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Electrically Conformal Antenna Array With Planar Multipole Structure for 2-D Wide Angle Beam Steering

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ABSTRACT Electrically conformal antenna arrays (ECAA) for 2-dimensional (2-D) beamforming configured by wide beamwidth multipole radiation elements are proposed. Unlike the conventional conformal antenna array with physically curved shape, the proposed arrays are planar structures with wide-angle beam steering. The wide range of beam steering with a low gain variation allows the planar array structure to achieve the electrically conformal phased array patterns. In order to verify the ECAA concept, two different types of ECAA in a 1×8 configuration using planar multipole antenna elements were fabricated at 5.8 GHz and compared to the conventional patch array. Each multipole element had half-power-beamwidth (HPBW) wider than 110° at both E- and H-planes with the maximum HPBW of 175° . The first type of ECAA showed a measured peak gain of 10.8 dBi with a measured half power steering angle of 155° while maintaining a side lobe level (SLL) less than -10 dB. Further, the second ECAA showed a measured peak gain of 12.8 dBi with a measured half power steering angle of 144° while keeping the SLL less than -10 dB. These scan angles of the first and second types were extended about 66.7% and 54.8%, respectively from the conventional patch array with the same size. Lastly, two types of 8×8 array modules for 2-D beam steering were verified at 5.8 GHz and the first type showed a maximum peak gain of 21.0 dBi. Further, the 2-D half power steering angles in E- and H-planes of the second type were about 145° and 137° , respectively.

INDEX TERMS Beamforming, electrically conformal antenna array (ECAA), phased array antenna, multipole antenna, wide angle 2-D beam steering.

I. INTRODUCTION

With the advent of 5G communications, the increasing demand for the effective use of beamforming technique has been more accelerated than ever. Although many different building blocks are required towards a successful adoption of beamforming technology, the challenges in the antenna array must be primarily concerned because it determines the overall system efficiency. Since the conventional patch antenna has a half power beamwidth (HPBW) less than $\pm 50^\circ$, beam steering capability of the patch array gets also limited. With the use of conventional patch antennas for wide scan applications, larger array size is required to satisfy specific target gain at edge angles. Moreover, large peak gain variation at different

steering angles, a great number of expensive RF-chains, large power consumption, fabrication difficulty and large system volume cannot be avoided. Thus, a single antenna element with wide beamwidth must be required to overcome the issues of the conventional phased array antenna structures. Although there have been previous researches for antennas having wide beamwidth characteristics such as Huygens source antennas [1]–[3], magneto-electric dipole antennas [4]–[6] and planar magnetic dipole antennas [7]–[9], they suffer from either complicated geometry, very narrow bandwidth, high profile, one-dimensional expansion of beamwidth or need for a large ground plane. To overcome these drawbacks, a new planar antenna concept based on multipole radiation element has been recently proposed [10]. However, since the phased array performance of the multipole antennas has not been investigated yet, the phased array implementation

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with the multipole elements and the actual beam steering performance must be verified. Further, there have been few 2-dimensional (2-D) beam steering antenna array proving the practical performances of wide HPBW radiation elements. Therefore, the practical 2-D beamforming performance for the antenna array with wide HPBW radiation element like multipole antenna needs to be investigated.

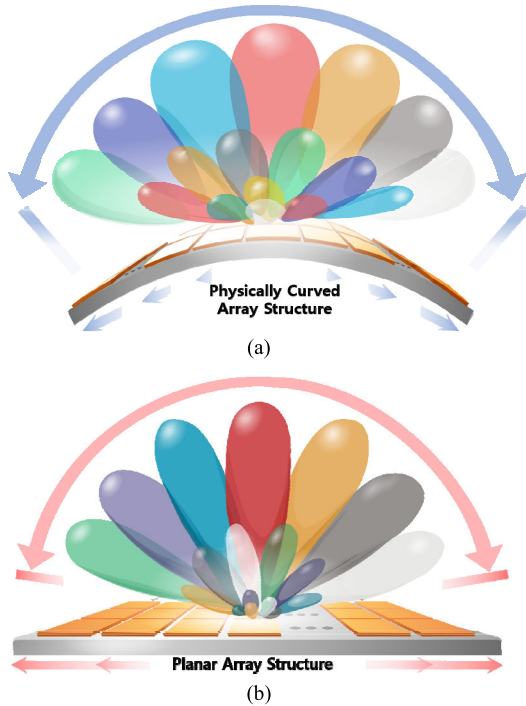


FIGURE 1. Wide-angle antenna array based on (a) physically conformal and (b) electrically conformal structures.

Fig. 1 (a) shows an example of conformal antenna for wide beam coverage. The typical conformal antenna has printed or integrated radiation elements on a physically curved substrate [11]–[13]. However, the curved structure increases the fabrication difficulty and the beam patterns are limited by the curved structure of main body. Since the conformal antenna has an omnidirectional azimuthal coverage, one-dimensional switched beamforming along the curved body is typically used. Further, due to the nonlinear construction of multiple waves in propagation space, phased array performance is limited with narrow scan angles and large gain variation at different angles. To overcome the limitations of physically conformal structure, the new concept of electrically conformal antenna array (ECAA) is proposed in this communication for the first time. As shown in Fig. 1(b), ECAA is a physically planar antenna array with a conformal beam steering capability. The main distinctions from the conventional phased array are the wider scan angle with potentially smaller array size and low gain variation across the steering angles, making the electrically conformal beam steering patterns. For example, if the conventional phased array needs to increase the target gain at the edge angles, the whole array size would be doubled

to ideally increase the gain by 3dB. Consequently, the overall system budget will be heavily loaded with respect to the size, number of required parts and power efficiency, etc. Also, the transceiver power adjustment by power amplifiers (PA) or low noise amplifiers (LNA) to balance the large gain variation between the center and the edge beams can cause additional degradation in system power efficiency. Further, the increase in the array size might not be working due to the rise of grating lobes. Moreover, since the technical trend of beamforming IC is the full integration with antennas as a single module, the compact and planar array structure with hemispherical beam coverage such as the ECAA is introduced for the first time in this paper.

II. SIMULATED BEAM PATTERNS OF THE PROPOSED ECAA

A. OVERVIEW OF THE MULTIPOLE RADIATION ELEMENTS

The concept of multipole antenna includes the use of multiple electric poles, multiple magnetic dipoles (or shorted patch), or combination of both magnetic dipole and electric dipoles and Fig. 2 shows some examples of the multipole antenna structures [10]. The type-A multipole antenna has 3-element magnetic dipole and an extra conductor to spread out magnetic field widely. Also, the type-B multipole antenna has multiple magnetic dipole sources with a diversity in current loops and electric field coupled across each conductor. Having the geometric parameters summarized in Table 1, the reported HPBWs in xz and yz planes for type-A and type-B are 111° and 160°, and 175° and 133°, respectively with the maximum peak gain of 6.3 dBi. The detailed information and analysis about the individual multipole elements are discussed in [10] and thus omitted in this paper.

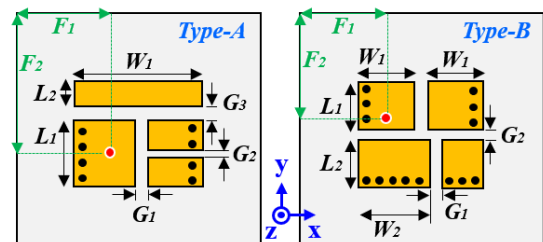


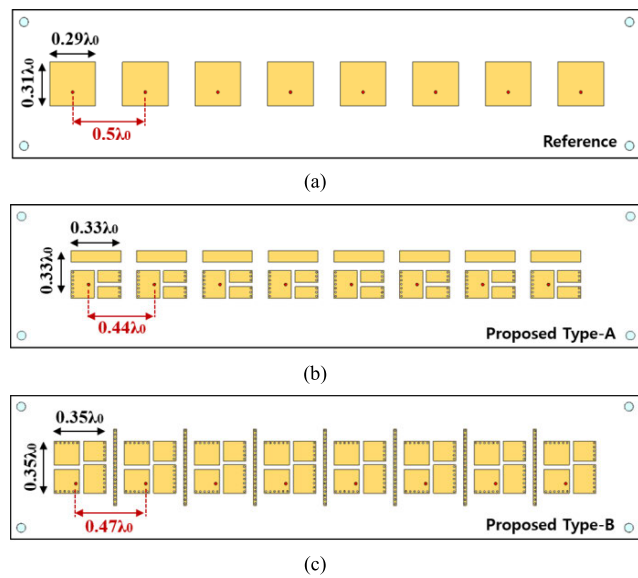
FIGURE 2. Examples of multipole antenna structures.

B. SIMULATION OF ECAA WITH PLANAR MULTIPOLE ANTENNA

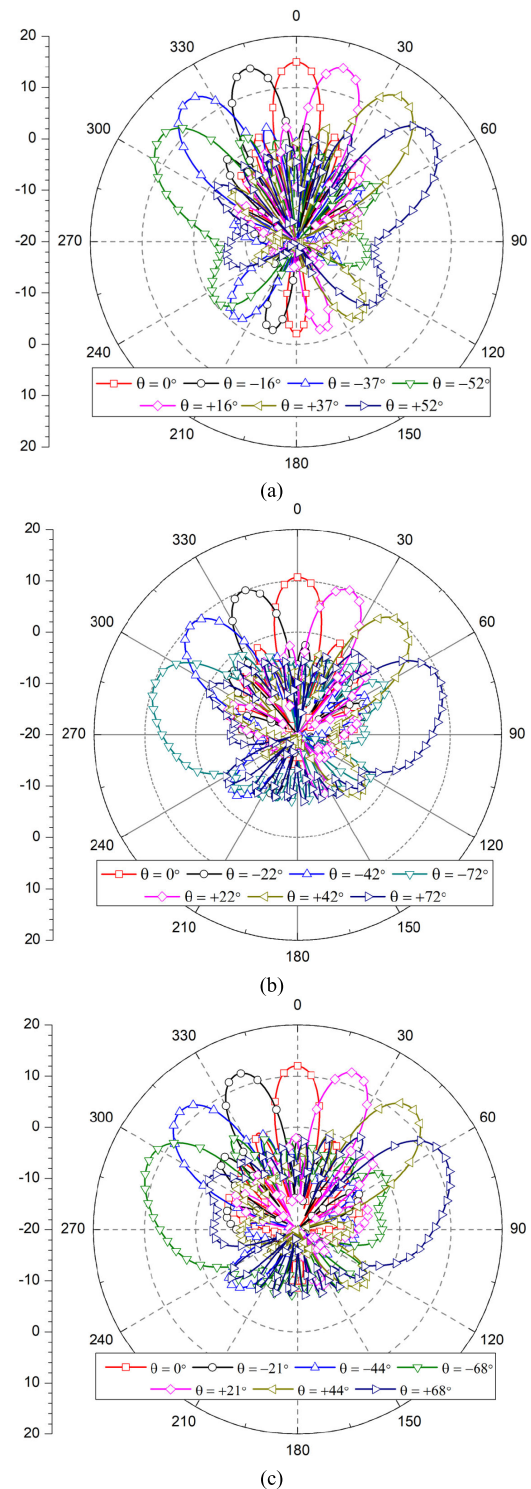
To verify the performance of 1-D ECAA, two multipole antenna elements from Fig. 2 are configured in 1×8 array structure at 5.8 GHz and compared with the conventional patch as shown in Fig. 3. The reference patch array volume including the ground plane is $1\lambda_0 \times 4.25\lambda_0 \times 0.03\lambda_0$. The other two proposed arrays have the identical volume including the ground plane of $1\lambda_0 \times 4.25\lambda_0 \times 0.02\lambda_0$. Although the general structures of the single multipole elements are not modified from [10], the locations of feed points and the distances between elements are optimized for the 1×8 array

TABLE 1. Summary of the parameters in Figure 2.

Parameters: (mm)	Multipole antenna types: Type-A	Type-B
W_1	17.1	8.3
W_2	-	9.7
L_1	9.8	8.8
L_2	4	7.8
G_1	1.2	1.5
G_2	1.4	1.4
G_3	3	-
F_1	27.4	24.3

**FIGURE 3.** The 1×8 array structures with the (a) typical patch, (b) type-A multipole and (c) type-B multipole antennas.

configuration. Also, the proposed array type-B as shown in Fig.3 (c) has additional magnetic walls in between the elements to keep the element spaces closer. The simulated bandwidths for the reference, type-A and type-B arrays are 3.4%, 1.7% and 10.5%, respectively. Further, the isolations among the elements for the reference, type-A and type-B arrays are always better than 15dB, 11dB, and 14 dB, respectively within the operation bandwidths. These simulated results are presented in the next section with the measured results. Once the reflection coefficients and isolation characteristics are optimized for the 1×8 configuration, several beam steering patterns are simulated as shown in Fig.4. The beam patterns are shifted with several arbitrary angles until the side-lobe level (SLL) exceeds -10 dB. The achievable peak scan angles with the SLL less than -10 dB for the patch, type-A and type-B arrays are about $\pm 45^\circ$, $\pm 72^\circ$ and $\pm 67^\circ$, respectively. According to the beam patterns shown in Fig.4 (a), the patch array has the highest peak gain at the center, but the gain drops faster than the other two structures due to the limited HPBW of the single patch element. The type-A array as shown in Fig. 4 (b) shows the widest steering coverage and the

**FIGURE 4.** The simulated 1×8 array beam patterns for (a) typical patch, (b) type-A multipole and (c) type-B multipole antennas at 5.8 GHz.

lowest gain variation less than 0.7 dB over the peak angles. Also, Fig. 4 (c) shows the type-B array having the higher gain than the type-A and the gain variation less than 1 dB over the peak angles. Both types show the larger scan angles than the reference and thus satisfy the electrically conformal beamforming patterns.

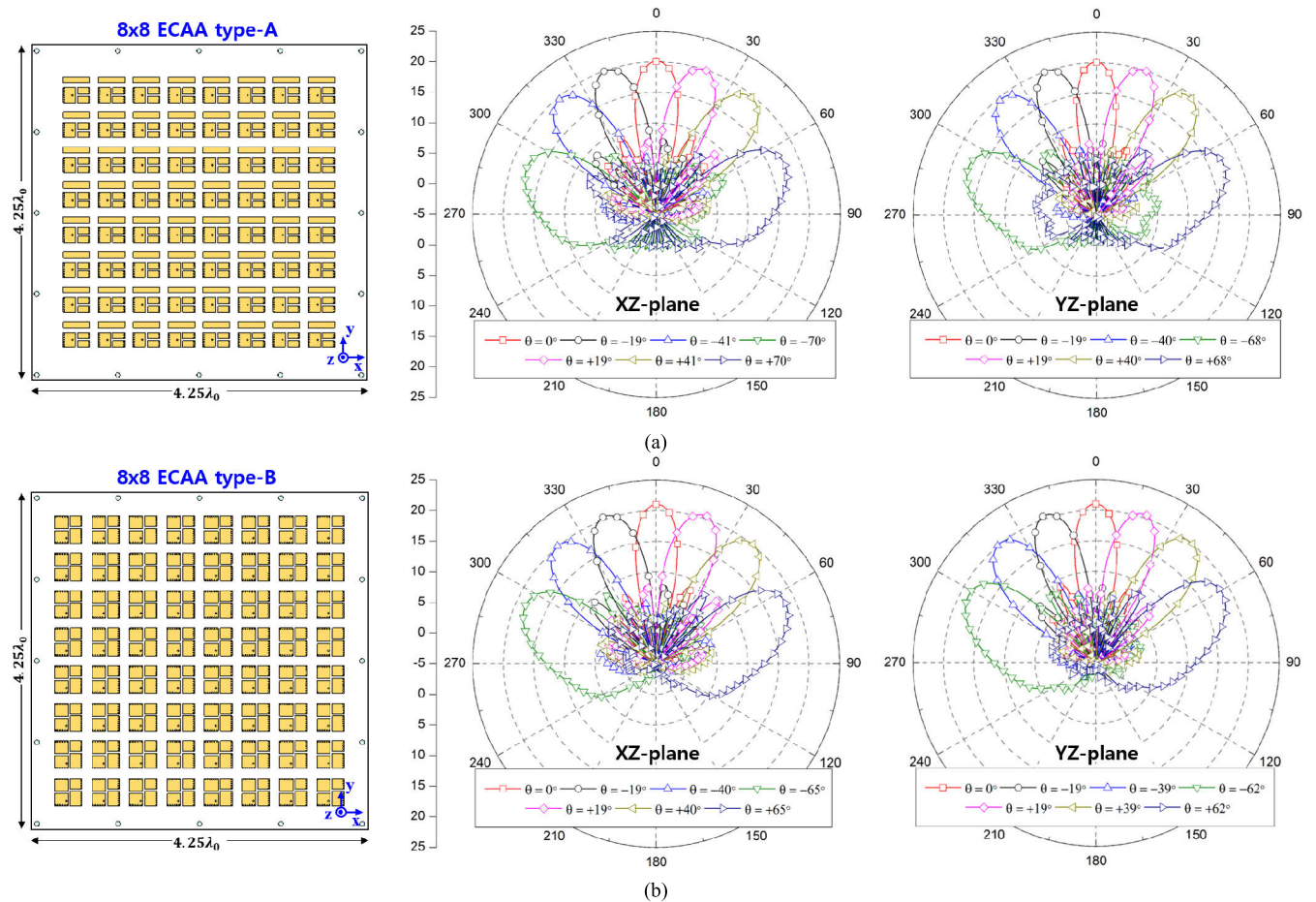


FIGURE 5. The Simulated radiation patterns of the 8×8 ECAA (a) type-A and (b) type-B structures in both xz and yz planes.

Further, if half power decrease with respect to the peak gain is used for measuring the scan angles, the simulated angle ranges for the 1×8 patch, type-A and type-B arrays are about $\pm 53^\circ$, $\pm 83^\circ$ and $\pm 78^\circ$, respectively. Here, the grating lobe of the patch array rises as high as the main beam beyond $\pm 53^\circ$, resulting in the impractical operation. On the other hand, the SLLs of the other two types at their maximum angles are still lower than -10 dB, proving the better performance and feasibility of the ECAA regarding both the half power scan angle and SLL.

2-D ECAA with 8×8 configuration is also designed with a center frequency of 5.8 GHz as shown in Fig. 5. Both type-A and type-B structures are designed with the volume including the ground plane of $4.25\lambda_0 \times 4.25\lambda_0 \times 0.02\lambda_0$. Fig. 5 (a) shows the type-A ECAA with radiation patterns in both xz and yz planes. The achievable peak scan angles with the SLL less than -10 dB for xz and yz planes are about $\pm 70^\circ$ and $\pm 68^\circ$, respectively. The simulated peak gain is about 20.1 dBi and the gain variation within the scan angles satisfying -10 dB SLL is less than 2.5 dB for both planes. Fig. 5 (b) shows the type-B ECAA with radiation patterns in both xz and yz planes. The achievable peak scan angles with the SLL less than -10 dB for xz and yz planes are about $\pm 65^\circ$

and $\pm 62^\circ$, respectively. The simulated peak gain is about 21 dBi and the gain variation within the scan angles referring to the -10 dB SLL is less than 2.4 dB for both planes. Lastly, if half power decrease with respect to the peak gain is used for determining the scan angles, the simulated beam steering angles for 8×8 ECAA type-A in xz and yz planes are about $\pm 74^\circ$ and $\pm 72^\circ$, respectively. Also, the simulated beam steering angles for 8×8 ECAA type-B in xz and yz planes are about $\pm 72^\circ$ and $\pm 69^\circ$, respectively. For both types, the SLLs are still less than -10 dB within the beam steering angles. Although 2-D beam steering angles are slightly less than 1-D beam steering angles due to the extended coupling effect in 2-D array, the proposed type-A and type-B ECAA still show wide scan angles with high performances.

III. MEASUREMENT FOR THE PROPOSED ECAA

A. 1-D BEAM STEERING

The 1×8 reference patch, type-A and type-B arrays are fabricated with Taconic TLX-9 substrate having a relative permittivity of 2.5 and loss tangent of 0.0019 to verify the real performances. Fig. 6 (a) shows the selected views of the fabricated type-A, type-B and the bottom view including the RF connectors. The pure reflection coefficients and

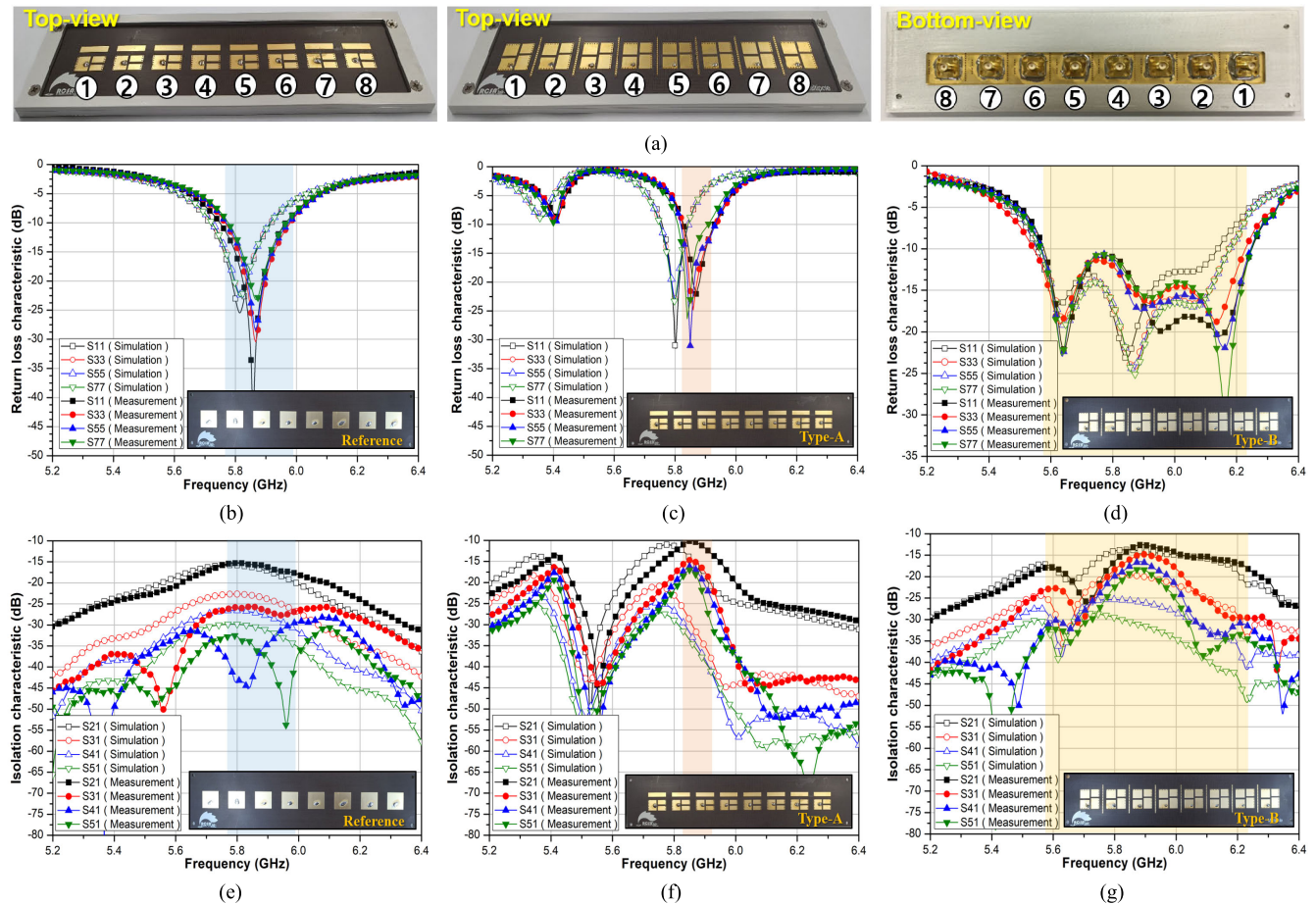


FIGURE 6. The fabricated (a) type-A, type-B array and type-B's bottom-view, and the simulated and measured results for (b)-(d) reflection coefficients and (e)-(g) isolation characteristics of the 1×8 patch, type-A and type-B arrays.

isolation characteristics for selected antenna elements within the array configuration are measured and compared with the simulated results as shown in Fig. 6 (b)-(g). The shaded region in each plot indicates the measured 10-dB impedance bandwidth for each structure. Fig. 6 (b), (c) and (d) showed the 10-dB impedance bandwidths of 3.60% (5.73-5.94 GHz), 2.06% (5.82-5.94 GHz) and 11.72% (5.57-6.25 GHz) for the 1×8 reference patch, type-A, and type-c arrays, respectively. Within the operation bandwidth, the measured antenna element-to-element isolation characteristics for the 1×8 reference, type-A and type-B arrays were always better than -15 dB, -10 dB, and -13 dB, respectively as shown in Fig. 6 (e)-(g). The slightly smaller isolation of the type-A and type-B compared to the patch was due to the antenna spacing and vias connected to the ground plane. Nevertheless, the realized 1×8 array configurations were confirmed to have a good agreement between the simulated and measured S-parameters. Then, the complete phased array module configured by an 1×8 Wilkinson divider, an 8×8 beamformer block and three different types of 1×8 antenna array was implemented as shown in Fig. 7. The beamforming circuits were fabricated with 4-layer PCB based on RF-35 Taconic ($\epsilon_r = 3.5$, $\delta = 0.0018$) and FR4 ($\epsilon_r = 4.7$, $\delta = 0.018$) substrates as

shown in Fig. 7 (a). The 1×8 Wilkinson divider was designed with 2-layer RF-35 Taconic substrate to equally distribute an input RF signal to the eight RF-chain where each consists of a phase shifter and an attenuator. The measured insertion loss of the divider was about 1 dB and the loss variation among each port was less than 0.1 dB at 5.8 GHz. The return loss was also always better than 15 dB from 5.4 to 6.2 GHz. Further, commercially available RF phase shifters (MAPS-011008) and attenuators (MAAD-000523) were adopted for the 8×8 beamformer and controlled by an Aduino MEGA2560 micro-controller unit (MCU) as shown in Fig. 7 (b). Both phase shifters and attenuators were 6-bit controlled, resulting in the phase shift and attenuation level resolutions of 5.6° and 0.5 dB, respectively. Before measuring the radiation pattern, the phase and magnitude mismatches among each RF-chain in the 8×8 beamformer at different control-states for beam steering were first measured by vector network analyzer. Then, the required phase and magnitude balances for different steering angles were manually calibrated later at each measurement case. Finally, the three phased array antennas were measured at the anechoic chamber for verifying the proposed beamforming performances at 5.8 GHz as shown in Fig. 7 (c). The measured results are shown in Fig. 8 where

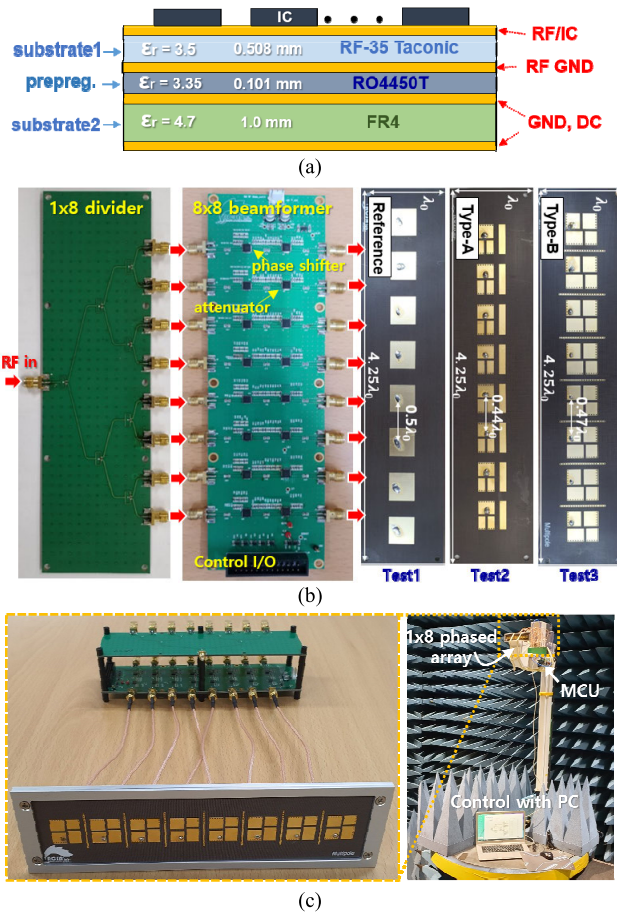


FIGURE 7. Configuration of the (a) beamformer PCB structure, (b) phased array architecture and (c) test setup.

the 1×8 divider, 8×8 beamformer module and RF test cable losses are compensated to present the pure gain characteristic of each antenna array. First, Fig. 8 (a) shows the measured beam steering characteristics of the 1×8 patch array where the measured peak gain at the center was 14.8 dBi with SLL of -12.6 dB. With the SLL kept below -10 dB, the measured half power scan angle was about 93° (-45° to 48°). Second, Fig. 8 (b) shows the measured beam steering characteristics of the 1×8 type-A array. The measured peak gain at the center was 10.8 dBi with SLL of -12.7 dB. With the SLL maintained less than -10 dB, the measured half power scan angle was about 155° (-78° to 77°). Lastly, the measured peak gain of the 1×8 type-B array at the center was 12.8 dBi with SLL of -12.6 dB as shown in Fig. 8 (c). Having the SLL lower than -10 dB, the measured half power scan angle was approximately 144° (-74° to 70°). These measured results showed small deviation from the simulated results because the fabricated beamformer included slight amplitude and phase imbalances among each port compared to the ideally simulated models. If the HPBW was used as the criteria to determine the maximum beam steering angles with the SLL kept -10 dB, the 1×8 patch, type-A and type-B arrays showed the steering angles about 99° , 160° and 150° , respectively. Further, the 1×8 patch, type-A

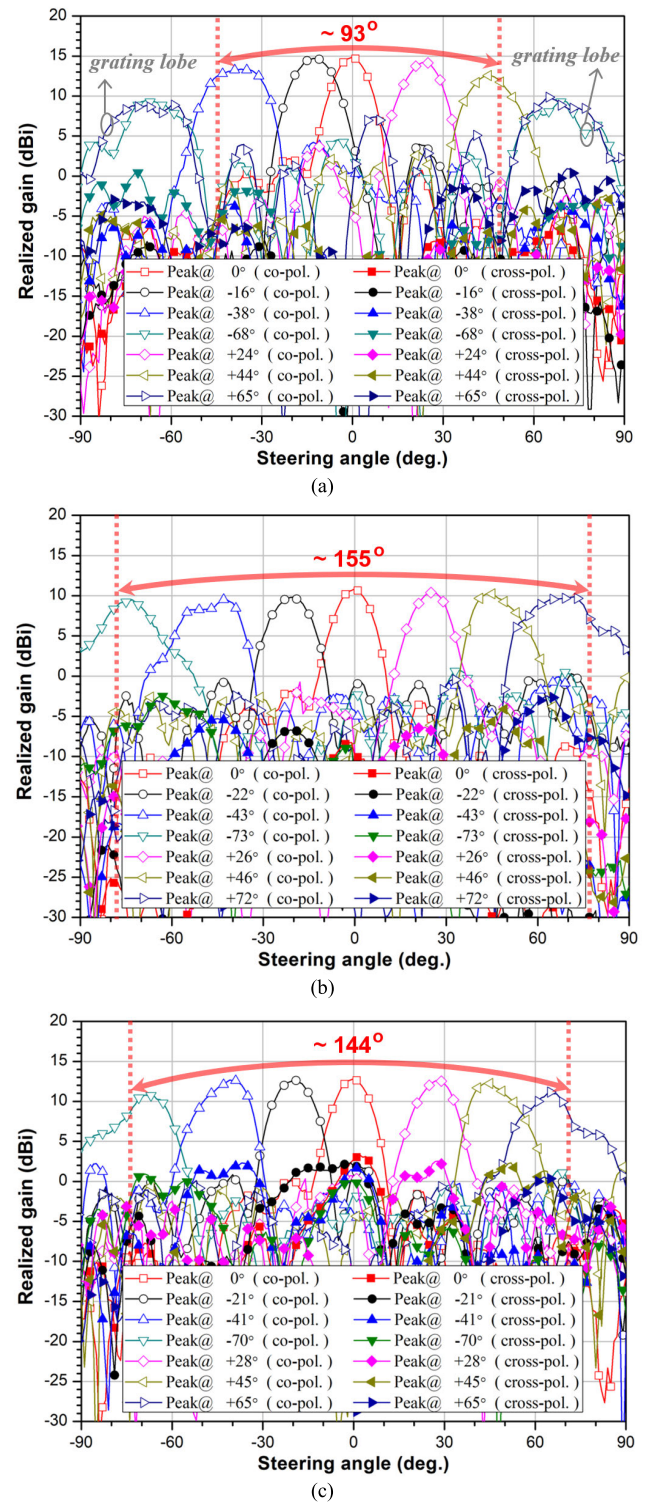


FIGURE 8. Measured beamforming characteristics of the fabricated 1×8 (a) patch, (b) type-A and (c) type-B arrays.

and type-B arrays showed the minimum cross-polarization discrimination levels of 9 dB, 12 dB and 10 dB, respectively within the whole steering angles.

It should be noted that the patch array could steer the main lobe beyond the measured half power scan angle of 93° ,

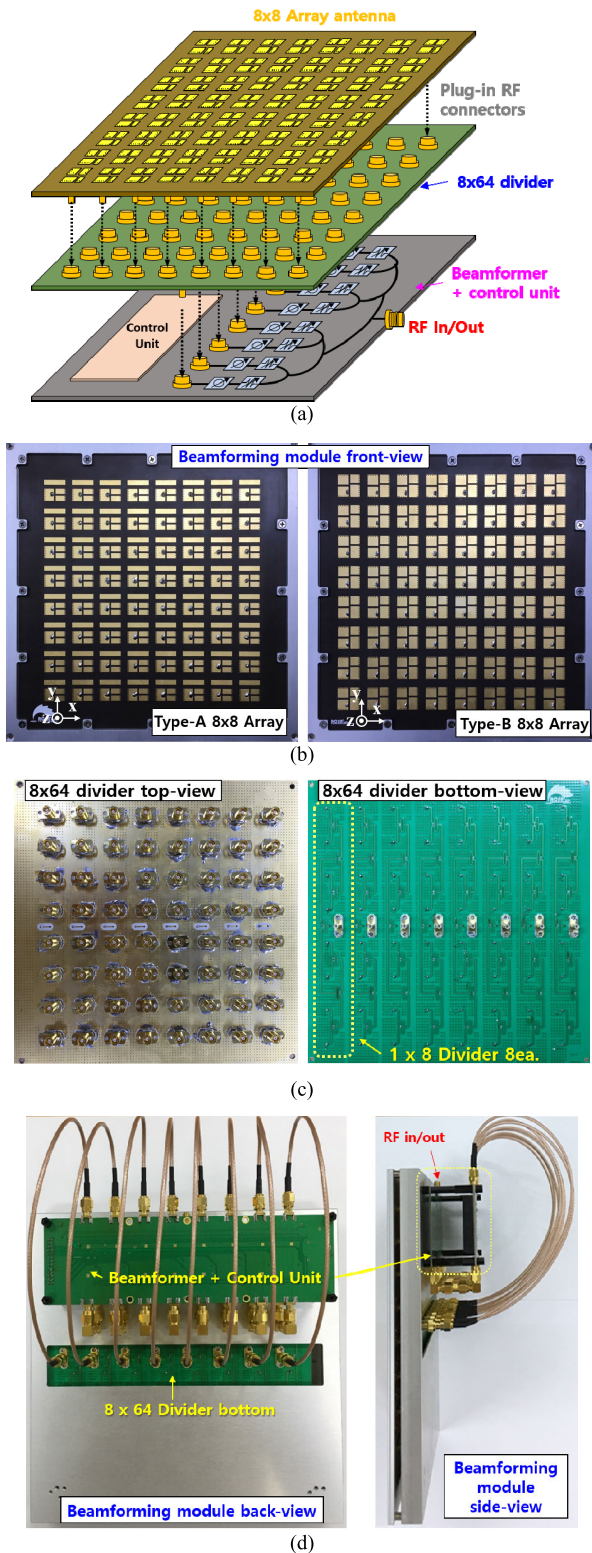


FIGURE 9. Implementation of the proposed 2-D ECAA module: (a) integration overview, (b) array front-view, (c) 8×64 divider, and (d) complete module back and side views.

but the peak gain dropped very fast while the grating lobe increased up to the same level as the main lobe. For example, although the peak gain of the 1×8 patch array at -60° or

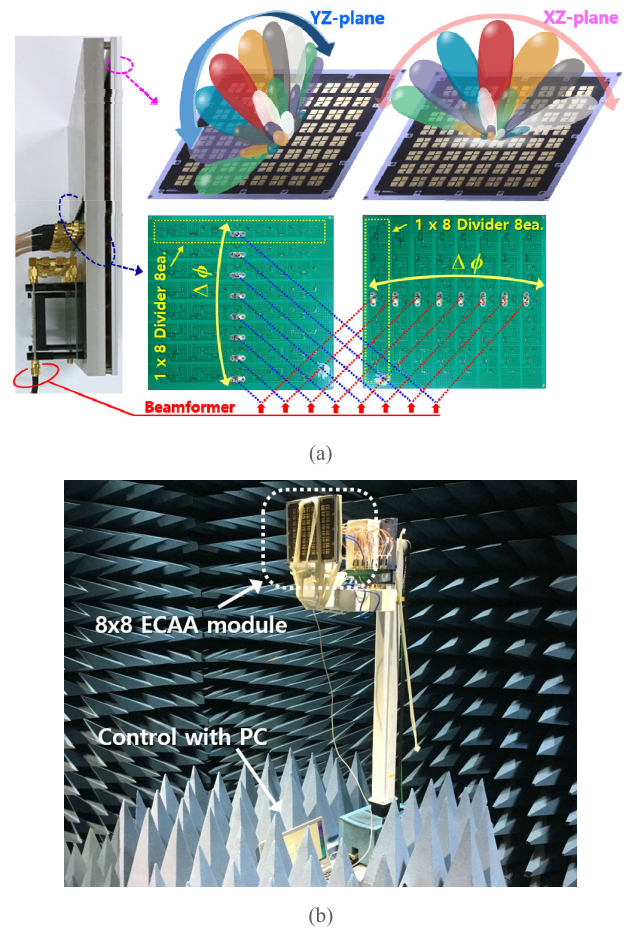


FIGURE 10. (a) Plug-in direction of the 8×64 divider board with respect to the antenna array for beam steering in YZ and XZ planes, and (b) the measurement setup.

62° was about the same level as the type-A array as shown in Fig. 8 (a) and (b), these angles could not be used because the grating lobe was as high as the main lobe. That is, the conventional patch array cannot form the electrically conformal beam steering pattern. On the other hand, the proposed arrays can cover the wider scan angle with lower SLL and the peak gain variation over the whole scan angles is very small.

B. 2-D BEAM STEERING

To verify wide angle 2-D beamforming characteristic of ECAA, a complete 8×8 antenna module was implemented at 5.8 GHz as described in Fig. 9 (a). To reduce design optimization time, the magnetic walls among each radiation element in type-B were eliminated in the 8×8 configuration. The PCB was fabricated by using the same Taconic substrate used for the 1×8 implementation. Further, for the ease of measuring each ECAA type, the 8×8 antenna array in Fig. 9 (b) and the array feed network in Fig. 9 (c) were implemented with separate PCBs having plug-in male and female SMB connectors (SMB-502, SMB-501) from DONGJIN TI. Also, to reduce the required number of RF-chains with phase shifters and attenuators, each row or column was grouped by 1×8 power

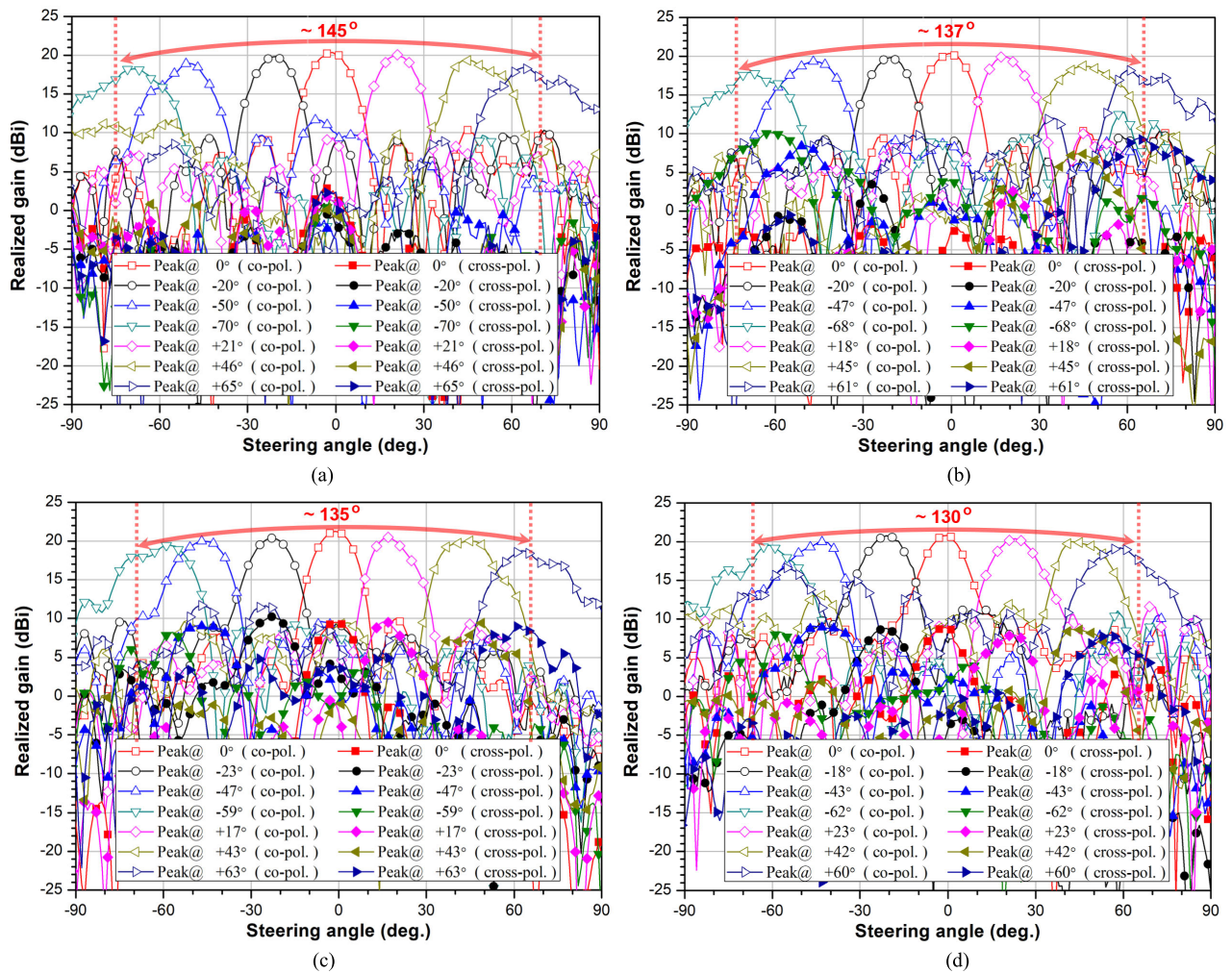


FIGURE 11. The 8×8 ECAA beam steering patterns for (a) type-A in xz, (b) type-A in yz, (c) type-B in xz and (d) type-B in yz planes.

TABLE 2. Comparison of the proposed ECAA type A and B performances at 5.8 GHz.

Proposed ECAA Type	Array Size	Total volume with ground plane	Min. BW (%)	Peak Gain (dBi)	Peak Half-Pwr. Steering Angle (E / H-planes; °)	HPBW Steering Angle (E / H-planes; °)	Total Efficiency (%)
A	1x8	$1\lambda_0 \times 4.25\lambda_0 \times 0.02\lambda_0$	2.06	10.8	155 / -	160 / -	81
	8x8	$4.25\lambda_0 \times 4.25\lambda_0 \times 0.02\lambda_0$	2.06	20.1	145 / 137	163 / 157	81
B	1x8	$1\lambda_0 \times 4.25\lambda_0 \times 0.02\lambda_0$	11.72	12.8	144 / -	150 / -	85
	8x8	$4.25\lambda_0 \times 4.25\lambda_0 \times 0.02\lambda_0$	11.72	21.0	135 / 130	154 / 149	85

divider and connected to beamformer. Thus, total eight 1×8 power dividers were integrated together as a single 8×64 feed network as shown in Fig. 9 (c). The magnitude and phase balances among output ports of the 8×64 divider at 5.8 GHz were less than 0.5 dB and 3° , respectively. Then, the same 8×8 beamformer used for the 1×8 array measurement was reused to configure the complete ECAA module as shown in Fig. 9 (d). Further, 2-D beam steering performances in both xz and yz planes were measured by manually rotating and plugging the feed network according to the required phase shift direction with respect to the 8×8 antenna array

as shown in Fig. 10 (a) and (b). Finally, the beamforming radiation patterns of the proposed 8×8 ECAA array were measured at 5.8 GHz anechoic chamber as shown in Fig. 10 (c). Fig. 11 (a) and (b) show the measured beam steering patterns of the proposed ECAA type-A in xz and yz planes, respectively. According to the half power decrease in peak gain, the proposed type-A shows the scan angles of 145° and 137° in xz and yz planes, respectively. If the HPBW was used as the criteria to determine the maximum beam steering angles, the proposed type-A beam steering angles in xz and yz planes were about 163° and 157° , respectively.

Further, Fig. 11 (c) and (d) show the measured half power beam steering angles of the proposed ECAA type-B with 135° and 130° in xz and yz planes, respectively. Having the HPBW as the criteria to determine the maximum beam steering angles, the ECAA type-B shows 154° and 149° in xz and yz planes, respectively. Further, the 8×8 type-A and type-B arrays showed the minimum cross-polarization discrimination levels of 8 dB and 10 dB, respectively within the whole steering angles and planes. For both types, if the feed network and beamformer losses were compensated, the pure peak gains of the 8×8 arrays in both planes were calculated as approximately 20 dBi or better. Having the measured performances summarized in Table 2, the type-B showed a wider bandwidth characteristic while the type-A had a wider beam steering angle. Depending on applications, if the wide bandwidth characteristic is not required, the type-A can be preferred. On the other hand, if the bandwidth and peak gain with the reasonable beam steering range are simultaneously considered, the type-B can be a good candidate. Therefore, the integration of multipole radiation elements to form ECAA module was successfully demonstrated with the 2-D beams steering performances.

IV. CONCLUSION

To enable the beamforming technique que as a core technology in the future 5G and beyond-5G (B5G), highly integrated phased array antenna technologies with high system efficiency and scalability as well as affordability must be developed. In order to meet the requirement, the concept of ECAA for planar array structure was proposed and verified by two types of 1×8 and 8×8 ECAA structures at 5.8 GHz. The type-A and type-B ECAA modules showed the excellent performances in both 1-D and 2-D beam steering. The wider scan angles with low SLLs of the planar antenna structures confirmed the feasibility of ECAA based on multipole antennas.

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