Reflection Phase of Mushroom-Type Metasurface Reflector with Multi- and Single-Via Structures

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Abstract Although the structures with the wide reflection phase range are necessary to design the metasurface reflector with the high efficiency and sharp reflected beam, the conventional metasurface structures are difficult to realize the higher positive reflection phases (near +180°). In our previous paper, the multi-via structure metasurface was proposed to obtain these higher reflection phases by changing the structural parameters of the vias (grounding conductors). In this paper, the grounding conductor effect of the mushroom-type metasurface is investigated to clarify the effect of the multi-via structure. According to our electromagnetic simulation results, the reflection phases near +180° in the mushroom-type metasurface can be obtained by expanding the via area. It is confirmed that the reflection phase of the multi-via structure metasurface shows the similar property to that of the single-via structure metasurface with the same grounding area.

Keyword Metasurface, Metamaterial, Multi-via, Reflection Phase, Simulation

1. Introduction

Recently, the higher frequency band is used in the fifth generation (5G) mobile communication systems to realize the broader bandwidth, greater transmission efficiency, and higher data rates [1]. Due to the high propagation loss and directivity of the high frequency band, the signal coverage is severely limited. To address this issue, various metasurface reflectors and reflectarrays have been proposed as methods for improving the radio wave environment [2]-[5].

In order to design the reflection angle, it is necessary to obtain an arbitrary reflection phase from -180° to +180° at the design frequency. However, the conventional mushroom-type metasurface is difficult to obtain the higher positive and lower negative reflection phases such as near -180° and +180° (e.g., < -140° and > +140°) [2, 3]. The reflection phases near +180° could be obtained by decreasing the loop inductance L or gap capacitance C according to the normal incidence LC resonant theory [6]. In [4], the reflection phases near +180° could be achieved by changing the thickness of the substrate for each patch to decrease the loop inductance L in the electromagnetic simulation. However, it is difficult to manufacture the different thicknesses within the same substrate. The authors proposed the multi-via structure metasurface to obtain the reflection phases near +180° by changing the structural parameters of the vias (grounding conductors) [5]. In this paper, the grounding conductor effect of the mushroom-type metasurface is investigated to clarify the effect of the multi-via structure.

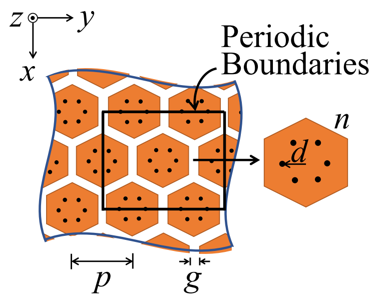
2. Metasurface Structures

The multi-via structure metasurface is shown in Fig. 1 (a) [5]. In this structure, the hexagonal patches are connected to the ground plane on the back through several vias represented by the black dots. In this figure, d is the distance from the patch center to the vias, n is the number of vias. The gap size g between hexagonal patch elements of 0.6 mm is chosen for ease of manufacturing. The simulation frequency f_0 of 6 GHz, which is used for the 5G communication of the sub-6 GHz band, is chosen. The distance (pitch) p between the patch centers of 6 mm is small enough in comparison with the wavelength λ_0 of 50 mm corresponding to f_0. Fig. 1 (b) shows the simulation model example, where the x- and y-polarized plane waves illuminate perpendicular to the metasurface on the x-y plane. The periodic boundary conditions are set for two pairs of parallel side planes, respectively, where the periodic boundaries are also shown in Fig. 1 (a). Assuming the flame-retardant type 4 (FR-4) substrate, its relative permittivity ε_r of 4.7, dielectric loss tangent tan δ of 0.015, and thickness t of 1.6 mm are used for the simulations.

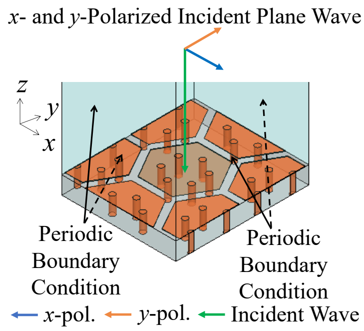
In this paper, in order to clarify the effect of the multi-via structure, the grounding conductor effect of the mushroom-type metasurface is investigated. The mushroom-type metasurface with a single grounding conductor cylinder (single-via structure metasurface) is shown in Fig. 2 (a). In this structure, the hexagonal patches are connected to the ground plane on the back through the conductor cylinders represented by the black circles. In this figure, r is the radius of the conductor cylinder. Fig. 2 (b) shows the simulation model example, where the x- and y-polarized plane waves illuminate perpendicular to the metasurface on the x-y plane. The periodic boundary conditions are set for two pairs of parallel side planes, respectively, where the periodic boundaries are also shown in Fig. 2 (a). The thickness t and other parameters of the substrate, the gap size g, and the pitch p are the same as the multi-via structure metasurface.

3. Results and Discussions

Fig. 3 shows the simulation results of the reflection phase for the multi- and single-via structure metasurfaces at 6 GHz. In this figure, the lower horizontal axis is the distance d from the patch center to the vias for the multi-via structure and the upper horizontal axis is the via radius r for the single-via structure, respectively. The solid and dashed lines show the reflection phase corresponding to the x- and y-polarized incident waves, respectively, where the dots represent the simulated values. Because of the low polarization dependent properties, the solid and dashed lines are overlapped each other. In the multi-via structure metasurface, the reflection phase corresponding to the via number n of 4, 6, and 12 are shown, where the vias placements corresponding to the via number n of 4, 6, and 12 for multi-via structure metasurface are shown in Fig. 4. In the multi-via structure metasurface, the reflection phase range from +137° to +175° could be obtained by changing the distance d and the via number n. On the other hand, in the single-via structure metasurface, the reflection phase range from +131° to +172° could be obtained by changing the radius r. Therefore, it is confirmed that changing the via number n and distance d in the multi-via structure realize the same effect as increasing the via area in the single-via structure.

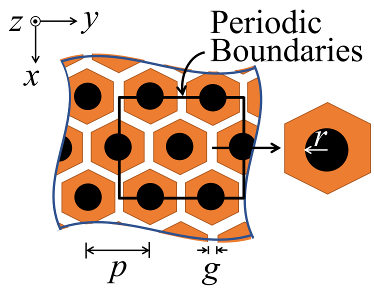


(a) Patch element shape.

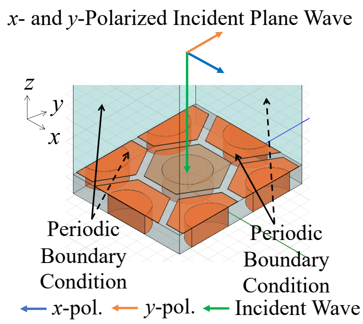


(b) Simulation model example.

Fig. 1 Multi-via structure metasurface.



(a) Patch element shape.



(b) Simulation model example.

Fig. 2 Single-via structure metasurface.

By the way, according to the formula in the papers [7, 8], the reflection phase of the single-via mushroom-type metasurface for the normal incident plane wave should not change corresponding to the via radius. It would be considered that this discrepancy was caused that the previous formula was derived in the assumption of the thin vias. According

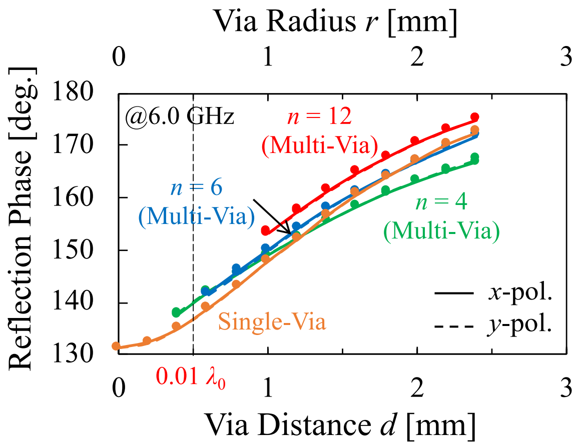


Fig. 3 Simulation results of reflection phase.

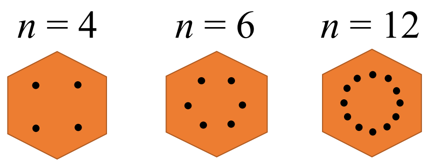


Fig. 4 Via placement of multi-via structure metasurface.

to our simulation results shown in Fig. 3, in the case for that r is larger than 0.01 λ_0 mm, the reflection phase is significantly changed.

The grounding conductor effects of the mushroom-type metasurface would be briefly discussed. It could be qualitatively interpreted that the reflection phase of the metasurface would be close to the reflection phase +180° of the metal conductor board (PEC: Perfect Electric Conductor) by expanding the via area. However, changing the via radius in nearly continuous steps and making large radius conductor cylinder for the single-via structure are difficult to be realized in the normal printed circuit board fabrication. In the multi-via structure that is easy to manufacture, the equivalent effect with the single-via structure could be obtained by increasing the via area (the number n and the distance d).

4. Conclusion

In this paper, the grounding conductor effect of the mushroom-type metasurface was investigated to clarify the effect of the multi-via structure metasurface. It was confirmed that the reflection phase of the multi-via structure metasurface shows the similar property to that of the single-via structure metasurface with the same grounding area. The multi-via structure metasurface contributed to easier of manufacturing, since changing the via radius in nearly continuous steps and making large radius conductor cylinder for the single-via structure metasurface were difficult to be realized in the normal printed circuit board fabrication.

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