Compact Elliptically Tapered Slot Antenna with Non-uniform Corrugations for Ultra-wideband Applications

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Abstract. *A small size elliptically tapered slot antenna (ETSA) fed by coplanar waveguide (CPW) for ultra-wideband (UWB) applications is proposed. It is printed on an FR4 substrate and occupies a size of 37×34×0.8 mm^3. A pair of quarter circular shapes is etched on the radiator to reduce the size. To overcome the limitation of uniform corrugation, non-uniform corrugation is utilized to reduce the cross-polarization level. A parametric study is carried out to investigate the effects of circular cut and corrugations. In order to validate the design, a prototype is fabricated and measured. Both simulated and measured results confirm that the proposed antenna achieves a good performance of a reflection coefficient below -10 dB from 3.1 GHz to 10.6 GHz, including a maximum antenna gain of 8.1 dBi, directional patterns in the end-fire direction, low cross-polarization level below -20 dB and linear phase response. The antenna is promising for applications in UWB impulse radar imaging.*

Keywords

UWB impulse radar, UWB imaging, tapered slot antenna, UWB antenna, cross-polarization.

1. Introduction

Since the allocation of the frequency band from 3.1 GHz to 10.6 GHz by the Federal Communications Commission (FCC) in 2002, UWB is a promising technology for UWB imaging radar applications due to its large bandwidth, low power consumption, and resistance to the multipath phenomenon [1]. This means that the UWB radar can identify target classes and types with a high resolution. Tapered slot antennas (TSAs) feature a wide operational bandwidth, directional patterns and distortionless pulse transmission/reception [2]. It can be fabricated by using printed circuit board (PCB) technology which can make it integrate with other RF circuits easily and low cost. Therefore, the tapered slot antenna is a popular candidate for UWB radar system [3].

Tapered slot antennas were first introduced in the late 1950s [4]. A typical tapered slot antenna consists of a tapered slot cut in a thin film of metal with or without an electrically thin substrate on one side of the film [5]. There are several shapes — the "Vivaldi" (exponential taper), the LTSA (linear taper), and the CWSA (constant width). In general, the beam widths are narrowest for the CWSA shape, followed by the LTSA, and then the Vivaldi, while the side lobes are highest for the CWSA, followed by the LTSA, and the Vivaldi [6]. Compared with single sided tapered slot antenna, antipodal tapered slot antenna has a higher cross-polarization level [7] and lower antenna gain [8]. To reduce the high cross-polarization level, a balanced antipodal Vivaldi antenna for wide bandwidth phased arrays is proposed in [7]. A further layer of metallization is added to form the balanced antipodal Vivaldi antenna. Satoru et al. has proposed the use of corrugation to adjust the *E*-plane radiation pattern of the tapered slot antenna by varying the lengths of the corrugation for mm-wave imaging applications in 1998 [9]. Geometrical gratings are applied on the edges of the radiator to improve the antenna gain and reduce cross-polarization level of the tapered slot antenna for UWB applications [10]. However, the limitation of the corrugation is that the depth of the corrugation should be less than a quarter of the effective wavelength at the lowest operating frequency (3.1 GHz) [11]. Otherwise, it will lead to a notched-frequency band within UWB frequency range.

This paper has proposed non-uniform corrugations to reduce the cross-polarization levels for UWB applications. A compact size ETSA is presented. It is printed on an FR4 substrate and fed by CPW line. A pair of quarter circular shapes is etched on the radiator to reduce the size. To overcome the limitation of uniform corrugation, non-uniform corrugation is applied to reduce the cross-polarization level. The effects of both uniform and non-uniform corrugations are investigated in the terms of voltage standing wave ratio (VSWR) and radiation patterns. An antenna prototype is fabricated and tested to validate the design. Both simulated and measured results are shown and discussed in details.

2. Antenna Configuration and Design

The configurations of three types of elliptically tapered slot antennas are shown in Fig. 1(a)-(c). They have

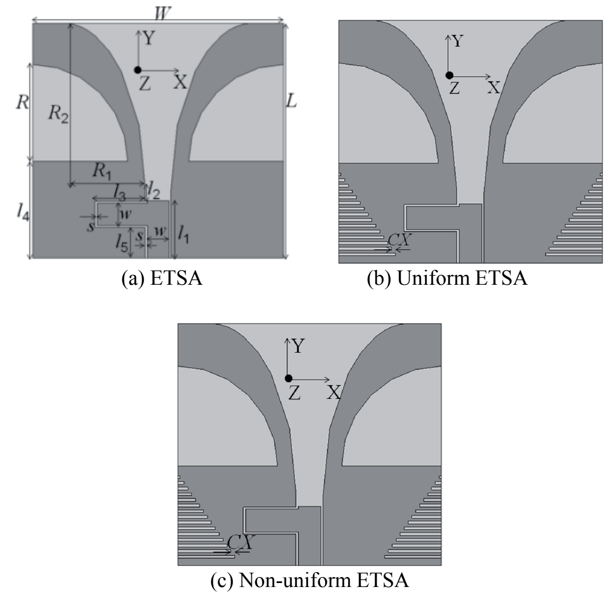


Fig. 1. Configurations of three types of ETSAs.

the same size of 37 mm by 34 mm and are printed on an FR4 substrate with thickness of 0.8 mm and permittivity of 4.55. Fig. 1(a) presents the elliptically tapered slot antenna without corrugation. A pair of quarter circular cuts is employed on the radiator to reduce the size. The feed network consists of three sections: the CPW feed, delay slotline, and CPW to slot transition [12]. The characteristic impedance of the feed line is 50 Ω. The ETSA with uniform corrugation for reducing the cross-polarization is denoted as uniform ETSA and shown in Fig. 1(b). *CL* and *CW* are the length and width of the slits respectively. The periodicity of the slit is 2*CW*. The uniform corrugation may lead to a notched frequency band. To overcome the drawback, the non-uniform corrugation is applied on the radiator as shown in Fig. 1(c). The difference of lengths between two close slits is denoted as *CX*. Given the thickness of the substrate (h) and its effective permittivity (ε_r), the width (W) of the antenna depends on the lowest operating frequency f_l (f_l = 3.1 GHz) [2]:

$$W = \frac{c}{f_1}\sqrt{\frac{2}{\varepsilon_r + 1}} \tag{1}$$

where c is the speed of light in free space. The major radius and secondary radius of the ellipse are chosen from the following formula:

$$R_1 = \frac{R_2}{2}\,. \tag{2}$$

Parameter	W	L	R	R_1	R_2	w
Value	37	34	14	12	24	3.2
Parameter	s	l_1	l_2	l_3	l_4	l_5
Value	0.3	8.3	1.8	7.4	4.4	1.4

Tab. 1. The dimensions of the designed antenna (Unit: mm).

The parameter R plays an important role in the reduction of the size and will be investigated in the next section. The full wave software HFSS is employed in the antenna design process. The variables and optimized dimensions of the designed antenna are shown in Tab. 1.

3. Results and Discussions

In this section, a parametric study is carried out to investigate the effects of the cut radius R and the effects of both uniform and non-uniform corrugations. The parametric analysis is carried out while holding the remaining parameters with the dimensions presented in Tab. 1.

3.1 Effect of the Quarter Circular Cut

The effect concerning the VSWR by the quarter circular cut is shown in Fig. 2. It shows that the length of the slit has a significant role on the lowest operating frequency. The lowest frequency changes from 3.7 to 3.1 GHz for VSWR ≤ 2 when the radius R increases from 8 to 14 mm. It is due to the cut which leads to lengthening electric length and contributes to the lower frequency.

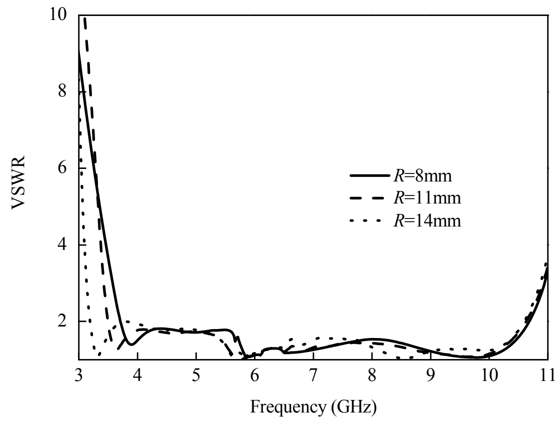


Fig. 2. Simulated effects on VSWR in terms of *R*.

3.2 Effect of the Corrugation

Since the radiation patterns can be adjusted by applying corrugated edges [9], and the cross-polarization level can be reduced by etching corrugations [10], the effects of the length is studied in this section. The comparison of VSWR when varying the lengths of the slit is shown in Fig. 3. It exhibits that the VSWR is less than 2 over the entire FCC frequency band when *CL* equals to 4 mm. However, when the length increases to 8 mm, the impedance matching near 4.5 GHz becomes poor which means a notched band. The variations of radiation patterns at 7 GHz in the *E*-plane (*XY*-plane) and *H*-plane (*YZ*-plane) in terms of *CL* are shown in Fig. 4. The cross-polarization level in the *E*-plane at 8 GHz is lower than that of 4 GHz in the end-fire direction. And the cross-polarization level in the *H*-plane is reduced when the length of the slit increases from 4 mm to 8 mm. It can be concluded that, the cross-polarization level can be reduced by lengthening the length of the slit. However, it will cause a notched frequency band over the designed frequency band.

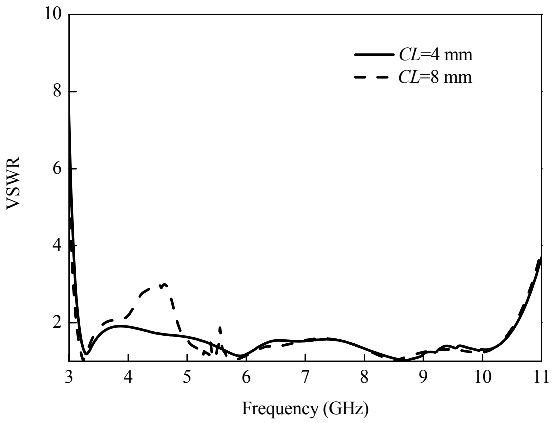
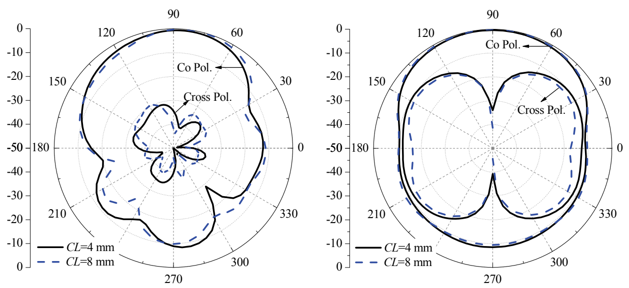


Fig. 3. Simulated effects on VSWR in terms of *CL*.



(a) (b)

Fig. 4. Simulated radiation patterns at 7 GHz in terms of *CL* (a) *E*-plane, and (b) *H*-plane.

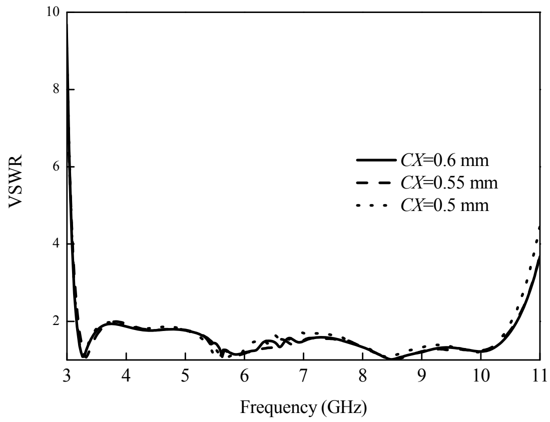
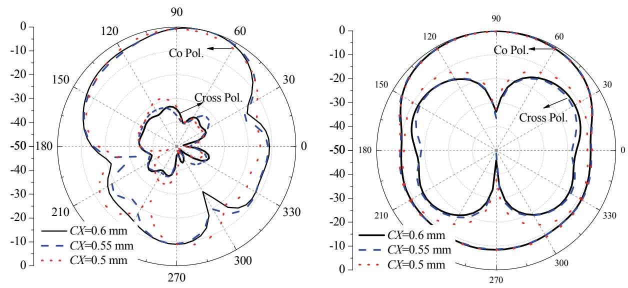


Fig. 5. Simulated effects on VSWR in terms of *CX*.

To overcome the limitation of the uniform corrugation, the non-uniform corrugation is applied to reduce the cross-polarization level. The effect concerning the VSWR in terms of *CX* when *CL* is fixed at 8 mm is shown in Fig. 5. Compared with the effect of the uniform corrugation, as shown in Fig. 3, the antenna achieves a frequency band from 3.1 to 10.6 GHz when *CX* decreases from 0.6 to 0.5 mm. The comparisons of radiation patterns at 7 GHz in the *E*- and *H*-planes in terms of *CX* are shown in Fig. 6. The cross-polarization level is lowest for 0.55 mm, followed by 0.6 mm, and then 0.5 mm. Therefore, the optimized dimensions of the non-uniform corrugation are *CL* = 8 mm, *CX* = 0.55 mm. It can be concluded that, the non-uniform corrugation can be applied to reduce the cross-polarization level effectively whereas it won't cause a notched frequency band within the entire frequency range.



(a) (b)

Fig. 6. Simulated radiation patterns at 7 GHz in terms of *CX*. (a) *E*-plane, and (b) *H*-plane.

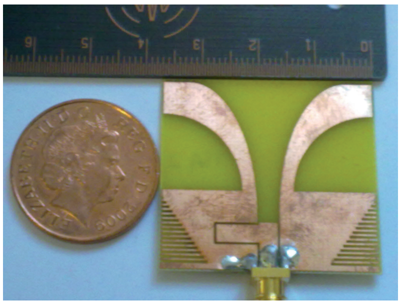


Fig. 7. Photo of the fabricated antenna prototype.

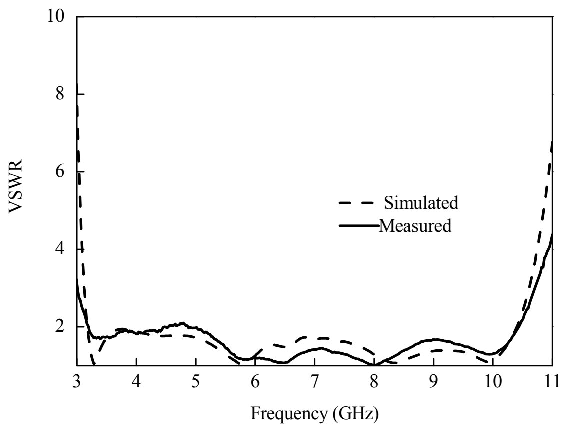


Fig. 8. Simulated and measured VSWR of the proposed antenna.

3.3 Simulated and Measured Results

The antenna prototype (shown in Fig. 7) is fabricated and tested. The simulated and measured VSWR are shown in Fig. 8. Both simulated and measured results confirm that the VSWR is less than 2 over the entire frequency band (3.1-10.6 GHz). Measurements of the radiation patterns of the prototype were carried out in a far-field anechoic chamber using an elevation-over-azimuth positioner, at the University of Bradford. Fig. 9 presents the simulated and measured radiation patterns in both *E*- and *H*-planes at 3.5 GHz, 7 GHz, and 10 GHz. As expected, the proposed antenna has end-fire radiation with the main lobe in the direction of the tapered slot. The cross-polarizations level in both *E*- and *H*-planes at 3.5 GHz, 7 GHz, and 10 GHz are below -20 dB in the end-fire direction. A reasonable agreement between simulated and measured co-polarizations is observed in Fig. 9.

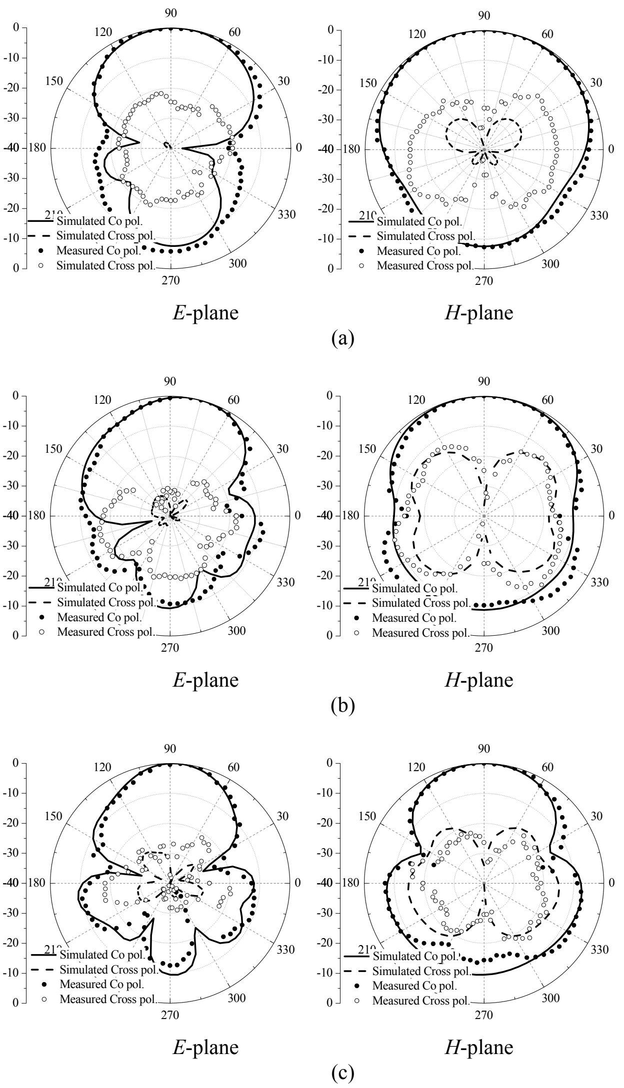


Fig. 9. Simulated and measured radiation patterns in the *E*- and *H*-planes at: (a) 3.5 GHz, (b) 7 GHz, and (c) 10 GHz.

The measured antenna gain response over the entire frequency band is shown in Fig. 10. The value of the gain extends from 1.5 dBi to 8.1 dBi. The gain at 3.1 GHz is over 4 dBi. This is due to the radiation of the cut which contributes to the high gain at lower operating frequency.

The measured pulse result in the time domain is presented to study the ability of distortionless pulse transmission/reception. Two identical proposed antennas are placed face by face by a separated distance of 30 cm. Two antennas are connected to the ports of Vector Network Analyzer (VNA). Inverse Fast Fourier Transform (IFFT) is used to convert the frequency response to time domain. The measured result is shown in Fig. 11, where the amplitudes of the transmitted and received pulses are normalized to have a peak value to 1. Both pulses are synchronized in the figure. The fidelity of the proposed antenna is predicted using the similar method in [13] and found to be larger than 93% which means that the proposed antenna is suitable for impulse radar system.

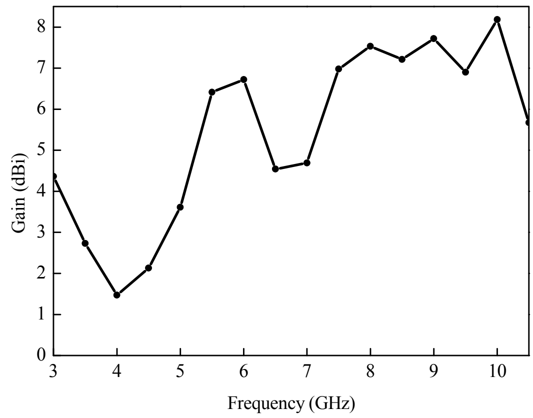


Fig. 10. Measured antenna gain over the entire frequency band.

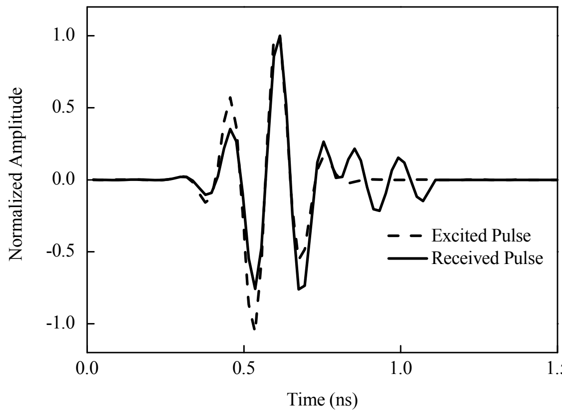


Fig. 11. Measured impulse response of the proposed antenna.

4. Conclusion

A compact elliptically tapered slot antenna (ETSA) is proposed in this paper. It has a size of 37×34×0.8 mm^3. It is printed on an FR4 substrate which leads to low cost. Compared with uniform corrugation, non-uniform corrugation is applied on the radiator to reduce the cross-polarization level. Hardware realization is used to evaluate and validate the design theory. Performance of the antenna design features a compact size, directional radiation patterns, low cross-polarization level and distortionless pulse transmission, thus promising for portable impulse UWB imaging radar applications.

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