Design of a Printed 5G Monopole Antenna With Periodic Patch Director on the Laminated Window Glass

Sangwoon Youn, Doyoung Jang, Nak Kyoung Kong, and Hosung Choo, *Member, IEEE*

***Abstract*—This letter proposes a printed fifth-generation (5G) monopole antenna with a periodic patch director that can be applied to a laminated window glass of a vehicle. The proposed monopole antenna is printed on the laminated window glass, which does not require additional mounting space. The rectangular disk is loaded at the end of the monopole to improve a bore-sight gain. To further improve the gain characteristic, the periodic patch director elements are arranged with optimized array spacing. To verify the antenna performances, such as reflection coefficients and radiation patterns, the proposed antenna is fabricated and measured in a full anechoic chamber. The results demonstrate that the proposed monopole antenna with the periodic patch director is suitable for applying in vehicle 5G communication band of n257.**

***Index Terms*—Disk-loaded antenna, fifth-generation (5G) autonomous vehicle, glass antenna, monopole antenna, periodic patch director.**

I. Introduction

RECENTLY, vehicles require large amount of information about other vehicles, road infrastructure, and pedestrians around them to achieve a high level of autonomous driving [1]–[4]. However, owing to the insufficient data throughput and latency issue of conventional communication technologies, increasing attempts have been made to apply fifth-generation (5G) communication systems to vehicles [5]–[7]. In order to apply 5G communication systems to vehicles, it is necessary to install a 5G antenna in the vehicle without an additional mounting space. In general, the shark-fin antennas are installed on a car roof considering the vehicle's appearance and air resistance [8], [9]. There are many communication antennas in the shark-fin housing such as global positioning system, long-term evolution, and AM/FM radio. The physical size of the millimeter wave (mmWave) antenna can be small enough to fit into the shark-fin housing. However, the 5G antenna will be applied as an array system using the mmWave in which electromagnetic waves are significantly affected by the surrounding structures. For beam steering, there must be no reflecting obstacles in aperture of the antenna, and to receive information in various directions, at least two array antennas should be installed (for example, one facing the left and the other facing the right). When the array antenna systems are mounted in the shark-fin housing, the mutual coupling and blockage problems will occur because these array antennas will surround the other antennas [10], [11]. To overcome this problem, various techniques, such as using parasitic elements, extended ground plane, and ferrite materials have been proposed [12]–[16]. Although previous research has reduced the mutual coupling characteristics between each antenna element, it is still difficult to obtain the desired performance in a limited space such as shark-fin housing. In contrast, a glass antenna technique for printing an antenna pattern on the vehicle window glass does not require additional mounting space. There are some previous researches using the window glass as an antenna substrate in the AM/FM band [17], [18]. However, the vehicle window glass antenna drastically reduces the antenna gain due to the high dielectric loss of the electrically thick glass substrate in the 5G mmWave band [19]−[21]. Therefore, it is necessary to design a 5G on-glass antenna considering electrically thick glass substrates.

In this letter, we propose a printed 5G monopole antenna with a periodic patch director that can be applied to the laminated window glass of a vehicle. The proposed monopole antenna is printed on the inside of the laminated window glass, which does not require additional mounting space on the vehicle. In addition, a rectangular disk is loaded at the end of the monopole element to improve the bore-sight gain. The periodic patch director is applied to the outside of the laminated glass, which also enhances the bore-sight gain even on the thick laminated glass. The periodic patch director elements are arranged in 6×6 with an optimized array spacing to maximize the bore-sight gain. To verify the feasibility, the antenna characteristics, such as reflection coefficients and radiation patterns are obtained using the CST Microwave Studio [22]. Then the monopole antenna with the periodic patch director is fabricated and measured in a full anechoic chamber. The results demonstrate that the proposed

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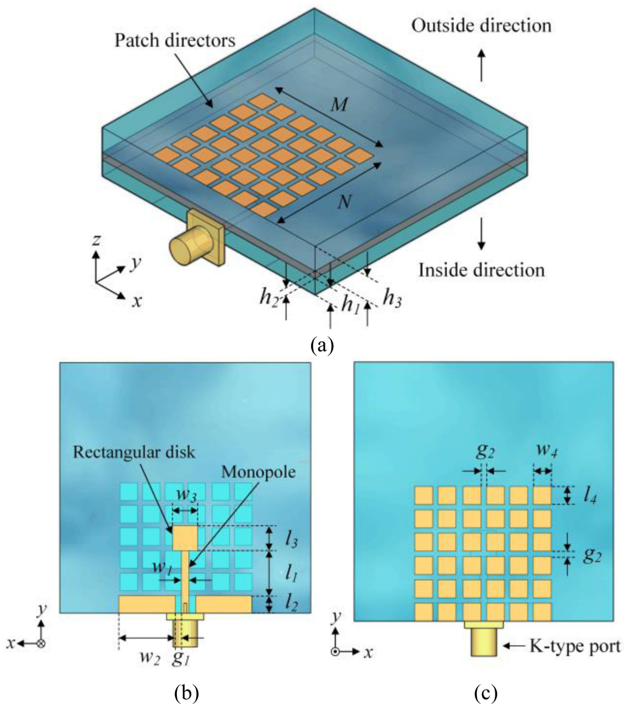

Fig. 1. Geometry of the proposed 5G monopole antenna. (a) Isometric view. (b) Bottom view. (c) Top view.

monopole antenna with the periodic patch director is suitable for applying in vehicle 5G communications (n257 frequency band from 26.5 to 29.5 GHz).

II. Geometry and Performance of the Proposed Antenna

Fig. 1 presents the geometry of the proposed 5G monopole antenna, which can be applied to vehicle's laminated window glass. The proposed antenna consists of a coplanar waveguide (CPW) feed line, a disk loaded monopole, and a periodic patch director, which is printed on the thick laminated glass as shown in Fig. 1(a). The two thick glasses ($\varepsilon_r = 6.9$, tan$\delta = 0.038$) are attached with a polyvinyl butyral (PVB) film ($\varepsilon_r = 2.56$, tan$\delta = 0.04$) to comprise the laminated window glass. The inner and outer glasses of the thick laminated window glass have heights of h_1 and h_3, respectively, and the PVB film has a height of h_2 with a width and a length of 30 mm. The monopole antenna is printed on the inner glass substrate with a length of l_1 and a width of w_1, as shown in Fig. 1(b). An input signal is fed to printed monopole antenna through the CPW transmission line, which has a ground plate of width w_2 and length l_2 and a signal line of width w_1 and length l_2, and gap of g_1. The proposed antenna uses a single-layered CPW transmission line because the laminated window glass is electrically thick so that an electrically valid ground plane cannot be constructed. Then, a rectangular disk is loaded at the end of the monopole element with length l_3 and width w_3 to improve the bore-sight gain. However, it is still difficult to obtain sufficient gain characteristics because the proposed antenna is printed on an electrically thick laminated glass which has a high dielectric loss in the 5G mmWave band. Thus,

TABLE I
Parameters of the Proposed Antenna

Parameters	Values
w_1	0.5 mm
w_2	7.02 mm
w_3	1.6 mm
w_4	1.6 mm
l_1	3.5 mm
l_2	3 mm
l_3	2 mm
l_4	1.6 mm
h_1	1.6 mm
h_2	0.76 mm
h_3	2.1 mm
M	6 elements
N	6 elements
g_1	0.23 mm
g_2	0.2 mm

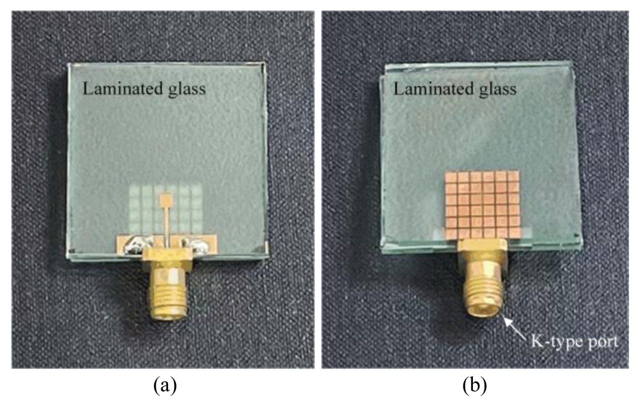

Fig. 2. Photograph of the fabricated antenna. (a) Bottom view. (b) Top view.

to more improve the bore-sight gain, a periodic patch director is applied on the outer glass, as shown in Fig. 1(c). Each element of the periodic patch director is optimized to a length of l_4 and width of w_4 considering the thickness and dielectric constant of the laminated window glass. In addition, the periodic patch director elements are arranged in 6 × 6 with gap of g_2 to maximize the bore-sight gain. Herein, the design goals for this work are as follows: operating frequency band from 26.5 to 29.5 GHz (BW = 3 GHz) in 5G NR n257, reflection coefficient less than −10 dB, bore-sight gain of more than 0 dBi, linear polarization, and the thick laminated window glass substrate. To achieve these goals, the proposed antenna is simulated using the CST Microwave Studio, and the detail optimized parameters are listed in Table I.

Fig. 2 shows a photograph of the fabricated monopole antenna, which is printed on the thick laminated window glass. In general, the glass antenna is difficult to fabricate by the method of making typical printed antennas, because of the smooth surface of the glass substrate. Instead, a silk screen method is commonly used to fabricate glass antennas [23]. However, as the silk screen method has a poor manufacturing tolerance, it is not suitable for manufacturing 5G antennas with small antenna

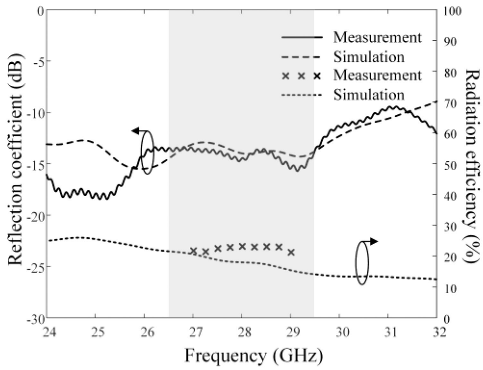

Fig. 3. Simulated and measured reflection coefficients and radiation efficiencies of the proposed antenna.

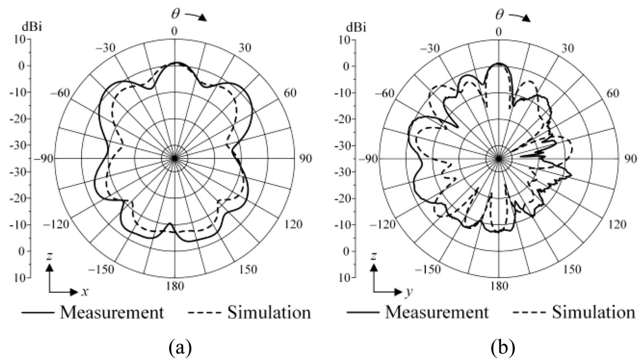

Fig. 4. Simulated and measured radiation patterns of the proposed antenna at the frequency of 28.75 GHz. (a) *zx* plane. (b) *zy* plane.

patterns. Therefore, to fabricate the proposed monopole antenna, a copper film is attached on the vehicle's window glass using thermosetting adhesive. This attached copper film is etched to make the desired antenna pattern. The environmental abrasion may occur when the proposed antenna is applied to the outside of the vehicle window glass. However, in this letter, only the design feasibility of the 5G antenna on the thick laminated glass substrate is confirmed, and the environmental abrasion is not considered. The UV films may be considered to reduce the abrasion of our 5G antenna, which is generally used to the vehicle window glass to block sunlight [24]. To demonstrate the feasibility of the proposed glass antenna, its characteristics, such as the reflection coefficient and radiation patterns are measured in the full anechoic chamber. Fig. 3 presents the measured and simulated reflection coefficients and the radiation efficiencies of the proposed antenna according to the frequency. The measured and simulated reflection coefficients are -14.3 dB and -13.8 dB at 28.75 GHz in the n257 frequency band, which are specified by solid and dashed lines, respectively. The measured radiation efficiency is 23.3% at the 28.75 GHz which is indicated with the "$\times$" markers, and it has similar tendency with the simulation results which is indicated in dotted line. Fig. 4 represents the measured and simulated two-dimensional (2-D) radiation patterns of the proposed antenna in the *zx* and *zy* planes at 28.75 GHz. The proposed antenna is linearly polarized, which is widely employed in vehicle 5G communications because it has

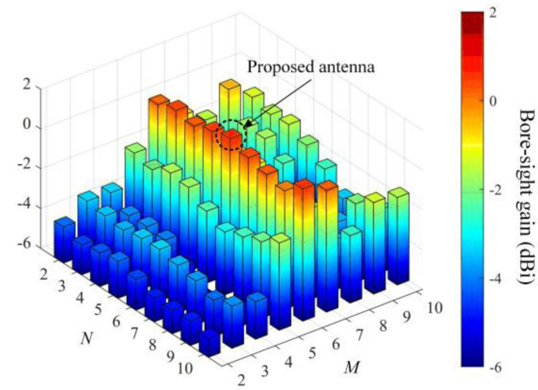

Fig. 5. Bore-sight gain in accordance with the variations of number of director elements.

some advantages such as ease of an antenna design and fabrication [25]–[28]. The measured and simulated bore-sight gains obtained using the optimized periodic patch director is 1.0 dBi and 0.8 dBi at 28.75 GHz, respectively. The results verify that the proposed monopole antenna with a periodic patch director is suitable for applying in the vehicle 5G communications although the laminated window glass has the high dielectric loss.

III. Antenna Analysis and Measurement

To validate the feasibility of the components of the proposed antenna, such as rectangular disk and periodic patch director, we examine the bore-sight gain depending on the design parameters of each component. Fig. 5 illustrates the bore-sight gain at 28.75 GHz in accordance with the variation of the antenna parameters *M* and *N*, which indicate the number of elements along the *x*- and *y*-axes, respectively. The observed range for *M* and *N* are from 2 to 10 elements. As shown in Fig. 5, a maximum bore-sight gain of 0.8 dBi is observed when the patch director elements are arranged in 6×6. Herein, the size of each patch director element and the gap between elements are also important conditions for improving the bore-sight gain. Thus, the bore-sight gain at 28.75 GHz is examined as a function of the parameters w_4 and g_2 as shown in Fig. 6. To find the optimum bore-sight gain when both *M* and *N* are set to 6, the parameter w_4 is varied from 0.5 to 2.6 mm in intervals of 0.1 mm, and g_2 is varied from 0.1 to 0.8 mm in intervals of 0.02 mm. The bore-sight gain of more than 0 dBi is obtained when w_4 ranges from 1 to 2 mm. According to the result in Fig. 6, a maximum gain of 1.2 dBi is observed when the design parameters of width and gap are 1.4 and 0.5 mm, respectively. In comparison, the proposed antenna with a width and a gap of 1.6 and 0.2 mm has a 0.8 dBi, which is similar to the previous case. Since the antenna can have smaller size despite the similar gain, we choose the proposed design parameters to less interference with the driver's sight. The proposed antenna has the small size but not optically transparent. To enhance the visibility, transparent conductors or mesh structures can be applied in future work. Fig. 7 presents the bore-sight gains and reflection coefficients depending on the antenna configuration, which clearly indicates how much each component helps to improve the bore-sight gain. The first case

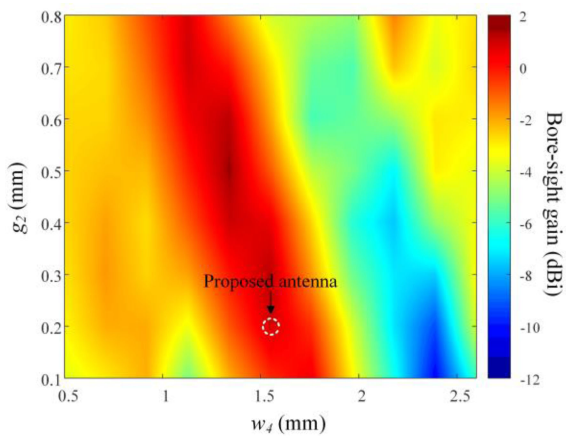

Fig. 6. Bore-sight gain in accordance with the variations in parameters w_4 and g_2.

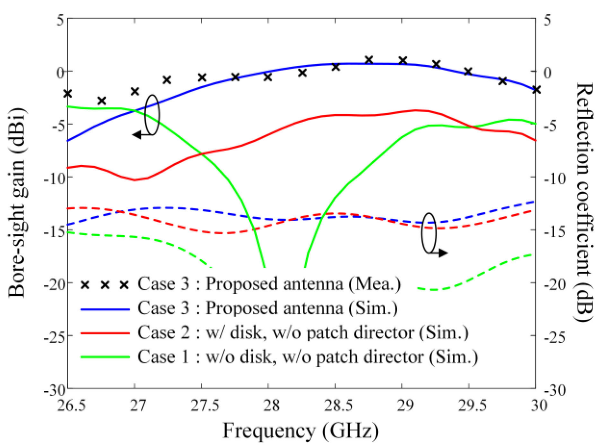

Fig. 7. Bore-sight gains and reflection coefficients depending on the antenna configuration.

(green solid line) is a conventional monopole antenna without the rectangular disk and the patch director. The second case (red solid line) is a monopole antenna with a rectangular disk at its end. Under the condition of a thick laminated window glass, the first case cannot radiate at a frequency of 28.75 GHz. The second case has a bore-sight gain of -4.2 dBi, although the gain is enhanced by 5.4 dB more than the first case. Thus, it still has an insufficient gain to be used as a 5G communication antenna. In contrast, the proposed antenna with the disk and patch director has a simulated bore-sight gain of 0.8 dBi (blue solid line), and a measured bore-sight gain of 1.0 dBi ("$\times$" markers). The trend of the measured bore-sight gain results in accordance with the frequency agrees well with the simulation results. The reflection coefficients are also indicated by dashed lines of the same color as each case.

In the case of a conventional monopole antenna without the disk and the patch director, the gain characteristic is extremely reduced. To obtain the high gain characteristic, sufficient currents should be coupled to the patch radiator. Without the rectangular disk structure, the capacitive coupling decreases, and this consequently results in reducing the overall antenna gain. To confirm this, we simulate the electric field distributions on the patch director with and without the disk. The maximum electric field on the director in the case with the disk is 80 dBV/m (when the input power is 0.5 W), which is 6 dB higher than the case without the disk. This clearly shows that the rectangular disk at the end of the monopole radiator improves the bore-sight gain. In addition, we investigate the gain reduction according to the loss tangent of the glass substrate. When the dielectric is assumed to be lossless, the antenna has a bore-sight gain of 4.7 dBi which is 3.9 dB higher than the gain with a tanδ of 0.038 at 28.75 GHz. We also simulate the radiation efficiency depending on the loss tangent. It has a high efficiency of 75.5% when the loss tangent is ideally 0, which is much higher than the proposed antenna's radiation efficiency of 16.5%. The total power loss of 0.4174 W is observed when the total input power is 0.5 W. Herein, out of the total power loss, the power loss in the upper glass is 0.2 W, and the loss in the bottom glass is 0.18 W. The power loss in the PVB film is 0.0318 W, and that in the copper layer is 0.0056 W. Therefore, it can be seen that the dielectric loss of the thick glass substrate has a significant effect on the antenna gain.

IV. Conclusion

In this letter, we investigated the 5G monopole antenna with the periodic patch director that can be printed on the laminated window glass. The proposed monopole antenna was printed on the inside of the laminated window glass, which did not require additional mounting space on the vehicle. To improve the bore-sight gain, the rectangular disk was loaded at the end of the monopole element, and a periodic patch director was applied to the outer glass. The periodic patch director was optimized to obtain high gain characteristics for the laminated glass with high dielectric loss. The proposed antenna had a measured reflection coefficient of -13.8 dB, and a bore-sight gain of 1.0 dBi at 28.75 GHz. The results demonstrated that the proposed monopole antenna with the periodic patch director was suitable for applying in the 5G communications which were designed on the thick laminated glass.

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