Miniature Millimeter-Wave 5G Antenna Fabricated Using Anodized Aluminum Oxide for Mobile Devices

Jongsun Choi, Jaehyun Choi, and Woonbong Hwang*

ABSTRACT: A miniature millimeter-wave 5G antenna fabricated using anodized aluminum oxide (AAO) is devised and demonstrated for mobile devices. The proposed structure creates a dielectric layer on an aluminum plate using AAO topology and allows the antenna pattern to be placed on the dielectric layer. The proposed AAO-based antenna reduces the size (1.87 (0.18λ₀) mm × 2.34 (0.22λ₀) mm) of the antenna in proportion to the dielectric constant (εᵣ = 6.7), which is higher than those of the conventional materials such as polycarbonates (PC) or a flame retardant (FR4). In addition, it is possible to precisely control the dielectric layer dimensions and generate a dielectric layer on the metal substrate itself, which greatly increases the design freedom. As a result, the devised antenna resonates at 29 GHz, and the measured gain is 5.02 dBi.

1. INTRODUCTION

In recent years, data traffic has increased exponentially with the evolution of communication technology. Accordingly, mobile users and related industries are demanding faster data processing speeds and lower traffic. Fifth Generation New Radio (5GNR) technology is being actively researched to satisfy customers and new business models that require the prompt processing of a large quantity of data in different fields such as artificial intelligence,¹−⁴ virtual reality,⁵−⁷ and autonomous driving.⁸−¹² 5G technology can handle a larger amount of data than the previous-generation technologies because it uses a higher-frequency range. The spectrum available for 5G technology is divided into frequency range 1 (FR1) and frequency range 2 (FR2). For realizing the true potential of 5G technology, the utilization of FR2, which is called the millimeter-wave (mmWave) frequency range and which covers a wide bandwidth (400 MHz),¹³,¹⁴ is essential. Hence, studies on FR2 are necessary.

One of the components that make 5G technology possible is the mobile antenna, which plays an important role in the final stage of communication. Hence, research on the mobile antenna is crucial for realizing 5G networks. Mobile antennas reported in the literature have mainly been developed using well-known substrate-based processes that use low-temperature cofired ceramics,¹⁵−¹⁷ Teflon,¹⁸−²⁰ printed circuit boards,²¹−²³ etc. In other words, because research has so far been conducted according to given process technology, there are limitations to technology evolution. In addition, most of the previous research studies have been conducted on the antenna structure, and the research is very limited and lacking in terms of the material science technology used to manufacture the antenna. Because commercially available mobile devices are high-density devices that incorporate a large number of components, the degree of freedom available in terms of the design space of the antenna is considerably low. Therefore, the miniaturization of the antenna size is a very important field of study, and the miniaturization can be realized through research in the field of material science, which
can be used to control the dielectric constant characteristics of the antenna.

The anodized aluminum oxide (AAO) fabrication process can precisely fabricate an Al₂O₃ ceramic layer, which is a dielectric layer, from the aluminum base metal. The AAO layer has a higher dielectric constant than the conventional dielectric materials such as polycarbonate (ε_r ≈ 3.5) or FR4 substrate (ε_r ≈ 4.4) used to fabricate antennas, and this property is an excellent advantage for the miniaturization of the antenna. In addition, because the AAO layer can be applied directly to the aluminum metal frame used in the existing mobile phones and the ground and dielectric layers can be integrally manufactured, the degree of freedom in antenna design can be greatly increased.

In this study, the AAO fabrication method was applied to the antenna design of a mobile device. The antenna was designed to operate in FR2 (29 GHz) through the ANSYS analysis and equations, and the desired dimensions were perfectly produced by the anodization process. The antenna performance was verified using the simulation results and measured data. Based on the experimental results, it was confirmed that AAO could be used as a fabrication material for an actual mobile 5G antenna.

2. RESULTS AND DISCUSSION

Figure 1 shows the scanning electron microscopy (SEM) images of the fabricated AAO layer. As shown in Figure 1a, dozens of nanometer-sized pores are formed on the aluminum surface. In this study, the one-step anodization process was used to shorten the manufacturing time and simplify the process. Although the alignment of the nanopores is not regular, the width of the antenna transmission line and the size of the patch are very large compared to the size of the nanopores, so the alignment does not considerably affect the antenna performance. The AAO dielectric layer is integrally formed on the aluminum raw material, as shown in Figure 1b. An AAO layer with optimal thickness of 400 μm calculated from the simulation results is evenly produced with high precision along the entire surface. Hence, the fabrication of the dielectric layer has been confirmed to be precisely controlled.

Figure 2 shows the reflection coefficient of the proposed mmWave 5G antenna fabricated using AAO. The reflection coefficient was measured using a performance network analyzer (Keysight). The fabricated antenna resonates at 29 GHz with an impedance matching of −20 dB, which is the same as that obtained in the simulation. The results indicate that the AAO-based antenna can cover the mmWave 5G spectrum. The measured radiation patterns containing copolarization/crosspolarization are shown in Figure 3. The microstrip patch antenna consists of a metal patch on one side of the board and the ground plane on the other side. When a radio-frequency signal is applied to the patch through the feed transmission line, the patch is emitted by the fringe field at both edges owing to a sinusoidal variation. Because the maximum efficiency is achieved when the antenna impedance perfectly matches the system impedance, the radiation pattern is measured at 29 GHz. Figure 3a,b shows the far-field radiation patterns. The patterns for the E-plane are measured in the xz-coordinate plane, and those for the H-plane are measured in the yz-coordinate plane. The simulated and measured realized gains are 5.62 and 5.02 dBi, respectively. It should be noted that the measurements for the E-plane are...
performed only at angles of 0°–150° owing to the difficulties inherent in the measurement system. Because the radio-frequency cable and K-connector used in the test affect the far-field radiation pattern slightly during measurement, there is a slight difference between the simulation and measurement results. However, this is a problem caused by the measurement system, and the proposed antenna is not expected to cause problems for broadside radiation in the z-axis direction, as shown in Figure 3.

Research is being conducted in numerous areas to successfully realize 5G technology, and one of the important research areas for 5G technology is the 5G antenna. Antenna structures have been studied in terms of high gain and miniaturization. In addition, the fabrication material is the main factor that determines the performance of the antenna. To the best of the authors’ knowledge, there have been no reports so far on research that involves nanotechnology such as the use of AAO for fabricating antennas, whereby antennas can be formed with a dielectric layer on a metal base. Furthermore, a material with a high dielectric constant, such as AAO, has the advantage of facilitating the volume reduction of antennas, thereby making it possible to realize miniaturization (eqs 1 and 3).

Figure 4 shows the conceptual diagram of the proposed antenna incorporated into a recent mobile phone. According to the recent trend seen in handset devices, smartphones have not only increased in size but also exhibit a high screen-to-body ratio. Because space utilization in mobile phones is still inefficient, the challenge is to reduce the size of the antenna. Therefore, the AAO-based antenna can be incorporated into the limited real area of recent mobile phones. As shown in Figure 4, AAO-based antenna has the potential to be integrated into the metallic middle frame of the mobile phone. Consequently, the miniaturization of the antenna based on AAO will facilitate the incorporation of a massive antenna array in a limited space.

3. CONCLUSIONS

In this study, an AAO-based 5G antenna is fabricated and its performance is demonstrated and verified. The proposed antenna is designed to operate in the mmWave 5G spectrum. The 5G antenna is expected to be utilized in mobile devices, and it has the advantages of precise manufacturing and size miniaturization. In addition, this research is novel in that it involves a multiphysics study that integrates the fields of material science and electronics. Based on the study results, various follow-up studies in the fields of material science and electronics can be conducted.

4. METHODS

4.1. Fabrication of the AAO Layer. Figure 5a shows the manufacturing process of the mmWave 5G antenna. An aluminum sheet with a purity of 99.999% and a thickness of 0.5 t was used in the anodization process. The sheet was cut to form a 5 cm × 10 cm section, and a polishing process was performed for 10 min by applying a voltage of 20 V in a 10 °C polishing solution (HClO4/C2H5OH = 1:4 v/v). Subsequently, a 0.3 M solution of oxalic acid was prepared using distilled water, and the temperature of the solution was adjusted to 0 °C. To quickly create an oxide layer, anodization must be performed by applying a high voltage, but this process involves the risk of specimen burning. To prevent this problem, anodization was performed at 40 V for 20 min to generate a protective layer. Finally, the anodization process was performed at 130 V to produce an AAO layer having the desired thickness.

4.2. Antenna Design. The proposed patch-type miniature 5G antenna is shown in Figure 5b. The design parameters were calculated as:

\[
\text{width} = \frac{c}{2f_0 \sqrt{\varepsilon_{\text{eff}}}}
\]

\[
\varepsilon_{\text{eff}} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \sqrt{1 + \frac{12}{\varepsilon_r}}
\]

\[
\text{length} = \frac{c}{2f_0 \sqrt{\varepsilon_{\text{eff}}}} - 0.824h \left( \frac{\varepsilon_{\text{eff}} + 0.3}{h} + 0.264 \right) - 0.258h \left( \frac{\varepsilon_{\text{eff}} - 0.58}{h} + 0.8 \right)
\]

where \( f_0 \) is the resonant frequency of the antenna, \( \varepsilon_r \) is the relative dielectric constant, \( \varepsilon_{\text{eff}} \) is the effective dielectric constant, \( c \) is the free-space velocity of light, \( h \) is the substrate thickness, and \( w \) is the width of the patch. According to eqs 1–3, the dimensions of the patch were calculated. Once the resonant frequency was determined, the calculation procedure was carried out using the dielectric constant and the height of the substrate to be used as the antenna (the AAO layer was
Because the dielectric constant of AAO was 6.7 and the height was 400 μm, the designed dimensions were 1.87 mm × 2.34 mm (0.18λ₀ mm × 0.22λ₀ mm). Typically, conventional patch antennas resonate (in the TM₁₀ mode) with a half wavelength. However, the proposed AAO-based patch indicated that the width and length of the antenna could be adjusted by varying the relative dielectric constant, according to eqs 1 and 3. Because the relative dielectric constant of the proposed AAO layer was 6.7, the length of the patch could be considerably reduced.

For feeding the patch antenna, various feeding methods are used, such as proximity- and aperture-coupled feeding, coaxial probe feeding, and microstrip line feeding. In this study, the microstrip line method was used for ease of fabrication. The radiating edge impedance in the feed direction of the patch antenna can be written as:

\[ G = \frac{\pi W}{\eta \lambda_0} \left( 1 - \frac{(kH)^2}{24} \right) \]  

(4)

\[ R = \frac{1}{2G} \]  

(5)

where \( G \) is the conductance, \( \eta \) is the impedance of free space, \( \lambda_0 \) is the free-space wavelength, \( W \) is the width of the patch, \( k \) is the wavenumber (2π/\( \lambda \)), \( H \) is the height of the patch, and \( R \) is the resistance. eqs 4 and 5 indicate that the radiating edge impedance is higher than that of a 50 Ω transmission line. Therefore, to match the system impedance and antenna, the feed was inserted 0.8 mm from the edge, maintaining a gap of 180 μm. In the experiment, a 50 Ω mmWave K-connector (2.92 mm, DC to 40 GHz) was used to provide the feed to the antenna.

4.3. Experimental Setup. Figure 6 shows the experimental setup used for AAO production. First, a circulator used for maintaining the temperature was connected to a double jacket, where anodization was to be realized. A stirrer was installed to mix the solution and thereby maintain a constant temperature. A power supply system supplied constant DC power to the aluminum section. Figure 7 shows the antenna measurement system. To evaluate the antenna performance, antenna parameters such as the reflection coefficient (s-parameter), polarization, and antenna gain should be measured. In this study, these parameters were measured and verified. The reflection coefficient was measured using the one-port option of a vector network analyzer (Keysight), and the antenna gain and far-field radiation pattern were measured using the two-port option of the analyzer. The experiments in the E-plane and H-plane were performed as shown in Figure 7. The fabricated mmWave antenna (device under test (DUT)) was fixed at the center of the measurement system, whereas the horn antenna (antenna under test (AUT)), which measured the propagated signal from the DUT, was rotated in a 360°
range by a motor. The $E$-plane experiment measured the plane of the copolarization of the DUT, whereas the $H$-plane experiment measured the vertical plane of the antenna polarization.

■ AUTHOR INFORMATION

Corresponding Author

Woonbong Hwang — POSTECH Department of Mechanical Engineering, Pohang University of Science and Technology, Pohang, Gyeongbuk 37673, Republic of Korea; orcid.org/0000-0001-9072-9732; Phone: +82-54-279-2174; Email: whwang@postech.ac.kr; Fax: +82-54-279-5899

Authors

Jongsun Choi — POSTECH Department of Mechanical Engineering, Pohang University of Science and Technology, Pohang, Gyeongbuk 37673, Republic of Korea

Jachyun Choi — POSTECH Department of Mechanical Engineering, Pohang University of Science and Technology, Pohang, Gyeongbuk 37673, Republic of Korea

Complete contact information is available at: https://pubs.acs.org/10.1021/acsomega.0c03795

Author Contributions

J.S. contributed the most to the experimental work and drafted the manuscript. J.H. designed the study. W.H. is the guarantor. All authors reviewed the manuscript.

Notes

The authors declare no competing financial interest.

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