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Design of Comb-Line Array Antenna for Low Sidelobe Level in Millimeter-Wave Band

JAE-HO LEE[1], SANG-HOON LEE[2], HYUN JOON LEE[1], JUNG-HOON OH[1], JANG-YEOL KIM[1], IN-KUI CHO[1], AND DONG-WOOK SEO[2], (Senior Member, IEEE)

[1]Electronics and Telecommunications Research Institute (ETRI), Daejeon 34129, South Korea

[2]Division of Electronics and Electrical Information Engineering/Interdisciplinary Major of Maritime AI Convergence, Korea Maritime and Ocean University, Busan 49112, South Korea

Corresponding author: Dong-Wook Seo (dwseo@kmou.ac.kr)

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ABSTRACT In this paper, a deformed radiating element is proposed to design a comb-line array antenna for low sidelobe levels in the millimeter-wave band. To design the comb-line array antenna with a low sidelobe level, the use of the wide radiating elements for a relatively large radiation conductance is required. However, the conventional rectangular radiating element has transverse current flows on it, resulting in undesirable transverse radiation conductance for cross-polarization. On the contrary, in the proposed radiating element, which is implemented by cutting obliquely the connection part to the feeding line from a rectangular element, the radiations from the transverse currents cancel each other, and low radiation conductance for cross-polarization and dominant radiation conductance for co-polarization are achieved. A 17-element linear comb-line array antenna with the sidelobe below −20 dB is designed and measured at 79 GHz. Using the proposed radiating elements, we obtained the sidelobe level of −21.9 dB in the array, but the array using the conventional radiating elements shows the sidelobe level of −16.9 dB. This letter demonstrates the availability of the proposed element for the easy and accurate design of the comb-line array antenna with the low sidelobe level.

INDEX TERMS Antenna array, comb-line antenna, low sidelobe, microstrip antenna, millimeter-wave.

I. INTRODUCTION

Despite the lossy microstrip line, microstrip antennas are still competitive as millimeter-wave antennas thanks to their inherent advantages of low profile, low cost, and easy fabrication [1], [2]. A comb-line array structure has a relatively low loss compared to the other microstrip patch antennas and is, thus, an effective candidate for the microstrip antennas in the millimeter-wave band [3].

Lately, several comb-line array antennas operating in traveling-wave [4]–[6] and standing-wave modes [7]–[9] have been developed in the millimeter-wave band. In the conventional comb-line microstrip antenna, the rectangular stubs are used as radiating elements and the radiation conductance (or power) is controlled by their widths [3]–[9]. Therefore, the use of wide radiating elements is inevitable in the conventional comb-line array antenna for the suppressed sidelobe design, in which the tapered amplitude distributions are required to achieve the desired sidelobe level (SLL). However, on the wide radiating element, current flows not only in the longitudinal direction but also in the transverse direction of the element, which results in significant conductance (or radiation) for cross-polarization [10]. Since this problem was overlooked in the previous work [7], the obtained SLL was −17.2 dB even though the comb-line array antenna was designed to have a SLL of −20 dB. To overcome this problem, the modified radiating elements, such as a reflection-canceling stub [4], slit structure [6], or a stub-integrated element [10], have been proposed in the traveling-wave array. For the same purpose, capacitively coupled elements [11] and stubbed-elements [12] have been also discussed in the standing-wave array. Nevertheless, the above elements still cause the design complexity and require highly precise fabrication.

In this paper, we propose a deformed element with a narrow connection with the feeding line by cutting obliquely

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the connecting parts from a rectangular element. By doing that, the transverse currents on both ends of the element are in opposite directions to each other and the radiations from them are cancelled out. Consequently, the longitudinal currents on the proposed element dominate the total radiation conductance (or power), and low conductance for cross-polarization is expected. Especially, the proposed element is useful in designing a low sidelobe comb-line array antenna that requires wide radiating elements in the middle of the array for relatively high conductance.

The rest of this paper is organized as follows: The configuration of the microstrip comb-line array antenna is described in Section II. The characteristics of the proposed element and conventional element are studied, and the unit design and array design are described in Section III. In Section IV, the fabricated 1×17 comb-line array antennas are introduced and the simulated and measured results are discussed. At last, the paper is concluded in Section V.

II. CONFIGURATION

Figure 1 shows the configuration of the microstrip comb-line array antenna in which the proposed radiating elements is partially adopted for a low sidelobe. The antenna consists of several radiating elements directly connected to a straight microstrip feeding line, which is terminated in an open-end for the standing-wave operation. The conventional rectangular elements are placed around the input and termination of the array for a small conductance, and the proposed elements are arranged in the middle of the array for a relatively larger radiation conductance. The proposed element is narrowly connected to the feeding line by cutting off two small pieces of the triangular shape (base: $(W_{pi} - W_m)/2$, height: g) at the corners of the rectangular element meeting the feeding line.

The radiation conductance of each element is controlled by the width of the element W_{pi}. The length of the radiating element L_{pi} is close to a half guided-wavelength ($\lambda_g/2$) and finely tuned according to the width. The radiating elements are alternatively arranged on either side of the feeding line, and the distance d_{pi} between adjacent elements is also approximately $\lambda_g/2$ of the feeding line so that all the elements are excited in phase.

To show the applicability of the proposed element to the comb-line array antenna, we designed a linear 17-element ($N = 17$) array with SLL below -20 dB [2], [4], [6]–[8], [11]–[12], [18]. The design frequency was considered 79 GHz, which is the allocated frequency band to the millimeter-wave automotive radar applications [13], [14]. We adopted the Isola's ASTRA MT77 substrate (thickness $t = 0.127$ mm, $\varepsilon_r = 3.0$, and $\tan\delta = 0.0017$). The antenna design was simplified by fixing several parameters: $W_f = 0.3$ mm, and $g = 0.3$ mm. The parameter $W_m = 0.1$ mm was also fixed in consideration of actual fabrication tolerance. The overall designs and analyses were carried out by using Ansoft's HFSS, a commercial electromagnetic solver based on the finite-element method.

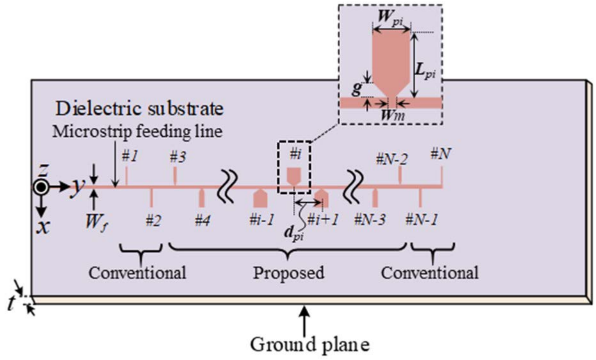

FIGURE 1. Configuration of the microstrip comb-line array antenna composed of the proposed (deformed) and conventional (rectangular) elements.

III. DESIGN

A. TYPES OF GRAPHICS

The characteristics of the two radiating elements, the proposed element and conventional element, were studied and compared using the analysis models shown in Fig. 2(a) and (b). The equivalent circuit of the resonant radiating elements can be illustrated as shown in Fig. 3 [10]; G_0 and G_r represent the characteristic conductance of the feeding line and radiation conductance of the radiating element, respectively. The radiation conductance (G_r) consists of radiation conductance for co-polarization (G_{r_lo}) and cross-polarization (G_{r_tr}), which indicate radiation conductance components due to the longitudinal and transverse current flows on the element, respectively. The more current flows on the element, the larger the radiation conductance.

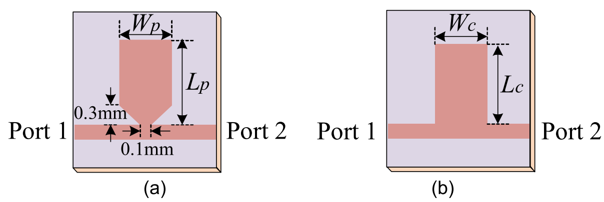

FIGURE 2. Analysis models of radiating elements. (a) Proposed (deformed) element. (b) Conventional (rectangular) element.

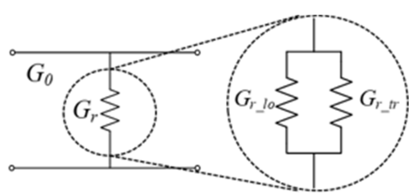

FIGURE 3. Equivalent circuit of the resonant radiating elements.

The current distributions on the conventional (rectangular) element and the proposed element, when they resonate at 79 GHz, are depicted in Fig. 4. With regard to the rectangular element, the current flows mainly in the longitudinal direction on the narrow one ($W_c = 0.1$ mm) as shown in Fig. 4(a), however, the transverse flow as well as longitudinal flow of the current is strong on the wide element ($W_c = 0.7$ mm) as shown in Fig. 4(b). The transverse currents on both ends of the wide conventional element are in the same direction and thus increase the transverse component of radiation conductance G_{r_tr} and cross-polarized radiation. On the other hand, the transverse currents on both ends of the proposed element with the same width ($W_p = 0.7$ mm) are in the opposite direction to each other as shown in Fig. 4(c), therefore, the radiations from them are expected to be cancelled out. Accordingly, the longitudinal currents are dominant in the radiation of the element, and then the radiation conductance for co-polarization G_{r_lo} makes up most of the radiation conductance G_r.

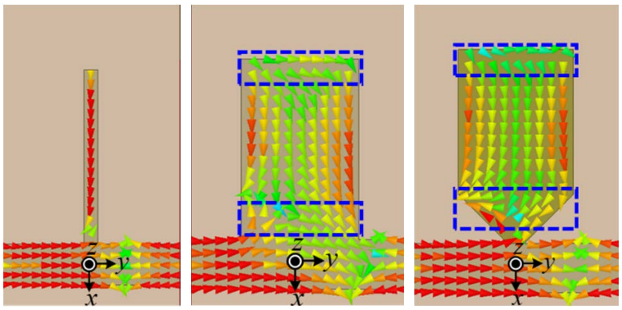

FIGURE 4. Current distributions on (a) narrow conventional (rectangular) element ($W_c = 0.1$mm, $L_c = 1.27$ mm); (b) wide conventional (rectangular element ($W_c = 0.7$ mm, $L_c = 1.03$ mm); and (c) proposed element ($W_p = 0.7$ mm, $L_p = 1.14$ mm).

Fig. 5 shows the simulated radiation patterns in the *yz*-plane for co-polarization and cross-polarization of the proposed and conventional elements with the same width ($W_p = W_c = 0.7$ mm). The cross-polarization level of the proposed element was 9.8 dB lower than that of the conventional element.

The polarization ratio, which is defined as the magnitude ratio of ϕ-component (E_ϕ) to θ-component (E_θ) of the electric field radiated in front of the radiating element ($\theta = 0^o$ and $\phi = 0^o$), were estimated with respect to the widths of the elements, as shown in Fig. 6. The polarization ratio ($|E_\phi|/|E_\theta|$) of the conventional radiating element increases rapidly as increasing of its width. On the other hand, even for the wide element, the polarization ratio of the proposed element is much smaller than that of the conventional element with the same width. This also because the radiation by the transverse current is weaker in the proposed element than in the conventional element. Therefore, it is advantageous to use the proposed element for the larger radiation conductance in designing a low sidelobe array antenna.

B. UNIT DESIGN OF RADIATING ELMENTS

The procedure in [11] was followed for the standing-wave comb-line array antenna design. The unit design of the radiating elements not only for the proposed but also for the conventional was performed using the model in Fig. 2. By changing the widths of the elements (W_p and W_c), the resonant lengths (L_p and L_c) were determined and then the radiation conductance g_r, normalized to the admittance of the feeding line, was obtained by the formula [11], [15]

$$g_r \left(= \frac{G_r}{G_0}\right) = -2\frac{S_{11}}{S_{11}} = 2\frac{1 - S_{21}}{S_{11}}, \tag{1}$$

where S_{11} and S_{21} are the scattering parameters and can be obtained from electromagnetic simulation.

Figure 7 shows the results of unit design for the proposed and the conventional radiating elements. The wider the width of the radiating element, the greater the amount of the current on the element and thus higher the radiation conductance. Here, g_r includes the components for cross-polarization as well as co-polarization. As the width of the radiating elements increases, the difference between the radiation conductance of the two elements with the same width also increases. This is because the conductance component for cross-polarization becomes higher as the width of the conventional element increases.

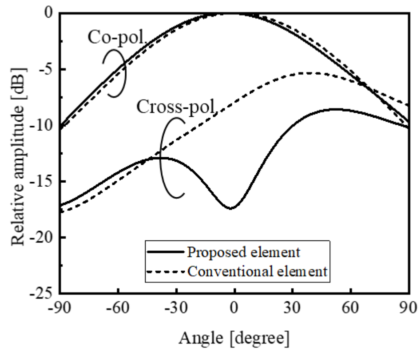

FIGURE 5. Simulated radiation patterns for co-polarization and cross-polarization in yz-plane (Wp = Wc = 0.7 mm).

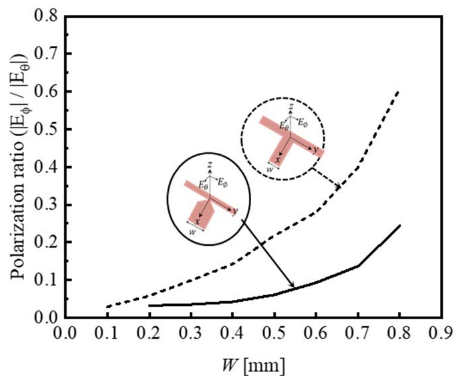

FIGURE 6. Magnitude ratio of E_θ to E_ϕ in front of the radiating elements ($\theta = 0°$ and $\phi = 0°$) for various widths.

C. ARRAY DESIGN FOR A LOW SIDELOBE LEVEL

A 17-element linear comb-line array antenna with a low SLL was designed. To suppress the SLL, the amplitude of each element was tapered to provide a Taylor distribution with

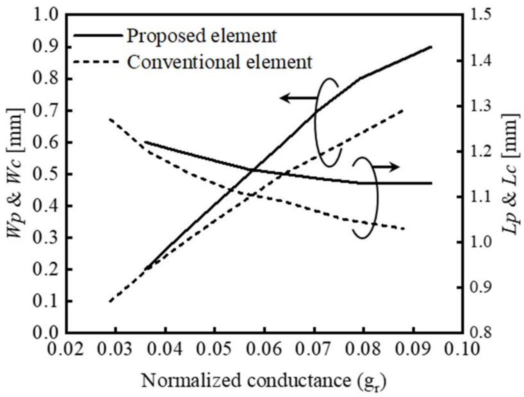

FIGURE 7. Unit design results for the proposed and conventional radiating elements.

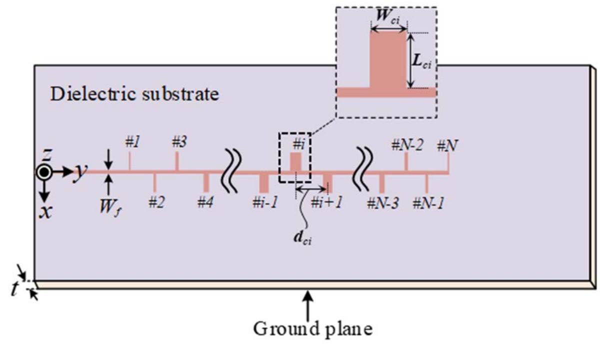

FIGURE 8. Configuration of the conventional microstrip comb-line array antenna with rectangular elements.

TABLE 1. Parameters of the Comb-Line array with proposed elements and conventional elements.

Element Number (i = 1–17)	Conductance ratio	Width [mm] (W_{ci} for =1,2,16,17 and W_{pi} for i=3–15)	Length [mm] (L_{ci} for i=1,2,16,17 and L_{pi} for i=3–15)
1, 17	1.0	0.10	1.29
2, 16	1.12	0.18	1.23
3, 15	1.35	0.24	1.15
4, 14	1.71	0.41	1.11
5, 13	2.16	0.61	1.08
6, 12	2.65	0.72	1.08
7, 11	3.12	0.78	1.08
8, 10	3.45	0.80	1.08
9	3.57	0.81	1.09

TABLE 2. Parameters of the Comb-Line array with conventional elements.

Element Number (i = 1–17)	Conductance ratio	Width [mm] (W_{ci})	Length [mm] (L_{ci})
1, 17	1.0	0.10	1.29
2, 16	1.12	0.18	1.23
3, 15	1.35	0.32	1.17
4, 14	1.71	0.48	1.13
5, 13	2.16	0.61	1.1
6, 12	2.65	0.68	1.09
7, 11	3.12	0.73	1.08
8, 10	3.45	0.75	1.07
9	3.57	0.76	1.05

the sidelobe lower than −20 dB. The required amplitude distribution can be controlled by the radiation conductance of each element [11]. Due to the manufacturing tolerance that the proposed element has a thickness of 2 mm or more, the conventional elements with narrow widths were used around the input and the termination of the antenna, $i = 1, 2, 16$, and 17, for a small radiation conductance. The proposed elements were arranged from $i = 3$ to 15 for a relatively higher radiation conductance. The width and length of each element were determined from the unit design in Fig. 7, according to the relative conductance required for the Taylor distribution of −20 dB sidelobe. After fine optimization, the final parameters were determined for the comb-line array antenna as given in Table 1.

A comb-line array antenna with the conventional rectangular elements, as shown in Fig. 8, was also designed for comparison. The number of the radiating elements and the relative radiation conductance of each element were made equal to those of the array antenna with the proposed elements. Except for the radiating elements, the design method and procedure were the same as those of the proposed elements. The designed parameters of the comb-line array antenna with only the conventional elements were also given in Table 2.

IV. SIMULATION AND MEASUREMENT RESULTS

Figure 9 illustrates the simulated radiation patterns at 79 GHz of the two designed array antennas and the array factor calculated with the desired radiation conductance of each element. For the sidelobe levels, the level is well suppressed to −20.5 dB for the array with the proposed plus conventional elements, however, the level is −16.8 dB for the array with the conventional elements; in the former array, the suppressed sidelobe level as designed reveals that the amplitude distribution of each element is well tapered as desired, but the latter is not. This is because, as discussed in the previous section, the relative radiation conductance for co-polarization in the wide conventional elements is lower than the desired value because the radiation conductance for cross-polarization is large.

To confirm the feasibility of the proposed elements for the comb-line array antenna, we fabricated the prototype antennas with the proposed plus conventional elements as well as the conventional elements, as shown in Fig. 10. The inputs of the array antennas were matched to a 50 Ω microstrip line with a quarter-wave transformer for measurement [16]. The antenna performance was measured in terms of reflection characteristics and radiation patterns. To make the measurements easy, the prototypes were placed on the metallic jig and connected to a WR-10 standard waveguide through a broadband microstrip-to-waveguide transition with backshort [11], [17].

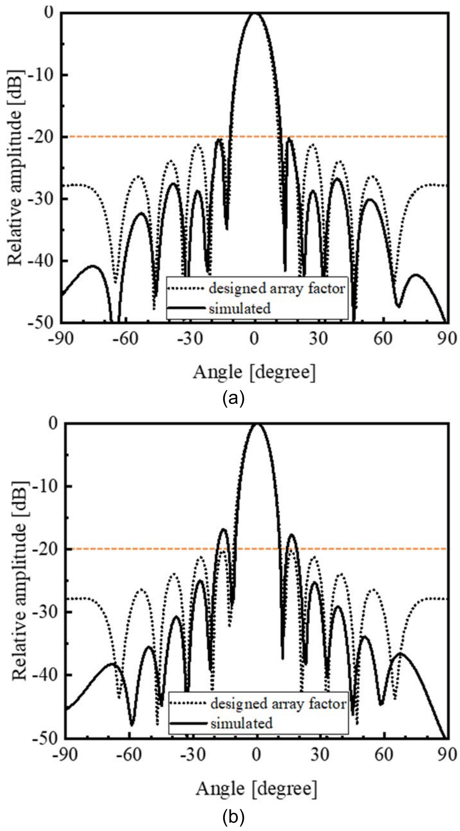

FIGURE 9. Simulated radiation patterns and designed array factor. (a) Comb-line array antenna with the proposed elements and the conventional elements. (b) Comb-line array antenna with the conventional elements.

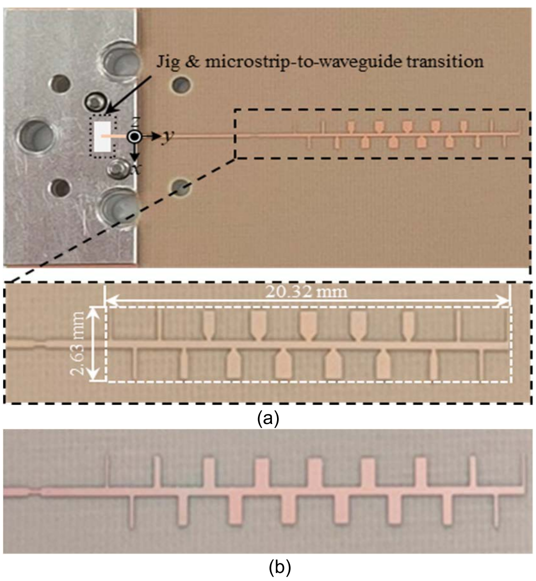

FIGURE 10. Fabricated antenna prototypes. (a) Comb-line array antenna with the proposed plus conventional elements. (b) Comb-line array antenna with the conventional elements.

Figure 11 and 12 show the measured and simulated reflection characteristics for the array antennas with the proposed plus conventional elements and with only the conventional

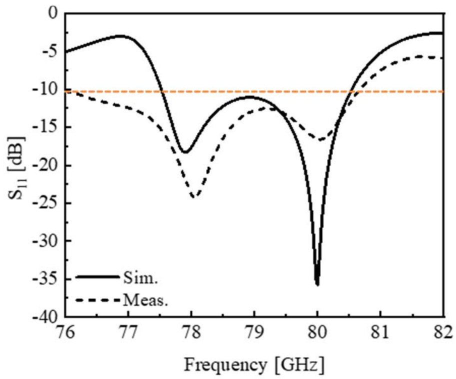

FIGURE 11. Simulated and measured reflection characteristics of the comb-line array with the proposed plus conventional elements.

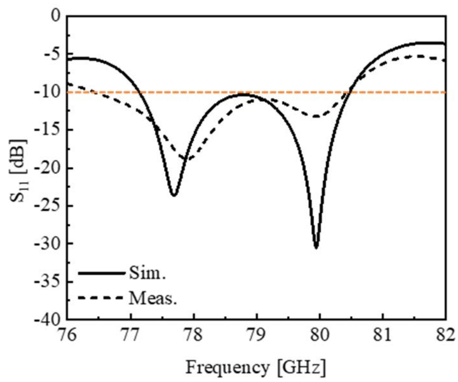

FIGURE 12. Simulated and measured reflection characteristics of the comb-line array antenna with the conventional elements.

elements. The measured frequency bandwidths with −10 dB criterion were 4.67 GHz (76.0–80.67 GHz) and 4.0 GHz (80.43–76.43 GHz) for the arrays with the proposed plus conventional elements and the conventional elements.

Figure 13 illustrates the simulated and measured radiation patterns of the array with the conventional elements in the *yz*-plane and *xz*-plane at 78, 79, and 80 GHz. The measured patterns are well agreed with the simulated ones in both planes. The antenna gains were 14.48 dBi and 16.48 dBi in measurement and simulation. However, the measured and simulated SLLs were −16.9 dB and −15.9 dB, respectively, and were not suppressed to the target level of −20 dB. These high SLLs explain that the amplitude distribution for co-polarization does not satisfy the desired ratio values for the sidelobe below −20 dB in the array.

The simulated and measured radiation patterns of the array antenna with the proposed plus conventional elements are also presented in Fig. 14. The measured patterns are in good agreement with the simulated ones in both planes, and SLLs below −20 dB are achieved at all the measured frequencies of 78, 79, and 80 GHz. The SLLs were −21.9 dB and −21.0 dB in the measurement and simulation at the design frequency of 79 GHz. The measured and simulated maximum gains were 15.31 dBi and 16.92 dBi at the design

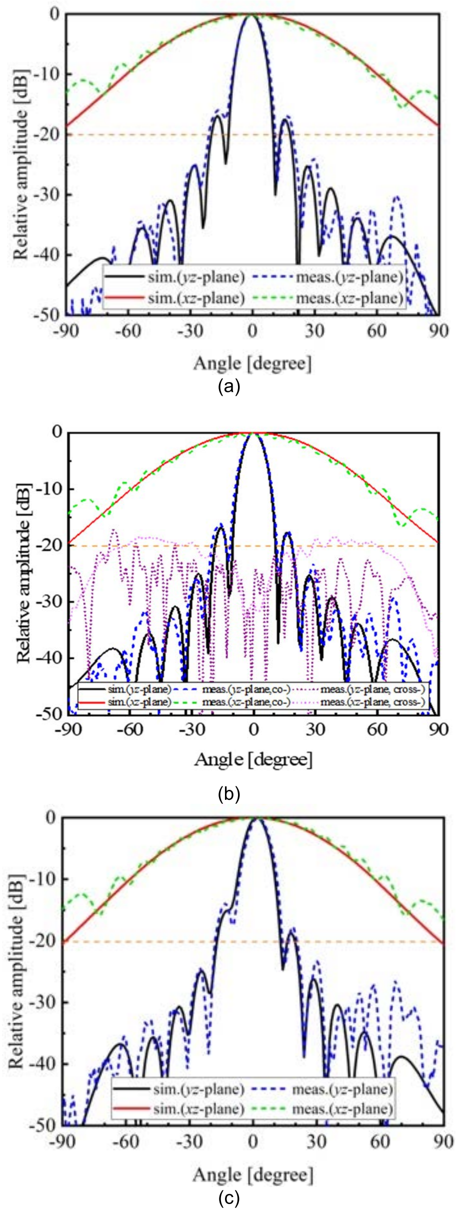

FIGURE 13. Radiation patterns of the comb-line array antenna with the conventional elements. (a) 78 GHz. (b) 78 GHz. (c) 80 GHz.

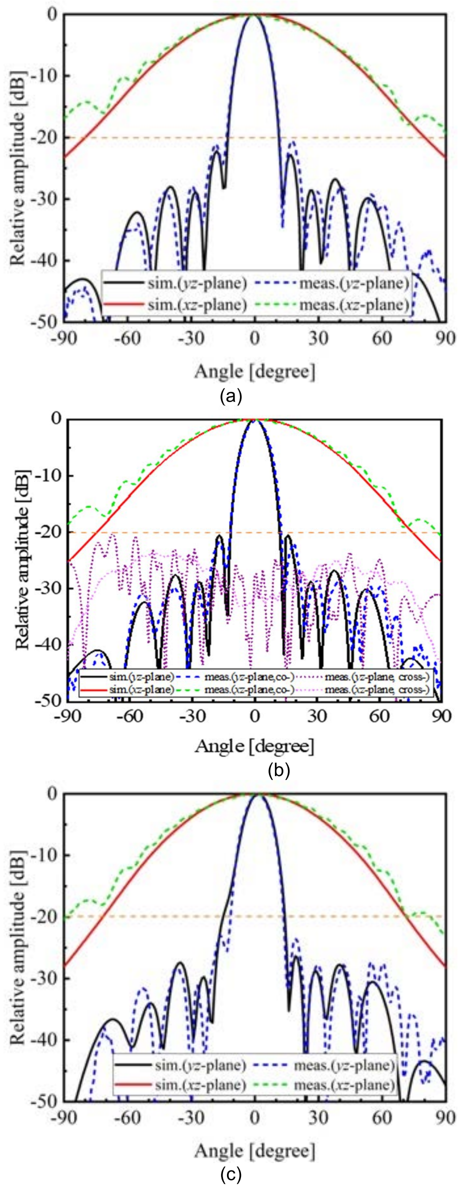

FIGURE 14. Radiation patterns of the comb-line array with the proposed plus conventional elements. (a) 78 GHz. (b) 79 GHz. (c) 80 GHz.

frequency of 79 GHz in the boresight direction. The measured (simulated) antenna gain was also improved by 0.83 dBi (0.44 dBi) by using the proposed elements compared to the array with the conventional elements. The gain differences between measurement and simulation may be explained by losses in the substrate material and feeding lines [2], [5]. The antenna aperture efficiency was evaluated to be 72.8% at 79 GHz by using the relationship in [5]. The above results reveal that the radiation conductance is accurately distributed as designed to achieve the SLL below −20 dB by using the proposed elements and confirm that the proposed element is useful to the comb-line array antenna for easy and accurate design.

TABLE 3. Comparison of the proposed work with published Comb-Line array antennas.

	Array	Design Frequency (GHz)	Field distribution	SLL (dB)	Gain(dBi)
[11]	1×18	79	Taylor	-19.3	13.94
[9]	1×25	76.5	Taylor	-16	17.56
[7]	1×13	77	Taylor	-17.2	10.73
[18]	1×13	76.5	Taylor	-16.5	11.4
our work	1×17	79	Taylor	-21.9	15.31

A comparison between this work and reported comb-line array designs with −20 dB Taylor distribution is presented in Table 3. Contrary to our work, except for [11], the other arrays have higher SLLs than the designed −20 dB. This means that for low sidelobe level designs it is important to use the radiating elements with a dominant co-polarized radiation power. Finally, the gain of the proposed array is also comparable to those of the comparison arrays.

V. CONCLUSION

In this paper, we proposed a deformed radiating element for low SLL. The proposed element has a narrow connection with the feeding line by cutting obliquely the connection part from a rectangular element. The longitudinal currents on the proposed element dominate the total radiation

conductance (or power), and negligibly low conductance for cross-polarization is expected. The proposed element is useful in designing a millimeter-wave comb-line array antenna with a low SLL, in which the wider element is used to taper the amplitude distribution. In addition, a low cross-polarization is expected in the proposed element.

The comb-line array antenna using the proposed radiating elements was designed for the sidelobe below −20 dB at the design frequency of 79 GHz. The array antenna using only the conventional elements was also designed for comparison. The measurement and simulation of the two antennas showed a good agreement in reflection characteristics and radiation patterns. However, the measured SLL was −21.9 dB and −16.9 dB for the array antenna with the proposed plus conventional elements and the conventional elements. Considering the target sidelobe below −20 dB, the proposed element is demonstrated to be useful for the comb-line array antenna design with ease and accuracy. Although 17-element linear array is presented in this paper, the number of elements can be suitably determined depending on the antenna requirement according to the various applications, and can also be expanded to a planar configuration.

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JAE-HO LEE was born in Daegu, South Korea, in 1974. He received the B.S. degree in electronic and electrical engineering from Kyungpook National University, Daegu, in 2002, the M.S. degree in electrical and electronic engineering from the Korea Advanced Institute of Science and Technology (KAIST), Daejeon, South Korea, in 2004, and the Ph.D. degree in electrical and electronic engineering from the Tokyo Institute of Technology (TIT), Tokyo, Japan, in 2010. From 2004 to 2005, he worked at the Mobile Communication PM Team, Institute of Information and Technology Assessment (IITA), Daejeon. From 2010 to 2012, he worked with the Radar Research Center, Samsung Thales, Yongin, Gyeonggi-do, South Korea. Since 2013, he has been a Principle Researcher at the Electronics and Telecommunications Research Institute (ETRI), South Korea. His research interests include waveguide slot arrays, millimeter-wave antennas, radar systems, biomedical implantable devices, and magnetic communications. He received a Presidential Award for Leaders of the 21st Century from the Ministry of Education of Korea, in 2002.

SANG-HOON LEE received the B.S. and M.S. degrees in radio communication engineering from Korea Maritime and Ocean University (KMOU), Busan, South Korea, in 2018 and 2021, respectively.

HYUN JOON LEE received the B.S., M.S., and Ph.D. degrees from the Department of Physics, Pusan National University, Busan, South Korea, in 2008, 2011, and 2018, respectively. From 2018 to 2019, he was a Postdoctoral Associate in optical magnetometry with the Korea Research Institute of Standards and Science. Since 2019, he has been with the Electronics and Telecommunications Research Institute, Daejeon, South Korea. His research interests include ultra-low field magnetic resonance and the development of highly sensitive quantum sensors.

JUNG-HOON OH received the B.S. degree in electronics from Kyungpook National University, Daegu, South Korea, in 1997, and the M.S. degree in electronic engineering from the Korea Advanced Institute of Science and Technology (KAIST), Daejeon, South Korea, in 1999.

He is currently with the Electronics and Telecommunications Research Institute (ETRI), Daejeon. His research interests include magnetic field communication in extreme environments and atomic-based electric field measurement.

JANG-YEOL KIM received the B.S., M.S., and Ph.D. degrees in information and communication engineering from Chungbuk National University, Cheongju, South Korea, in 2010, 2012, and 2017, respectively. Since 2012, he has been with the Electronics Telecommunications Research Institute (ETRI), Daejeon, South Korea. His research interests include antenna design, thermal therapy algorithms, microwave sensing, and magnetic transceiver systems.

IN-KUI CHO received the B.S. and M.S. degrees from the Department of Electronic Engineering, Kyungpook National University, Daegu, South Korea, in 1997 and 1999, respectively, and the Ph.D. degree in electrical engineering from the Korea Advanced Institute of Science and Technology (KAIST), Daejeon, South Korea, in 2007. Since May 1999, he has been with the Electronics and Telecommunications Research Institute (ETRI), Daejeon, where he has designed and developed optical backplane, optical chip-to-chip interconnect system, and magnetic resonance wireless power transfer. His current research interests include simulation and development of WPT components and magnetic field communication, such as planar magnetic resonators, magnetic resonators for three-dimensional WPT and electromagnetic sensors, and magnetic transceiver systems.

DONG-WOOK SEO (Senior Member, IEEE) received the B.S. degree in electrical engineering from Kyungpook National University, Daegu, South Korea, in 2003, and the M.S. and Ph.D. degrees in electrical engineering from the Korea Advanced Institute of Science and Technology (KAIST), Daejeon, South Korea, in 2005 and 2011, respectively. From 2011 to 2012, he was a Senior Researcher with the Defense Agency for Technology and Quality (DTaQ), Daegu. From 2012 to 2017, he was a Senior Researcher with the Electronics and Telecommunications Research Institute (ETRI), Daegu. Since September 2017, he has been with Korea Maritime and Ocean University (KMOU), Busan, South Korea, where he is currently an Associate Professor with the Division of Electronics and Electrical Information Engineering. His current research interests include numerical techniques in areas of electromagnetics, radar cross-section analysis, wireless power transfer, and automotive radar systems.