Air Substrate 2-D Planar Cavity Antenna With Chessboard Structure

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***Abstract*—In this letter, an air substrate two-dimensional chessboard cavity antenna with scalable radiating aperture is proposed for high-gain applications. The proposed cavity antenna is composed of $M \times N$ open cavity units, arranged properly in a planar chessboard topology structure. Benefiting from the structure scalability, a much larger radiating aperture with high gain can be achieved using an appropriate excitation approach. Another merit from the chessboard structure is the air-filled medium without suffering from the high dielectric loss for high-frequency usage. Each unit of the cavity antenna can be supported stably by the shorting sidewalls of itself and adjacent units, not by substrate as usual. To validate the design strategy, a 4 × 5 air-filled chessboard cavity antenna is built and tested. The peak gain of 17.28 dBi is measured in the operation band of 8.35–8.74 GHz (4.56%), exhibiting the potentials in the directional wireless communication applications.**

***Index Terms*—Air substrate, antenna aperture, antenna gain, cavity resonators, chessboard structure, Fabry–Perot (FP) resonant.**

I. Introduction

IN TELECOMMUNICATION and radar sensor systems, high-gain antennas are essential to compensate the high path losses. Cavity antennas, such as single-cavity antennas, Fabry–Perot (FP) cavity antennas, and microstrip arrays, are widely used. Open-ended waveguide antennas are the simple forms of single-cavity antennas [1]–[3]. FP cavity antenna, which consists of a ground plane and a partially reflective surface separated by a certain distance, was first proposed by Trentini in 1956 [4]. FP cavity antennas have the merit of easy excitation: The basic radiating element such as patch, slot, or open waveguide can be used as the feeding source [5]–[8]. Artificial magnetic conductor is applied as either of the two metallic reflectors to lower the profile from the traditionally half-wavelength to quarter-wavelength [9]. Dielectric substrate is filled within the cavity to further decrease the height to one-ninth wavelength [5]. Microstrip antenna arrays have been widely used due to the merits of low profile, light weight, and easy fabrication. The hybrid-fed microstrip arrays are most widely adopted to achieve high gain, and they are easier to form large-scale two-dimensional (2-D) arrays [10]. However, the feed networks are complex.

Another hindrance for high gain is the dielectric substrate that is used to support the antenna but introduces extra dielectric loss, especially in relative high-frequency bands. Air-filled substrate antennas are an effective solution to overcome the drawback. They have many advantages compared to the conventional antennas supported by substrates, such as low cost, wide bandwidth, high gain, fast heat-dispelling performance, and high-power capacity [8], [11]–[13]. One of the important functions of the substrates is to support the main body of antennas.

An air substrate 2-D planar chessboard cavity antenna with scalable radiating aperture operating in X-band for high-gain applications is proposed. The proposed cavity antenna is composed of $M \times N$ open cavity units, arranged properly in a planar chessboard topology structure. Attributing to the novel chessboard structure, using proper feed network, the radiating aperture has the merit of being scalable to achieve high gain. The shorting sidewalls of the chessboard act as the structural support, leading to a stably air-filled structure without any dielectrics. A 4×5 air-filled 2-D planar chessboard cavity antenna is designed and fabricated to make a proof. The fabricated prototype with a measured bandwidth of 4.56% (8.35–8.74 GHz) and a broadside gain up to 17.28 dBi demonstrates the feasibility for directional wireless communications.

II. Two-Dimensional Scalable Chessboard Cavity Antenna

Based on the analysis of the 1-D cavity antennas [14], [15], the 2-D chessboard cavity antennas with the scalability feature constructed using M columns of the N-unit 1-D cavity antenna are shown in Fig. 1, which illustrates two chessboard scales. The dimension of the cavity unit is the same, and the ground plane sizes are optimized individually. An H-shaped slot excited by a lump port located in the center is used to feed each antenna. The software ANSYS High Frequency Structure Simulator version 14 is used for design and optimization.

The design guideline is given as follows.

1) Based on the target frequency, select proper height, initial length (l_1), and width (w_1) of the cavity unit according to

Manuscript received February 23, 2016; accepted May 28, 2016. Date of publication June 1, 2016; date of current version March 6, 2017. This work was supported by the National Basic Research Program of China under Contract 2013CB329002, the National Natural Science Foundation of China under Contract 61371012, and the China Postdoctoral Science Foundation funded Project 2015T80084.

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Digital Object Identifier 10.1109/LAWP.2016.2574815

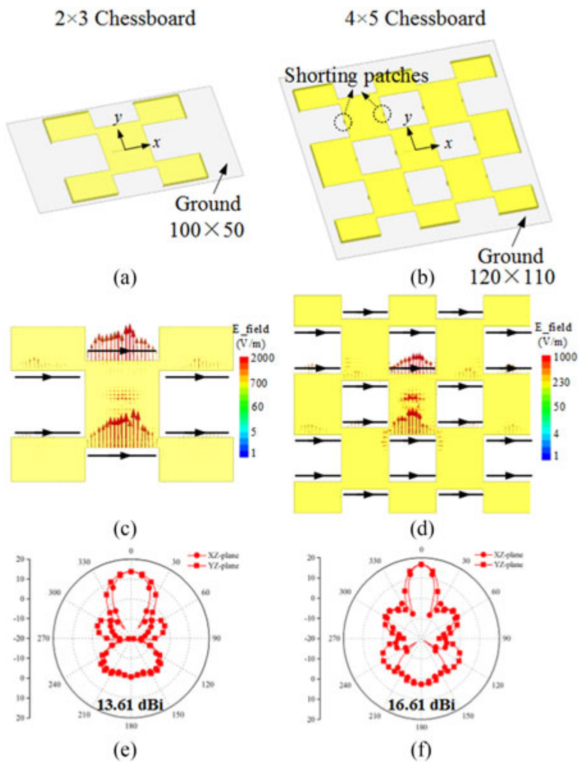

Fig. 1. Two scales of 2-D planar chessboard cavity antennas using single feed (unit: mm), vector electric field distributions, and their equivalent magnetic current arrays and radiation directivity patterns. The (a)–(c) 2 × 3 and (d)–(f) 4 × 5 2-D planar chessboard cavity antennas cases. (The yellow color refers to the chessboard, and the light gray color refers to the ground plane.)

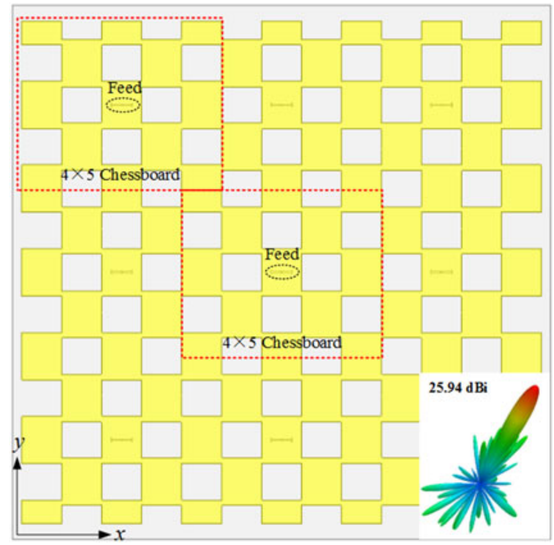

Fig. 2. 12 × 7 chessboard cavity antenna consists of nine 4 × 5 chessboards. The resultant 3-D beam is given in the inset when it is fed using nine feeds. (The yellow color refers to the chessboard, and the light gray color refers to the ground plane.)

the cavity theory

$$k_x{}^2 + k_y{}^2 + k_z{}^2 = k_0{}^2$$

$$k_x = \frac{\pi}{l_1} \quad k_y = \frac{0.5 \times \pi}{w_1} \quad k_z = 0 \quad k_0 = \frac{2 \times \pi \times f_0}{c}.$$

2) Based on the desired gain, select proper chessboard size denoted by M and N; that is, M columns of the M-unit 1-D cavity antenna.
3) Select proper overlapped width to constitute the N-unit 1-D cavity antenna. Optimize the cavity unit width and length to make sure that the N-unit 1-D cavity antenna operates at the target frequency. A detailed analysis including the higher mode analysis of the 1-D cavity antenna is found in [14].
4) Use the M columns of the N-unit 1-D cavity antenna to construct the 2-D chessboard cavity antenna. According to the chessboard scale, proper excitation approach should be adopted to make sure each cavity unit operates in the TM_{1n0} $(n = 0.5)$ mode.

First, two small scales of the chessboard cavity antenna using the single feed are analyzed. The 2 × 3 2-D chessboard cavity antenna that is composed of two columns of the three-unit 1-D cavity antenna is shown in Fig. 1(a). The three-unit 1-D cavity antenna connects with its mirrored counterpart with the overlapped shorting sidewalls removed. The vector electric field distribution at 8.5 GHz is shown in Fig. 1(b), and the fringing fields are with the same phase, so the 2 × 3 2-D chessboard cavity antenna is equivalent to a 2 × 3 magnetic current array, which is denoted by black arrow lines. Fig. 1(c) shows that a broadside directivity of 13.61 dBi is achieved. The 4 × 5 2-D planar chessboard cavity antennas is shown in Fig. 1(d): Different from the two-column cases, in the four-column cases, these two 1-D cavity antennas that are arranged at the two ends are excited by coupling, so the energies coupled to them are relatively small. To maintain the pure N-order mode of the N-unit 1-D cavity antenna, several shorting patches are added in the yz-plane with their centers aligned with the overlapped planes as shown in Fig. 1(d). The vector electric field distribution and the equivalent magnetic current array, are shown in Fig. 1(e) and (f), respectively. A pencil beam with a broadside directivity of 16.61 dBi is obtained. It is worth mentioning that the maximum chessboard size is 4 × 5 using the single-slot feed approach here. Further enlarging the chessboard size will cause the field distribution to be desultory.

Then, a large-scale chessboard cavity antenna can be achieved using the 4 × 5 chessboard as the basis. Here, multiple feeds are required to guarantee each cavity unit operating in the TM_{1n0} $(n = 0.5)$ mode and to obtain relatively uniform aperture. The large-scale 12 × 7 chessboard cavity antenna is shown in Fig. 2: Nine 4 × 5 chessboards are arranged in the 3 × 3 array style with the neighboring chessboards along the x-direction intersected with each other. Nine in-phase lump ports are used to feed the 12 × 7 chessboard, and the resultant 3-D beam is given in the inset: A narrow beam with the directivity of 25.94 dBi is obtained. In practical realization, any nine-way power divider with the identical output magnitude and phase can be used as the feed network.

Therefore, benefitting from the structure scalability, a much larger radiating aperture with high gain can be achieved if appropriate feed network is adopted.

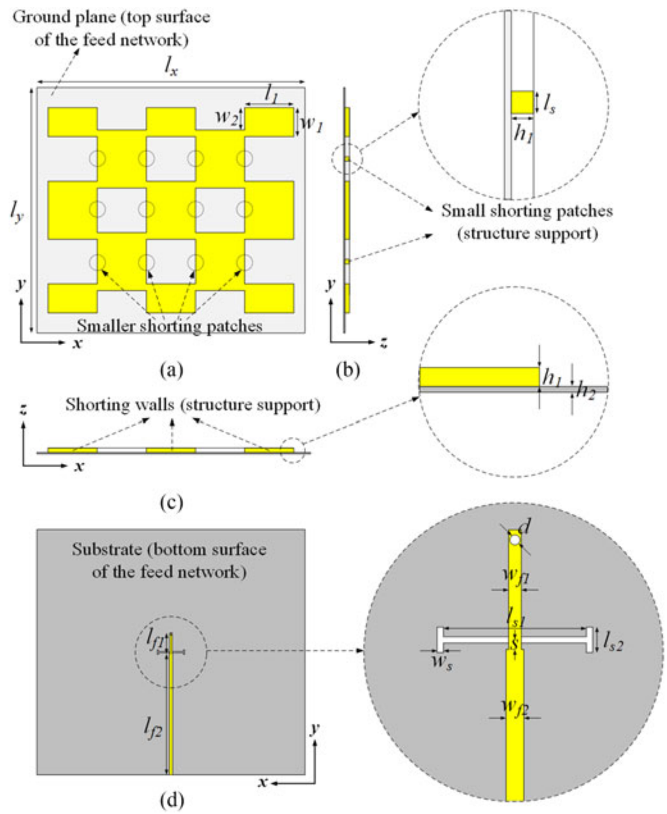

Fig. 3. Geometry of the proposed 4 × 5 2-D chessboard cavity antenna. (a) Top view, (b) and (c) side view, and (d) bottom view. (The yellow color refers to the chessboard and microstrip line, the light gray color refers to the ground plane, and the dark gray refers to the substrate.)

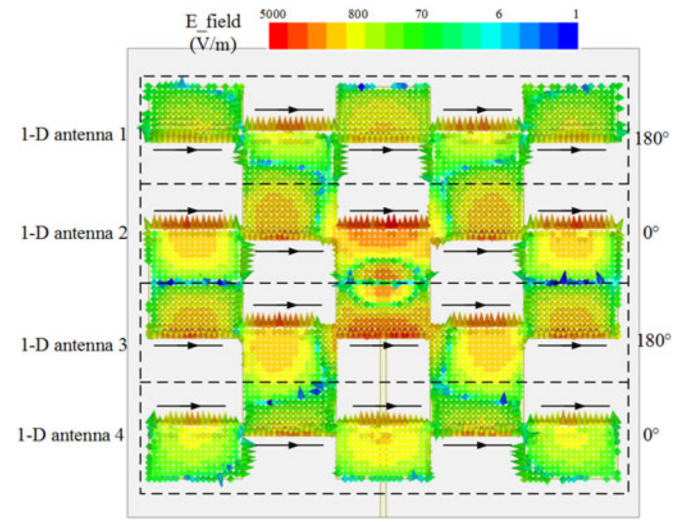

Fig. 4. Operating mechanism of the proposed antenna.

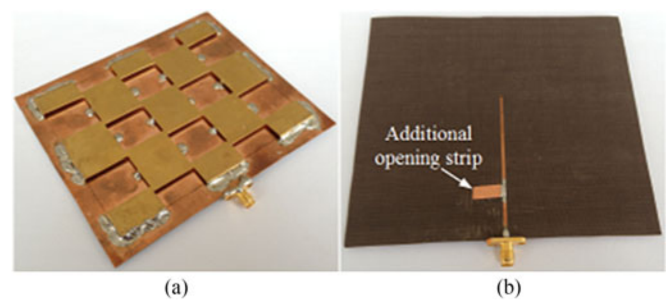

Fig. 5. Prototype of the proposed antenna. (a) Top view and (b) bottom view.

TABLE I
DETAILED DIMENSION OF THE PROPOSED ANTENNA (UNIT: mm)

Parameter	l_x	l_y	$l_1 l_1$	w_1	w_2	l_s	h_1	h_2	w_s
Value	120	110	22	13	10	2	2	0.6	0.5
Parameter	l_{s1}	l_{s2}	l_{f1}	w_{f1}	s	d	l_{f2}	w_{f2}	
Value	11.2	2	9.4	1	0.75	0.8	54.25	1.4	

III. 4 × 5 2-D CHESSBOARD CAVITY ANTENNA

In this letter, the 4 × 5 2-D chessboard antenna cavity antenna shown in Fig. 1(d) is designed and fabricated. Fig. 3 illustrates the structure in detail, and the detailed dimension is listed in Table I. The overlapped shorting sidewalls of the five-unit 1-D antenna at the joints are replaced by smaller patches orthogonal to them with the dimension of 2 × 2 mm^2 as depicted in the inset of Fig. 3(a). The optimized dimension of the ground plane is 120 × 110 mm^2. As seen from the side view of Fig. 3(b) and (c), the shorting patches and sidewalls are used to support the chessboard. The enlarged view of the feed network is depicted in the inset of Fig. 3(d). The H-shaped slot has a width of 0.5 mm, and the longer and shorter sides are 11.2 and 2 mm, respectively. It is etched away from the Taconic TLX-8 substrate $(\varepsilon_r = 2.55, \tan\delta = 0.0019)$ with a thickness of 0.6 mm. An end-shorted microstrip line with a width of 1 mm and a length of 9.4 mm is applied to excite the slot, and it is shorted to the ground through a metallized via hole with a diameter of 0.8 mm. The distance from the end of this line to the center of the slot is 0.75 mm. A longer 50-Ω microstrip line with a width of 1.4 mm and a length of 54.25 mm is used to extract the matched point to the edge of the substrate to connect to a 50-Ω SMA connector.

The operating mechanism is illustrated in Fig. 4. The electrics at the two sides of the feeding slot are phase-reversed, making 1-D antennas 2 and 3 excited differentially. One-dimensional antennas 1 and 4 are excited by couplings through antennas 2 and 3, respectively, and the interconnection joints between antennas 1–4 are electric nulls, so the coupled fields are reversed. On one hand, the adjacent 1-D antennas are excited out of phase. On the other hand, the adjacent antennas are mirrored with each other. Therefore, all the fringing fields are with the same phase. This can be verified by the vector electric field distribution in the figure: All the fringing fields are with the identical phase, resulting in 20 synchronous equivalent magnetic currents as denoted by these black arrow lines. Finally, a broadside high-gain pencil beam is achieved.

IV. SIMULATED AND MEASUREMENT RESULTS

Photographs of the fabricated prototype are shown in Fig. 5. The 2-D chessboard is fabricated by line-cutting a 0.5-mm-thick copper plate. The reflection coefficients are measured using an N5247A vector network analyzer (10 MHz to 60 GHz), and

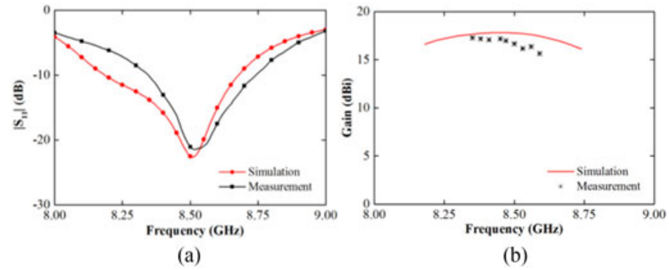

Fig. 6. Measured and simulated (a) magnitudes of reflection coefficients and (b) gains of the proposed antenna.

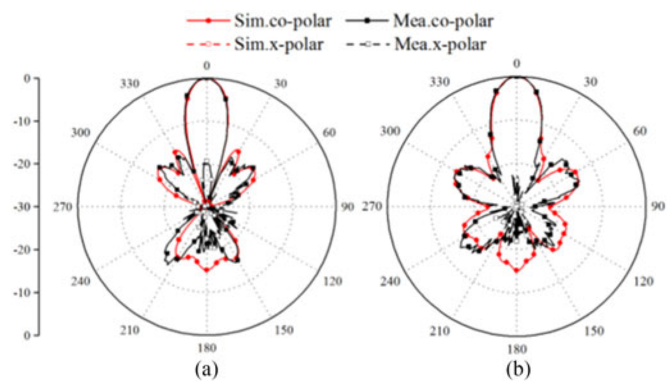

Fig. 7. Measured and simulated normalized (a) *H*- and (b) *E*-plane radiation patterns of the proposed antenna at 8.5 GHz.

the gains and radiation patterns are measured in an anechoic chamber.

The feeding microstrip line has a little difference. Some permittivity and fabrication errors may lead to deviation in frequency. An additional opening strip that is a sticky copper foil is manually attached to the longer line, aiming to correct the resonant frequency [16]. The simulated magnitude of reflection coefficient and the measured result after correction are shown in Fig. 6(a). The simulated bandwidth is 5.69% from 8.19 to 8.67 GHz, whereas the measured bandwidth is 4.56% from 8.35 to 8.74 GHz, and they agree well. Fig. 6(b) shows the measured and simulated broadside gains. The simulated gains range from 16.61 to 17.82 dBi, whereas the measured gains are slightly lower, which vary from 15.66 to 17.28 dBi around the center frequency.

Fig. 7 shows the measured and simulated normalized radiation patterns in two principal planes at 8.5 GHz. The pencil-shaped beams are observed in the two cut planes. The simulated 3-dB beamwidths in the *E*- and *H*-planes are both 18°, whereas the measured results are 19° and 17°, respectively. The energy is excited in the center of the proposed antenna and spreads to outer units, so the aperture magnitude has taper distributions along two dimensions, resulting in slow sidelobe levels (SLLs). The simulated first SLLs in the *E*- and *H*-planes are –13.98 and –14.94 dB, whereas the measured results are –13.91 and –15.68 dB, respectively. The *x*-pol levels are higher than the simulated results, but they are still in a rather low level. The maximum measured *x*-pol levels are –21.95 and –19.36 dB in the *E*- and *H*-planes, respectively.

V. Conclusion

An air substrate 2-D planar chessboard cavity antenna with scalable radiating aperture is presented in this letter. A planar chessboard topology structure is obtained by properly arranging the $M \times N$ open cavity units. Benefiting from the structure scalability, a much larger radiating aperture with high gain can be achieved using proper excitation approach. Attributing to the structure configuration, an air-filled substrate antenna can be obtained together with good performance. A 4 × 5 2-D air substrate chessboard cavity antenna with a bandwidth of 4.56% and a pencil beam with a gain up to 17.28 dBi is fabricated to demonstrate the design strategy.

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