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Broadbanding of Printed Bell-Shaped Monopole Antenna by Using Short Stub for UWB Applications

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Abstract—This paper presents a design and evaluation for a miniaturized ultra-wideband (UWB) printed monopole antenna. The design integrates a UWB printed bell-shaped monopole antenna with a short stub. This antenna improves the matched impedance in the lower frequency band of 3.1 $\sim$ 4.0 GHz by using the short stub structure. The proposed antenna is formed on a low-cost FR-4 dielectric substrate with the size: $28 \times 20 \times 1.6\,\text{mm}^3$. The designed antenna operates with impedance bandwidth of 3.1 $\sim$ 10.6 GHz. The omnidirectional radiation patterns are obtained over the frequency range. Calculation and measurement show that this antenna acquires broadband characteristics covering the required frequency band of UWB system. The proposed antenna is assumed for applying to UWB radar, etc.

1. INTRODUCTION

Ultra-wideband (UWB) systems have been used in various systems such as position estimation, radar, body area network (BAN), and high-speed radio communication [1, 2]. The U.S. Federal Communication Commission (FCC) authorized the unlicensed use of the 3.1 $\sim$ 10.6 GHz frequency band in 2002, so a broadband antenna satisfying this frequency band is required. Monopole antenna has been examined for various wireless applications because of its simple structure and characteristic of omnidirectional radiation pattern. For UWB applications, recently, various antenna structures have been reported, such as rectangular, elliptical, circular, square, hexagonal, and pentagonal ones [3–8]. The bandwidths of several planar monopole antennas with various geometries have been compared [3]. In the results, the circular and elliptical monopole antennas obtained much wider bandwidth performance than other antennas. A planar monopole antenna consisting of two kinds of elliptical elements [5] and printed circular monopole disk antenna [6] have been reported as a technique for acquiring broadband characteristics. Moreover, antenna impedance matching techniques for broadband monopole antennas have been reported, such as a cutting notch at ground plane, a double feed line, and a trident-shaped feeding strip structure [9–14]. A planar circular disk monopole antenna combining the microstrip feed line of different widths [9] and a square planar monopole antenna using a trident-shaped feeding line [11] have been reported as a technique for increased impedance matching. Additionally, the return loss has been optimized at the lower frequency by applying the modified ground plane of the elliptical disc planar monopole antenna [12]. In order to realize miniaturization and impedance matching of the antenna, we have already reported the miniaturization design of a printed monopole antenna for a UWB system [15, 16]. This antenna structure can be miniaturized by attaching a short stub. Our proposed antenna realizes compact volume using FR-4 substrate and acquires broadband characteristic covering the UWB system frequency band.

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In this paper, we report the theoretical design and evaluation of a fabricated miniaturized UWB printed monopole antenna. This structure enables the antenna to be miniaturized by using a short stub [15, 16]. This compact ($28 \times 20 \times 1.6\,\text{mm}^3$ volume) antenna is formed on the front and back sides of an FR-4 dielectric substrate with the same size. The antenna improves the antenna impedance matching in the lower frequency band and acquires the broadband characteristics needed to achieve the required frequency band of a UWB system. The proposed antenna is assumed for applying to UWB radar, etc.

The rest of this paper is organized as follows. Section 2 explains the antenna design of the proposed UWB printed bell-shaped monopole antenna with the short stub. Section 3 describes the calculation and measurement results obtained for the antennas. Section 4 concludes the paper with a summary.

2. ANTENNA DESIGN

UWB printed monopole antennas achieve a broadband characteristic by changing the three-dimensional structure of a biconical antenna and volcano smoke antenna known as a broadband antenna to the planar structure. Fig. 1 shows the structure of the proposed UWB printed bell-shaped monopole antenna with a short stub. The antenna is fed by a $50\,\Omega$ microstrip transmission line to the hanging bell-shaped monopole on a dielectric substrate, and the short stub is composited to the ground plane of the microstrip transmission line from the central lower part of the monopole. The hanging bell-shaped monopole antenna consists on the dielectric substrate. On the front side of the dielectric substrate, the hanging bell-shaped monopole and microstrip transmission line are formed, and on the back side, the circularity-shaped ground plane part and the shot stub line are formed. The monopole and short stub line are connected through a via hole.

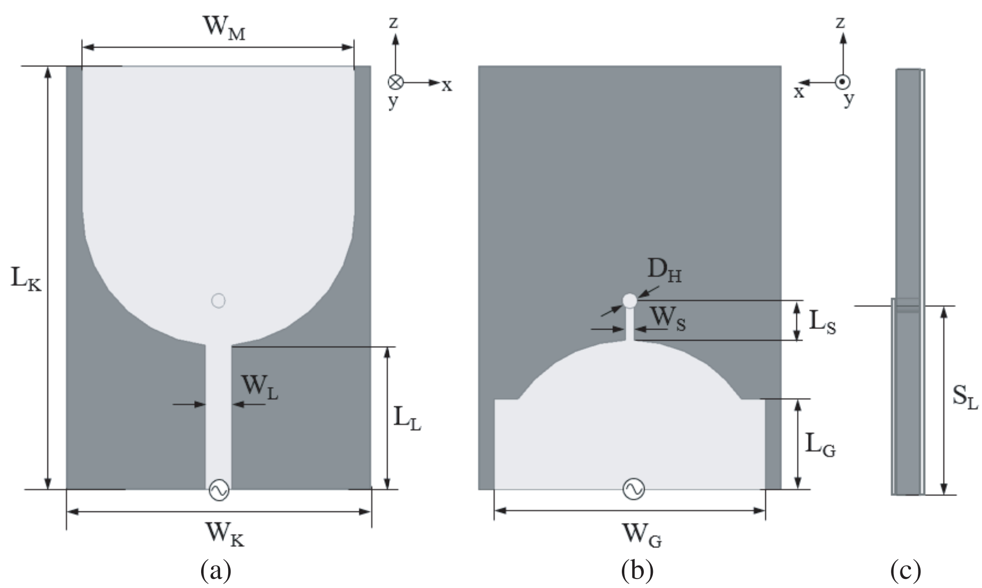


Figure 1. Structure of the proposed UWB printed bell-shaped monopole antenna with short stub: (a) is front-side view, (b) is back-side view, and (c) is lateral-side view.

Figure 2 shows the equivalent circuit of the UWB printed bell-shaped monopole antenna with a short stub. Electrical models are indeed useful for understanding antenna performance [17, 18]. The equivalent circuit of the UWB antenna can be expressed by an RLC parallel resonant circuit [19]. The broadband characteristic of the antenna can be achieved as a result of several resonances. The short stub of the printed monopole antenna operates as a parallel inductor to the RLC circuit. Input impedance of the equivalent circuit of monopole antenna can be expressed as follows:

$$Z_M = \sum_{k=1}^{n} \frac{j\omega R_{Mk} L_{Mk}}{R_{Mk}(1 - \omega^2 L_{Mk} C_{Mk}) + j\omega L_{Mk}} \tag{1}$$

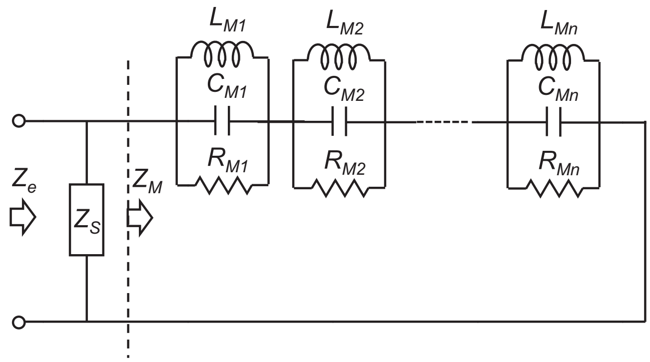


Figure 2. Equivalent circuit of UWB printed bell-shaped monopole antenna with short stub.

where R_{Mk}, L_{Mk}, and C_{Mk} ($k = 1, 2, \ldots, n$) are the resistance, inductance, and capacitance of UWB monopole antenna.

RLC parallel resonant circuits produce the antenna impedance. The short stub operates as a parallel impedance to the UWB printed monopole antenna. The input impedance of the equivalent circuit of the proposed antenna is expressed as follows:

$$Z_e = \frac{Z_S Z_M}{Z_S + Z_M} \tag{2}$$

where Z_S is the impedance of the sort stub.

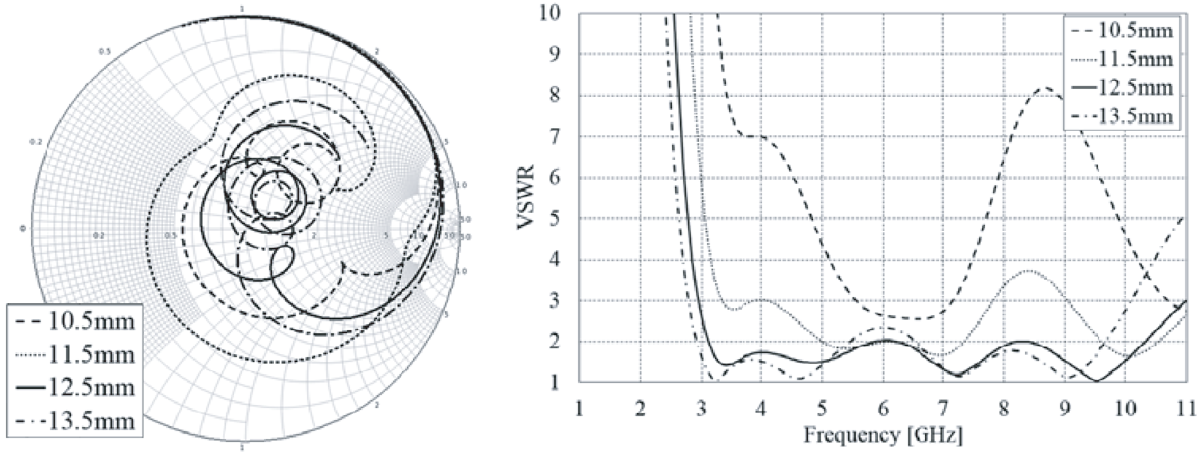
The antenna impedance can be matched by adjusting the parameter of the short stub appropriately. A short stub can be modelled by an LC series circuit connected in shunt with the antenna (Fig. 2). Therefore, when this impedance is combined with that of the antenna, a broadband behavior can be obtained. This is aligned with a similar model, where the bandwidth of a patch is increased using an LC circuit [20]. The configuration of the ground plane of the antenna is rounded for impedance matching. Attaching the short stub to the proposed antenna can improve the antenna impedance matching in the lower frequency band.

To achieve a broadband characteristic for the proposed antenna for impedance matching, the antenna parameters in Fig. 1 are adjusted by parametric study. The parameters are the interval between the feed point and through-hole (S_L), the width of short stub (W_S), the diameter of the through-hole (D_H), and the length of the ground plane (L_G). The default values of these parameters are $SL = 12.5\,\text{mm}$, $WS = 0.6\,\text{mm}$, $DH = 1\,\text{mm}$, $LG = 6\,\text{mm}$. The width of the ground plane is $WK = 18\,\text{mm}$. The width and length of the microstrip transmission line are $WL = 1.8\,\text{mm}$ and $LL = 9.5\,\text{mm}$. The antenna is $28 \times 20 \times 1.6\,\text{mm}^3$, and its characteristic impedance is $50\,\Omega$.

First, Fig. 3 compares the calculated input impedances and voltage standing wave ratios (VSWRs) obtained by varying the interval S_L. The other parameters are the same as the default values. Broadband characteristics are achieved because a parallel inductance ingredient and the resonant impedance are made larger by expanding S_L. Next, Fig. 4 compares the calculated input impedances obtained by varying the width W_S. The frequency band barely changes and is shifted to a higher frequency by widening W_S.

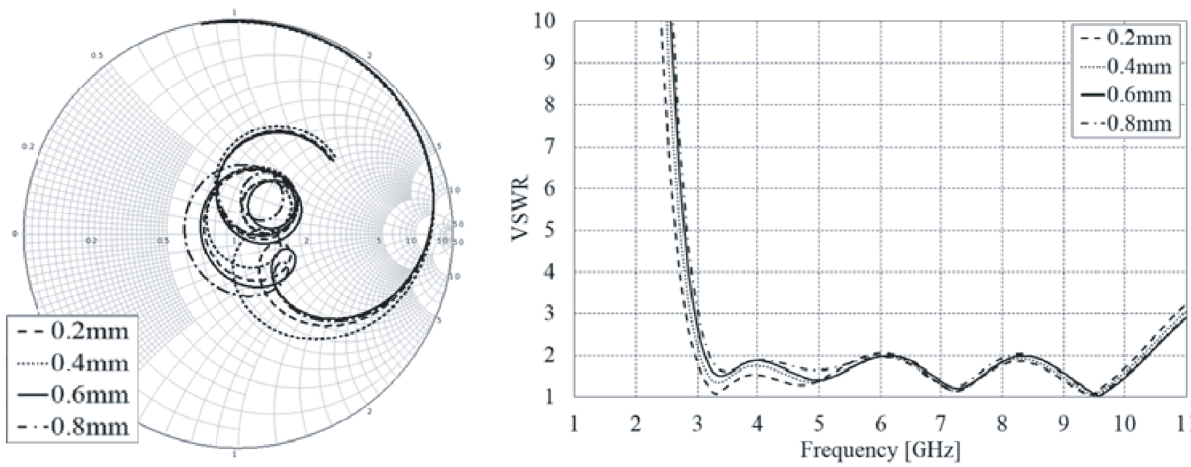
Moreover, the capacitance ingredient of the input impedance tends to be made larger by widening W_S. Fig. 5 compares the calculated input impedances obtained by varying the diameter D_H. The resistance ingredient of the input impedance is shifted to a lower value and lower frequency by narrowing D_H. Fig. 6 compares the calculated input impedances obtained by varying the length L_G. The frequency band barely changes, and the resonant impedance is made smaller by shortening L_G.

The results reveal that the input impedance can be adjusted by changing three parameters of the antenna structure: the interval between the feed point and through-hole, the width of short stub, and the ground plane shape. This antenna achieves the impedance matching in the lower frequency band and acquires the required broadband characteristic.



(a) (b)

Figure 3. Comparison of calculated input impedance (S_L is varied): (a) input impedance and (b) VSWR.



(a) (b)

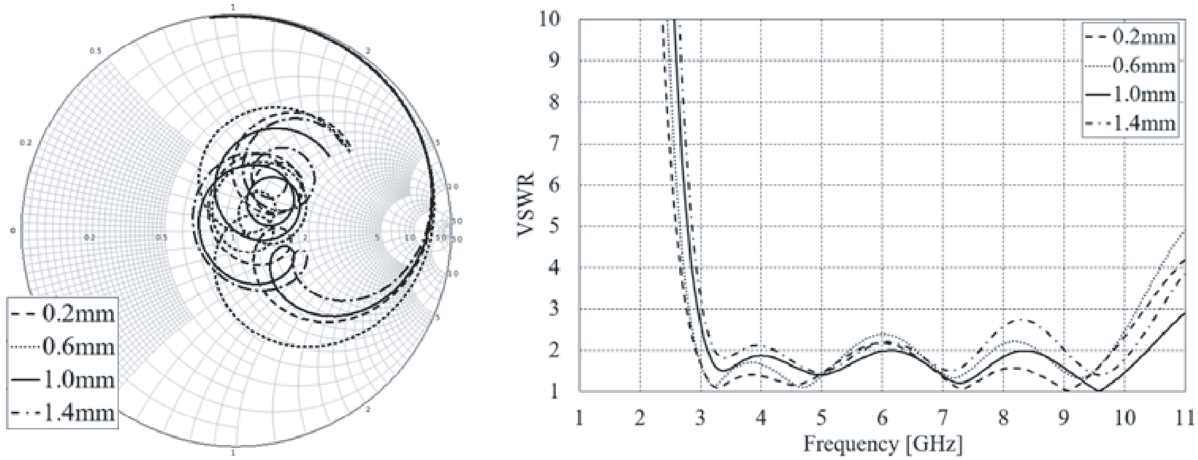
Figure 4. Comparison of calculated input impedance (W_S is varied): (a) input impedance and (b) VSWR.

3. CALCULATION AND MEASUREMENT RESULTS

The proposed antenna is formed on an FR-4 dielectric substrate ($\varepsilon_r = 4.4$, $\tan\delta = 0.02$), and the antenna size is: $L_K = 28\,\text{mm}$, $W_K = 20\,\text{mm}$, and $t = 1.6\,\text{mm}$. The calculation of the antenna uses the 3D electromagnetic simulator of KeysightEMPro. The optimized antenna parameters are obtained from the parametric study results in the previous section. The propagation delay using the proposed antenna is not considered in this paper.

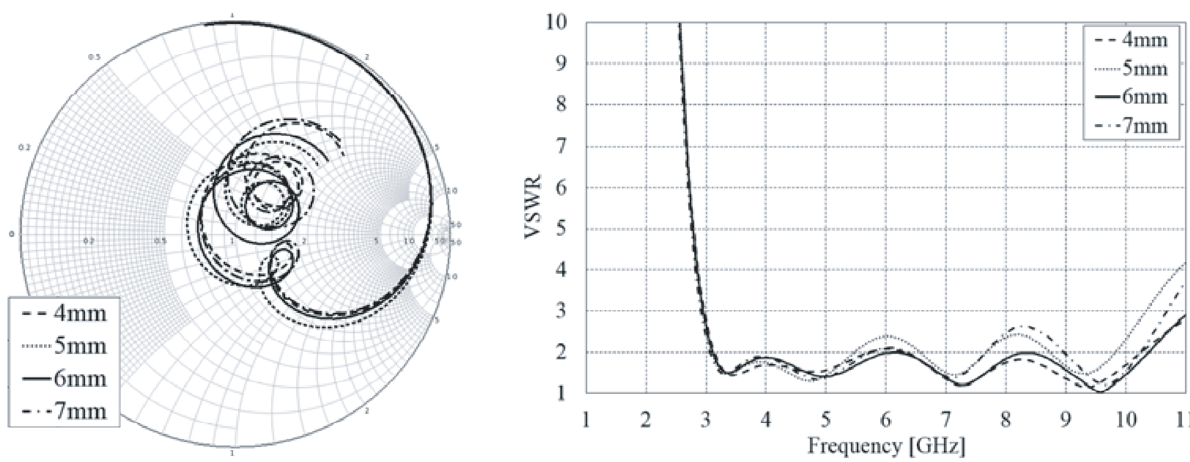
3.1. VSWR

Figure 7 shows the simulation results for VSWR. The characteristic impedance is $50\,\Omega$. This figure compares the characteristics between the antennas with and without the short stub. The compared UWB antenna without short stub has the same size as the proposed antenna. The antenna w/o short stub does not satisfy VSWR2 in the lower frequency band. The antenna impedance is difficult to match by only applying the rounded ground plane because the antenna is small. On the other hand, attaching



(a) (b)

Figure 5. Comparison of calculated input impedance (D_H is varied): (a) input impedance and (b) VSWR.



(a) (b)

Figure 6. Comparison of calculated input impedance (L_G is varied): (a) input impedance and (b) VSWR.

the short stub to the proposed antenna can improve the impedance matching in the low frequency band. From the calculation results, the proposed antenna acquires the broadband characteristic needed to achieve the required frequency band of a UWB system.

3.2. Current Distribution

Figure 8 shows the simulated current distributions at different frequencies for the antenna parameters of the default values shown in Section 2. The calculation frequencies are 3.5, 5, 6, 8, 9, and 10 GHz. The results for frequency 3.5 GHz show the current distribution near the first resonance. From the calculation results, the current is mainly distributed along the edge of the hanging bell-shaped monopole. On the ground plane of the proposed antenna, the current is mainly distributed on the upper edge along the y-direction. It means that the portion of the ground plane close to the disc acts as the part of the radiating structure.

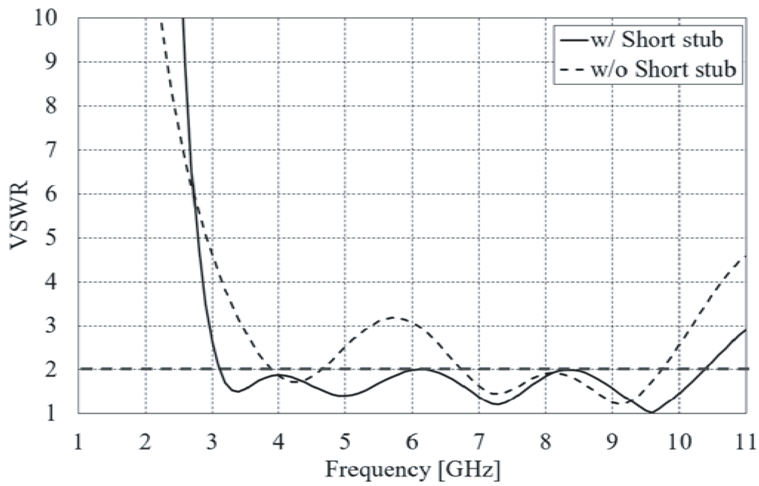


Figure 7. Comparison of calculated VSWR (with and without short stub).

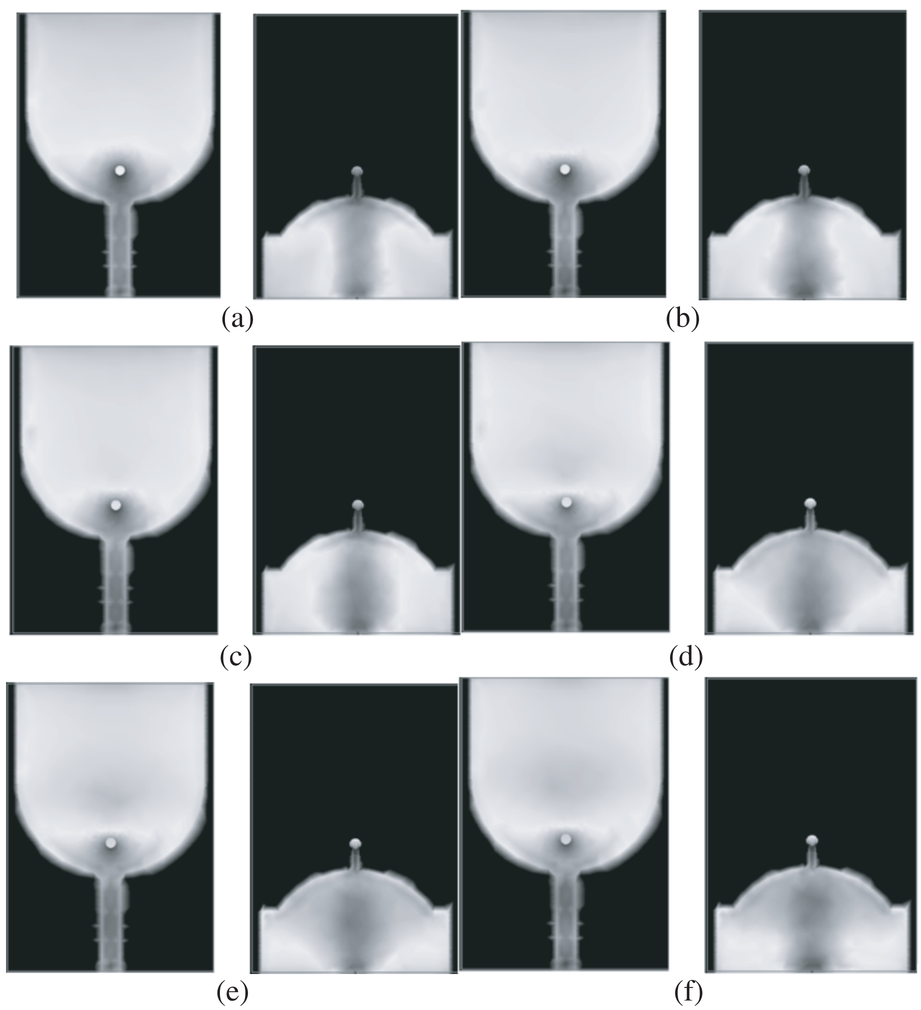


Figure 8. Calculation results of current distribution (front-side and back-side): from (a) to (f) are the frequencies of 3.5 GHz, 5 GHz, 6 GHz, 8 GHz, 9 GHz, and 10 GHz.

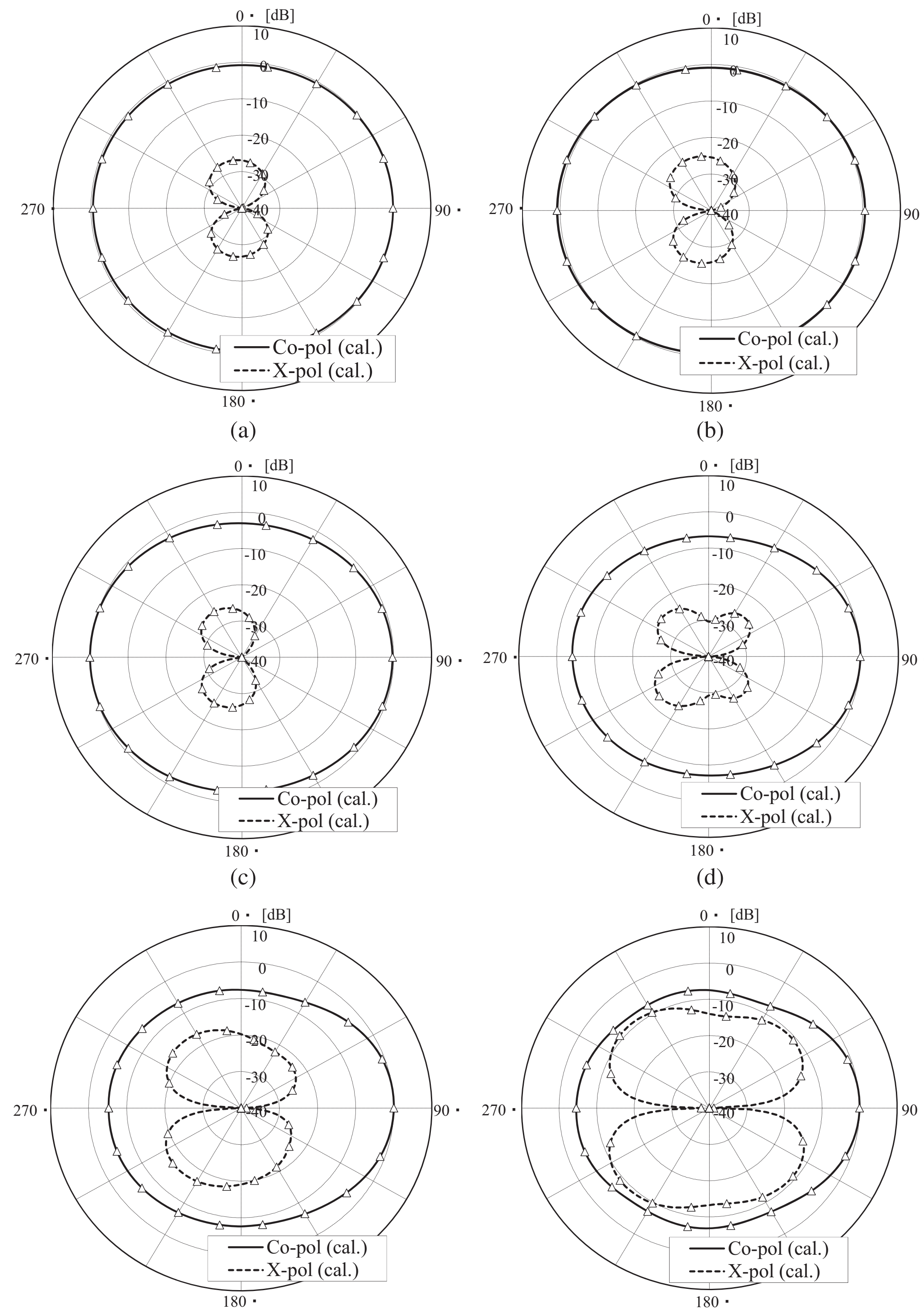


Figure 9. Calculation result of radiation patterns (x-y plane): from (a) to (f) are the frequencies of 3.5 GHz, 5 GHz, 6 GHz, 8 GHz, 9 GHz, and 10 GHz.

3.3. Radiation Patten

Figure 9 shows the simulation results for radiation patterns. The calculation frequencies are the same as those in Fig. 8. The radiation patterns are plotted along the x-y plane. The co-polarization and cross-polarization patterns are shown. The antenna gains of each frequency are 2.1 dBi, 2.6 dBi, 3.7 dBi, 4.7 dBi, 4.3 dBi, and 3.6 dBi, respectively. From the calculation results, almost omnidirectional radiation patterns are obtained at each frequency. As the frequency band becomes higher, the level of the cross polarization increases, and the level of the co-polarization decreases. A method of reducing the cross polarization at frequency 10 GHz is to be studied in the future.

Next, we fabricate a UWB printed bell-shaped monopole antenna with a short stub, as shown in Fig. 10. This antenna has the same parameters as the calculated model shown in Fig. 1. The fabricated antenna is formed on an FR-4 dielectric substrate ($\varepsilon_r = 4.4$, $\tan\delta = 0.02$) that is $L_K = 28$ mm, $W_K = 20$ mm, and $t = 1.6$ mm. Fig. 11 compares the measured and calculated results for VSWR. The characteristic impedance is 50 Ω. Fig. 12 shows the measurement results of radiation patterns. The measurement frequencies are the same as those in Figs. 8 and 9. The radiation patterns are plotted along the x-y plane, and the co-polarization and cross-polarization patterns are shown.

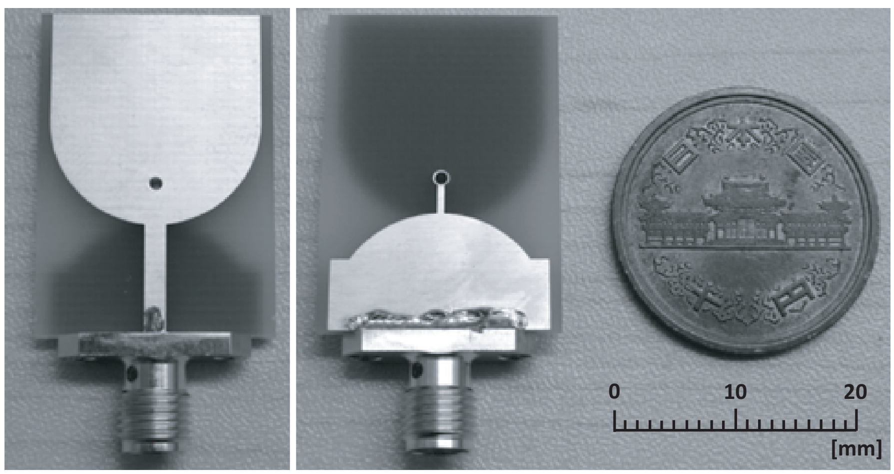


Figure 10. Fabricated UWB printed bell-shaped monopole antenna with short stub (front-side and back-side).

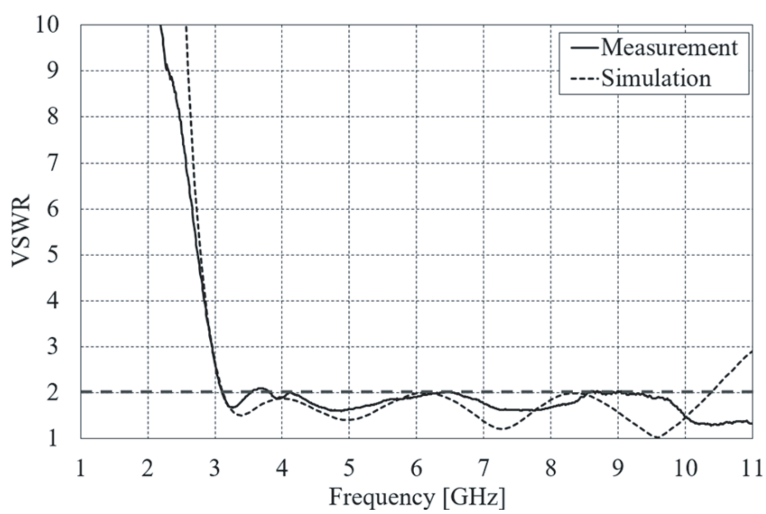


Figure 11. Comparison of calculated and measured VSWR.

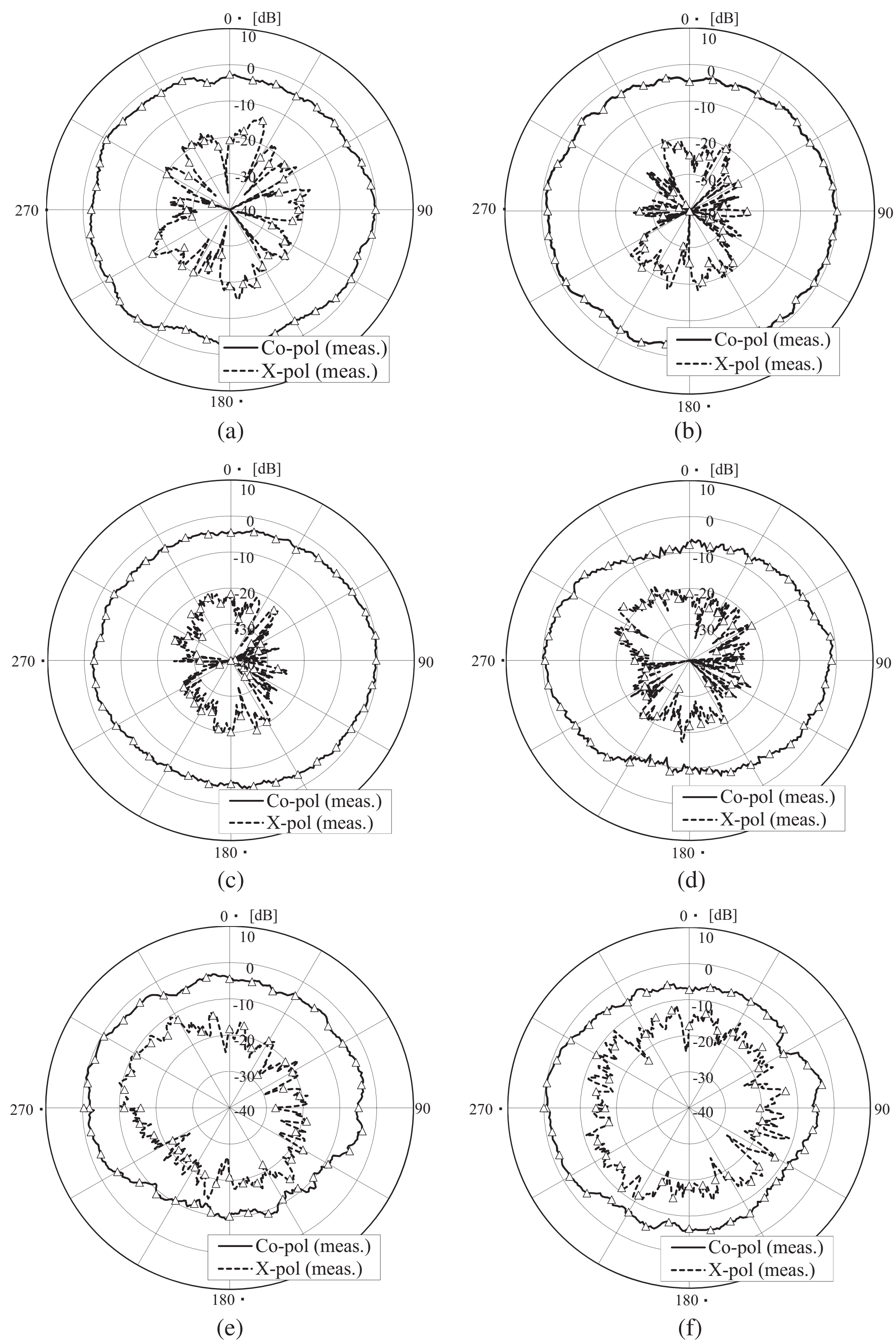


Figure 12. Measurement result of radiation patterns (x-y plane): from (a) to (f) are the frequencies of 3.5 GHz, 5 GHz, 6 GHz, 8 GHz, 9 GHz, and 10 GHz.

An examination of the results reveals that the proposed antenna acquires a broadband characteristic that satisfies the required frequency band of the UWB system. It is considered that the difference between the measured and calculated values is by the influence of the cable and connector used for the measurement. It confirms that attaching the short stub to the proposed antenna can improve the impedance matching in the low frequency band side. From the measurement results of radiation patterns, almost omnidirectional radiation patterns are obtained at each frequency. As the frequency band becomes higher, the level of the cross polarization increases, and the level of the co-polarization decreases, the same as in the calculated results. For all frequency results, the calculated and measured values agree well.

The dimensions and performances of different UWB printed monopole antennas are shown in Table 1. The comparison parameters are antenna dimensions, 10 dB return loss bandwidth, and antenna gain. It can be confirmed that the proposed antenna realizes good characteristics with a small size.

Table 1. Comparison of different UWB printed monopole antennas.

Parameter	Proposed	Ref. [6]	Ref. [21]	Ref. [22]	Ref. [23]
Dimensions [mm]	$28 \times 20 \times 1.6$	$50 \times 42 \times 1.5$	$50 \times 41 \times 1.575$	$35.5 \times 30.5 \times 1.575$	$50 \times 45 \times 0.762$
10 dB return loss bandwidth [GHz]	$3.1 \sim 10.6$	$2.69 \sim 10.16$	$3.0 \sim 11.4$	$4.1 \sim 7.0$, $8.7 \sim 13.3$ (Dual-band)	$3.0 \sim 10.0$
Antenna gain [dB]	$2.1 \sim 4.7$	$3.5 \sim 6.7$	$3.4 \sim 5.2$	$2.0 \sim 4.3$	$2.0 \sim 7.4$

4. CONCLUSIONS

The authors have proposed a miniaturized ultra-wideband (UWB) printed bell-shaped monopole antenna with a short stub and reported the theoretical design and evaluation results of the fabricated antenna. Compared to an antenna without a short stub, the operating lower limit frequency of the antenna is lowered from 3.9 GHz to 3.1 GHz, achieving about 20% reduction. This paper describes that the proposed antenna achieves miniaturization and broadband characteristic required frequency band for a UWB system.

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