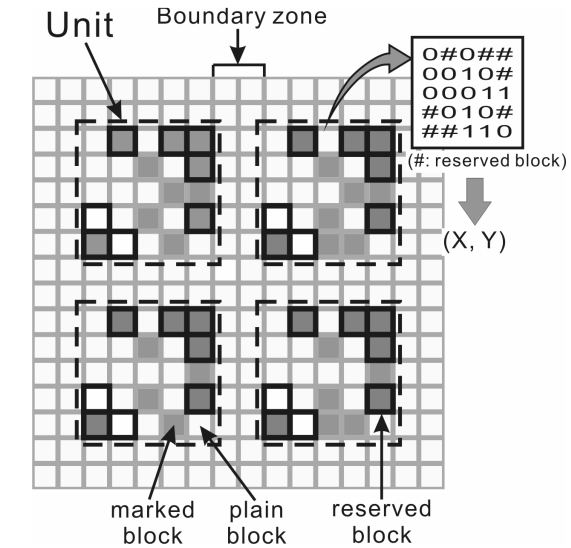


Figure 2. The position encoding scheme on the 2DST sheet.

nescent wave depends on the mesh shape of the top conductive layer, while the pattern of the mesh does not affect the propagation of the electromagnetic wave if it is designed under the constraint that the macroscopic sheet inductance is kept constant [1]. Therefore it is possible to assign a unique mesh pattern to each location on the 2DST sheet without obstructing the propagation of the electromagnetic wave. By detecting the pattern of the evanescent wave generated on the 2DST sheet, it is possible for sensor nodes to identify their location on the 2DST sheet.

In the design of our positioning system, we set the following goals of specifications,

- Unique identification on the 2DST sheet larger than 10 m square.
- Millimeter precision of position sensing.
- The size of the detector is about 10 cm square or smaller.

To achieve these goals, we develop the position encoding scheme and the method to detect the encoding pattern. The details are described in the following sections.

III. POSITION ENCODING ON THE 2DST SHEET

In order to encode the position on the 2DST sheet, the pattern of the mesh is designed as follows.

The 2DST sheet has a meshed structure as shown in Fig. 1. In our position encoding scheme, one block of the grid represents one bit of information by changing its shape. We call the modified block a "marked block," and the non-modified block a "plain block." We make a "Unit" which is constructed with 5×5

blocks. One Unit represents its X-Y coordinate value on the 2DST sheet. There are 8 reserved blocks consisting of 6 marked blocks and 2 plain blocks in each Unit. The reserved blocks represent the boundary and the orientation of a Unit. The other 17 blocks correspond to the bit pattern of the binary X-Y coordinate value respectively. For separating neighbor Units, double width lines containing only plain blocks are used. We call this area a “Boundary zone.” It is easy to detect and identify the Boundary zone because the reserved blocks prevent any Unit from having double-width-plain-block lines in the Unit.

We calculate how large area the proposed 2DST sheet can cover. A Unit has 17 bits information. Therefore we can arrange 2^9 Units laterally and 2^8 lengthways. If we assume a $d = 7$ mm pitch mesh sheet as used in [1], one Unit occupies the area of 49×49 mm², including the Boundary zone. Hence, the area covered with the sheet is about 25×12.5 m². This is sufficiently large for our purpose of position identification on the room size 2DST sheet.

In addition, we confirm how large area a position detector requires to identify its position and orientation on the 2DST sheet. As a result of simulations, if the detector has the size of 11×11 cm², it can cover one whole Unit everywhere on the sheet regardless of the orientation. The detector size is almost enough small for our design goals.

Once the detector finds a whole Unit, it can detect its own precise position and orientation from the alignment of blocks as well as identifying the code. The accuracy of detected position depends on the spatial resolution of the detector. Sub-mesh precision is possible by a high-resolution detector.

IV. PHYSICAL ENCODING

A. Physical Quantity for Position Pattern Detection

The next problem to be examined is what physical quantities should be measured to identify the codes. We have already reported the method using magnetic field sensing with a small coil array in [2]. Though the method was effective to detect the edges of the code patterns for realizing sub-millimeter accuracy, the problem was that the detector should have a very high resolution. A low-resolution detector could not detect the codes since the pattern lacked low spatial frequency components. In this paper, we select the vertical electric field component E_z as the measurand. The reason of the selection is that E_z pattern is insensitive to the direction of the signal wave, and simulations and experiments suggested that the E_z pattern contains a larger low spatial frequency component than the magnetic field has. Any directional component of the electromagnetic field is written in the form as

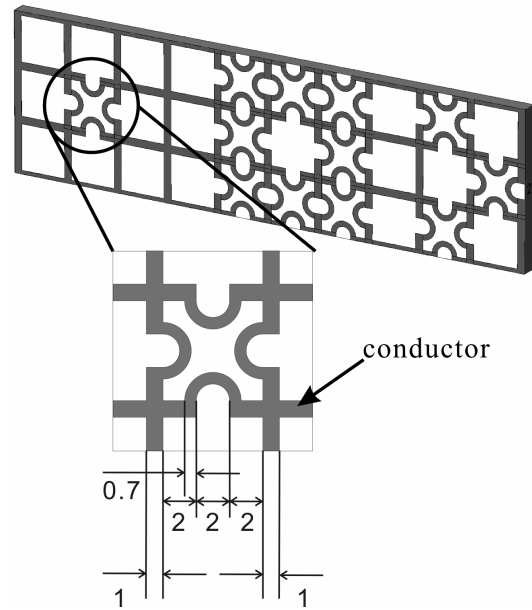


Figure 3. One of the simulation models of a 2DST sheet for analyzing the electromagnetic field above the surface of the sheets. In this model, a marked block is realized with winding lines.

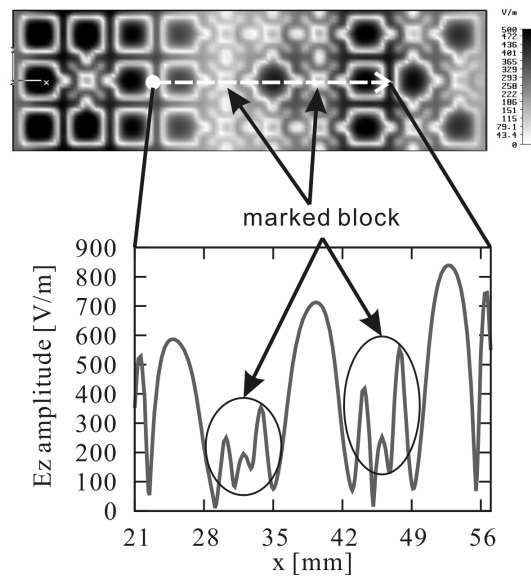


Figure 4. The result of the simulation. The model is shown in Fig. 3. (a): The time average of the vertical electric field 1 mm above the sheet surface is shown. The contrast of E_z amplitude in the single grid is apparently different between the plain and marked block. (b): The E_z amplitude on the dash line shown in (a).

$$\begin{aligned}
f(x, z) &= A \exp(-jkx) \left(\sum_{n=-\infty}^{\infty} B_n(z) \exp\left(j \frac{2\pi n}{d} x\right) \right) \\
&= AC_0 \exp(-jkx) \exp(-k_1 z) \\
&+ A \exp(-jkx) \sum_{n \neq 0} C_n \exp\left(j \frac{2\pi n}{d} x\right) \exp\left(-\frac{2\pi n}{d} |z|\right) \quad (1)
\end{aligned}$$

along the surface, where $d \ll 2\pi/k$, the electromagnetic waves run along x direction, and k is the wavenumber of the 2D electromagnetic wave. As we explain later, we design the block pattern so that k and k_1 are common between the plain and the marked blocks. We detect the code from the difference of C_n ($n \neq 0$) between the plain and the marked blocks. The paper shows that the pattern of vertical electric field E_z provides clear difference in $C_{\pm 1}$, while the magnetic field was found to have small energy in $C_{\pm 1}$. The lower resolution detector realized by E_z measurement is more practical for our purpose in terms of the simplicity of the sensor.

B. Electric Field above the 2DST Sheet

We conducted some electromagnetic field simulations with the MW-STUDIO software (AET Japan Inc.). The details of the analysis model were as follows. As to the dielectric layer, the relative permittivity ϵ_r was 1.5 and the thickness was 2.0 mm. At the bottom of the dielectric layer, perfect conductive boundary condition was used, instead of modeling the physical conductive layer. The top conductive mesh layer was a $d = 7$ mm pitch mesh with 1 mm width conductor. The proposed pattern of the “marked block” is shown in Fig. 3. We explain how to determine the shape later. 2.4 GHz electromagnetic waves were applied from the one side of the 2DST sheet model. Fig. 4 shows the simulation results of the vertical electric field 1 mm above the mesh conductive layer. The result shows the apparent difference in C_1 between the plain and the marked blocks, that is, the contrast of E_z amplitude in the single block is apparently different between both cases. The difference can be detected by spatial sampling with a period smaller than $d/2$.

We also designed and evaluated the shape of the marked block through a simulation. In order to avoid the unexpected reflection of electromagnetic waves at the boundary of the plain and the marked block, the macroscopic sheet inductance of the top layer should be kept constant [1]. The sheet inductance is evaluated by the magnetic energy

$$U_B = \int_V |\mathbf{B}|^2 dV \quad (2)$$

induced by the given surface current I . We conducted some simulations to evaluate the sheet inductance. The analysis models are shown in Fig. 5. A line of blocks was used to obtain the inductance of a block. In the model, the domain of the integration in (2) is the rec-

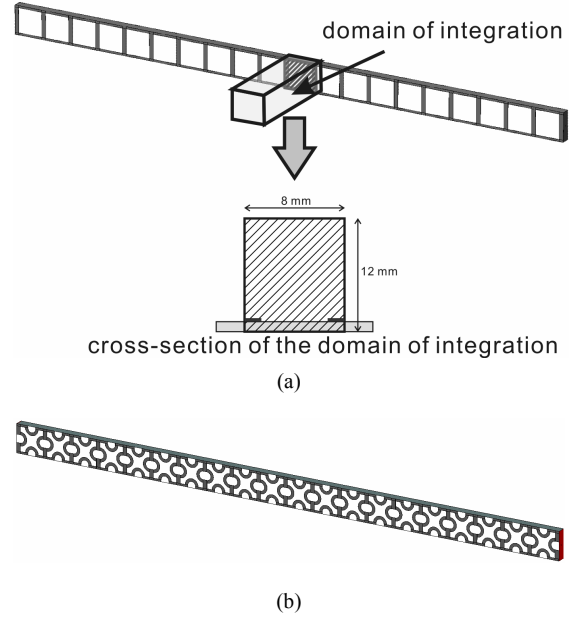


Figure 5. The simulation models to evaluate the inductance of the proposed marked block. (a) is the basic model with all plain blocks. In (a), the region for the volume integration of magnetic energy density is shown. The dimensional parameters were chosen so that the sheet inductance of model (b) was the closest to that of the normal mesh (a). The detailed configuration is shown in Fig. 3.

tangular solid shown in Fig. 5 (a). This solid is the height of 12 mm from the bottom of the sheet within one block area. We tried the plain block model and several marked block pattern models and obtained the value of U_B / I^2 for each model. The pattern which has the closest value to that of the plain block is selected finally. The details of the model are shown in Fig. 3 and Fig. 5 (b).

V. EXPERIMENTS

Based on the discussion in Section 4, we conducted several experiments to confirm the principle of position code detection. To provide the same condition as the simulation of Fig. 3, we prepared an experimental setup shown in Fig. 6. A part of the 2DST sheet was fabricated so that it was smoothly connected to 50 Ω microstriplines. On both sides of the sheet, 50 Ω SMA connectors were attached.

The vertical component of the electric field at 1 mm above the sheet surface was measured with a small probe shown in Fig. 7. The probe was connected to a high frequency oscilloscope and the root mean square value of the output was recorded. The apex of the probe was placed at 1 mm above the sheet surface. The single probe was scanned in the measurement region shown in Fig. 8 (a).

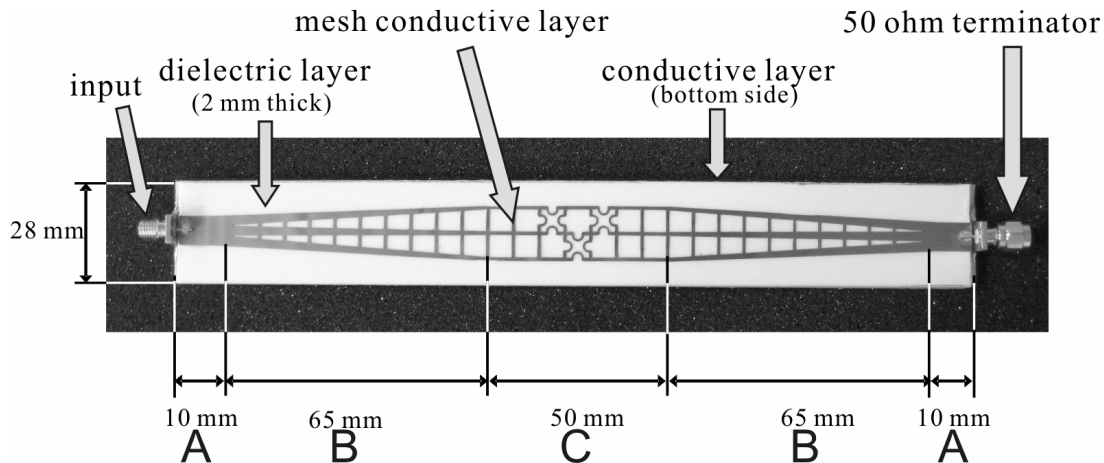


Figure 6. The photograph of the partial 2DST sheet for the experiment. A part of the 2DST sheet top layer was fabricated in C. This grid pattern includes both the plain and the marked blocks. The part B has the horn structure so that C is smoothly connected to 50 Ω microstriplines A. The intermediate layer was 2 mm thick polyethylene sheet ($\epsilon_r = 1.4$). The bottom layer is continuous conductive layer and its size was the same as the intermediate dielectric layer. The right end was terminated by a 50 Ω terminator. This sheet structure sufficiently eliminates microwave reflection and provides the same condition as the simulation in Fig. 3, 4 and 5.

The result of the measurement is shown in Fig. 8 (b). The difference between the marked and the plain blocks is clearly observed. We should notice the difference between the simulation and the experimental results. The simulation showed the contrast of E_z amplitude in a single block was different between the plain and marked blocks. The theory tells us that the average of E_z is common between both cases. On the other hand, the detected signal amplitude was strong simply over the metal area of the top layer pattern, in the experiment.

The disparity is ascribed to the interaction between the probe and the sheet surface. When the probe is placed near the sheet, electric field is expected to be induced between the probe conductor and the mesh conductor, which was not considered in the simulation. The property found in the experiment seems favorable for practical uses in which a low resolution detector detects the code stably. We can also obtain more accurate position by the metal area pattern measured with a higher resolution detector.

In Section 4, we described that the difference between the plain and the marked blocks can be detected by spatial sampling with a period smaller than $d/2$, where d is the pitch of the mesh. The diameter of the probe in Fig. 7 is 1.2 mm and enough thin to fabricate the required resolution of the probe array if we use the $d = 7$ mm pitch mesh sheet.

VI. CONCLUSION

In this paper, we proposed a method to detect the positions and orientations of sensor nodes on the 2DST sheet. First, we described the scheme for encod-

ing the position information on the 2DST sheet, and verified that this scheme is sufficient for fulfilling the design goals described in Section 2. Next, we proposed the new method for physical detection of the position pattern based on the electric field measurement. We showed the simulation results and confirmed the effectiveness of this method. We fabricated the 2DST sheet which consists of the marked and the plain blocks, and measured the vertical electric field with the miniature electric field probe. The measurement results were sufficiently clear for distinguishing the marked blocks from the plain blocks, and even for recognizing the shape of the mesh conductor. From these results, we confirmed that the proposed method is capable of coding the position information on the 2DST sheet.

The fabrication and examination of the E_z field probe array is left as future works. According to the discussion in Section 5, the required resolution of a probe array is 3.5 mm. We already confirmed that the size of the measuring circuit for each probe in the array is less than 3.5 mm square. We are currently developing the prototype model as Fig. 9 shows.

ACKNOWLEDGMENT

We thank Dr. Youiti Kado and Dr. Zhang Bing, NICT, who motivated this research and provided useful suggestions. This work was partly supported by the Japan Society for the Promotion of Science, and a Grant-in-Aid for Scientific Research from the Ministry of Education, Culture, Sports, Science and Technology of Japan.

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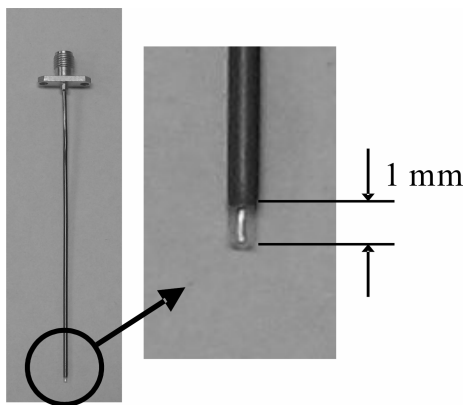


Figure 7. The miniature electric field probe for measurement of vertical electric field on the 2DC sheet. We fabricated this probe by peeling the metallic shield of a semi-rigid cable. This probe senses the vertical component of the electric field.

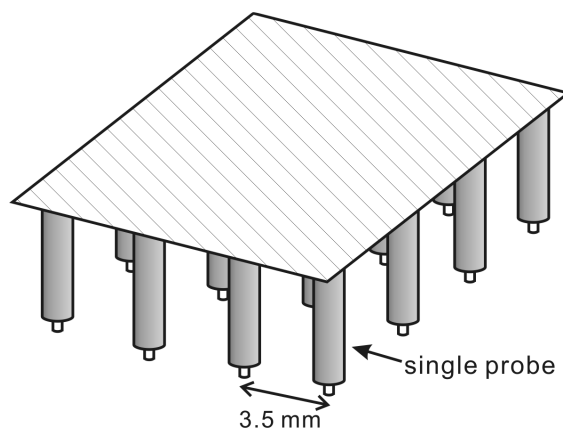


Figure 9. The diagram of an electric field probe array.

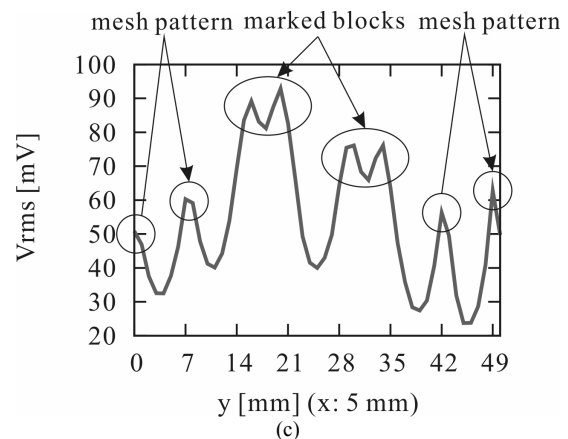
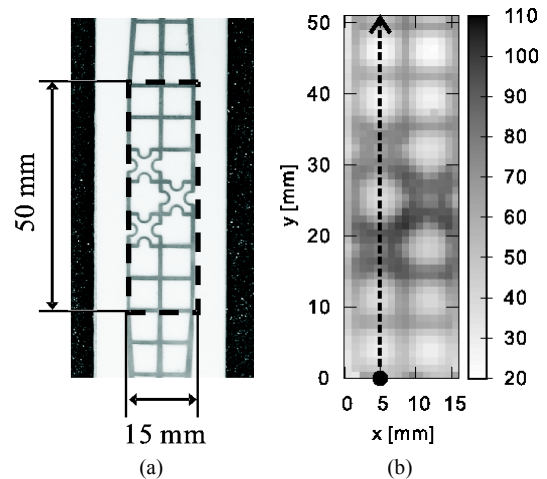


Figure 8. (a) The measurement region. The microwave was applied from the lower side of this picture. We measured the vertical electric field with a 1 mm interval. The result is shown in (b). (c) is the result on the line of $x = 5$ mm which is shown in (b) with a dash line. We can distinguish marked blocks from plain blocks clearly. Since we can detect the mesh conductor pattern, it is expected that we can obtain more accurate position information by the details.