

High-Gain Patch Antenna with Stacked Director Patches Using an End-Fire Theory for Microwave Power Transfer Applications

Changhyeon Im¹  · Eunjung Kang²  · Hosung Choo^{1,*} 

Abstract

This paper proposes a high-gain patch antenna with stacked director patches. The proposed antenna is composed of a driven patch and seven stacked director patches, which enable it to achieve high gain. The driven patch is printed on a TLY-5 substrate, and the director patches are stacked in seven layers on top of the driven patch. The proposed antenna has a reflection coefficient of -21.7 dB at 5.8 GHz. The bore-sight gain of the proposed antenna is improved by 6.65 dB on average over the frequency range from 5.4 GHz to 6.2 GHz compared to a driven patch without director patches. At 5.8 GHz, the measured bore-sight gain is 12.5 dBi, which is a 5.5 dB increase compared to a driven patch without director patches. The measured half-power beamwidths are 48° and 42° in the zx - and zy -planes, respectively.

Key Words: End-Fire Theory, High-Gain Antenna, Microwave Power Transmission (MPT), Stacked Director.

I. INTRODUCTION

Wireless power transmission (WPT) technologies have been used to supply power to various electronic applications, such as smartphones, vehicles, and medical devices [1–9]. These WPT technologies are typically classified into three types: magnetic induction, magnetic resonance, and microwave radiation. In particular, microwave power transmission (MPT) has the advantage of transmitting power from a single transmit antenna (Tx) to a receive antenna (Rx) located in various directions through electronic beam steering if the Tx is designed as an array antenna [10–14]. In addition, compared to magnetic induction and magnetic resonance, MPT can transmit power over

longer distances [15–17]. However, the drawback of MPT is that as the distance between a Tx and an Rx increases, propagation loss in free space also increases, which results in lower transmission efficiency. To overcome this problem, extensive efforts have been made to enhance the gain of the Tx by using back-to-back structures to microstrip antennas [18, 19], metasurfaces [20, 21], and superstrates on the patch antenna [22]. Although these antennas can achieve high-gain characteristics, they have several disadvantages, including high fabrication costs, complicated design processes, and bulky, heavy structures.

In this paper, we propose a high-gain patch antenna with director patches to enhance the gain for MPT applications. The proposed antenna is composed of a driven patch and seven stacked

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¹Department of Electronic and Electrical Engineering, Hongik University, Seoul, Korea.

²Agency for Defense Development, Daejeon, Korea.

*Corresponding Author: Hosung Choo (e-mail: hschoo@hongik.ac.kr)

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director patches. The driven patch is printed on a substrate and designed to operate the antenna at the fundamental mode. Then, seven director patches, which have the same distance between them, are stacked above the driven patch to enhance the bore-sight gain. The width of each director patch is determined using an arithmetic sequence. To obtain theoretical insight into gain enhancement, the end-fire array concept is applied to the proposed antenna based on the conventional Yagi antenna principle. To verify the theoretical approach, the radiation patterns obtained by simulation using the simulation software CST Studio Suite Full EM [23] are compared with those obtained by theory. To verify the feasibility of the proposed antenna, it is fabricated and measured in a full anechoic chamber to obtain the antenna properties, such as reflection coefficients, radiation patterns, and gains. The results demonstrate that the proposed antenna has high-gain characteristics and is suitable for MPT applications.

II. PROPOSED ANTENNA DESIGN AND ANALYSIS

Fig. 1 shows the geometry of the proposed high-gain patch antenna with stacked director patches. The proposed antenna consists of a driven patch and seven stacked director patches. The driven patch has a length w_r and is printed on a TLY-5 substrate ($\epsilon_r = 2.2$, $\tan\delta = 0.0009$) with dimensions of $w_s \times w_s \times t_s$ (width $\times$ length $\times$ thickness). To operate the antenna in the fundamental mode (TM_{010}), w_r is derived according to Eq. (1):

$$w_r = \frac{\lambda_0}{2\sqrt{\epsilon_r}}, \quad (1)$$

where λ_0 is the wavelength at an operating frequency of 5.8 GHz, and ϵ_r is the permittivity of the substrate. Above the

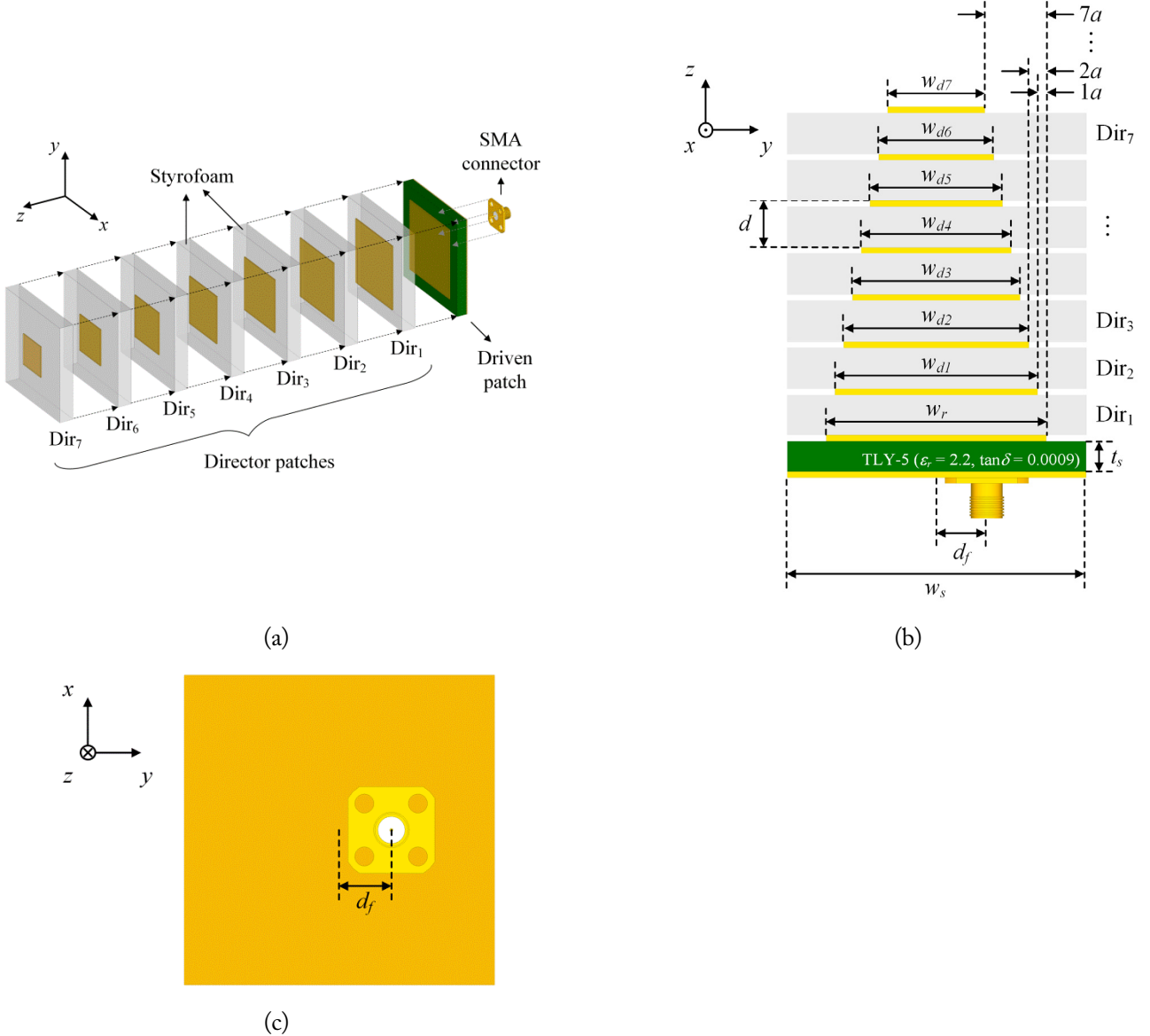


Fig. 1. Geometry of the proposed antenna: (a) isometric view, (b) top view, and (c) bottom view.

driven patch, seven director patches ($\text{Dir}_1, \text{Dir}_2, \dots, \text{Dir}_7$) are stacked at a distance d of $0.15\lambda_0$. The director patches can enhance bore-sight gain using an end-fire array based on the conventional Yagi antenna principle. Each director has a width of w_{dn} , which is determined by Eq. (2), expressed as an arithmetic sequence:

$$w_{dn} = w_r - (2 \times a) \times n, \quad (2)$$

where n is the order of the director patch and $2 \times a$ is the common difference of the arithmetic sequence. Styrofoam substrates ($\epsilon_r = 1.11$) with dimensions of $w_s \times w_s \times d$ (width $\times$ length $\times$ thickness) are employed, and the director patches are attached on top of the substrates. The antenna is fed directly by an SMA connector from the bottom of the driven patch, and the feeding point is denoted as d_f , which is the y -axis distance from the center of the driven patch.

Fig. 2(a) illustrates a side view of a conceptual patch antenna with stacked director patches applying the end-fire array. To obtain theoretical insight, we analyzed the patch antenna with stacked director patches using the end-fire array. The geometry of the proposed antenna can be assumed to be that of an end-fire array because it has a similar geometry to the Yagi antenna, an antenna which has the geometry of an end-fire array. To observe the tendency of the array gain, the radiation pattern of the array elements was calculated, and based on this, the array gain was obtained by varying the distance between the patch elements and their phases. The far-field radiation pattern of each array element (G_n) was obtained using Eq. (3):

$$G_n(\theta) = A(\theta)e^{j(n-1)(kd\cos\theta+\varphi)}, \quad (3)$$

where $A(\theta)$ is the magnitude of the radiating pattern for a conventional patch antenna, d is the distance between each element, and φ is the phase difference. The total radiation pattern (G_{total}) is expressed by Eq. (4):

$$G_{total}(\theta) = \sum_{n=1}^N G_n(\theta), \quad (4)$$

where N is the number of patches. In this study, the N of the proposed antenna was 8, which is the sum of one driven patch and seven director patches. Fig. 2(b) shows a comparison of the simulated and theoretical far-field radiation patterns. Solid and dashed lines indicate the theory and simulation results according to the application of the end-fire array, respectively, and the dotted line indicates the single-patch antenna. To verify the analysis of the theoretical approach, the radiation patterns of the end-fire array were compared with the results using CST. The theoretical bore-sight gain of the arrayed antennas was 11.7 dBi, an increase of 5.3 dB compared to the single-patch antenna. The simulated bore-sight gain of the arrayed antennas was 11.6 dBi, an increase of 5.2 dB compared to the single-patch antenna. These results showed similar tendencies of gain enhancement when applying stacked director patches using an end-fire array. Based on these results, the design variables were optimized through parameter studies for driven patches and director patches to maximize the gain.

Fig. 3 shows the simulated bore-sight gains in accordance with w_r and a . The results show bore-sight gain in the parameter ranges of $15 \text{ mm} \leq w_r \leq 17 \text{ mm}$ and $0 \text{ mm} \leq a \leq 0.5 \text{ mm}$. A maximum gain of 11.6 dBi was obtained when

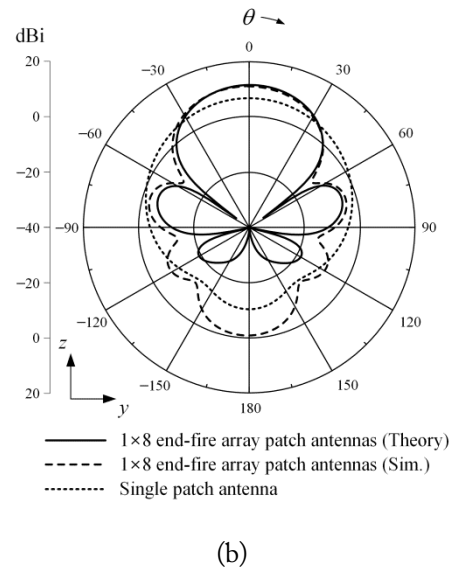
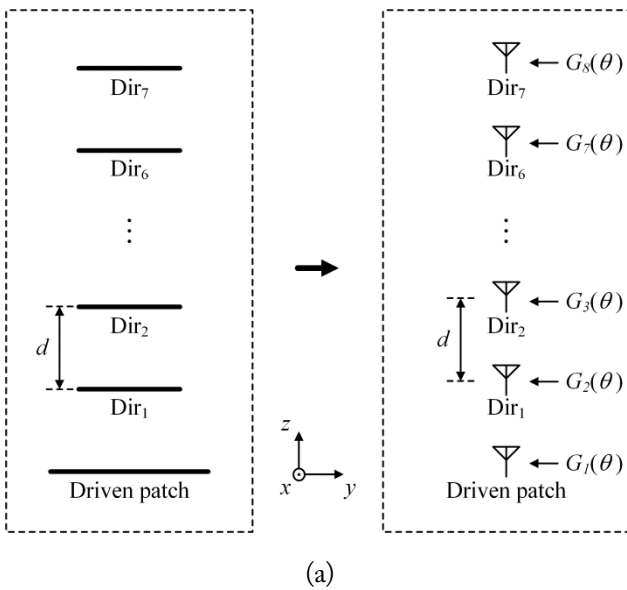


Fig. 2. Conceptual patch antenna with stacked director patches applied with the end-fire array concept: (a) side view and (b) comparisons of simulated and theoretical far-field radiation patterns.

the optimal values of w_r and a were 16.3 mm ($0.32\lambda_0$) and 0.15 mm ($0.003\lambda_0$), respectively. Fig. 4 presents the simulated bore-sight gains according to the number of director patches n and distance d . Considering the limitation of the mounting space size of our MPT system, the bore-sight gain was observed within the range where the total antenna height $h = d \times (n - 1)$ was less than 60 mm. Within this range, the maximum gain was found when n and d were 7 and 8 mm ($0.15\lambda_0$), respectively. The optimized design parameters are listed in Table 1.

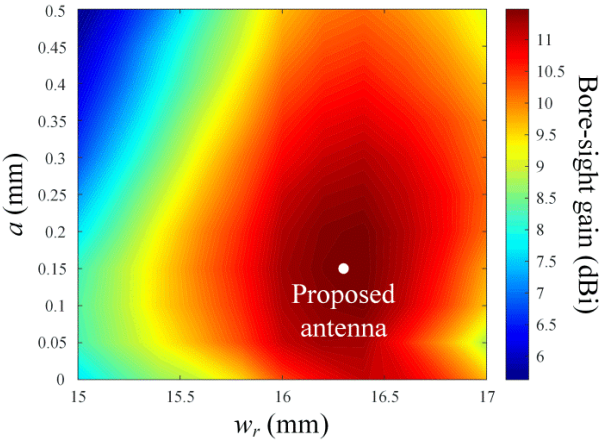


Fig. 3. Bore-sight gain in accordance with parameters w_r and a .

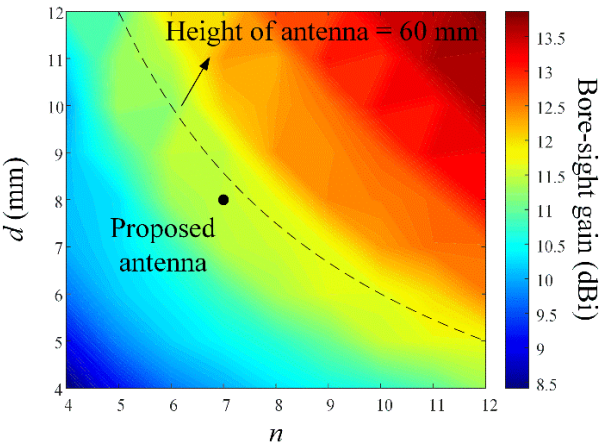


Fig. 4. Bore-sight gain in accordance with parameters n and d .

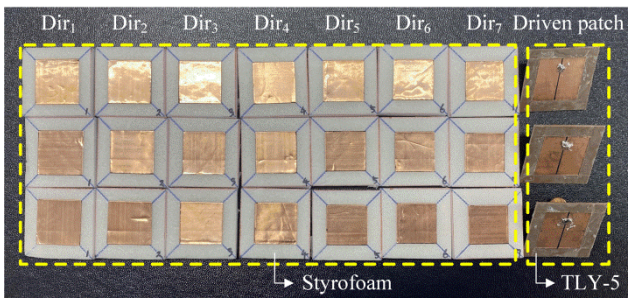
III. ANALYSIS

Fig. 5 presents photographs of the fabricated high-gain patch antenna, which consists of a driven patch and director patches. The driven patch is fabricated on a TLX-5 substrate with a thickness of 0.8 mm ($0.015\lambda_0$). As shown in Fig. 5(a), there are seven director patches, and they decrease in width from Dir₁ to Dir₇. These director patches are attached on Styrofoam with a thickness of 8 mm ($0.15\lambda_0$). Fig. 5(b) represents the isometric view of the fabricated antenna. Director patches attached to Styrofoam are stacked on top of the driven patch. Fig. 5(c) shows the bottom view of the fabricated antenna, which is fed by the SMA connector.

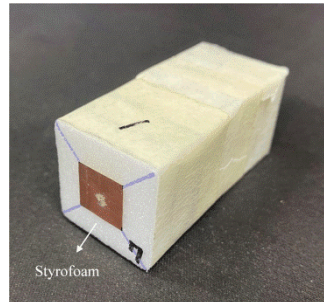
Fig. 6 represents the reflection coefficients of the proposed antenna, where solid and dashed lines indicate the measured and simulated results, respectively. The measured reflection coefficient is less than -10 dB from 5.64 GHz to 5.89 GHz (fractional bandwidth of 4.3%), and the simulated reflection coefficient is less than -10 dB from 5.66 GHz to 5.89 GHz (fractional bandwidth of 4.0%). In particular, at 5.8 GHz, the measured and simulated reflection coefficients are -21.7 dB and -14.7 dB. Fig. 7 shows the measured and simulated bore-sight gains of the proposed antenna. To confirm the bore-sight gain improvement of the proposed antenna, the average bore-sight gains with and without director patches were compared in the

Table 1. Parameters of the proposed antenna

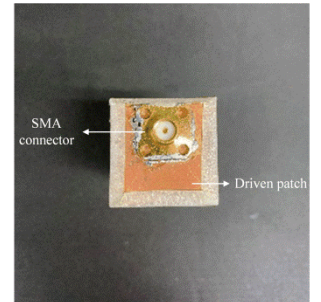
Parameter	Value (mm)	Parameter	Value (mm)
w_r	16.3	w_{d6}	14.5
w_s	25	w_{d7}	14.2
w_{d1}	16	d	8
w_{d2}	15.7	d_f	4.5
w_{d3}	15.4	a	0.15
w_{d4}	15.1	ts	0.8
w_{d5}	14.8	—	—



(a)



(b)



(c)

Fig. 5. Photographs of the proposed antenna: (a) director patches and the driven patch, (b) isometric view, and (c) bottom view.

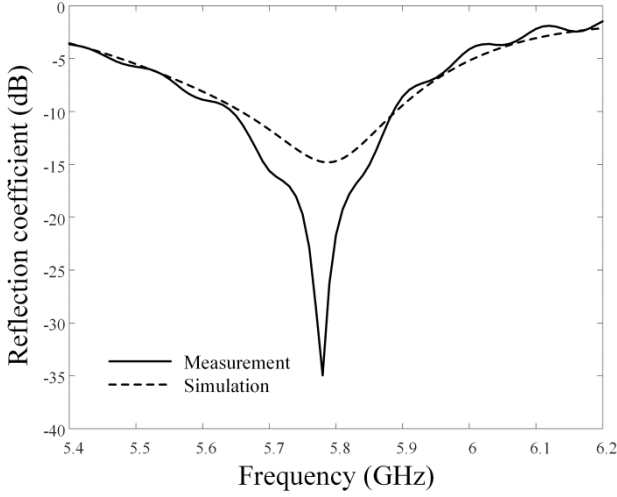


Fig. 6. Measured and simulated reflection coefficients of the proposed antenna.

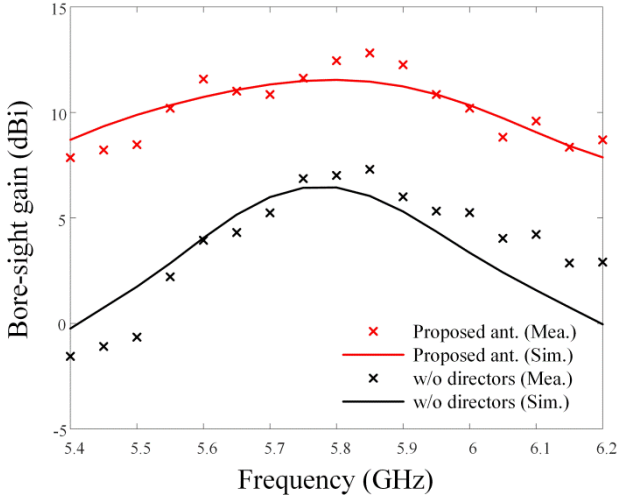
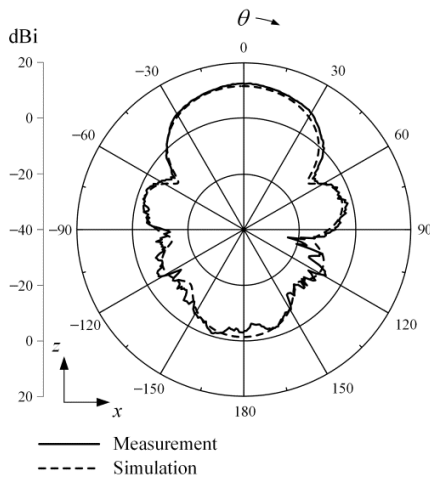
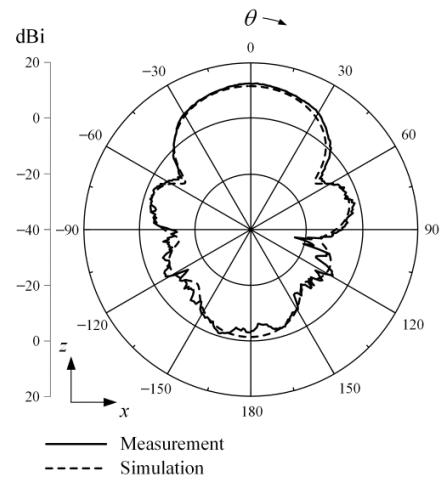


Fig. 7. Measured and simulated bore-sight gains of the proposed antenna and the driven patch without director patches.



(a)



(b)

Fig. 8. Measured and simulated 2D radiation patterns of the proposed antenna at 5.8 GHz: (a) zx -plane and (b) zy -plane.

frequency range from 5.4 GHz to 6.2 GHz. The "x" markers and solid line in Fig. 7 indicate the measurement and simulation results, respectively. The average bore-sight gains with and without director patches were 10.3 dBi and 3.6 dBi. The average gain improvement of 6.25 dB was achieved by applying the end-fire array with director patches. More specifically, at a target frequency of 5.8 GHz, the measured and simulated bore-sight gains of the proposed antenna were 12.5 dBi and 11.6 dBi. On the other hand, without director patches, the measured and simulated bore-sight gains were 7 dBi and 6.4 dBi, respectively. Fig. 8 illustrates the measured and simulated 2D radiation patterns of the proposed antenna in the zx - and zy -planes at 5.8 GHz. The measured and simulated half-power beamwidths (HPBW) can be seen to be 48° and 50° in the zx -plane, while they are 42° and 44° in the zy -plane. These results demonstrate that the proposed antenna is suitable for MPT applications due to its high-gain characteristics.

IV. CONCLUSION

In this paper, we have proposed a high-gain patch antenna with stacked director patches. To achieve a high gain, the antenna performance was analyzed from the perspective of an end-fire array. The driven patch was printed on a substrate, and the director patches were stacked in seven layers on top of the driven patch. The proposed antenna achieved a reflection coefficient of -21.7 dB at 5.8 GHz. The bore-sight gain was improved by 6.25 dB on average over the frequency range from 5.4 GHz to 6.2 GHz compared to the case of the driven patch without director patches. At 5.8 GHz, the measured bore-sight gain was 12.5 dBi, which was an increase of 5.5 dB compared to the driven patch without director patches. The measured HPBW were 48° and 42° in the zx - and zy -planes, respectively.

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Changhyeon Im

<https://orcid.org/0000-0002-8973-4398>



received his B.S. degree in electronic and electrical engineering in 2021 from Hongik University, Seoul, South Korea, where he is currently pursuing a Ph.D. degree in electronic and electrical engineering. His research interests include mesh reflector antennas, 5G applications, wireless power transfers, and UWB antennas.

Hosung Choo

<https://orcid.org/0000-0002-8409-6964>



received his B.S. degree in radio science and engineering from Hanyang University, Seoul, South Korea, in 1998, and his M.S. and Ph.D. degrees in electrical and computer engineering from the University of Texas at Austin, in 2000 and 2003, respectively. In September 2003, he joined the School of Electronic and Electrical Engineering, Hongik University, Seoul, where he is currently a professor. His principal areas of research include electrically small antennas for wireless communications, reader and tag antennas for RFID, on-glass and conformal antennas for vehicles and aircraft, and array antenna for GPS applications.

Eunjung Kang

<https://orcid.org/0000-0002-0265-1144>



received her B.S. degree in electronic and electrical engineering from Hongik University, Sejong, South Korea, in 2016, and her M.S. and Ph.D. degrees in electronic and electrical engineering from Hongik University, Seoul, South Korea, in 2020 and 2024, respectively. She was a Research Engineer with the Korea Electronics Technology Institute (KETI), Seongnam, South Korea, from 2016 to 2017. She is currently a senior researcher with the Agency for Defense Development, Daejeon, South Korea. Her research interests include array antenna for electronic warfare, wireless power transfer systems, LEO satellite electromagnetic wave propagation, direction finding, and GPS antennas.