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RESEARCH ARTICLE

Design of a Compact Direction-Finding Antenna Using Single-Radiator Multiple-Port for UWB Mobile Applications

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ABSTRACT This paper proposes a compact ultra-wideband (UWB) direction-finding antenna with a single-radiator multiple-port (SRMP) design. The proposed antenna consists of a single-radiator, self-decoupling feed structure (SDFS), and via walls considering the limited mounting space for mobile applications. The SDFS is optimized to improve isolation characteristics between adjacent ports. To verify the feasibility, the proposed SRMP antenna is fabricated, and antenna performance such as reflection coefficients, mutual couplings, and radiation patterns are measured in a full anechoic chamber. The SRMP antenna achieves a broadband of 2.1 GHz (from 6.3 GHz to 8.4 GHz) and a low mutual coupling of −21.22 dB at 8 GHz. In addition, a bore-sight gain of 0.78 dBi is measured at the target frequency of 8 GHz. To investigate the direction of arrival (DoA) estimation of the SRMP antenna, we utilize the Qorvo test board with the DW3000 chip, generally used in commercial UWB direction-finding systems. At distances of 1 m and 2 m, average estimated errors of 2.35° and 2.13° are obtained, respectively. These results demonstrate that the proposed compact SRMP antenna is suitable for UWB direction-finding systems of smart devices.

INDEX TERMS Single-radiator multiple-port, self-decoupling feed structure, ultra-wideband, direction-finding, channel impulse response.

I. INTRODUCTION

Recently, localization technology using ultra-wideband (UWB) has been widely used to obtain more accurate location of other devices on a variety of mobile applications such as smartphones, smart keys, and smart homes [1], [2]. The UWB is defined by the Federal Communications Commission (FCC) as a broadband communication method utilizing a wide frequency range from 3.1 GHz to 10.6 GHz, separated by 14 channels, each with a 500 MHz bandwidth [3], [4]. In South Korea, only Channel 9 (7.737 GHz to 8.236 GHz) is authorized for UWB communications in mobile devices [5]. To achieve location information in mobile applications, an array system capable of obtaining both distance and direction is needed [6]. The distance information can be obtained using the time of flight (ToF) method, which calculates the delay time between the transmitted and received signals. In addition, the angle of arrival (AoA) method is used to determine the direction by the phase difference of received signals from an array antenna system [7], [8], [9]. Typically, an array system with at least three individual antenna elements is required to achieve a direction-finding result in both the azimuth and elevation directions [10], [11]. However, as the antenna mounting space decreases due to the miniaturization of UWB mobile devices, there is a growing demand for research on a compact array antenna system. To reduce the size of array systems, studies have been conducted on miniaturization technologies for individual antenna, such as U-shaped structure [12], [13], [14], slot structure [15], [16], [17], [18], and truncated structure [19], [20], [21], [22]. However, the array systems have limitations for size reduction, because an array spacing of about half wavelength is required to accurately measure the phase information of each antenna. To resolve these problems, studies on single radiator with

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multiple feed structures that do not require array spacing have been conducted [23], [24]. Although the size of the array system has been reduced through a single radiator, these studies still have a size of more than 1 λ due to the additional parasitic structures to improve isolation characteristics. In addition, these studies are designed for Wi-Fi and LTE frequency bands in MIMO access-point applications. Therefore, in-depth studies are needed to improve the isolation characteristic of a single radiator antenna with a size less than 1 λ considering the limited mounting space of mobile devices. In this paper, we propose a compact UWB direction-finding antenna using a single-radiator multiple-port (SRMP) design. The proposed antenna consists of a single-radiator, co-planar waveguide with ground (CPWG) feeders, and via walls. A single patch radiator which does not require array spacing of λ/2 is adopted to replace multiple radiators, considering the limited mounting space for mobile devices. The feed structure is designed using the CPWG, which has stable matching characteristics for UWB channel 9 (7.7 GHz to 8.2 GHz). Then, the self-decoupling feed structure (SDFS) is designed with the CPWG by optimizing the upper layer ground to improve isolation characteristics between adjacent ports. In addition, via walls are applied outside the radiator to enhance gain characteristics by reducing the leakage fields. To verify the feasibility, the proposed SRMP antenna is fabricated, and antenna performance such as reflection coefficients, mutual couplings, and radiation patterns are measured in a full anechoic chamber. Subsequently, to observe the direction-finding performance, the direction of arrival (DoA) estimation is investigated using the Qorvo's DW3000 chip, which is widely used in commercial UWB direction-finding systems. The DoA estimations, calculated from the phase difference of the channel impulse response (CIR) data, are carried out for incident angles from −30° to 30°. The results demonstrate that the proposed antenna is appropriate for a UWB direction-finding system on smart devices.

II. FABRICATION AND MEASUREMENT OF THE PROPOSED SRMP DESIGN

Fig. 1 shows the geometry of the proposed SRMP direction-finding antenna, which utilizes a single patch radiator with three feeding ports placed at intervals of 120°. The proposed antenna consists of a single-radiator, CPWG feeders, and via walls on an FR-4 substrate ($\varepsilon_r = 4.2$, $\tan\delta = 0.018$), as shown in Fig. 1(a). The FR-4 substrate has a radius r_1 and a thickness h. A single patch radiator is adopted to replace the array system with multiple radiators, considering the limited mounting space for small mobile devices. The patch radiator is optimized to obtain broadband characteristics at the center frequency of 8 GHz (UWB channel 9) through an edge curve defined by the quadratic polynomial design function $f(y)$ with coefficients of a and l_1 as represented in Fig. 1(b). Then, the SDFS is designed with the CPWG by optimizing the upper layer ground to improve isolation characteristics between adjacent ports at a target frequency of 8 GHz. The

TABLE 1. Optimized SRMP antenna design parameters.

Parameters	Optimized values
l_1	4.7 mm
r_1	9 mm
h	1.6 mm
l_c	3.75 mm
w_c	4.75 mm
w_f	1.5 mm
g_d	0.7 mm
v_g	1.2 mm
v_l	4 mm
v_n	6
a	0.084

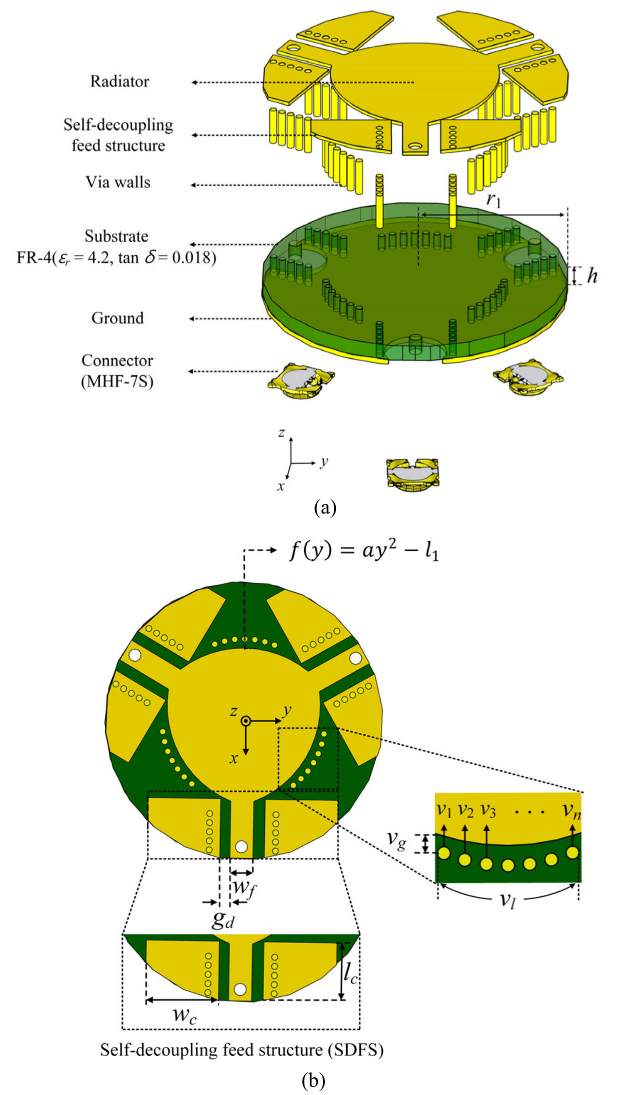

FIGURE 1. Geometry of the proposed SRMP antenna. (a) Isometric view. (b) Top view.

CPWG feeder has a signal line with the width w_f and the length l_c. The gap g_d is the distance between the upper layer ground and the signal line. The upper ground width w_c is very sensitive to isolation and is thus determined to have the maximum isolation characteristics between adjacent ports. In addition, for feeding, the proposed antenna adopts small connectors to reduce the leakage current and to improve isolation between ports. The via walls outside the radiator are optimized to improve the gain characteristics by reducing the leakage fields. The variables v_g, v_l, and v_n are refers to distance from the edge of radiator, the total length of the via wall, and the number of vias, respectively. The design parameters are optimized by observing important antenna performance with an ANSYS high-frequency structure simulator (HFSS) [25]. The optimized antenna design parameters are listed in Table 1.

Fig. 2(a) shows the photograph of the fabricated SRMP antenna in top view. The single patch radiator and the SDFS are etched on a compact FR-4 substrate with the diameter of less than half wavelength (at 8 GHz). Then, the via walls are applied outside the radiator to improve gain characteristics. The proposed antenna is fed by extremely small I-PEX MHF-7S connectors to reduce the leakage current and to improve isolation between ports, as shown in Fig. 2(b). Fig. 3 shows the reflection coefficients by measurement (solid line) and simulation (dashed lines). Mutual couplings are

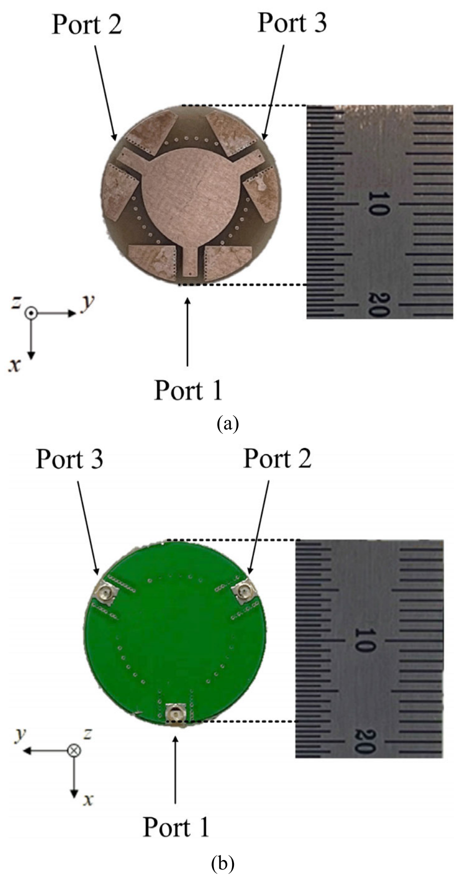

FIGURE 2. Fabrication of the proposed SRMP antenna. (a) Top view. (b) Bottom view.

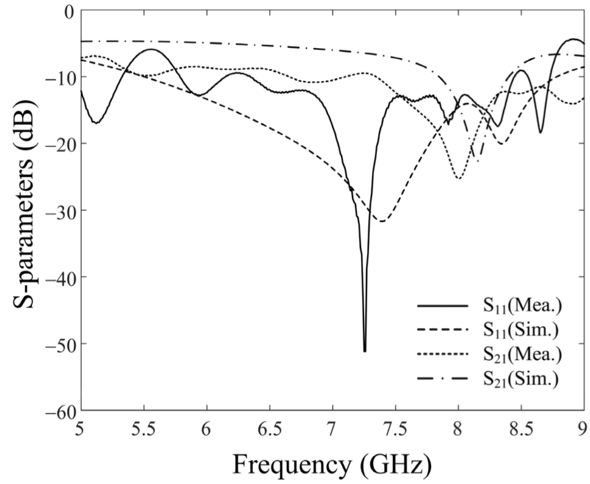

FIGURE 3. Simulated and measured reflection coefficients and mutual couplings of the proposed antenna.

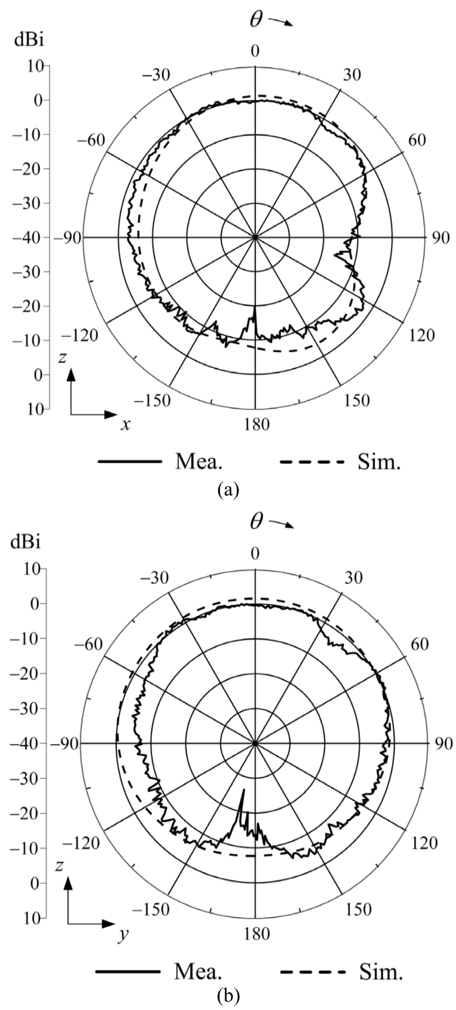

FIGURE 4. Simulated and measured radiation patterns of the proposed antenna for the port 1. (a) Radiation patterns for the *zx*-plane. (b) Radiation patterns for the *zy*-plane.

also plotted in the same figure (dotted line by measurement and dash-dotted line by simulation). The measured reflection coefficient shows a broadband of less than −10 dB from 6.3 GHz to 8.4 GHz through the optimized edge curve of the patch radiator. The measured result of −14.33 dB agrees with the simulated result of −12.08 dB at 8 GHz. A low mutual coupling of −21.22 dB is measured between ports 1 and 2, which is similar to the simulated result of −20.83 dB with an optimal width of the upper layer ground of the SDFS. Fig. 4 shows the measured and simulated 2D radiation patterns (*zx*- and *zy*-planes) for port 1. An improved bore-sight gain of 0.78 dBi is measured (solid line) at the target frequency of 8 GHz through via walls outside the radiator. It also has a good agreement with the simulated gain (dashed line) of 1.86 dBi.

III. DESIGN ANALYSIS AND DoA ESTIMATION PERFORMANCE

To obtain broadband characteristic for the SRMP antenna, the quadratic coefficient a of the polynomial design function $f(y)$ is investigated. Fig. 5(a) shows the simulated reflection coefficients according to the coefficient a (from 0.064 to 0.104). As shown in the figure, for all cases, a bandwidth of more than 2 GHz is obtained, which is wider than the target bandwidth of 500 MHz. Especially, the broad bandwidth of 2.69 GHz is obtained with the a of 0.084. The variation of the coefficient a affects the shape of the radiator, which is dominant to the gain characteristics. Therefore, the bore-sight gain is examined according to the coefficient a, as shown in Fig. 5(b). It has a maximum gain of 1.62 dBi with the same a of 0.084 at 8 GHz, which is the highest gain compared to 0.86 dBi and 0.4 dBi for the other cases. As a result, the quadratic coefficient a is optimized to 0.084 with a broad bandwidth of 2.69 GHz and a bore-sight gain of 1.62 dBi.

Then, to further improve the gain characteristics, the via walls are applied to reduce the leakage fields. Fig. 6(a) presents the variation of bore-sight gains with respect to the v_g (from 0.7 mm to 1.2 mm) and the v_l(from 2 mm to 5 mm). The maximum gain of 2.07 dBi is achieved with the v_g of 1.2 mm and the v_l of 5 mm. However, the lowest mutual coupling of −19.79 dB is achieved at the v_g of 1.2 mm and the

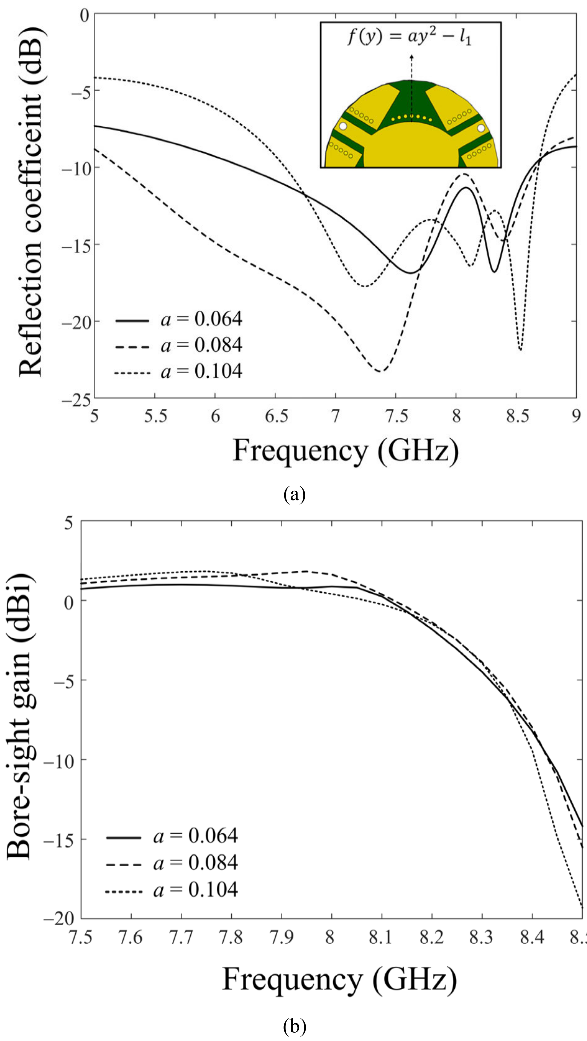

FIGURE 5. Analysis of bandwidth and bore-sight gain depending on the quadratic coefficient *a*. (a) Comparison of bandwidths. (b) Comparison of bore-sight gains.

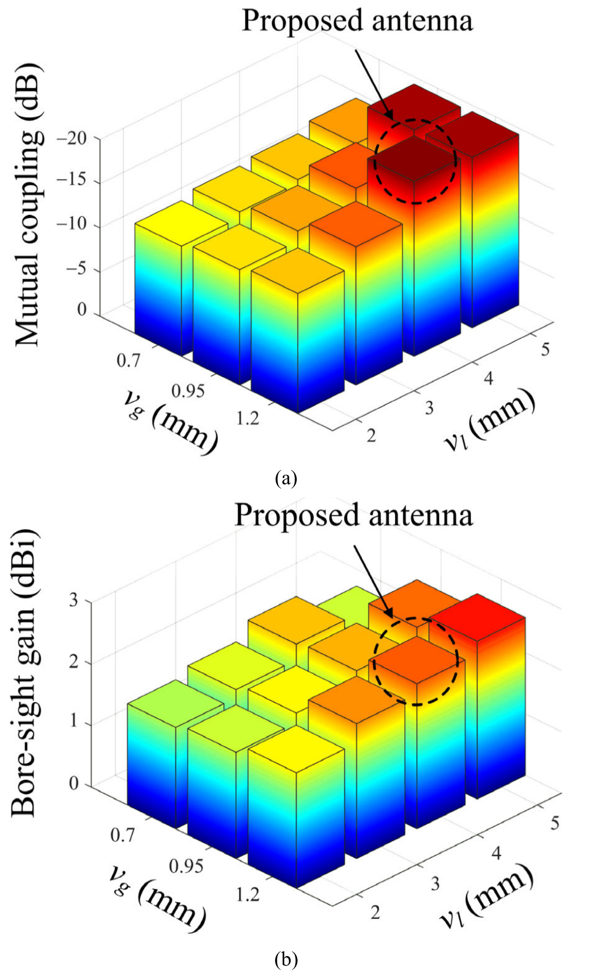

FIGURE 6. Optimization of the via walls considering both bore-sight gain and mutual coupling. (a) Mutual couplings depending on the v_g and v_l. (b) Bore-sight gains depending on the v_g and v_l.

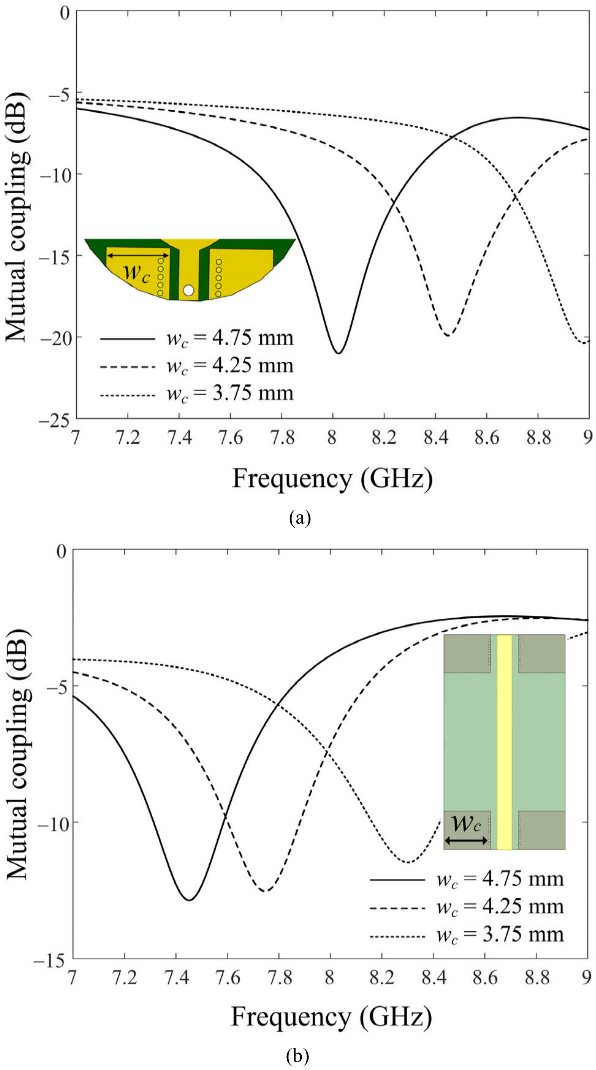

FIGURE 7. Analysis of mutual coupling depending on the width w_c. (a) Mutual couplings of the SDFS. (b) Mutual couplings of the CPWG transmission line.

v_l of 4 mm, respectively, as illustrated in Fig. 6(b). To enhance the accuracy of the received signals for UWB direction-finding, a lower mutual coupling characteristic is required. Therefore, to obtain the lowest mutual coupling of −19.79 dB while improving the gain characteristic to 1.86 dBi, v_g and v_l are designed with 1.2 mm and 4 mm, respectively.

In addition, we investigate the key design parameter that can shift the deep of the mutual coupling at UWB channel 9. In the proposed SRMP design, an E-field resonance occurs by the size of upper layer grounds. Thus, we analyze the variation of the mutual coupling according to the width w_c (from 3.75 mm to 4.75 mm) of the CPWG. As shown in Fig. 7(a), the deep of the mutual coupling is shifted to higher frequency band when the width w_c decreases. Then, the deep of the mutual coupling is moved at 8 GHz (center frequency of UWB channel 9) with a w_c of 4.75 mm, which is approximately $\lambda_{eff}/4$. To verify whether this operation can be generally applied, the two-port transmission line with the

TABLE 2. Comparisons of antenna characteristics.

	Proposed antenna	[26]	[27]	[28]
Antenna type	**SRMP**	Slot	Horn	Patch
Operating Frequency	**6.3–8.4 GHz**	868 MHz	1.5–5.5 GHz	6.3–6.8 GHz 7.8–8.1 GHz
The number of radiators	**1**	8	8	4
Aperture size	**0.48 λ × 0.48 λ (at 8 GHz)**	0.98 λ × 0.98 λ (at 868 MHz)	1.4 λ × 1.46 λ (at 3.5 GHz)	0.74 λ × 0.74 λ (at 6.5 GHz)
Antenna thickness	**1.6 mm**	280 mm	316 mm	0.7 mm

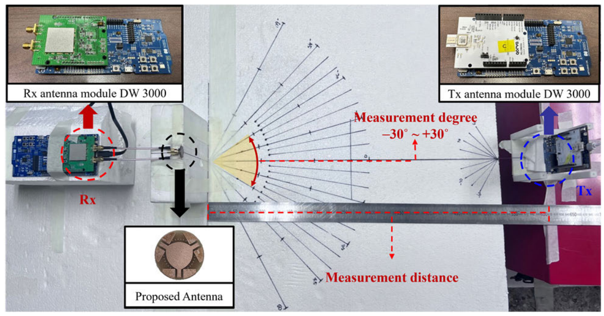

FIGURE 8. Measurement setup for UWB DoA estimation.

CPWG feeder is analyzed with the same design parameter w_c, as presented in Fig. 7(b). Similar to the results of the proposed antenna, the deep point is also shifted to higher frequency band when the w_c decreases. As observed by the parametric study, the upper ground width w_c is very sensitive to isolation and determines the deep of mutual coupling between adjacent ports. Consequently, the feed structure is optimized with CPWG, which is referred to as SDFS that can improve the isolation characteristics using the key parameter w_c of 4.75 mm.

To emphasize the advantages of the proposed antenna, performances such as antenna type, operating frequency, number of radiators, aperture size, and antenna thickness are compared with recently published papers [26], [27], [28]. As listed in Table 2, the proposed antenna, which has 0.48 λ × 0.48 λ of aperture size at 8 GHz, is smaller than any other direction-finding antennas. Furthermore, it has a bandwidth of 6.3 to 8.4 GHz, which is appropriate for the UWB Channel 9.

Fig. 8 illustrates the measurement setup for evaluating the DoA estimation performance of the proposed antenna. In UWB direction finding systems, DoA estimation performance is verified by utilizing CIR data, which is a convolution of transmitted and received signals. The CIR data obtained at each port can be represented in index order, as shown in Figure 9. Among them, the first signal that

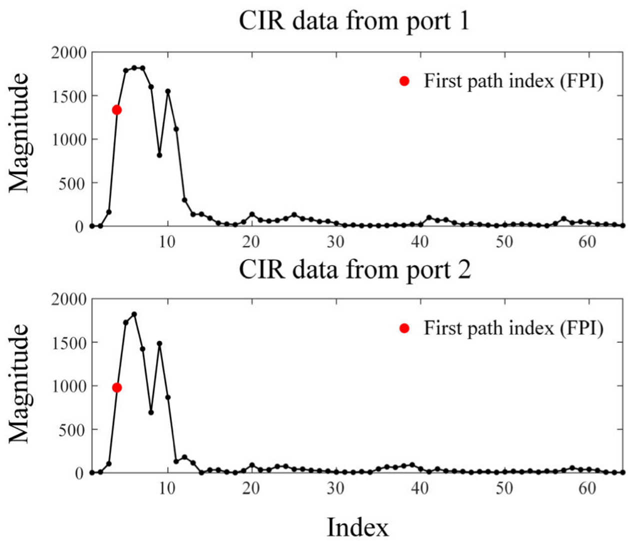

FIGURE 9. Received CIR data from port 1 and port 2.

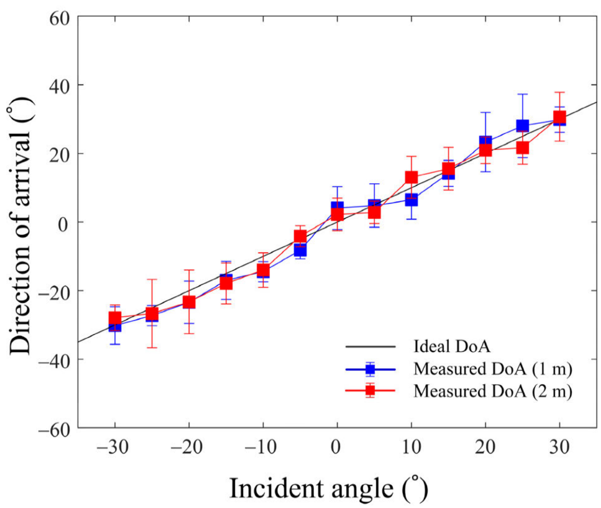

FIGURE 10. Measured DoA estimations according to incident angles.

exceeds the predefined threshold is referred to as the first path index (FPI). By utilizing the FPI, the direct path propagated from the Tx module can be separated from the indirect paths in a multipath propagation environment. To obtain the measured CIR data, we utilize the Qorvo test board with the DW3000 chip, which is used in commercial UWB direction-finding systems. In addition, we utilize the Nordic board nRF52840 DK to adjust the DW3000 chip, such as operating frequency, pulse intervals, and received CIR data. The transmit signal is radiated through the monopole chip antenna from the Tx module at UWB channel 9 with intervals of 500 μs. The proposed antenna is then connected to the Rx module, which is fabricated to estimate the direction-finding performance using the two SMA connectors. Then, the DoA estimations are conducted using the phase difference of arrival (PDoA) method through the CIR data for each port. The DoA estimation is carried out for two cases of distances (1 m and 2 m) by fixing the Tx module and rotating the Rx module from $-30°$ to $30°$ in increments of 5°, with 20 times of measurements. Fig. 10 presents the DoA estimations, obtained using ports 1 and 2 ($\varphi = 30°$), for incidence angles from $-30°$ to $30°$. The DoA estimations are presented with blue and red solid lines for each case of 1 m and 2 m, respectively. The averages of the 20 estimations for each incident angle are indicated by square markers, and the measurement error ranges for the highest and lowest results are represented by horizontal lines. Then, the average results are compared with the ideal DoA estimations, which is presented as a black solid line. At a distance of 1 m, a maximum error of 4.47° is observed at incident angle of 10°. Also, an average estimated error of 2.35° is calculated for every incident angle. Similarly, at a distance of 2 m, a maximum error of 3.98° (at incident angle of 10°) and an average estimated error of 2.13° are obtained. It has a maximum error of less than 5°, with an average error of less than 3° for every measured distance. Consequently, these measured DoA estimations demonstrate that the proposed SRMP antenna utilizing the miniaturized single patch radiator is suitable for smart devices with UWB direction-finding systems. In future work, we can utilize the machine learning techniques such as CNN and ResNet, which can improve the accuracy of DoA estimation [29], [30].

IV. CONCLUSION

In this paper, we proposed a compact UWB direction-finding antenna for mobile applications using the SRMP design. To replace the array system, the proposed antenna consisted of a single-radiator, SDFS, and via walls. The measured reflection coefficient had a broadband of less than -10 dB from 6.3 GHz to 8.4 GHz through an optimized edge curve of the patch radiator. In addition, a low mutual coupling of -21.22 dB was measured at 8 GHz with an optimal width of the upper layer ground of the SDFS. An improved bore-sight gain of 0.78 dBi was measured for port 1 at the target frequency of 8 GHz through via walls outside the radiator. Then, to further analyze the DoA estimation of the SRMP antenna, we utilized the Qorvo test board with the DW3000 chip, which is generally used in commercial UWB direction-finding systems. The DoA estimation was carried out at two distances (1 m and 2 m) by fixing the Tx module. The 20 received signal were measured using the Rx module from $-30°$ to $30°$. At distances of 1 m and 2 m, average estimated errors of 2.35° and 2.13° were obtained, respectively. These results demonstrated that the proposed SRMP antenna utilizing the miniaturized single patch radiator was suitable for smart devices with UWB direction-finding systems. In future work, we can utilize the machine learning techniques such as CNN and ResNet, which can improve the accuracy of DoA estimation.

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