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Novel Compact UWB Planar Monopole Antenna Using a Ribbon-Shaped Slot

SEUNGYONG PARK AND KYUNG-YOUNG JUNG, (Senior Member, IEEE)
Department of Electronic Engineering, Hanyang University, Seoul 04763, South Korea

Corresponding author: Kyung-Young Jung (kyjung3@hanyang.ac.kr)

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ABSTRACT Ultra-Wideband (UWB) is a wireless communication technology that can be utilized for precise indoor positioning system. UWB is low power-consuming and resistant to complex multipath environments, thanks to a short pulse signal. Since the main desired characteristics of the UWB antennas for radio-frequency localization systems are wide bandwidth, omnidirectional radiation pattern, and low profile for simple integration with printed circuit boards, various planar monopole antennas for UWB applications were proposed to meet the requirements. In order to satisfy these conditions, in this paper, a novel compact UWB planar monopole antenna operating in 3.1 GHz–10.8 GHz is designed on FR-4 substrate. The overall size of the antenna is $12.5 \times 12.5 \times 1$ mm^3, which is $0.129\ \lambda_0 \times 0.258\ \lambda_0 \times 0.01\ \lambda_0$ in free space at the lowest frequency. The transmission line is designed based on a coplanar waveguide with ground (CPWG) and vias in the CPWG are employed to eliminate non-radiating phenomenon at some specific frequencies. The shape of the radiator is modified from the hexagonal shape and a ribbon-shaped slot inside the radiator is adapted to improve the operating frequency range. The proposed UWB planar monopole antenna is fabricated and measured. The proposed antenna provides good antenna performance from 3.1 to 10.8 GHz and also the radiation patterns at various frequencies are omnidirectional pattern.

INDEX TERMS UWB, planar monopole antenna, slot.

I. INTRODUCTION

Ultra-Wideband (UWB) technology was perceived in 1960 with study of a linear time-invariant system via characteristic impulse response. Since there was no infrastructure to build UWB at that time, the interest in UWB was renewed in the late 20th century. In particular, UWB was grafted for military purposes as communications security and radar in the United States [1]. UWB was exclusively used by military and government agencies. However, ever since 2002, Federal Communications Commission deregulated UWB, the frequency range of 3.1 GHz to 10.6 GHz, to civil use for wireless communication in indoor environments. As the private use restrictions were lifted, UWB was an interesting research from 2002 to 2010 [1]. WiMedia Alliance, which consists of Intel, Microsoft, and HP, was also founded to encourage connectivity and interoperability of wireless multimedia between devices in personal area network in 2002. The WiMedia sought prosperity of UWB by pursuing wireless universal serial bus, but the interest of UWB languished after 2010, as the Wi-Fi, which is rival of UWB, released IEEE 802.11ac as the response to wireless universal serial bus [2], [3].

Recently, interest in the UWB technology is surging again. From 2019, smartphone manufacturers have started to apply the location estimation technology by embedding a UWB chip in their phones, and also numerous companies are building indoor location tracking systems based on the UWB technology in various industry fields such as smart factories, smart home, etc. [4]. The reason why UWB's popularity has lately re-emerged is the accuracy and reliability of UWB signals. Although other radio frequency signal-based positioning systems, including GPS, Wi-Fi, and Bluetooth, already exist, GPS signals cannot be used due to non-line-of-sight satellite signals and other technologies do not provide sufficient accuracy and reliability in indoor environments [4]–[7]. Note that UWB short pulse signals can increase the transmission speed, overcome multipath fading and frequency

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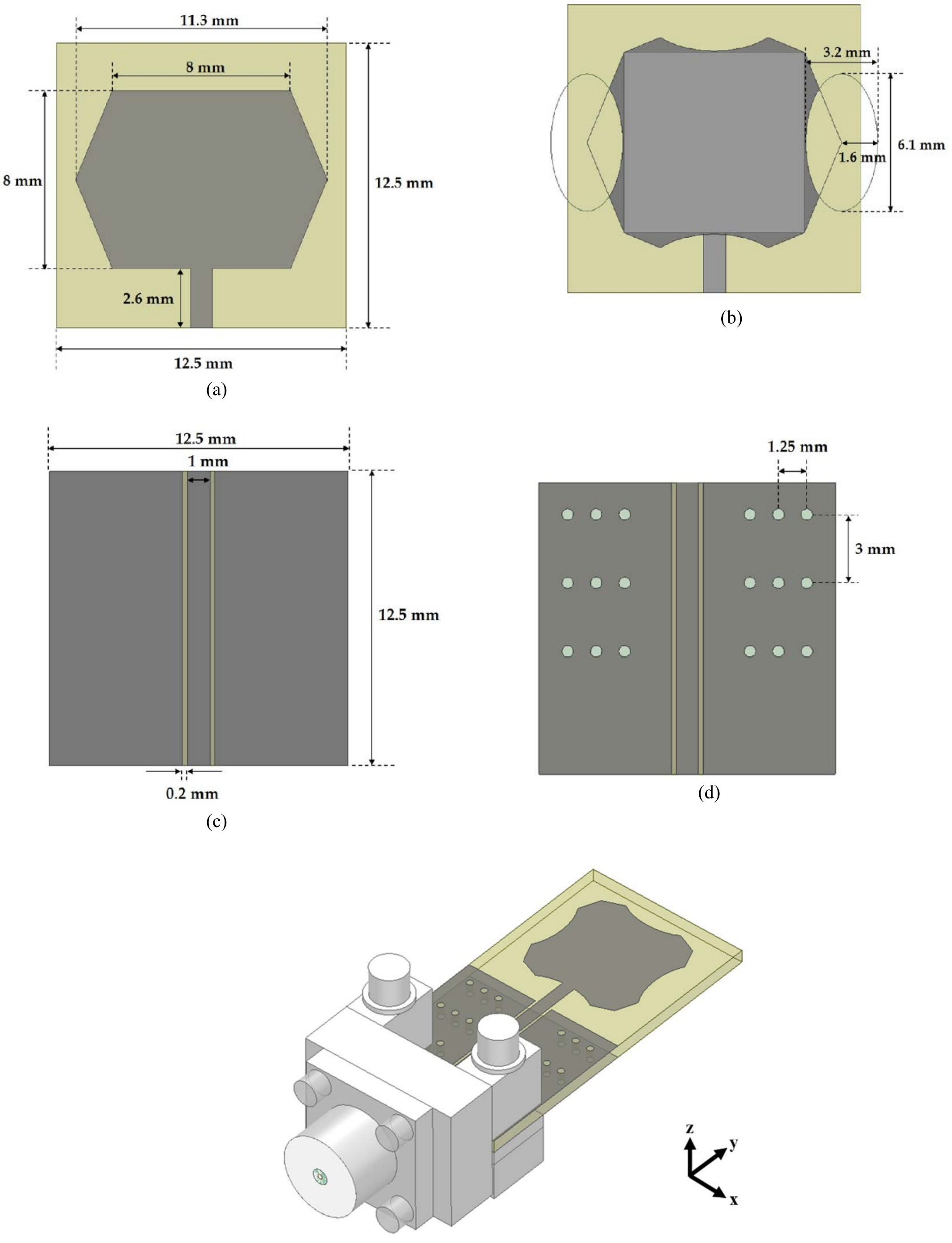
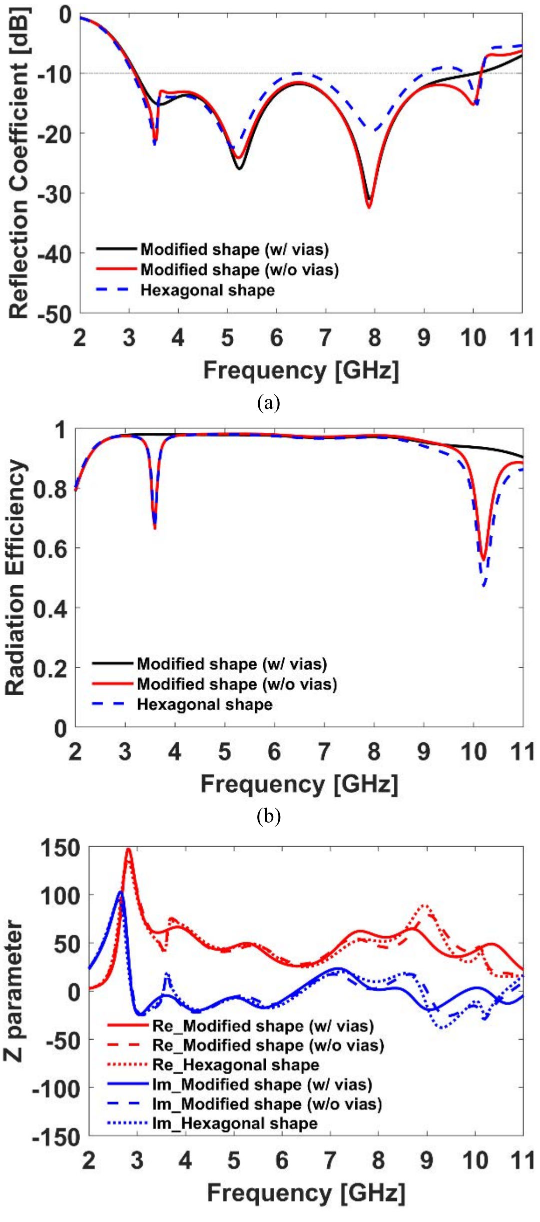


FIGURE 1. Planar monopole antenna. (a) Hexagon-shaped radiator. (b) Modified shaped radiator. (c) CPWG (w/o vias). (b) CPWG (w/ vias). (b) Overall schematic.

selective fading, and offer the high security and resolution for precise indoor positioning systems [8]–[10].

In general, for UWB-based indoor positioning systems, the main desired characteristics of UWB antennas are wide bandwidth, omnidirectional pattern, and compact size [11]. Recently, some researchers proposed UWB antennas that satisfy the aforementioned characteristics in many different ways [12]–[26]. Various planar monopole antennas for UWB systems were studied for miniaturization by employing an electromagnetic-bandgap [12], a metamaterial [13], a partial ground plane [14], and two triangular and one circular sector slots [15]. In addition, various shaped compact UWB planar antennas were proposed, including a symmetrical hexagon-shaped radiator [16], a z-shaped radiator [17], a compact



(a)

(b)

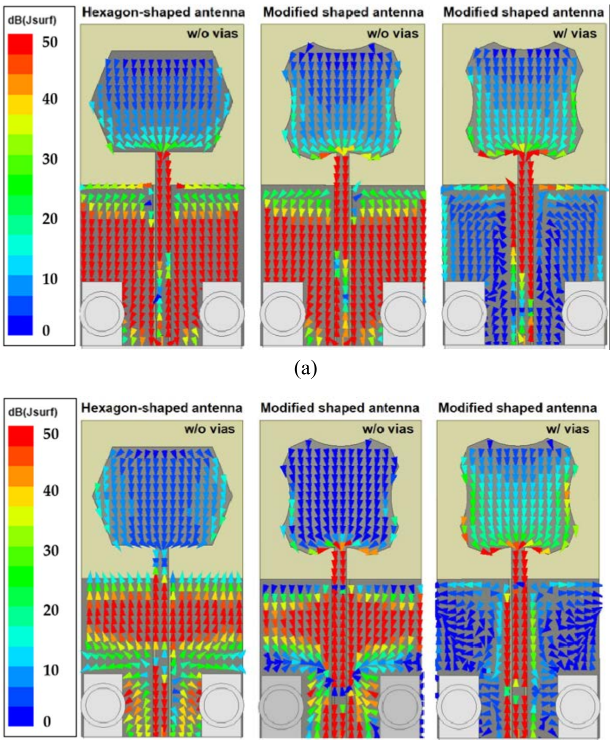
(c)

FIGURE 2. Simulated antenna parameters. (a) Reflection coefficient. (b) Radiation efficiency. (c) Impedance.

tapered-shape slot [18], a bow tie-shaped antenna [19], and so on [20]–[26].

We propose a novel compact UWB planar monopole antenna using a new shape to yield good antenna performance in the frequency range of 3.1 GHz–10.8 GHz. Our proposed UWB antenna is developed by the following three-step procedure:

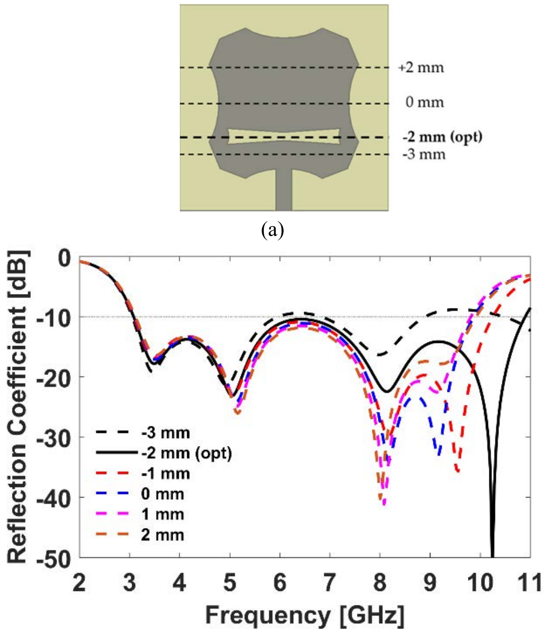
1. Basic design of a hexagon-shaped radiator
2. Modification of a hexagon-shaped radiator to improve matching performance
3. Insertion of a ribbon-shaped slot to increase the bandwidth



(a)

(b)

FIGURE 3. Surface current density distribution. (a) 3.6 GHz. (b) 10.2 GHz.



(a)

(b)

FIGURE 4. Simulated reflection coefficient performance of the designed antenna depending on the position of the ribbon-shaped slot. (a) Optimized position of ribbon-shaped slot. (b) Reflection coefficient versus the position of the ribbon-shaped slot.

In this work, the transmission line is made of a coplanar waveguide with ground (CPWG). The proposed antenna performance is investigated in both frequency and time domains

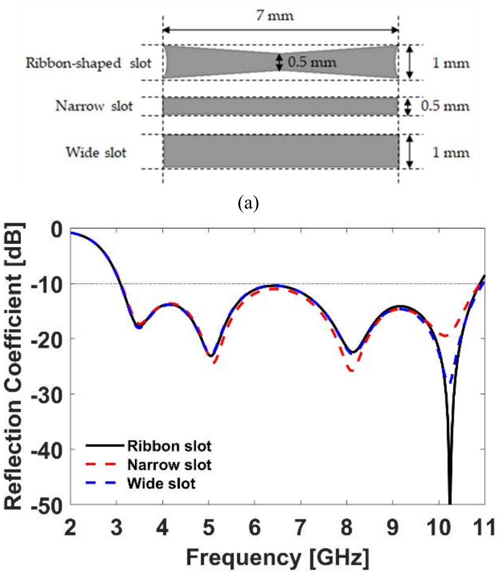


FIGURE 5. Simulated reflection coefficient performance of the designed antenna depending on the shape of the slots. (a) Ribbon-shaped slot shape and rectangular slots shape with minimum and maximum width of the ribbon. (b) Reflection coefficient versus the shape of the slot.

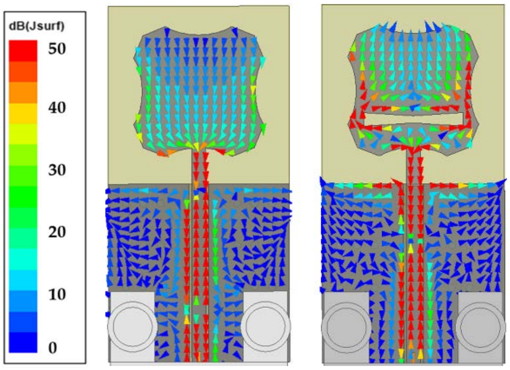


FIGURE 6. Surface current density distribution at 10.2 GHz.

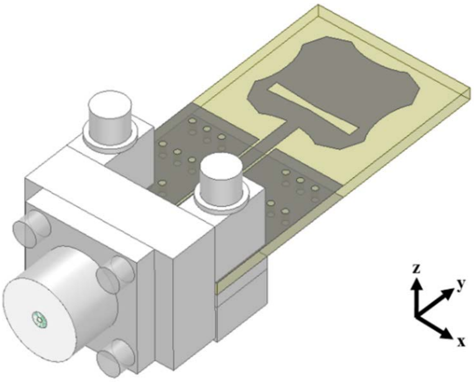
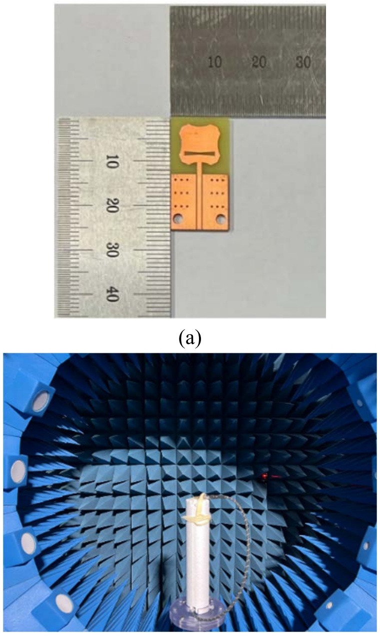


FIGURE 7. Schematic of the proposed UWB planar monopole antenna.



(b)

FIGURE 8. Fabrication and measurement setup of the proposed UWB planar monopole antenna. (a) Fabrication. (b) Measurement setup.

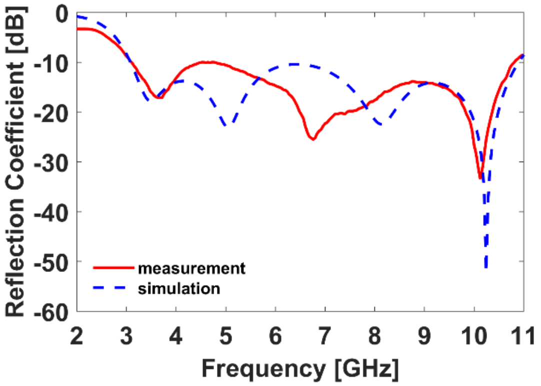


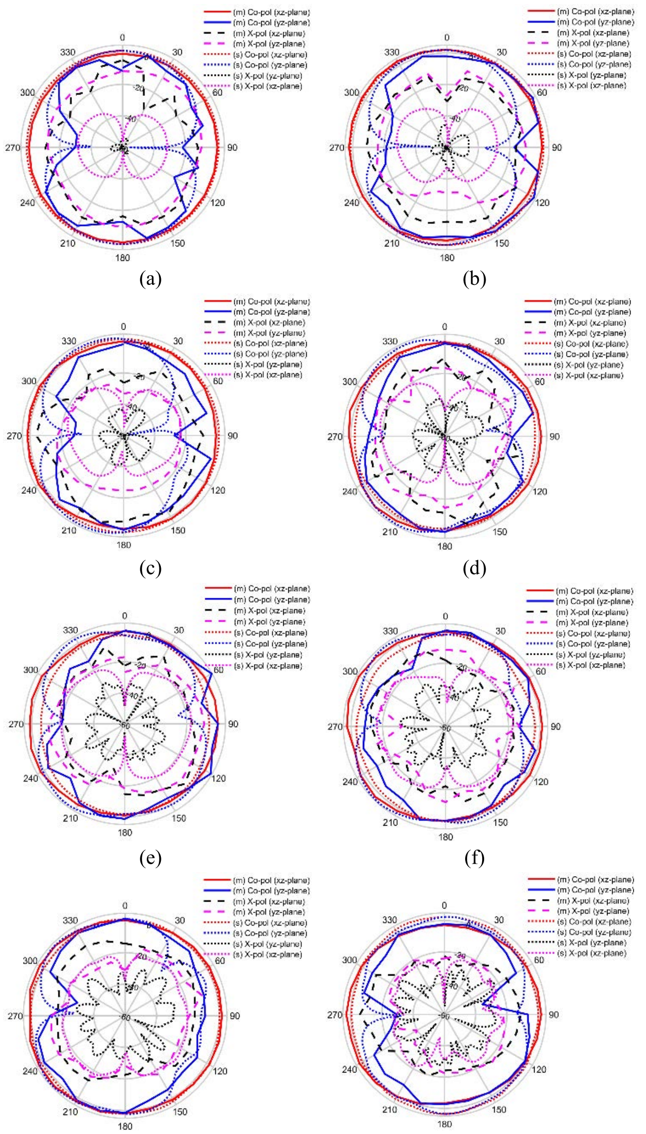
FIGURE 9. Reflection coefficient of the proposed UWB planar monopole antenna.

such as reflection coefficient, radiation pattern, gain, efficiency, and fidelity factors. The main contributions of our work include compact size, elimination of radiation efficiency deterioration, and comprehensive analysis of antenna performance. The remainder of this paper is organized as follows. We first present the UWB planar monopole antenna operating the frequency range from 3.1 GHz to 10 GHz. And then, vias are employed in the CPWG to prevent unwanted electromagnetic phenomenon at 3.6 GHz and 10.2 GHz. Next, we propose the UWB planar monopole antenna operating the frequency range from 3.1 GHz to 10.8 GHz by inserting a slot inside the radiator. Moreover, the effects of the position and the shape for the slot are investigated. The proposed UWB planar monopole antenna is fabricated and its experimental results are presented. Finally, concluding remarks are provided.

II. DESIGN

A. UWB PLANAR MONOPOLE ANTENNA

As alluded previously, in this work, the UWB planar monopole antenna is designed for compact size, broad



(a) (b) (c) (d) (e) (f) (g) (h)

FIGURE 10. Simulated and measured radiation patterns. (a) 3 GHz. (b) 4 GHz. (c) 5 GHz. (d) 6 GHz. (e) 7 GHz. (f) 8 GHz. (g) 9 GHz. (h) 10 GHz.

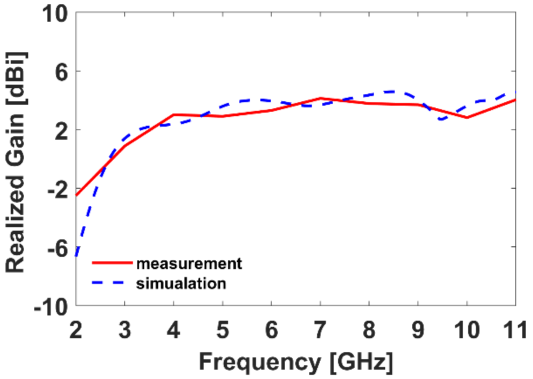


FIGURE 11. Realized gain versus frequencies of proposed antenna.

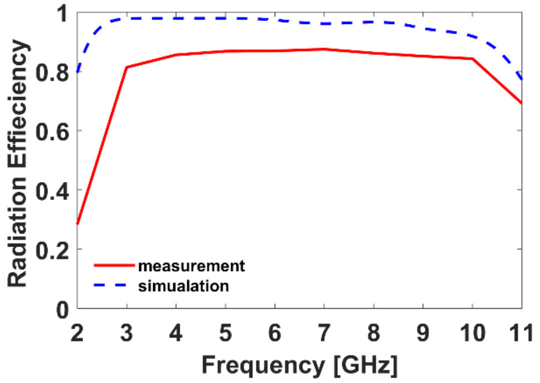


FIGURE 12. Radiation efficiency of proposed antenna.

bandwidth, and omnidirectional pattern. Fig. 1 (a) shows the planar monopole antenna, which is adopted by a hexagon-shaped radiator [16]. The lowest operating frequency (3.1 GHz) is considered to initially design the hexagon-shaped radiator. The lowest operating frequency (3.1 GHz) is considered to initially design the hexagon-shaped radiator. The lowest frequency of the planar monopole antenna can be approximately calculated by equating its area to an equivalent cylindrical monopole antenna [27]:

$$2\pi rl = \text{area of the radiator} \tag{1}$$

$$f_l = \frac{c_0 \times 0.24}{l + r} \tag{2}$$

where c_o is speed of light in free space, l is the height of the radiator, and r is the equivalent radius. Note that the effects of the substrate and the feed gap are not considered in the above design equation [28]. In this work, we choose the height (l) of the hexagon-shaped radiator as 8 mm and its area as 77.2 mm^2 (its equivalent radius r of 1.54 mm). Since the substrate effect cannot be considered analytically, we adjust the feed gap by the EM simulator (HFSS) such that the lowest operating frequency of the radiator is 3.1 GHz. Fig. 1 (a) shows our hexagon-shaped radiator with the feed gap of 2.6 mm.

The hexagon-shaped radiator is transformed to a modified shaped radiator, where both sides are partially cut into an oval shape to have a concave shape and both top and bottom shapes are the same as that of both sides in order to improve the reflection coefficient performance, as illustrated in Fig. 1 (b). The CPWG consists of the spacing of 0.2 mm and the width of 1 mm for a given 50 Ω impedance as shown in Fig. 1 (c). Fig. 1 (d) shows the CPWG with vias of which diameter of 0.5 mm. The input port is fed by an end-launch 2.92 mm connector and it is connected with the CPWG. Fig. 1 (e) displays the overall schematic of the modified shaped antenna. FR-4 (thickness = 1 mm, $\varepsilon_r = 4.4$, $\tan\delta = 0.02$) is employed as the substrate. The width of the substrate, which is selected by the size of the end-launch 2.92 mm connector, is 12.5 mm and the total length of the substrate is 25 mm.

Fig. 2 (a) shows the simulated reflection coefficient for the conventional hexagon-shaped antenna and the modified

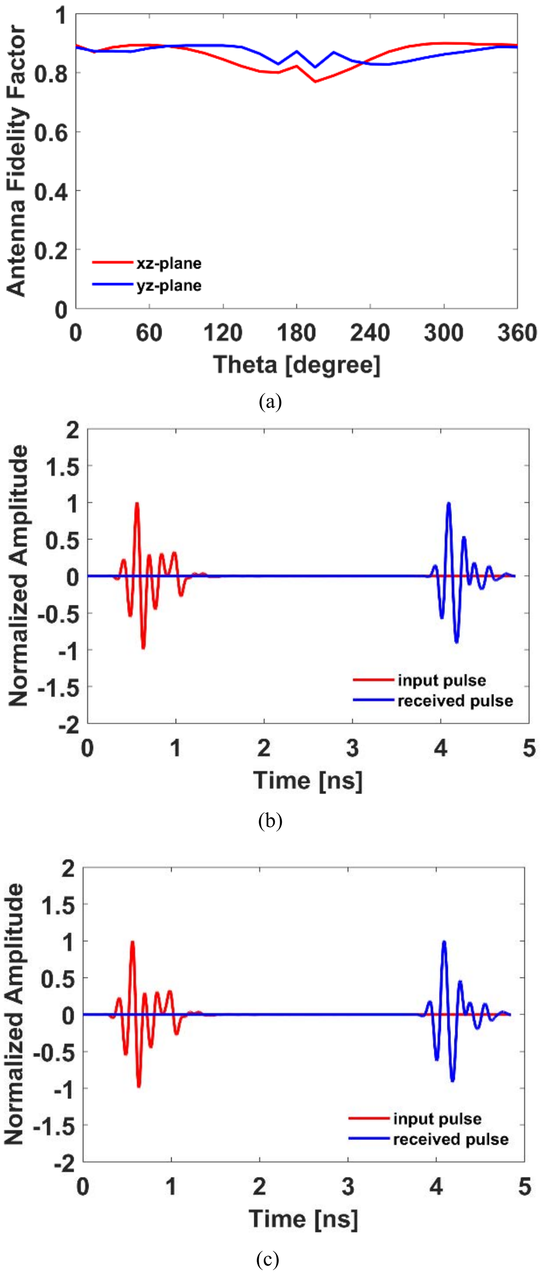
TABLE 1. Comparison of UWB planar monopole antennas.

Ref.	Antenna Size (unit: mm (λ_0))	Antenna Substrate	Operating frequency range (criteria: VSWR < 2, unit: GHz)	Time-domain analysis (fidelity factors and group delay)
This work	12.5×25×1 (0.129×0.258×0.01)	FR-4	3.1 – 10.8	Yes
[12]	30.5×31×1.575 (0.268×0.273×0.014)	$\varepsilon_r = 2$	2.64 – 12.9 (except: 4.8 – 5.9, 7.1 – 7.8)	No
[13]	14.5×22×1.6 (0.149×0.226×0.016)	FR-4	3.08 – 14.1	Partially (group delay)
[14]	26×25×1.6 (0.277×0.267×0.017)	FR-4	3.2 – 12	No
[15]	30×30×1.52 (0.34×0.34×0.017)	Taconic RF-30	3.4 – 9	Partially (group delay)
[16]	20×25×1.6 (0.207×0.258×0.017)	FR-4	3.1 – 12.18	No
[17]	35×38×1.57 (0.327×0.355×0.015)	Roger 5880	2.8 – 22.7	Yes
[18]	22×24×1.6 (0.22×0.24×0.016)	FR-4	3 – 11.2	No
[19]	24.5×20×1.6 (0.256×0.213×0.017)	FR-4	3.2 – 11	Yes
[20]	27×19×1.6 (0.255×0.179×0.015)	FR-4	2.83 – 11.56 (except: 3.3 – 4.2, 4.9 – 6)	Yes
[21]	50×50×1.575 (0.467×0.467×0.015)	Taconic TLP	2.8 – 11	No
[22]	38×40×1 (0.393×0.413×0.01)	FR-4	3.1 – 10.6 (except: 3.6, 5.5)	No
[23]	24.5×20×1.6 (0.249×0.203×0.016)	FR-4	3.05 – 11.25	Yes
[24]	20×23×1.6 (0.213×0.245×0.017)	FR-4	3.2 – 10.5 (except: 4 – 5.78, 6.83 – 8.22)	No
[25]	22×13×0.87 (0.217×0.126×0.008)	Taconic TLY-5	2.9 – 23.5 (except: 4.9 – 6.1)	No
[26]	20×18×1.6 (0.24×0.216×0.019)	FR-4	3.6 – 15.46	No

shaped antenna. For the modified shaped antennas, two types of CPWGs (without vias and with vias) are considered. It is observed that the reflection coefficient of the hexagon-shaped monopole antenna is larger than −10 dB from 9 GHz to 9.8 GHz. For the two modified shaped antennas, the reflection coefficients are less than −10 dB from 3.1 GHz to 10.1 GHz, different from the hexagon-shaped antenna. Fig. 2 (b) illustrates that radiation efficiency is significantly deteriorated at 3.6 GHz and 10.2 GHz for the hexagon-shaped antenna and the modified shaped monopole antenna without vias. In addition, Fig. 2 (c) shows that the imaginary values of the impedance for these antennas are rapidly changed near the same frequencies. To further investigate how the antennas operates at these frequencies, we examine surface current density distribution for the considered antennas at the corresponding frequencies. As shown in Fig. 3, the surface current densities are concentrated on the transmission line for the antennas based on the CPWG without vias and lower current flows on the radiator, which leading to poor radiation efficiency. On the other hand, for the antenna based on the CPWG with vias, non-radiating phenomenon does not occur and thus radiation efficiency is significantly improved compared to the non-vias counterparts. Therefore, the CPWG with vias is selected for the transmission line of the UWB monopole antenna in this work. Note that the return loss is not larger than 10 dB at high frequencies (>10.1 GHz) for the designed UWB planar antenna up to now. Therefore, the operating bandwidth of the UWB planar antenna should be further increased and this will be discussed in the following subsection.

B. UWB PLANAR MONOPOLE ANTENNA WITH A RIBBON-SHAPED SLOT

In this subsection, a ribbon-shaped slot is applied inside the designed modified shaped planar monopole antenna to satisfy the entire UWB band (3.1 GHz–10.6 GHz). A ribbon-shaped slot that becomes narrower from both ends of the radiator toward the center is formed and both ends of the slot

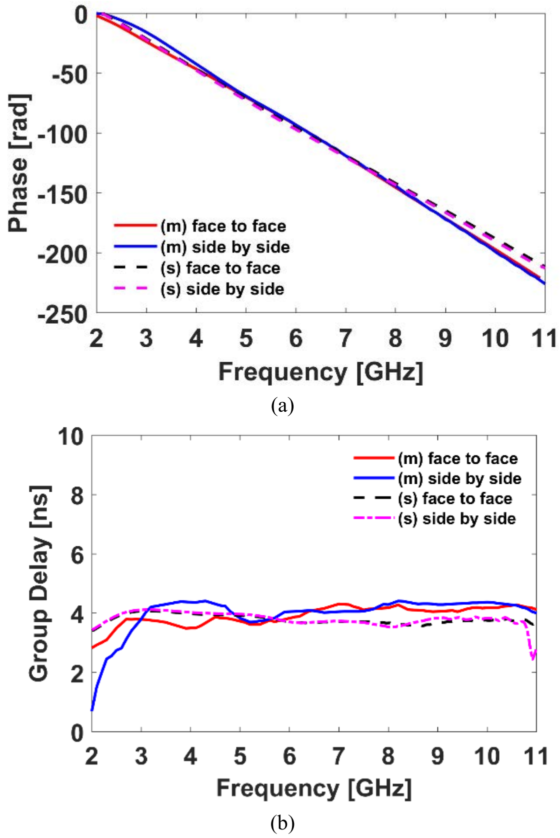


(a)

(b)

(c)

FIGURE 13. Simulated fidelity factor. (a) Antenna fidelity factor. (b) Normalized input and received pulse signals in face-to-face case. (c) Normalized input and received pulse signals in side-by-side case.



(a)

(b)

FIGURE 14. Measured phase and group delay of two proposed antennas away from 1 m. (a) Phase. (b) Group delay.

have a concave cut shape to minimize reflection coefficient. Figure 4 shows how the reflection coefficient performance of the antenna changes depending on the position of the ribbon-shaped slot. According to Fig. 4 (b), the -10 dB S_{11} bandwidth is improved due to the additional resonance at 10.2 GHz, when the position of the ribbon-shaped slot is -2 mm. Also, we analyzed how the performance changes when a rectangular slot is applied to the antenna based on the minimum and maximum widths of the ribbon. Fig. 5(a) displays the rectangular slot with minimum and maximum widths of the ribbon and Fig. 5 (b) demonstrates that the reflection coefficient for the ribbon-shaped slot antenna near 10.2 GHz is significantly small compared to the other rectangular slot antennas. As shown in Fig. 6, it is illustrated that the ribbon-shaped slot resonates at 10.2 GHz and thus the operating bandwidth is extended to cover the whole UWB band. Fig. 7 shows the final design schematic of the proposed UWB planar monopole antenna, consisting of the modified shaped radiator (which is transformed from a hexagonal shape for bandwidth enhancement), the CPWG with vias (which can eliminate undesired non-radiating phenomenon), and the ribbon-shaped slot (which extends the operating bandwidth by resonance at 10.2 GHz).

III. FABRICATION AND MEASUREMENT

The designed UWB planar monopole antenna is fabricated and measured, as shown in Fig. 8. The simulated and measured results of the reflection coefficient for the proposed UWB antenna is shown in Fig. 9. The measured result is generally in agreement with the simulated result. Somewhat discrepancies between the measurement result and simulation result may be caused by errors of fabrication and measurement. It is observed that the measured reflection coefficient of the fabricated UWB antenna is below -10 dB from 3.1 GHz to 10.8 GHz. The measured radiation patterns for the cross polarization and the co polarization at various frequencies are also shown in Fig. 10. Omnidirectional radiation patterns can be observed, similar to the simulated radiation patterns. Fig. 11 show the simulated and measured gains of the proposed antenna and it is observed that its maximum measured gain is 4.12 dBi at 7 GHz. Fig. 12 provides the simulated and measured radiation efficiencies and some discrepancies are caused by the fabrication and measurement errors. Also, the time-domain behaviors of the proposed antenna are investigated by CST EM simulations [17], [19], [20], [23], [29], [30]. The antenna fidelity factor can be obtained by calculating with the cross-correlation between the input pulse and the radiated E-fields. Fig. 13 (a) demonstrates the antenna fidelity factor of 0.8-0.9 values for all angles. The system-fidelity factor is calculated by cross-correlation between the transmitted pulse and the received pulse. To verify the system-fidelity factor, the two same proposed antennas are placed in 1 meter away from each other and the two cases of face-to-face and side-by-side are considered. Fig. 13 (b) and (c) show the normalized transmitting pulse and received pulse for the two cases. The system-fidelity factors for the face-to-face and the side-by-side are 91.8% and 82.6% respectively. Fig. 14 shows the phase and group delay of S_{21} between the two proposed antennas placed in 1 meter from each other. The measured phase and group delay are in good agreement with the simulated results.

Finally, Table 1 shows comparison between the proposed UWB planar monopole antenna and the previous UWB antennas in literature. Note that the λ_0 is the wavelength at the lowest frequency of the operating bandwidth in free space. As shown in the table, the UWB antenna proposed in [25] is the smallest size, but the authors did not provide the time-domain analysis such as fidelity factors and group delay, which are important characteristics for UWB antennas discussed in [30]. Although the proposed UWB antenna is not the smallest size, our antenna is comprehensively analyzed in both frequency domain and time domain and is sufficiently compact compared to other UWB antennas.

IV. CONCLUSION

In this paper, a novel compact UWB planar monopole antenna is proposed. The proposed UWB antenna consists of a modified shaped radiator from a hexagonal shape and the CPWG with vias. The modified shaped radiator is designed to improve the -10 dB S_{11} bandwidth from 3.1 GHz to 10.1 GHz and vias in the CPWG are used to avoid the unwanted electromagnetic field phenomenon at specific frequencies. Also, a ribbon-shaped slot which resonates at 10.2 GHz is applied inside radiator to extend the operating frequency band. The overall size of the proposed antenna is $12.5 \times 25 \times 1$ mm^3, ($0.129\ \lambda_0 \times 0.258\ \lambda_0 \times 0.01\ \lambda_0$). The proposed UWB antenna is fabricated and measured. Experimental results indicate that -10 dB S_{11} bandwidth is from 3.1 GHz to 10.8 GHz and the radiation pattern is omnidirectional pattern in the frequency range of interest. The proposed UWB planar antenna has compact size, omnidirectional radiation pattern, and good performance in both frequency and time domains in the UWB band and thus it is highly suitable for UWB indoor positioning systems.

REFERENCES

[1] H. Nikookar and R. Prasad, *Introduction to Ultra Wideband for Wireless Communications*, 1st ed. New York, NY, USA: Springer, 2005.

[2] W. S. Jeon, H. S. Oh, and D. G. Jeong, "Decision of ranging interval for IEEE 802.15.4z UWB ranging devices," *IEEE Internet Things J.*, vol. 8, no. 20, pp. 15628–15638, Oct. 2021.

[3] K. S. Gopalan, A. Bansal, and A. R. Kabbinale, "Tracking resurgence of ultra-wideband—A standards and certification perspective," in *Proc. 14th Int. Conf. Commun. Syst. Netw. (COMSNETS)*, Jan. 2022, pp. 4–8.

[4] D. Coppens, E. De Poorter, A. Shahid, S. Lemey, and C. Marshall, "An overview of ultra-WideBand (UWB) standards(IEEE 802.15.4, FiRa, Apple): Interoperability aspects and future research directions," 2022, *arXiv:2202.02190*.

[5] S. Chilukuri and S. Gundappagari, "A wide dual-band metamaterial-loaded antenna for wireless applications," *J. Electromagn. Eng. Sci.*, vol. 20, no. 1, pp. 23–30, Jan. 2020.

[6] D. K. Naji, "Miniature slotted semi-circular dual-band antenna for WiMAX and WLAN applications," *J. Electromagn. Eng. Sci.*, vol. 20, no. 2, pp. 115–124, Apr. 2020.

[7] R. Shanmugam, "Design and analysis of a frequency reconfigurable penta-band antenna for WLAN and 5G applications," *J. Electromagn. Eng. Sci.*, vol. 21, no. 3, pp. 228–235, Jul. 2021.

[8] Z. Xu, Y. Zhou, S. Chen, L. Lu, G. Zhou, J. Chen, and L. Zhou, "Optical generation of UWB pulses utilizing Fano resonance modulation," *Frontiers Optoelectron.*, vol. 14, no. 4, pp. 426–437, Dec. 2021.

[9] M. I. Khan, M. I. Khattak, and M. Al-Hasan, "Miniaturized MIMO antenna with low inter-radiator transmittance and band rejection features," *J. Electromagn. Eng. Sci.*, vol. 21, no. 4, pp. 307–315, Sep. 2021.

[10] B. R. Shookooh, A. Monajati, and H. Khodabakhshi, "Theory, design, and implementation of a new family of ultra-wideband metamaterial microstrip array antennas based on fractal and Fibonacci geometric patterns," *J. Electromagn. Eng. Sci.*, vol. 20, no. 1, pp. 53–63, Jan. 2020.

[11] L. Brás, N. B. Carvalho, P. Pinho, L. Kulas, and K. Nyka, "A review of antennas for indoor positioning systems," *Int. J. Antennas Propag.*, vol. 2012, pp. 1–14, Dec. 2012.

[12] Y. Wang, T. Huang, D. Ma, P. Shen, J. Hu, and W. Wu, "Ultra-wideband (UWB) monopole antenna with dual notched bands by combining electromagnetic-bandgap (EBG) and slot structures," in *Proc. IEEE MTT-S Int. Microw. Biomed. Conf. (IMBioC)*, May 2019, pp. 6–8.

[13] S. S. Al-Bawri, H. H. Goh, M. S. Islam, H. Y. Wong, M. F. Jamlos, A. Narbudowicz, M. Jusoh, T. Sabapathy, R. Khan, and M. T. Islam, "Compact ultra-wideband monopole antenna loaded with metamaterial," *Sensors*, vol. 20, no. 3, p. 796, Jan. 2020.

[14] N. A. Jan, S. H. Kiani, D. A. Sehrai, M. R. Anjum, A. Iqbal, M. Abdullah, and S. Kim, "Design of a compact monopole antenna for UWB applications," *Comput. Mater. Continua*, vol. 66, no. 1, pp. 35–44, Oct. 2020.

[15] M. N. Hasan and M. Seo, "A planar 3.4–9 GHz UWB monopole antenna," in *Proc. Int. Symp. Antennas Propag. (ISAP)*, Oct. 2018, pp. 23–26.

[16] B. Roy, S. K. Chowdhury, and A. K. Bhattacharjee, "Symmetrical hexagonal monopole antenna with bandwidth enhancement under UWB operations," *Wireless Pers. Commun.*, vol. 108, no. 2, pp. 853–863, May 2019.

[17] S. Ullah, C. Ruan, M. S. Sadiq, T. U. Haq, and W. He, "High efficient and ultra wide band monopole antenna for microwave imaging and communication applications," *Sensors*, vol. 20, no. 1, p. 115, Dec. 2019.

[18] R. Azim, M. T. Islam, and N. Misran, "Compact tapered-shape slot antenna for UWB applications," *IEEE Antennas Wireless Propag. Lett.*, vol. 10, pp. 1190–1193, 2011.

[19] M. M. Alam, R. Azim, N. M. Sobahi, A. I. Khan, and M. T. Islam, "An asymmetric CPW-fed modified bow tie-shaped antenna with parasitic elements for ultra-wideband applications," *Int. J. Commun. Syst.*, vol. 35, no. 9, pp. 1–11, Feb. 2022.

[20] S. S. Mirmosaei, S. E. Afjei, E. Mehrshahi, and M. M. Fakharian, "A dual band-notched ultra-wideband monopole antenna with spiral-slots and folded SIR-DGS as notch band structures," *Int. J. Microw. Wireless Technol.*, vol. 8, no. 8, pp. 1197–1206, Apr. 2015.

[21] J. Y. Siddiqui, C. Saha, and Y. M. M. Antar, "A novel ultrawideband (UWB) printed antenna with a dual complementary characteristic," *IEEE Antennas Wireless Propag. Lett.*, vol. 14, pp. 974–977, 2015.

[22] H. Liu and Z. Xu, "Design of UWB monopole antenna with dual notched bands using one modified electromagnetic-bandgap structure," *Sci. World J.*, vol. 2013, pp. 1–9, Sep. 2013.

[23] M. Mottahir Alam, R. Azim, I. M. Mehedi, and A. I. Khan, "Coplanar waveguide-fed compact planar ultra-wideband antenna with inverted L-shaped and extended U-shaped ground for portable communication devices," *Chin. J. Phys.*, vol. 73, pp. 684–694, Oct. 2021.

[24] W. A. Awan, A. Zaidi, N. Hussain, A. Iqbal, and A. Baghdad, "Stub loaded, low profile UWB antenna with independently controllable notch-bands," *Microw. Opt. Technol. Lett.*, vol. 61, no. 11, pp. 2447–2454, Jun. 2019.

[25] N. Hussain, M. Jeong, J. Park, S. Rhee, P. Kim, and N. Kim, "A compact size 2.9–23.5 GHz microstrip patch antenna with WLAN band-rejection," *Microw. Opt. Technol. Lett.*, vol. 61, no. 5, pp. 1307–1313, Feb. 2019.

[26] B. R. Perli and M. R. Avula, "Design of wideband elliptical ring monopole antenna using characteristic mode analysis," *J. Electromagn. Eng. Sci.*, vol. 21, no. 4, pp. 299–306, Sep. 2021.

[27] N. P. Agrawall, G. Kumar, and K. P. Ray, "Wide-band planar monopole antennas," *IEEE Trans. Antennas Propag.*, vol. 46, no. 2, pp. 294–295, Feb. 1998.

[28] R. Singh and G. Kumar, "Broadband planar monopole antennas," Electron. Syst. Group, Dept. EE, IIT Bombay, Mumbai, Maharashtra, India, M. Tech Credit Seminar Rep., Nov. 2003.

[29] S. Park, S. Kim, D. K. Kim, J. Choi, and K.-Y. Jung, "Numerical study on the feasibility of a 24 GHz ISM-band Doppler radar antenna for near-field sensing of human respiration in electromagnetic aspects," *Appl. Sci.*, vol. 10, no. 18, p. 6159, Sep. 2020.

[30] G. Quintero, J. F. Zurcher, and A. K. Skrivervik, "System fidelity factor: A new method for comparing UWB antennas," *IEEE Trans. Antennas Propag.*, vol. 59, no. 7, pp. 2502–2512, Jul. 2011.

SEUNGYONG PARK received the B.S. degree from the School of Information and Communication Engineering, Chungbuk University, Cheongju, Republic of Korea, in 2016. He is currently pursuing the Ph.D. degree in electrical engineering with Hanyang University, Seoul, Republic of Korea. His current research interests include Doppler radar for medical application, UWB antenna for an indoor positioning systems, and antenna design for next generation wireless communication systems.

KYUNG-YOUNG JUNG (Senior Member, IEEE) received the B.S. and M.S. degrees in electrical engineering from Hanyang University, Seoul, Republic of Korea, in 1996 and 1998, respectively, and the Ph.D. degree in electrical and computer engineering from The Ohio State University, Columbus, OH, USA, in 2008.

From 2008 to 2009, he was a Postdoctoral Researcher at The Ohio State University. From 2009 to 2010, he was an Assistant Professor with the Department of Electrical and Computer Engineering, Ajou University, Suwon, Republic of Korea. Since 2011, he has been working at Hanyang University, where he is currently an Associate Professor with the Department of Electronic Engineering. His current research interests include computational electromagnetics, bioelectromagnetics, and nanoelectromagnetics.

Dr. Jung was a recipient of the Graduate Study Abroad Scholarship from the National Research Foundation of Korea, the Presidential Fellowship from The Ohio State University, the HYU Distinguished Teaching Professor Award from Hanyang University, and the Outstanding Research Award from the Korean Institute of Electromagnetic Engineering and Science.

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