Low Profile Multi-Slot Loaded Antenna with Enhanced Gain-to-Volume Ratio and Efficiency

Ye-Bon Kim, Member, IEEE, Jin-Woo Kim and Han Lim Lee, Member, IEEE
School of Electrical and Electronics Engineering, Chung-Ang University, Seoul, 06974 South Korea

Corresponding author: Han Lim Lee (e-mail: hanlimlee@cau.ac.kr).

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ABSTRACT A printed circuit board (PCB) implementable multi-slot loaded antenna with a low-profile air-gapped structure for both gain and efficiency enhancement is proposed. The proposed planar antenna is configured by the upper substrate with a radiation patch separated from the lower substrate consisting of a pair of matching pads and a ground plane by the air-gap. The radiation patch on the upper substrate is loaded by two rectangular slots and a single narrow slot with a symmetrically placed feed point and a shorting pin. The narrow slot on the center of the radiation patch with the shorting pin improves both gain and radiation efficiency. The pair of two additional rectangular slots increase the gain while maintaining the required air-gap very low. Further, the symmetric matching pads are integrated along the feed and shorting vias to improve the realized antenna gain for the whole operation band. As a result, the proposed structure obtains a high gain-to-volume ratio as well as the enhanced efficiency. The proposed structure was fabricated at 5.9 GHz with the overall volume of 1.08 \( \lambda_0 \times 1.08 \lambda_0 \times 0.05 \lambda_0 \) (55 mm x 55 mm x 2.7 mm) including the whole ground plane. The measured antenna gain was 9.4 dBi at 5.9 GHz verifying the high realized gain-to-volume ratio. Also, the measured half power beamwidths in E and H planes were about 72\(^\circ\) and 74\(^\circ\), respectively. Lastly, the measured 10-dB impedance bandwidth of the proposed structure showed approximately 5.5\%.

INDEX TERMS Antenna gain enhancement, high efficiency antenna, low-profile antenna, slot-loaded antenna, shorted patch antenna

I. INTRODUCTION

With the increasing demand for multiple antenna-based applications such as active electronically scanned array (AESA) radar, multiple-input and multiple-output (MIMO), and phased array communication, the demand for highly efficient and light weight antenna technique is also growing. Since high gain antenna elements can eventually reduce the required number of both antenna elements and beamforming transmit-receive (T/Rx) chains in an array configuration, the communication system’s overall size, weight, number of required RF components, cost, fabrication difficulty and power consumption can be effectively reduced. Therefore, a high directivity antenna element must be thoroughly investigated to optimize both physical size and efficiency. Although the microstrip patch antennas are typically used due to the merits of easy fabrication, light weight, low-profile and planar structure, they suffer from narrow bandwidth and low gain. To overcome these drawbacks, many extensive researches for high gain antenna structures have been previously reported. Although many cavity-backed or slot-loaded structures have shown both gain and bandwidth enhancement [1]-[6], the high-profile cavity or complicated geometry make them impractical regarding their gain enhancement ratio over the required antenna volume. Other antenna structures based on periodic structures, or dielectric resonators have been also reported to increase the gain [7]-[12], but they still require large dimension as well as high profile. Also, different types of vertically stacked patch or shorted patch antennas have been proposed [13]-[17], but the relatively low gain enhancement ratio with respect to the increase in the stack height or ground plane size compared to the conventional planar patch antenna seems to be less effective. Further, the patch antennas with a conventional shorting pin structure suffer from the narrow operation bandwidth. Some other structures like magneto-electric
dipole antennas have been also studied for both gain and bandwidth enhancement [18]-[25]. However, these structures still require either high profile, metallic sidewalls, large ground plane or fabrication difficulty in printed circuit board (PCB) due to complicated feed line structures. Further, metasurface and lens antennas have been reported as high gain array antennas [26]-[30], but they also suffer from high profile or large occupation of extra layers limiting applications as well as narrow operation bandwidth. Since most of the previously reported antenna structures for gain enhancement commonly suffer from the sacrifice of the overall volume to improve the gain, the realized antenna gain-to-volume ratio must be considered instead of merely focusing on the achieved gain itself. Thus, a new antenna configuration for improving both gain and radiation efficiency with the minimal increase in profile to achieve a high gain-to-volume ratio is proposed in this article.

II. ANALYSIS AND DESIGN OF THE PROPOSED ANTENNA STRUCTURE

The structural evolution of the proposed planar antenna from the conventional patch configuration is described in Fig. 1 (a). With the conventional patch antenna as a reference, the Type-A is configured by an additional slot and a shorting pin loaded on the reference structure. Further, the Type-B is configured by adopting an air-gap structure with an upper substrate having the slot-loaded patch and a lower substrate having a ground plane. The signal and shorting pins are connected through the air-gap. Lastly, the proposed structure is evolved from the Type-B by integrating a pair of rectangular slots symmetrically across the center slot to minimize the air-gap profile as low as possible. To further stabilize the gain characteristics of the proposed structure, vertically loaded matching pads are also integrated on the middle layers. The detailed configuration of the proposed antenna is shown in Fig. 1 (b), where two dielectric substrates with total four layers are separated by low-profile spacers to implement the air-gap. The top layer consists of multi-slot loaded patch antenna while the layer 2 and 3 consist of a pair of matching pads on each layer. Lastly, the bottom or layer 4 consists of the ground plane. The detailed design steps and analysis are discussed in the following section.

A. DESIGN APPROACHES TO THE PROPOSED ANTENNA FROM THE CONVENTIONAL PLANAR STRUCTURE

Referring to the Fig. 1 (a), the Type-A is the generally used microstrip patch antenna structure for an enhanced radiation efficiency. To briefly see the effect of the slot and shorting pin, both slotted antennas with and without having the shorting pin are designed as shown in Fig. 2 (a). Here, the embedded slot acts as an extra radiator while the shorting pin can further optimize the radiated field through the slot. Thus, the radiation efficiency and gain can be improved. The parameters W and L are set to 0.33 \( \lambda_0 \) and 0.3 \( \lambda_0 \), respectively for the center frequency of 5.9 GHz without a slot. Further, the ground plane size is fixed by 1.08 \( \lambda_0 \) x 1.08 \( \lambda_0 \) and maintained for the different types as well. Then, the slot with the dimension denoted by \( C_v \) and \( C_g \) are added. Having the \( C_v \) value fixed to 1 mm corresponding to 0.019 \( \lambda_0 \) at 5.9 GHz, the variation rate of the center frequency and radiation efficiency according to the changes in \( C_g \) is described in Fig. 2 (b). The slotted patch antenna with the shorting pin shows a lower rate of changes in the center frequency over the slot size variation and the radiation efficiency is also improved. Here, the insensitive variation with respect to the slot size suggests the antenna with the capability of fine tuning on the operation frequency and higher immunity to a potential
fabrication error. Further, the variation of peak directivity of the Type-A is simulated according to different values of $C_g$ as shown in Fig. 2 (c). With the $C_g$ of $0.15 \lambda_0$, the peak gain observed to be slightly less than 8 dBi while the 10-dB impedance bandwidth is about 2.4%. Thus, to further increase the gain and bandwidth from the Type-A structure, the planar air-gap structure as denoted by Type-B can be considered. Since the air-gap structure must be practically implementable by using a printed circuit board (PCB) fabrication, two substrates with the thickness of 0.006 $\lambda_0$ and 0.02 $\lambda_0$ are used for practical simulation as shown in Fig. 3 (a). Having the slotted patch dimension $W$ and $L$ fixed to 0.33 $\lambda_0$ and 0.3 $\lambda_0$, respectively, the reflection coefficient and peak directivity for the air-gapped structure are simulated according to the variations in both $C_g$ and $S$ as shown in Fig. 3 (b). Here, even with the slight increase in the air-gap spacing, $S$, between the upper and lower substrates, a drastic change in the matching characteristics is resulted. According to Fig. 3 (b), the fixed $C_g$ of $0.15 \lambda_0$ and the increase in $S$ only cannot satisfy the center frequency of 5.9 GHz. Further, the extension of $C_g$ is also tried up to the nearly maximum value of the patch width while keeping the $S$ of 0.03 $\lambda_0$. However, the only increase
in Cg still cannot satisfy the target frequency as depicted in Fig. 3 (b). Thus, the length of the slotted patch, \( L \), is modified according to the Cg values as shown in Fig. 3 (c). Although the increase in \( L \) with the fixed Cg of 0.15 \( \lambda_0 \) makes the center frequency to shift down toward 5.9 GHz, the quality factor does not get improved yet. Then, Cg is also modified to 0.25 \( \lambda_0 \) making the center frequency matched at 5.9 GHz with the \( L \) of 0.33 \( \lambda_0 \) as shown in Fig. 3 (c). To further optimize the air-gap spacing, the reflection coefficient, radiation efficiency and peak directivity are re-simulated with the determined Cg and \( L \) values according to the variation in S. Fig. 4 (a) shows the enhanced bandwidth with good radiation efficiency achieved by the S of 0.024 \( \lambda_0 \). Also, Fig. 4 (b) suggests the optimal value of S to be 0.024 \( \lambda_0 \) because the higher S does not show the sufficient increase in gain. Although the target frequency is 5.9 GHz, the maximum achievable directivity for the given geometry is observed at 6.2 GHz.

To improve the maximum achievable gain at the center frequency of 5.9 GHz, a pair of rectangular slots is inserted on the radiating patch surface as described in Fig. 1. Here, the rectangular slots with the identical size are placed symmetrically along the center slot. Since the additional slots can provide the apertures that additional magnetic field can radiate through, the antenna gain can be further increased. To verify the effect of the multi-slots added on the Type-B, the proposed prototype and the Type-B are simulated as shown in Fig. 5. Here, since the pair of rectangular slot size has not been optimized and the matching stacks as described in Fig. 1 (b) are not integrated yet, the architecture with multi-slots is temporarily referred as the proposed prototype. The Fig. 5 (a) shows the surface current distribution for both Type-B and the proposed prototype. The proposed prototype shows additional current flowing through the rectangular slots that can increase the strength of magnetic field. The magnetic field distributions according to different cut-plane views are shown in Fig. 5 (b) and stronger magnetic field are observed by the proposed prototype comparing with the Type-B. To optimize the rectangular slot areas, the slot parameters \( C_x \) and \( C_y \) are defined with the air-gap spacing of 0.024 \( \lambda_0 \) as shown in Fig. 6 (a). Then, peak directivity is simulated over the variations in both \( C_x \) and \( C_y \) at 5.9 GHz as shown in Fig. 6 (b). The simulated result for the maximum achievable peak directivity is found to be approximately 9.35 dBi with \( C_x \) of
0.12 λ₀ and Cy of 0.08 λ₀. The result shows the directivity enhancement by 0.45 dB compared to the simulated peak directivity for the Type-B at 5.9 GHz. Having the proposed prototype with the optimized rectangular slot area, the reflection coefficient and realized gain are finally fine-tuned regarding Cg again as shown in Fig. 7 (a). It is shown that the addition of rectangular slots has shifted the center frequency slightly down and thus Cg is finally adjusted to 0.23 λ₀. Further, the slight decrease in realized gain taking the impedance matching characteristic into account is observed when comparing with the previously simulated peak directivity. Fig. 7 (b) shows the impedance characteristics of the proposed prototype where a parasitic inductance is observed at 5.9 GHz whereas the resistance is matched to 50 Ohm by Cg of 0.23 λ₀. Thus, to cancel the parasitic reactance and improve the realized gain close to the peak directivity, a vertically loaded matching stacks are integrated on the middle layers along the signal feed and shorting pin vias as described in Fig. 1 (b).

B. OPTIMIZATION OF THE PROPOSED ANTENNA WITH A SYMMETRICALLY INTEGRATED MATCHING STACK

Fig. 8 (a) shows the integrated matching pads on both layer 2 and layer 3 making a vertical stack pair across the air-gap. The matching pads are connected through both signal feed and shoring vias providing the shunt capacitance to compensate the inductance along the feed lines. Fig. 8 (b) shows the effect of the matching pad size denoted by Px and Py. The increase in Px and Py is identically applied to both layer 2 and 3. The initial impedance without the matching pads is represented by Px of 0 and Py of 0 and then, the increase in Px with the fixed Py of 0.024 λ₀ cancels the unwanted inductance, resulting in the optimized Px value of 0.12 λ₀. Further, the reflection coefficient and peak realized gain comparison between the proposed antenna with and without the matching pads is shown in Fig. 8 (c). Having the optimized matching pad stack, the 10-dB impedance bandwidth and gain characteristics over the whole frequency band are improved. Finally, the overall configuration of the proposed antenna with the design parameter summary is presented by Fig. 9. The proposed structure can be practically implemented by two dielectric substrates with four conducting layers and via pins. Moreover, the required air-gap is maintained very low as 1.27 mm which can be also easily implemented with a low-profile spacer. Having all the designed parameters are found, the simulated total efficiency over the operation band is also shown in Fig. 10 (a). The total
efficiency at the center frequency of 5.9 GHz is about 98% showing an excellent matching characteristic. The simulated 10-dB impedance bandwidth is about 5.5%. Further, Fig. 10 (b) shows the simulated realized gains of 9.1 dBi and 9.2 dBi in xz and yz planes of the proposed antenna, respectively. The simulated half-power beamwidths (HPBW) in both xz and yz planes show approximately 72° and 60°, respectively. The simulated radiation efficiency and peak gain for different types including the reference patch are summarized in Table I.

III. FABRICATION AND MEASURED RESULT FOR THE PROPOSED ANTENNA

The proposed antenna was fabricated with a Taconic TLX-9 substrate having a dielectric constant of 2.5 and a loss tangent of 0.0019 as shown in Fig. 11 (a). The upper and lower dielectric substrates have the thicknesses of 0.38 mm and 1.14 mm, respectively. To keep the rigidity of the proposed antenna, the lower substrate was chosen to be thick. Further, small pieces of FR-4 substrate with the thickness of 1.27 mm was inserted as the spacer to form the air-gap structure as shown in Fig. 11 (a). Having the ground plane of 55 x 55 mm² and the air-gap spacing of 1.27 mm, the overall volume of the proposed low-profile antenna at 5.9 GHz was finally achieved by 1.08 λ₀ x 1.08 λ₀ x 0.05 λ₀. Also, RF SMA connector is adopted for a probe-feed. Fig. 11 (b) shows the simulated and measured reflection coefficients of the proposed low-profile multi-slot loaded antenna. The measured 10-dB impedance bandwidth was approximately 5.5% showing an excellent agreement with the simulated
impedance bandwidth. Then, the radiation patterns in both xz and yz planes of the proposed antenna were measured at 5.9 GHz as shown in Fig. 12 (a) and (b). The measured copolarization peak gains were 9.1 dBi and 9.4 dBi, respectively in xz and yz planes. Further, the measured HPBWs in xz and yz planes were about 72° and 74°, respectively. To clarify the cross-polar discrimination (XPD) characteristic of the proposed antenna, the simulated and measured co-polarization and cross-polarization are replotted as XPD level as shown in Fig. 12 (c). Within the HPBW range, the XPD levels in xz and yz planes were always better than approximately 20 dB and 90 dB, respectively. Further, within the half spherical area over the proposed antenna, the minimum XPD of 15 dB was always satisfied as well. Lastly, to compare the enhanced gain ratio over the whole antenna volume including the ground plane, the performance summary of the proposed antenna with the previously reported high gain antenna structures is presented by Table II. Although the realized gain of the proposed antenna itself is not shown as the maximum in the table, the key figure-of-merit (FoM) for the high gain antennas, the gain-to-volume ratio of the proposed antenna is the highest. Therefore, the effective gain enhancement ratio can be achieved by the proposed architecture being a promising solution for high gain antenna applications.

III. CONCLUSION

In this paper, a new antenna structure based on the multi-slot and low-profile air-gap for the enhanced antenna gain-to-volume ratio and total efficiency was proposed. The proposed structure had the integrated matching pad stacks vertically loaded along the signal and shorting pins. The proposed antenna was fabricated with the conventional PCB process and showed the overall volume of 1.08 λ₀ x 1.08 λ₀ x 0.05 λ₀ including the air-gap and ground plane. The measured peak gain was about 9.4 dBi with the minimum XPD level of 20 dB within the HPBW showing the excellent gain-to-volume ratio.

FIGURE 10. The proposed low-profile multi-slot loaded antenna with the simulated (a) reflection coefficient and total efficiency, and (b) realized gain in both xz and yz planes at 5.9 GHz

FIGURE 11. The (a) implementation of the proposed antenna with low profile air-gap and multi-slots, and (b) simulated and measured reflection coefficient
FIGURE 12. The simulated and measured (a) co-polarization radiation patterns, (b) cross-polarization radiation patterns and (c) cross-polar discrimination (XPD) level in both xz and yz planes of the proposed antenna

| Ref. | Total volume w/ ground plane (λ₀)³ | Center frequency (GHz) | Total efficiency (%) | Impedance bandwidth (%) | Realized gain [dBi(c)] | Realized gain-to-volume ratio [dBi(c)/λ₀]³ |
|------|-----------------------------------|------------------------|----------------------|------------------------|------------------------|-----------------------------------------|
| [13] | 1.17λ₀ x 1.17λ₀ x 0.099λ₀          | 2.5                    | -                    | 19.6                   | 10.4                   | 84.5                                    |
| [14] | 1.5λ₀ x 1.5λ₀ x 0.03λ₀            | 2.9                    | 91                   | 1.1                    | 10.6                   | 158.2                                   |
| [15] | 1.39λ₀ x 1.39λ₀ x 0.04λ₀           | 3.6                    | 91                   | 1.4                    | 10.3                   | 133.7                                   |
| [16] | 1.19λ₀ x 1.19λ₀ x 0.08λ₀          | 2.6                    | -                    | 19                     | 11.0                   | 97.3                                    |
| [17] | 0.96λ₀ x 0.96λ₀ x 0.14λ₀          | 5.8                    | 85                   | 7.2                    | 9.6                    | 74.4                                    |
| [18] | 3.47λ₀ x 1.73λ₀ x 0.03λ₀          | 5.2                    | -                    | 13.1                   | 12.2                   | 67.7                                    |
| [19] | 0.95λ₀ x 0.95λ₀ x 0.315λ₀         | 2.2                    | -                    | 45.4                   | 8.7                    | 30.6                                    |
| [20] | 0.99λ₀ x 0.99λ₀ x 0.097λ₀         | 1.95                   | -                    | 28.2                   | 10.3                   | 108.4                                   |
| [21] | 1.09λ₀ x 1.09λ₀ x 0.447λ₀         | 2.75                   | 85                   | 73.3                   | 8.2                    | 15.4                                    |
| [22] | 0.57λ₀ x 0.57λ₀ x 0.26λ₀          | 3.7                    | -                    | 37                     | 9.36                   | 111.4                                   |
| [23] | 1λ₀ x 1λ₀ x 0.15λ₀                | 1.6                    | -                    | 48                     | 11                     | 73.3                                    |
| [24] | 1.1λ₀ x 1.1λ₀ x 0.58λ₀           | 30                    | 93                   | 50                     | 14.2                   | 24.5                                    |
| [25] | 1.01λ₀ x 1.01λ₀ x 0.164λ₀        | 2.4                    | -                    | 41                     | 9.74                   | 58.3                                    |
| This work | 1.08λ₀ x 1.08λ₀ x 0.05λ₀           | 5.9                    | 98                   | 5.5                    | 9.4                    | 162.1                                   |
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Ye-Bon Kim received the B.S. and M.S. degrees in electrical and electronics engineering from Chung-Ang University, Seoul, South Korea, in 2018 and 2020, respectively, where he is currently pursuing Ph.D. degree. His research interests include smart antenna, phased array antennas, mmWave antennas, antenna-in-package, RF circuit and antenna calibration.

Jin-Woo Kim received the B.S. degree in electrical and electronics engineering from Chung-Ang University, Seoul, South Korea, in 2020, where he is currently pursuing M.S. degree. His research interests include mmWave antennas, RF circuits and communication systems.

Han Lim Lee (M’16) received the B.A.Sc. degree in electronics engineering from Simon Fraser University, BC, Canada, in 2008 and the M.S. and Ph.D. degrees in electrical engineering from KAIST, Daejeon, South Korea, in 2010, 2014, respectively. From 2014 to 2015, he was a senior engineer in DMC research center at Samsung Electronics. Since 2015, he joined the school of electrical and electronics engineering in Chung-Ang University as an assistant professor. His research interests include RF circuits and communication systems, mmWave beamforming antennas and phased array systems, antenna-in-package, RFIC/MMIC, scalable-RF module, and microwave wireless power transmission (MWPT).