High Gain Dual-Polarized Cross-Slot Antenna for Next-Generation Railway Communications

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***Abstract*—This paper presents a high gain and dual-polarized antenna for next-generation railway communications. In practical railway communication scenarios, the channels are characterized as line-of-sight (LOS) and non-line-of-sight (NLOS) conditions. Therefore, an antenna providing high gain and dual polarization under both LOS and NLOS conditions is required. The proposed antenna achieves high gain through a cross-slot structure and supports dual polarization through its symmetrical geometry and orthogonally positioned equal feed configuration. The antenna is modeled as an array of equivalent magnetic currents, and this array configuration contributes to the gain enhancement. It achieves a 10-dB impedance bandwidth of 130 MHz, 125MHz and a peak gain of 11.70 dBi, 11.45dBi respectively for ports 1 and 2. These results confirm the potential for deployment in next-generation railway communications.**

***Keywords*— High gain antenna, dual-polarization, cross-slot structure, private 5G, railway communications.**

I. Introduction

Recently, in Korea, active research is underway to develop a next-generation railway communication network by designating the 4.7 GHz band within the private 5G spectrum as the private 5G-R (Railway) band and securing 100 MHz of bandwidth [1]. A railway communication system based on private 5G-R can offer improved performance, including low latency, high data rates, and enhanced reliability compared to a conventional communication system based on LTE-R (Long-Term Evolution-Railway). These capabilities can accelerate the digital transformation of the railway industry by enabling autonomous train operation, real-time inter-wagon and wagon-to-infrastructure communication and train maintenance utilizing AR (Augmented Reality) and VR (Virtual Reality) [2]. To secure the bandwidth to provide these functions, the 5G-R systems operate in a higher frequency band than the conventional LTE-R systems, which increases the path loss. Meanwhile, in practical railway communication scenarios, Line-of-sight (LOS) conditions are often obstructed by trackside objects, surrounding infrastructure, and railway structures such as tunnels and retaining walls. Therefore, both LOS and non-line-of-sight (NLOS) scenarios should be considered when designing antennas for railway communication systems [3], [4]. In NLOS conditions, wave propagation primarily occurs through indirect mechanisms such as reflection, diffraction and scattering. These interactions cause changes in the propagation characteristics and induce depolarization, which means a change in the original polarization state.

This paper presents a high gain, dual-polarized cross-slot antenna for next-generation railway communications (5G-R).

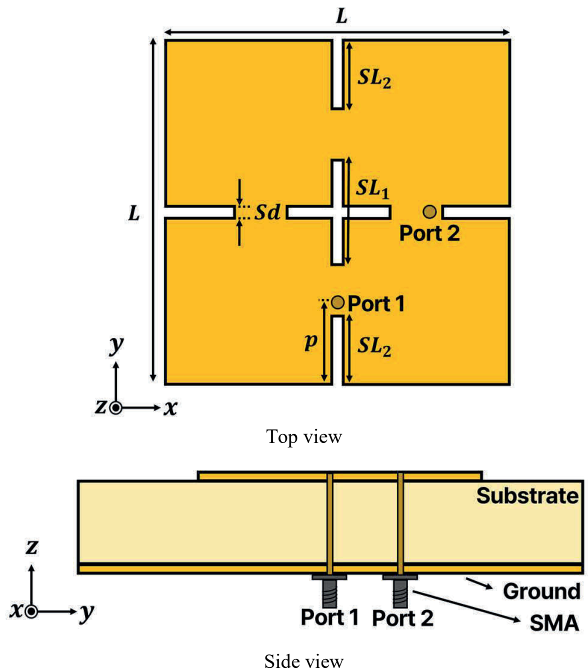
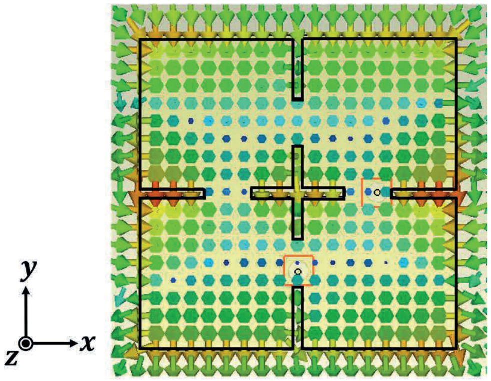


Fig. 1. Geometry of the proposed antenna.

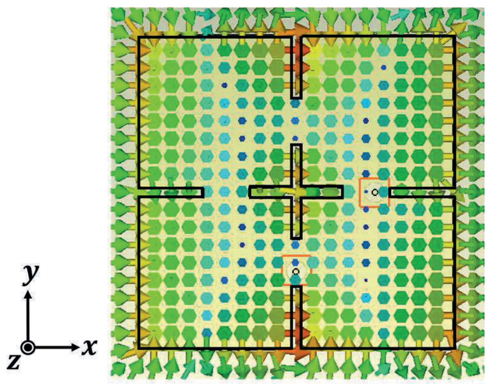
The proposed antenna design includes a symmetrical geometry to support dual polarization and a cross-slot structure for gain enhancement. The high gain and dual polarization characteristics of the proposed antenna compensate for the signal attenuation due to path loss and can effectively receive the depolarized signals in the NLOS conditions. As a result, the proposed antenna has characteristics suitable for the practical railway communication environment of 5G-R.

TABLE I. DESIGN PARAMETERS

Parameters	Length	Electrical length
L	45.8 mm	$0.728\lambda_0$
SL_1	13.7 mm	$0.218\lambda_0$
SL_2	9.16 mm	$0.146\lambda_0$
Sd	1.2 mm	$0.019\lambda_0$
p	11.4 mm	$0.181\lambda_0$



(a)



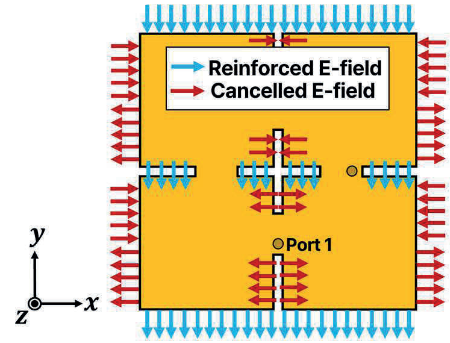
(b)

Fig. 2. (a) Electric field distribution of the proposed antenna excited through port 1. (b) Electric field distribution of the proposed antenna excited through port 2.

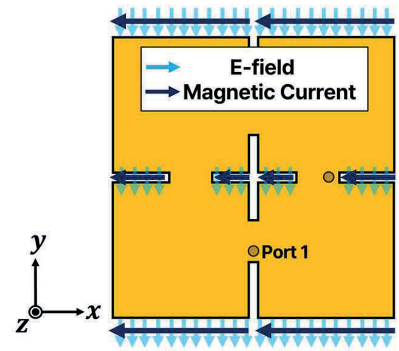
II. Antenna Design

The geometry of the proposed antenna is shown in Fig. 1. It is designed on a single-layer Taconic RF-30 substrate with a thickness of 3.04 mm, a relative permittivity of 3, and a loss tangent of 0.0014. The overall physical dimensions of the proposed antenna are 102 mm × 102 mm. A cross-shaped slot is loaded at the center, and four side slots are symmetrically loaded along the x- and y-directions at equal distance from the central cross-shaped slot. The antenna is excited by two ports located at equal distances in the x- and y-directions from the center. The detailed design parameters were optimized through full-wave simulation and are summarized in Table I. The simulated electric field distributions of the proposed antenna are shown in Fig. 2. Figs. 2(a) and 2(b) correspond to the cases when the proposed antenna is excited through port 1 and port 2, respectively. When the antenna is excited through port 1, the electric fields along the x-axis edges are oriented in the same direction on both sides, whereas the fields along the y-axis edges are oriented in opposite directions across the center. Conversely, when the antenna is excited through port 2, the fields along the y-axis edges are oriented in the same direction across the center.

Figs. 3(a) and 4(a) illustrate simplified models of these electric field distributions under excitation from both ports. In Figs. 3(a) and 4(a), the blue and red arrows indicate the electric fields with constructive interference and destructive interference, respectively. The electric fields indicated by blue arrows reinforce each other, while those indicated by red arrows cancel each other out. Therefore, the electric fields

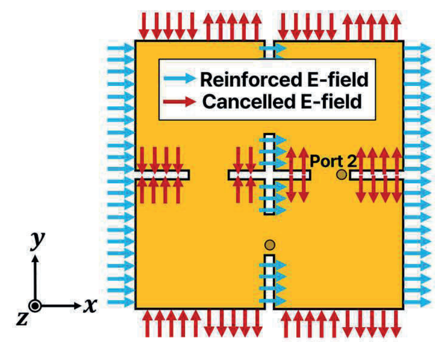


(a)

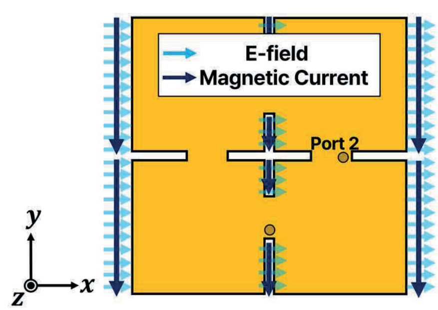


(b)

Fig. 3. (a) Simplified model of electric field distribution of the proposed antenna excited through port 1. (b). Equivalent magnetic current distribution of the proposed antenna excited through port 1.

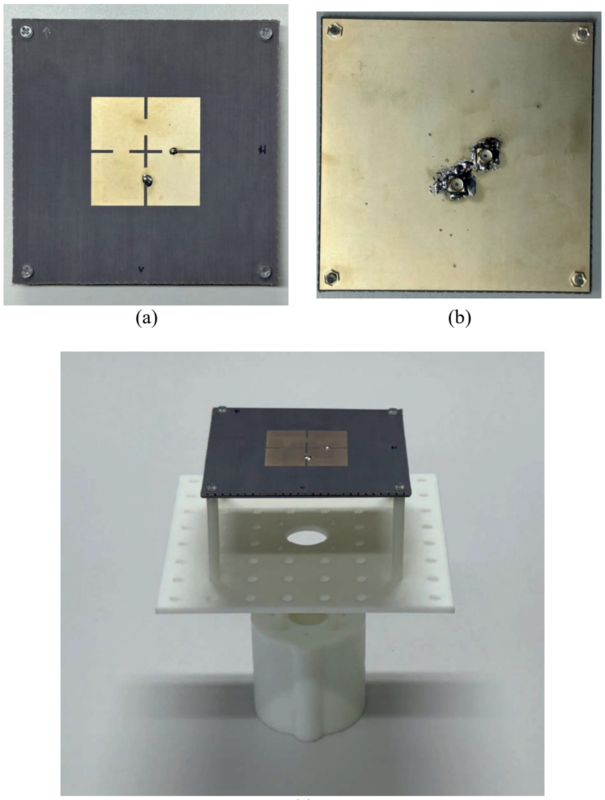


(a)



(b)

Fig. 4. (a) Simplified model of electric field distribution of the proposed antenna excited through port 2. (b). Equivalent magnetic current distribution of the proposed antenna excited through port 2.



(a) (b)

(a)

Fig. 5. Fabricated cross-slot antenna: (a) top view, (b) bottom view, (c) mounted on the jig

indicated by the blue arrows mainly contribute to radiation. These radiated electric fields can be modeled as equivalent magnetic currents based on Huygens' principle [5]. The equivalent magnetic currents can be derived using equation (1), where $\vec{M}$, $\vec{E}$, and $\hat{n}$ represent the magnetic current, electric field, and the unit normal vector at the boundary, respectively.

$$\vec{M} = -\hat{n} \times \vec{E} \quad (1)$$

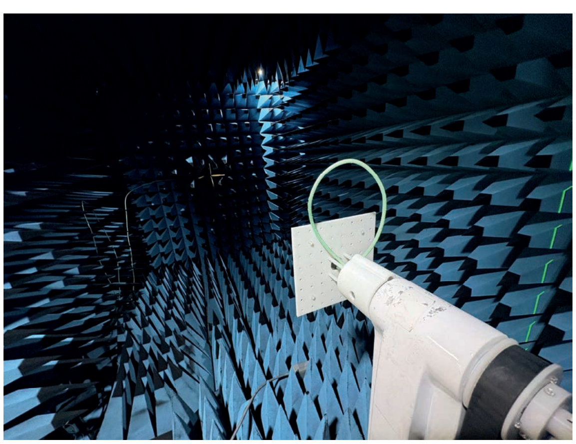
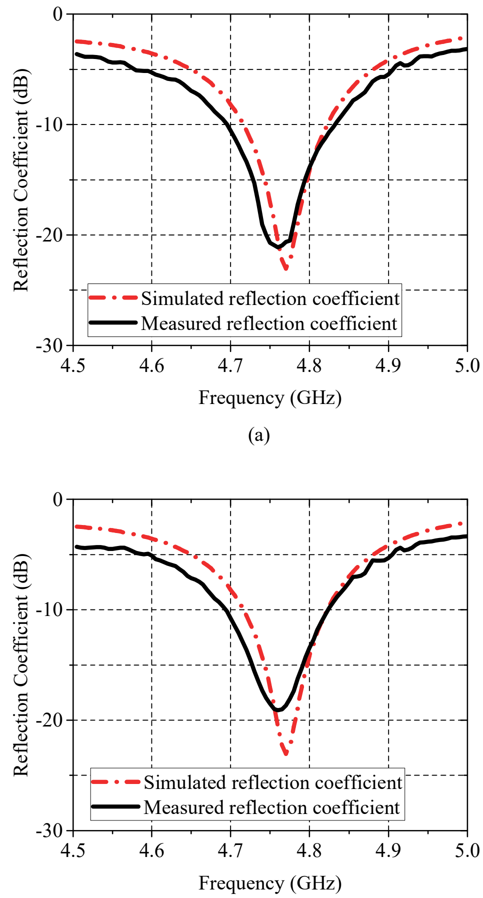


Fig. 6. Radiation pattern measurement in the anechoic chamber



(b)

Fig. 7. Measured and simulated reflection coefficient of the proposed antenna for (a) port 1 and (b) port 2.

The equivalent magnetic current distributions of the proposed antenna are illustrated in Figs. 3(b) and 4(b). The cross-slot structure induces multiple magnetic current paths within the antenna. These magnetic currents, arranged with regular spacing, cause constructive interference in a specific direction, similar to an array antenna, thereby enhancing the antenna gain. From the simplified models shown in Figs. 3 and 4, it can be observed that excitation through port 1 generates a vertically polarized signal, while excitation through port 2 generates a horizontally polarized signal. The symmetrical structure therefore enables dual polarization and improves communication performance by supporting the reception of both polarizations. The symmetrical structure enables dual polarization, while the cross-slot structure provides high gain. Therefore their combined effect confirms the suitability of the proposed antenna for next- generation railway communication systems.

III. Experimental Results

To verify the performance and characteristic of the proposed antenna, the antenna was fabricated on a Taconic RF-30 substrate with a thickness of 3.04 mm, a relative permittivity of 3, a loss tangent of 0.0014, and a 0.035-mm-thick copper layer and two 50-Ω SMA connectors were orthogonally mounted and soldered the antenna to provide feeding as shown in Figs. 5(a) and 5(b). A custom jig was fabricated to guarantee accurate alignment of the measurement of the proposed antenna. The configuration of the jig with the antenna mounted is presented in Fig. 5(c). The reflection coefficients of the fabricated antenna were measured with a vector network analyzer (Anritsu MS46122B), and the radiation patterns were measured in the anechoic chamber as shown in Fig .6. The measured and simulated reflection coefficients of the proposed antenna for ports 1 and 2 are shown in Fig. 7. The simulated 10-dB impedance bandwidths for ports 1 and 2 of the proposed antenna are 4.72–4.82 GHz and 4.72–4.82 GHz, respectively. The measured 10-dB impedance bandwidths for ports 1 and 2 of the proposed antenna are 4.70–4.83 GHz and 4.695–4.82 GHz, respectively, which agree with the simulated 10-dB impedance bandwidths of the antenna for both ports. The observed similarity between the reflection coefficients of port 1 and port 2 arises from the symmetric structure and equal feed configuration of the proposed antenna. This similarity further contributes to the formation of similar radiation patterns for each feeding positions. These results for the proposed antenna meet the frequency specifications of 5G-R, which is the 4.72–4.82 GHz band, thereby confirming its suitability for practical railway communication systems.

The measured and simulated radiation patterns of the proposed antenna at 4.77 GHz for port 1 and port 2 in the zx– and xy-planes are shown in Fig. 8. The simulated peak gains of the proposed antenna are 11.92 dBi and 11.92 dBi for ports 1 and 2 , respectively. The measured peak gains of the cross-slot antenna are 11.70 dBi and 11.45 dBi for for ports 1 and 2 , respectively, which agree well with the simulated results of both antennas. These measured results indicate the high-gain performance of the proposed antennas. This result of the proposed antenna is attributed to the array of equivalent magnetic currents model, further verifying the effectiveness of the proposed approach. Figs. 8(a) and 8(b) illustrate the antenna characteristic of generating the vertical polarization signals corresponding to the co-polarization for port 1, while Figs. 8(c) and 8(d) illustrate that of generating the horizontal polarization signals corresponding to the co-polarization for port 2. As observed, the cross-polarization components are sufficiently suppressed, confirming that the proposed antenna effectively supports dual polarization. Furthermore, due to the symmetrical geometry of the antenna and the equal, orthogonally positioned feed configuration, the results are consistent regardless of the feeding port, except for differences in radiation direction, as shown in Figs. 7 and 8. These results confirm the effective operation of dual polarization. Table 1 provides a summary of the simulated and measured results and demonstrate that the proposed antenna

TABLE II. PERFORMANCES OF THE PROPOSED ANTENNA

		Proposed antenna	
		Simulated	***Measured***
Bandwidth (MHz)	***Port 1***	100	130
	Port 2	100	125
Gain (dBi)	***Port 1***	11.92	11.70
	Port 2	11.92	11.45

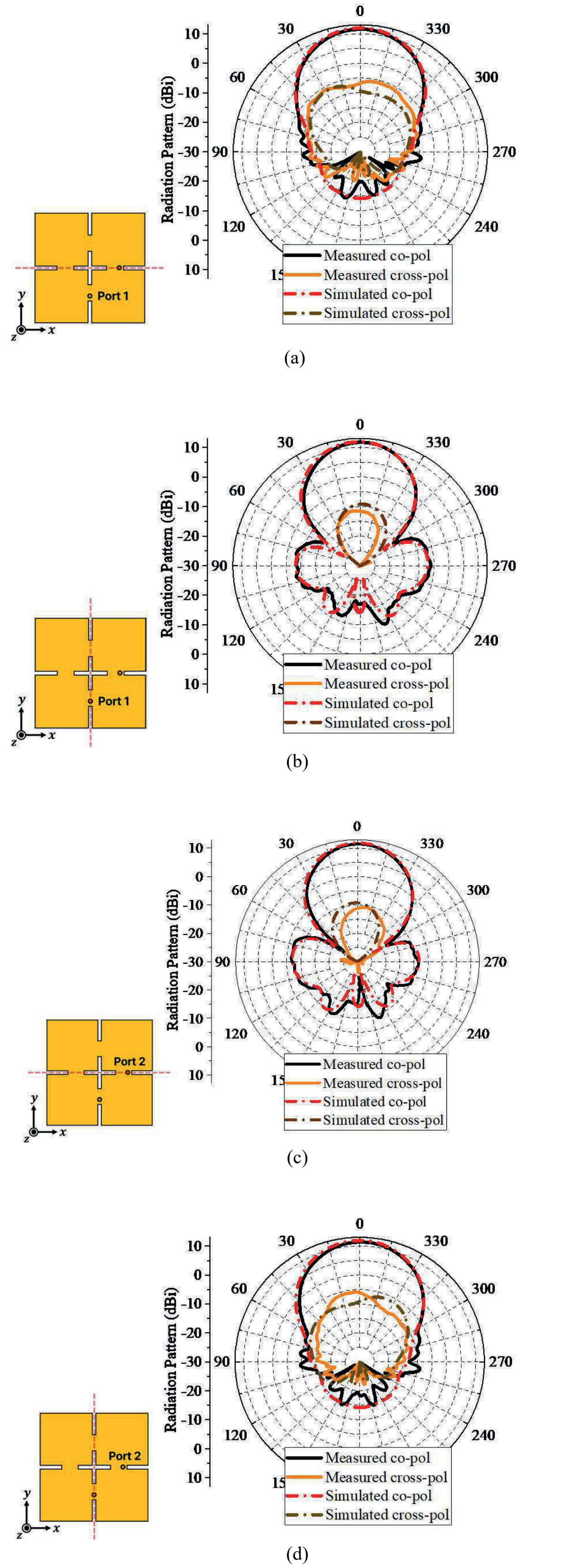


Fig. 8. Measured and simulated radiation patterns of the proposed antenna: (a) port 1 in the zx-plane, (b) port 1 in the xy-plane, (c) port 2 in the zx-plane, and (d) port 2 in the xy-plane.

exhibits high-gain and dual-polarization performance suitable for next-generation railway communication system

IV. Conclusion

In this paper, a high-gain dual-polarized cross-slot antenna is proposed for practical railway communications. High gain is achieved through the cross-slot structure, while dual polarization is realized through the symmetrical geometry with an orthogonally positioned feed. These characteristics are essential in both LOS and NLOS conditions. The measured 10-dB impedance bandwidth and peak gain of the proposed antenna are 4.70–4.83 GHz and 4.695–4.82 GHz, respectively and 11.70 dBi and 11.45 dBi for ports 1 and 2, respectively. The dual polarization is demonstrated through the similarity of the measured radiation patterns between port 1 and port 2. These results verify that the proposed antenna is suitable for next-generation railway communication systems.

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