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Miniaturized UWB Stepped Open-Slot Antenna

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Abstract—In this paper, a method to miniaturize a stepped open-slot antenna (SOSA) for ultra-wideband (UWB) applications is proposed. The antenna consists of a stepped open slot, J-shaped slots, and two strip directors. A broadband microstrip-to-slotline transition with circular stubs is applied to feed the antenna. J-shaped slots are inserted on the ground plane of the antenna to create a new resonance in the low-frequency region, thereby miniaturizing the size of the antenna. Finally, two strip directors are appended above the stepped open slot in order to increase the gain in the middle- and high-frequency regions, as well as to enhance input impedance matching in the high-frequency region. A prototype of the miniaturized SOSA is fabricated on an FR4 substrate with dimensions of 30 mm × 32 mm. It shows a measured frequency band of 2.99–10.87 GHz for a voltage standing wave ratio < 2, which ensures UWB operation, and the measured gain range is 3.2–7.3 dBi in the band with a front-to-back ratio > 8.7 dB.

1. INTRODUCTION

Ultra-wideband (UWB) technology using the 3.1–10.6 GHz frequency band has been widely researched in many fields, such as short range wireless communications, location tracking, distance measurement, radar, and imaging systems, because of its high-speed transmission, wide bandwidth, very low spectral power density, and excellent multipath immunity. For such applications, wideband antennas capable of transmitting and receiving UWB signals with a bandwidth of 7.5 GHz are indispensable [1].

Among the wideband antennas for UWB applications, small planar omnidirectional antennas such as monopole, dipole and loop antennas have been extensively investigated for portable or mobile devices. A horn antenna, a spiral antenna, a log-periodic dipole array antenna, and a tapered slot antenna are used for applications requiring relatively high gain with directional radiation patterns [2–5]. In general, an omnidirectional antenna has a small size but low gain. On the other hand, a directional antenna has high gain but a large size. Therefore, it is necessary to design a compact UWB antenna having a small size and directivity.

To cover the UWB, a microstrip-fed step slot antenna was introduced by generating multiple resonances using a staircase-shaped slot in the ground plane of the antenna, but its gain is low at 1–4 dBi, and the direction of the main beam changes in the high-frequency band [6]. A linear tapered slot antenna with a modified microstrip-slotline feed structure operating in the 2.95–14 GHz band was proposed, but it also has low gain of 1.5–4 dBi [7]. A microstrip-fed tapered slot antenna with no feed balun and corrugations in the radiating slot and ground plane was reported with gain of 2.5–7.8 dBi. However, it has disadvantages in that the direction of the main beam is slightly shifted in the center, and a substrate with high dielectric constant of 10.2 is used [8]. A compact asymmetrical linear tapered slot antenna at 35 mm × 36 mm × 0.8 mm using a triangular slot and corrugations was developed for portable UWB imaging systems [9]. A compact stepped open-slot antenna using L-shaped slots on the ground plane was reported for UWB applications [10, 11].

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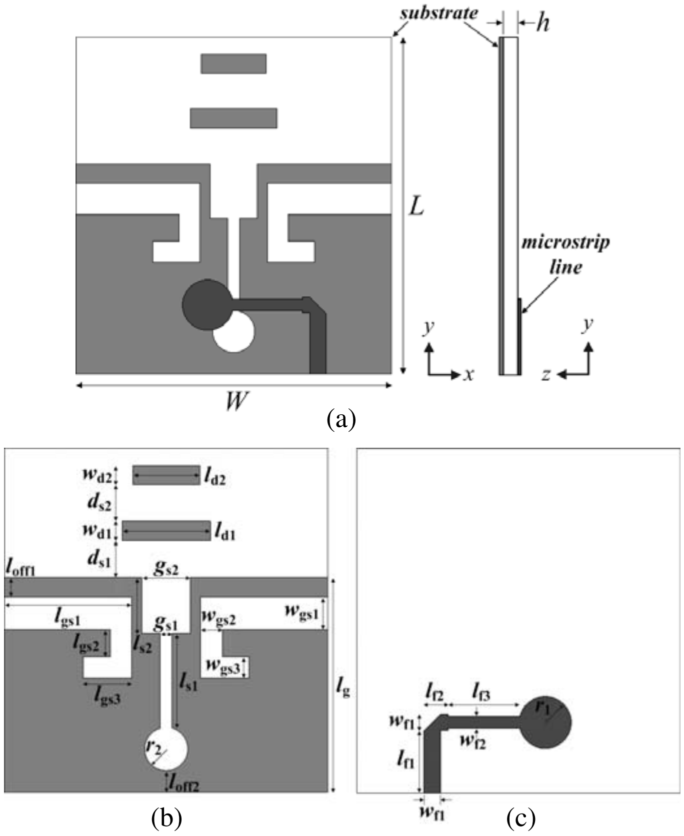
The design of a miniaturized UWB stepped open-slot antenna (SOSA) is presented in this paper. The basic configuration of the proposed antenna is similar to that in [10] and [11], but the feed location, the shape of the ground slot, and the number of the directors are modified in order to make it easier miniaturization and to increase the gain in the middle- and high-frequency regions. First, a reference SOSA with a broadband microstrip-to-slotline transition with circular stubs was designed. In order to reduce the size of the SOSA, J-shaped slots were inserted on the ground plane of the SOSA, which creates a new resonance in the low-frequency region. Next, two strip directors were appended above the stepped open slot to increase the gain in the middle- and high-frequency regions. The effects of the length of the J-shaped slots, the distance between the directors and the stepped open slot, and the length of the first director on the input reflection coefficient and the realized gain characteristics of the proposed antenna were analyzed. Full-wave simulation results of the antenna were obtained with the commercial electromagnetic simulator CST Microwave Studio.

2. ANTENNA GEOMETRY AND DESIGN PROCEDURE

Figure 1 shows the geometry of the proposed miniaturized SOSA. A ground plane with a staircase-shaped stepped open slot and J-shaped slots and two strip directors were printed on the top of the substrate. A microstrip feed line consisting of a circular end stub and a two-stage bent transmission line with different widths was printed on the bottom.

As shown in Figure 1, the stepped open slot consists of two rectangular slots with different widths and an end circular slot. The end circular slot is $l_{off2} = 2\,\mathrm{mm}$ away from the end of the ground plane and has a radius of $r_2 = 4\,\mathrm{mm}$. The length and width of the first rectangular slot connected to the end circular slot are $l_{s1} = 8.8\,\mathrm{mm}$ and $g_{s1} = 1.1\,\mathrm{mm}$, whereas those of the second slot are $l_{s2} = 5.2\,\mathrm{mm}$ and



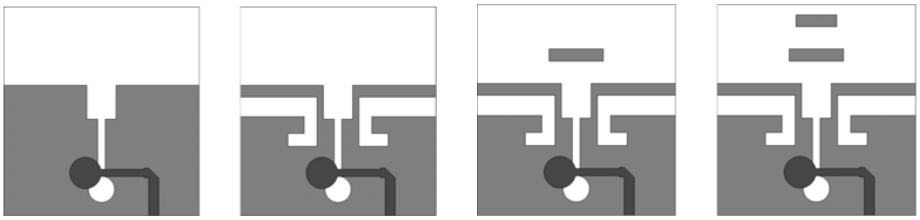
(a)

(b) (c)

Figure 1. Geometry of the proposed miniaturized SOSA: (a) 3D view, (b) top view, and (c) bottom view.

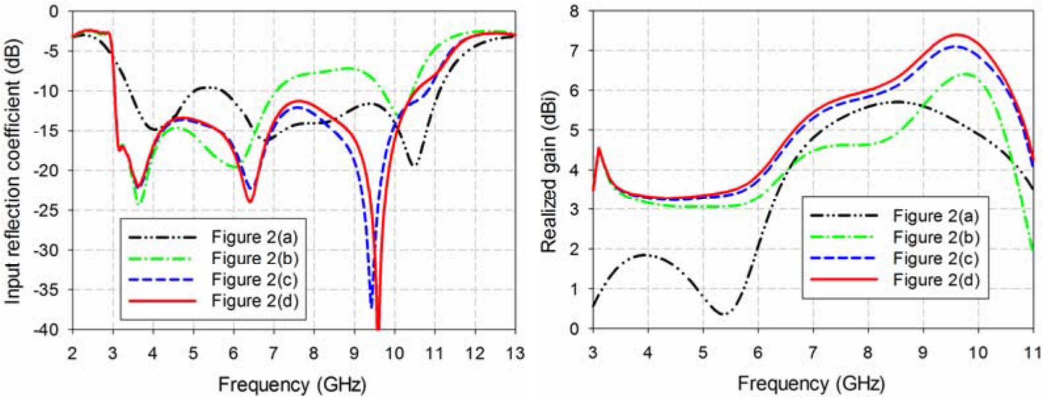
$g_{s2} = 4.5\,\text{mm}$. The lengths of the straight the 90-degree bent, and the 180-degree bent portions of the J-shaped slots inserted symmetrically with respect to the center of the ground plane are $l_{gs1} = 11.8\,\text{mm}$, $l_{gs2} = 2.6\,\text{mm}$, and $l_{gs3} = 4.5\,\text{mm}$, respectively, and their widths are $w_{gs1} = 3\,\text{mm}$, $w_{gs2} = 2\,\text{mm}$, and $w_{gs3} = 2\,\text{mm}$, respectively. The distance between the J-shaped slots and the upper end of the ground plane is $l_{off1} = 1.8\,\text{mm}$. The distance between the first director and the upper end of the ground plane is $d_{s1} = 3.4\,\text{mm}$, and the length and width of the first director are $l_{d1} = 8.2\,\text{mm}$ and $w_{d1} = 1.8\,\text{mm}$. The distance between the first director and the second director is $d_{s2} = 3.4\,\text{mm}$, and the length and width of the second director are $l_{d2} = 6.2\,\text{mm}$ and $w_{d2} = 1.8\,\text{mm}$. The dimensions of the microstrip feed line are as follows: $l_{f1} = 6.2\,\text{mm}$, $l_{f2} = 225\,\text{mm}$, $l_{f3} = 6.6\,\text{mm}$, $w_{f1} = 1.5\,\text{mm}$, $w_{f2} = 1.1\,\text{mm}$, and $r_1 = 4.8\,\text{mm}$. The antenna was printed on an FR4 substrate with a dielectric constant of 4.4 and a thickness of $h = 0.8\,\text{mm}$ (loss tangent $= 0.025$). The width and length of the substrate are $W = 30\,\text{mm}$ and $L = 32\,\text{mm}$, respectively.

To help understand the design procedure, four antenna structures are considered for performance comparison, as shown in Figure 2. The corresponding simulated input reflection coefficient and gain characteristics for the four antenna structures are presented in Figure 3. Figure 2(a) shows the reference SOSA without the J-shaped slots and two directors, and Figure 2(b) depicts the SOSA with only the J-shaped slots. Figure 2(c) is the SOSA with the J-shaped slots and the first director, whereas Figure 2(d) is the proposed SOSA with the J-shaped slots and two directors.



(a) (b) (c) (d)

Figure 2. Four antenna structures for performance comparison: (a) a reference SOSA without J-shaped slots and directors, (b) a SOSA with only J-shaped slots, (c) a SOSA with J-shaped slots and the first director, and (d) the proposed SOSA with J-shaped slots and two directors.



(a) (b)

Figure 3. Comparison of input reflection coefficient and gain characteristics for the antenna structures in Figure 2: (a) input reflection coefficient, and (b) realized gain.

For the reference SOSA without the J-shaped slots and two directors shown in Figure 2(a), the frequency band for voltage standing wave ratio (VSWR) < 2 is 3.37–11.15 GHz, which does not satisfy the UWB (3.1–10.6 GHz). Gain in the UWB is 0.3–5.7 dBi. It is worthwhile to note that gain in the low-frequency region below 6 GHz is 2 dBi or less.

In order to increase the impedance bandwidth toward 3.1 GHz, J-shaped slots were inserted on the ground plane, as shown in Figure 2(b). As the J-shaped slots are added, a new resonance occurs at around 3.08 GHz, so that the lower limit of the frequency band at VSWR < 2 becomes 3.03 GHz, and the frequency band moves to a lower frequency. However, impedance matching deteriorated in the high-frequency region, and the upper limit of the frequency band became 7.14 GHz, thereby reducing the bandwidth. Gain in the UWB band increased to 3.1–6.4 dBi. In particular, the gain enhancement in the frequency band below 6 GHz is 1.5–3.5 dB.

As shown in Figure 2(c), the addition of the first director in Figure 2(b) improves impedance matching in the high-frequency band above 7.14 GHz, and increases gain in the middle- and high-frequency regions. In this case, the frequency band at VSWR < 2 satisfies the UWB at 3.03–10.88 GHz. Gain is 3.2–7.1 dBi within the UWB. Compared with Figure 2(b), gain increased by 0.2–1.5 dB in the 4–10.6 GHz band.

Finally, when the second director was added, gain in the middle- and high-frequency regions increased further by 0.1–0.3 dB. The VSWR < 2 frequency band is 3.03–10.62 GHz, whereas gain in the UWB is 3.3–7.4 dBi.

3. PARAMETRIC STUDY

In this section, a parametric study on the dimensions of the proposed miniaturized SOSA is presented to ascertain the effect on the input reflection coefficient and gain characteristics of the antenna. The geometric parameters considered for the parametric study are as follows: the length of the 180-degree bent portion of the J-shaped slots (l_{gs3}), the distance between the first director and the upper end of the ground plane (d_{s1}), and the length of the first director (l_{d1}).

3.1. Effects from Varying l_{gs3}

Figure 4 shows the input reflection coefficient and gain characteristics of the proposed SOSA based on length l_{gs3} of the 180-degree bent portion of the J-shaped slots. As l_{gs3} increases from 2.5 mm to 6.5 mm, the lower limit frequency for a VSWR < 2 shifts to a lower frequency, but gain in the low-frequency region below 6 GHz is reduced. For example, when $l_{gs3} = 2.5$ mm, the frequency bands for a VSWR < 2 are 3.21–10.47 GHz, which does not satisfy the UWB, and the gain range is 3.6–6.9 dBi in the band. As l_{gs3} is increased to 4.5 mm, the frequency band for a VSWR < 2 is 3.03–10.62 GHz to meet the UWB, and the gain range is 3.3–7.4 dBi in the UWB. However, when l_{gs3} is further increased to 6.5 mm, the frequency band for a VSWR < 2 increases to 2.87–10.79 GHz, but impedance match deteriorates in the 6.81–7.86 GHz frequency range with a gain reduction. In this case, the gain range is 2.5–7.6 dBi in the UWB.

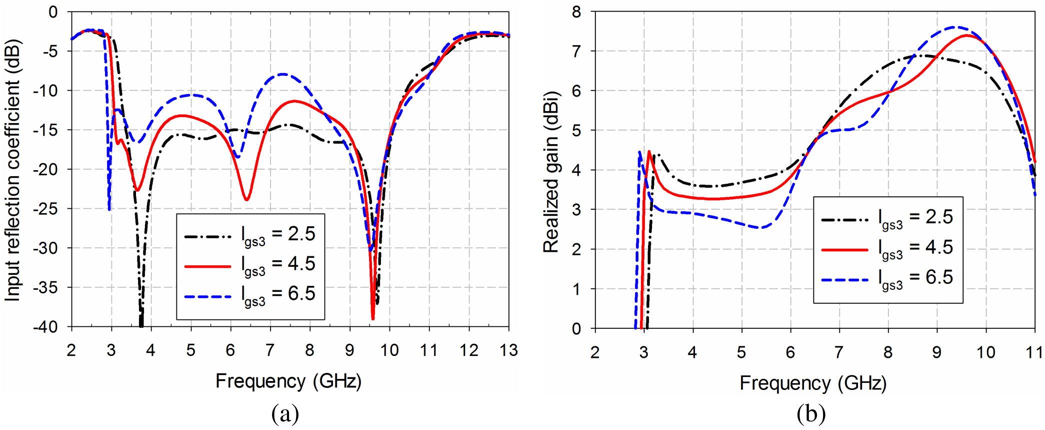
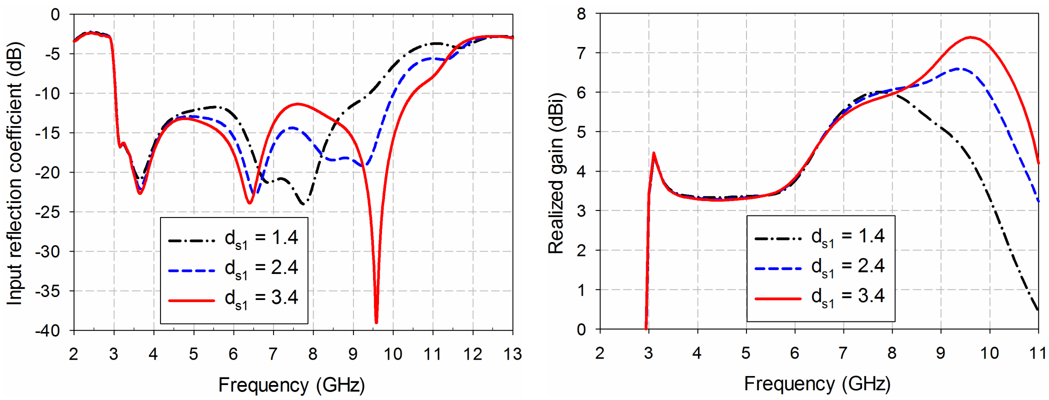


Figure 4. The effect from varying l_{gs3} on input reflection coefficient and realized gain characteristics of the proposed SOSA: (a) input reflection coefficient, and (b) realized gain.

3.2. Effects from Varying d_{s1}

Secondly, the effects on the input reflection coefficient and gain characteristics of the proposed SOSA from varying distance d_{s1} between the first director and the upper end of the ground plane were investigated, as shown in Figure 5. When d_{s1} increases from 1.4 mm to 3.4 mm, the lower limit frequency for a VSWR < 2 does not change, but the upper limit frequency increases. For instance, when $d_{s1} = 1.4$ mm, the frequency bands for a VSWR < 2 are 3.03–9.50 GHz, which does not satisfy the UWB, and the gain range is 3.3–6.0 dBi. As d_{s1} is increased to 2.4 mm, the frequency band for a VSWR < 2 is 3.03–10.06 GHz, which still cannot satisfy the UWB, and the gain range is 3.3–6.6 dBi. When d_{s1} is further increased to 3.4 mm, the frequency band for a VSWR < 2 increases to 3.03–10.62 GHz, and the gain range is 3.3–7.4 dBi in the UWB band.

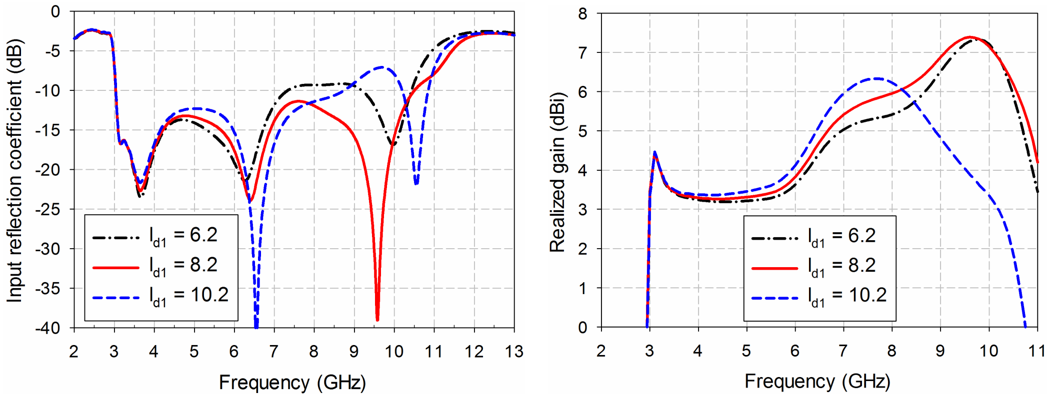


(a) (b)

Figure 5. The effect from varying d_{s1} on input reflection coefficient and realized gain characteristics of the proposed SOSA: (a) input reflection coefficient, and (b) realized gain.

3.3. Effects from Varying l_{d1}

The third parameter for this parametric study is length l_{d1} of the first director, as shown in Figure 6. When l_{d1} increases from 6.2 mm to 10.2 mm, the lower limit frequency for a VSWR < 2 does not change, but the impedance match and gain in the middle- and high-frequency regions vary, sensitive to l_{d1}. For example, when $l_{d1} = 6.2$ mm, the frequency bands for a VSWR < 2 are 3.02–10.46 GHz,



(a) (b)

Figure 6. The effect from varying l_{d1} on input reflection coefficient and realized gain characteristics of the proposed SOSA: (a) input reflection coefficient, and (b) realized gain.

which does not satisfy the UWB band. In addition, an impedance mismatch exists in the frequency range of 7.53–9.04 GHz. The gain range is 3.2–7.3 dBi in the band. As l_{d1} is increased to 8.2 mm, the frequency band for a VSWR < 2 is 3.03–10.62 GHz to meet the UWB, and the gain range is 3.3–7.4 dBi in the UWB. However, when l_{d1} is further increased to 10.2 mm, the frequency band for a VSWR < 2 is slightly increased to 3.03–10.86 GHz, but impedance match deteriorates in the frequency range of 8.87–10.16 GHz with the gain reduction. In this case, the gain range is 3.4–6.3 dBi in the band.

Figure 7 depicts the simulated surface current distributions of the proposed antenna at 3.08 GHz and 9 GHz. We can see that the surface currents are strong on the J-shaped slots, and they are weak on the directors at 3.08 GHz. This ensures that the J-shaped slots create a resonance at this frequency. However, the surface currents on the directors are enhanced at 9 GHz, which means the parasitic directors are working effectively in the high-frequency region.

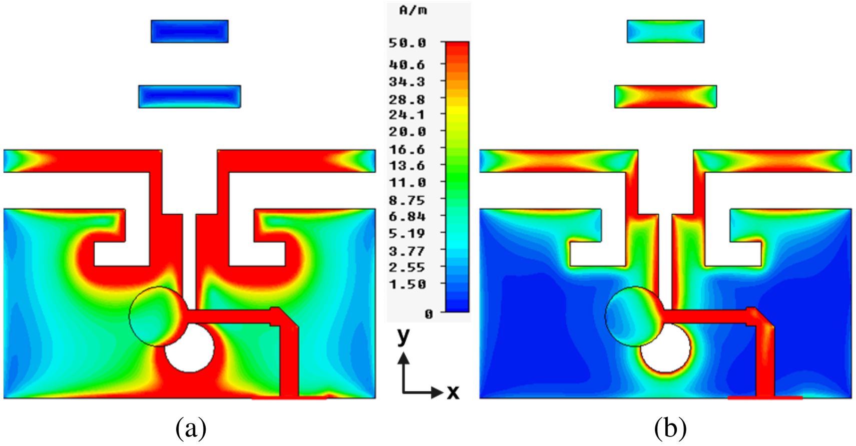


Figure 7. Simulated surface current distribution of the proposed SOSA: (a) 3.08 GHz, and (b) 9 GHz.

4. EXPERIMENT RESULTS AND DISCUSSION

Based on the study of the design procedure in the previous section, a prototype of the proposed miniaturized SOSA was fabricated as shown in Figure 8. The performance of the fabricated antenna was measured by using an Agilent N5230A network analyzer and the anechoic chamber, and the results were compared in Figure 9. The measured frequency band for a VSWR $<$ 2 is 2.99–10.87 GHz. The lower limit frequency is slightly decreased, compared to the simulated one, whereas the upper limit increases a little bit. The measured peak gain is 3.2–7.3 dBi, which are similar to the simulated result.

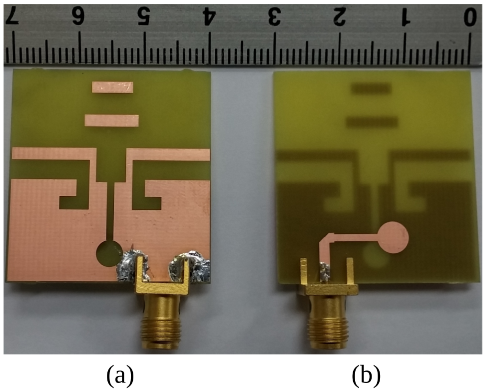
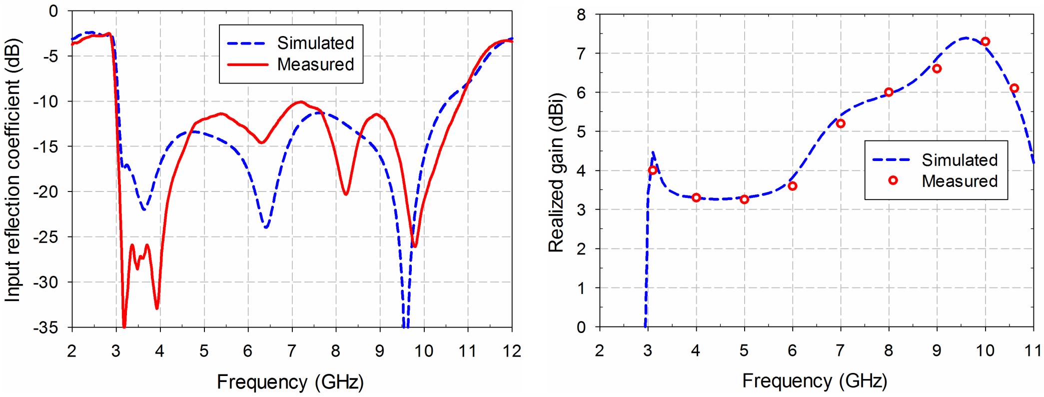


Figure 8. Photographs of the fabricated antenna: (a) front view, and (b) back view.



(a) (b)

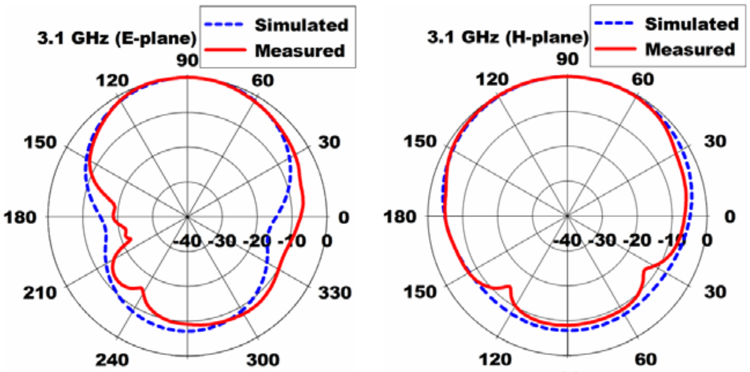
Figure 9. Measured performance of the fabricated SOSA on (a) the input reflection coefficient, and (b) the realized gain.

The radiation patterns of the fabricated antenna in the *E*-plane (x-y plane) and *H*-plane (y-z plane) are plotted in Figure 10, in which the measured patterns for both planes agree well with the simulated results. The proposed antenna has unidirectional (end-fire) beam patterns with a measured front-to-back ratio > 8.7 dB.

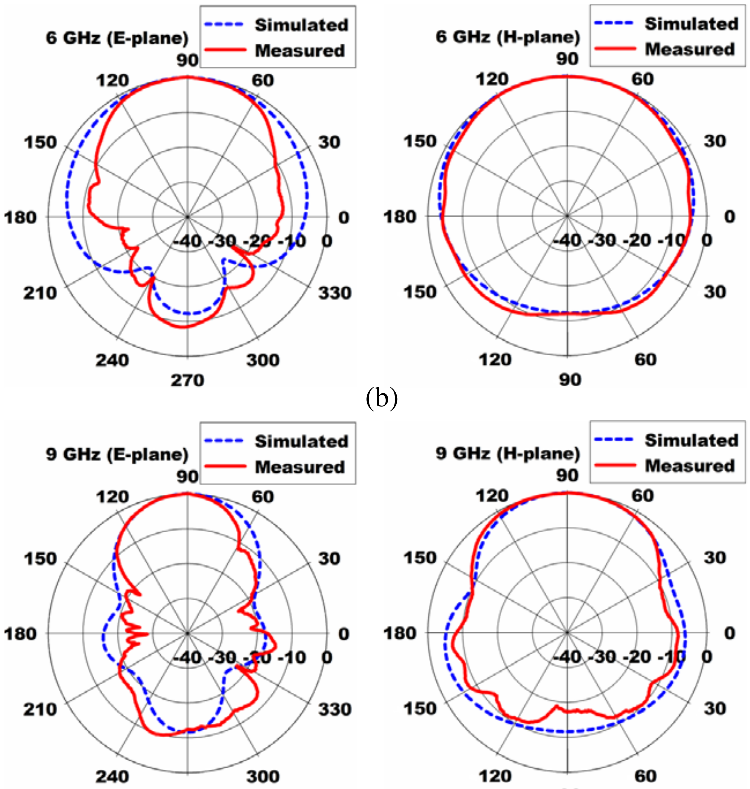
Figure 11 shows the measured group delay of the proposed antenna. Two proposed SOSAs faced each other along the end-fire direction for the measurement. The distance between the two antennas was 300 mm. We can see that the measured group delay remains almost constant, with variations of less than ±0.5 ns, which indicates good time domain performance with the proposed antenna.

Table 1. Comparison of dimensions, performance, and substrate permittivity of compact UWB antennas.

Reference	Dimensions (mm)	Bandwidth (GHz)	Gain (dBi)	Substrate permittivity
[4]	40 × 35 × 1.6	3.00–11.00	1–4	4.4
[5]	30 × 17 × 1.6	2.95–14.0	1.5–4	4.4
[6]	30 × 25 × 0.64	1.75–10.75	2.5–7.8	10.2
[7]	35 × 36 × 0.8	3.1–11.00	2.0–8.0	4.4
This work	30 × 32 × 0.8	2.99–10.87	3.2–7.3	4.4



(a)



(b)

(c)

Figure 10. Measured radiation patterns of the fabricated SOSA for the E- and H-planes at (a) 3.1 GHz, (b) 6 GHz, and (c) 9 GHz.

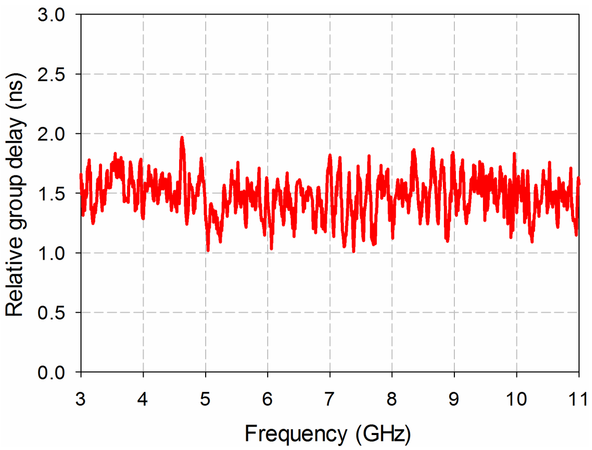


Figure 11. Measured group delay.

Table 1 compares the dimensions, VSWR < 2 bandwidth, gain in the UWB, and substrate permittivity of the proposed miniaturized SOSA with other compact UWB antennas reported in the literature [4–7]. Note that the size of the proposed SOSA is relatively small considering the substrate permittivity, and gain in the low-frequency region is about 1 dB higher, compared to the others.

5. CONCLUSION

A miniaturized SOSA covering the whole UWB of 3.1–10.6 GHz was designed using J-shaped ground slots and two strip directors. New resonance was created by inserting J-shaped slots on the ground of the antenna, thereby reducing the antenna size; gain in the middle- and high-frequency regions was enhanced, along with impedance match improvement, by appending the two directors.

The fabricated prototype of the proposed antenna shows a frequency band of 2.99–10.87 GHz for a VSWR < 2 with UWB gain of 3.2–7.3 dBi and good group delay performance.

For future work, the design of the best miniaturized antenna model using computationally efficient optimization methods might be investigated.

The proposed miniaturized SOSA is expected to be used as a small directional antenna for UWB communications and UWB radar, or as a portable directional antenna for radio spectrum measurement.

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REFERENCES

1. Schantz, H., *The Art and Science of Ultrawideband Antennas*, Artech House, Norwood, 2005.
2. Denidni, T. A. and G. Augustin, *Ultrawideband Antennas for Microwave Imaging Systems*, Artech House, Norwood, 2014.
3. Balanis, C. A., *Antenna Theory — Analysis and Design*, Wiley-Interscience, Hoboken, 2005.
4. Chen, D. and C. H. Cheng, "A novel compact ultra-wideband (UWB) wide slot antenna with via holes," *Progress In Electromagnetics Research*, Vol. 94, 343–349, 2009.
5. Feng, H., L. Xu, P. Wang, and P. Gao, "Miniaturized UWB monopole-like slot antenna with low un-roundness of H-plane radiation patterns at high-frequency band," *Progress In Electromagnetics Research Letters*, Vol. 70, 107–113, 2017.
6. Gopikrishna, M., D. D. Krishna, C. K. Aanandan, P. Mohanan, and K. Vasudevan, "Design of a microstrip fed step slot antenna for UWB communication," *Microw. Opt. Technol. Lett.*, Vol. 51, No. 4, 1126–1129, Apr. 2009.
7. Gopikrishna, M., D. D. Krishna, C. K. Aanandan, P. Mohanan, and K. Vasudevan, "Compact linear tapered slot antenna for UWB applications," *Electron. Lett.*, Vol. 44, No. 20, 1174–1176, Sep. 2008.
8. Abbosh, A. M., "Miniaturized microstrip-fed tapered-slot antenna with ultrawideband performance," *IEEE Antennas Wireless Propag. Lett.*, Vol. 8, 690–692, 2009.
9. Zhu, F., S. Gao, A. T. S. Ho, C. H. See, R. A. Abd-Alhameed, J. Li, and J. Xu, "Compact-size linearly tapered slot antenna for portable ultra-wideband imaging systems," *Int. J. RF Microwave Comput. Aided Eng.*, Vol. 23, No. 3, 290–299, May 2013.
10. Yeo, J. and J. I. Lee, "Design of compact stepped open slot Antenna for UWB applications," *J. Korea Inst. Inf. Commun. Eng.*, Vol. 21, No. 1, 1–7, Jan. 2017.
11. Yeo, J., J. I. Lee, and Y. K. Cho, "Miniaturized stepped open slot antenna for UWB applications," *2018 IEEE International Symposium on Antennas and Propagation*, 1–2, Boston, Massachusetts, 2018.