Broadband Metasurface-Based Antenna Using Hexagonal Loop Elements

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Abstract—**A broadband metasurface-based antenna with hexagonal loop radiating elements is presented. To achieve broadband response, an array of hexagonal loop elements is taken as the main metasurface-based radiator. The antenna is fed by a microstrip line through a coupling slot. To reveal the underlying modal behaviors, the characteristic mode analysis was used for modeling, analyzing, and optimizing the antenna structure. The proposed broadband hexagonal loop based antenna with an overall size of 1.1 λ_0 × 1.1 λ_0 × 0.06 λ_0 can achieve 56% fractional bandwidth and a relatively stable gain of 7-11 dBi over the operating band.**

Index Terms—**Broadband, characteristic mode analysis (CMA), metasurface (MTS), antenna.**

I. INTRODUCTION

Due to the increasing need of modern wireless communication systems, broadband antennas are of great demand. Microstrip patch antennas have been widely used in various applications because of the low-profile and low-cost features. Unfortunately, this type of antenna suffers from narrow bandwidths, which limits its applications, especially in broadband imaging communication systems with the range from 4 to 9 GHz [1]. Many researchers have proposed different methods to deal with this problem. These methods include using capacitive coupling feed, parasitic elements, stacked patches, thicker air substrate and reactive slot loading, as discussed in [2]. The above-mentioned methods still need a thick substrate material with a low dielectric constant, which makes the antenna having a high profile and bulky size. To improve the performance of an antenna with a low profile and wide bandwidth, a promising method named metasurface(MTS) -based antenna has been explored [3]-[6].

In [3], a dual-mode MTS-based antenna with multiple identical square patch arrays and a resonant slot feeding structure is presented. This design combines the concept of MTS-based antenna with the characteristic mode analysis (CMA), which provides insightful physical understanding of the operating mechanisms of the antenna. Recently, many designs have adopted the idea of using CMA to analyze the antenna mechanism for different applications. For example, [4] proposes a shared-aperture antenna using a multi-function metasurface for 5G. The radiating units realizes two different functions: as a frequency selective surface at the K-band and as a modal resonance at the S-band. This design supports the antenna operating separately without the interaction. While a lot of MTS-based antenna designs use solid patch radiating elements, [5] proposes a non-periodic square-ring MTS-based antenna, which is able to broaden the bandwidth by combining different resonance modes together. The authors found that adjusting the widths of these square rings could achieve different resonant frequencies. Loop radiating elements also have longer current paths compared with solid elements. In [7], it was proved that for radiating elements, the loop type can give designers a wide range of bandwidths from narrow to super wide, compared with the solid type. Among all loop elements, none are superior to the hexagon.

In this work, a broadband MTS-based antenna using seven hexagonal loop radiating elements is proposed. Hexagonal loop radiating elements are used to achieve broadband performance. Twelve smaller hexagon loop elements are arranged at the edge to further improve the bandwidth. The radiation pattern of the antenna with a simple feeding structure is very stable over the operational band of interest.

II. BROADBAND ANTENNA USING HEXAGON LOOP METASURFACE

In metasurface design, it is normally challenging to design a broadband metamaterial using compact unit cell structures. The geometry and type of the radiating elements usually determine the resonant frequency and bandwidth of the whole design. Therefore, it is necessary to study the performance of different metasurface structures related to the frequency and bandwidth. As explained in [7], the voltage distribution between adjacent elements of a metasurface is drawn in Fig. 1. The voltage distribution for the fundamental mode (half wavelength) leads to a strong voltage difference between the gap of unit elements, which greatly pulls the resonant frequency downward. In contrast to the first harmonic, there is no voltage difference between the gap at the second harmonic (full wavelength), so there is no downward pulling of that frequency. The difference between the voltage distribution could explain the broadband performance. The bigger the voltage distribution difference is, the broader the bandwidth will be. For the same gap between unit cell, compared with other loop elements such as a square one, the total area of the adjacent gap of the hexagon loop element will be bigger, which results in a bigger voltage distribution difference.

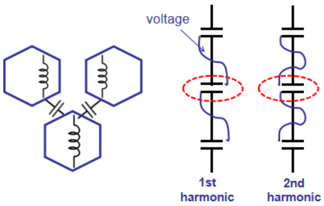
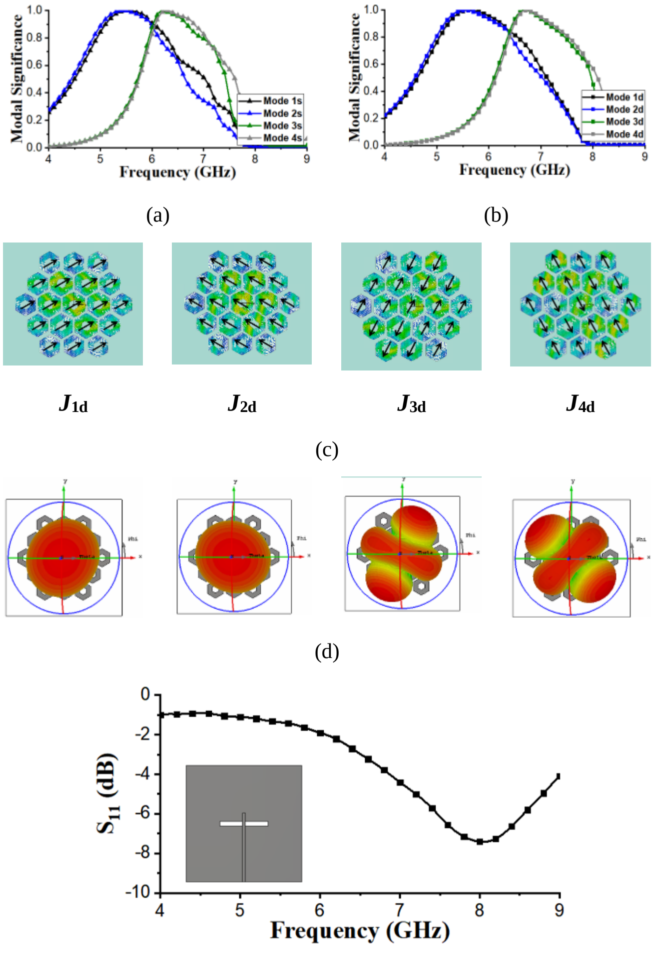


Fig. 1. The voltage distribution along the circumference of a typical hexagon element [7].



(a) (b)

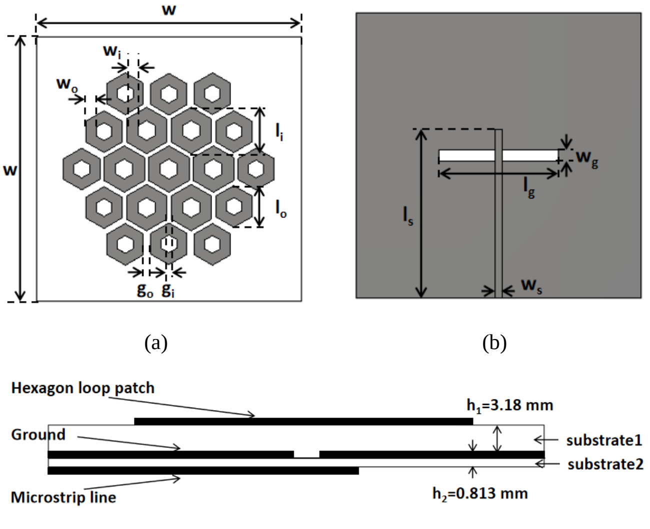
(c)

(d)

(e)

Fig. 2. Modal significance of the MTS-based antenna with (a) the same size of hexagon loop unit cells, and (b) two different sizes of hexagon loop unit cells. (c) Modal currents of Modes 1-4. (d) Modal radiation patterns of Modes 1-4. (e) Simulated S-parameter of the feeding system without the MTS.

Based on hexagon loop radiating elements, an MTS structure is analyzed. The feeding system is not considered and open boundaries are set in all six directions in this analysis. As can be seen, the modal significance shown in Fig. 2(a) is the MTS with nineteen hexagon loop elements of the same size. While the modal significance shown in Fig. 2(b) is for the MTS seven hexagon loop elements in the middle and twelve smaller hexagon loop elements at the edge. From the comparison in modal significance, it can be observed that the two higher modes, Mode 3d and Mode 4d are shifted to higher frequencies, at around 6.9 GHz because of the shrinked size of the hexagon loop elements at the edge. But, the resonant frequency of two fundamental modes Mode 1d and Mode 2d keep almost unchanged, which is mainly contributed by the seven center hexagon loop elements. The modal current distribution in Fig. 2(c) has verified this. The modal current distribution of $\boldsymbol{J}_{1d}$ and $\boldsymbol{J}_{2d}$ are both oriented along one direction, so only one lobe could be found in the first two modal radiation patterns, which indicates that these two modes are fundamental ones. By contrast, there exist opposite directions of the modal current distributions for $\boldsymbol{J}_{3d}$ and $\boldsymbol{J}_{4d}$, so there exist two side lobes in the radiation patterns of these two higher modes. As can be observed from Fig. 2(d), all four radiation patterns have a strong main lobe, so these four modes are chosen for the excitation.



(a) (b)

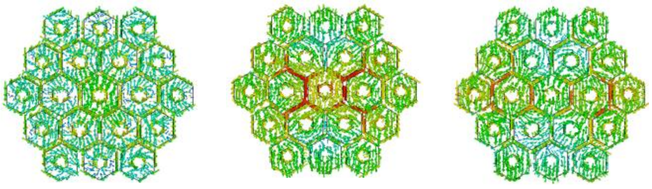
(c)

Fig. 3. Geometry of the proposed MTS antenna using hexagon loop unit cells. (a) Top view. (b) Bottom view. (c) Side View. (W= 60 mm, l_i= 10.5 mm, l_o= 9.5 mm, w_i= 2.6 mm, w_o= 2.3 mm, g_i= 1 mm, g_o= 1.7 mm, l_g= 25 mm, w_g= 2.4 mm, l_s= 35.5 mm, w_s= 1.55 mm).

Based on the above analysis, an aperture-coupled feeding system is used to excite the modes at the vertical direction. The reflection coefficient of the feeding system is shown in Fig. 2(e), it can be found that the resonant frequency of the feeding structure is at around 8GHz.

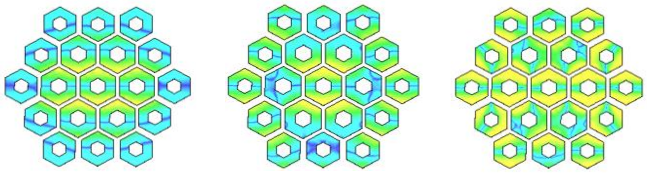
III. SIMULATED AND MEASURED RESULTS

To verify the analysis above, a broadband hexagon loop antenna is designed accordingly. The geometry of the MTS layer and the feeding layer is shown in Fig. 3. As shown, the antenna is composed of three metallic layers, containing an MTS layer, the ground plane layer with a coupling slot, and a microstrip feed line. A Rogers RO4003c substrate is used for the first and the second layer, whose dielectric constant is 3.38. The heights of the first and second layer are 3.18 mm and 0.813 mm, respectively. Detailed dimensions of the proposed antenna are given in Fig. 3.



(a) (b) (c)

Fig. 4. Surface currents on the proposed MTS at different frequencies. (a) at 5.1 GHz. (b) at 6.9 GHz. (c) at 8.1 GHz.



(a) (b) (c)

Fig. 5. Electric field distribution on the proposed MTS at different frequencies. (a) at 5.1 GHz. (b) at 6.9 GHz. (c) at 8.1 GHz.

To analyze the resonant frequencies, the current distributions on the MTS of the proposed antenna at 5.1 GHz, 6.9 GHz and 8.1 GHz are given in Fig. 4. From the surface current distribution, the vectors which indicate the current directions at the three frequencies are nearly uniform while the amplitudes at each frequency are non-uniform. The higher amplitude at 5.1 GHz is at center unit cells (center) while the higher amplitude at 6.9 GHz focuses on both sides of center unit cells (inner ring). At 8.1 GHz, the higher amplitudes are on two sides of the whole unit array (outer ring). It is found that the main radiation of the whole structure is shifted from the center to the outer ring as frequency increases.

It is more intuitive to observe the electric field distribution of the proposed MTS antenna at these three frequencies, as shown in Fig. 5. The gaps adjacent to the center radiating element are excited at 5.1 GHz while both the radiating gaps at the center and on two sides are excited at 6.9 GHz. At 8.1 GHz, the gaps between each unit cell are excited to some extent.

For verification, the proposed broadband hexagon loop MTS-based antenna is fabricated and measured. Fig. 6 shows the comparison between the simulated and measured S-parameters. As can be seen, the measured bandwidth is from 4.8 to 8.5 GHz, whose fractional bandwidth is around 57%, and the resonance frequencies are 5.2, 6.9, and 7.8 GHz, respectively. As a comparison, the simulated fractional bandwidth is 56%. The frequency shift at higher frequencies might be due to the fabrication precision. Fig. 7 demonstrates the top and bottom view of the antenna. From the results in Fig. 7, the range of the simulated gain is from 7.7 to 11 dBi. By contrast, the measured peak gain is 7-11 dBi, which agrees well with the simulation.

IV. CONCLUSION

A broadband MTS-based antenna using hexagon loop unit cell has been proposed, analyzed and experimentally verified. The bandwidth has been broadened by using hexagon loop structures as the radiating unit cells, combined with a simple aperture-coupled feeding structure. The fractional bandwidth achieved is 56% from 4.65 to 8.25 GHz. The proposed antenna can maintain relatively stable radiation patterns with a gain of 7-11 dBi. This antenna demonstrates a great potential for the applications of broadband imaging communication systems.

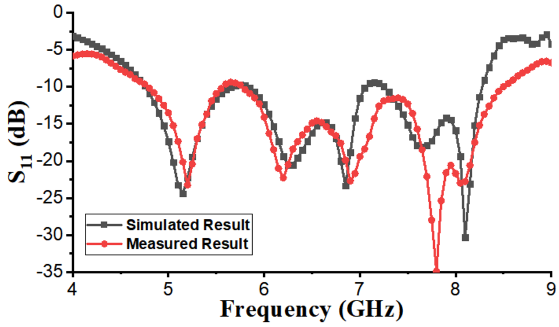


Fig. 6. Simulated and measured S parameter of the proposed antenna.

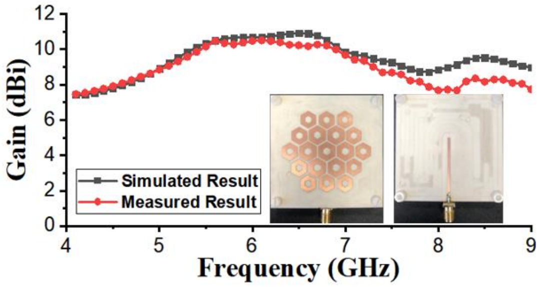


Fig. 7. Simulated and measured gain of the proposed antenna.

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