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Design of Compact Beam-Steering Antennas Using a Metasurface Formed by Uniform Square Rings

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ABSTRACT In this paper, we propose two designs of slot-fed metasurface antenna for beam steering applications. Both designs have the same two-layer stacked configuration consisting of either a single-slot or a double-slot radiator and a metasurface superstrate. In contrast to existing phase-gradient metasurfaces with varying unit elements for beam steering, our proposed metasurface is formed by uniform square rings. At operating frequencies, each square ring acts as an individual resonating element. By exciting the elements in sequence with different phase delays through the slot radiator, the generated antenna beam can be steered. In the first design, the position of the single-slot radiator is shifted to achieve the beam steering functionality; while for the second antenna, to avoid mechanically moving the feeding slot, a double-slot-feeding structure is proposed with two slots excited with varying phase differences. Simulation and experimental results show that beam steering angles of $-35°$ to $35°$ can be achieved for the single-slot-feeding design and beam steering angles of $-30°$ to $30°$ are realizable for the double-slot-feeding configuration. Comparing with conventional phased array antennas, our proposed designs have compact size with moderate to high antenna gain.

INDEX TERMS Beam-steering, metasurface, slot antenna.

I. INTRODUCTION

Metamaterials are defined as artificial periodic structures which possess desirable electromagnetic properties that have not been found in naturally occurring materials [1]. Notable applications of metamaterials include superresolution imaging [2], [3], cloaking [4], and perfect wave absorption [5] etc. The applications of metamaterial structures to antenna designs have long been investigated along with the development of metamaterials [6], [7]. However, early designs require bulk metamaterial structures which pose challenges in their practical realization [8]. The recent development of metasurfaces [9], [10] has brought wide interests in their applications in antenna designs lately [11]–[16]. In addition to antenna applications, metasurfaces have also been shown to possess exceptional abilities to control electromagnetic waves, allow cost-effective fabrications, and may hold promises for future applications in imaging, sensing, and quantum information processing etc. [10].

In antenna applications, metasurfaces can be used to enhance antenna gain, improve bandwidth and efficiency, reduce backward radiation, convert polarization, as well as steer antenna beams. For antenna gain enhancement, the metasurface can be used to form a Fabry-Perot cavity to excite the leaky-wave mode of the structure [13], [14]; the metasurface can be also designed to function as a lens to generate a highly focused beam [17], as well as act as a spatial filter to convert and pass through wave vectors parallel to the propagation direction [18], [19]. The bandwidth enhancement of antennas by metasurfaces is usually attributed to the additional impedance matching or parasitic resonance introduced by the metasurface superstrate, and the reduction of backward radiation is typically due to the stop-band of the electromagnetic bandgap (EBG) structure formed by the metasurface. For beam steering, most of the antenna designs are based on phase-gradient metasurfaces, i.e. each metasurface element creates a different phase shift to the incident wave. According to the generalized Snell's law [20], anomalous transmission or reflection occurs at the metasurface, and beam steering can be achieved [21]. However, the complexity of phase-gradient metasurface design lies in the selection of unit elements to cover complete phase shifts from 0 to 2π radians. Moreover, the drawback of constant-phase-gradient metasurface is that beam can only be steered to a particular direction, which limits the functionality of beam steering antennas. In order to steer the transmitted/reflected beam to a different direction, a new phase-gradient metasurface needs to be designed. For continuous beam steering using the same metasurface, either the feeding source can be mechanically moved in the focal plane for the case of lens antennas [22]–[24], or the metasurface superstrate can be mechanically rotated or moved [25], [26]. It is worth mentioning that conventionally electrical control of beam steering is realized. However, a complex feeding network with a large number of phase shifters and a biasing network are required [27].

In this paper, we propose two designs of compact slot-fed metasurface antenna for two-dimensional beam steering. Closed square rings are chosen as the metasurface element due to the simplicity of the structure. Comparing with open rings such as the typical split-ring resonator (SRR), our proposed metasurface formed by closed square rings offers a relatively larger beam steering angle range. On the other hand, in contrast to circular rings, square rings have a higher in-surface coupling efficiency which is essential for highly efficient beam steering antenna design, as well as a larger beam steering angle range. For the feeding structure, we propose two types of design using single-slot and double-slot configurations. In the single-slot metasurface antenna design, the feeding slot is shifted horizontally (a different slot radiator is used for each slot position) to achieve different beam steering angles; while for the double-slot configuration, the radiated beam from the antenna can be steered by feeding two slots with varying phase differences, and a Wilkinson power divider is used to equally divide the input power from a single port. The main advantages of our metasurface design over phase-gradient metasurfaces include high efficiency, low sensitivity to polarization, and simplicity in the design process.

II. ANTENNA DESIGNS AND SIMULATION RESULTS

A. METASURFACE FORMED BY UNIFORM SQUARE RINGS

There are many types of metasurface elements including SRRs, square or circular patches and cross-shaped structures etc. In the current design, we select the closed square ring due to its simplicity and symmetrical geometry for supporting dual polarizations. Figure 1(a) shows the unit cell of the metasurface and its dimensions. A plane-wave analysis is performed to study the transmission and reflection characteristics of the metasurface with varying angle of incidence. The boundary conditions are defined as perfect electric conductor (PEC) along both ends of the unit cell normal to y-direction, and periodic boundary condition (PBC) in x-direction. Using the calculated transmission and reflection coefficients, a parameter retrieval method [28] is applied to extract effective material parameters for varying angles of incidence, $\theta_i = 0$ (normal incidence) to $\theta_i = 80$ (when the slot radiator is moved to the edge of the antenna, see details in the next subsection). The extracted material parameters are shown in Fig. 1(b). It can be seen that at the frequencies below 3 GHz, the effective permittivity is relatively large, while the effective permeability along the metasurface is near zero. Besides, as the angle of incidence increases, at the frequencies of interest between 2.4 and 2.5 GHz, the effective permeability further approaches zero but remains positive. The near-zero permeability is the required material parameter for achieving high gain and wide-bandwidth antennas as detailed in our previous work [11], [12]. The gain enhancement by mu-near-zero (MNZ) metasurface is due to the near-zero refractive index for altering outgoing wave vectors as well as the increase in antenna's effective aperture size, and the bandwidth improvement is attributed to the proximity coupling between the primary source and the unit cell of the MNZ metasurface. In the following, we show that not only high antenna gain can be achieved, but when the position of the feeding source (slot) is shifted, the radiated beam from the metasurface can be steered in the opposite direction accordingly.

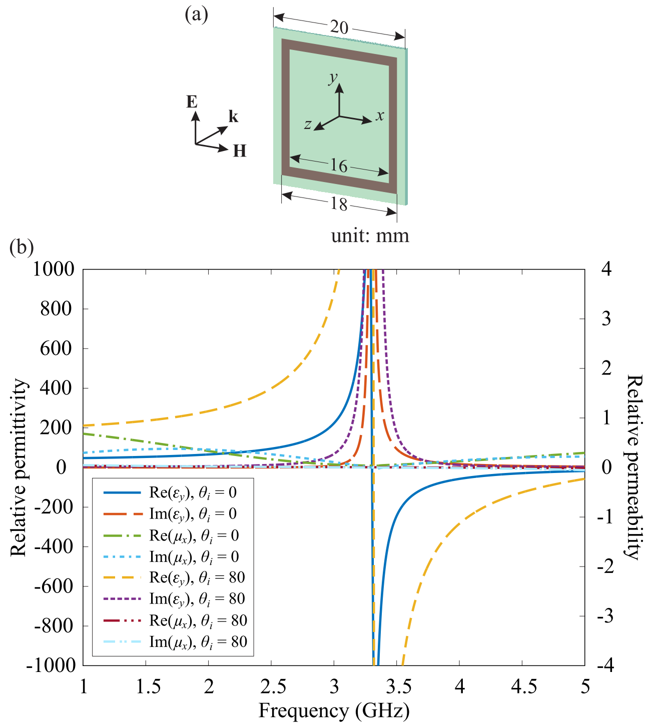

FIGURE 1. **(a) Unit cell of the metasurface formed by closed square rings. The polarization of incident wave in the transmission analysis is also shown. (b) Retrieved relative permittivity and permeability of the metasurface formed by closed square rings for two angles of incidence, $\theta_i = 0$ (normal incidence) and $\theta_i = 80$ degrees.**

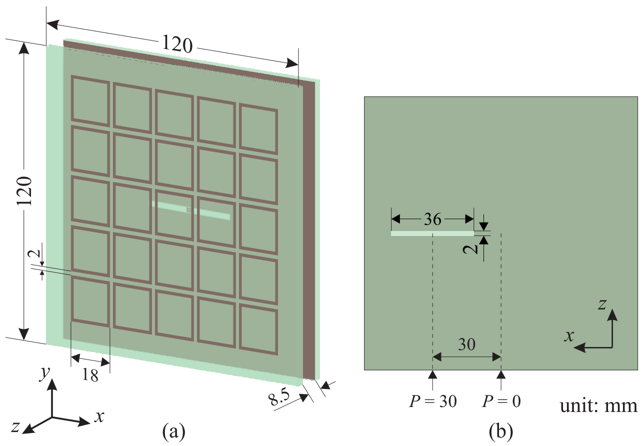

FIGURE 2. **(a) Geometry of the single-slot metasurface antenna consisting of a metasurface superstrate formed by closed square rings, and a conventional slot radiator as the feeding source. (b) The case when the slot is shifted to the position of $P = 30$ mm from the center of the antenna.**

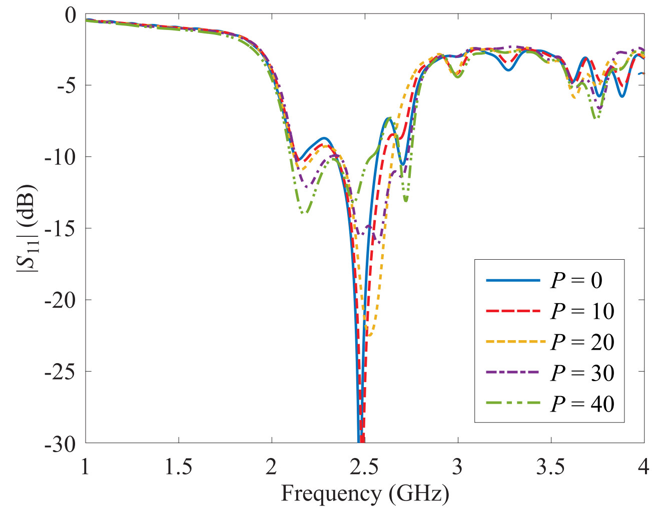

FIGURE 3. **Simulated S_{11} (magnitude) of the single-slot metasurface antenna with varying slot positions.**

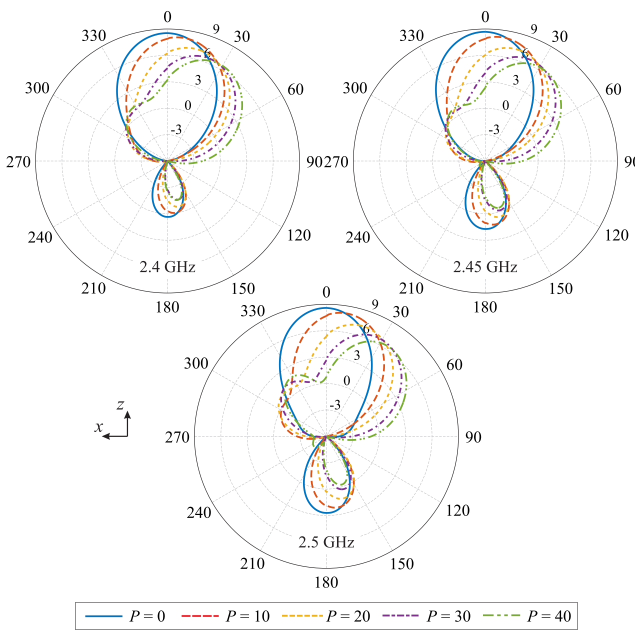

FIGURE 4. **Simulated radiation patterns (gain) in the *x-z* plane at 2.4, 2.45, and 2.5 GHz for the single-slot metasurface antenna with varying slot positions on the ground plane.**

B. SINGLE-SLOT FEEDING WITH VARYING SLOT POSITION FOR BEAM STEERING

The conventional slot radiator is chosen as the feeding source due to the required magnetic field component along the structure (x-direction) which can strongly interact with the metasurface. The geometry of the designed antenna is shown in Fig. 2(a). The antenna is designed to operate at the industrial, scientific and medical (ISM) frequency band of 2.45 GHz. The dimensions of the metasurface's unit cell are the same as those in Fig. 1(a) used in the plane-wave analysis. The number of square-ring elements in the metasurface is 5×5, which is chosen such that a sufficient maximum beam steering angle can be obtained with a high antenna gain, while a low profile of the overall antenna structure is maintained. The gap between the slot radiator and the metasurface superstrate is 8.5 mm ($0.07\lambda_0$ where λ_0 is the free-space wavelength at 2.45 GHz), which is selected after the parametric study detailed later in this section. The shifting of the location of slot radiator is represented by the change of the slot position on the ground plane, and the feeding microstrip line is also changed together with the slot. In total five discrete shifting steps are considered in our simulations: $P = 0 \rightarrow 40$ mm (along $+x$-direction) with a uniform step of 10 mm, where P is the distance from the center of the slot to the center of the ground plane, as shown in Fig. 2(b). The proposed antenna is simulated using CST Microwave Studio™ and the calculated S-parameter ($|S_{11}|$) is shown in Fig. 3. It can be seen that for different slot positions, the impedance matching of the antenna is only slightly affected due to the coupling effect between the metasurface superstrate and the slot radiator. Nonetheless, at the frequencies of interest between 2.4 and 2.5 GHz, the values of $|S_{11}|$ for all cases are below -10 dB. Figure 4 shows the simulated radiation patterns at 2.4, 2.45 and 2.5 GHz for the antenna with varying slot positions on the ground plane. The maximum gains of the antenna achieved for the case of $P = 0$ are 8.54, 8.69 and 8.60 dBi at 2.4, 2.45, and 2.5 GHz, respectively. When the position of slot is shifted, the antenna gain decreases accordingly which is a typical effect for phased array antennas at higher steering angles. It is also evident from Fig. 4 that the radiated beam is steered from the center of 0 degree for $P = 0$, to the maximum steering angle of approximately 35 degrees for the case of $P = 40$, and the beam is steered in the opposite direction to the movement of slot position. Note that the position of slot is only changed in one direction in simulations, i.e. $P > 0$. If the slot is moved in both directions, the beam steering angle range of -35 to 35 degrees can be realized. It is also shown from the radiation patterns that at higher frequencies,

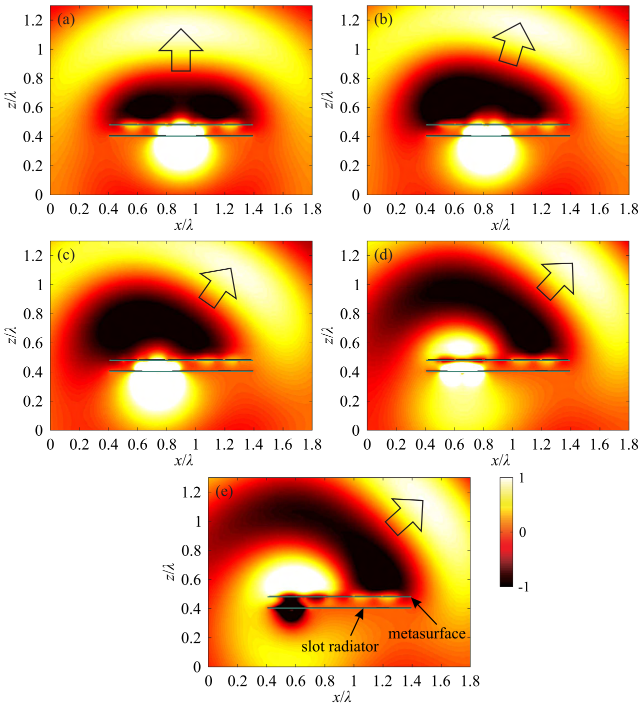

FIGURE 5. Normalized electric field distributions for the side-view of single-slot metasurface antenna for different slot positions ((a)-(e): $P = 0$ to $P = 40$) showing different angles of radiated beam (indicated by the directions of arrows).

backlobes become larger, and a beam splitting effect in the forward direction starts to appear (the increase of sidelobe). To further investigate the radiation mechanism, electric field distributions for side-view of the antenna are plotted for different slot positions and shown in Fig. 5. By observing the radiation mechanism in simulations, it is found that energy is first coupled from the slot radiator to the nearest square ring, and then the neighboring rings are excited in sequence with different time delays. Effectively, different metasurface elements (square rings) are excited with different phase delays. We also record the radiated electric field component at a distance of 6 mm above the metasurface and the distributions of normalized magnitude and phase at 2.4 GHz for varying slot positions are listed in Table 1. It can be observed that for all cases, the magnitude variations are insignificant, while phase progresses along square ring elements. For the case of the slot located in the center of the antenna ($P = 0$), due to the symmetrical layout of square ring elements on both sides, the average phase delay, $\overline{\Delta\phi}$ from element #5 to element #1 is zero, and the resulting radiated beam is directed upwards (0 degree). When the slot position is shifted, the value of $\overline{\Delta\phi}$ gradually increases, thus the radiated beam is steered to an increasing angle accordingly, as shown in Fig. 4. To validate the above results, we use the following equation to calculate the theoretical phase delay for the case of $P = 40$ by using parameters of the proposed metasurface:

$$\Delta\phi = \frac{2\pi \cdot d \cdot \sin\theta}{\lambda_g} \tag{1}$$

TABLE 1. Distributions of normalized magnitude, $|E|$ (a.u.) and phase, ϕ (degree) at 2.4 GHz for varying slot positions at a distance of 6 mm above the metasurface. The square ring elements are numbered as 1 to 5 from the right to left ends of the metasurface, see Fig. 5.

Slot Position		Square Ring Element # 1	2	3	4	5	$\overline{\Delta\phi}$
$P = 0$	$\|E\|$	0.8	0.87	0.5	0.87	0.8	0
	ϕ	126	152	200	152	126	
$P = 10$	$\|E\|$	0.54	0.64	0.61	0.79	0.85	16.3
	ϕ	89	128	183	186	154	
$P = 20$	$\|E\|$	0.54	0.54	0.66	0.76	0.87	30.5
	ϕ	46	95	151	196	168	
$P = 30$	$\|E\|$	0.57	0.49	0.61	0.8	0.81	42.8
	ϕ	22	72	137	186	193	
$P = 40$	$\|E\|$	0.66	0.51	0.62	0.87	0.82	50.6
	ϕ	-4.5	43	115	156	198	

where $d = 20$ mm is the periodicity of metasurface elements, $\theta = 31$ degrees is the beam steering angle for $P = 40$ at 2.4 GHz, and λ_g is the guided wavelength on the metasurface which can be approximated as $\lambda_0/\sqrt{(\varepsilon_r + 1)/2}$, where λ_0 is the free-space wavelength at 2.4 GHz, and $\varepsilon_r = 4.3$ is the dielectric constant of the substrate. The calculated theoretical phase delay is 46.9 degrees according to Eq. (1), which is close to the value of 50.6 obtained from numerical simulations, and indicates that beam steering is indeed due to sequential excitation of square-ring elements.

In the above results, all parameters are the optimized ones which are found from parametric studies in simulations. It would also be interesting to observe different parameters such as the gap between the metasurface and slot radiator. In Fig. 6, the radiation patterns for two additional gap sizes of 6 and 11 mm are shown. When the gap is small, more energy can be transmitted through the metasurface, and the backlobe is significantly reduced. However, the maximum steering angle is also reduced to about 24 degrees at 2.5 GHz. On the other hand, if the gap is too large, not only the backlobe is significantly increased due to reflections from the metasurface, the radiated beam in the forward direction also starts to split, especially at higher frequencies. Therefore it is important to choose an optimum gap size to achieve sufficient steering angle and avoid large sidelobe of the antenna.

In addition, different numbers of square ring elements in the metasurface are also considered in simulations: 5×4, 5×6, and 5×7, with the number of elements in y-direction being unchanged and varying number of elements in x-direction (see Fig. 2(a)). The simulated radiation patterns are shown in Fig. 7. In each case, the gap between the metasurface superstrate and slot radiator is varied to find the optimum gap size and the slots are shifted to the edge of the ground plane for achieving the maximum obtainable steering angle. It can be observed that when the transverse dimension of the metasurface is increased, although the antenna gain can be slightly improved, the increase in sidelobe level becomes more significant. Besides, the maximum beam steering angle

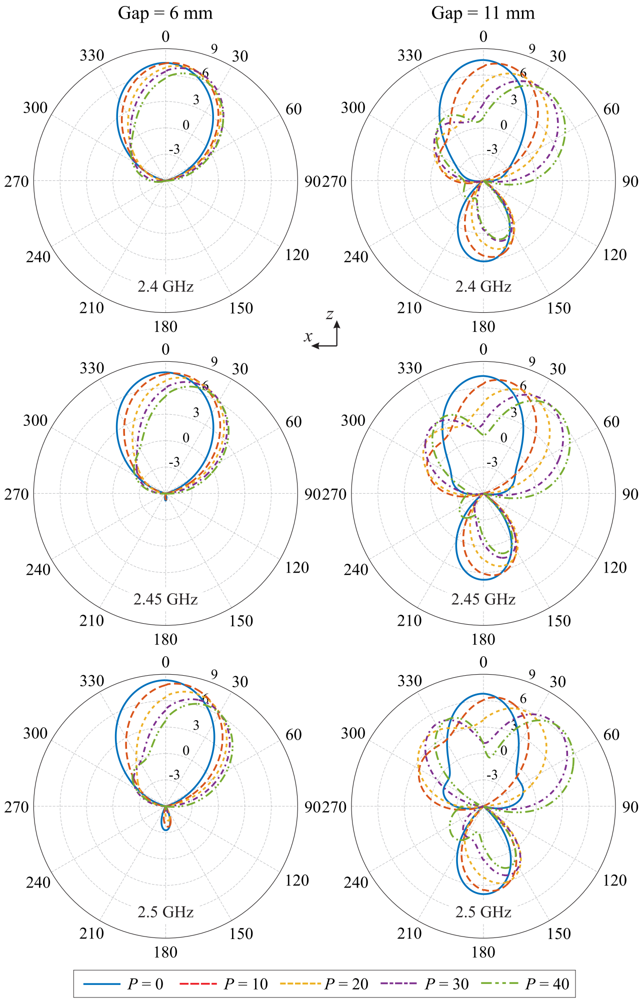

FIGURE 6. Simulated radiation patterns (gain) in the *x*-*z* plane for the single-slot metasurface antenna when the gaps between the metasurface superstrate and the slot radiator are 6 mm and 11 mm.

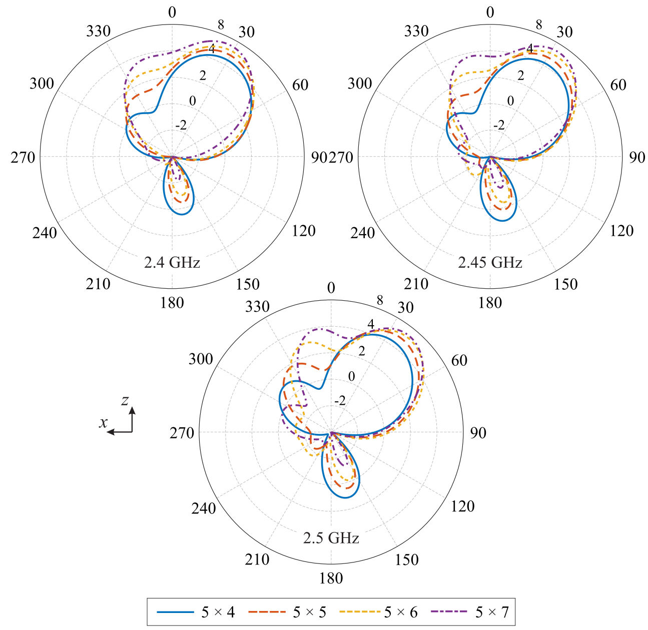

FIGURE 7. Comparison of radiation patterns (gain) in the *x*-*z* plane for the single-slot metasurface antenna consisting of different numbers of elements: 5 × 4 (gap = 10.5 mm, *P* = 30), 5 × 5 (gap = 8.5 mm, *P* = 40), 5 × 6 (gap = 7.5 mm, *P* = 50), and 5 × 7 (gap = 6.5 mm, *P* = 60). Only the maximum steering angle for each case is shown.

remains similar for different metasurface sizes although the slot is shifted further from the center. Therefore from the above comparison, the number of elements in our design is chosen to be 5 × 5.

It is important to note that using the slot radiator alone without the metasurface superstrate, when the slot position is shifted, nearly no beam steering effect can be observed.

C. DOUBLE-SLOT FEEDING WITH VARYING PHASE DIFFERENCE FOR BEAM STEERING

In practice, the above single-slot design requires mechanically moving the feeding slot. In this section, we show that by introducing an additional slot and excite two slots with phase differences, beam steering can be also realized. Figure 8 shows the geometry of the double-slot metasurface antenna design. A Wilkinson power divider is used to equally divide the input power from a single port excitation to both slots, and different lengths of microstrip lines are designed to create a feeding phase difference between two slots, as shown in Fig. 8(b). The phase difference can be adjusted by varying the length of a section of the microstrip line for one slot according to the values listed in Table 2. The positions of two slots remain unchanged for all cases. The simulated $|S_{11}|$ for different phase differences between two slots, $\Delta\Phi$ is plotted in Fig. 9. When the phase difference between two slots is small, i.e. $\Delta\Phi < 90$ degrees, the antenna has a good impedance matching with $|S_{11}| < -10$ dB across the frequency band of 2.4 – 2.5 GHz. However, when the phase difference is large, the antenna becomes mismatched and additional tuning is performed by adjusting the length of both slots to 28 mm. The simulated radiation patterns for varying phase differences are shown in Fig. 10. When two slots are fed in phase ($\Delta\Phi = 0$), the main beam is directed upwards (0 degree), and when the phase difference increases (the value of Δl increases), the beam can be gradually steered to the direction toward the slot fed by the longer microstrip line. Depending on the phase difference between two slots (positive or negative), a maximum beam steering angle range of around -35 to 35 degrees can be achieved. However, as it is also shown in the radiation patterns, when two slots are fed out of phase ($\Delta\Phi = 180$ degrees), a null is created at the 0 degree direction due to the cancellation of radiated fields from both sides of the metasurface, and the beam is split into two directions. Therefore we conclude

TABLE 2. Values of Δl for creating a phase difference between two slots.

Phase Difference, $\Delta\Phi$ (degree)	0	45	90	135	180
Δl (mm)	0	5.2	9.5	13.7	18.0

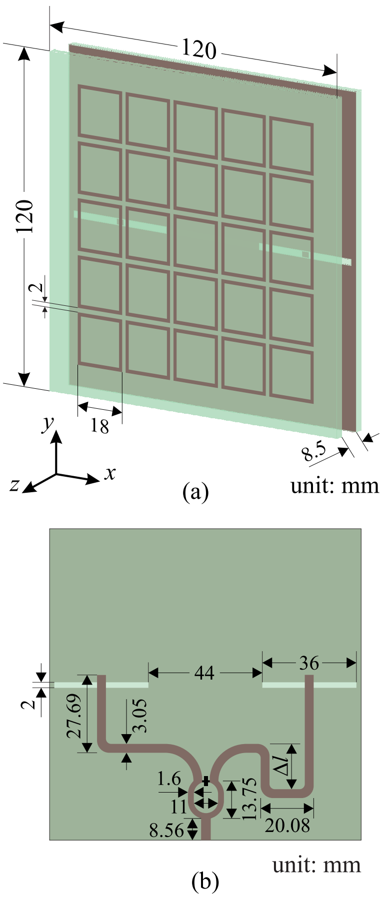

FIGURE 8. (a) Geometry of the double-slot metasurface antenna. Each slot is fed by a microstrip line with different initial phase. (b) The bottom view of the double-slot feeding structure. A Wilkinson power divider is used to equally divide the input power for two slots. A resistance of 100 Ω is used between two microstrip lines. The phase difference can be adjusted by varying the length of a section of one microstrip line, Δl.

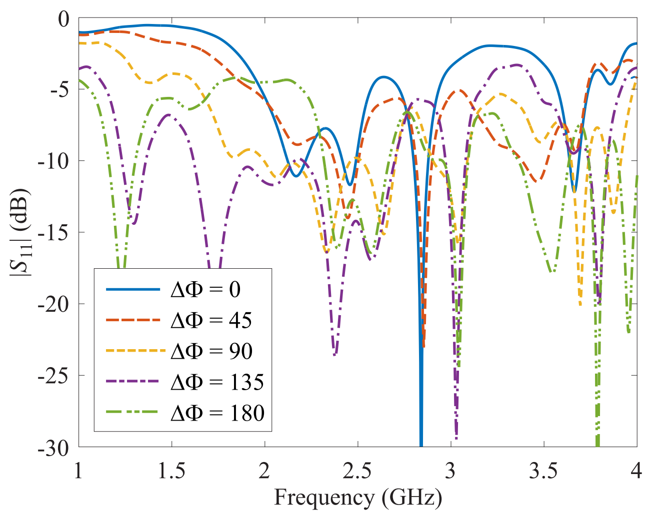

FIGURE 9. Simulated S_{11} (magnitude) of the double-slot metasurface antenna with varying feeding phase difference between slots.

that the angle range for practical beam steering using the double-slot design is approximately −30 to 30 degrees. In order to alleviate the beam splitting issue, a further study

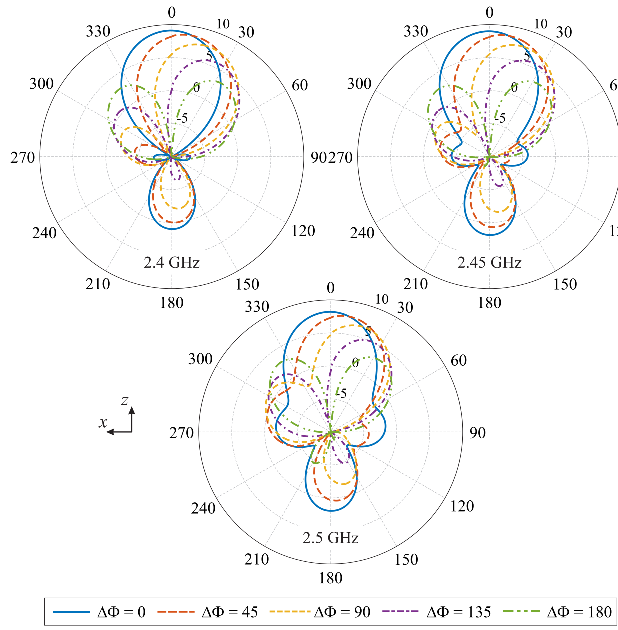

FIGURE 10. Simulated radiation patterns (gain) in the x-z plane at 2.4, 2.45, and 2.5 GHz for the double-slot metasurface antenna with varying feeding phase difference between slots.

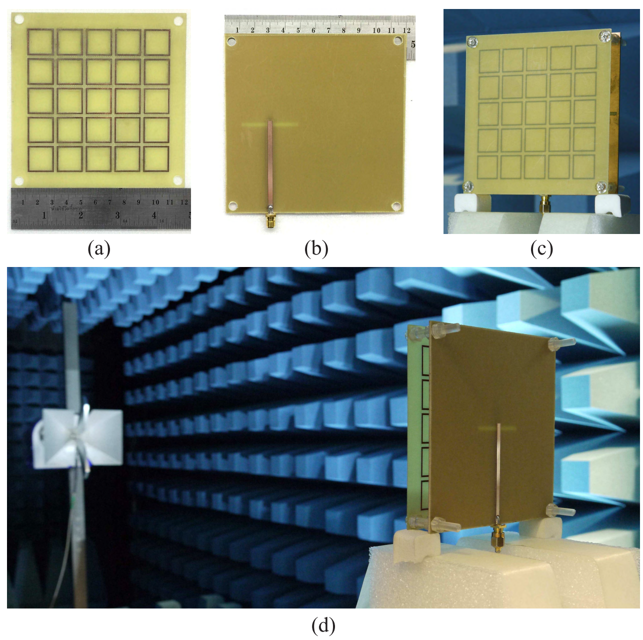

FIGURE 11. The fabricated single-slot metasurface antenna: (a) Top view of the metasurface, (b) Bottom view of the slot radiator for $P = 30$, (c) Perspective view when the slot radiator and metasurface are assembled, (d) Picture of the measurement setup.

can be performed such as by feeding two slots with different power ratios etc., which will be investigated in our future work.

From the above presented results, we have shown that beam steering can be realized by a metasurface with uniformly arranged identical closed square rings. The main

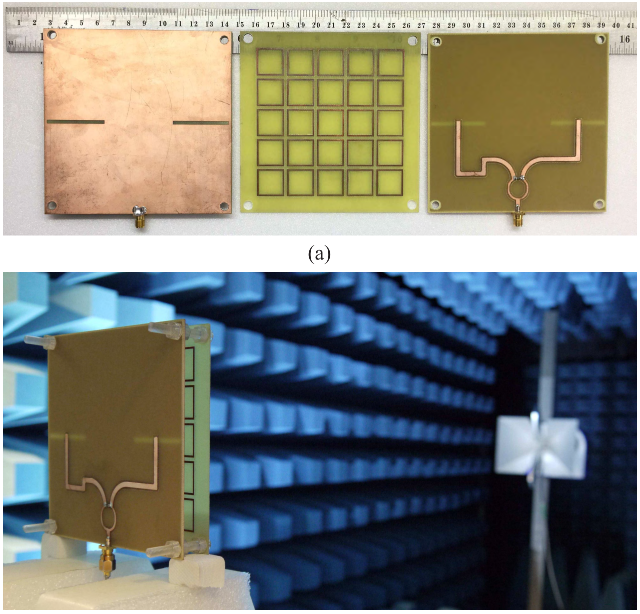

FIGURE 12. The fabricated double-slot metasurface antenna: (a) Top views of the slot-antenna and metasurface, and bottom view of the microstrip feeding lines, (b) Picture of the measurement setup.

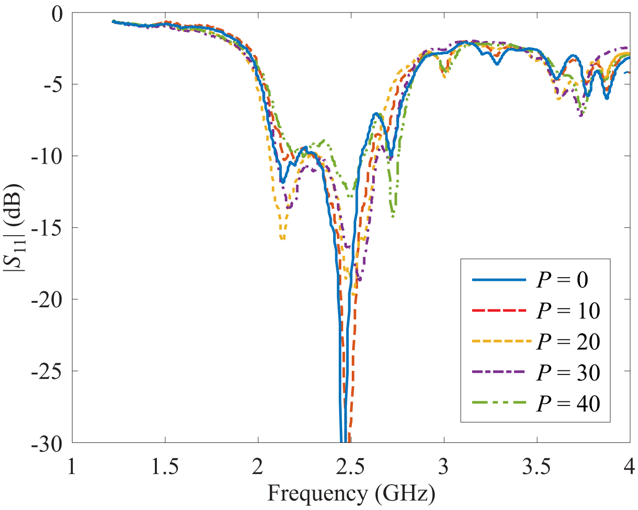

FIGURE 13. Measured S_{11} (magnitude) for the single-slot metasurface antenna with varying slot positions.

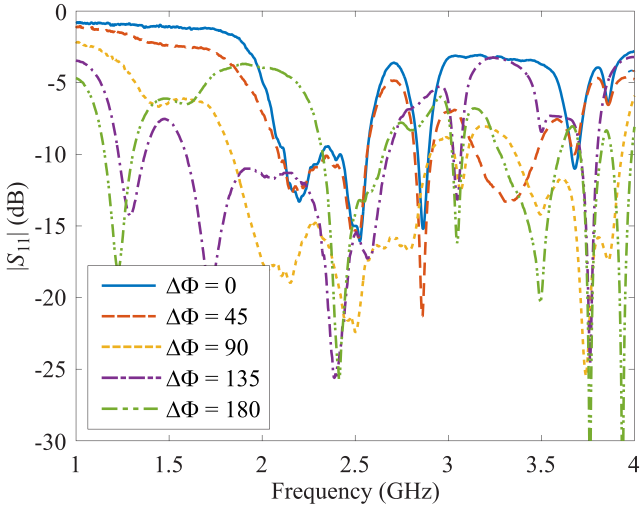

FIGURE 14. Measured S_{11} (magnitude) for the double-slot metasurface antenna with varying feeding phase difference.

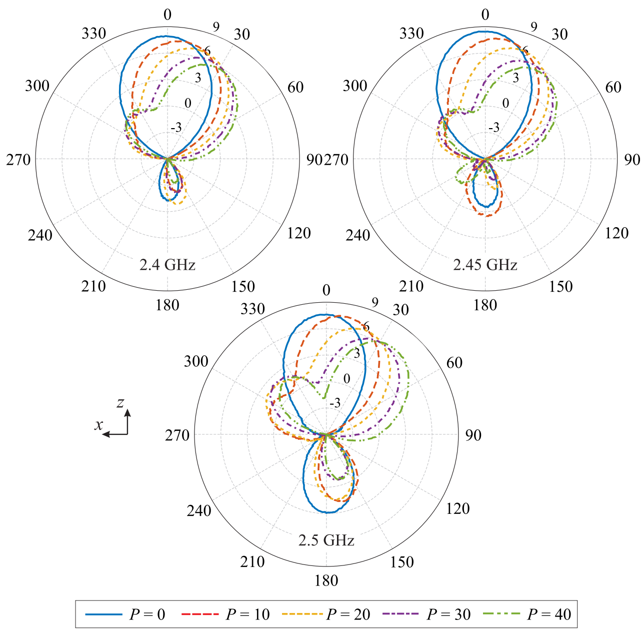

FIGURE 15. Measured radiation patterns (gain) in the elevation plane for the single-slot metasurface antenna with varying slot positions.

mechanism of radiation is due to the excitation of each row of square rings in sequence with a time delay. This is in contrast to previous metasurface designs for beam steering which use non-identical unit elements to create different phase shifts. In addition, in our design the metasurface can be excited using either a single-slot source with mechanical movement, or a double-slot source excited with a phase difference. The double-slot configuration follows a similar concept to the dual-fed phased array proposed in [29], while our design provides a wider beam scanning range. Comparing the cases of with and without the proposed metasurface, for the single-slot design, using the metasurface not only allows the radiated beam to be steered, but also enhances the antenna gain by a maximum value of 6.3 dB; while for the case of double-slot configuration, applying the metasurface reduces both backlobe and sidelobe levels of the antenna, as well as enhance the antenna gain by up to 4 dB. Comparing with conventional phased array antennas, to achieve the same antenna gain, steering angle range and operating bandwidth, our proposed designs offer more compact size ($0.96\lambda_0 \times 0.96\lambda_0 \times 0.07\lambda_0$) and do not require a complex feeding network. We would like to emphasize that in the present work, we focus on proposing a metasurface design for beam steering

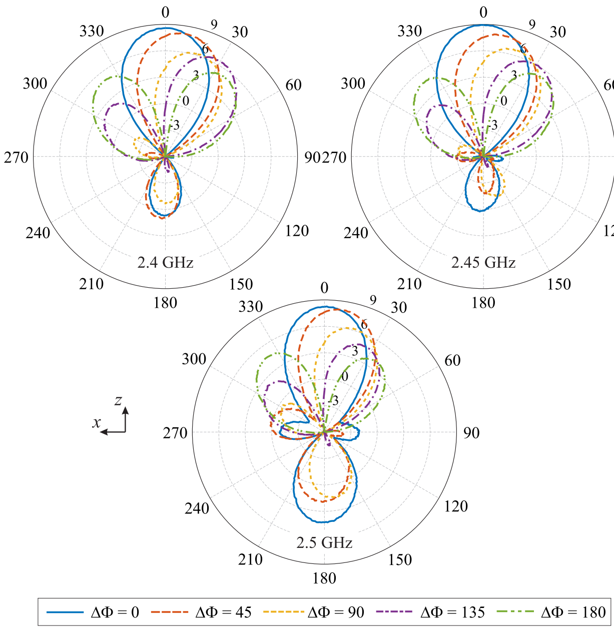

FIGURE 16. **Measured radiation patterns (gain) in the elevation plane for the double-slot metasurface antenna with varying phase difference between two slots.**

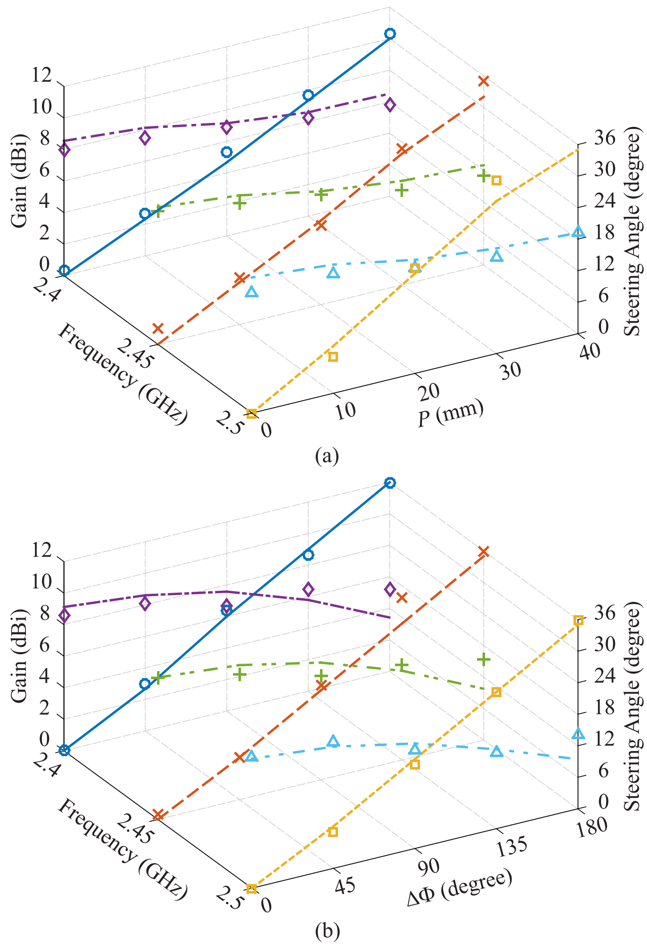

FIGURE 17. **Comparison between simulated (lines) and measured (symbols) gains and steering angles for (a) single-slot metasurface antenna with varying slot position, and (b) double-slot metasurface antenna with varying feeding phase difference.**

applications, rather than developing a complete and practical antenna prototype. Therefore both the single-slot and double-slot metasurface antenna designs need to be further developed. Specifically, for the single-slot design, selective feeding of one of multiple slot radiators can be considered; while for the case of double-slot configuration, electronic phase shifters can be used to vary the phase difference between two slots in a single design, such that electrically controlled beam steering antennas can be realized.

III. EXPERIMENTAL VALIDATION

The proposed antenna designs are fabricated on FR-4 substrates with dielectric constant of 4.3. The thicknesses of the substrates are 1.6 mm and 0.8 mm for slot radiators and the metasurface, respectively. Figures 11 and 12 show the fabricated single-slot and double-slot metasurface antennas, respectively. In order to measure S-parameters and radiation patterns for varying slot positions, in total five slot radiators with different slot positions for $P = 0$ to $P = 40$ are fabricated. Acrylic screws are used to assemble the slot radiator and metasurface. The gap between the slot radiator and metasurface is fixed at 8.5 mm, i.e. the optimum value found in simulations. For the double-slot design, the slots are located at positions $P = 40$ and $P = -40$, and five designs of microstrip lines with Wilkinson power divider are fabricated covering the phase difference between two slots of 0, 45, 90, 135, and 180 degrees. In the measurement, a vector network analyzer Rohde & Schwarz NVB Z20 is used to measure S-parameters and the results are shown in Figs. 13 and 14. It is shown that the measured $|S_{11}|$ agrees well with simulations which validates our design. For the radiation pattern measurement, both antenna designs are placed in the center of an automatic turn table and measured in an anechoic chamber. The horn antenna used in the measurement is Rohde & Schwarz HF907 which covers 800 MHz – 18 GHz range with linear polarization and excellent voltage standing wave ratio (VSWR) performance. The gain of the horn antenna varies from 5 to 14 dBi across the operating frequency band. The distance between the center of the antennas under test and the front side of the horn antenna is 2.5 m which ensures that the radiation pattern measurement is performed in the far-field region of the antennas. The measured co-polar (with electric field oriented vertically) radiation patterns for both antenna designs are shown in Figs. 15 and 16, respectively. It can be seen that for both single-slot and double-slot designs, the measured radiation patterns agree well with simulation results. For the single-slot case, the measured gains are slightly lower due to the cable loss effect etc., and the sidelobe levels and their directions differ slightly from simulation results, which may be caused by imperfect alignment of slot radiator and metasurface. Such effects are also present for the case of double-slot design. Moreover, at high frequencies (∼2.5 GHz), the backlobes of antennas in measured radiation patterns are more severe than simulated ones, which may be caused by reflections from the turn table or mounting frame etc. Nonetheless, in order to reduce backward radiation, a ground plane acting as a back reflector can be used.

Finally, all data from simulations and measurement for both single-slot and double-slot metasurface antennas are gathered and their comparisons are shown in Fig. 17. It is demonstrated that for both antennas, the beam steering angle is linearly dependent on the slot position and feeding phase difference, respectively. Both antennas have a moderate to high gain performance considering their compact size.

IV. CONCLUSION

In conclusion, we have proposed two metasurface antenna designs for beam steering applications. The metasurface superstrate is formed by uniformly arranged identical square rings. The main mechanism of radiation is due to the excitation of square rings in sequence with different phase delays. The overall radiated beam can be steered to different directions depending on the initial excitation of square ring elements. Specifically, in order to achieve beam steering, either a single-slot radiator with mechanical movement can be used as the excitation source, or a double-slot design with fixed slot positions but varying feeding phase difference between two slots can be used. The proposed antennas are simulated and fabricated to validate the design. Measurement results show excellent agreement with simulations, and demonstrate that a beam steering angle range of −35 to 35 degrees can be achieved for the single-slot design, and −30 to 30 degrees can be realized for the double-slot configuration. Based on the structures proposed in this paper, to further realize practical beam-steering metasurface antennas, the selective excitation of multiple slots on the same ground and electronic phase shifters can be applied for the single-slot and double-slot designs, respectively.

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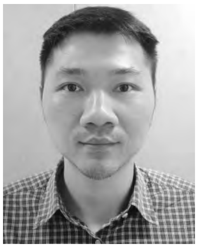

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