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A Gain Enhancement and Flexible Control of Beam Numbers Antenna Based on Frequency Selective Surfaces

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ABSTRACT This paper describes a beam-switching antenna with high gain and flexible control of beam numbers based on frequency selective surfaces (FSSs). The proposed antenna is composed of an omnidirectional monopole antenna, a hexagon FSS screen, and six metallic sheets that surround the monopole antenna. The hexagon FSS screen contains six columns, each is made up of two FSS unit-cells. The beam-switching antenna is divided into six equal portions by six metallic sheets, which are employed here to improve the gain of the antenna. The proposed FSS unit-cell consists of the two metallic crosses connected by a pin-diode. The transmission characteristics of the FSS unit-cell are investigated for different pin-diode states. Therefore, by changing the states of the pin-diodes in the hexagon FSS screen, the proposed antenna can sweep six directions with gain enhancement in the azimuth plane. Moreover, it can also flexibly operate at multiple beams modes, including two-beam mode and three-beam mode with low power. This proposed antenna is fabricated and measured, showing good performances at 5.2 GHz. The maximum enhancement of the antenna gain is up to 7 dB, which is achieved by using the metallic sheets and verified with simulated and measured results, which show good agreement.

INDEX TERMS Beam-switching, high gain, reconfigurable antennas, frequency selective surfaces.

I. INTRODUCTION

High gain antennas have intensively been investigated because they can be applied in a variety of wireless communication systems, such as cellular base stations, point-to-point and long-range communication links. In general, a high gain antenna has a narrow beamwidth, which means its signal coverage is small. This characteristic can effectively reduce interference. Beam-switching antennas have been proposed whose radiated power is restricted in some prescribed directions rather than transmitting the signal into all the directions. This approach can significantly reduce the effect of interference coming from undesired radiation and improve the system capacity, leading to a good enhancement of the communication system performance [1]–[5].

During the last decades, various methods for designing beam-switching antennas were reported. The phased antenna arrays as a conventional method have been used to achieve beam-switching antenna, while their complex feed networks made the systems complicated and brought about high cost [6]–[8]. In past several years, more people have been raising their interests in artificial materials/surfaces, such as artificial magnetic conductors (AMCs) [9]–[11], electromagnetic band-gap (EBG) structures [12]–[14] and frequency selective surfaces (FSSs) [15], [16]. Recently, applying FSSs to the design of beam-switching antennas has become more popular. FSSs work as space filters to electromagnetic (EM) waves, which can be either transmitted or reflected in the operating frequency band. Furthermore, their transmission or reflection characteristics could be modified in the operating frequency band when they work together with active devices like pin-diodes or varactor diodes. In this way, FSSs could achieve a high level in controlling over EM wave propagation [17]–[23].

Conventional FSS based beam-switching antennas can change the radiation pattern but do not have a high gain, or flexibly control beam number. Zhang *et al.* [21] have proposed a multi-beam functionality beam steerable antenna system using active frequency selective surfaces. By controlling the bias voltage, both the single-beam mode and the dual-beam mode are achieved; however, the maximum gain is only 7dBi. Li *et al.* [22] have reported a dual-band beam switching antenna with FSS at 2.45 GHz and 5.2 GHz. By switching the pin diodes, the antenna main beam can be switched at two frequencies; however, it could not flexibly control the beam number at operating frequencies.

In this paper, based on our recent work [24], a gain enhancement and flexible control of beam numbers antenna is proposed. The radiating source is a monopole antenna, which is surrounded by a hexagon FSS screen and six metallic sheets, operates at 5.2 GHz. The transmission characteristics of the proposed FSS unit-cell are investigated for different pin-diode states. The FSS unit-cell with Off-state of pin-diodes has a high transmission coefficient and is almost transparent for incident electromagnetic (EM) waves. The FSS unit-cell with On-state of pin-diodes provides a high reflection coefficient for incident EM waves. The methods of operating at different modes with different beam numbers including single-beam mode and multi-beam modes are discussed. By controlling the states of pin-diodes in different column combinations of the FSS screen, different beam numbers of the proposed antenna can be achieved in the azimuth plane at 5.2 GHz. In addition, six metallic sheets presented in this design are used to shape the radiation pattern for the gain improvement of the proposed antenna. Both simulated and measured results show that the proposed antenna could flexibly control the numbers of beam with good gain. A good matching is also obtained, with this feature, this antenna can be used in WLAN systems at 5.2 GHz.

The rest of this paper is organized as follows. In Section II, the design of the FSS unit-cell with transmission response is presented. In Section III, the schematic of proposed beam-switching antenna with gain enhancement is described and divided into two sub-sections, including the omnidirectional monopole antenna and the operation mechanism of the proposed antenna. The crucial design parameters are discussed in Section IV. The fabrication of the proposed antenna prototype and experimental results are provided and discussed in Section V. At last, this work is concluded in Section VI of this paper.

II. FSS UNIT-CELL DESIGN

As the FSS unit-cell is the key element to realize the beam-switching antenna, the design of the FSS unit-cell with reconfigurable transmission coefficients is described in this section. The cross structure is a good candidate due to its simplicity and symmetrical structure, and can provide an acceptable angular and polarization stability. Another reason for applying a cross structure here is that its resonance frequency is lower than strip structure one in a same length, which means the size of the cross FSS unit cell is smaller than the strip unit cell. Thus, two metallic crosses with a pin-diode integrated in the gap are employed in this work. The geometry

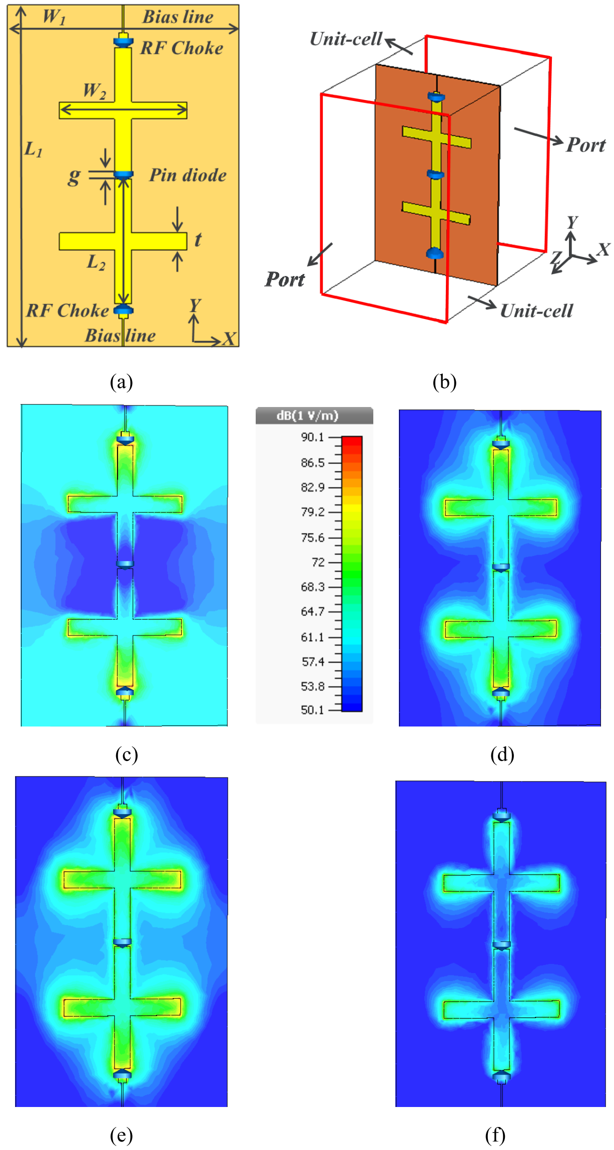


FIGURE 1. (a) Geometry of FSS unit-cell. (b) Configuration of FSS unit-cell simulation. (c) E-field distribution at 2.5 GHz. (d) E-field distribution at 4.8 GHz. (e) E-field distribution at 5.2 GHz. (f) E-field distribution at 5.8 GHz.

of the proposed FSS unit-cell is shown in Fig. 1 (a). As can be seen from it, two RF chokes and biasing circuits are also taken into account in the simulation for the accuracy of simulated results. The RF chokes are used to isolate the RF lines from the DC line during the experiment. This FSS unit-cell is simulated using CST Microwave Studio by locating the unit-cell boundary along the x and y axis with two ports arranged along the z-direction, shown in Fig. 1 (b). The simulated electric field distributions at 2.5 GHz, 4.8 GHz, 5.2 GHz and 5.8 GHz are also shown in Fig.1. The proposed FSS unit-cell structure is printed on RT/duroid®5880 substrate with a thickness of 0.254 mm and a relative permittivity of 2.2. The final dimensions of the FSS unit-cell are listed in Table I. In the simulation, the pin-diode is modeled with its equivalent

TABLE 1. Final dimensions of FSS unit-cell (unit: mm).

Parameters	W_1	L_1	W_2	L_2	g	t
Value	20	30	11	11	0.5	1.5

RC circuit. For state ON, the diode is modeled as a forward resistance $R_s = 1.8\ \Omega$. For state OFF, the diode is mainly equal to a capacitance of $C_p = 0.09$ pF and an inductance of $L_p = 0.5$ nH in series [19].

Switching the pin-diode ON and OFF states makes two metallic crosses either connected or isolated electrically. As a result, the transmitting characteristics of the FSS unit-cell can be changed. The simulated transmission coefficients of the FSS unit-cell in different pin-diode states are plotted in Fig. 2, illustrating that this FSS unit-cell provides a band-stop and band-pass at 5.2 GHz when the pin-diode is ON and OFF, respectively. This means electromagnetic waves are reflected and transmitted depending on the diode state.

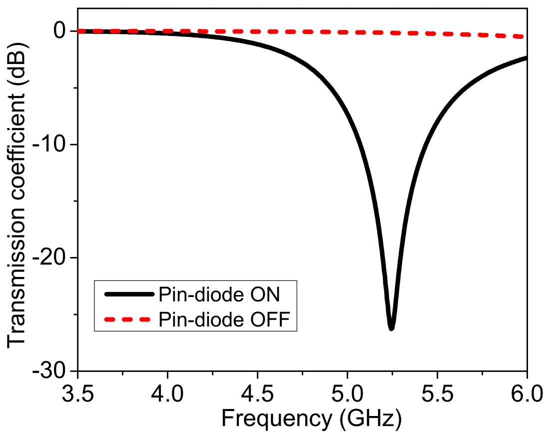


FIGURE 2. Simulated transmission coefficients of FSS unit-cell in different pin-diode states.

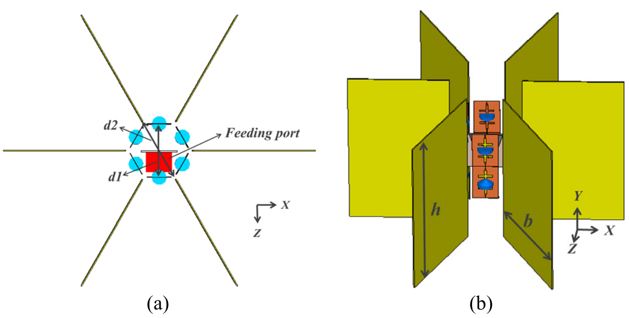


FIGURE 3. Proposed beam-switching with high gain antenna structure: (a) Top view, (b) Side view.

III. BEAM-SWITCHING ANTENNA DESIGN WITH HIGH GAIN

The schematic of the proposed beam-switching antenna is shown in Fig. 3. This proposed antenna is composed of a monopole antenna as an excitation source, a reconfigurable hexagon FSS screen and six metallic sheets placed around

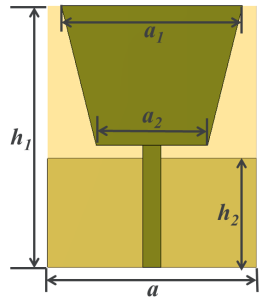


FIGURE 4. Structure of the monopole antenna.

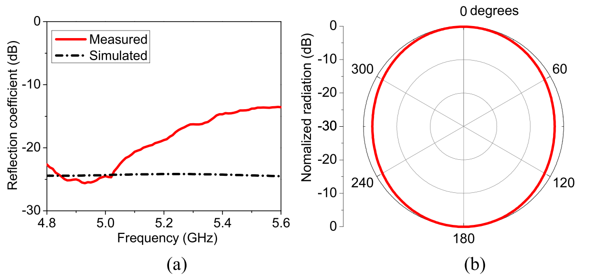


FIGURE 5. Simulation results of the monopole antenna: (a) Reflection coefficient. (b) Normalized radiation pattern at 5.2 GHz.

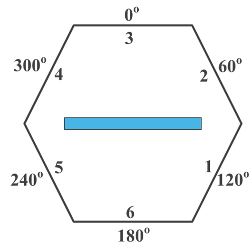


FIGURE 6. Schematic diagram of beam-switching antenna.

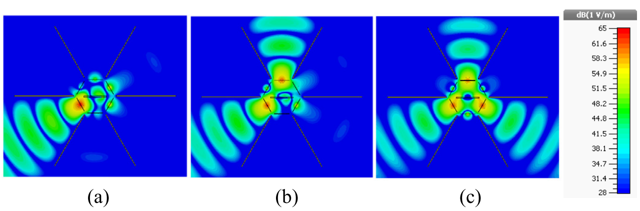


FIGURE 7. E-field distribution of the antenna at 5.2 GHz: (a) Single-beam mode. (b) Two-beam mode. (c) Three-beam mode.

this monopole antenna. This antenna is divided into six equal portions by the hexagon FSS screen together with six metallic sheets. The hexagon FSS screen has 6 columns inside, each includes two FSS unit-cells with two pin-diodes, described in Section II. Through a parametric optimization based on a comprehensive study on the gain, matching of antenna and 3 dB beamwidth, the final dimensions of the entire antenna structure are given as follows: $d1 = 41$mm, $d2 = 56$ mm, $h = 130$ mm and $b = 100$ mm.

A. THE EXCITATION SOURCE

In this work, an omnidirectional monopole antenna operating at 5.2 GHz is employed as an excitation source, as shown

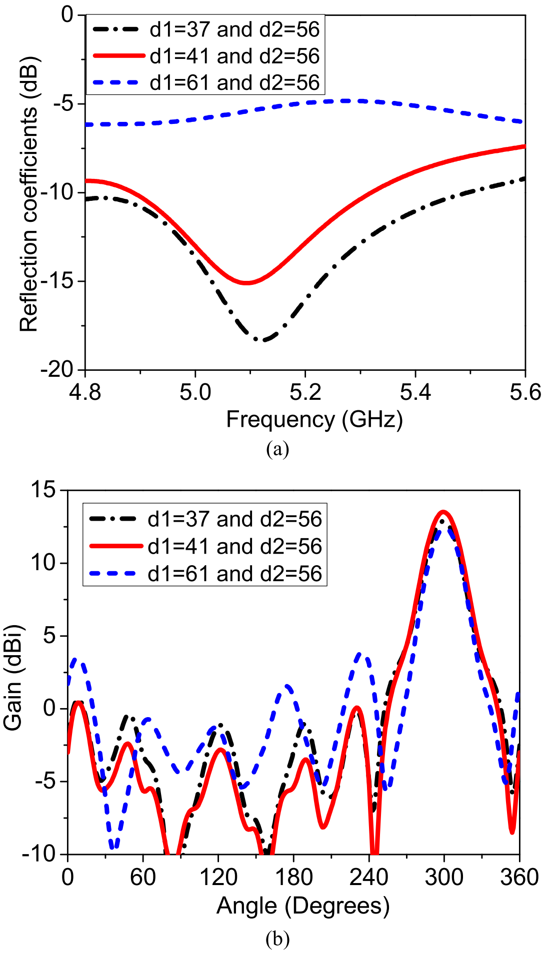


FIGURE 8. **The effect of *d1* on the proposed antenna performances: (a) Reflection coefficients. (b) Gain.**

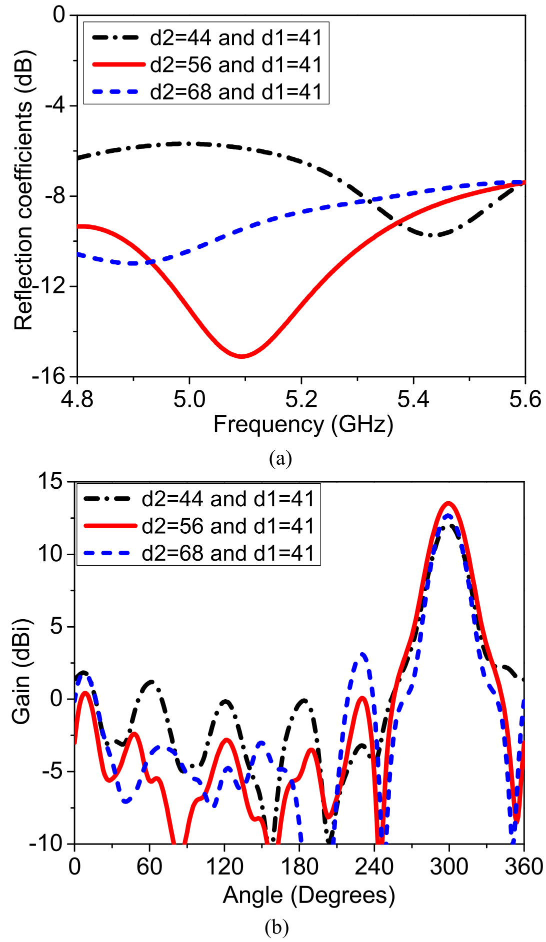


FIGURE 9. **The effect of *d2* on the proposed antenna performances: (a) Reflection coefficients. (b) Gain.**

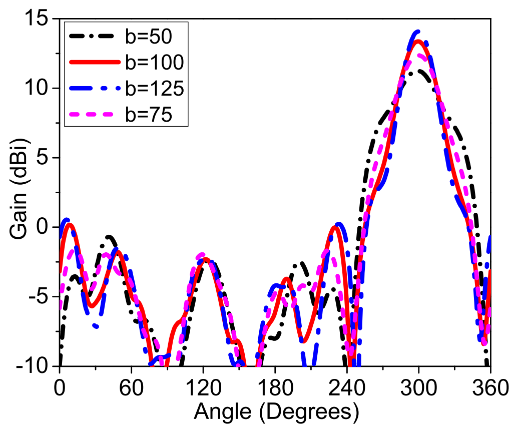


FIGURE 10. **The effect of *b* on the radiation patterns of proposed antenna.**

in Fig. 4, which is similar to the antenna reported in [25]. The difference between them lies in the substrate. This monopole antenna is composed of an inverted trapezoid element as a main resonator and a small ground plane on the bottom of the substrate, which is fed by a microstrip line. It is selected here for its simple structure, low loss, light weight, easy fabrication, and ability to provide an omnidirectional radiation pattern in the azimuth plane at 5.2 GHz, which is required to realize beam-switching. This monopole antenna is constructed on RO4350B substrate with a relative dielectric constant of 3.66 and a thickness of 1.5 mm, with its geometry parameters given as follows: $a_1 = 26$ mm, $a_2 = 16$ mm, $a = 30$ mm, $h_1 = 30$ mm, and $h_2 = 12.5$ mm. The simulated and measured reflection coefficient and normalized radiation pattern are shown in Fig. 5 (a) and Fig. 5 (b), respectively. It is clear that this monopole antenna has a wide bandwidth and performs a good impedance matching at 5.2 GHz. Moreover, an omnidirectional radiation pattern is achieved at 5.2 GHz.

B. MECHANISM OF THE BEAM-SWITCHING ANTENNA WITH GAIN ENHANCEMENT

As the proposed beam-switching antenna is divided into six equal portions by the hexagon FSS screen and six metallic sheets, a schematic diagram of the proposed antenna is shown in Fig. 6. The number from 1 to 6 represents the six columns of the hexagon FSS screen and the blue rectangle in the center represents the monopole antenna. To realize the beam-switching antenna with flexible beam numbers, the following operation mechanism is taken. For the single-beam mode, in each step of operation, the pin-diodes in one

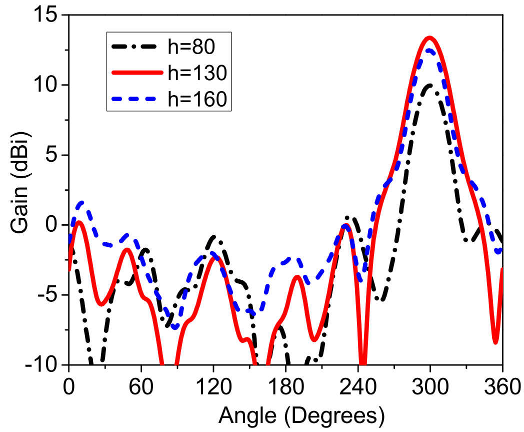


FIGURE 11. The effect of *h* on the radiation patterns of proposed antenna.

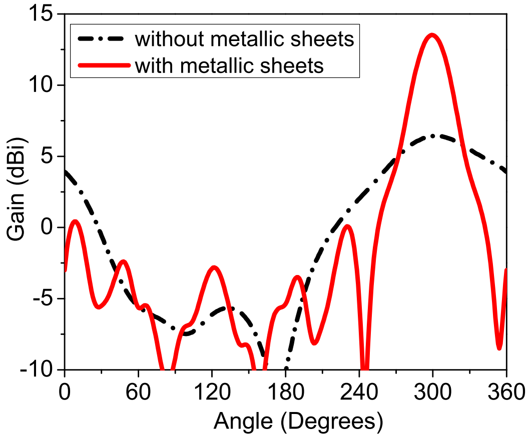


FIGURE 12. Simulated radiation patterns of antenna with and without metallic sheets in the azimuth plane at 5.2 GHz.

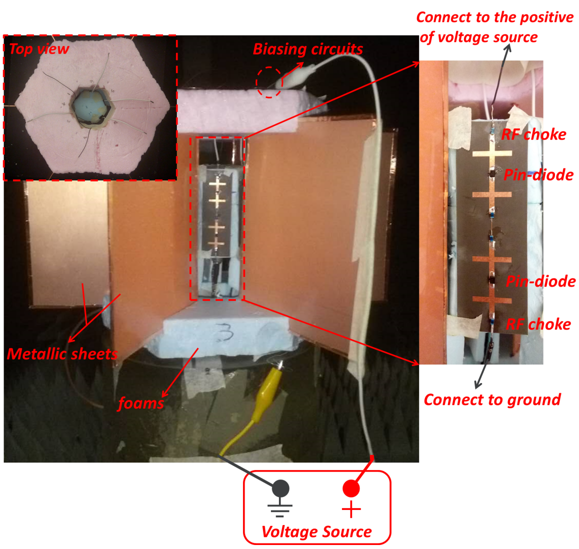


FIGURE 13. Photograph of the fabricated antenna in anechoic chamber.

column are in OFF state and the other pin-diodes in the rest columns are in ON state. As analyzed in Section II, the FSS unit-cell with OFF-state diodes has a high

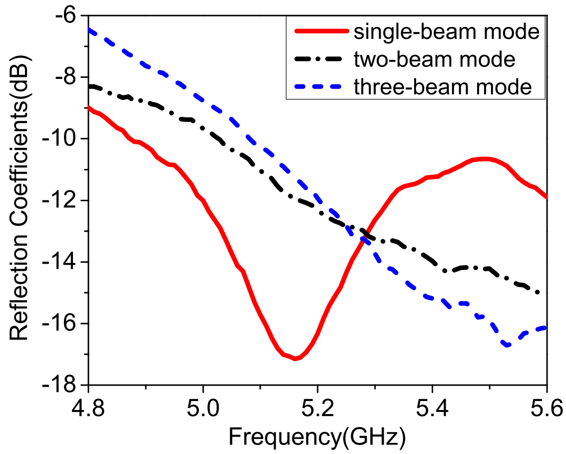


FIGURE 14. Measured reflection coefficient results of proposed antenna in different modes.

transmission coefficient and the unit-cell with ON-state pin-diodes provide a high reflection coefficient. Hence, the electromagnetic waves radiated from the central monopole antenna can transmit through the OFF-state column and are blocked by the ON-state columns. In this way, by switching pin-diodes between ON and OFF-states in each FSS column, the radiation pattern is able to scan the azimuth plane in the 6 steps at 5.2 GHz. Moreover, multi-beam modes can also be achieved by changing the states of the pin-diodes in different column combinations. When the pin-diodes in any two columns are in OFF states and the pin-diodes in the rest columns are in ON states, two beams radiation pattern can be achieved. Using the same operation method, three beams can be also obtained. Thus, the proposed antenna can flexibly operate at single-beam mode and multi-beam modes. Fig. 7 depicts the simulated E-field distribution of single-beam mode, two-beam mode and three-beam mode at 5.2 GHz in *xz*-plane, which agrees well with the design principle. In addition, six metallic sheets are loaded vertically surrounding the outside of the monopole antenna in this design, which is used to shape the radiation pattern for improving the gain of the proposed antenna. Consequently, the proposed antenna can flexibly control beam numbers.

IV. PARAMETRIC STUDIES

Parametric studies are described in this section. The reflection coefficient of the antenna is mostly affected by the parameters *d1* and *d2* shown in Fig. 3 and they also have a minor effect on the gain of the proposed antenna. The parameter *d1* is the distance between two opposite FSS unit-cells in the hexagon FSS screen and the parameter *d2* is the distance between two opposite metallic sheet. The effect of the parameters *d1* and *d2* on the reflection coefficients and gain of the antenna are illustrated in Fig. 8 and Fig. 9, respectively. Fig. 8 (a) shows that the matching of the antenna becomes worse when increasing *d1*, while Fig.8 (b) clearly shows that the maximum gain is achieved when *d1* is set as 41mm (0.7 λ)

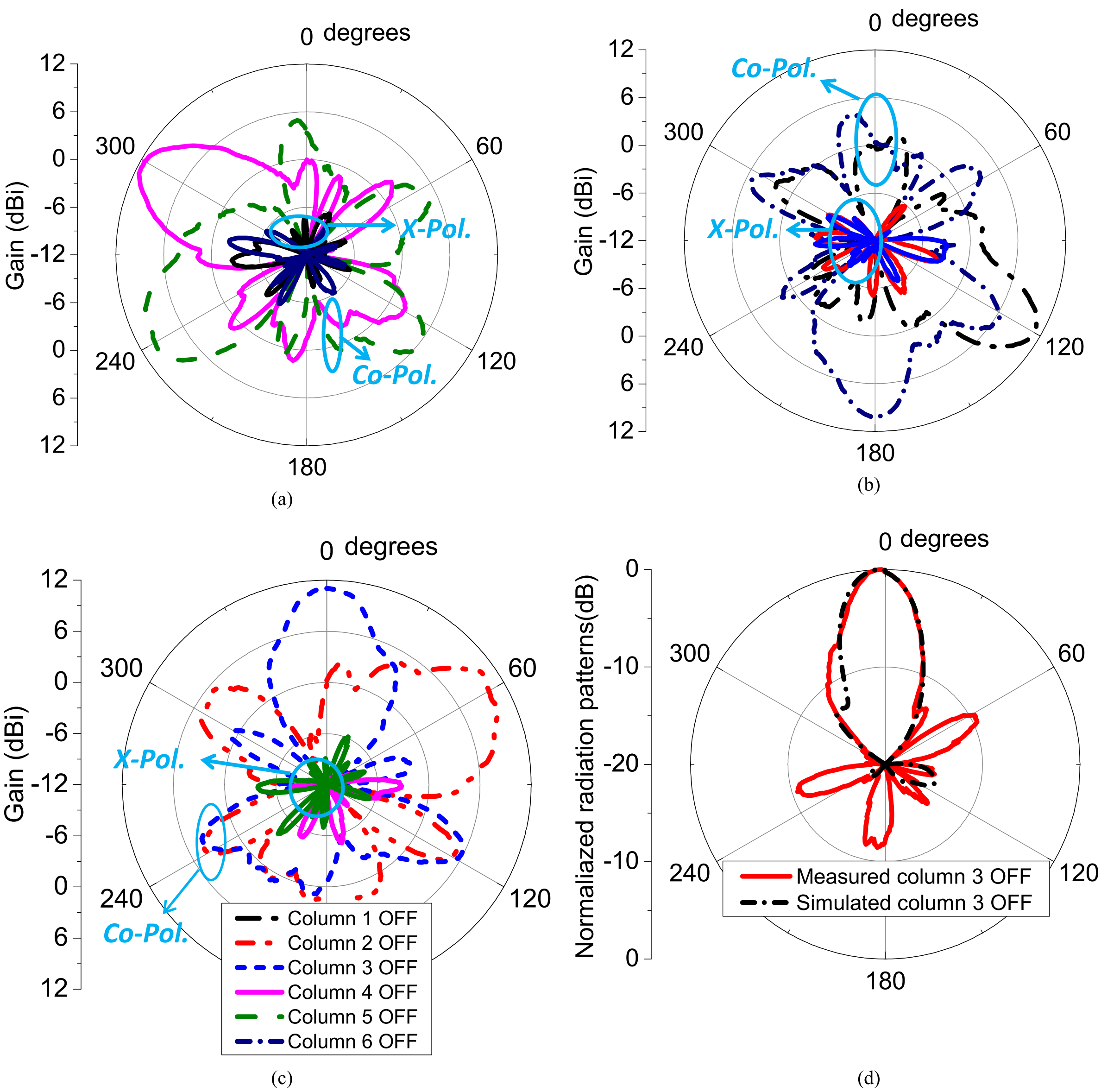


FIGURE 15. Measured radiation patterns of a single-beam mode at 5.2 GHz: (a), (b) and (c) in azimuth plane, (d) in elevation plane.

at 5.2 GHz. Hence, the optimal value of *d1* for our application is 41mm. From Fig. 9, it can be seen that the reflection coefficient of the antenna can be modified by changing the value of *d2*. The maximum gain is achieved when *d2* is given 56 mm with good matching at 5.2 GHz. Hence, the optimal value of *d2* for our application is 56 mm.

Since the parameters of length (b) and height (h) of the metallic sheet mainly influence the 3 dB beamwidth and the antenna gain, it is necessary to investigate them separately. Fig.10 shows the radiation pattern of the antenna in the *xz*-plane at 5.2 GHz with different lengths of the metallic sheet. The results clearly show that the 3 dB radiation beamwidth reduces when increasing the b value.

The reason is that the radiating aperture in *xz*-plane increases with increasing the value of b. Hence, taking into account the whole size of antenna, the beamwidth and gain, the value of b is chosen as 100 mm, leading to a beamwidth of 30 degrees with gain of 13.5 dBi at 5.2 GHz. As indicated above, the height of the metallic sheet mainly affects the gain of the antenna. The effect of the variation of h on the radiation patterns of the antenna is illustrated in Fig. 11. These results clearly indicate that the maximum gain is obtained in *xz*-plane at 5.2 GHz, when the height h is 130 mm. With all the analysis results in this section, the final antenna dimensions are given in Section III. Moreover, the radiation patterns of the beam-switching antenna with and without metallic sheets in *xz*-plane at 5.2 GHz are shown in Fig.12, demonstrating that the 7 dB gain enhancement is achieved by comparing the gain values of the beam-switching antennas with and without metallic sheets.

V. FABRICATION AND MEASUREMENT RESULTS

To validate the performance of the proposed concept, an experiment prototype was fabricated and its performances were measured. The photograph of the fabricated prototype antenna in an anechoic chamber is given in Fig. 13. The hexagon FSS screen is printed on substrate RT/duroid®5880 with a permittivity of 2.2 and thickness of 0.254 mm. As shown in Fig. 13, six FSS unit-cells are wrapped onto the hexagon foam. Furthermore, there is a centered rectangular aperture in the hexagon foam to accommodate the monopole antenna which is fed through a coaxial cable from the bottom of the structure. Twelve high frequency pin-diodes GMP-4201 from Microsemi are inserted into the FSS screen [26]. RF chocks with 18 nH from Murata are employed in the FSS screen to isolate the RF signal from biasing lines. The pin-diodes in each column of the FSS screen are fed with DC feeding lines from the top and bottom. The DC voltage is supplied by an external voltage source during the measurements. The pin-diodes in one column of the FSS screen are in OFF state, when the DC voltage is supplied zero to this column. When the DC voltage is given 2.15 V to one column of the FSS screen, the pin-diodes in this column are in ON state.

To validate the proposed antenna concept with flexible controlling beam numbers, the measurement methods are divided into three modes including single-beam mode, two-beam mode and three-beam mode. For the single-beam mode measurement, one column is supplied zero DC voltage and the others are given positive voltage, which means that the pin-diodes in zero voltage column are in OFF states and the pin-diodes in positive voltage columns are in ON states. Therefore, from the analysis in Part B of Section II, the radiation pattern of the proposed antenna can be switched in six directions in the azimuth plane at 5.2 GHz by supplying the zero voltage to each column in turn. For the multi-beam modes (two-beam and three-beam modes), when any two or three columns of the FSS screen are given zero voltage and the others are supplied positive voltage, the two beams and three beams radiation patterns of the proposed antenna can be achieved.

The reflection coefficient is measured using Agilent 8722ES vector network analyzer. The measured reflection coefficients of the single-beam mode and multi-beam modes are shown in Fig. 14, indicating that there is a good matching over 4.8-5.6 GHz. Furthermore, it can be observed that there is a perfect matching at the resonant frequency of 5.2 GHz and the single-beam mode has a better matching than the multi-beams mode.

The radiation patterns are measured in an anechoic chamber. Fig.15 (a), (b) and (c) shows the measured radiation patterns of a single-beam mode in the azimuth plane at 5.2 GHz. The simulated and measured radiation patterns when the pin-diodes in column 3 are in OFF state in elevation plane at 5.2 GHz are shown in Fig.15 (d). It is clear that six different directional beams with a 3dB beamwidth of 30 degrees in the azimuth plane are obtained at 5.2 GHz.

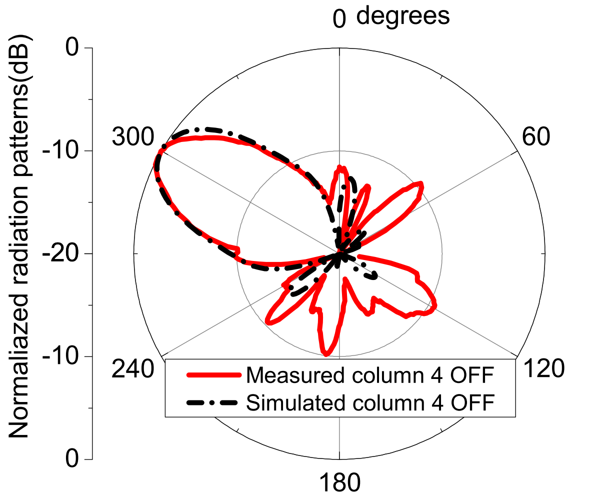
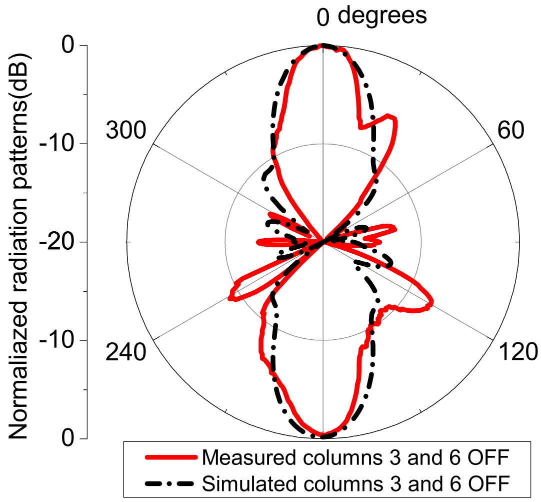


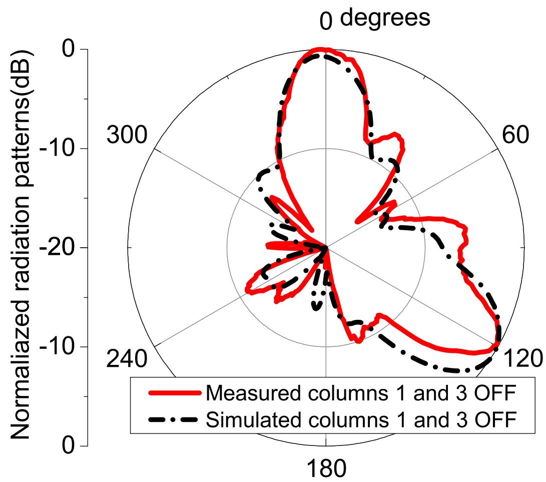
FIGURE 16. Simulated and measured radiation patterns of single-beam mode when column 4 OFF at 5.2 GHz in azimuth plane.

The 3dB beamwidth of this proposed antenna is much smaller compared to one in [17], which means this proposed antenna has a higher angular resolution for beam-switching application.

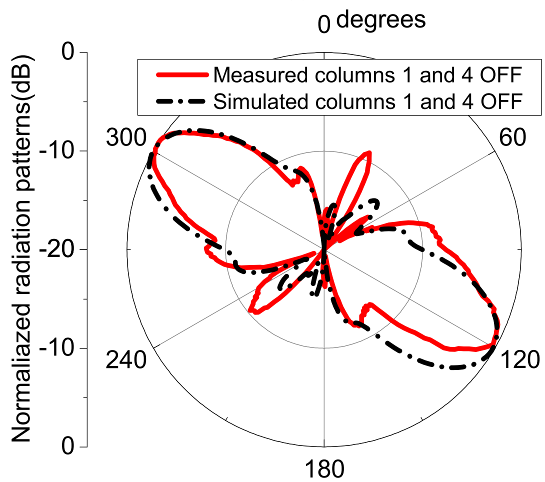
The simulated and measured radiation patterns when the pin-diodes in column 4 are in OFF state at 5.2 GHz are shown Fig.16. The results clearly show that measured results agree very well with the simulated ones. Fig. 17 shows the simulated and measured radiation patterns of two-beam mode at 5.2 GHz in azimuth plane. From the Fig. 6 and previous analysis, the beam directions of proposed antenna should be 0 degree and 180 degrees when the pin-diodes in columns 3 and 6 are OFF. Fig.17 (a) depicts the simulated and measured radiation patterns when the pin-diodes in columns 3 and 6 are OFF. From the results, it is seen that the two beams are in the directions of 0 and 180 degrees, respectively, which agrees well with the design principle. Moreover, the experimental results also clearly show that measured result agrees very well with the simulated one. Fig.17 (b) and (c) shows the simulated and measured radiation patterns when the pin-diodes in columns 1, 3 are OFF and those in columns 1, 4 are OFF. It is clearly seen that the measured results match well with simulated ones. Additionally, it is noticed that the measured beamwidth of the beam pointing to 120 degrees is narrower than the simulated one. The main reason for this difference could be attributed to the assembly tolerance and errors. The simulated and measured radiation patterns of three-beam mode at 5.2 GHz in azimuth plane are shown in Fig. 18, which shows that the directions of the three beams are 0 degree, 120 degrees and 240 degrees, respectively. It also can be seen that the measured radiation pattern of the three-beam mode is in agreement with the simulated ones, except that the measured beamwidth of the beam pointing to 120 degrees, which is narrower than the simulated one because of the assembly tolerance and errors. Hence, from these measured radiation patterns, it is proved



(a)



(b)



(c)

FIGURE 17. **Simulated and measured radiation patterns of two-beam mode at 5.2 GHz in azimuth plane: (a) Columns 3 and 6 OFF. (b) Columns 1 and 3 OFF. (3) Columns 1 and 4 OFF.**

that the proposed antenna can flexibly operate at different beam numbers modes including a single-beam, two-beam and three-beam modes.

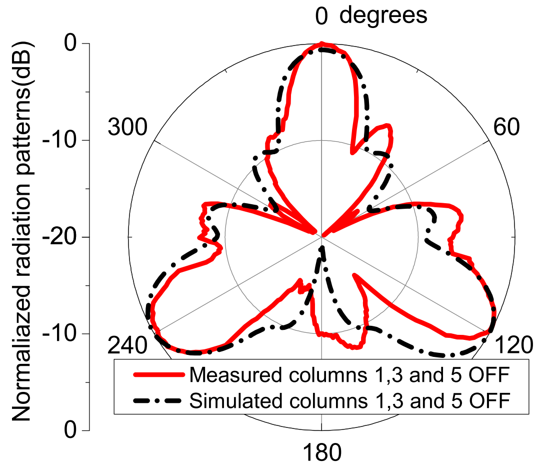


FIGURE 18. **Simulated and measured radiation patterns of three-beam mode at 5.2 GHz in azimuth plane when column 1, 3 and 5 OFF.**

TABLE 2. **The simulated and measured gain of different modes.**

Gain (dBi)	Single-beam mode	Two-beam mode	Three-beam mode
Simulation	13.5	10.7	9.01
Measurement	11.54	9.0	7.34

The gain of the proposed antenna is also measured by the comparison method, and listed together with the simulated gain in Table 2. It can be seen that the measured gain is 11.54 dBi, 9 dBi and 7.34 dBi in the single-beam mode, the two-beam mode and three-beam mode, respectively, at 5.2 GHz. It is also found that the measured gain is less than the simulated one. The fabrication tolerance, assembly and measurement errors could be the main reasons for the difference between the simulated and measured gain. Moreover, the actual physical characteristics of the pin-diode enclosure could be another reason for this.

VI. CONCLUSION

This paper has proposed a beam-switching antenna with gain enhancement and flexibly controlling beam numbers based on frequency selective surfaces (FSSs) operated at the resonating frequency of 5.2 GHz. A centered omnidirectional monopole antenna has been designed as a radiating source which is surrounded by a proposed hexagon FSS screen and six metallic sheets. From the experimental results, the proposed antenna with a high gain (11.54 dBi) is effectively operating at 5.2 GHz. The maximum gain of the antenna enhancement of 7 dB has been achieved when the six metallic sheets applied. By changing the states of pin-diodes in different column combinations of the hexagon FSS screen, this proposed antenna has realized a single-beam switching in six directions and multiple beams at 5.2 GHz in the azimuth plane with low voltage (2.15 V). Furthermore, the measured results have shown a good agreement with the simulated ones.

With these features, the proposed antenna is a good candidate for modern communication systems.

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