Compact Design of Non-uniform Meta-surface for Patch Antenna Main Beam Steering

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Abstract **─** A compact design of non-uniform meta-surface for patch antenna main beam steering is presented in this paper. The proposed design is realized using printed circuit board technology. By adding the non-uniform meta-surface to a patch antenna, the main-beam direction of the patch antenna can be steered by an angle up to 30° from the boresight direction. The meta-surface together with the patch antenna here is called meta-surfaced antenna, which has a very compact structure since there is no air gap between the meta-surface and the patch antenna. The meta-surfaced antenna is studied and designed to operate around 2.45GHz. To verify the results of simulation, the meta-surfaced antenna is fabricated and measured. Measured results show that the antenna has an operating bandwidth from 2.35-2.5GHz and peak realized gain of 7.1dBi.

Index Terms **─** Beam steering, compact design, non-uniform meta-surface.

I. INTRODUCTION

As a transducer to transmit or receive electromagnetic (EM) wave, antenna has played an increasingly significant role in modern wireless communication systems [1-3]. In general, we need to make the main beam of an antenna point in a specific direction to achieve highly efficient transmission of EM energy into a given area. One straightforward solution to the beam pointing is adjusting the attitude of the antenna itself. This method is certainly the simplest but not feasible always, since the adjustment to antenna's attitude would require more mounting space in most cases. Moreover, if the antenna is conformally installed on the surface of aircrafts or some other mobile platforms [4-6], it would be impossible to change the antenna's attitude arbitrarily. For the reasons mentioned above, a solution with low cost and simple structure, which is capable of steering the antenna main beam without adjusting the attitude of the antenna itself, is highly desirable to modern wireless communication systems.

Adding meta-surface to antenna is a potential solution to beam steering [7-9]. Take the patch antenna for instance, of which the main beam is along the boresight direction, to steer the main beam direction without adjusting the attitude of the patch antenna, the meta-surface is supposed to work as a prism, which can deflect the EM wave radiated from patch antenna. However, because of the symmetric and uniform layout of the unit cells, most of current meta-surfaces are designed for gain enhancement or polarization conversion [10-12], where the main beam direction is still along the boresight after going through the meta-surface. Moreover, air gap between the meta-surface and antenna is usually required, leading to a bulky structure of the final antenna design. Surface of four parallel strips are fed through the slot-to-CPW transition in a very compact way in [13], composing a quasi-periodic radiating aperture. By optimizing the geometry of the quasi-periodic aperture and the slot-to-CPW transition, the fundamental TM_{10} mode and anti-phase TM_{20} mode can be efficiently excited, coupled, and matched over a broad bandwidth. However, the main-beam is still along the boresight direction after adding the quasi-periodic aperture. Similar design can also be seen in [14].

In this paper, a compact design of asymmetrical and non-uniform meta-surface for patch antenna main beam steering is proposed. The meta-surface is printed on one side of substrate and the other side (non-copper) of the substrate is placed in direct contact with the patch antenna. Therefore, on one hand, the total size of the antenna is barely changed after adding meta-surface, on the other hand, the main beam of the patch antenna can be deflected after going through the meta-surface. Moreover, the deflection angle can also be adjusted by properly designing the sizes and layout of the unit cells of meta-surface.

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II. DESIGN OF META-SURFACE AND PATCH ANTENNA

The meta-surface and patch antenna are both designed using planar technology, as shown in Figs. 1. The patch antenna is designed on a double-sided substrate, with one side being the ground plane and the other side a patch as shown in Fig. 1. The meta-surface as shown in Fig. 2 is designed on a single-sided substrate, composing of a number of rectangular-strip unit cells with different lengths. The unit cells are placed periodically along the x-axis but non-uniformly along the y-axis directions on the substrate.

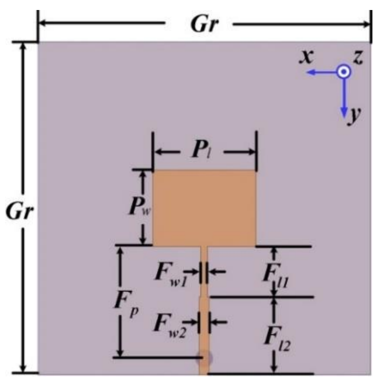

Fig. 1. Top view of patch antenna.

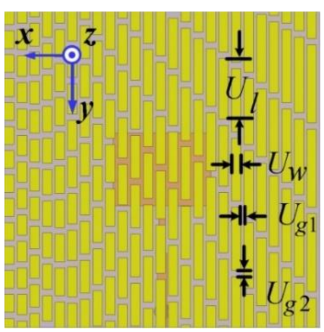

Fig. 2. Top view of non-uniform meta-surface.

The perspective view and assembly schematic are shown in Figs. 3 and 4. The non-copper side of the meta-surface is placed on the top of and in direct contact with the patch antenna. It will be shown later that the main beam of the patch antenna can be steered from +z-axis in x-z plane by adding the meta-surface. The deflection angle can be changed by adjusting the layout of the unit cells on meta-surface. The FR-4 substrate, with a thickness of 1.6 mm and a dielectric constant of $\varepsilon_r = 4.4$, is used for the designs of the patch antenna and the meta-surface. Optimized dimensions are listed in Table 1 and these dimensions are used to fabricate the prototypes of patch antenna and meta-surface as shown in Figs. 5 and 6.

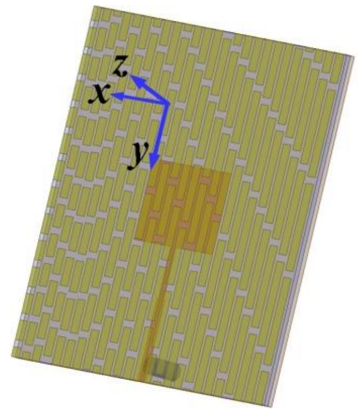

Fig. 3. Perspective view.

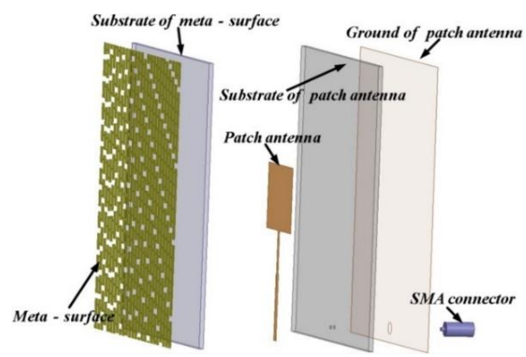

Fig. 4. Assembly schematic.

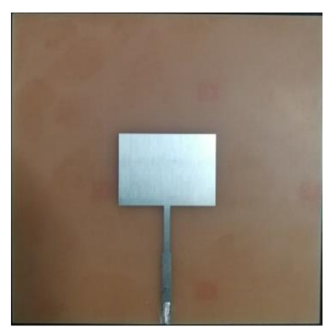

Fig. 5. Prototype of patch antenna (top view).

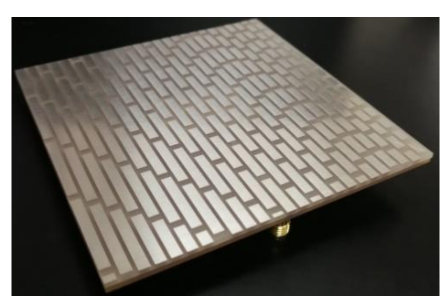

Fig. 6. Prototype of non-uniform meta-surface on patch antenna.

Table 1: Dimensions of meta-surface and patch antenna (mm)

P_l	P_w	F_{l1}	F_{l2}	F_{w1}	F_{w2}
31	23	15	23.5	2	3
U_w	U_{g1}	U_{g2}	G_r	F_p	U_l
3	1	2	100	33.5	4 - 25

III. WORKING PRINCIPLE OF NON-UNIFORM META-SURFACE

It was shown in [15] that the meta-surface placed atop of antenna would behave like a dielectric substrate and different lengths of unit cells along polarization direction would present different equivalent relative permittivity (ε_r) of the substrate. To be more specific, when strip is used as the unit cell, longer strip along polarization direction would present higher equivalent ε_r. Therefore, if we make the length of unit cells keep constant in one column and decrease gradually among different columns from right to left side as shown in Fig. 2, we are essentially placing unit cells with higher equivalent ε_r on one side (right side in Fig. 2) of the meta-surface and lay out unit cells with lower equivalent ε_r gradually to the other side. Such configuration makes the meta-surface an equivalent prism which is planar and placed very close to the patch antenna as shown in Fig. 7. Both simulated and measured results have shown that the main beam of the patch antenna is steered from +z-axis in x-z plane by a certain angle as expected.

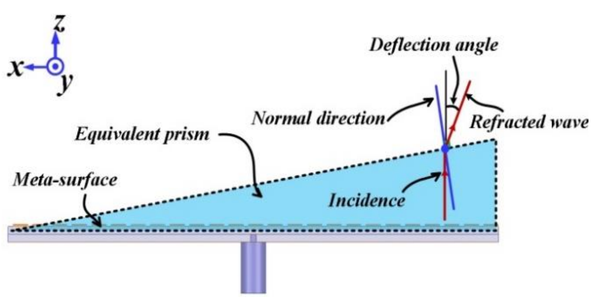

Fig. 7. Equivalent prism realized from non-uniform meta-surface.

By adjusting the variation range of the unit cell length, we can have different variation range of equivalent ε_r accordingly, the deflection angle is then changed. However, as it will be shown later, tradeoff must be made between deflection angle and overall performance of antenna, because excessive deflection angle will lead to lower peak gain and unacceptable side lobe. Moreover, the impedance matching will become more difficult when the variation range of the unit cell length is too wide. As compromise between deflection angle and other antenna performance in simulation, the main beam of the patch antenna can be steered by an angle up to 30° at operating frequencies around 2.45GHz.

IV. SIMULATED AND MEASURED RESULTS

Simulated and measured results of S11 are shown in Fig. 8. The antenna has a simulated impedance bandwidth from 2.35 to 2.5GHz, for S11 less than about -10dB. It should be noted that compared to a patch antenna working around 2.45GHz without meta-surface, the size of patch antenna in this paper is smaller, since adding the meta-surface atop of it generally shifts the operating frequency down. Besides fabrication error, the discrepancy between the simulated and measured S11s is mainly because that the relative permittivity (ε_r) of the FR4-substrate in fabrication is not exactly 4.4 as in simulation.

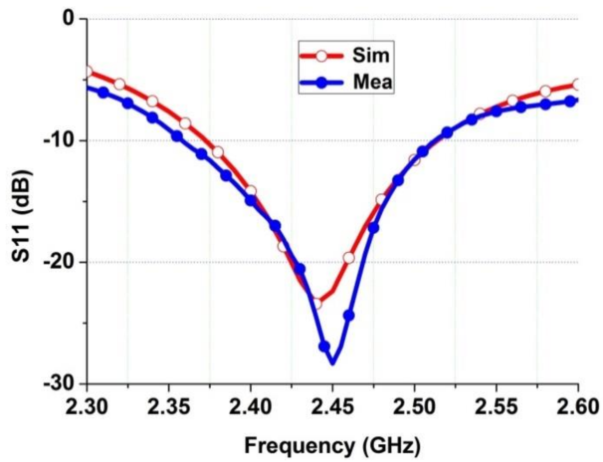

Fig. 8. Simulated and measured S11.

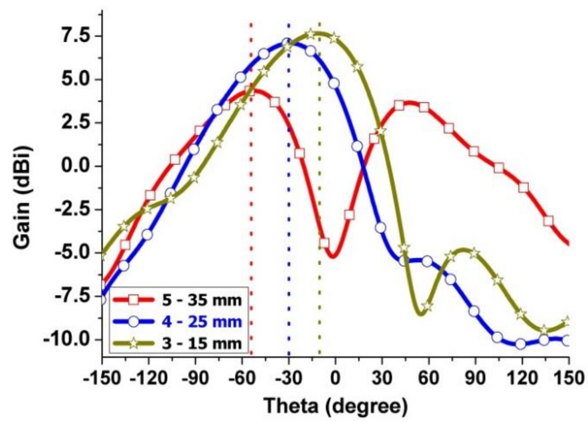

Fig. 9. Main beam directions in x-z plane for different variation range of the unit cell length.

As for radiation pattern, after adding the meta-surface, the antenna main beam is deflected from +z-axis in x-z plane as expected. As mentioned above, tradeoff must be made between deflection angle and overall performance of antenna. Therefore, here the variation range of the unit cell length is chosen to be from 4mm-25mm, as a result, the deflection angle is -30° which can be seen in Fig. 9 indicated by blue line. To show the relationship between the deflection angle and the variation range of the unit cell length, simulated results for unit cells vary from 5mm to 35mm and from 3mm to 15mm are also shown in the same figure for comparison. It can be seen from Fig. 9 that when the variation range of unit cell length is set to be from 5mm to 35mm, the deflection angle can be further increased to -55° as indicated by red line, however, unacceptable side lobe will appear around +57°.

The polar plots of simulated and measured two-dimensional radiation patterns are shown in Fig. 10, where it can be seen that the measured realized gain reaches a peak of 7.1dBi at 2.45GHz. The half power beam-width (HPBW) is 66° (-2°to -64°). The cross-polarizations are too small to be shown in the same figure and so omitted. It should be pointed out that the co-polarization of the antenna in far-field is still linear. Result of simulated three-dimensional radiation plot is shown in Fig. 11.

The simulated and measured efficiencies are plot in Fig. 12, where it can be seen the proposed antenna has simulated and measured peak efficiencies of 95% and 91% respectively around 2.45GHz.

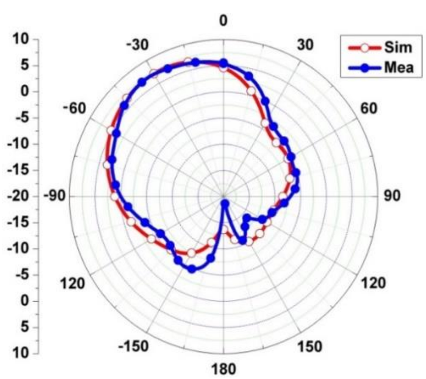

Fig. 10. Simulated and measured 2D radiation patterns.

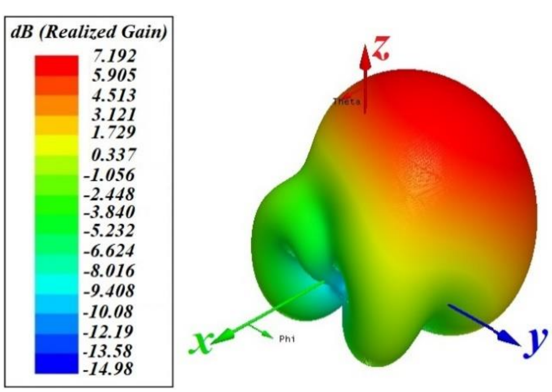

Fig. 11. 3D radiation pattern.

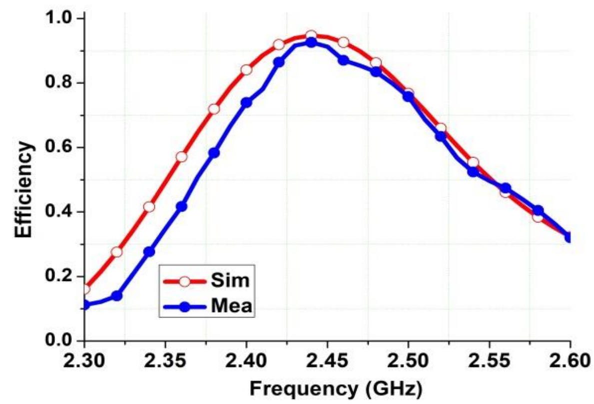

Fig. 12. Simulated and measured efficiencies.

V. CONCLUSION

Compact design of non-uniform meta-surface for patch antenna main beam steering has been proposed. Through adjusting the dimensions and layout of unit cells of meta-surface, the main beam of patch antenna can be steered by an angle up to 30°. Measured results have shown that the peak realized gain of the main beam can reach up 7.1dBi with a half power beam width of 66°, the final operating bandwidth is from 2.35 to 2.5GHz. Based on the meta-surface proposed in this paper, our future work will focus on the design of radiation-pattern-reconfigurable antenna using meta-surface, which is possible to be achieved if we use diodes or varactors to tune the electrical lengths of the unit cells on meta-surface.

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