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A Novel Miniaturized Vivaldi Antenna for Ultra-Wideband Applications

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Abstract—A novel Vivaldi antenna utilizing a tapered slot edge with a stepped structure (TSESS) to achieve miniaturization is presented in this paper. Compared with a conventional Vivaldi antenna of the same size, the proposed TSESS significantly extends the low-end bandwidth limitation and also improves the low-end antenna gain and radiation characteristics. The proposed antenna is fabricated and tested for validating the reliability of the design. The measured results show reasonable agreement with simulated ones. Moreover, a good time-domain response is indicated from the measured group delay, showing that the antenna meets the requirements of a UWB system.

1. INTRODUCTION

Due to the rapid development of communication market, ultra-wideband (UWB) technology has attracted increasing interest in recent years. UWB antenna, which uses very narrow pulse signal to convey information, is critical to the success of a UWB system [1]. UWB antenna has been widely used not only in military and civil wireless communication, but also in biomedical detection, because of its unique features such as broad impedance bandwidth and high speed data rate [2, 3]. After the Federal Communication Commission (FCC) approved the opening of 3.1–10.6 GHz band to the business in 2002 [4], various kinds of UWB antennas have been studied and designed, such as Vivaldi antenna, printed monopole antenna, and wide slot antenna [5–7].

As the kind of end-fire traveling wave antennas, a Vivaldi antenna has theoretically infinite bandwidth, especially for high frequencies. However, the low-end operating band is practically limited by the width of the antenna [8]. Therefore, in order to have a better low-end performance, a larger antenna size is usually required. According to [9], only the slot width of a Vivaldi antenna that reaches at least half-wavelength of the corresponding frequency can be effective radiation. In [10], the authors use a stepped connection structure to obtain a broad bandwidth. In [11], two pairs of eye-shaped slots are presented to obtain good unidirectional radiation pattern and higher antenna gain. The aforementioned Vivaldi antennas are undoubtedly with a compact size and have a wide impedance bandwidth especially for high frequencies. However, the low-end of the working band is still limited by the width of the antenna.

In order to improve the radiation performance at low frequencies, various types of modified Vivaldi antennas have been proposed. [12] utilized a tapered slot edge (TSE) structure to achieve miniaturization. The antenna can obtain a lower low-end cutoff frequency and broad impedance bandwidth. However, it also requires a relatively large size. [13] utilized a tapered slot edge with a resonant cavity (TSERC) structure to achieve miniaturization. However, the antenna gain is lower at high frequencies than the reference antenna. In [14], a novel feeding structure is used to achieve miniaturization. However, the antenna gain is very low.

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A novel miniaturized Vivaldi antenna is designed and studied in this paper. In particular, a pair of symmetrical TSESSs is applied to extend the low-end cutoff frequency, which is extended to 2.35 GHz from 3.10 GHz. It means that the size of the TSESS Vivaldi antenna can be reduced to $0.282\lambda_L \times 0.235\lambda_L$ from the original $0.372\lambda_L \times 0.310\lambda_L$ (λ_L refers to the wavelength of the low-end cutoff frequency), which achieves a size reduction of 42.5%. In addition, the relative impedance bandwidth has been increased by about 17% while keeping the antenna size unchanged. Moreover, the antenna gain has a significant increase in the lower frequency band. Hence, the proposed design has the capability to improve the antenna's radiation characteristics in the lower frequency band.

2. ANTENNA DESIGN

The proposed design is shown in Figure 1. The dimension of the TSESS Vivaldi antenna is 36 mm × 30 mm. In comparison, a conventional Vivaldi antenna (CVA) with the same size is also shown as a reference. Both antennas are printed on an FR4 substrate with a thickness of 1 mm, dielectric constant of 4.4 and loss tangent of 0.02. The detailed design process is described as follows (Unit: mm).

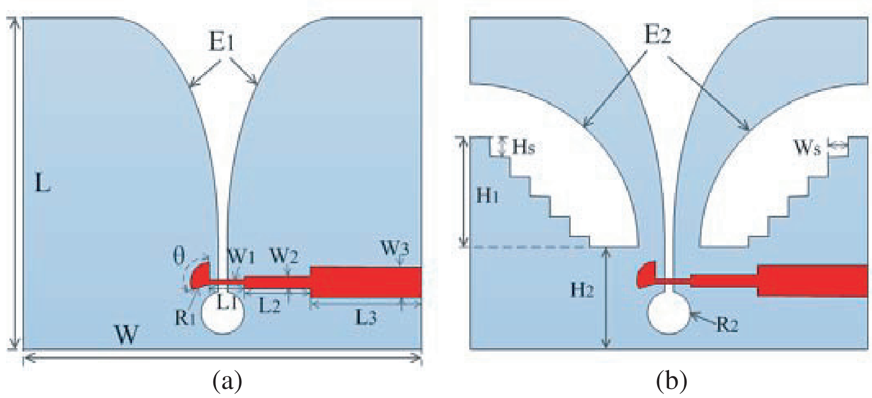


Figure 1. Configurations of the Vivaldi antennas: (a) CVA, (b) TSESS Vivaldi antenna.

The CVA shown in Figure 1(a) is used as our starting point. The exponential curves E1 are governed by Equation (1)

$$x = \pm c_1 \cdot \exp\left[r_{ex1} \cdot (y-6)\right] \mp (c_1 - c_2)\,, \quad (6 \le y \le 36) \tag{1}$$

where c_1, c_2 and r_{ex1} are set as 0.14, 0.15 and 175000, respectively.

In order to reduce the low-end cutoff frequency without increasing the width of the antenna, the TSESS is therefore proposed. A pair of symmetrical TSESSs is inserted on both sides of the antenna to

Table 1. Optimized parameters of the proposed antenna.

parameter	value	parameter	value
L	30 mm	W	36 mm
$L1$	2.9 mm	$W1$	0.6 mm
$L2$	6.2 mm	$W2$	1.3 mm
$L3$	10.3 mm	$W3$	2.0 mm
HS	2.0 mm	WS	2.0 mm
$R1$	2.9 mm	$H1$	10.8 mm
$R2$	1.85 mm	$H2$	8.2 mm
θ	115 deg		

increase the effective length of the current path in order to excite lower-frequency resonances (showing in Figure 1(b)). The exponential curves E2 are described by Equation (2)

$$x = \pm c_3 \cdot \exp\left[r_{ex2} \cdot (y - 6)\right] \mp (c_3 - c_4), \quad (8.2 \le y \le 23.76) \tag{2}$$

where $c_3 = 0.09$, $c_4 = 0.28$ and $r_{ex2} = 330000$. Other parameters are shown in Table 1 via optimization.

A microstrip feeding line with a balun structure is adopted to achieve a good impedance matching. Besides, in order to better matching the $50\,\Omega$ coaxial connector, the width of the port is set to 2 mm. The detailed parameters of the feeding line are also optimized and shown in Table 1.

3. RESULTS AND ANALYSIS

A prototype of the TSESS Vivaldi antenna is fabricated and measured to further validate the performance of the proposed design. Top and bottom photographs of the fabricated antenna are shown in Figure 2. In our measurement, return loss and group delay are measured using PNA-L Network

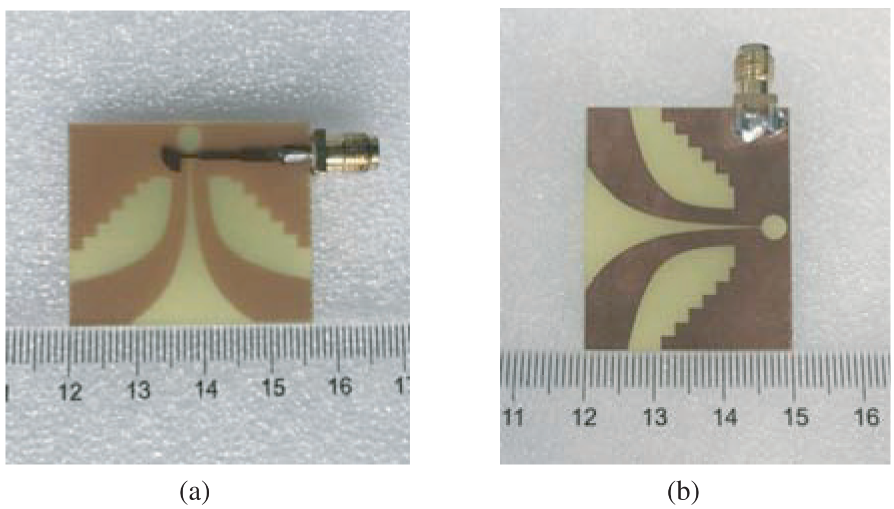


Figure 2. Photographs of the fabricated antenna: (a) Top view, (b) bottom view.

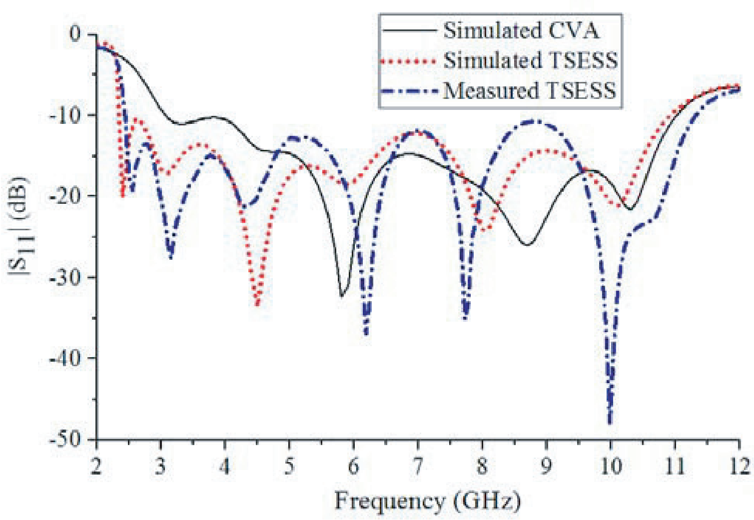


Figure 3. Simulated and measured return loss of the proposed antenna.

Analyzer N5235A, and antenna gain and radiation patterns are measured using a microwave anechoic chamber. Simulations are carried out using the software High Frequency Structure Simulator (HFSS).

The simulated $|S_{11}|$ variation with frequency is shown in Figure 3, where the TSESS Vivaldi antenna is compared with the CVA reference. It can be observed that the low-end bandwidth limitation of the TSESS Vivaldi antenna is extended to 2.35 GHz from the original 3.10 GHz. This simply means that to have the same low-end limitation, the proposed TSESS can miniaturize the antenna size to achieve miniaturization. The measured $|S_{11}|$ of the fabricated TSESS Vivaldi antenna is also plotted in Figure 3. It can be seen that the measured and simulated results are in reasonable agreement. The discrepancy is probably caused by the fabrication error.

The effect of parameter $H1$ on return loss of the proposed TSESS Vivaldi antenna is simulated and studied in Figure 4. It can be observed that the length of $H1$ has a great impact on return loss at low frequencies. Increasing the length of $H1$ properly can obtain a lower low-end cutoff frequency. Besides, the effects of parameters Ws and Hs on return loss of the TSESS are also simulated and studied in Figure 5 and Figure 6, respectively. It can be observed that the length of Ws has a great impact on return loss at high frequencies. Besides, the length of Hs also plays a crucial role in return loss. When

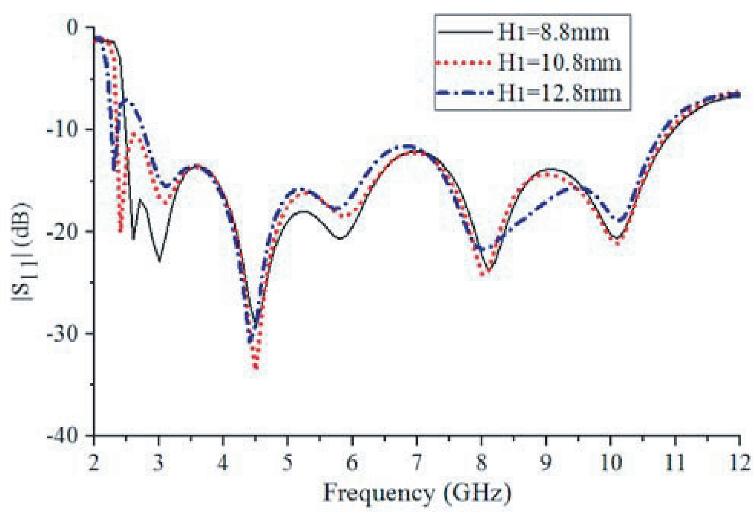


Figure 4. Simulated return loss of the proposed antenna with different value of $H1$.

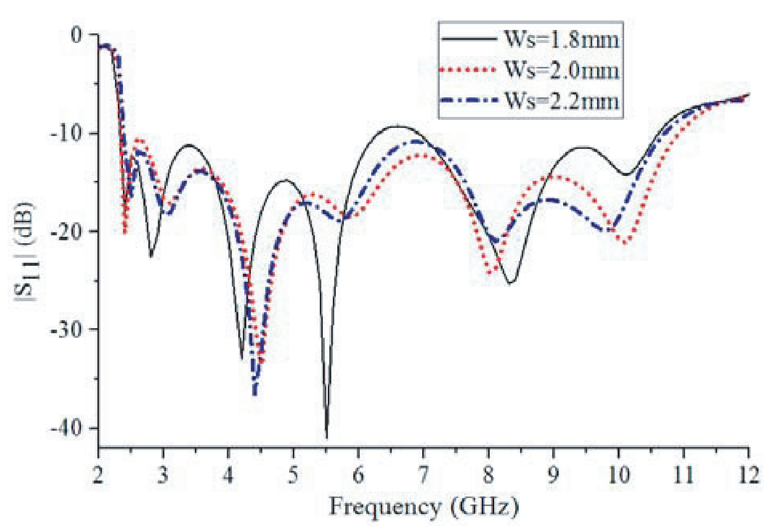


Figure 5. Simulated return loss of the proposed antenna with different value of Ws.

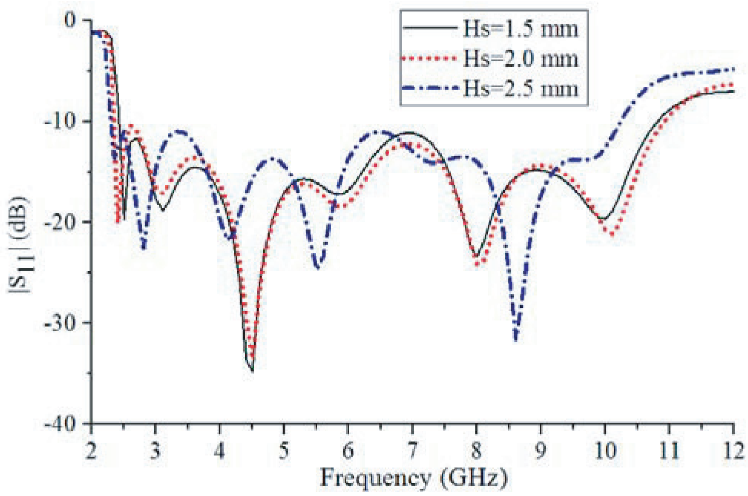


Figure 6. Simulated return loss of the proposed antenna with different value of Hs.

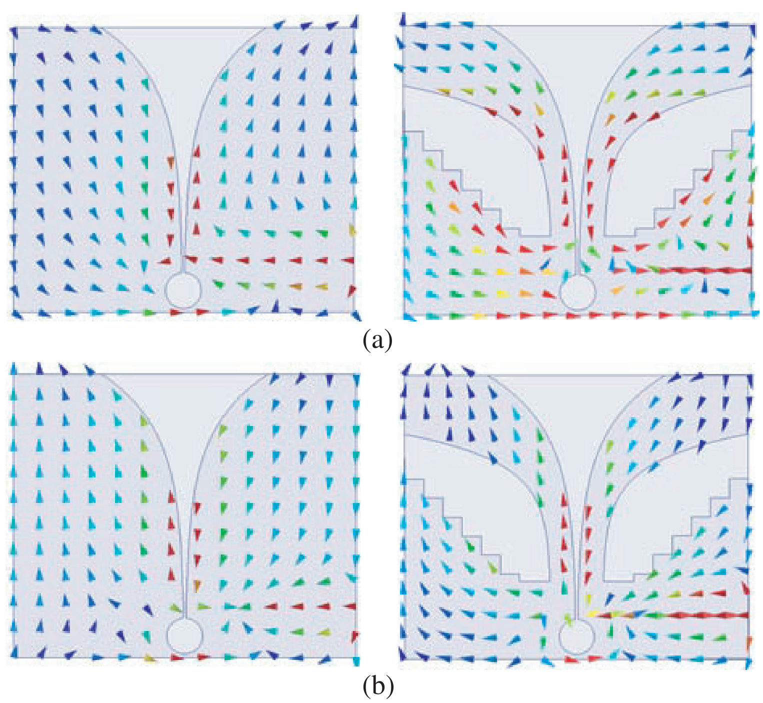


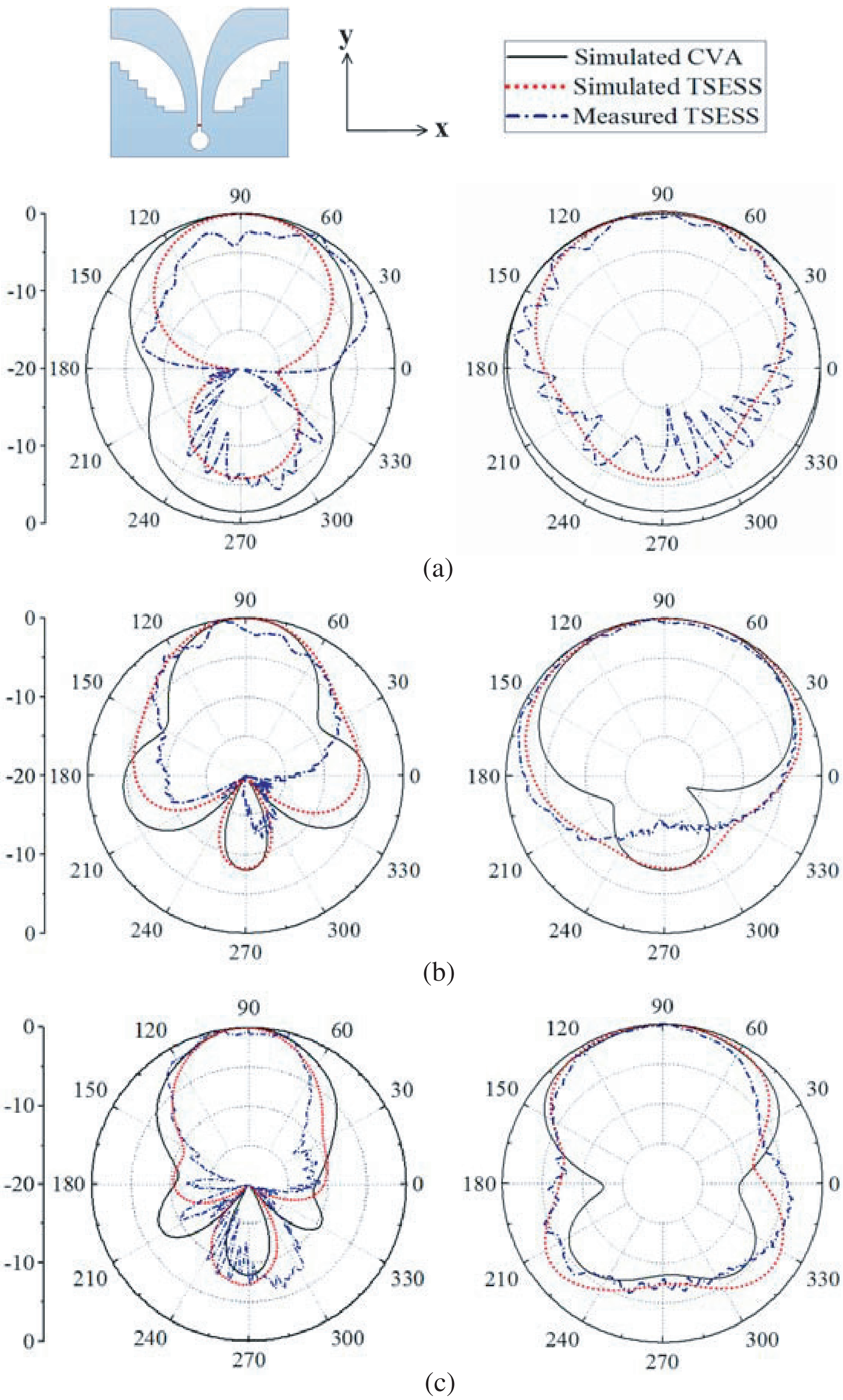
Figure 7. Surface current distribution of the CVA and the proposed antenna at (a) 2.4 GHz, (b) 4 GHz.

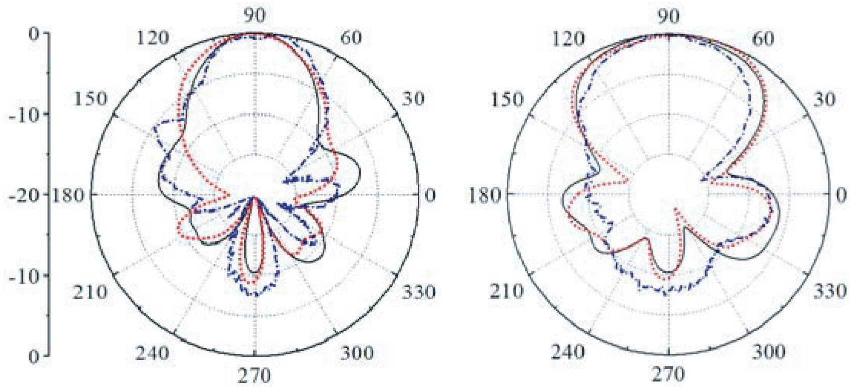
$Ws = 2.0$ mm and $Hs = 2.0$ mm, the proposed antenna can obtain a relatively satisfactory return loss with a lower low-end cutoff frequency.

In order to further understand the radiation principle of the TSESS Vivaldi antenna at lower frequencies, surface current distributions of the CVA and the TSESS Vivaldi antenna at 2.4 GHz and 4 GHz are shown in Figure 7. At 2.4 GHz, the surface currents mainly concentrate along the TSESS which indicates that the effective length of the current path is increased, and lower-frequency resonances are excited. On the other hand, at 4 GHz, the surface currents on both antennas are mainly distributed along the tapered slot, which indicates that the TSESS is more effective at lower frequencies.

The radiation patterns of the TSESS Vivaldi antenna at 2.4 GHz, 5 GHz, 7 GHz and 9 GHz are measured and plotted in Figure 8. For comparison, the simulated radiation patterns of the CVA are also plotted. It can be observed that the directivity of the TSESS Vivaldi antenna has a significant improvement at the low frequencies, and the radiation patterns remain approximately the same as the CVA at high frequencies. Besides, the simulated and measured results of the TSESS Vivaldi antenna are roughly the same, and the difference is probably due to the effect of the SMA connector and experimental environment (Unit: dB).

The simulated and measured antenna gains of the proposed design are plotted in Figure 9. Besides, the simulated gain of the CVA is also plotted for comparison. It can be seen that the gain of TSESS Vivaldi antenna can achieve a significant increase in the lower frequency band (2.35–3.1 GHz), which further verifies the effectiveness of the proposed design. Besides, in the original low-end radiation





(d)

Figure 8. Radiation patterns of the antennas in E-plane (xoy) and H-plane (yoz) at (a) 2.4 GHz, (b) 5 GHz, (c) 7 GHz, (d) 9 GHz.

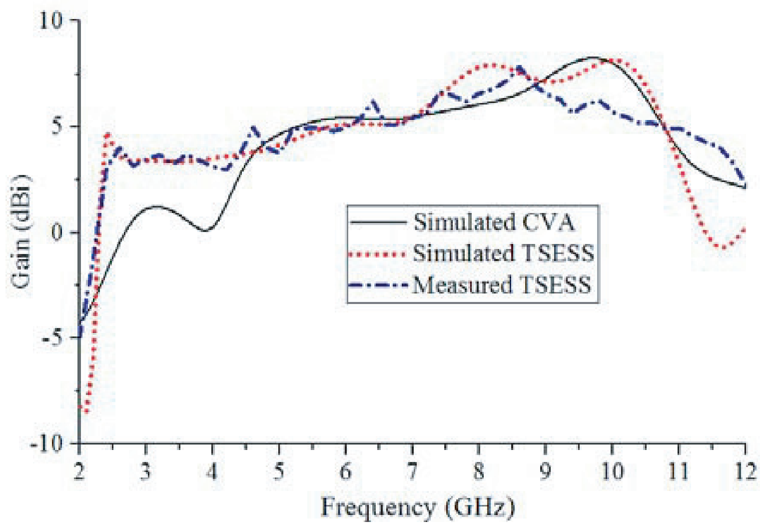


Figure 9. Simulated and measured gain of the proposed antenna.

Table 2. Comparison between proposed antenna and literatures.

Ref.	**Dimension** ($\lambda_L \times \lambda_L$)	**B.W** (GHz) low	high	**Substrate**	**Gain** (dBi)	**Group delay** (ns)
[10]	0.41×0.48	3	15.1	FR4 (4.4)	5.1–8.2	1.3 ± 0.5
[11]	0.36×0.36	3	12.8	FR4 (4.4)	3.7–8.3	1.2 ± 0.5
[12]	0.384×0.480	2.4	> 14	FR4 (4.6)	3.7–10	2.0 ± 1.0
[13]	0.25×0.43	0.5	6.0	FR4 (4.6)	0.5–7.5	—
[14]	0.386×0.397	3.05	10.3	RO4003(3.38)	1.73–4.96	—
[15]	0.319×0.418	3.3	13.6	RO5880(2.2)	2.4–9.9	—
[16]	0.33×0.37	2	> 12	FR4 (4.4)	1.5–5.2	—
[17]	0.36×0.37	3.1	10.6	FR4 (4.55)	2.0–8.5	—
proposed	0.282×0.235	2.35	11	FR4 (4.4)	3.0–7.8	1.6 ± 0.5

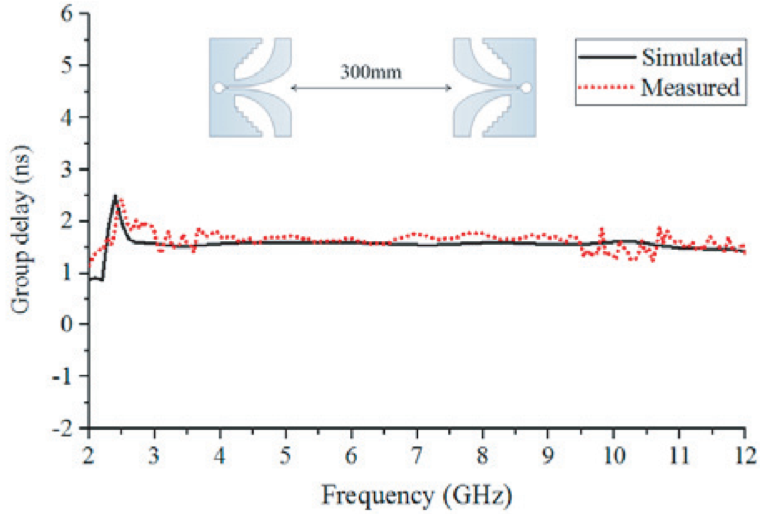


Figure 10. Simulated and measured group delay of the proposed antenna.

frequency band (3.1–5 GHz), the radiation performance can also be improved since the TSESS makes the surface current distribute along the tapered slot [11]. However, the measured gains are different from the simulated ones in the high frequency band (9–12 GHz). This may be caused by the SMA connector and experimental environment. In the band between 2.35 GHz and 11 GHz, the proposed design can obtain a moderate antenna gain, ranging from 3.0 dBi to 7.8 dBi.

Group delay is another vital parameter for a UWB antenna, because it is an effective measure of the waveform distortion in the time domain. Two identical antennas are placed face to face along the main radiation direction with a distance of 300 mm to emulate the transmission and receiving of signals. As shown in Figure 10, the measured group delay is around 1.6 ns with a small variation less than 0.5 ns. Therefore, it is relatively flat in the entire operating band which meets the requirement of a UWB system.

Finally, the dimension of the TSESS Vivaldi antenna is compared with other antennas reported in the literature, shown in Table 2. The size of the proposed antenna is $0.282\lambda_L \times 0.235\lambda_L$, which is a quite compact size for Vivaldi antennas.

4. CONCLUSIONS

A planar printed miniaturized Vivaldi antenna with a pair of symmetrical TSESSs is designed and studied in this paper. By inserting a pair of symmetrical TSESSs, the low-end cutoff frequency of the proposed design can be reduced to 2.35 GHz from 3.10 GHz of CVA. It means that to achieve the same low-end cutoff frequency, the size of the TSESS Vivaldi antenna can achieve a reduction of 42.5%. In addition, the relative impedance bandwidth has been increased by about 17%. Moreover, the radiation direction and gain are significantly improved in the lower frequency band, which further verifies the validity of the TSESS. Finally, a good time domain response is obtained in the entire working bandwidth, which is an important requirement of a UWB system.

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