Progress In Electromagnetics Research, PIER 85, 227–242, 2008

BIDIRECTIONAL ULTRA-WIDEBAND ANTENNA USING RECTANGULAR RING FED BY STEPPED MONOPOLE

S. Lamultree and C. Phongcharoenpanich

Faculty of Engineering
King Mongkut's Institute of Technology Ladkrabang
Bangkok, 10520 Thailand

Abstract—This paper presents an ultra-wideband rectangular ring fed by stepped monopole antenna. The initial parameters of rectangular ring are first considered to obtain the bidirectional pattern with the desired resonant frequency. Subsequently, the parameters of stepped monopole for enhancing impedance bandwidth are investigated. To study the impedance and radiation behaviors, the simulations of the proposed antenna have been carried out. It is found that this antenna offers a bidirectional beam with the impedance bandwidth (return loss lower than −10 dB) covered the frequency range from 3.1 to 10.6 GHz. At the desired direction along this frequency band, the gain of 2.33–5.21 dBi is achieved. Furthermore, the prototype antenna was fabricated and measured to verify the simulated results. Obviously, the simulation and measurement are reasonably in good agreement.

1. INTRODUCTION

Since the Federal Communications Commissions (FCC) announced the decision to allow the unlicensed use of the bandwidth of 3.1–10.6 GHz [1], ultra-wideband (UWB) antennas are gaining prominence and becoming very attractive in modern wireless and mobile communication systems. Many researches and developments on UWB antennas have been continuously conducted [2–17]. Among the UWB antenna designs in the recent literature, monopole antennas [18–21] are widely employed because of their simple structure and low cost. Many techniques have been reported to extend the antenna bandwidth of the conventional narrow-band antenna such as using the additional substrate [22], introducing several types of sleeves [23–25], adding parasitic elements [26] and adopting proximity-coupled configuration with multilayer structure [27]. Most of these antennas yield omnidirectional radiation patterns.

In general, the base station antennas in microcellular system for the urban areas are located lower than the surrounded buildings along the streets and located in the underground areas; the communicable cell is formed along the street. For these environments, the omnidirectional pattern is degraded when it places closed or attached to the wall or metal. If a bidirectional antenna is applied, the deterioration on the omnidirectional antenna performance can be avoided. In addition, the bidirectional antenna is suitable for the street cell because its radiation pattern can be formed along the street. Therefore, the developments on UWB antennas possessing bidirectional pattern are desirable. From the previous works, a simple-structure and cost-effectiveness linear monopole excited a rectangular ring antenna [28, 29] was proposed. The bidirectional pattern can be achieved because the omnidirectional beam of linear monopole is forced by the rectangular ring to radiate the bidirectional beam viz., beam peaks direct only in forward and reverse directions. However, the bandwidth is relatively narrow. This paper presents a bidirectional UWB antenna using rectangular ring fed by stepped monopole instead of linear monopole to enhance the impedance bandwidth. To keep the bidirectional pattern, the initial parameters of rectangular ring are first designed to operate at the lower edge frequency of the UWB. Then, the parameters of the stepped monopole are varied relating with the upper edge frequency to extend the bandwidth to cover UWB range. The suitable parameters of the antenna to achieve the bidirectional pattern along the UWB coverage are provided.

This paper is organized as follows. Section 2 shows the antenna structure. The antenna design and experimental results are presented in Section 3. Finally, conclusions are provided in Section 4.

2. ANTENNA STRUCTURE

The configuration of the antenna consists of the stepped monopole excitation and the rectangular ring as shown in Fig. 1(a). The stepped monopole in Fig. 1(b) is connected to the center conductor of the coaxial transmission line at the feeding point. The coaxial transmission line with air dielectric has a characteristic impedance of 50 Ohms. From Fig. 1(b), the parameters of the stepped monopole comprises the top width (w_1), the middle width (w_2), the bottom width (w_3), the middle height (h_1), the bottom height (h_2) and the total height

(h). The thickness of the stepped monopole is represented by d. This stepped monopole is surrounded by the rectangular ring with the ring width of a, the ring height of b and the ring length of c. In addition, the gap between the ground plane (the bottom of the rectangular ring) and the bottom of the stepped monopole is defined by δ.

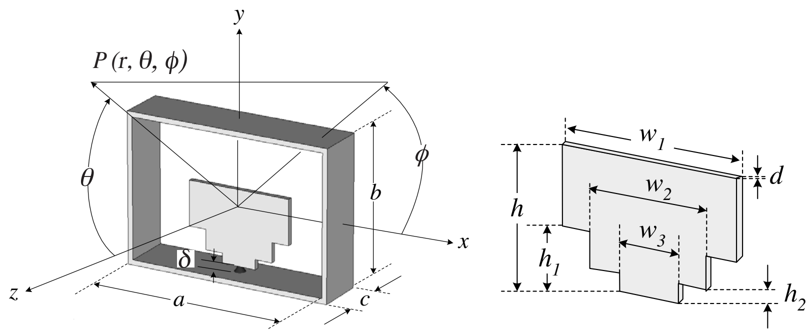

Figure 1. Antenna structure: (a) perspective view and (b) stepped monopole excitation.

3. ANTENNA DESIGN

In this section, the parametric studies of the proposed antenna are performed to investigate their effects to impedance and radiation characteristics. In addition, antenna fabrication and measurement were also carried out. To study the antenna parameters, the simulations using CST Microwave Simulation [30] excluding a coaxial connector in the antenna model are performed.

3.1. Parametric Study

In order to accomplish the bidirectional pattern along the UWB frequency range from 3.1 to 10.6 GHz, the antenna design is separated into two steps for rectangular ring and stepped monopole, respectively. It is found that the bidirectional pattern and resonant frequency are significantly affected by the rectangular ring, whereas the stepped monopole influences to the bandwidth enhancement. Starting with the rectangular ring, its initial width (a) is designed with TE_{10} mode to operate at the lower edge frequency of UWB range. Therefore, the initial ring width (a) is 48 mm. The quarter wavelength of the linear monopole at 3.1 GHz (h = 24 mm) is also initialized. Fig. 2 shows the bandwidth of the nearest resonant frequency of 3.1 GHz of the rectangular ring fed by the quarter-wave monopole for various ring parameters. From this figure, the height (b) and the length (c) of rectangular rings are determined from the widest bandwidth. For compact size, the ring length (c) of 15 mm and b/a of 0.7 are selected.

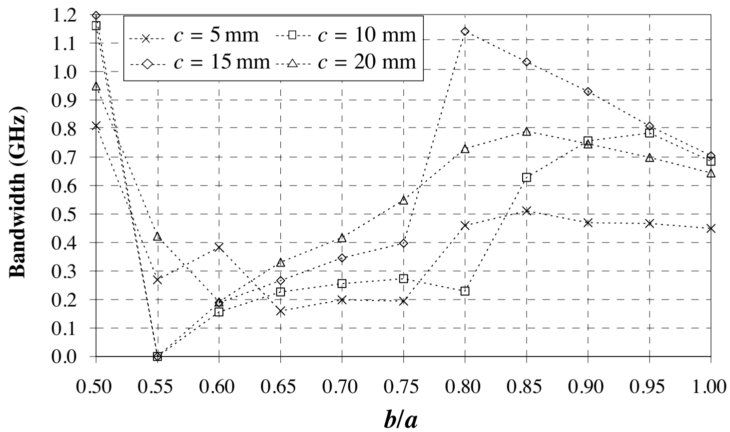

Figure 2. Bandwidth of the lowest resonant frequency as the function of b/a ($a = 48$ mm, $h = 24$ mm).

After the initial parameters of a, b and c are chosen, the length of the linear monopole (h) is varied in terms of h/b for different b/a to determine the suitable condition of resonant frequencies for UWB. The lower and the upper resonant frequencies as function of h/b are shown in Fig. 3 and Fig. 4, respectively. Obviously, the suitable parameters that provide the lower and the upper resonant frequencies nearly 3.1 GHz and 10.6 GHz are tabulated in Table 1. For the compact antenna size, b/a of 0.7 and h/b of 0.6 are appropriately chosen.

Table 1. Suitable parameters that obtain the lower and upper resonant frequencies nearly 3.1 GHz and 10.6 GHz.

h/b	0.42	0.46	0.52	0.60
b/a	1.00	0.90	0.80	0.70

Moreover, the ring width (a) can be varied to adjust the lower and the upper resonant frequencies as shown in Fig. 5. To achieve the lower and the upper resonant frequencies very close to 3.1 GHz and 10.6 GHz respectively, the ring width (a) of 40 mm is chosen. Therefore, the suitable parameters of rectangular ring fed by linear monopole that

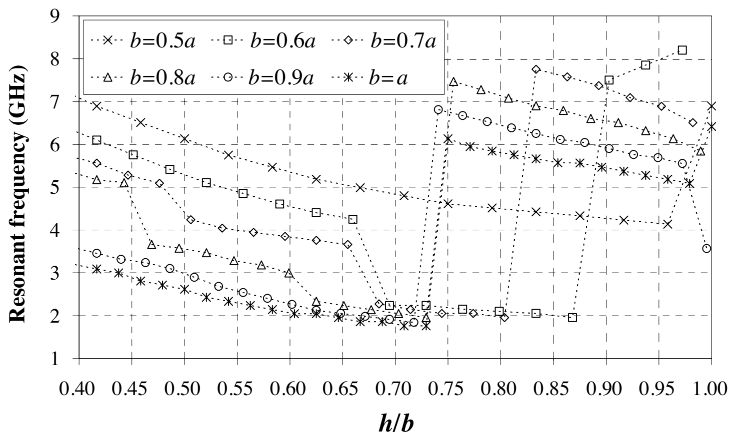

Figure 3. The lower resonant frequency for various h/b ($a = 48\,\text{mm}$, $c = 15\,\text{mm}$).

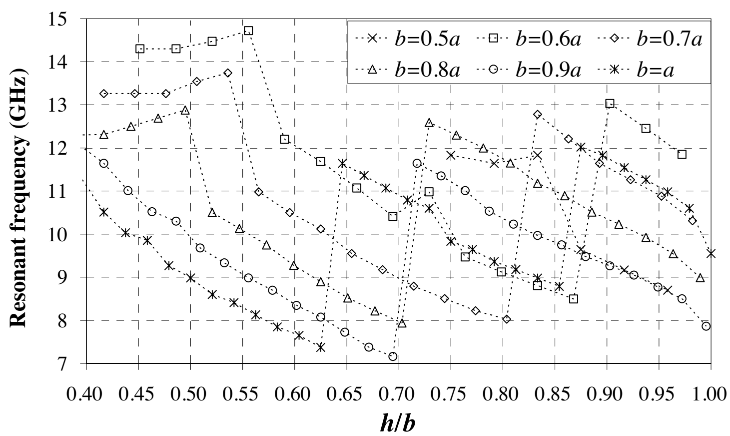

Figure 4. The upper resonant frequency for various h/b ($a = 48\,\text{mm}$, $c = 15\,\text{mm}$).

obtains the resonant frequencies proximity to 3.1 GHz and 10.6 GHz are as follows: $a = 40\,\text{mm}$, $b = 0.7a = 28\,\text{mm}$, $c = 15\,\text{mm}$ and $h = 0.6b = 16\,\text{mm}$. These parameters will be used throughout this paper.

To achieve the UWB characteristics, the return loss along the lower and upper resonant frequencies must be better than 10 dB. Thus, the stepped monopole is introduced to excite the rectangular ring instead of linear monopole. To design the stepped monopole, the

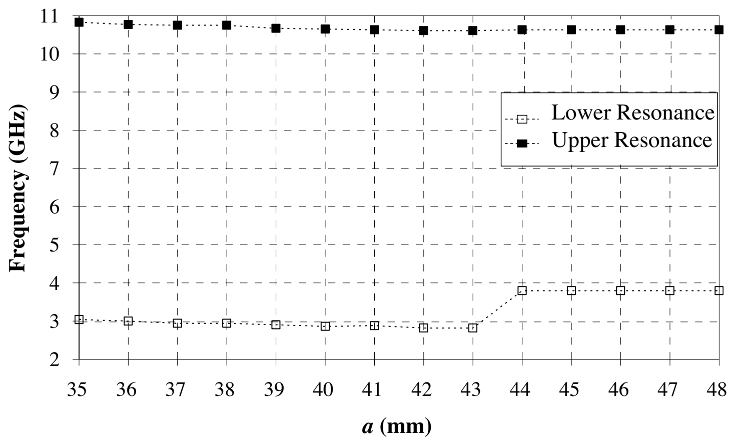

Figure 5. Resonant frequency for various a ($b = 33.6\,\mathrm{mm}$, $h = 0.6b = 20\,\mathrm{mm}$).

dimension should be related with $n\lambda_U/4$, where λ_U is the wavelength of the upper edge frequency of UWB (10.6 GHz) and n is positive integer number. This is due to the fact that the current distribution will be dense at the stepped monopole excitation rather than the rectangular ring at the high frequency. For impedance matching, the choice of h_1 is approximately to $n\lambda_U/4$, and it is geometrically restricted to be shorter than h. For $h = 16\,\mathrm{mm}$ in this case, n can be either 1 or 2 that corresponding to h_1 of 7 mm and 14 mm, respectively. However, h_1 of 14 mm is very close to h ($h = 16\,\mathrm{mm}$), and it is difficult to adjust the parameters for further bandwidth improvement. Therefore, h_1 of 7 mm is selected because of the flexible design. To further improve the return loss, additional step is introduced in term of h_2. From Fig. 6, h_2 is varied to observe its influence to return loss versus frequency. It is apparent that h_2 of 3 mm and 5 mm can be selected because the return loss is lower than -10 dB along the UWB range. Comparing between h_2 of 3 mm and 5 mm, it is preferable to choose h_2 of 3 mm because the return loss at 3.1 GHz and 10.6 GHz is lower.

Furthermore, the widths of stepped monopole are designed in term of $n\lambda_U/4$ with the condition that $w_1 > w_2 > w_3$. It should be noted that w_1 is limited by the ring width (a) and its ranges must from $0.5a$ to $0.7a$. From the design criteria, w_1 of 21 mm, w_2 of 14 mm and w_3 of 7 mm are chosen according to n of 3, 2 and 1, respectively. The influence of these parameters to the return loss along the frequency is shown in Fig. 7 to Fig. 9. It should be pointed that if one parameter is varied, the remaining parameters are fixed. Apparently,

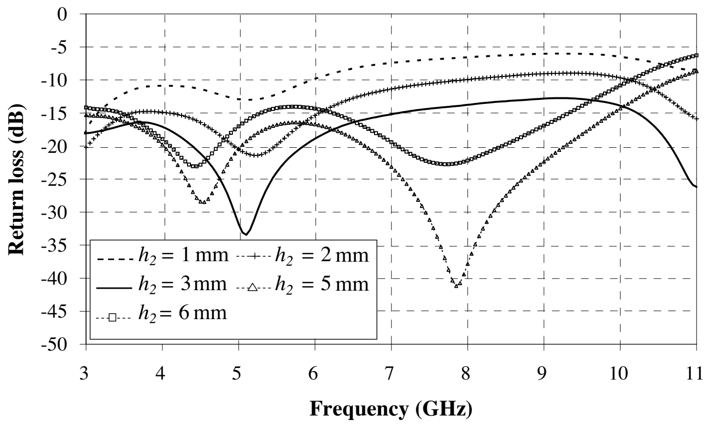

Figure 6. Return loss for various h_2.

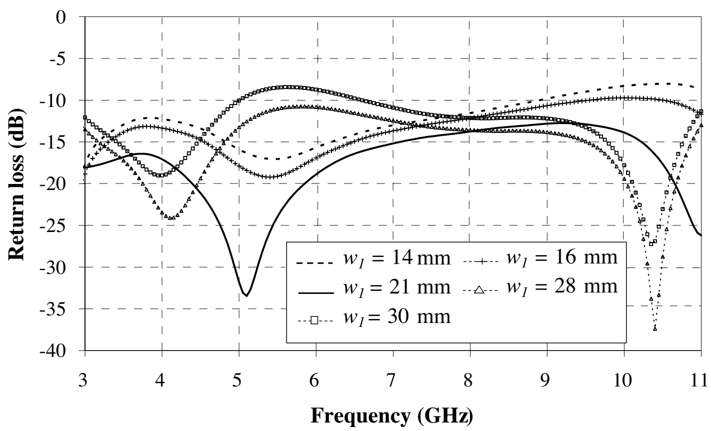

Figure 7. Return loss for various w_1.

the stepped monopole can improve the return loss along the bandwidth of 3.1–10.6 GHz. The designed parameters are ultimately tabulated in Table 2.

It is noted from Fig. 5 that other ring widths (a) rather than 40 mm can be also selected as required. In this paper, the ring width (a) of 40 mm is chosen due to available material in the market. The smaller ring width yields more compact antenna size at the expense of slightly gain degradation. By following the guidelines of antenna design as mentioned above, other parameters such as b, c, h and w_1 can be determined. After that, h_1, w_2 and w_3 are subsequently obtained. The parameter h_2 can be used to improve the return loss.

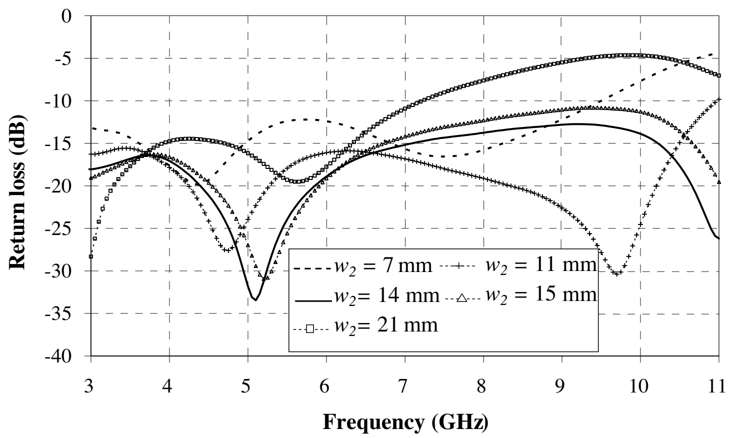

Figure 8. Return loss for various w_2.

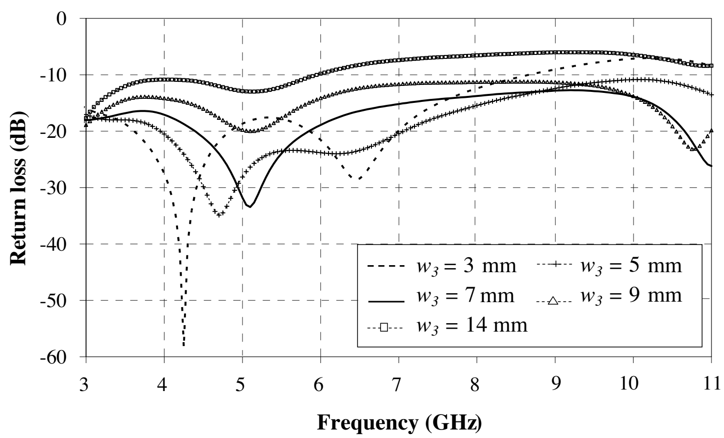

Figure 9. Return loss for various w_3.

3.2. Experimental Results

To confirm the validity of the design and simulations, the prototype antenna was fabricated from brass with the designed dimensions in Table 2. The photograph of the prototype antenna including coaxial feeding port is shown in Fig. 10. Using an HP8720C Network Analyzer, radiation and impedance characteristics of the proposed antenna are measured and discussed next.

For the far field radiation patterns, the designed antenna provides fairly stable bidirectional pattern over the UWB frequency as along

Table 2. Designed parameters.

Parameters	a	b	c	h	h_1	h_2	w_1	w_2	w_3	d	δ
Physical size (mm)	40	28	15	16	7	3	21	14	7	1	1

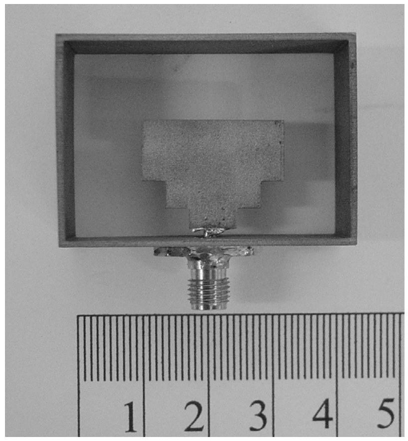

Figure 10. A prototype antenna.

the UWB frequency of 3.1, 6.5 and 10.6 GHz as shown in Fig. 11 through Fig. 13. For the desired direction, the maximum radiated field directs along the street cell in $+z$ and $-z$ directions. It is found that the radiation pattern in yz-plane tilts from z axis because the stepped monopole is located at the bottom of the ring making unsymmetrical structure along yz-plane. The beam peak in yz-plane from the simulation directs at 4, 30 and 39 degrees whereas the measured one directs at 10, 30 and 30 degrees for the frequencies of 3.1 GHz, 6.5 GHz and 10.6 GHz, respectively. At these three frequencies, the simulated half-power beamwidths are 86, 63 and 64 degrees, and the measured half-power beamwidth are 70, 60 and 55 degrees, respectively. Nevertheless, the field is still efficiently strong at the desired direction ($\theta = 0°$ and $\phi = 90°$). For the symmetrical structure along xz-plane, the radiation pattern is symmetry in this plane. The beam peak in xz-plane of simulation points at 0, 27 and 0 degrees, for the frequencies of 3.1 GHz, 6.5 GHz and 10.6 GHz respectively, with the simulated half-power beamwidth of 82, 112 and 44 degrees and the measured beam peak directs at 0 degree for those all frequencies with the measured half-power beamwidth of 60, 55 and 35 degrees. Moreover, the same trend of the radiation patterns from

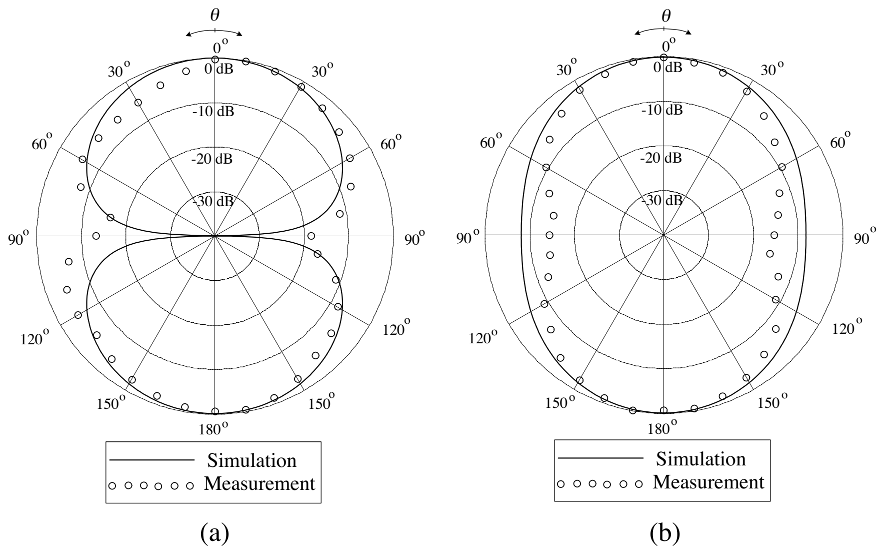

Figure 11. Radiation pattern at 3.1 GHz: (a) yz-plane and (b) xz-plane.

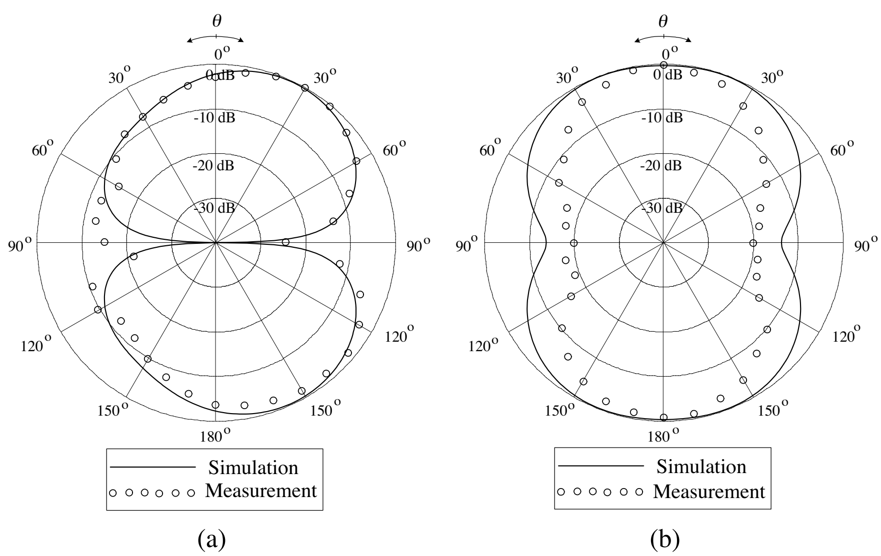

Figure 12. Radiation pattern at 6.5 GHz: (a) yz-plane and (b) xz-plane.

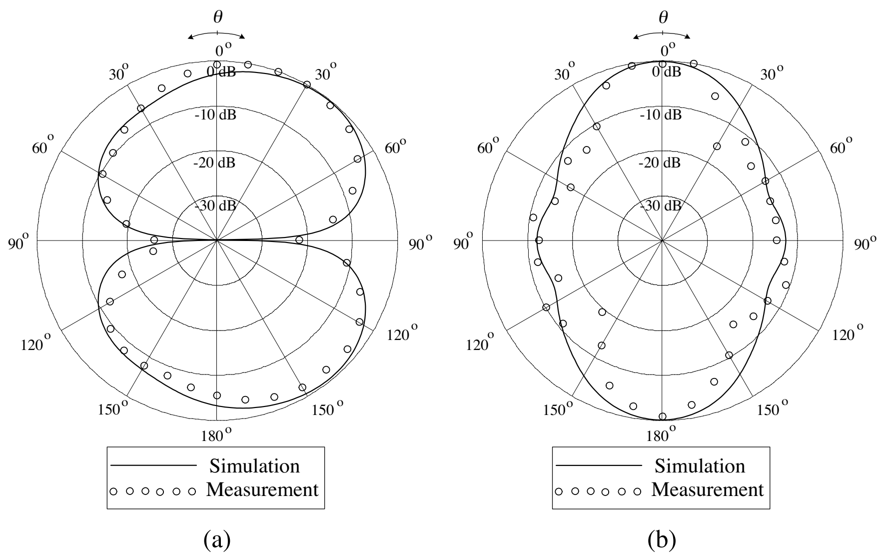

Figure 13. Radiation pattern at 10.6 GHz: (a) yz-plane and (b) xz-plane.

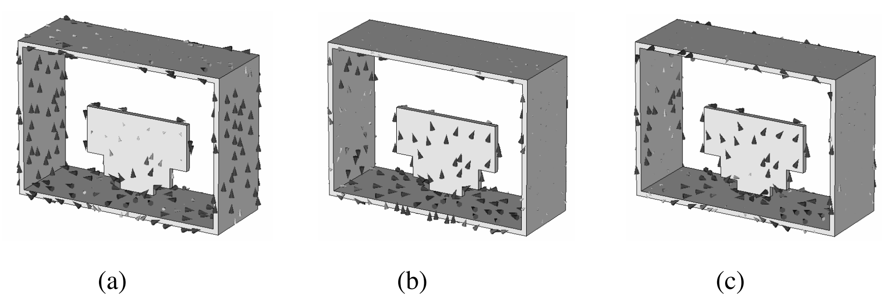

Figure 14. Surface current distributions: (a) $f = 3.1\,\text{GHz}$, (b) $f = 6.5\,\text{GHz}$ and (c) $f = 10.6\,\text{GHz}$.

the simulation and measurement for different frequencies is obtained.

The surface current distributions for different frequencies are shown in Fig. 14. It is found that they mainly distribute in the same direction along the side walls and bottom of the ring at the lower frequency, but they are weak along the stepped monopole. At the high frequency, they are mostly strong along the bottom of the ring and along the stepped monopole. These behaviors mean that the lower resonant frequency is affected by the rectangular ring, and the stepped monopole has little effect on the performances at lower frequency. On the other hand, the upper frequency is more affected by the currents at the bottom of the ring and the stepped monopole, but there are little effects from the currents at the side walls of the ring. These can explain the radiation behaviors for different frequencies.

In addition to radiation patterns, the gain of the antenna was also measured as shown in Fig. 15. It is apparent that the measured and simulated gains, at the desired direction ($\theta = 0°$ and $\phi = 90°$) along the frequency range from 3.1–10.6 GHz, are 2.44–4.98 dBi and 2.33–5.21 dBi, respectively; the minimum and maximum gains of measurement and simulation are yielded at the same frequencies of 6 GHz and 9.5 GHz, respectively. They are in fairly agreement. Furthermore, radiation efficiency of the proposed antenna is simulated. It is higher than 95% across the entire UWB.

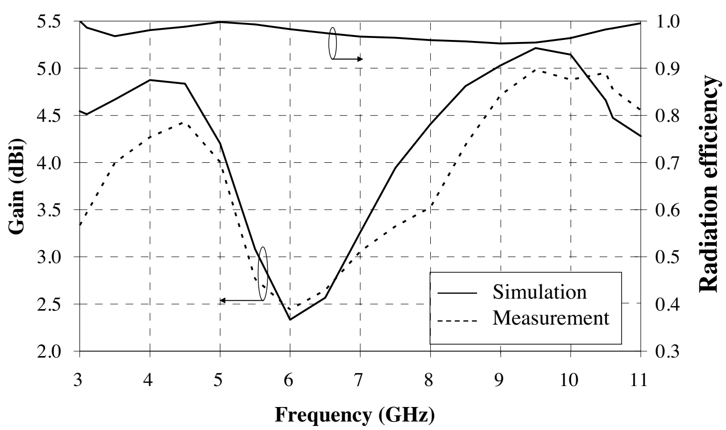

Figure 15. Simulated and measured gains, and simulated radiation efficiency versus frequency.

In addition to the radiation characteristics, the impedance characteristics in terms of return losses are investigated. It is found that the comparison between the simulated (simulation without SMA connector) and measured return losses as shown in Fig. 16 is different at the frequency higher than 7.2 GHz due to the effect from the coaxial feed connector because the coaxial connector is excluded in the simulation to study only the antenna parameters without connector. However, to verify the discrepancy, the simulation with SMA connector is performed and found that the same trend of simulated and measured results is obtained as shown in Fig. 16. The minimum value of -26.15 dB and maximum value of -11.39 dB of the simulated return

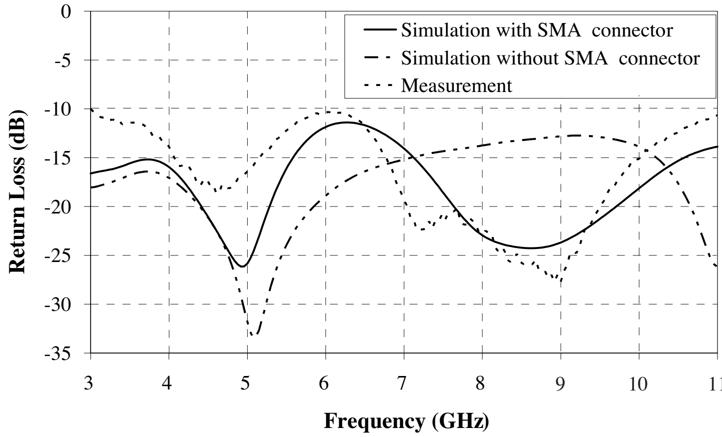

Figure 16. Comparison of the simulated and measured return loss.

loss with SMA connector are obtained at the frequencies of 4.92 GHz and 6.28 GHz, respectively. Nevertheless, the return losses from both simulations with and without SMA connectors and the measurement are lower than −10 dB over the frequency range from 3.1–10.6 GHz which is significantly improved over the rectangular ring antenna fed by linear monopole [28, 29].

4. CONCLUSIONS

A bidirectional antenna using rectangular ring excited by stepped monopole is proposed in this paper to cover the UWB frequency range. The initial parameters of the antenna as well as the suitable parameters for enhancing bandwidth are investigated. In the design, the ring dimension is varied to obtain the desired upper and lower resonant frequencies. The lower frequency has been strongly influenced from ring contribution that can be seen from the dense currents. The bandwidth can be enhanced by improving the return loss that can be done by adjusting the parameters of stepped monopole. As the results, values of a of 40 mm, b/a of 0.7 and h/b of 0.6 are appropriately chosen providing the lower and the upper resonant frequencies at 3.1 and 10.6 GHz with compact antenna size. At $b/a = 0.7$, the ring length is selected at the widest bandwidth with compact size. Moreover, the heights and the widths of stepped monopole are designed relating to the quarter wavelength of the upper edge frequency of 10.6 GHz in terms of $n\lambda_U/4$. Apparently, the bandwidth can be enhanced using stepped monopole excitation compared to the conventionally linear monopole. Furthermore, the return loss is lower than −10 dB, and it provides the fairly stable bidirectional radiation pattern over the frequency range from 3.1 to 10.6 GHz. At the desired direction, the simulated gain of 2.33–5.21 dBi with the radiation efficiency more than 95% is yielded. To verify the simulated results, the antenna prototype was fabricated and measured. It is found that the simulation and measurement are reasonably in good agreement. These results are very useful to design a bidirectional UWB antenna as well as for others wide band applications.

ACKNOWLEDGMENT

This work was supported by the Thailand Research Fund (TRF) under the grant number RSA5080009.

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