Design of Wide Angle Reflection Reflectarray Using Multi-layer Mushroom Structure to Improve Propagation

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Abstract

This paper proposes a multi-layer mushroom reflectarray to achieve a wide angle of reflection (AOR) reflectarray at a super high frequency that can be used to improve the Multiple-In-Multiple-Out capacity in a line-of-sight environment. The paper also presents a detailed design chart to satisfy the desired AOR by applying LC resonant circuit theory. A 70 degree-AOR reflectarray at 11 GHz is designed and the proposed reflectarray exhibits good performance based on Finite Element Method calculations.

1. Introduction

We previously proposed the use of a reflectarray to achieve high data rate wireless communications and improve the Multiple-In-Multiple-Out (MIMO) capacity at a super high frequency (SHF) [1]. By using a reflectarray in a line-of-sight (LOS) channel, multipaths can be created and the MIMO channel capacity can be improved [1]. In [1] we investigated the setting position of reflectarrays, and in [2] we investigated how the beam width of the scattering radiation pattern of a reflectarray and its angle of reflection (AOR) influence the MIMO capacity. According to these studies, we expect to achieve good performance when placing a reflectarray at a distance of 10 m from the transmission antenna (TX) with a wide angle reflection beam, i.e., more than 70 degrees at 11 GHz. However, the design of wide angle beam scanning array is generally difficult because mutual interaction between elements should be occurred when the distance of elements is closed [3]. On the other hand, we proposed a multi-layer mushroom reflectarray [4], [5] that uses mushroom structure [6], [7] that elements are smaller than the wavelength and showed that the structure can be designed using LC resonant circuit theory [8]. In the mushroom-structured reflectarray, the capacitance value, which changes the reflection phase, is determined by gaps between the elements. However, the variable range of the reflection phase is limited. To address this issue, we previously proposed the use of a reflectarray with multi-layer mushroom-like structure and showed that the parallel set capacitance increases the variable capacitance range [4] and a combination of different length via holes can increase the variable range of the inductance [5]. However, it is not enough to show the design method when the desired frequency or beam control angle is changed. The purpose of this study is to show a design chart and its application range for a multi-layer mushroom reflectarray using LC resonant circuit theory as a candidate for a wide AOR reflectarray. Finite Element Method (FEM) calculations show that the designed reflectarray exhibits good performance.

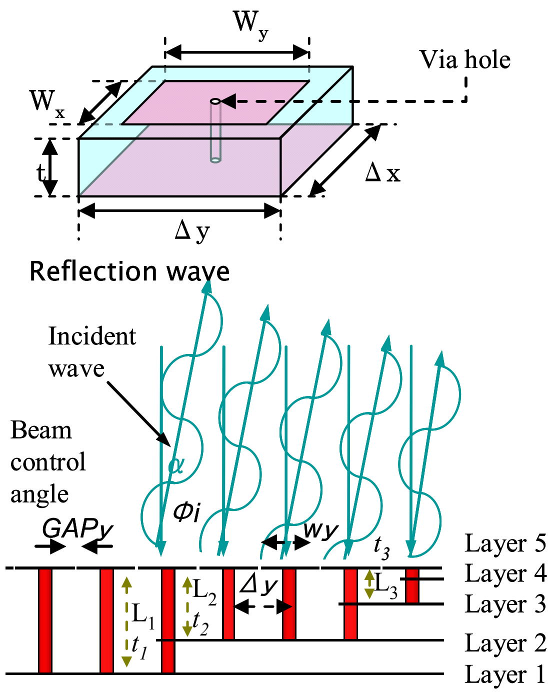

Fig.1. The design concept of multi layer mushroom reflectarray using inductance *Li* variation.

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2. Design Theory and Design Chart for Multi-layer Mushroom Reflectarray for Wide Angle Beam Control at Desired Frequency

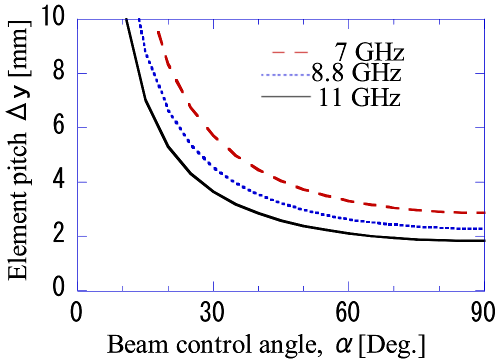

Fig. 2. Element pitch, Δy, vs. beam control angle, α

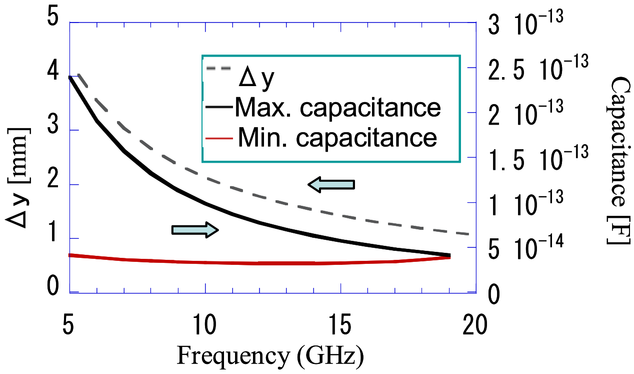

Fig. 3 Capacitance *C* and element pitch, Δy, vs. Frequency

The design concept of multi layer mushroom reflectarray using inductance L variation proposed by member of authors [4] is shown in Fig. 1. The design concept behind the multi layer mushroom structure reflectarray is to control the direction of reflected waves using phase difference ΔΦ of the reflection coefficient between adjacent mushroom structures and reflection phase Φ can be changed by using gap size between element "*GAPy*" and via hole length "*ti*" as discussed in more detail below.

Reflection coefficient Γ and reflection phase Φ are expressed in Eq. (1) using surface impedance Zs.

$\Gamma = (Zs-\eta) / (Zs+\eta) = |\Gamma| \exp(j\Phi)$ …(1)

The surface impedance, Zs, is expressed in Eq. (2) using capacitance *C* and inductance *L*.

$Zs = j\omega L / (1-\omega^2 L \cdot C)$ … (2)

Inductance L_i in Fig. 1 is approximated by the product of permeability and the thickness t_i of the substrate (via hole length) expressed as Eq. (3). Capacitance C is determined by gap "*GAPy*" between the adjacent mushroom elements expressed in Eq. (4) when the distance between mushroom elements have pitch Δy as shown in Fig. 1. The direction of the electric field of the incident plane wave is assumed to be parallel to the Y axis.

$$L = \mu \bullet t \quad \ldots (3)$$

$$C = \frac{\varepsilon_0 (1+\varepsilon_r) Wx}{\pi} \operatorname{arccos} h\left(\frac{\Delta y}{GAPy}\right). \quad \ldots (4)$$

$\Delta\Phi = 2\pi/k$ …(5)

In the design, phase difference ΔΦ is determined using Eq. (5) when k is a natural number and 2π is one period of the reflection phase. These k pieces of mushroom elements are one combination of a period for the mushroom array.

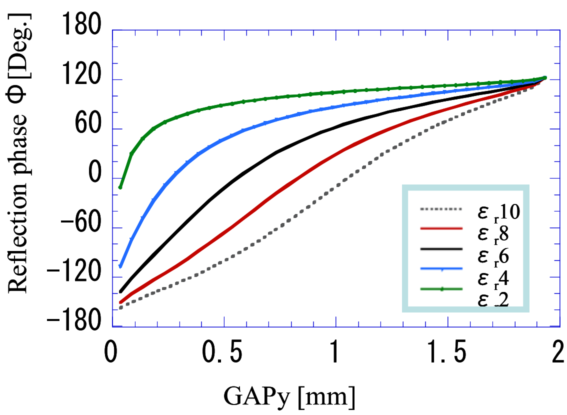

Fig. 4. Reflection phase vs. element gap, GAPy when relative permittivity is parameterized.

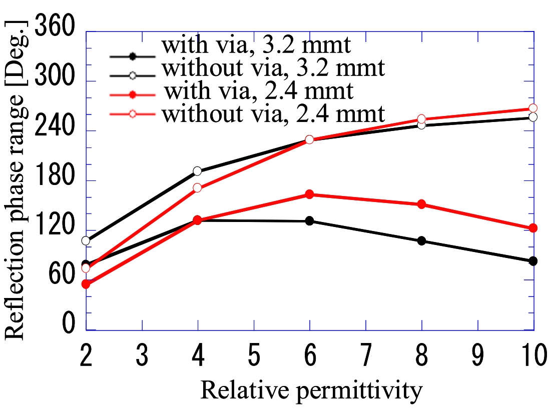

Fig. 5. Relative permittivity vs. reflection range

We can construct the desired size of the reflectarray using a periodic structure. The pitch, Δy, of the mushroom element is decided by Eq. (6) using the desired beam control angle, α, phase difference ΔΦ, and wave length λ at the desired frequency.

$$\Delta y = \frac{\Delta\phi}{2\pi} \bullet \frac{\lambda}{\sin(\alpha)} \quad \ldots(6)$$

We derive Eq. (7) from Eq. (1) where surface impedance *Zs* is expressed as a function of the reflection phase.

$$Zs = f(\phi) = \frac{\eta \bullet (1+\exp(j\phi))}{1-\exp(j\phi)} \quad \ldots (7)$$

Equation (8) is obtained from Eq. (2) where the capacitance is shown as a function of surface impedance *Zs*.

$$C = g(Zs) = g(f(\Phi)) = \frac{Zs - j\omega L}{Zs\omega^2 L} \quad \cdots \quad (8)$$

Equation (9) is obtained from Eq. (4) where the gap between patches, *Gapy*, is expressed as the function of capacitance *C*.

$$Gapy = h(c) = h(g(f(\phi))) = \frac{\Delta y}{\cosh\left(\frac{C \bullet \pi}{\varepsilon_0(1+\varepsilon_r)W_x}\right)} \quad ..(9)$$

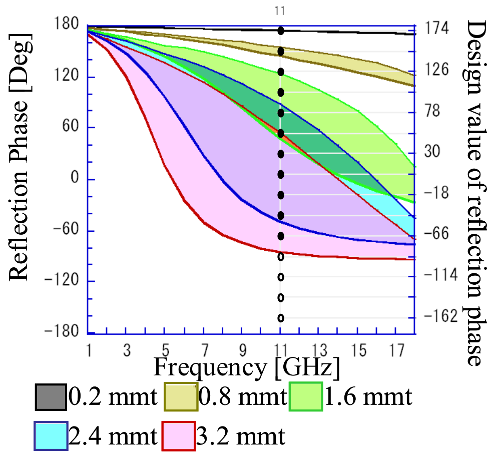

Fig. 6 Reflection phase range vs. frequency for each substrate thickness and design value of reflection phase

Based on Eq. (7) and Eq. (9), the Gap is expressed as a function of reflection phase *Φ*. Therefore, Gapy can be designed using reflection phase $\tilde{\Phi}$.Beam control angle α versus the element pitch, Δy, when we set k equal to 15 is shown in Fig. 2. The figure shows that when α increases Δy decreases. To maintain the fabrication accuracy, a gap size of greater than 0.1 mm is required and a patch size of greater than 1 mm is required to construct a via hole. Therefore, the capacitance range is narrower when the desired beam AOR is larger and the frequency is higher as shown in Fig. 3. In Fig. 3, the relative permittivity of the dielectric substrate is set to 3.6. We can see from Fig.3 that when the desired frequency is higher than 19 GHz, a mushroom structure cannot be fabricated using the method. The capacitance value is varied by relative permittivity. Figure 4 shows element gap GAPy versus reflection phase Φ when the relative permittivity is a parameter at 11 GHz using a 2.4-mm thick dielectric substrate. Although the capacitance range appears larger when a higher permittivity is used, the capacitance range is changed when the range of the gap variation is limited to less 1 mm to fabricate via holes as shown as Fig. 5. When a 2.4-mm thick substrate is used and the via hole is set, However, we choose a polyphenyleneether (PPE) substrate and the relative permittivity is 3.6. From Eqs. (1) to (9) we obtain several reflection phases when we change inductance *Li* based on substrate thickness "t_i" and capacitance *C* by gap size "*GAPy*." Figure 6 shows the frequency dependency of the reflection phase range on the thickness of each substrate calculated using above Eqs. (1) to (9). Using the graph for the design chart, we can decide the substrate thickness corresponding to the desired frequency and reflection phase. At the 11 GHz, black circles show the selected substrate thickness that satisfies desired reflection phase and white circles show they can not select adequate substrate to satisfy desired reflection phase. When the frequency is higher, the range in which the capacitance varies becomes small. Therefore, there are some reflection phases for which an adequate patch size cannot be selected. It is also difficult to achieve a reflection phase from -180 to -120 degrees for all frequencies. To achieve the desired reflection phase at the

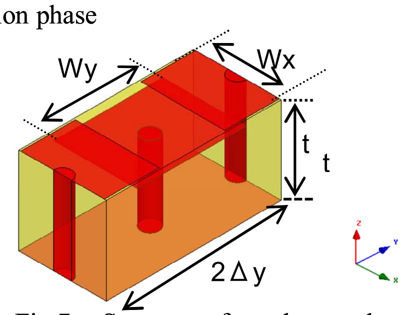

Fig.7. Structure of overlap patches

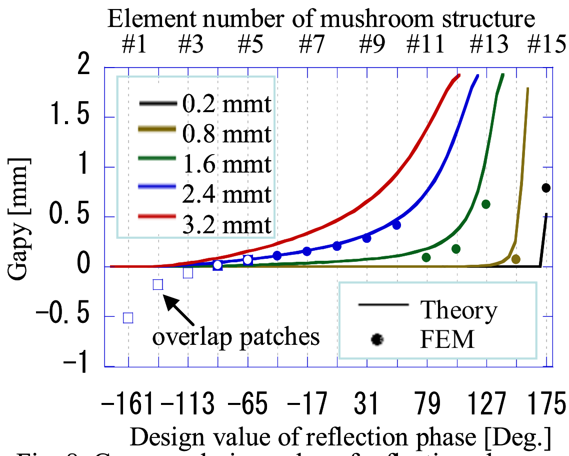

Fig. 8. Gapy vs. design value of reflection phase for each element number of mushroom structure at 11 GHz.

region, we propose to overlap patches and creating a large capacitance shown as Fig. 7. Figure 8 shows gap sizes versus the design value of reflection phase for each element number of mushroom structure at 11 GHz when substrate is parameter. In the graph, the solid lines represent the theoretical results using LC resonant theory, the solid circles represent the FEM simulation results and white squares represent the FEM simulation results of overlap patches respectively. Both theoretical and FEM simulation results are in good agreement. In the graph, the grid lines are set in 24-degree steps from -161 to 175 degrees. We can design a multilayer mushroom like structure to determine the substrate thickness and patch size using the graphs in Figs. 7 and 8. The design process of multi-layer mushroom reflectarray is discussed as follows using from Fig. 1 to Fig.8 as design chart. When the target beam AOR and desired frequency are determined, we select the element pitch using Figs. 2 and 3.Next, we select the substrate thickness based on Fig. 6 and finally we determine the gap size besed on Fig. 8. Figure 9 shows the FEM analysis model of final design structure of the multi-layer mushroom reflectarray for a 70-degree beam AOR at 11 GHz. The structure consists of 15 mushroom elements and has a 5-layer structure. The figure shows one periodic structure and we can obtain the desired size reflectarray by periodic arrangement of the structure. The far field scattering pattern FEM calculated results are shown in Fig. 10. We confirm that the reflection beam AOR is 70 degrees as desired. In the simulation, the size of the reflectarray is assumed to be 200 mm by 200 mm.

3. Conclusion

To achieve a wide angle beam AOR reflectarray at a SHF to improve the MIMO capacity in a LOS environment, this paper proposed using a multi-layer mushroom reflectarray and presented a detailed design chart to satisfy the desired wide AOR at a SHF using LC resonant circuit theory. The 70-degree AOR reflectarray for 11 GHz is designed using the design chart. The paper also showed the structure and characteristics based on FEM calculations.

4. Acknowledgment

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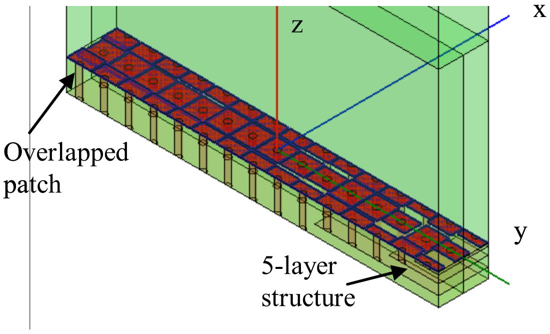

Fig. 9. FEM analysis model of design structure of multi-layer mushroom reflectarray for 70 degree beam control at 11 GHz.

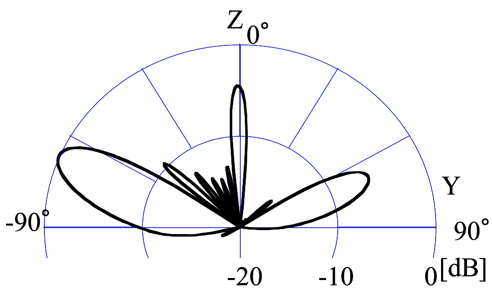

Fig. 10. Scattering radiation pattern of multi-layer mushroom reflectarray for 70 degree beam control at 11 GHz (200 mm ×200 mm).

5. References

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