Multi-Beam Patch Antenna Based On Metasurface

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ABSTRACT In this paper, a multi-beam antenna based on metasurface is proposed. By employing the metasurface as radiating element, steering the beam in the elevation plane is realized. Also, the substrate placing above the metasurface helps to further improve the beam performance. The results indicate that the realized antenna radiate four beam pointing at \((\theta, \phi) = (32^\circ, 0^\circ), (32^\circ, 90^\circ), (32^\circ, 180^\circ), (32^\circ, 270^\circ)\). Based on this, by adjusting the feeding network, beam is steered in azimuth plane. When the length of the left patch decrease from 11.95 mm to 10.45 mm, the azimuth angle of four beams can be adjustable between \(0^\circ \sim 22^\circ, 90^\circ \sim 112^\circ, 180^\circ \sim 202^\circ, 270^\circ \sim 292^\circ\), respectively.

INDEX TERMS Metasurface, multibeam antenna, patch antenna, beamforming.

I. INTRODUCTION

Multi-beam antennas have received extensive attention in various fields, such as satellite communication, radar system and wireless local area network [1], [2]. This type of antenna can provide an effective method to reduce multi-path fading and offer a higher signal-to-noise ratio, gain and data transmission rate. Multi-beam antennas usually are fed with beamforming network (BFN), such as Butler matrices and Rotman lens. In [3], the multi-beam antenna based on \(4 \times 4\) Butler matrix has been proposed. It consists of four \(90^\circ\) couplers, two crossovers and two \(45^\circ\) phase shifters. In [4], multi-beam antennas based on Rotman lens are designed according to the quasi-optical method. Rotman lens replace a large number of phase shifters and connectors to antenna array. In [5], a compact SIW beamforming network is employed to feed for a multi-beam antenna. It uses the back cavity effect to improve the bandwidth and radiation performance.

In recent years, some scholars have proposed multi-beam antennas without beamforming network. In [6], a multi-beam antenna consisting of four \(L\)-shaped microstrip line is presented for pattern-switchable applications. When one of the four ports is excited, the antenna provides a tilted beam with a gain of 8.6 dBi. In [7], a nine-beam antenna is proposed. It consists of \(3 \times 3\) microstrip patches fed with probes. All the patches can radiate effectively due to the mutual coupling.

Metasurface is an artificial structure synthesized by a group of sub-wavelength units in a periodic or aperiodic manner. It can adjust the amplitude and phase of the EM wave at the sub-wavelength scale by controlling the periodic unit. Recently, a metasurface-based multi-beam transmitarray has also been demonstrated [8], [9]. In [9], a planar metasurface antenna with dual polarization and multi-beam radiation characteristics is proposed.

In this paper, a microstrip multi-beam antenna based on metasurface is proposed. Steering the beam in the elevation plane is realized by arranging metasurface above the feeding network. Furthermore, placing the substrate above the metasurface improves the beam performance. By exciting different ports, four beams pointing to different directions can be obtained. The operating frequency of the antenna is 5.82 GHz, and the gain can reach 9.3 dBi. At the same time, beam is steered in azimuth plane by adjusting the feeding network.

II. ANTENNA CONFIGURATION

Figure 1 shows the geometry of proposed multiple-beam antenna. It includes 3 layer dielectric substrate, Sub 1, 2 and 3 as shown in Figure 1 (a) and (b). Sub 1 is FR-4 with \(\varepsilon_r = 4.3\) and \(\tan\delta = 0.01\). On its upper and lower sides, four feeding networks and ground planes are arranged. Every feeding network is composed of two patches and microstrip feeding line as shown in Figure 1 (c). Four ground planes are connected through cross microstrip lines. The Sub 2 and Sub 3 are...
FIGURE 1. The geometry of the proposed antenna. (a) Perspective view. (b) Side view. (c) Feeding network. (d) Metasurface and position relative to feeding network.

TLF-35A with \( \varepsilon_r = 3.5 \) and \( \tan \delta = 0.002 \). On the top of the Sub 2, four central symmetrical metasurfaces formed by 4 × 4 square patch array (shown in Figure 1 (d)) are etched. Every square patch has a dimension of \( l \times l \) and \( l \) approximately equals to \( 0.3\lambda_g \) (\( \lambda_g \), guided wavelength at central frequency). In addition, there is an air layer with a height of \( h_3 \) between Sub 1 and Sub 2. Here, \( h_3 \) is close to multiples of \( 0.1\lambda_g \). Compromising profile and gain of antenna, \( 0.1\lambda_g \) is selected.

To verify the design idea, an antenna operating at 5.82 GHz is designed and the optimized dimensions are given in Table 1.

### III. BASIC WORKING PRINCIPLE

#### A. DESIGN AND MODE OF METASURFACE

In this antenna, the unit of metasurface is square with sides of \( 0.25\lambda_g \). The design principle can be explained by analyzing the main mode excited in the patch element and the metasurface. Figure 2 is a schematic diagram of a rectangular patch antenna and its electric field distribution. According to the antenna radiation mechanism, the rectangular patch antenna can excite TM\(_{10}\) mode.

As for the metasurface formed by 4 × 4 patch, as shown in Figure 3 (a), it is equivalent to etching gaps on the patch at an equal interval. The interval is much smaller than the edge length of the patch, so it will also excite the TM\(_{10}\) mode, as shown in Figure 3 (b). In addition, higher-order modes will be excited. At this time, an electric field distribution similar to TM\(_{10}\) mode will be generated on each patch. Therefore, the entire 4 × 4 metasurface can be regarded as generating a quasi-TM\(_{40}\) electric field distribution, and the currents have the same direction. In this case, no side lobes are generated in the pattern and a good radiation performance can be realized. Also, by adjusting the current distribution in every element of metasurface, different pattern can be formed.
B. MULTI-BEAM FORMING TECHNOLOGY

In order to realize multi-beam radiation, four metasurfaces formed by square patches and Sub 3 are placed above the feeding network. Without losing generality, we take the case that port 1 is excited to investigate the realization mechanism and the results at 5.82 GHz are shown in Figures 4 and 5. For comparison, an antenna placed an integral metal above the feeding network is studied firstly. It is observed in Figure 4(a), this antenna radiates wave in many directions and has a maximum gain of 2.36 dBi as shown in Figure 5. When the metasurface is loaded, the main beam with the gain of 7.41 dBi is steered to \((\theta, \phi) = (32^\circ, 0^\circ)\) and it has a half power beamwidth (HPBW) of 40°. In order to improve the radiation pattern, Sub 3 is introduced further. In this case, the HPBW is diminished to 30° and a radiation null appears at \(+z\)-axis. The gain also rises to 9.3 dBi.

The improvement mechanism of Sub 3 can be discussed by analyzing the current distribution shown in Figure 6. In Figure 6 (a), for the antenna without Sub 3, it is observed the current on the left is basically symmetrical to that on the right. Therefore, a larger radiation along the \(z\)-axis is produced. After the Sub 3 is arranged, the currents on most symmetrical patches (except that in the first line) are opposite and their contribution to radiation along \(+z\)-axis direction can be offset. Therefore, radiation along \(z\)-axis is reduced largely and a radiation null appears as shown in Figure 4 (c).

When the ports 1-4 are excited, the antenna generates four different beams, and the result is showed in Figure 7. It can be observed that the maximum radiation level of the four oblique beams are \((\theta, \phi) = (32^\circ, 0^\circ), (32^\circ, 90^\circ), (32^\circ, 180^\circ),\) and \((32^\circ, 270^\circ)\).

IV. STEERING BEAM IN AZIMUTH PLANE

In section III, every feeding network is symmetrical. Therefore, the beams locate \(\phi = 0^\circ, 90^\circ, 180^\circ\) and \(270^\circ\) in azimuth plane. In this part, how to adjust \(\phi\) by changing length of patch \((d)\) in the feeding network will be investigated. Here, we still illustrated taking port 1 as an example. Figure 8 shows the radiation pattern (cut at \(\theta = 32^\circ\)) for different \(d\). When \(d =\)
11.88 mm, the same energy is radiated from left and right patches and the main beam is located in the plane of $\phi = 0^\circ$. When the length of the left patch is reduced to $d = 11.38, 11.08, 10.88$ and $10.38$ mm, the energy radiated by the right patch is stronger than that from left patch, and the beam tilts to y-axis. The corresponding azimuth angle $\phi$ is $3^\circ, 9^\circ, 12^\circ$ and $22^\circ$, respectively, which increasing gradually. Similarly, when ports 2, 3 and 4 are excited, the $\phi$ varie in the ranges of $90-112^\circ, 180-202^\circ$, and $270-292^\circ$. Furthermore, if we want to obtain a beam tilting to -y-axis, the length of the right patch should be decreased.

V. PARAMETER ANALYSIS
The parameters analysis for the antenna is made using HFSS. The results indicate that the $g$ and $h_3$ have larger influence than other parameters on the radiation performance and the results are displayed in Figures 9-10.

Figure 9 shows the gain pattern in the $\phi = 0^\circ$ plane at 5.82 GHz for different $g$. It is observed that $g$ has obvious influence on radiation pattern. For comparison, some radiation characteristics are listed in Table 2. It can be found, when $g = 2$ and $2.5$ mm, the antenna has higher gain and lower sidelobe level than that in other two cases. To obtain an antenna with a narrow beam, the $g$ is chosen as 2 mm.

The height of the air layer, $h_3$, will affect the distribution of the electromagnetic field, so it will affect the HPBW. Figure 10 shows the gain pattern for different $h_3$ in the $\phi = 0^\circ$ plane at 5.82 GHz. When $h_3 = 1.02$ and $2.02$ mm, large HPBW of $46^\circ$ and low gain of $6.3$ dBi are observed because the wave is weakened each other when reflecting in the air layer. In case of $h_3 = 3.02$ mm, the antenna has a gain of $9.3$ dBi and the HPBW of $30^\circ$. When $h_3$ increases to $4.02$ mm, the gain, HPBW and level of sidelobe all are increased. Finally, the $h_3 = 3.02$ mm is selected to obtain a narrow beam.

| $g$ (mm) | Gain of main lobe (dBi) | Level of 1$^\text{st}$ sidelobe (dBi) | Level of 2$^\text{nd}$ sidelobe (dBi) | HPBW ($^\circ$) |
|---------|------------------------|------------------------------------|------------------------------------|----------------|
| 1       | 8                      | 1.5                                | -1.2                               | 35             |
| 1.5     | 8.5                    | 0.5                                | -2.4                               | 33             |
| 2       | 9.3                    | -2                                 | -3                                 | 30             |
| 2.5     | 9.4                    | -3.1                               | -2.8                               | 34             |
VI. SIMULATED AND MEASURED RESULTS

To validate the proposed design, a prototype of the antenna, as shown in Figure 11, is fabricated and measured. All results are shown in Figures 10-12. Here, S-parameters are measured using an Agilent N5230A vector network analyzer and the gain and radiation pattern are measured in an anechoic chamber.

Figure 12 shows S-parameters of proposed antenna. It could be found that the simulated −10 dB impedance bandwidths are 6% (5.58 − 5.93 GHz). The measured results for four ports are in the ranges of 5.6-5.98 GHz, 5.75-6.1 GHz, 5.61-5.97 GHz and 5.74-6 GHz, respectively. Meanwhile, the isolation of the antenna when port 1 is excited is provided and it is better than 28 dB (results for other ports are similar with port 1 and have not been displayed). The measured results are matching with the simulated one and the difference between them is caused by fabrication errors.

Figure 13 shows the gain and efficiency of the antenna. Considering the symmetry of the antenna, only the results when port 1 is excited is provided. It can be seen that the measured results are slightly smaller than the simulated one. The simulated gain of change between 3 and 9.3 dBi in the operating band, and the measured maximum value of 9.1 dB appears at 5.82 GHz. The range of efficiency is 80% to 83% within the operating band.

Figure 14 shows the normalized radiation patterns of four beams at 5.82 GHz and details of the four beams is shown in Table 3. When four ports are excited, measured four beams point at (θ, φ) = (32°, 0°), (31°, 90°), (−31°, 0°), and (−32°, 90°), which essentially corresponding to (θ, φ) = (32°, 0°), (32°, 90°), (−32°, 0°) and (−32°, 90°). The maximum gain is 9.1 dBi and HPBW is 29°, which is slightly lower than the simulated value.

VII. CONCLUSION

In this communication, a new type of multi-beam antenna based on metasurface has been proposed. By placing the metasurface and substrate above the feeding network, the multi-beam radiation is realized. Furthermore, steering beams in azimuth plane is realized by adjusting the feeding network. The proposed antenna has the advantages of low
profile and high gain. Therefore, it can be a good candidate for wireless communication systems.

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