Controlling Radiation Beams by Low-Profile Planar Antenna Arrays with Coding Elements

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ABSTRACT: Beam diversity enables antenna arrays to play important roles in radar, communications, imaging, and next-generation wireless systems. However, achieving flexible control of beams in a low-cost way is still very challenging. Here, we propose low-profile planar antenna arrays with coding elements to control and engineer radiation patterns more freely and flexibly. The proposed planar antenna array consists of binary radiating elements which are characterized by digital codes “0” and “1”. By designing spatial coding patterns of the radiating elements, multifarious functionalities can be well realized, such as beam splitting, beam scanning, and beam deflection. More importantly, coding metasurfaces can be properly arranged around the digital radiating elements to reduce the radar cross section of the antenna, while the radiation performance is well preserved. The low-profile, high-gain, lightweight digital antenna arrays are verified numerically and experimentally in the microwave band. The proposed digital coding planar antenna arrays derive a new paradigm to control the radiation patterns in low-overhead and advanced digital design fashions and offer promising applications in multitasked and intelligent antenna devices and new information systems.

1. INTRODUCTION

Antenna arrays have continuously attracted extensive attention and been widely investigated in physics and engineering because of their high gain, wide coverage, and beam controllability. 1−10 In recent years, to increase the communication capacity and boost the multitasking capacity of the antennas for satisfying the growing number of wireless communication users, beam-forming networks, a kind of multi-input and multi-output feed networks, are widely studied and applied in array antennas, which lead to the boom of switched beam antennas, such as multibeam antennas 11,12 and beam-scanning antennas. 13,14 In general, the beam-forming networks can be classified into matrix type and lens type. 15−18 These two kinds of beam-forming networks have their own advantages, and both can be used to enable array antennas to generate various beam patterns. Despite the success of beam-forming networks in realizing beam switching, design difficulties and high cost restrain their further developments and applications toward miniaturization and integration. Hence, realizing free controls of beams of antenna arrays using compact feed networks and in a low-cost way still remains a big challenge.

More recently, the new concept, coding metamaterials or metasurfaces, was proposed and realized by manipulating electromagnetic (EM) waves in a digital way. 19−24 By changing the spatial or frequency coding pattern (or coding sequence), different scattering patterns can be easily achieved using the coding metamaterials. Because of its great convenience in tailoring EM waves, the digital coding method has been extended to acoustics 25 and terahertz bands 26−30 for realizing specific functional metadevices. Moreover, because the units in the coding metamaterials are characterized by finite discrete states (e.g., 1-bit coding has two digital states of “0” and “1”), the active elements such as diodes and varactors can be easily adopted to construct dynamic reconfigurable devices or further achieve different functions in real time by combining programmable devices. 31−35

On the basis of the merit of the digital design method, the simplest digital signal processing, convolution operation, was successfully performed on digital coding metasurfaces for the first time to steer the scattering pattern to an arbitrarily predesigned direction, which provides a new strategy to flexibly deflect the beams. 36 More interestingly, the digital coding metasurfaces have been recently evaluated using Shannon entropy from the information perspective, which will offer unprecedented opportunities for realizing many new concept information systems. 37 Despite their exceptional capability to control the EM beams, however, all the currently demonstrated digital coding metasurfaces, containing reflection and transmission types, need a horn antenna or other forms of antenna as their primary feed, which will bring some assembly problems that result in larger volume, higher system complexity, and higher cost.

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In this work, we propose the concept of a low-profile coding planar antenna array without any complex air-feed structures. Different from the previous work, the coding elements in the digital antenna arrays are identical, but the “coding” status is constructed and designed by the special planar feeding structures. Such an ingenious design enables the antenna arrays to not only have the advantage of low profile but also control the radiation beams with great flexibility. Here, the planar coding antenna arrays are preferentially implemented by a microstrip antenna array, which has low profile and is simple. The realized coding microstrip antenna array is composed of 16 microstrip radiating elements, and each radiating element is characterized by the binary coding “0” or “1”. Under different coding patterns, the digital microstrip antenna arrays are able to generate the sum beam, dual beam, and quad beam. Moreover, the convolution operations are realized for the first time on the digital microstrip antenna arrays for further achieving radiation pattern deflections because of the digitized design of the microstrip antenna arrays. Furthermore, to reduce the radar cross section (RCS) of the coding microstrip antenna array and avoid the adverse effects on antenna performance, coding metasurfaces with given coding patterns are designed and properly arranged around the digital antenna elements. The above concepts and physical phenomena are theoretically and numerically demonstrated and further experimentally verified by five fabricated different samples in the microwave region.

2. CODING ANTENNA DESIGN AND SIMULATION RESULTS

2.1. Design of a Digital Radiating Element. To realize the aforementioned digital coding microstrip antenna arrays, as illustrated in Figure 1a, we first design the low-profile microstrip antenna element with the operating frequency of 3.5 GHz, as shown in Figure 1b. In our design, the substrate of the microstrip antenna element is the low-loss dielectric material F4B, which has a dielectric constant of 2.65 and a loss tangent of 0.001. The thickness of the substrate is 1.0 mm, which is just about 0.0117λ (λ is the free-space wavelength at 3.5 GHz). On the top of the substrate, there are a rectangular radiation patch and a feeding microstrip line. To realize impedance matching and also reduce the overall size of the antenna element, a groove with a width of g and a depth of d is opened at the center of the bottom edge of the patch, and the microstrip line is directly inserted into the groove to feed the patch. The length L and the width W of the patch are precalculated by the design formulas of the microstrip antenna and further optimized by the software CST Microwave Studio. Finally, the four optimized values of L, W, g, and d are chosen as 26.2, 28.0, 6.8, and 8.0 mm, respectively.

The width w₁ of the feeding microstrip line is 2.8 mm, which is calculated by using the impedance calculation plug-in incorporated in the CST for matching the 50 Ω input impedance. The thickness of the patch, the microstrip line and the metallic sheet backing of the substrate is selected as 0.018 mm, and other geometry parameters of the antenna element.
are adopted as $a = 45.0 \text{ mm}$, $b = 55.0 \text{ mm}$, and $h = 30.0 \text{ mm}$. The simulated amplitude of the reflection coefficient $S_{11}$ of the microstrip antenna element is less than $-20 \text{ dB}$ at the center frequency of 3.5 GHz, as shown in Figure 1c. The designed antenna element has a strong resonance at 3.5 GHz, and its surface-induced current distribution is illustrated in the inset of Figure 1c. The maximum radiation direction of the antenna element is directed to the $z$-axis, and the simulated gain of the antenna element is 6.86 dB at 3.5 GHz, as shown in Figure 1d. It is noted that in the following designed coding antenna arrays, the coding elements are identical for each array, but the “coding” status is constructed and designed by the special planar feeding lines.

2.2. Coding Sequence in One Direction. The proposed first schematic of the low-profile digital coding microstrip antenna array that consists of such $4 \times 4$ radiating elements is illustrated in Figure 2a. The designed coding antenna array has four parallel main feeding lines, which are simultaneously excited with equal amplitude and phase by a four-way power divider fed by a $50 \Omega$ coaxial connector. Each main feeding line feeds four series antenna elements, and each antenna element is connected to the main feeding line by a quarter-wavelength impedance conversion line for realizing impedance matching. Under the series—parallel hybrid feed network, the four parallel antenna elements along the $y$ direction have the identical excitation current. However, the initial phases of the excitation

Figure 2. (a) First structure of the proposed low-profile digital coding microstrip antenna array. (b) Simulated surface-induced current distribution of the coding antenna array at 3.5 GHz with the sequence of “0000”. (c,d) 3D far-field radiation patterns of the coding antenna array at 3.5 GHz with the sequences of “0000” (c) and “x-0101” (d). (e) 2D far-field radiation patterns of the coding antenna array at 3.5 GHz with the sequences of “x-0011” and “x-0110”.
currents of the four antenna elements along the $x$ direction depend on their connection positions on the main feeding line because of the fact that the microwave signal is transmitted to the four series antenna elements in turn through the main feeding line. The width $w_2$ of the impedance conversion line is $1.55 \text{ mm}$ and the length is $\frac{\lambda_g}{4}$. The guide wavelength $\lambda_g$ of the microstrip line is

$$\lambda_g = \frac{\lambda_0}{\sqrt{\mu_r \varepsilon_r}}$$

(1)

where $\lambda_0$ is the wavelength in the free space and $\mu_r$ and $\varepsilon_r$ are the relative permeability and effective permittivity, respectively.

In our simulation, $\mu_r = 1$, and $\varepsilon_r$ is calculated by the impedance calculation plug-in. When $w_1 = 2.8 \text{ mm}$, $\varepsilon_r = 2.18$, and then $\lambda_g$ is $58.0 \text{ mm}$ at 3.5 GHz; when $w_2 = 1.55 \text{ mm}$, $\varepsilon_r = 2.10$, and then $\lambda_g$ is $58.8 \text{ mm}$ at 3.5 GHz. The constant phase difference $\Delta \phi_n$ between the two adjacent antenna elements along the $x$ direction is written as

$$\Delta \phi_n = \frac{360^\circ}{\lambda_g} \times d_{nn} \quad (n = 1, 2, 3)$$

(2)

Hence, according to eq 2, the normalized phase difference between the two adjacent antenna elements can be tuned.
For the 1-bit digital coding array, we need two opposite phase responses to mimic the digital “0” and “1” states. Because the phase difference of the two adjacent antenna elements in the microstrip antenna array can be tuned to 180°, these two antenna elements are able to act as the binary “0” and “1” elements, respectively. Hence, the proposed first scheme of the microstrip antenna array is capable of realizing the digital coding with different spatial coding sequences by flexibly controlling the distances \(d_{x1}, d_{x2}\), and \(d_{x3}\). Additionally, because the digital states of the four parallel antenna elements are always the same, we can simply use one “0” unit or “1” unit to describe these four antenna elements.

To verify that the designed digital coding microstrip antenna array has the good performance of generating different spatial coding sequences, we first set the distances as \(d_{x1} = d_{x2} = d_{x3} = 88.0 \text{ mm} = \lambda_{0}\), and the whole antenna array covers an area of 274 \( \times \) 320 mm\(^2\). According to eq 2, all the phase differences \(\Delta \phi_1, \Delta \phi_2, \) and \(\Delta \phi_3\) are 360°, which can be normalized to 0°. For this case, the simulated surface-induced current distribution of the coding antenna array at 3.5 GHz is shown in Figure 2b. We observe that the current directions of all the radiating elements are the same, that is to say, the 16 radiating elements indeed have the identical initial excitation phase. Hence, the 16 antenna elements can be described by the binary elements that have the same digital state. For example, we encode the digital antenna element as the “0” element. In this case, the coding sequence of the digital coding microstrip antenna array is “0000”. The simulated three-dimensional (3D) far-field radiation pattern of the digital coding microstrip antenna array with the sequence “0000” at 3.5 GHz is shown in Figure 2c. We observe that the coding microstrip antenna array generates a sum beam directed to the z-axis, and the gain is 18.8 dB.

In order to realize the coding sequence of “x-0101” ("x-" denotes the sequences varying along the x direction), theoretically, we shall adjust \(d_{x1}, d_{x2}\), and \(d_{x3}\) to \(\lambda_{0}/2\) for achieving a 180° phase difference. However, when the element spacing is \(\lambda_{0}/2\), the distance between the two adjacent antenna elements is too small, which will cause strong coupling and affect the radiating element performance. We set \(d_{x1}, d_{x2}\), and \(d_{x3}\) as 87.0 mm, which is equal to \(3\lambda_{0}/2\), and the coding microstrip antenna array totally covers an area of 361 \( \times \) 320 mm\(^2\). Hence, all the phase differences \(\Delta \phi_1, \Delta \phi_2, \) and \(\Delta \phi_3\) can be normalized to 180°. In such a case, the sum beam has split into two main beams symmetrically distributed in the xoz-plane, and the gain is 17.7 dB at 3.5 GHz, as shown in Figure 2d. The main beam direction angle can be predicted by \(30°\)

\[
\theta = \arcsin \left( \frac{1}{\sqrt{\frac{1}{\Gamma_{x}} + \frac{1}{\Gamma_{y}}}} \right)
\]  

(3)

\[
\phi = \pm \arctan \left( \frac{\Gamma_{x}}{\Gamma_{y}} \right) \text{ or } \phi = \pi \pm \arctan \left( \frac{\Gamma_{x}}{\Gamma_{y}} \right)
\]  

(4)

in which \(\Gamma_{x}\) and \(\Gamma_{y}\) represent the physical periodic lengths of the coding sequence along the x and y directions, respectively. For the coding sequence “x-0101”, by substituting \(\lambda_{0} = 85.7\) mm (at 3.5 GHz), \(\Gamma_{x} = 174.0\) mm, \(\Gamma_{y} \rightarrow \infty\) into eqs 3 and 4, we obtain an elevation angle \(\theta = 29°\) and two azimuth angles \(\phi = 0°\) and \(\phi = 180°\), respectively, which are in good agreement with the simulation results.

Additionally, we also give two other coding sequences of “x-0011” and “x-0110” that can both generate two symmetrical beams emitting with different direction angles, respectively, as shown in Figure 2e. Under the coding sequence “x-0110”, the elevation angle \(\theta\) of the main beam is 13°; under the coding sequence “x-0011”, the elevation angle \(\theta\) of the main beam is 20°. To realize the coding sequence “x-0011”, we chose \(d_{x1} = d_{x2} = 58.0\) mm and \(d_{x3} = 87.0\) mm, and we set \(d_{x1} = d_{x3} = 68.0\) mm and \(d_{x3} = 58.0\) mm for achieving the coding sequence “x-0110”.

2.3. Coding Sequences in Both Directions. The proposed digital coding microstrip antenna array can generate one-direction different spatial coding sequences to realize beam splitting and scanning in the x direction. To further realize the digital coding microstrip antenna array that can also generate coding sequences varying along the y direction, we present and design the second schematic of the microstrip antenna array, as shown in Figure 3a. The coding microstrip antenna array has two parallel main feeding lines, and each main feeding line excites four series antenna pairs along the x direction. Each antenna pair contains two parallel microstrip radiating elements, which are located symmetrically beside the line. The initial phases of the excitation currents of the two radiating elements have a 180° phase difference because of the mirror relation and the identical excitation mode. Hence, the two antenna elements in one antenna pair can be encoded as the binary elements, mimicking digital “0” and “1”, respectively. The coding microstrip antenna array is fed by a two-way power divider, which is finally connected to a 50 Ω coaxial connector.

When \(d_{x1} = d_{x2} = d_{x3} = 58.0\) mm, the whole antenna array has a dimension of 254 \( \times \) 370 mm\(^2\), and the simulated surface-induced current distribution of the coding microstrip antenna array at 3.5 GHz is shown in Figure 3b. It is clear that the current directions of the two radiating elements in each antenna pair are opposite, and the four series antenna elements have the same current direction, which can be encoded as “0” unit or “1” unit. Hence, the coding microstrip antenna array has the coding sequence of “y-0101”, where “y-” denotes varying sequences along the y direction. For this case, the coding microstrip antenna array generates two symmetrical main beams with the deviation angle of 24° in the yoz-plane, and the gain is 17.7 dB at 3.5 GHz, as shown in Figure 3c. For the coding sequence “y-0101”, \(\Gamma_{x} \rightarrow \infty\) and \(\Gamma_{y} = 205.4\) mm, the elevation angle \(\theta\) and two azimuth angles \(\phi\) can be theoretically calculated by eqs 3 and 4 as 24.6°, 90°, and 270°, respectively, which have excellent agreements with the simulations.

To further realize the complex coding patterns in a two-dimensional (2D) plane, we can change one of the three distances \(d_{x1}, d_{x2}\), and \(d_{x3}\) to obtain a 180° phase difference between the two series antenna elements. For example, we set \(d_{x1}, d_{x2}\), and \(d_{x3}\) as 87.0 mm. In such a case, the digital microstrip antenna array will have the coding pattern of “x-0101/y-0101” (chessboard coding pattern). The simulated 3D far-field radiation pattern of the coding microstrip antenna array with a dimension of 341 \( \times \) 355 mm\(^2\) at 3.5 GHz is shown in Figure 3d. We observe that there are four radiation beams in the upper-half space, which are directed to the angles at (38°, 42°), (38°, 138°), (38°, 222°), and (38°, 318°), respectively. By substituting \(\Gamma_{x} = 174.0\) mm and \(\Gamma_{y} = 205.4\) mm into eqs 3
and 4, we obtain $\theta = 40^\circ$ and $\phi = 40.2^\circ$, $139.8^\circ$, $220.2^\circ$, and $319.8^\circ$, respectively, which agree well with the simulated results. The simulated gain of the coding microstrip antenna array is 15.9 dB. We remark that for the two coding patterns of “y-0101” and “x-0101/y-0101”, the length $L$ of the microstrip antenna element has been optimized as 26.5 mm for ensuring that the center frequency of the coding microstrip antenna array is 3.5 GHz. It is noted that all the $S_{11}$ amplitudes of the above-mentioned six different coding microstrip antenna arrays are below $-18$ dB at 3.5 GHz, as shown in Figure 3e.

2.4. Convolution Operation on a Coding Antenna Array. So far, we have realized different spatial coding patterns based on the digital low-profile microstrip antenna arrays to achieve the desired single-beam radiation, beam splitting (such as dual beams and quad beams), and dual-beam scanning in the xoz-plane. Owing to the digital characteristics of the radiating elements in the microstrip antenna array, we further realize the convolution operation on the digital coding microstrip antenna array, which provides a great freedom for steering the radiation pattern to a predesigned direction. The concept of convolution operation is to mix a gradient coding sequence on the original coding pattern, which is an analogy to the single-carrier modulation in signal processing, and the final mixed coding pattern formed by calculating the modulus of these two coding matrices. According to eq 2, the phase difference of the two adjacent antenna elements along the $x$ direction can be tuned to an arbitrary value between $0^\circ$ and $360^\circ$ by changing the element spacing. Hence, we can achieve a specific gradient phase distribution varying along the $x$ direction by tuning the distances $d_{x1}$, $d_{x2}$, and $d_{x3}$ to the same value. As a proof of concept, we take a 2-bit coding sequence of “x-00011011” as the gradient coding sequence. The four digital codes “00”, “01”, “10”, and “11” in a 2-bit coding sequence “x-00011011” represent four different phase states of $(0^\circ + \phi_0)$, $(90^\circ + \phi_0)$, $(180^\circ + \phi_0)$, and $(270^\circ + \phi_0)$, respectively, and $\phi_0$ refers to the initial phase of the antenna element. In our design, the distance between the two adjacent antenna elements is set as $5\lambda/4$ for achieving a $90^\circ$ phase difference. To clearly illustrate the convolution operations, we use number “0” to “3” to denote the digits “00” to “11”, respectively.

To schematically illustrate our design, we present three mixed coding patterns and their corresponding 3D far-field radiation patterns at 3.5 GHz, as shown in Figure 4. The three mixed coding patterns are achieved by the moduli of gradient coding sequence “x-0123” and three original coding patterns, respectively. The pattern of the gradient coding sequence “x-0123” is illustrated in Figure 4a, in which the blocks with four different colors represent the “0”, “1”, “2”, and “3” radiating element, respectively. When the gradient coding pattern is added to the coding pattern “x-0020” in Figure 4bi, we get their modulus $M_2$, as shown in Figure 4bii. The corresponding 3D radiation pattern is shown in Figure 4e, from which we observe that the two beams distributed in the xoz-plane are both deviated from the $z$-axis by an angle of $17^\circ$. To realize the mixed coding pattern $M_1$ at 3.5 GHz using the digital microstrip antenna array, the distances $d_{s1}$, $d_{s2}$, and $d_{s3}$ are set as 101.5 mm, and the length $L$ of the antenna element is reoptimized as 25.9 mm.

The next example is achieved by adding the gradient coding sequence along the orthogonal direction. Figure 4ci,ii shows

Figure 4. Illustration of steering radiation patterns by convolution operations on the digital coding microstrip antenna arrays. (a) Gradient coding sequence “x-0123” varying along the $x$ direction. (b–d) Three mixed coding patterns $M_1$, $M_2$, and $M_3$ realized by the moduli of the gradient coding sequence “x-0123” and three original coding patterns, respectively. (e–g) Simulated 3D far-field radiation patterns of the digital coding microstrip antenna arrays at 3.5 GHz with the mixed coding patterns $M_1$, $M_2$, and $M_3$, respectively. (h) Corresponding $S_{11}$ amplitudes of the digital microstrip antenna arrays with the three different mixed coding patterns. (i) Three original coding patterns. (ii) Three mixed coding patterns.
the coding pattern “y-0202” and its mixed coding pattern $M_2$, respectively. For such a mixed coding pattern, the two beams of the coding microstrip antenna array are also tilted away from the normal axis by $17^\circ$, and then the two beams are redirected to the angles of $(44^\circ, 63^\circ)$ and $(44^\circ, 297^\circ)$, respectively, as shown in Figure 4f. In such a case, the distances $d_{x1}$, $d_{y2}$, and $d_{z3}$ are chosen as 72.5 mm, and the length $h$ is optically set as 10 mm for suppressing the grating lobe.

Figure 4dii illustrates the mixed coding pattern $M_3$ formed by the modulus of the coding sequence “x-0123” and the chessboard coding “x-0202/y-0202” in Figure 4di for shifting multiple beams. In this case, all the four beams of the coding microstrip antenna array are deflected, and the deflection angle is $16^\circ$, as shown in Figure 4g. The distances $d_{x1}$, $d_{y2}$, and $d_{z3}$ are given as 101.5 mm to realize this mixed coding pattern.

For the designed 2-bit gradient coding sequence “x-0123”, the deviation angles from the $z$-axis of the three different demonstrated mixed coding patterns $M_1$, $M_2$, and $M_3$ are the same and can be predicted by

$$\theta_d = \arcsin \left( \frac{\lambda}{2d_{z3}} \right)$$

(5)
In this case, the periodic length $\Gamma_x = 290.0$ mm, which is $5\lambda_0$. Hence, substituting $\lambda_0 = 85.7$ mm and $\Gamma_x = 290.0$ mm into eq 5, the deviation angle $\theta_d$ is calculated as $17.2^\circ$, which is in excellent agreement with the simulation result. It should be noted that according to our simplification, the coding patterns “x-0202”, “y-0202”, and “x-0202/y-0202” in Figure 4 represent the aforementioned coding sequences of “x-0101”, “y-0101”, and “x-0101/y-0101”, respectively. The dimensions of the three antenna arrays are 404.5 $\times$ 320 mm$^2$, 297.5 $\times$ 250 mm$^2$, and 384.5 $\times$ 355 mm$^2$, and the simulated gains are 18.2, 14.5, and 17.1 dB, respectively. All the simulated amplitudes of $S_{11}$ of the digital microstrip antenna arrays with three different mixed coding patterns are below $-17$ dB at the operating frequency of 3.5 GHz, as plotted in Figure 4h.

2.5. Simultaneous Control of the Radiating and Scattering Beam. Next, we also study the scattering characteristics of the proposed digital coding microstrip antenna arrays. In a high-frequency region, such as X-, K-, and Ka-bands, the backscattering of the coding microstrip antenna array will be very strong as the EM waves are projected onto the antenna array because of a larger ratio of antenna aperture to wavelength. The significant scattering is detrimental for the realization of the antenna stealth, especially in military applications.\textsuperscript{39,40} To reduce the scattering from the coding microstrip antenna array and meanwhile maintain its good radiation performance, we reasonably arrange the designed 1-bit digital coding metasurfaces around the radiating elements of the antenna array.

To construct the 1-bit digital coding metasurface, we first design a metasurface particle with subwavelength size. On both sides of the 1 mm thickness F4B substrate, there are a square metallic patch with a tunable width $e$ and a ground,
respectively, as shown in the inset of Figure 5a. The side length of the digital particle is 6.5 mm. Figure 5a shows the simulated reflection phases of the two particles with $\epsilon = 6.0$ mm and $\epsilon = 6.3$ mm, respectively. It is obvious that the phase difference is approximately 180° from 8.8 to 10.0 GHz. Hence, we use the particle with $\epsilon = 6.0$ mm to mimic “0” element and that with $\epsilon = 6.3$ mm to mimic “1” element.

We take the digital microstrip antenna array with the coding pattern “x-0101/y-0101” as a proof of principle to demonstrate our design for further realizing the low-scattering coding microstrip antenna array. The structure of the proposed low-scattering coding microstrip antenna array is shown in Figure 5b. Compared with the primary coding microstrip antenna array in Figure 3d, the low-scattering coding microstrip antenna array is loaded with many coding metasurface particles. To avoid the EM energy leaking from the radiating element to the coding metasurface and also minimize the RCS of the antenna array, some coding metasurfaces with chessboard-like coding patterns are properly arranged around the radiating elements, as shown in the inset of Figure 5b. Note that the configurations of the radiating elements and the feed network of the low-scattering antenna array are the same as those of the primary coding antenna array in Figure 3d.

The 3D scattering pattern of the low-scattering coding microstrip antenna array at 9.0 GHz is shown in Figure 5c, from which we observe that the normally $x$-polarized incident waves have been reflected to many directions. By contrast, the primary coding microstrip antenna array has only one main scattering beam with the half power (3 dB) beam width of 4.7°, which is directed to the $z$-axis under the normally $x$-polarized incident waves, as shown in Figure 5d. We also present two 3D scattering patterns of the low-scattering coding microstrip antenna array and the primary coding microstrip antenna array in the case of the $y$-polarized EM waves vertical incidence, as shown in Figure 5e,f, respectively. It is obvious that the monostatic RCS reductions are larger than 10.0 dB and that the bistatic RCSs are also effectively suppressed for both $x$- and $y$-polarized incident waves at 9.0 GHz.

Moreover, the radiation characteristic of the low-scattering digital microstrip antenna array with the coding pattern “x-0101/y-0101” is well preserved, as shown in Figure 5g. It is clear that the low-scattering coding antenna array also exhibits an interesting four-beam splitting phenomenon, and the four beams are directed to the angles at $(38°, 42°)$, $(38°, 138°)$, $(38°, 222°)$, and $(38°, 318°)$, respectively. The simulated gain is 15.9 dB at 3.5 GHz. The return loss of the low-scattering coding microstrip antenna array is less than $-30$ dB at 3.5 GHz, as shown in Figure 5h.

3. EXPERIMENTAL RESULTS

To experimentally verify the proposed concepts and design strategies, five samples of the digital microstrip antenna arrays with different coding configurations were fabricated and measured in the microwave chamber, as shown in Figure 6a. Because the computer-assisted testing turntable can only be rotated continuously by 360° in the horizontal plane (yoz-plane), only radiation beams distributed in the yoz-plane are measured. Hence, for testing the beams of the coding microstrip antenna arrays that do not appear in the yoz-plane, we rotate the samples $S_1$ and $S_5$ counter-clockwise by 48° and the sample $S_4$ clockwise by 27° based on the simulated 3D radiation patterns, as illustrated in the photographs of Figure 6a. We adopt a horn antenna with a gain of 15 dB working from 3.2 to 4.9 GHz as the standard gain horn for measuring the gains of the coding microstrip antenna arrays.

The measured 2D far-field radiation patterns of the samples $S_1$, $S_2$, and $S_3$ at 3.5 GHz with coding patterns “0000”, “y-0101”, and “x-0101/y-0101” are shown in Figure 6b–d, respectively. It is obvious that the coding microstrip antenna array $S_3$ has a main beam at $\theta = 0°$. The measured gain is 18.6 dB. The coding microstrip antenna array $S_4$ indeed generates two symmetrical beams at the elevation angles of $\pm 24°$, and the measured gain is 17.5 dB. We observe that there are also two main beams (around $\pm 38°$) of the coding microstrip antenna array $S_5$ and that the measured gain is 15.7 dB. Figure 6e shows the measured 2D far-field radiation pattern of the sample $S_4$ at 3.5 GHz with the mixed coding pattern $M_4$, from which we clearly observe one radiation beam with a gain of 14.3 dB appearing at the angle of 45°. The 2D far-field radiation pattern of the low-scattering coding microstrip antenna array $S_3$ is illustrated in Figure 6f. We also observe that there are two beams at angles $\pm 38°$ and the measured gain is 15.7 dB, which are the same as the ones in Figure 6d. Meanwhile, the low-scattering coding microstrip antenna array is able to reduce monostatic RCS more than 7 dB from 8.5 to 11.0 GHz (about 25.6% relative bandwidth) for both $x$ and $y$ polarizations, as shown in Figure 6h. All the measured radiation patterns and gains are in good agreement with the simulation results. The measured reflection coefficients of the five different fabricated digital coding microstrip antenna arrays are plotted in Figure 6g. It is clear that the return losses of the five samples are all below $-20$ dB at the working frequency of 3.5 GHz.

4. CONCLUSIONS

To summarize, we have proposed and confirmed the concept of low-profile digital coding microstrip antenna arrays to realize free controls of radiation beams. Digital information technologies of coding and digital convolution were effectively implemented in the designed microstrip antenna array consisting of 16 digital radiating elements for achieving beam splitting and scanning and radiation pattern deflection, respectively. Moreover, a class of low-scattering digital coding microstrip antenna arrays was also proposed and realized using coding metasurfaces. This kind of coding antenna array not only possesses excellent radiation performance but also has lower RCS, which shows enormous potential in military applications. As the proof of concept, five different digital coding microstrip antenna arrays were fabricated and measured. The measured results agree very well with the simulation ones. One of the most significant advantages of the proposed coding antenna arrays is using planar feeding structures to construct the coding elements, which enable the coding antenna arrays to have the merits of low profile, easy conformal, high spatial utilization, lightweight, and low cost. Benefitted from the digitized design method, an efficient and considerably less expensive approach for achieving the diversity of radiation beams, the proposed low-profile digital coding microstrip antenna arrays offer an alternative approach to produce switched beam antennas and huge potential to profoundly advance the relevant fields.

It is noted that the proposed methods are not limited to construct the passive coding microstrip antenna arrays. The approach can be further extended to realize the dynamically reconfigurable or even programmable low-profile digital coding microstrip antenna arrays by adopting PIN diodes and relevant
programmable devices for generating various radiation patterns in real time.

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**REFERENCES**

(1) Chang, L.; Li, Y.; Zhang, Z.; Feng, Z. Reconfigurable 2-Bit Fixed-Frequency Beam Steering Array Based on Microstrip Line. *IEEE Trans. Antennas Propag.* 2018, 66, 683–691.
(2) Ratni, B.; Yu, J.; Ding, X.; de Lustrac, A.; Zhang, K.; Piau, G.-P.; Burokur, S. N. Gradient Phase Partially Reflecting Surfaces for Beam Steering in Microwave Antennas. *Opt. Express* 2018, 26, 6724–6738.
(3) Gonzalez-Ovejero, D.; Minatti, G.; Chattopadhyay, G.; Maci, S. Multibeam by Metasurfaces Antennas. *IEEE Trans. Antennas Propag.* 2017, 65, 2923–2930.
(4) Wu, R. Y.; Li, Y. B.; Wu, W.; Shi, C. B.; Cui, T. J. High-Gain Dual-Band Transmitarray. *IEEE Trans. Antennas Propag.* 2017, 65, 3481–3488.
(5) Smith, D. R.; Yurduseven, O.; Manera, L. P.; Bowen, P.; Kundz, N. B. Analysis of a Waveguide-Fed Metasurface Antenna. *Phys. Rev. Appl.* 2017, 8, 054048.
(6) Mei, P.; Lin, X. Q.; Yu, J. W.; Zhang, P. C.; Boukarkar, A. A. Low Radar Cross Section and Low Profile Antenna Co-Designed with Absorbed Frequency Selective Radome. *IEEE Trans. Antennas Propag.* 2018, 66, 409–413.
(7) Wan, X.; Zhang, L.; Jia, S. L.; Yin, J. Y.; Cui, T. J. Horn Antenna with Reconfigurable Beam-Refraction and Polarization Based on Anisotropic Huygens Metasurface. *IEEE Trans. Antennas Propag.* 2017, 65, 4427–4434.
(8) Hu, J.; Hao, Z.-C.; Wang, Y. A Wideband Array Antenna with 1-Bit Digital-Controlled Radiation Beams. *IEEE Access* 2018, 6, 10858–10866.
(9) Pham, K.; Nguyen, N. T.; Clemente, A.; Di Palma, L.; Le Coq, L.; Dussopt, L.; Sauleau, R. Design of Wideband Dual Linearly Polarized Transmitarray Antennas. *IEEE Trans. Antennas Propag.* 2016, 64, 2022–2026.
(10) Nicholls, J. G.; Hum, S. V. Full-Space Electronic Beam-Steering Transmitarray with Integrated Leaky-Wave Feed. *IEEE Trans. Antennas Propag.* 2016, 64, 3410–3422.
(11) Li, Y.; Luk, K.-M. A Multibeam End-Fire Magnetoelectric Dipole Array for Millimeter-Wave Applications. *IEEE Trans. Antennas Propag.* 2016, 64, 2894–2904.
(12) Cheng, Y. J.; Hong, W.; Wu, K.; Kuai, Z. Q.; Yu, C.; Chen, J. X.; Zhou, J. Y.; Tang, H. J. Substrate Integrated Waveguide (SIW) Rotman Lens and Its Ka-Band Multibeam Antenna Array Applications. *IEEE Trans. Antennas Propag.* 2008, 56, 2504–2513.
(33) Yang, H.; Yang, F.; Xu, S.; Mao, Y.; Li, M.; Cao, X.; Gao, J. A 1-Bit 10 × 10 Reconfigurable Reflectarray Antenna: Design, Optimization, and Experiment. *IEEE Trans. Antennas Propag.* 2016, 64, 2246−2254.

(34) Li, L.; Cui, T. J.; Ji, W.; Liu, S.; Ding, J.; Wan, X.; Li, Y. B.; Jiang, M.; Qiu, C.-W.; Zhang, S. Electromagnetic Reprogrammable Coding-Metasurface Holograms. *Nat. Commun.* 2017, 8, 197.

(35) Rouhi, K.; Rajabalipanah, H.; Abdolali, A. Real-Time and Broadband Terahertz Wave Scattering Manipulation via Polarization-Insensitive Conformal Graphene-Based Coding Metasurfaces. *Ann. Phys.* 2018, 530, 1700310.

(36) Liu, S.; Cui, T. J.; Zhang, L.; Xu, Q.; Wang, Q.; Wan, X.; Gu, J. Q.; Tang, W. X.; Qi, M. Q.; Han, J. G.; Zhang, W. L.; Zhou, X. Y.; Cheng, Q. Convolution Operations on Coding Metasurface to Reach Flexible and Continuous Controls of Terahertz Beams. *Adv. Sci.* 2016, 3, 1600156.

(37) Cui, T.-J.; Liu, S.; Li, L.-L. Information Entropy of Coding Metasurface. *Light: Sci. Appl.* 2016, 5, No. e16172.

(38) Kara, M. Formulas for the Computation of the Physical Properties of Rectangular Microstrip Antenna Elements with Various Substrate Thicknesses. *Microw. Opt. Technol. Lett.* 1996, 12, 234−239.

(39) Zhang, C.; Gao, J.; Cao, X.; Xu, L.; Han, J. Low Scattering Microstrip Antenna Array Using Coding Artificial Magnetic Conductor Ground. *IEEE Antenn. Wireless Propag. Lett.* 2018, 17, 869−872.

(40) Su, J.; Kong, C.; Li, Z.; Yin, H.; Yang, Y. Wideband Diffuse Scattering and RCS Reduction of Microstrip Antenna Array Based on Coding Metasurface. *Electron. Lett.* 2017, 53, 1088−1090.