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Aperture Efficiency Improvement Using Metasurface

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Abstract—A method to improve the aperture efficiency of antennas using a non-uniform metasurface (MS) is studied in this paper. For illustration, a patch antenna and a planar MS having unit cells of square patches with different sizes are used. The sizes of the square patches on the MS follow a radial gradient index function. The aperture efficiencies of the patch antenna and the antenna using the MS are compared. For easy comparison, the patch antenna is designed to have an aperture size of $\lambda_0 \times \lambda_0$, where the λ_0 is wavelength at the operating frequency in free space. Simulation results show that, by placing the MS atop the patch antenna with a separating distance of 35 mm, the directivity of the patch antenna can be increased from 9.7 dBi to 11.6 dBi. With the aperture size remains unchanged, the aperture efficiency of the patch antenna is increased by more than 100%.

Index Terms—patch antenna, aperture efficiency, metasurface, radial gradient index function

I. INTRODUCTION

Owing to their compact planar structures, printed antennas are often used in portable wireless devices. Patch antennas, as a typical type of printed antennas having the advantages of low profile and high directivity, serve as good candidates for wireless communications terminals. However, the physical aperture size of a patch antenna on a wireless device is always limited.

When an electromagnetic wave impinges on an antenna, the power capturing characteristics of the antenna is related to its effective aperture area which is different from the physical aperture area of the antenna [1]. The maximum effective aperture (A_{em}) of an antenna is related to its maximum directivity (D_0) by $A_{em} = \lambda^2 / (4\pi) * D_0$ [1] and the aperture efficiency can be written as $E_{ac} = A_{em} / A_{ph}$, where the A_{ph} is the physical aperture size of the antenna [1]. Thus, the aperture efficiency of an antenna can be improved by increasing the directivity of the antenna, yet keeping the physical aperture size unchanged. For horn or reflector antennas in general, the aperture efficiency is from about 50% to 80% [2]. For the patch antenna studied in this paper, the aperture efficiency is around 78%.

One popular method to increase the directivity is to place a partially reflective surface (PRS) or a high permittivity dielectric slab atop of the radiating aperture. However, the area of the PRS employed is usually much larger than that of the radiating aperture. It can lead to lower aperture efficiency than that of the antenna without PRS. Employing dielectric slab is a promising method to enhance the directivity without increasing the aperture size. But they are high cost and bulky.

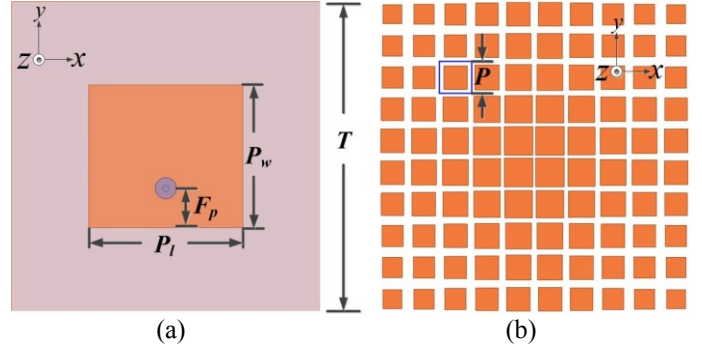


Fig. 1. Geometries of patch antenna and metasurface.

TABLE I. DIMENSIONS OF ANTENNA AND MS (UNIT:MM)

P_l	P_w	F_p	P	P_{max}	T	H
29	27	6.2	6	5.5	60	35

Metasurface (MS), a two-dimensional equivalent of metamaterial, is essentially a surface distribution of electrically small scatterers [3]. MS is also able to enhance the gain when placed atop of a radiator. Compared to PRS, it has a much smaller size. In this paper, a non-uniform MS is proposed to increase the aperture efficiency of a patch antenna. Both the patch antenna and the MS are designed using planar technology to operating at 5 GHz. The MS is placed at a distance away and atop of the patch antenna. The EM simulation tool CST is used to carry out the study. The aperture efficiencies of the patch antenna alone and with the MS together are compared. For easy comparison, the area of the patch antenna has an area of $\lambda_0 \times \lambda_0$, where the λ_0 is wavelength in free space, and the dielectric constant of the substrate is assumed to be the same as that of air. This is because if the relative dielectric constant of the substrate for antenna and MS are greater than 1, the effective aperture size of the antenna has to be rescaled and the recalculated results depend on not only the value of the dielectric constant but also the thickness of the substrate. To the best of the author's knowledge, by using the proposed single layer of MS with such a small area, the highest aperture efficiency is achieved compared to its counterparts [11-17].

II. DESIGN OF ANTENNA AND METASURFACE (MS)

The patch antenna used in the study is shown in Fig. 1(a) and designed to operate at 5 GHz. A coaxial cable is used to directly feed the patch antenna through the ground plane and the substrate. The patch antenna together with the coaxial cable is designed on a double-sided substrate with a dielectric constant of 1 and a thickness of 1.6 mm. The EM simulation tool CST is used to optimize the dimensions, in terms of directivity at the boresight direction and S11 at 5 GHz, with results listed in Table I.

The metasurface (MS) used is composed a number of unit cells in the forms of square patches with variable sizes, as shown in Fig. 2(b). The unit cells are placed periodically in the x - and y - directions of the substrate. To achieve higher directivity, the sizes of the square patches are varied according to a gradient index function, thus making the MS a gradient index (GRIN) material [4, 5]. However, the size of lattice for each unit cell is fixed at P , as shown in Fig. 1(b). The largest four unit cells with a patch size of $(P_{max})^2=(5.5)^2$ mm² are placed closest to the center of the MS. The unit cells further away from the center position of the MS have smaller sizes. The MS is placed atop of the patch antenna with a separating distance of $H=35$ mm to form a metasurfaced antenna (MS antenna).

III. RESULTS AND DISCUSSIONS

The simulated reflection coefficients S11 of the patch antenna alone and the MS antenna are shown in Fig. 2. It can be seen that both the patch antenna and MS antenna have the same resonant frequency of 5 GHz. Thus the MS does not have much effect on the resonance of the patch antenna. The impedance bandwidths (for S11 < -15 dB) of the patch antenna and MS antenna are 4.9-5.08 and 4.9-5.1 GHz, respectively, so the MS only slightly change the bandwidth of the patch antenna.

The simulated directivities at the boresight direction of the patch antenna and MS antenna are shown in Fig. 3(a), while the simulated aperture efficiencies are shown in Fig. 3(b). It can be seen that, the patch antenna and the MS antenna have the directivities of 9.7 dBi and 11.6 dBi at 5 GHz, thus the MS increases the directivity by 1.9 dB. As increasing directivity leads to increasing aperture efficiency as described previously. Fig. 3(b) shows that the aperture efficiency of the MS antenna reaches up to 117% at 5 GHz, which is due to the use of the MS. At 4.7 GHz, the aperture efficiency even reaches 121%. However, the MS antenna cannot work at 4.7 GHz because the S11 is only -2 dB as shown in Fig. 2. These results show that, by using a MS, the effective aperture size of a patch antenna can be larger than its physical aperture size.

The simulated 3D radiation pattern of the patch antenna and the MS antenna are shown in Fig. 4(a) and (b), respectively. It can be seen that the radiation pattern of the MS antenna is more directional in boresight direction than that of the patch antenna.

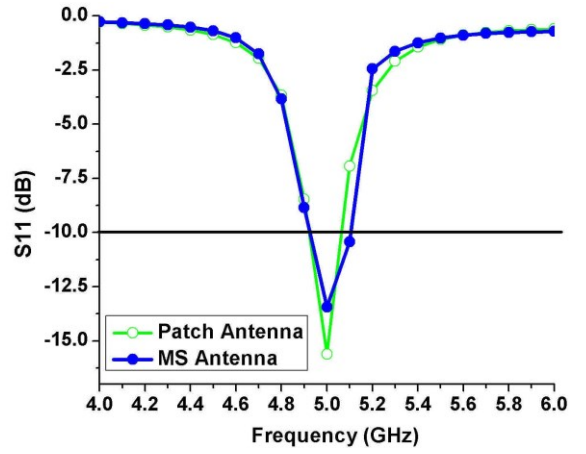


Fig. 2. Simulated S11 for patch antenna and MS antenna

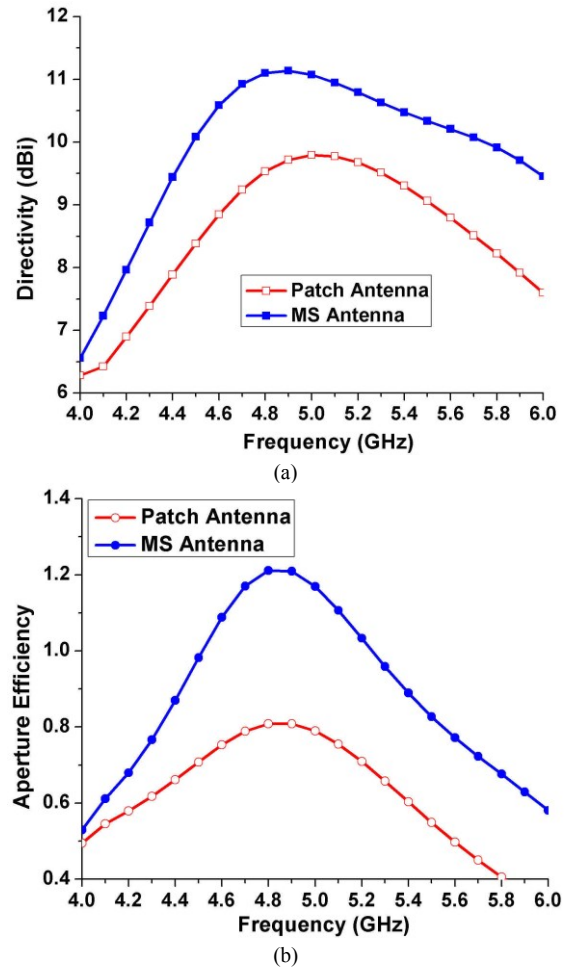


Fig. 3. Simulated (a) directivities and (b) aperture efficiencies of patch antenna and MS antenna

Although a patch antenna has been used for illustration, other antennas could produce similar results, which need more studies for verification.

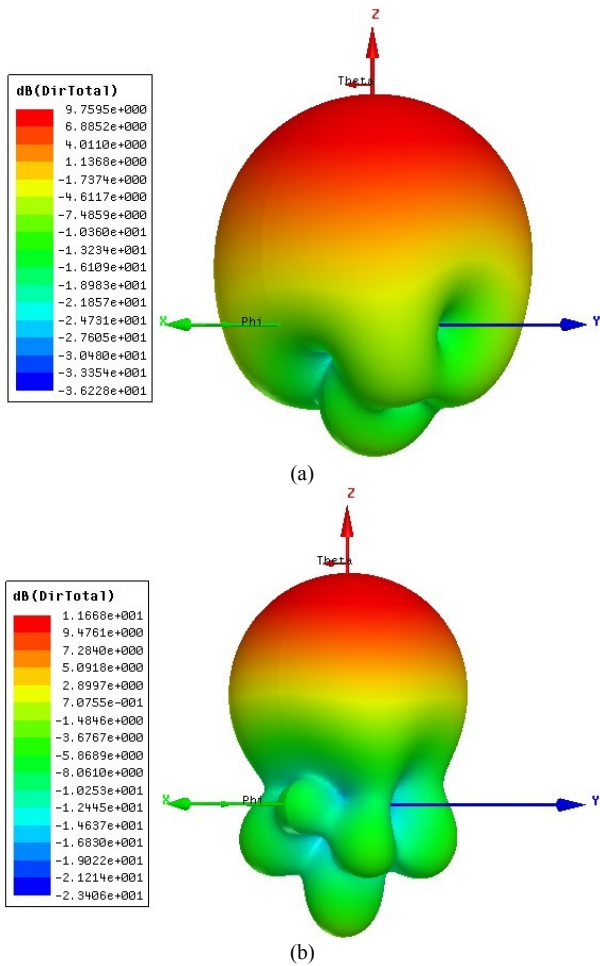


Fig. 4. 3D radiation pattern of (a) patch antenna and (b) MS antenna

IV. CONCLUSIONS

A method of increasing the aperture efficiency of antennas using a MS has been presented. A patch antenna has been used for illustration. Results have shown that by placing a MS at a distance atop of a patch antenna, the aperture efficiency can be increased from 78% to 117% at the operating frequency. Thus by using a MS, the effective aperture size of the patch antenna is larger than its physical aperture size.

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