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Gain Characteristic Maintained, Miniaturized LPDA Antenna Using Partially Applied Folded Planar Helix Dipoles

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ABSTRACT The miniaturization of a compact planar log-periodic dipole array (LPDA) antenna usually comes with a side effect of the gain deterioration phenomenon. To address this issue, a folded planar helix (FPH) dipole is designed as a miniaturized radiating element to replace parts of a conventional LPDA antenna composed of $\lambda/2$ dipoles in this paper. The FPH dipole has a radiation resistance and efficiency close to those of a $\lambda/2$ dipole with 39% reduced size and shows a higher radiation quality factor. The LPDA antenna with the longest $\lambda/2$ dipole replaced by the FPH element and the LPDA antenna with the longest and third-long $\lambda/2$ dipoles replaced by the FPH elements are examined. A conventional LPDA antenna can be miniaturized while avoiding gain degradation in the operation band of 400–800 MHz. The lowest impedance matched frequency and the frequency where the directional beam starts to appear are about the same for the proposed miniaturized LPDA antenna. Moreover, the front–back ratio can be improved by the proposed method. The prototype of the two-FPH-element applied LPDA antenna is built, and the design concept is verified experimentally. A size reduction of 39% and an average gain deterioration of -0.2 dB are achieved by the prototype in comparison with a conventional LPDA antenna. The proposed antenna can be utilized in the mobile radio wave direction-finding system.

INDEX TERMS Log-periodic dipole array (LPDA) antenna, antenna miniaturization, folded planar helix, radio wave direction-finding system.

I. INTRODUCTION

Recently, the drone market has grown explosively, and its unlicensed and indiscriminate operation makes the radio wave propagation environment more complex and crowded. Nevertheless, a qualified wireless service should be provided, and the efficient management of radio waves, including the detection of an illegal radio signal and the removal of its sources, has become a great issue. The mobile radio wave direction-finding (DF) system on vehicles has been actively studied for this purpose [1], [2]. Log-periodic dipole array (LPDA) antennas have been widely used in this system because of the radiation properties of its directional beam pattern and sufficient front-back ratio (FBR) over a wide frequency range [3].

The size reduction of the LPDA antenna is essential for mobile DF application because the installation space of the vehicle is usually limited and it minimizes the wind resistance. Not limited to DF applications, the LPDA antenna miniaturization has been intensively studied, and most of these studies were conducted by reducing the size of each radiating dipole element that composes the LPDA antenna [4]–[8]. The meander line, Koch-shape, or top loading dipole configuration was proposed to replace all the $\lambda/2$ dipoles of the LPDA antenna, and the input impedance bandwidth can be maintained successfully this way. However, the gain characteristic is deteriorated since the relationship between the radiating element and the feeder impedances is away from the corrected Carrel's table for the maximum directivity of the LPDA antenna composed of λ/2 dipoles [9]–[12]. That is, these reported small dipole elements do not show the input radiation resistance and efficiency close to those of a λ/2 dipole whereas the impedance bandwidth is well reproduced. We consider that the gain deterioration side effect can be minimized by utilizing small dipoles with the input resistance and the radiation efficiency close to a λ/2 dipole. We propose to replace only part of the λ/2 dipoles with these elements as a means of minimizing the gain deterioration phenomenon while pursuing LPDA antenna miniaturization. The partial replacement of original long dipole elements can be effective for miniaturization since the size of the LPDA antenna is usually determined by the longest dipole element. However, a smaller dipole showing radiation properties comparable to a λ/2 dipole should experience a narrower impedance bandwidth. Here, we pay attention to the fact that the impedance bandwidth of a conventional and reported miniaturized LPDA antennas are usually wider than the operating bandwidth (OB) where the directive beam is formed with good FBR, around the low-frequency bound [3]–[12]. The uni-directional beam characteristic is rarely observed at the frequencies lower than the OB although the input impedance is well matched. Therefore, a smaller dipole with a narrower bandwidth but maintains other radiation properties of the longest λ/2 dipole can be considered not only for miniaturizing the LPDA antenna but also for maintaining the directivity.

In this paper, we maintain the gain values in the forward direction and achieve impedance matching in the OB when an LPDA antenna is miniaturized. To this end, we design a highly efficient folded planar helix (FPH) electric dipole element with radiation properties that are close to a λ/2 dipole but with an inherent higher quality factor (Q). Subsequently, it is applied only to the lower band elements of a conventional LPDA antenna. The simulation and measurement show that the antenna size can be miniaturized by 39% in comparison with a conventional LPDA antenna while maintaining the average gain value in the OB. The numerical simulator HFSS from Ansys is used for all the computed expectations in this study. In the following sections, the design, radiation characteristic analysis, fabrication, and measurement results will be discussed.

II. FPH DIPOLE ELEMENT

A folding technique is one of the methodologies for stepping up the small radiation resistance of small antennas [13], [14]. Generally, for a folded dipole in which the top and bottom parts of each dipole are electrically connected, the radiation resistance R_{rad} can be represented by $R_{rad} \approx N^2 R_d$, where R_d is the radiation resistance of a single dipole arm and N is the number of the folded arms. The input resistance can be easily tuned this way in electrically small antennas [15]–[18], but N should be restricted to two in a planar structure. We design an FPH element as shown in Fig. 1a to overcome this restriction, which is basically a suppressed form of the folded cylindrical helix (FCH) dipole in [16] with two

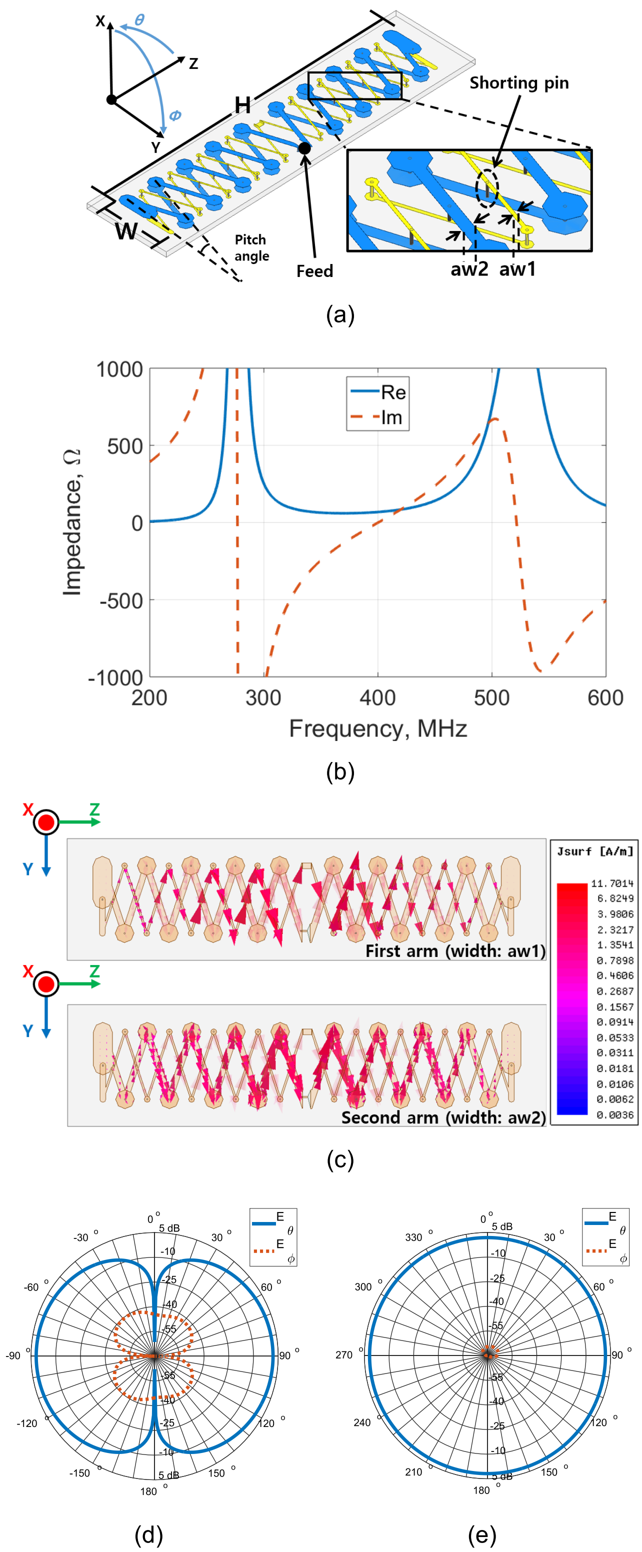

FIGURE 1. Proposed FPH dipole as a miniaturization radiating element for LPDA antennas. (a) Configuration, (b) Simulated input impedance, (c) Current distribution on each arm (top view), (d) Simulated θ-sweep radiation pattern, and (e) Simulated ϕ-sweep radiation pattern.

dipole arms. Note that each dipole arm is marked in blue and yellow, respectively. The design parameters of H and W show the height and the width of the element, respectively, and aw1 and aw2 show the width of each arm, respectively. The pitch angle of the arm is also represented.

When the current distribution on each arm of a folded dipole is not the same, the transformation ratio can be varied from N^2 by tuning the current magnitude ratio between the arms [19]. It means that the ratio of aw1 and aw2 can be adjusted to step up the small radiation resistance of the small dipole not restricted to the factor of N^2. In addition to this, the proposed FPH dipole without shorting pins shows capacitive input reactance since the gap of the two arms in the original volumetric FCH dipole became closer. Therefore, we place fourteen shorting pins between the two arms (see Fig. 1a) to compensate for the capacitive reactance.

The sample FPH dipole following this design guide is first designed to be self-resonant at 400 MHz with an input resistance of 68 Ω as shown in Fig. 1b. Its design values are H = 183 mm (0.25λ), W = 37 mm (0.05λ), and pitch angle = 18.5°. The ratio of aw1 and aw2 is 3.2 (aw1 = 2.5 mm, aw2 = 8 mm) and is patterned on an FR-4 substrate with 3.2T. It has a radiation efficiency of 95% at the resonant frequency with a reduced length of 39% in comparison with a λ/2 dipole on the same substrate. The impedance bandwidth of the designed FPH dipole is reduced to about one-third with the VSWR = 2 criterion (4% vs. 12%). The *Q*-value is 2.72 times higher than a λ/2 dipole which is calculated using (1) from [15].

$$Q \approx \frac{\omega}{2R_{in}}\sqrt{\left(\frac{dR_{in}}{d\omega}\right)^2 + \left(\frac{dX_{in}}{d\omega} + \frac{|X_{in}|}{\omega}\right)^2} \qquad (1)$$

where R_{in} and X_{in} are the frequency-dependent input resistance and reactance of the antennas, respectively, and ω is the angular frequency. Lastly, it is observed in Fig. 1c that the current distributions at each arm are in-phase, as same with a folded electric dipole antenna. It is also observed that the current magnitude flows on each arm is not the same. Figs. 1d and 1e show the radiation pattern at the resonant frequency. It is clearly seen that the pattern is omni-directional, with E_θ component being dominant over E_ϕ component. It is confirmed from the current distribution and the radiation pattern that the proposed FPH element operates as a small electric dipole. Table 1 summarizes the comparison of the radiation properties between the λ/2 dipole and the FPH dipole. The proposed FPH element is scaled properly when applied to the proposed LPDA antennas in the following sections.

III. LPDA ANTENNA MINIATURIZATION

A. LPDA ANTENNA WITH ONE FPH ELEMENT (LPDA-F1)

In this work, we target the frequency range of 400–800 MHz as the OB, in which frequent radio signal interference occurs and the national disaster safety network of Republic of Korea is [20]. A conventional LPDA antenna with a 50 Ω characteristic impedance of the feeder line, a scale factor $\tau = 0.794$, and a space factor $\sigma = 0.142$ is designed following the corrected Carrel's table as reference. Considering the truncation coefficient value of 0.6 by τ and σ [10], [12], the longest dipole element is designed to resonate at 320 MHz following (2), as shown at the bottom of this page, where 0.48 is the length of a λ/2 dipole antenna. The reference antenna geometry is shown in Fig. 2a. In this sub-section, an FPH element applied LPDA (LPDA-F1) antenna is designed by replacing the longest λ/2 dipole of the reference antenna with the FPH dipole element, as shown in Fig. 2b.

TABLE 1. Radiation properties of a λ/2 dipole and the proposed FPH dipole.

	Resonant frequency	Length	R_{in}	Efficiency	*Q*-value
λ/2 dipole (on FR-4)	400 MHz	300 mm (0.4λ)	65 Ω	99 %	4.53
FPH dipole (on FR-4)		183 mm (0.25λ)	68 Ω	95 %	12.32

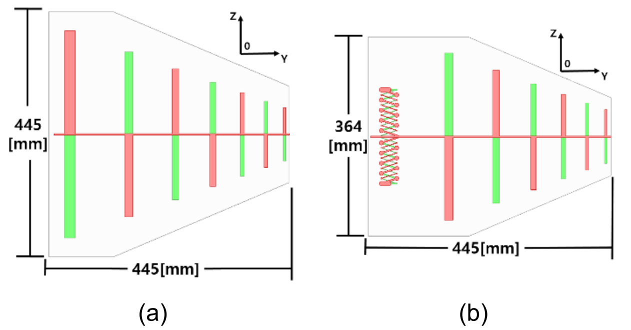

FIGURE 2. Geometries of the (a) Conventional LPDA antenna (reference), and (b) LPDA-F1 antenna. (top: red, bottom: green).

In Fig. 3a, it is found from the simulated results that the VSWR < 2 range is 300–900 MHz and the average forward gain (i.e., the direction toward the shortest λ/2 dipole element, when $\theta = 90°$ and $\phi = 90°$) in the OB is 5.7 dBi for the reference LPDA antenna. The OB is marked as a grey bar in the graph. The VSWR < 2 range is 346–900 MHz, and the average forward gain in the OB is 6.1 dBi for the LPDA-F1 antenna. About the same average gain value is obtained with a similar gain fluctuation behavior across the frequencies. In addition, the impedance and the gain vary more steeply outside the OB of 300–400 MHz region due to the higher *Q* of the FPH element than the λ/2 dipole. The FPH element also has an effect on the FBR and gain. As shown in the simulated radiation pattern in the H-plane in Fig. 3b, the FBR is low at about 6 dB for both antennas at 350 MHz.

$$\frac{[\textit{The lower frequency end of OB}(f1)] \times [\textit{Wavelength at } f1 \times 0.48]}{[\textit{Wavelength at } f1 \times 0.6]} \qquad (2)$$

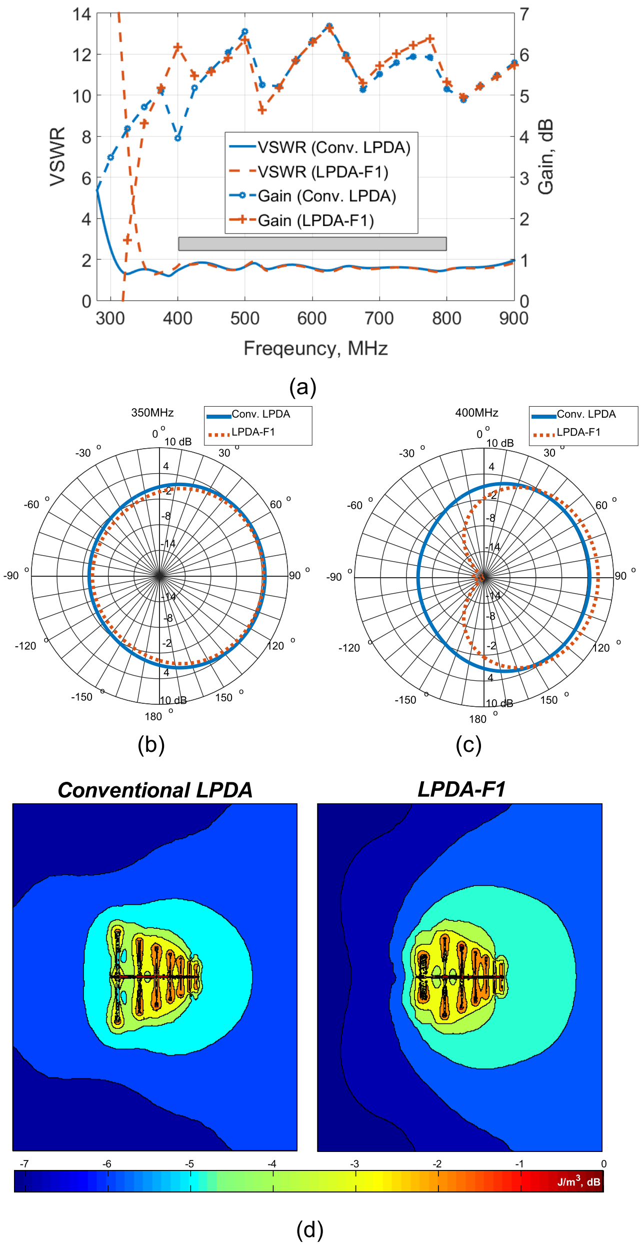

FIGURE 3. Simulated results of the conventional LPDA (reference), and LPDA-F1 antennas. (a) VSWR and gain, (b) H-plane radiation pattern at 350 MHz, (c) H-plane radiation pattern at 400 MHz, and (d) Electric energy density distribution at 400 MHz.

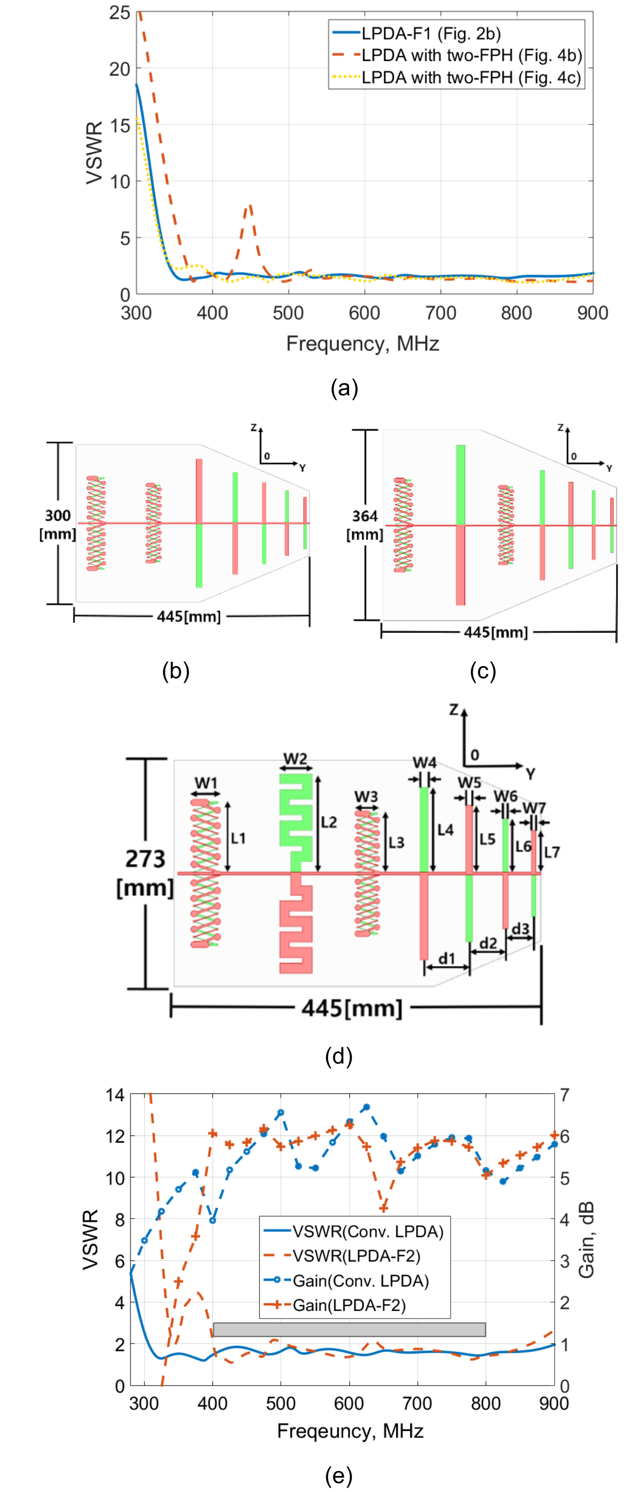

FIGURE 4. LPDA-F2 antenna. (a) Simulated VSWR, (b) Geometry of the two-FPH element continuously applied LPDA antenna (top: red, bottom: green), (c) Geometry of the two-FPH element applied LPDA antenna with a $\lambda/2$ dipole in between (top: red, bottom: green), (d) Geometry of the two-FPH element applied LPDA antenna with a meander dipole in between (LPDA-F2 antenna), (top: red, bottom: green), and (e) Simulated VSWR and forward gain of the LPDA-F2 antenna.

However, it greatly improves at 24 dB at 400 MHz for the LPDA-F1 antenna whereas it remains low at 7 dB for the reference antenna as shown in Fig. 3c. The FBR is related to the scattered wave toward the backward direction in the longest element. The high Q characteristic of the FPH element suppresses such truncation effect effectively. In Fig. 3d, electric energy distribution at 400 MHz is plotted and it is observed that more energy is confined to the FPH element of the LPDA-F1 antenna. It leads less energy to be scattered to the backward direction, and more to the forward direction. The higher gain of the LPDA-F1 antenna around 400 MHz can be explained likewise. Overall, the simulation shows that the LPDA-F1 antenna can exhibit a similar radiation characteristic to the reference LPDA antenna in the forward direction even with a reduced antenna dimension of 18.2%.

B. LPDA ANTENNA WITH TWO FPH ELEMENTS (LPDA-F2)

Further miniaturization is conducted by applying one more FPH element. When this element is installed beside the previously positioned FPH element as shown in Fig. 4b, impedance mismatch occurs at 450 MHz (Fig 4a) because of the strong coupling between the FPH elements. Such a mismatch can be resolved by increasing the distance between the elements, but doing so increases the antenna dimension as well and causes lower directivity. Inserting an additional matching section can degrade the radiation efficiency of the antenna [21], [22]. Instead, the second FPH element replaces the third-long λ/2 dipole as shown in Fig. 4c, and a better impedance matching can be achieved (see Fig. 4a). However, it only achieves the same miniaturization effect with the LPDA-F1 antenna in Fig. 2b. Therefore, the λ/2 dipole section between the FPH elements is meandered as shown in Fig. 4d. The total dimension of the thus-formed two-FPH element applied LPDA (LPDA-F2) antenna in Fig. 4d is 445 mm × 275 mm × 3.2 mm. The design parameters are described and the values are summarized in Table 2.

TABLE 2. Design values of the proposed LPDA-F2 antenna.

Parameters	mm	Parameters	mm
W1	36.2	L1	87.1
W2	39.6	L2	119
W3	29.7	L3	74.4
W4	9.76	L4	103
W5	7.75	L5	81.0
W6	6.15	L6	64.8
W7	4.89	L7	50.8
d1	54.7	d2	43.4
d3	34.5		

Fig. 4e shows the simulated VSWR and the forward gain of the proposed antenna, and those of the reference LPDA antenna are re-plotted in the figure for comparison. The impedance of the LPDA-F2 antenna is matched at 400–865 MHz, and the average gain in the OB is 5.7 dBi, which is the same as that in the reference antenna. The gain fluctuation behavior below 600 MHz is different, and it is caused by the lower input impedance of the inserted meander line. The input impedance of the other dipole elements is maintained around 65 Ω. The proposed LPDA-F2 antenna also shows a steep gain response below 400 MHz. It makes the lowest impedance matched frequency and the frequency where directional beam starts to appear about the same. In other words, instead of matching the frequency region of low directivity, the gain characteristic in the OB is maintained. The simulated radiation pattern and the measurement result will be presented in the following section. The antenna size is miniaturized by 39% without radiation performance degradation in the OB when compared with the reference LPDA antenna.

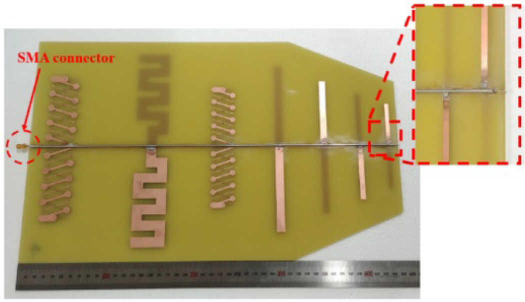

FIGURE 5. Built prototype of the proposed LPDA-F2 antenna.

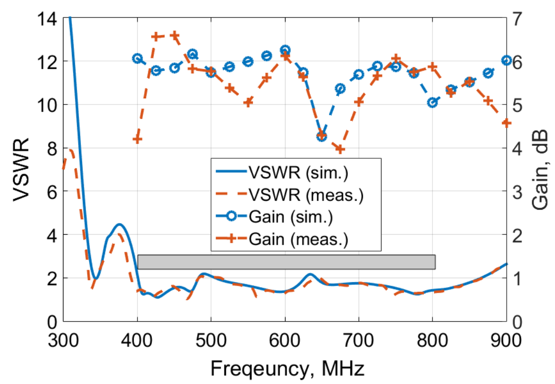

FIGURE 6. Simulated and measured VSWR and gain of the proposed LPDA-F2 antenna.

IV. FABRICATION AND MEASUREMENT

The proposed LPDA-F2 antenna is fabricated on an FR-4 substrate with a thickness of 3.2 mm as shown in Fig. 5. A coaxial infinite balun is built using a semi-rigid type SR-047 cable for feeding a wideband balanced signal [4], [7]. The simulated and measured gains and the VSWR of the proposed LPDA-F2 antenna are shown in Fig. 6. The measured VSWR agrees well with the computed expectation. The gain is measured in an anechoic chamber. The measured forward direction gain values follow the simulation across the frequency, and the average gain is calculated as 5.5 dBi, which is obtained from seventeen measured points in the OB with 25 MHz separation. It is very close to the simulation value of 5.7 dBi in the OB. The measured radiation patterns in the H-plane are given in Fig. 7, and they also show a good agreement with the simulation results.

Table 3 compares the size, relative bandwidth, and gain characteristic of the previously reported compact LPDA antennas with those of this work. A common feature of the previous works is that although the impedance bandwidth

TABLE 3. Comparison between the proposed LPDA-F2 antenna and the previously reported compact LPDA antennas.

Used miniaturization element	Size miniaturization ratio	Relative impedance bandwidth (value in the parenthesis means that of "before size miniaturization")	Gain deterioration
Koch dipole [4]	12.1 % 20.1 %	1:1.67 [1.9–3.15 GHz]* 1:1.5 [2.0–3.0 GHz]* (1:1.73 [1.85–3.2 GHz])*	−0.3 dB* −1.3 dB*
Fractal tree dipole [5]	32.5 % 38.75 %	1:11.4 [0.36–4.1 GHz]** 1:9.6 [0.37–3.55 GHz]** (1:6.95 [0.36–2.5 GHz])*	−2.0 dB** −2.5 dB**
Cylindrical-hat cover dipole [6]	49 %	1:1.45 [0.95–1.38 GHz]** (1:1.58 [0.9–1.42 GHz])**	−2.0 dB*
Top loading bow-tie dipole [7]	62.5 %	1:8.53 [0.87–7.42 GHz]** (1:6.15 [1.3–8.0 GHz])*	−3.0 dB**
T-shaped top loading dipole [8]	45 %	1:2.55 [0.82–2.09 GHz]** (1:2.39 [0.84–2.01 GHz])*	−1.5 dB*
This work (LPDA-F1) This work (LPDA-F2)	18.2 % 39.0 %	1:2.6 [346–900 MHz]* 1:2.16 [400–865 MHz]** (1:3.0 [300–900 MHz])*	+0.4 dB* −0.2 dB**

*: Simulated result, **: Measured result

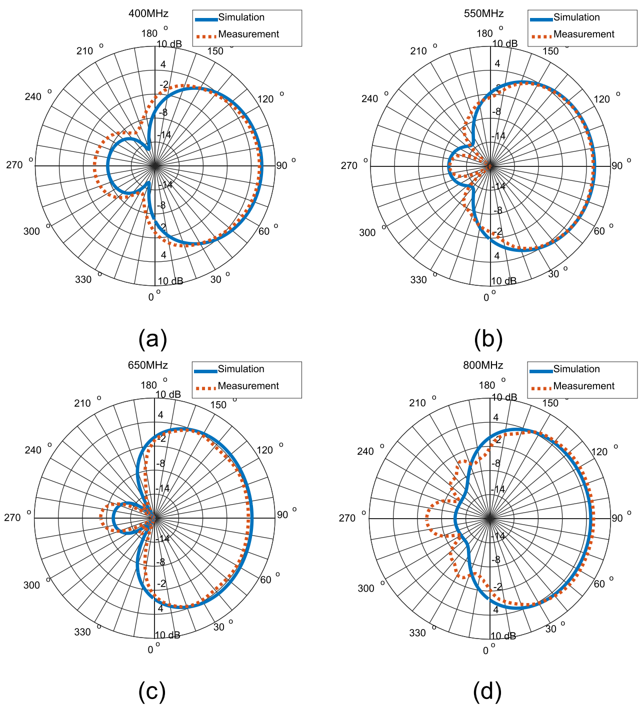

FIGURE 7. H-plane radiation patterns of the LPDA-F2 antenna. (a) 400 MHz, (b) 550 MHz, (c) 650 MHz, and (d) 800 MHz.

was more or less maintained, the gain characteristics were deteriorated. Specifically, the relative bandwidth is enlarged for the miniaturized LPDA antennas in [5], [7], and [8], but they experience gain loss to some degree. Conversely, the impedance bandwidth decreases and the gain characteristics are maintained in this study. However, the decreased bandwidth is for the frequency range located before the OB, where the radiation pattern is not directional and the FBR is low, thus the advantages of the LPDA antenna can be hardly observed. Lastly, comparing the LPDA-F1 antenna with [4], they show gain deterioration of +0.4 dB and −1.3 dB, but for the same relative bandwidth reduction (from 1:3.0 to 1:2.6 for LPDA-F1 antenna, from 1:1.73 to 1:1.5 for [4]), respectively. It is worth to note that the size miniaturization ratio is about the same.

V. CONCLUSION

This paper proposed an LPDA antenna miniaturization technique of replacing the longest $\lambda/2$ dipoles with high Q small electric dipoles selectively. It can minimize the gain deterioration phenomenon that usually comes along with the antenna miniaturization. To prove the design concept, we designed and applied an FPH dipole element to the parts of a conventional LPDA antenna to achieve size miniaturization while avoiding radiation performance degradation. As a result, the longitudinal size of the proposed LPDA-F1 and LPDA-F2 antenna is reduced by 18.2% and 39%, respectively. We highlight the finding that the gain characteristic is maintained with improved FBR even with such a size reduction effect owing to the radiation resistance and efficiency of the FPH dipole element, which are close to those of the $\lambda/2$ dipole antenna, and its high Q characteristic. The measured average gain in the forward direction of the built LPDA-F2 antenna is 5.5 dBi (reference LPDA: 5.7 dBi, from the simulation).

Although not reported in this study, we utilized the proposed LPDA-F2 antenna in our omni- and uni-directional dual-antenna-based DF system [23] and demonstrated its direction-finding performance indoor. The outdoor test is currently undergoing, and we intend to report the entire system soon.

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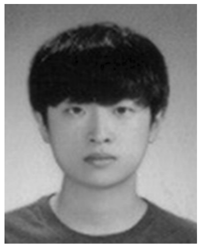

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