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Possibility of Wireless Sensor Chip without External Antenna Using 30GHz Phased Array Reader

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Abstract: This paper examines the possibility of 1 mW power transmission to extremely tiny chips through a wide aperture 30-GHz phased array. We assume that the chip size is 0.5 by 0.5 mm and do not have external antennas. Then we reveal that the optimal frequency is 30 GHz in case that the phase array length is fixed to 30 cm and demonstrate its feasibility. In addition, we realize a two-dimensional phased array by using new splitter and show that the system can transmit power more efficiently.

Keywords: Milliwave phased array, Wireless Power Transmission.

1. INTRODUCTION

Recently, very tiny RFID tags have been actively investigated for applications such as logistics or anti-counterfeit technology of securities. They will spread to wilder area of home and industry and passive sensor chips based on the RFID tag technology has begun to be commercialized. One problem in the current technologies is that such IC-Tags need several centimeter antennas even if the IC chips themselves are very small. This makes it difficult to put them in various materials and the bonding process between the IC chip and antenna is costly. If we can send power to and readout the signal from a small circuit without an external antenna, the application fields are dramatically widen. Various sensors combined with such communication circuits can put into clothes, surfaces of environment and even in human bodies easily.

In order to achieve such sensor chips, we propose new wireless power transmission (WPT) system. The ways of current WPT have two types: close-range proximity WPT and long-range remote WPT. Though the former system has the possibility of significant power transmission, the latter is desirable for wider applications of sensor operation. Long-range WPT can be realized by using electromagnetic (EM) radiation [1–3] or resonant inductive coupling [4]. These researches suppose that chips have a few cm sizes at least and there are no previous attempts to transmit power to extremely small tags.

Based on the above back ground, in this paper we propose a WPT system by using a wide aperture milliwave phased array. Our phased array scatters the EM wave propagating along waveguides and generates a focus. It does not need delay elements and thus the structure is simple. In our target device, we assume that the tag size is 0.5×0.5 mm and thus we need to generate a high power density at focus. Therefore the phased array is appropriate for our purpose. We examine the optimal frequency and propose a new structure of phased array for such a system. The waveguide length of phased array is limited to 30 cm. And we show that use of 30-GHz milliwave is a solution for the device.

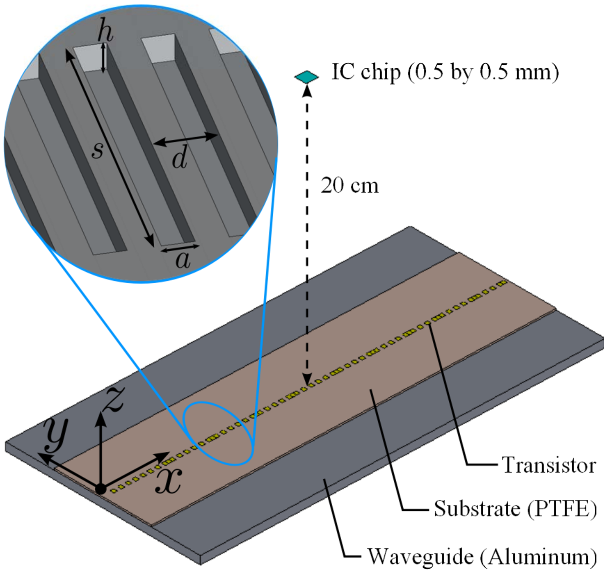

Fig. 1 Schematic view of our phased array. A sub figure in the upper left circle shows the waveguide structure under the PTFE substrate. In this research we transmit 1mW to the IC chip at a 20 cm distance from the phased array.

In addition, we also propose a structure to realize a two-dimensional phased array. For achiving high efficiency by a two-dimensional phased array with a feasible production process, we propose a surface wave splitter for GHz band. It is capable of dividing it into several waves efficiently as a continuous mode.

The organization of this paper is as follows. First, we propose the principle and structure of phased array. In Section 3, we show the validity to use milliwave with 30 GHz and propose a structure of phased array for the frequency. Then we simulate the model and confirm that the system can realistically transmit sufficient power (more exactly 1 mW) to a tiny tag. Then in Section 4, we introduce the new splitter for surface wave and the two-dimensional phased array with the splitter. Then we demonstrate that it enables efficient power transmission. Finally, we conclude in Section 5.

2. STRUCTURE OF PHASED ARRAY

Figure 2 shows structure of our wide-aperture phased array. The basic principle of focal point generation is based on a preceding research of microwave phased array [5]. It is composed of two layers, a waveguide and a substrate with transistors. Each material of the waveguide and substrate is aluminum and PTFE, respectively. The waveguide has periodic corrugation that is in the form of rectangular holes. This structure supports surface wave. In this paper, we supply power at $x = 0$ and the wave is guided along x-direction [6]. Each transistor is put on the PTFE substrate as bridging over a hole and is connected to neighbors by copper line (Fig. 2). If a transistor is set to pass current, it works as conductor and surface impedance is varied. From this, a part of guided wave is radiated into air. By selecting appropriate positions of active transistors electrically, we can get constructive interference at any points.

The way to select transistors being switched on is as follows (see Fig. 3). Suppose the first scatterer is located at $x = 0$. When we generate a focus at (x_f, 0, z_f), n-th scatterer position should satisfy the following equation:

$$k_g p_n + k_a\sqrt{(p_n - x_f)^2 + z_f^2} - k_a\sqrt{x_f^2 + z_f^2} = 2\pi n, \tag{1}$$

where k_g and k_a are the wave number in waveguide and in air. In addition, n is an integer. This equation indicates that the phase of two radiated wave, wave from the first scatterer and the one from n-th scatterer, are in phase. If the condition is satisfied, scattered waves overlap and interfere constructively. When we set scatterers in line, focuses draw an arc.

3. DESIGN FOR HIGH POWER TRANSMISSION

Power received by the tag P_R is calculated as

$$P_R = S_R \cdot \frac{\lambda^2}{4\pi} \cdot G_R, \tag{2}$$

where S_R represents power density at focus and G_R does antenna gain of the tag. We assume that G_R is constant to frequency. The equation suggests that received power depends on frequency. Therefore in this section we get the optimal frequency for power transmission when the waveguide length is fixed to 30 cm. Then the power received by the tag is evaluated.

3.1 Selection of frequency

We conducted a preliminary study under the following situation. We investigated the power density at focus in four cases: $f = 10, 20, 30, 40$ GHz. In case of $f = 10$ GHz, structure parameters of the phased array are set as follows: $s = 3$ cm, $a = 2.7$ mm, $d = 5.4$ mm, and $h = 2.4$ mm. These parameters are decided to be proportional to wavelength, that is, we set $s = 1$ cm in case of $f = 30$ GHz. A PTFE substrate with thickness 0.4 mm

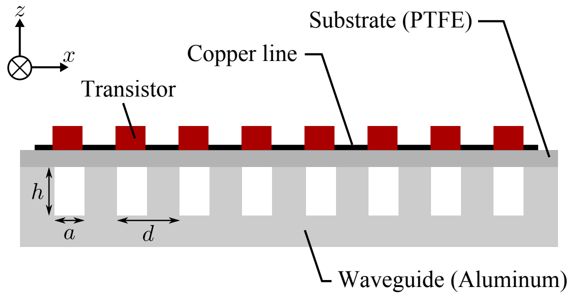

Fig. 2 Cross-sectional view of our phased array. Each transistor works as scatterer if it passes current.

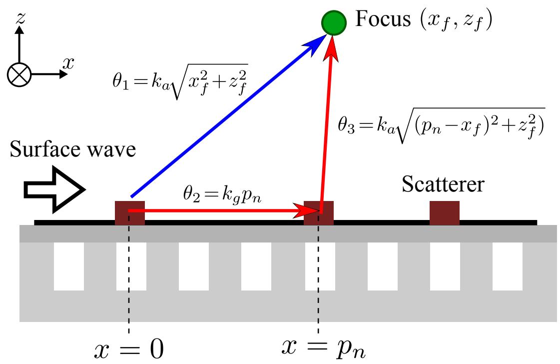

Fig. 3 Focusing principle of our phased array. Surface wave propagates from left to right in this figure along x-direction. When the phase difference between blue path and red one equals to a multiple of 2π, the wave is reinforced and generates a strong focus.

is on the aluminum-perforated plate. We model the transistors as copper plate with width 1 mm. The waveguide length is limited to 30 cm. Here we define coordinate axes as Fig. 1. The tag is located at (x_f, y_f, z_f) = (15 cm, 0 cm, 20 cm), which is 20 cm upward from the center of the waveguide. The distributions of electromagnetic wave are calculated through 3D full-wave simulations using CST Microwave Studio. Then by using Eq. (1), we calculate the power P_R received by the tag. The antenna gain G_R is set to be -10 dB, tentatively.

The simulation results are shown in Figs. 4 - 6. Fig. 4 suggests that as frequency becomes higher up to 30 GHz, the peak of magnitude distribution at focus becomes higher and more sharp-edged. In case of $f = 10$ GHz, a focus is not formed finely (Fig. 4(a)). It is due to shortage of scatterers because the waveguide length corresponds to less than 10λ . From this point of view, using higher frequency is better in the performance as phased array. Next we pay attention to the result in case of $f = 40$ GHz (Fig. 4(d)). The focus is generated clearly in the model but intensity at focus weakens. We think it is because that the surface wave is not excited well in the structure. Fig. 5 shows the power P_R received by the tag. We can see that using 30 GHz is appropriate for power transmission.

Moreover, using too high frequency is not good in a different perspective. At high frequency, transistors working in the band are costly. In addition, fabrication

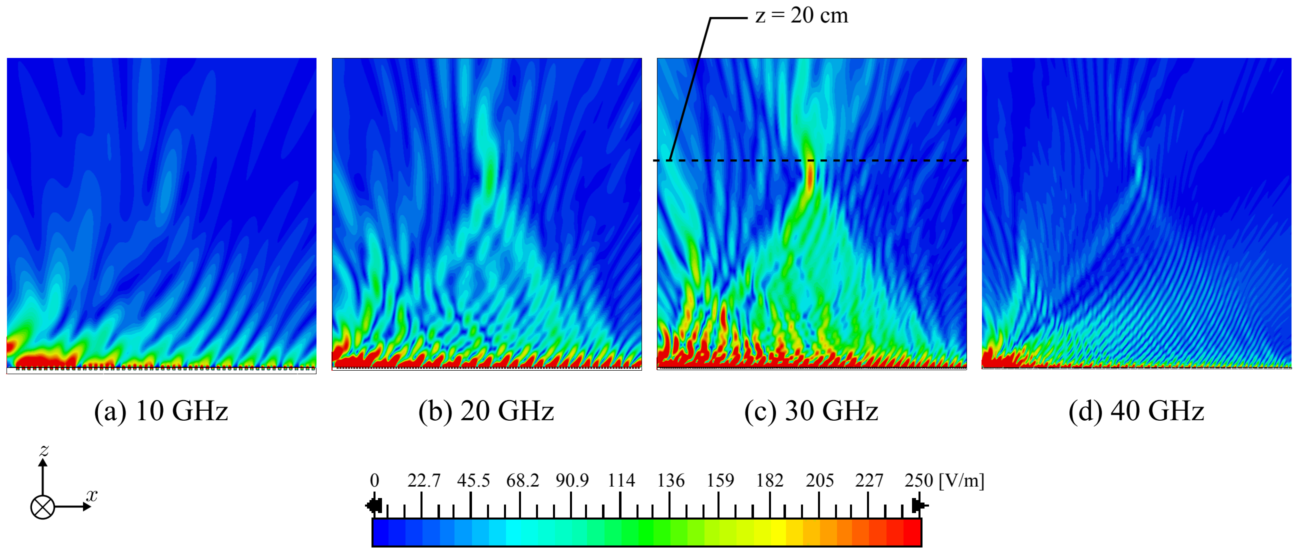

Fig. 4 Simulated electric field amplitude $|E_x|$ distribution map for four cases. As frequency becomes high, a focus is generated finely. This is because the number of scatterer increases as frequency is high. Thus in terms of the performance of phased array, we need to use electromagnetic wave with high frequency.

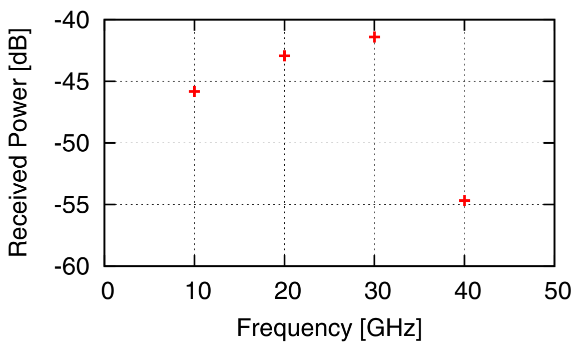

Fig. 5 Power received by the tag. They are calculated by Eq. (1). We can see that 30-GHz phased array is best for power transmission.

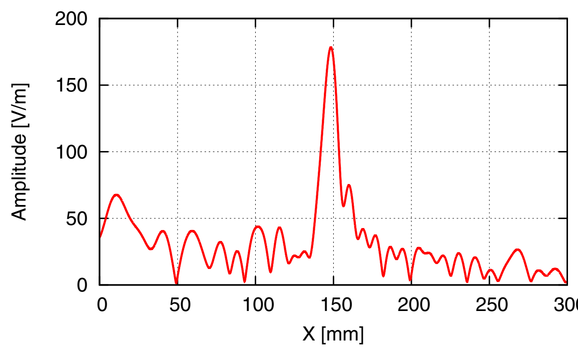

Fig. 6 Magnitude of electric fields $|E_x|$ along the dotted line in Fig. 4(c).

of the antenna with high gain is hard because the ohmic losses at conductor increase as the frequency is high. Therefore we use 30-GHz milliwave phased array.

3.2 Power received by the tag

Next we demonstrate that our 30-GHz phased array can feed sufficient power to the tag. Fig. 6 shows the magnitude of $|E_x|$ along the line of $z = 20$ cm. Half bandwidth of the focus is about 1.3λ and thus we suggest that the proposed phased array generates a strong focus at focal point finely. In addition, Fig. 5 shows that the intensity of power at the tag is measured at -41.4 dB. It means that the tag will receive 1 mW if we supply 13.8 W into our phased array. 1 mW is sufficient to detect the tag and this situation is realistic.

Focuses are generated at the position slightly below the target point. We think this is because the alignment of scatterers is discrete. Correcting the focal position error will contribute to generating a stronger focus.

4. DIRECTIVITY ENHANCEMENT

It is essential to increase the percentage of received power by the tag to power supplied to the phased array because enhancement of the ratio enables to decrease input power and suppress undesired EM radiation into air. For the purpose, we aim at two-dimensional alignment of scatterers because it is effective to the improvement of directivity. Thus we put several waveguides in parallel. We use only one feeding port for milliwave supply and the surface wave is divided and propagates to several waveguides equally. In an advanced research on similar structure in terahertz regime [6], Y-splitter is proposed for the purpose. However such structures require longer length of splitter than 10 cm in milliwave frequency. Therefore we propose new compact splitter in 30 GHz, which needs only 10 cm length in our research.

4.1 Proposal of milliwave splitter

The splitter is realized by coupling between waveguides. When two waveguides are close, powers in them exchange each other periodically. Consequently, by using

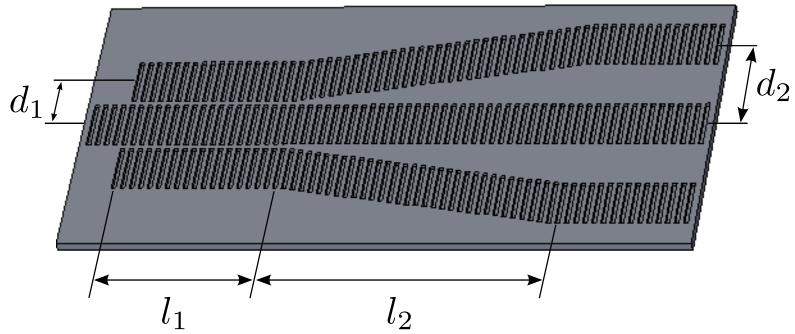

Fig. 7 Structure of proposed splitter for surface wave. A PTFE substrate, copper line and transistors are hidden in this figure. Surface wave is guided from left and spreads to several waveguides by coupling. In case of $d_1 = 1.1$ cm, $d_2 = 2$ cm, $l_1 = 3.24$ cm and $l_2 = 6.66$ cm, each waveguide on the right side receives 20% of input power, respectively.

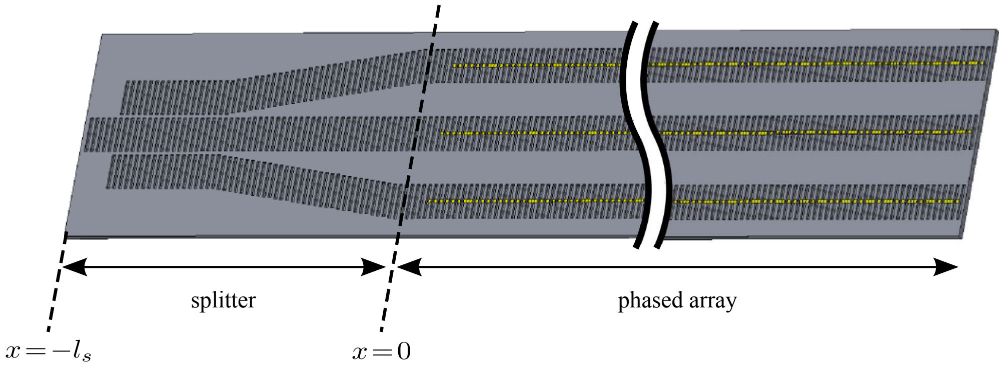

Fig. 8 Schematic view of our two-dimensional phased array. Phased array and splitter are connected as shown this figure. A PTFE substrate and copper lines are undrawn.

the structure shown in Fig. 7, we can separate the surface wave equally as a continuous mode.

The figure shows aluminum-perforated plate only. Hole shape is the same to that of the waveguide in Sec. 3. Surface wave is guided from the left and it propagates to close neighbor waveguides in the first area where distance between adjacent waveguides is set to be d_1. And then the waves spread in small steps and finally the distance between them equals to d_2. From the view point of fabrication, we set $d_1 = 1.1$ cm and $d_2 = 2$ cm. We tune parameters l_1 and l_2 to realize equipartition of power and get following values by numerical simulations: $l_1 = 3.24$ cm, $l_2 = 6.66$ cm. When we use these parameters, the splitter can transmit 20% of input power to each waveguide. The splitter length $l_s (= l_1 + l_2)$ is about 10 cm and it is a convenient form for use.

In this paper, we show the splitter which is divided into three waveguides. We can realize power distribution to much more waveguides in a similar manner.

4.2 Improvement of efficiency by using splitter

Connecting the proposed splitter to 30-GHz phased array in Sec. 3, we demonstrate that the two-dimensional phased array is effective for the improvement of transmission efficiency. The splitter is the same one in the previous section. In this simulation, we supply power into the splitter and generate a focus at (x_f, y_f, z_f) = (15 cm, 0 cm, 20 cm). The location of focus to the phased array is the same as the one in the simulation of Sec. 3. Though we obey Eq. (1) in case of one-dimensional phased array, we use the following equation in this case if we generate a focus at $(x_f$, 0, $z_f)$:

$$\theta + k_g p_n + k_a \sqrt{(p_n - x_f)^2 + z_f^2} - k_a \sqrt{(x_f + l_s)^2 + z_f^2} = 2\pi n, \quad (3)$$

where θ denotes the phase delay derived from propagating through splitter.

Simulation results are shown in Fig. 9. We see the radiation into the air from the splitter is small. Comparing Fig. 6 with Fig. 9, we see that the intensity of focus in two-dimensional phased array is stronger than the former simulation. It owes the improvement of y-axis directivity. Fig. 10 shows the $|E_x|$ distribution map in YZ plane. As mentioned in Sec. 2, one-dimensional phased array generates focuses with an arc shape. In contrast to it, the waves converge in y-direction in case of two-dimensional phased array. In this simulation, the power received by the tag is calculated as -39.8 dB, which means that this structure achieves improvement of 1.6 dB. If we supply 9.5 W into the phased array, the tag will receive 1mW.

5. CONCLUSION

This paper examined the possibility of power supply and signal readout via a phased array to a 0.5 × 0.5 mm IC chip. We revealed the relationships between the frequency and transmission loss. We designed the 30-GHz phased array and demonstrated the feasibility by numerical simulation. In addition, we proposed a compact split-

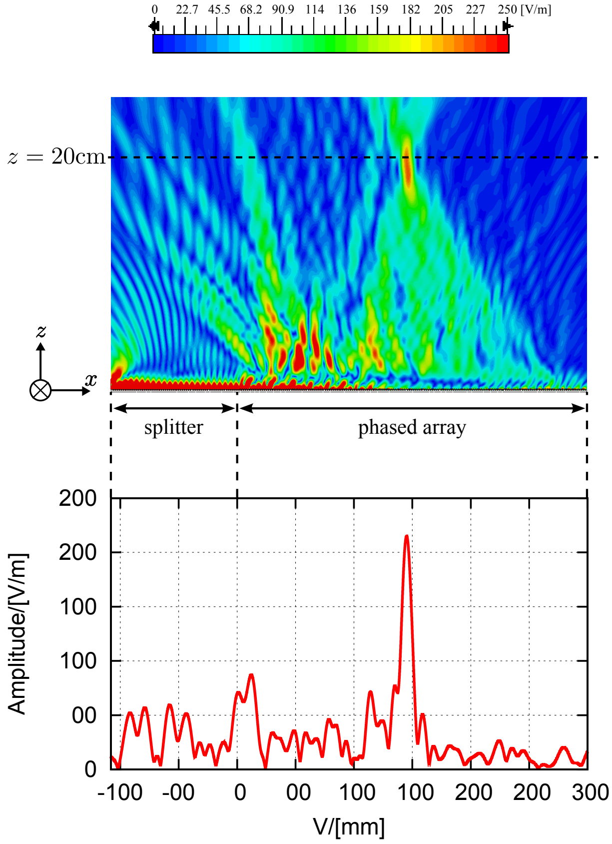

Fig. 9 (Top) Simulated electric field amplitude $|E_x|$ distribution map for the 30-GHz two-dimensional phased array with splitter. (Bottom) Magnitude of electric fields $|E_x|$ along the dotted line in upper figure.

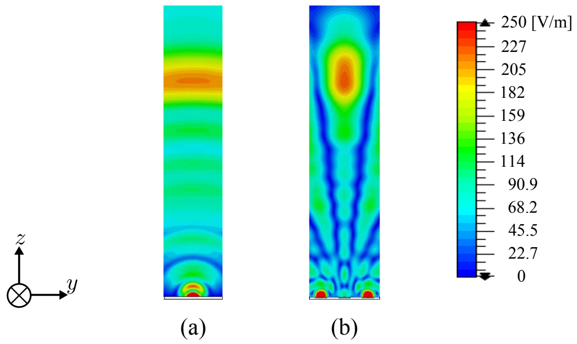

Fig. 10 Simulated electric field amplitude $|E_x|$ distribution map of the models in Sec. 3 (left) and Sec. 4 (right). Each plane is located at $x = 15$ cm, which comes across the focus.

ter for surface wave. We achieved a two-dimensional phased array by using the structure and showed the validity of directivity enhancement in numerical simulation. The result shows that the system can transmit 1mW to the tiny chip at a 20 cm distance from the phased array if 9.5 W power is fed into the system.

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