IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received 29 July 2022, accepted 6 September 2022, date of publication 20 September 2022, date of current version 27 September 2022.
Digital Object Identifier 10.1109/ACCESS.2022.3208099

RESEARCH ARTICLE

Novel Method for Sidelobe Level Suppression in Multielement Angled Dipole Array Antennas

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This work was supported in part by the National Research Foundation of Korea (NRF) Grant through the Korea Government Ministry of Science and ICT (MSIT) under Grant NRF-2022R1F1A1065324; in part by the Basic Science Research Program through the National Research Foundation of Korea (NRF) through the Korea Government (MSIT) under Grant 2020R1A2B5B01002251; and in part by the National Research Foundation of Korea (NRF) Grant through the Korea Government (MSIT) under Grant 2021R1A4A1030775.

ABSTRACT In this paper, we propose a one-dimensional (1D) array antenna with improved sidelobe level (SLL) and cross-polarization (x-pol) characteristics. The array elements constituting the 1D array antenna comprise different numbers of dipole elements, and each array element has a different gain and E-field phase. The positions of the array elements in the z-axis direction are adjusted to equalize their E-field phases in the far field, and the array elements are arranged symmetrically with respect to the z-axis to obtain a low x-pol. The same amount of power is supplied to all the array elements of the 1D array antenna of the proposed structure. Therefore, a complexly structured feeding network is not required to achieve a low SLL and low x-pol. The gain of the proposed array antenna with a corporate feeding network is 15.2 dBi, and its SLL and x-pol level are –21.3 dB and 20.3 dB, respectively. The –10 dB impedance bandwidth of the proposed array antenna is 35.6% (8.3–11.9 GHz).

INDEX TERMS Dipole array, endfire antenna, X-band, low sidelobe level, millimeter-wave antenna, printed dipole.

I. INTRODUCTION

Many communication systems in civilian and military applications require high-gain and low-sidelobe-level (SLL) antennas [1], [2], [3], [4], [5], [6], [7], [8], [9]. These demands have prompted many studies aimed at improving the gain and SLL characteristics of array antennas. Examples of high-gain and low-SLL antenna structures include reflector antennas [10], [11], [12], lens antennas [13], [14], [15], and array antennas with multiple radiating elements [16], [17], [18]. Among these antenna structures, reflector and lens antennas require high precision; they are therefore difficult and expensive to fabricate. Array antennas are widely used in various fields requiring high gain and low SLL characteristics because they are relatively simple in design and usually lighter and cheaper than reflector and lens antennas.

Generally, the SLL characteristics of an array antenna can be improved by adjusting the power supplied to each radiating element. The method of lowering the SLL by adjusting the power distribution ratio includes Chebyshev and Taylor distributions [19], [20], and such methods provide a low SLL, but they have a complicated feeding structure and are difficult to design. Instead of adjusting the power distribution ratio, a design featuring nonuniform spacing between adjacent radiating elements has been published as a method for improving SLL characteristics [21], [22]. However, the design and optimization of this method are highly complex. To overcome this problem, researchers have presented a method to lower the SLL that involves adjusting the gain of each radiating element [23], [24]. The presented structure improves the SLL characteristics by adding a complementary

The associate editor coordinating the review of this manuscript and approving it for publication was Sandra Costanzo.

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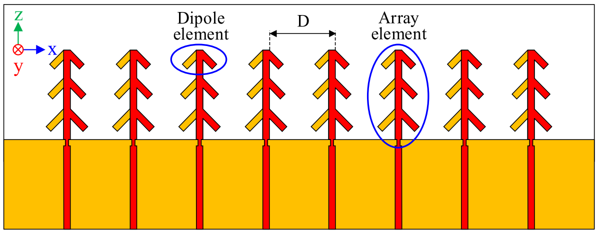


FIGURE 1. Geometry of 1 × 8 array antenna designed using three dipole elements.

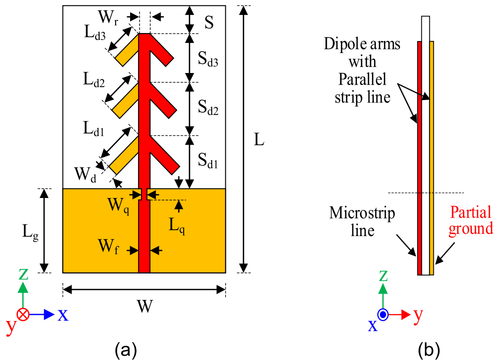


FIGURE 2. Array element with three angled dipole elements: (a) front view and (b) side view.

split-ring resonator (CSRR) structure to the patch antenna or by reducing the size of the patch itself to provide a weight to the array antenna. However, the overall gain of the array antenna decreases because these methods lower the gain of each radiating element.

Another factor that affects the radiation pattern of array antennas is the cross-polarization (x-pol) components of array elements [25]. As the number of array elements constituting the array antenna increases, the x-pol of each array element is combined to increase the x-pol of the array antenna, and a high x-pol adversely affects the radiation pattern of the antenna. To implement an array antenna with low x-pol, a method of arranging array elements symmetrically with respect to the H-plane and supplying power with a phase difference of 180° using a feeding structure has been proposed in [26], [27], and [28]. This method is widely used because the co-polarization (co-pol) of each array element is combined, and the x-pol is canceled to ensure a low x-pol level. However, the feeding structure becomes large and complicated due to the size of the array element when this method is applied to a patch array antenna.

In this study, a 1 × 8 array antenna is designed using array elements that have different gains and comprise different numbers of dipole elements. The endfire dipole antenna used as an array element can easily increase the gain by increasing the number of dipoles constituting the array element. Therefore, compared with array antennas with a low SLL using CSRRs or reducing the patch size, the proposed array antenna is advantageous for implementing a high gain and for its ease of controlling the SLL. The proposed array antenna has a simpler feeding structure than the method of adjusting the power distribution ratio of array elements or maintaining nonuniform spacing between adjacent array elements. In addition, in the proposed array antenna, array elements are symmetrically arranged with respect to the z-axis of the array center. It has a feeding structure that supplies power with a 180° phase difference to each symmetrical array element. Because of this, the x-pol components of the left and right array elements with respect to the array center are canceled so the x-pol level is lower than that of conventional arrays.

II. ANTENNA GEOMETRY

A series-fed endfire dipole antenna printed on a thin substrate is widely used in many communication systems because of its advantages of high gain, wide impedance bandwidth, inexpensive manufacture, low weight, and small size [29], [30], [31], [32], [33], [34]. In addition, the desired gain level can be achieved easily by varying the number of dipole elements constituting the antenna. Because of these advantages, an endfire dipole antenna is used as an array element of a one-dimensional (1D) array antenna. Hereafter, the elements of the 1D array antenna are denoted as array elements, and the elements constituting an array element are denoted as dipole elements, as shown in Fig. 1. A 1D array antenna comprises eight array elements, and each array element, in turn, comprises one, two, three, or six dipole elements. The ANSYS high-frequency structure simulator was used to design and optimize the array antennas.

A. ONE-DIMENSIONAL ARRAY ANTENNA HAVING ARRAY ELEMENTS COMPRISING THREE ELEMENTS

Fig. 2 shows the structure of an array element comprising three angled dipole elements at a center frequency of 10 GHz. The substrate used for the array element design is Rogers AD250C ($\varepsilon_r = 2.5$, $tan\delta = 0.0015$) with a thickness of 0.762 mm. The power input through the microstrip line is transmitted to each angled dipole element through the parallel stripline, and a quarter-wavelength impedance transformer is used to match the 50 Ω microstrip line. The length and spacing of the angled dipole elements are linearly reduced by, respectively, ΔL_d and ΔS_d to increase the impedance bandwidth [33]. The design parameters of the array element comprising the three optimized dipole elements are as follows: $W = 30\,mm$, $L_g = 15\,mm$, $W_f = 2.1\,mm$, $L_{d1} = 7.8\,mm$, $W_d = 2.1\,mm$, $\Delta L_d = 0.8\,mm$, $S_{d1} = 9.5\,mm$, $S_{d2} = 9.5\,mm$, $\Delta S_d = 0.8\,mm$, $W_r = 2.1\,mm$, $W_q = 1\,mm$, $L_q = 2\,mm$, and $S = 10\,mm$.

Fig. 3 shows the characteristics of an array element comprising three dipole elements. The –10 dB impedance bandwidth is 8.9–11.5 GHz, and the gain within the impedance bandwidth is in the range of 7.9–9.2 dBi. The gain at the center frequency of 10 GHz is 9.2 dBi, and the half-power beamwidths (HPBWs) of the E-plane and H-plane are 58.1° and 85.1°, respectively. Using the antenna in Fig. 2 as an

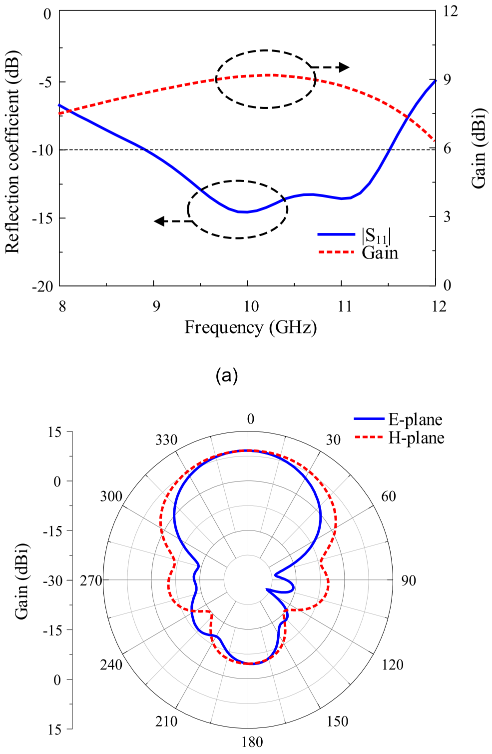


FIGURE 3. Simulation results of array comprising three dipole elements: (a) reflection coefficient and gain and (b) radiation pattern at 10 GHz.

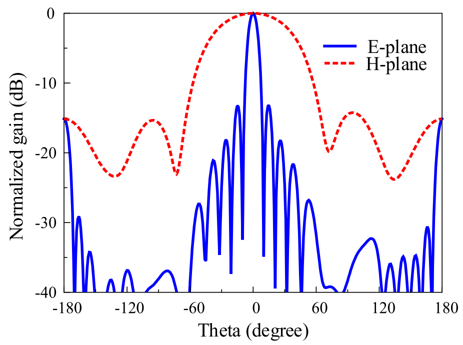


FIGURE 4. Radiation pattern of 1 × 8 array antenna designed using three dipole elements at 10 GHz.

array element, a 1 × 8 array antenna, as shown in Fig. 1, was designed and simulated. The distance D between adjacent array elements is 0.7λ, where λ is the free-space wavelength at 10 GHz. A port is set for each array element, and power with the same amplitude and phase is supplied to all the array elements. Fig. 4 shows the normalized radiation pattern of the 1 × 8 array antenna, where the gain is 16.8 dBi and the SLL is –13.1 dB.

B. ONE-DIMENSIONAL ARRAY ANTENNA HAVING ARRAY ELEMENTS COMPRISING DIFFERENT NUMBERS OF DIPOLES

To obtain array antennas with good SLL characteristics, array elements with different gains are designed. Fig. 5 shows array elements comprising one, two, three, and six dipole elements.

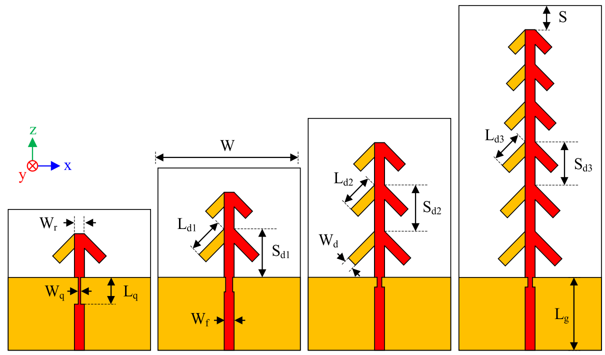


FIGURE 5. Array elements comprising (left to right) one, two, three, and six dipole elements.

TABLE 1. Design parameters of array elements comprising different number of dipole elements.

Design parameter	1 dipole element	2 dipole elements	3 dipole elements	6 dipole elements
W (mm)	30	30	30	30
L (mm)	34	42.5	52.7	76
L_g (mm)	15	15	15	15
S (mm)	10	10	10	10
W_f (mm)	2.1	2.1	2.1	2.1
W_d (mm)	2.1	2.1	2.1	2.1
L_d (mm)	6.5	7.5	7.8	8
S_{d1} (mm)	9	10	9.5	9.5
S_{d2} (mm)	–	7.5	9.5	9.5
ΔL_d (mm)	–	2	0.8	0.6
ΔS_d (mm)	–	–	0.8	0.6
W_r (mm)	2.1	2.1	2.1	2.1
W_q (mm)	0.5	1.5	1	1
L_q (mm)	5.5	3	2	2

Each of these array elements is designed in the same manner as the above-described array element comprising three dipole elements. Table 1 summarizes the design parameters of the array elements comprising one, two, three, and six dipole elements, and Fig. 6 shows their reflection coefficients, gains, and E-field phases on the *xz*-plane. The –10 dB impedance bandwidths of these array elements are 9.2–11.8 GHz, 8.3–11.6 GHz, 8.9–11.5 GHz, and 8.3–11.3 GHz, respectively. The difference in the gains of the array elements at the center frequency increases linearly by approximately 2.3–2.7 dB. In addition, the E-field phases at the same distance from the ground plane of each array element are 272.3°, 258.5°, 217.0°, and 175.2°, respectively. Fig. 7 shows the radiation patterns of these four array elements. At the center frequency of 10 GHz, their gains are 4.2 dBi, 6.5 dBi, 9.2 dBi, and 11.5 dBi, respectively. Table 2 summarizes the characteristics of the designed array elements. A 1D array antenna is designed using these four array elements (see Fig. 8), which are arranged symmetrically with respect to the z-axis to obtain a symmetrical radiation pattern and low x-pol. The ground plane between adjacent array elements is sectioned into triangles to minimize the effect of its discontinuity on the radiation patterns of the array elements. Each array element

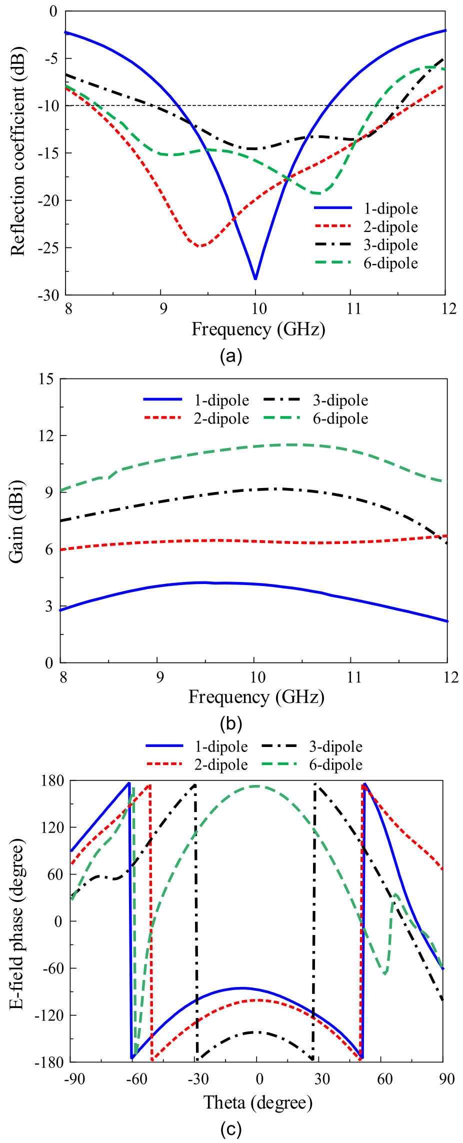


FIGURE 6. Characteristics of array elements comprising one, two, three, and six dipole elements: (a) reflection coefficient, (b) gain, and (c) E-field phases on the xz-plane.

TABLE 2. Comparison of characteristics of designed array elements comprising different number of dipole elements.

characteristic	1-dipole element	2-dipole elements	3-dipole elements	6-dipole elements
–10 dB IBW* (GHz)	9.2–11.8	8.3–11.6	8.9–11.5	8.9–11.3
Gain (dBi)	4.2	6.5	9.2	11.5
HPBW (E-/H-plane)	73.8° /220.6°	70.5° /149.2°	58.1° /85.1°	48.1° /61.5°
E-field phase	272.3°	258.5°	217.0°	175.2°

*IBW: impedance bandwidth

TABLE 3. E-field phase differences and position of antennas having different array elements.

	1-dipole element	2-dipole elements	3-dipole elements	6-dipole elements (ref.)
Phase difference	–97.1°	–83.3°	–41.8°	0°
Position (mm)	17.7	15.2	7.7	0

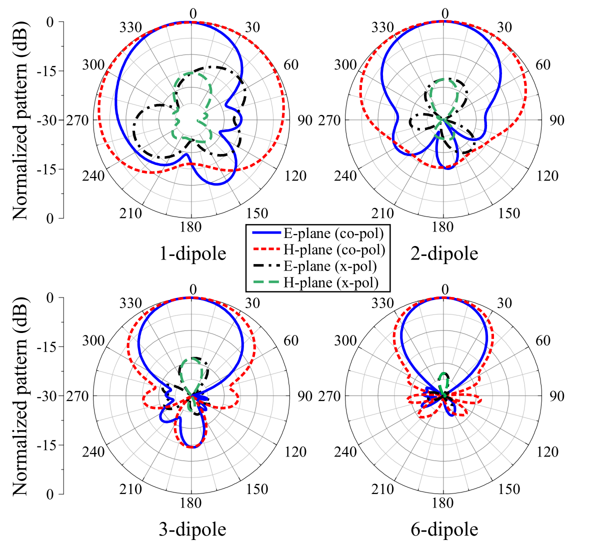


FIGURE 7. Radiation patterns of array elements comprising one, two, three, and six dipole elements.

has a different gain and phase in the far field, but this problem is overcome by adjusting the z-axis position of each array element. When the phase difference between the electric fields of two array elements in the far field is θ, the free-space wavenumber is k, the phase constant of the line is β, and the line length L_{pd} required to compensate for θ can be expressed as follows:

$$L_{\mathrm{pd}} = \theta/(\mathrm{k}\beta) \tag{1}$$

Based on the far-field phase of an array element comprising two centered six-dipole elements, the position of each array element is adjusted using the above equation to equalize the far-field phases. Table 3 summarizes the phase differences of the array elements comprising one, two, and three dipole elements relative to the array element comprising six dipole elements and the line lengths required for correcting the phase differences. Fig. 9 shows the normalized radiation pattern of the array antenna at 10 GHz, and its gain and SLL are 16.4 dBi and –21.0 dB, respectively. In the proposed array, the array elements are arranged symmetrically with respect to the z-axis, and power with a 180° phase difference is supplied to the array elements. Therefore, in the proposed array, the co-pol of each array element becomes in-phase, and the x-pol becomes 180° out of phase, so the x-pol level is low.

When an array is configured as an array element using multiple antennas, the radiation pattern of the array element in the array antenna is termed an active element pattern and

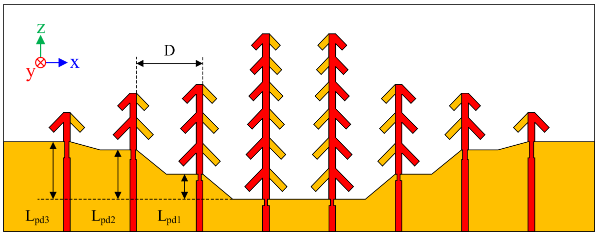


FIGURE 8. Structure of 1 × 8 array antenna designed using array elements comprising different numbers of dipole elements.

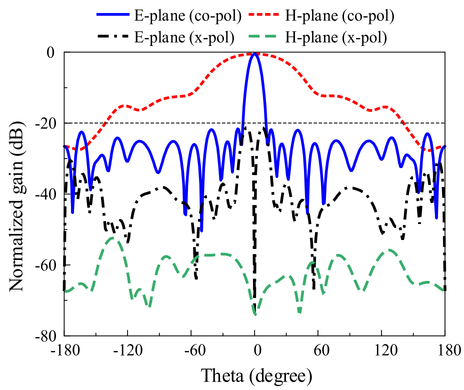


FIGURE 9. Simulated radiation pattern of 1 × 8 array antenna designed using array elements comprising different numbers of dipole elements.

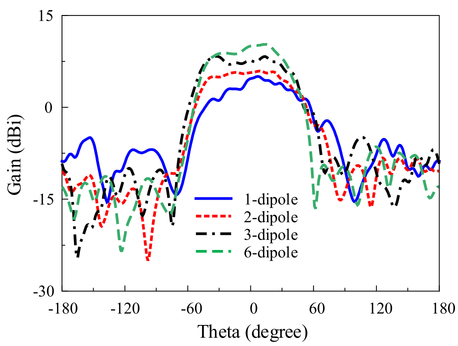


FIGURE 10. Active element patterns of array elements comprising one, two, three, and six dipole elements.

is different from that of an individual array element [35]. Fig. 10 shows the active element patterns of array elements comprising one, two, three, and six dipole elements, and their active element gains are 4.8 dBi, 5.8 dBi, 7.8 dBi, and 10.2 dBi, respectively. These gains are converted into a power distribution ratio and fed to a conventional 1D array antenna composed only of array elements comprising three dipole elements, and the radiation pattern of this array antenna is compared with that of the proposed array antenna structure. Fig. 11 shows the normalized radiation patterns of the proposed array antenna shown in Fig. 8 and of the conventional array antenna shown in Fig. 1. The radiation patterns of the conventional array antenna with a weighted power distribution and the conventional array antenna with a uniform power

TABLE 4. Radiation pattern characteristics.

	Proposed array	Conventional array with a uniform power distribution	Conventional array with a weighted power distribution
Gain (dBi)	16.4	16.8	16.4
SLL (dB)	–21.0	–13.1	–18.2

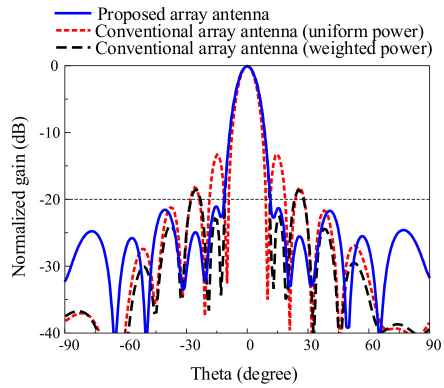


FIGURE 11. Normalized radiation patterns of three different array antennas.

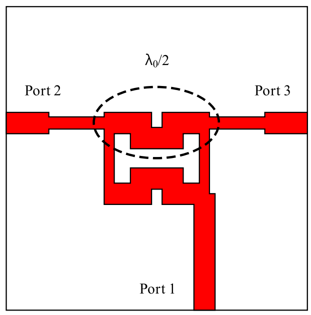
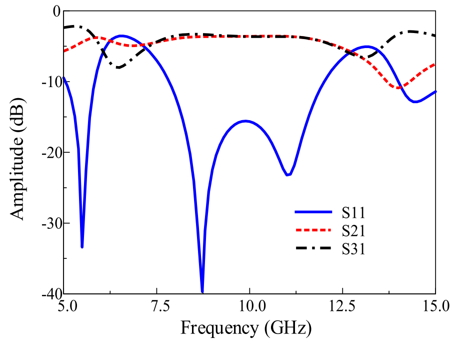


FIGURE 12. Geometry of modified rat-race coupler.

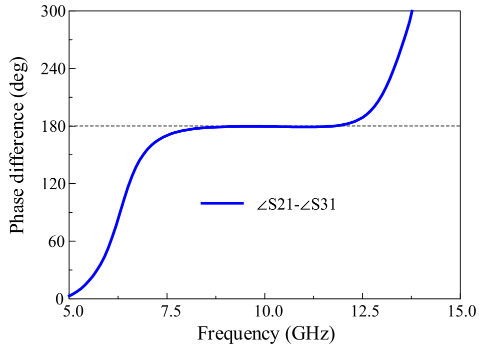
distribution are compared with the radiation pattern of the proposed array antenna. The proposed array antenna has a gain 0.4 dB lower than that of the conventional array antenna with a uniform power distribution but an SSL 7.7 dB lower. It can also be observed that the proposed array antenna has a similar radiation pattern to the conventional array antenna with a weighted power distribution. The gain of the proposed array antenna is identical to that of the conventional antenna with a weighted power distribution, and its SLL is 2.8 dB lower. These comparison results are summarized in Table 4.

III. FABRICATION AND MEASUREMENT

A 1 × 8 array antenna was designed and fabricated by combining the feeding network with the array antenna structure proposed in Section 2. In the proposed structure, the left- and right-side array elements are symmetrical with respect to the z-axis. Therefore, the phase difference between the left- and right-side output powers with respect to the center of the



(a)



(b)

FIGURE 13. Characteristics of modified rat-race coupler: (a) amplitude and (b) phase difference between output ports.

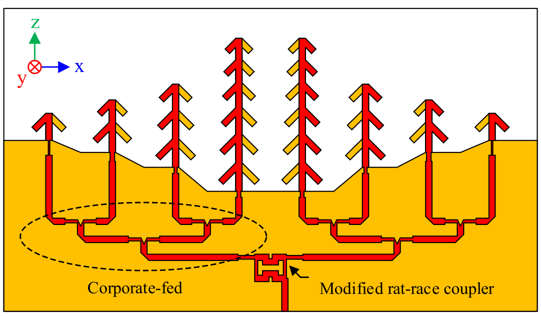
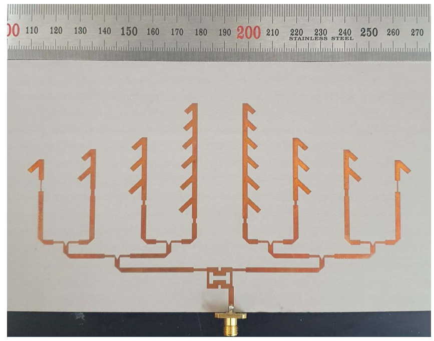


FIGURE 14. Geometry of proposed array antenna with feeding network.

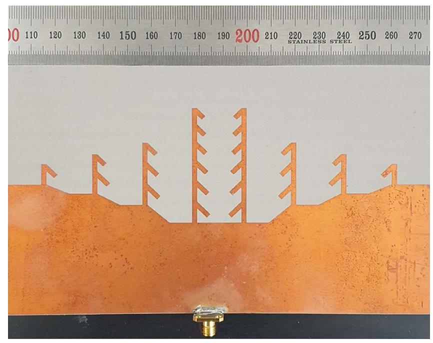
TABLE 5. Performance comparison of the antenna.

Antenna structure	Type of the array element	Number of array elements	–10 dB IBW (%)	Peak Gain (dBi)	Peak SLL (dB)
Ref [23]	Microstrip patch	12	1.8	16.1	–23
Ref [24]	Microstrip patch	13	2.3	N.A.*	–17.5
Proposed	Printed dipole	8	35.6	15.2	–21.3

* Not provided. IBW: impedance bandwidth.

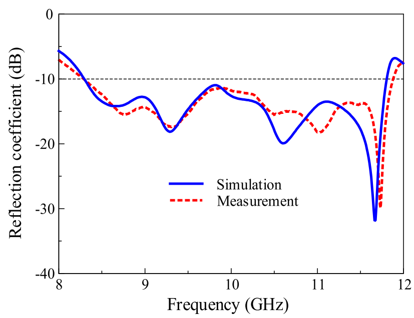


(a)



(b)

FIGURE 15. Photographs of fabricated antenna: (a) front side and (b) back side.



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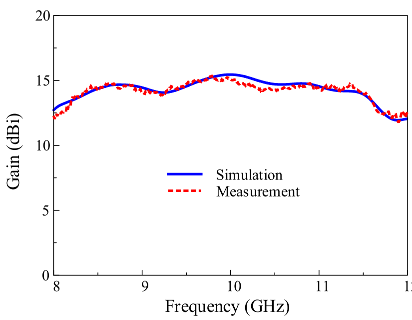

(b)

FIGURE 16. Simulation and measurement results of fabricated antenna: (a) reflection coefficient and (b) gain.

feeding network must also be 180° to ensure the phase of the power radiates from each array element in phase. A modified rat-race coupler was designed to achieve a phase difference of 180°, and Fig. 12 shows its geometry. The area occupied by the coupler was reduced by folding its transmission lines [36]. Fig. 13 shows the characteristics of the modified coupler,

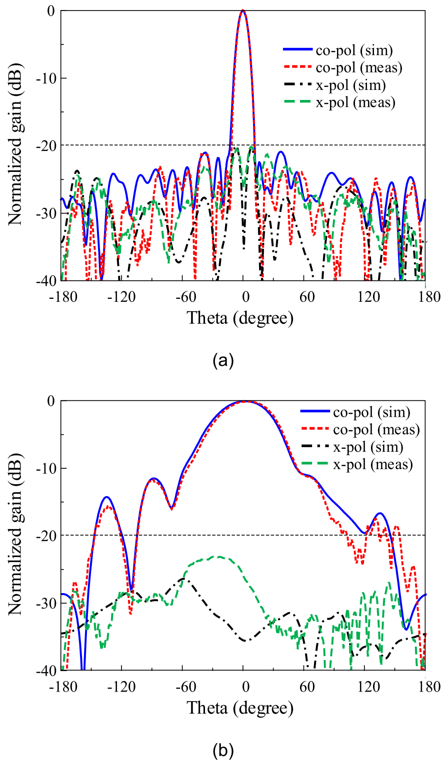

FIGURE 17. Simulated and measured radiation patterns at 10 GHz: (a) xz-plane and (b) yz-plane.

which has a good impedance match over a wide frequency range. In addition, the difference in the magnitude of the output power between the output ports is extremely small, and a phase difference of almost 180° is output over a wide frequency range. Fig. 14 shows the 1 × 8 array antenna with the feeding network. A simple T-junction power divider was used to design the feeding network, each output port of which produces the same amount of power. Fig. 15 shows photographs of the fabricated antenna, the characteristics of which (i.e., its reflection coefficient, gain, and radiation) were measured and compared with the corresponding simulation results.

The reflection coefficient was measured using a Rohde & Schwarz ZVA 67 vector network analyzer, and the radiation pattern and gain were measured using an MTG anechoic chamber. Fig. 16 shows a comparison of the simulated and measured characteristics of the proposed 1 × 8 array antenna. Specifically, Fig. 16(a) shows the simulated and measured reflection coefficients of the proposed array antenna. The –10 dB impedance bandwidth is 8.3–11.9 GHz (35.6%). Fig. 16(b) shows the simulated and measured gains of the proposed array antenna. Due to the loss in the feed network, the gain of the array antenna was reduced by about 1 dB compared to that of the array antenna without the feed network. The simulated and measured 3-dB gain bandwidths are 8.0–11.7 GHz and 8.0–11.8 GHz, respectively. Fig. 17 shows the simulated and measured radiation patterns of the proposed array antenna at 10 GHz, which are 15.4 dBi and 15.2 dBi, respectively, and the simulated and measured SLLs are –20.9 dB and –21.3 dB, respectively. The x-pol level of the proposed antenna is 20.3 dB. The simulation and measurement results can therefore be considered to have good agreement.

IV. COMPARISONS

The proposed 1 × 8 array antenna was compared with other gain-weighted array antennas. The patch array antenna presented in [23] implements a weighted gain array antenna by lowering the gain of CSRR-loaded array elements. The antenna proposed in [23] consists of 12 elements, and its gain and SLL are 16.1 dBi and −23 dB, respectively. However, because the impedance bandwidth of the array element is very narrow, the −10 dB impedance bandwidth of the antenna is only 1.8%. In [24], a patch array antenna with weighted gain using array elements of different sizes is presented. The antenna consists of 13 array elements; its gain is not provided, the SLL is −17.5 dB, and the −10 dB impedance bandwidth of the antenna is highly narrow, about 2.3%.

The array antenna proposed in this paper is composed of 8 array elements, and the gain and SLL are 15.2 dBi and –21.3 dB, respectively, so it has excellent characteristics compared to the number of array elements. In addition, the –10 dB impedance bandwidth is 35.6%, which is much wider than that of conventional array antennas with weighted gain. The characteristics of the proposed 1 × 8 array antenna and the conventional gain weighted array antennas are summarized in Table 5.

V. CONCLUSION

In this study, a 1 × 8 array antenna with a simple feeding structure and excellent SLL characteristics was designed by the method of adjusting the gain of each array element constituting the array antenna. Array elements comprising one, two, three, and six dipole elements were used to design the array antenna. The positions of the array elements were adjusted to equalize their phases in the far field. Four array elements were grouped and arranged symmetrically on the left and right sides to ensure symmetry of the radiation pattern. The gain and SLL of the proposed array antenna were 15.2 dBi and –21.3 dB, respectively, and its impedance bandwidth was 8.3–11.9 GHz (35.6%). The proposed structure can be useful in various applications that require high directivity and low SLL characteristics.

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