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A Miniaturized Ultra-Wideband Vivaldi Antenna With Low Cross Polarization

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ABSTRACT A miniaturized ultra-wideband Vivaldi antenna is proposed in this paper. Optimized slots are inserted in the radiation patches to obtain a low frequency resonance. Two substrates with radiation patches are put back to back, forming a double-layered structure. Thus, the transverse E-field of the double-layered structure is significantly reduced due to this symmetric treatment, which gives rise to very low cross polarization. The measured results show that an enhanced impedance bandwidth of approximately 126% in the range of 2.5–11 GHz ($S_{11} < -10$ dB) is achieved. The dimensions of the proposed antenna are 36 mm × 32 mm × 2 mm, and the relative dimensions are $0.3\lambda_0 \times 0.26\lambda_0 \times 0.02\lambda_0$, where λ_0 is the free-space wavelength at the lowest operating frequency. Furthermore, the cross polarization is −40 dB over the bandwidth. The time-domain behavior of the Vivaldi antenna is tested, and the results show a low cross polarization in the time domain and admirable time-domain responses.

INDEX TERMS Ultra-wideband (UWB), Vivaldi antenna, miniaturized, low cross-polarization.

I. INTRODUCTION

In February 2002, the Federal Communications Commission (FCC) assigned the spectrum from 3.1 GHz to 10.6 GHz, the UWB spectrum, to commercial use. The applications that use UWB technology have been greatly developed due to appealing characteristics such as high speed transmission rates and high multi-pathway resolution, among others [1]–[3]. Many UWB antennas have been reported in recent years [4], [5]. The Vivaldi antenna is a typical candidate for UWB technology, as it provides a satisfactory performance in the time domain, operates over a wide band, and has a high gain [6], [7]. However, there are some challenges concerning Vivaldi antennas, including their large size and high cross-polarization. To overcome many of these problems, various kinds of designs have been previously researched [8]–[16].

Slot edge structures are utilized to reduce the size of Vivaldi antenna [8]–[11]. These Vivaldi antennas utilize tapered, regular, and periodic slot edge structures to extend the low-end frequency limitations for miniaturizing the antenna. In [12], another design, petals, is introduced to match the termination. A bending feed line structure and a sinusoidal modulated Gaussian tapered slot are used to make the Vivaldi antenna compact [13]. Structural modifications in the radiation patch are utilized to increase the electrical length, thereby reducing the lower operating frequency. In [14], a compact antipodal Vivaldi antenna with dimensions of 42 mm×36 mm×1.6 mm is proposed. Reference [15] proposed a miniaturized CPW-fed antipodal Vivaldi antenna. In this design, elliptically shaped strip conductors are used to lower the antenna's operating frequency. However, these antennas have a high cross-polarization. To correct for this, a dielectric lens balanced antipodal Vivaldi antenna with low cross-polarization is proposed [16]. The performances of the referenced antennas [8]–[16] are given in Table 1.

In this paper, a miniaturized Vivaldi antenna with low cross-polarization is proposed. Modified radiation structures are deployed to form a low frequency resonance. This resonance significantly increased the bandwidth and reduced the size of this antenna. An excellently symmetrical dual-layer structure is applied to the proposed Vivaldi antenna. In this way, the transverse E-field component, which is perpendicular to the E-plane, can be canceled. Due to this, low cross-polarization is achieved. In addition, when the time-domain behavior of the Vivaldi antenna was tested, the results showed a low cross-polarization in the time domain and admirable time domain responses. The performance of this antenna is also summarized in Table 1.

This paper is organized as follows. The design of the miniaturized UWB Vivaldi antenna with low cross-polarization

TABLE 1. **Compare of proposed antenna and reference antennas.**

Ref	Dimensions (λ_0)	Operating frequency band (GHz)	Cross-polarization (dB)
[8]	0.5×0.6	2.4-14	-
[9]	0.88×0.66	4-30	-
[10]	0.45×1.02	3.4-40	-
[11]	0.32×0.46	1-30	-
[12]	0.48×0.48	2.4-14	<-15
[13]	0.33×0.37	2-12	-
[14]	0.52×0.44	3.7-18	<-18
[15]	0.41×0.42	1.32-17	-
[16]	0.96×0.5	3-18	<-20
This work	0.3×0.26	2.5-11	<-40

along with its parametric study is presented in Section II. In Section III, we study the surface current distributions of both conventional Vivaldi antennas and the proposed antenna to reduce the size of the Vivaldi antenna and the transverse E-field to achieve low cross-polarization. The experimental results of the proposed Vivaldi antenna are also given, including the frequency domain and time domain behaviors. Some conclusions summarizing our achievements are drawn in Section IV.

II. ANTENNA DESIGN

The idea behind the design of the proposed antenna is based on the conventional Vivaldi antenna [17]. Figure 1 shows the geometry of three Vivaldi antennas, namely, a conventional Vivaldi antenna, a single-layer Vivaldi antenna, and a dual-layer Vivaldi antenna. All three have already been optimized. The dimensions of all antennas are 36 × 32 mm^2. All the substrates are designed with standard FR-4 with a thickness of 1 mm.

The configuration of the proposed dual-layer Vivaldi antenna, which consists of two substrates, is shown in Fig. 1(c). This antenna consists of two radiation patches, two substrates, and a stripline-to-slotline transition structure. The exponential profile curves E_1 employed in this design can be described by

$$y = \pm c_1 \cdot \exp(r_{ex1} \cdot x) \mp (c_1 - c_2) \tag{1}$$

Where $c_1 = 0.14$, $rex_1 = 0.18$, $c_2 = 0.34$.

A pair of symmetrical exponential slots is inserted on the radiation patches, which are used to reduce the size of the antenna. The exponential curves E_2 and E_3 of the slots can be described by

$$y = \pm c_3 \cdot \exp(r_{ex1} \cdot x) \mp (c_3 - c_4) \tag{2}$$

$$y = \pm c_5 \cdot \exp(r_{ex1} \cdot x) \mp (c_5 - c_6) \tag{3}$$

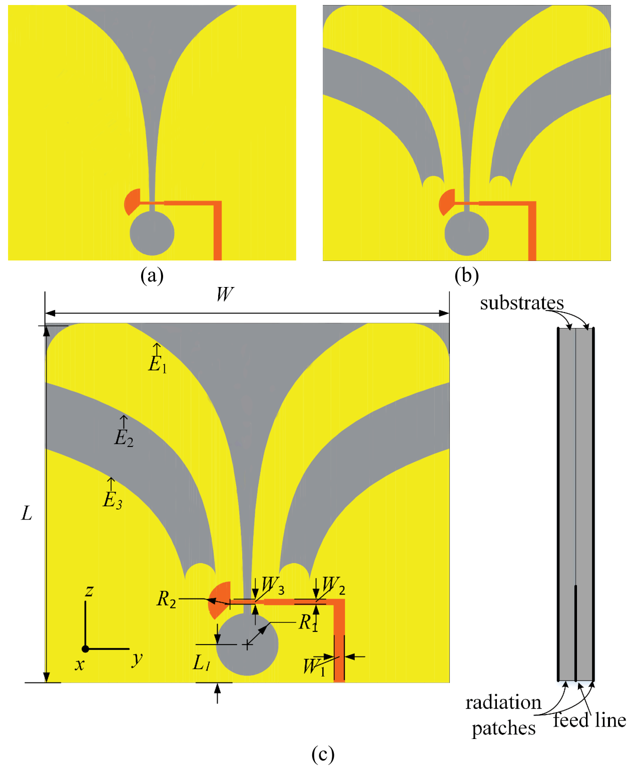

FIGURE 1. **Configurations of the three Vivaldi antennas:(a) conventional Vivaldi antenna, (b) single-layer Vivaldi antenna, (c) dual-layer Vivaldi antenna.**

Where $c_3 = 0.35$, $c_4 = 2.8$, $rex_2 = 0.22$. $c_5 = 0.1$, $c_6 = 5.5$, $rex_3 = 0.22$.

Two substrates are mounted back-to-back to achieve a dual-layer structure. Two radiation patches are placed on the other side of the dual-layer structure. They form a symmetrical structure. In the middle of the dual-layer structure, a stripline-to-slotline transition structure is printed to connect the feeding probe to the 50 Ω SMA launcher. The stripline-to-slotline transition structure is utilized to excite the Vivaldi antenna. In this design, a stepped stripline is used for good impedance matching. For this dual-layer, due to the symmetric design, the E-field generated by both sides are in opposite directions, giving rise to cancellations of the transverse E-field. This results in a lower cross-polarization.

Some key optimized parameters of the antenna are specified as follows: $W = 36$ mm, $L = 32$ mm, $W_1 = 1$ mm, $W_2 = 0.55$ mm, $W_3 = 0.35$ mm, $R_1 = 2.8$ mm, $R_1 = 2.6$ mm, and $L_1 = 3.4$ mm.

III. RESULTS AND ANALYSES

A working prototype of the proposed Vivaldi antenna was fabricated. Fig. 2 shows a picture of the manufactured antenna.

To better understand the performance of the proposed antenna, the simulated surface current distributions of both a conventional Vivaldi antenna and the proposed antenna

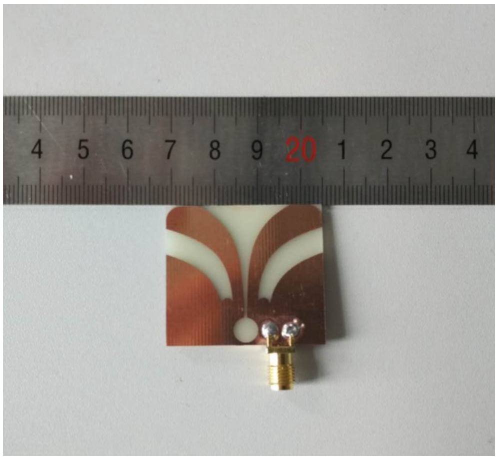

FIGURE 2. The dual-layered Vivaldi antenna.

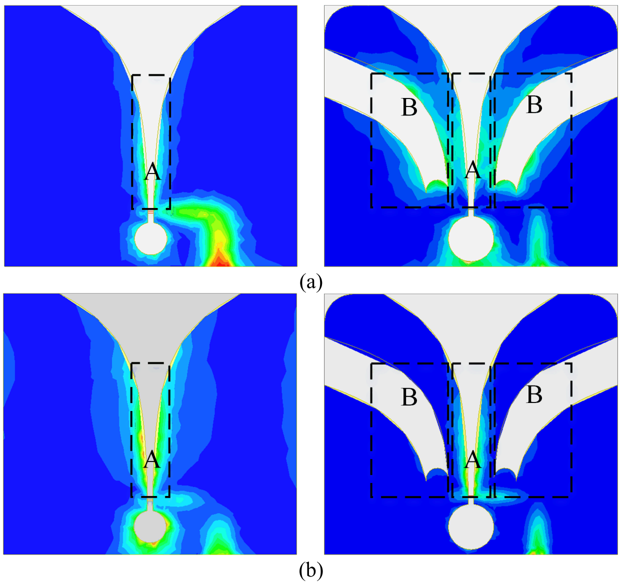

FIGURE 3. The surface current distributions of both conventional Vivaldi antenna and proposed antenna at (a) 2.5 GHz, (b) 4 GHz.

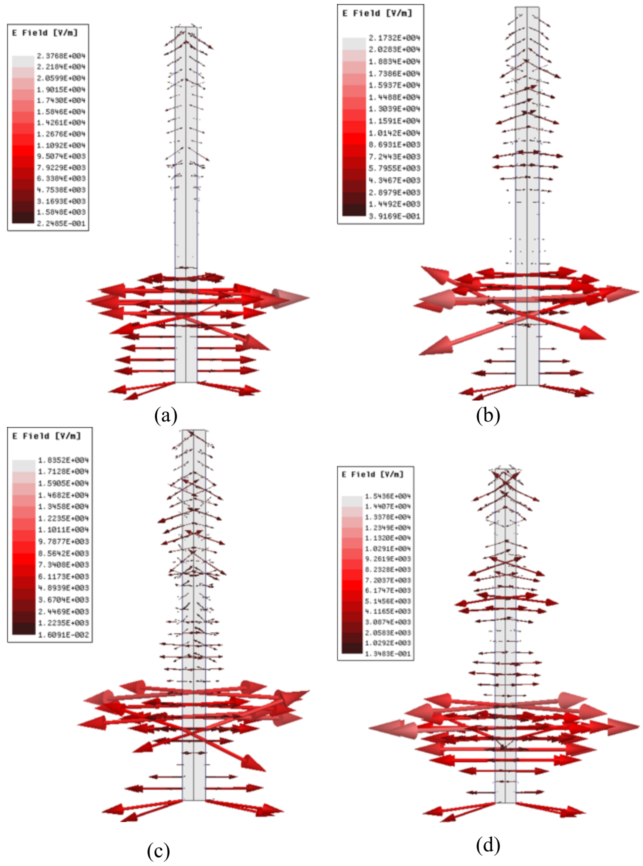

FIGURE 4. Simulated results of the of the E-field at (a) 2.5 GHz, (b) 5GHz, (c) 7.5 GHz, and (d) 10 GHz.

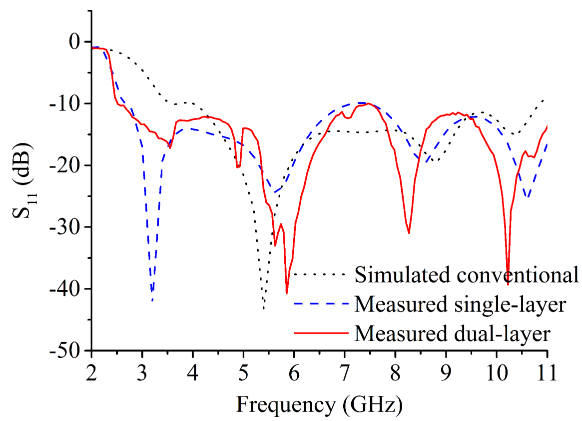

FIGURE 5. S_{11} of the conventional Vivaldi antenna, single-layer Vivaldi antenna and dual-layer Vivaldi antenna.

at 2.5 GHz and 4 GHz are shown in Fig. 3(a) and (b), respectively. As shown in Fig. 3(a), the currents concentrate on the B regions of the proposed antenna at 2.5 GHz. However, for the conventional Vivaldi antenna, the current is mostly distributed around the microstrip taper. This phenomenon indicates that an additional frequency resonance is formed because of the symmetrical slots. At 4 GHz, the surface currents on both antennas are mainly distributing along the A region, which indicates that the symmetrical slots are more effective at lower frequencies.

To further investigate the effects of the dual-layer structure, a transverse E-field perpendicular to the radiation patches is simulated. Some simulation results of the E-field lines are shown in Fig. 4. It is obvious that the symmetrical radiation patches induce an opposing transverse E-field. In this case, the transverse E-field component perpendicular to the radiation patches is counteracted; thus, the cross-polarization is reduced.

A. FREQUENCY-DOMAIN BEHAVIOR

Figure 5 shows the magnitude of S_{11} for the conventional Vivaldi antenna, single-layer Vivaldi antenna, and dual-layer Vivaldi antenna. It can be seen from the figure that the low-end $S_{11} < -10$ dB limitation of the conventional Vivaldi

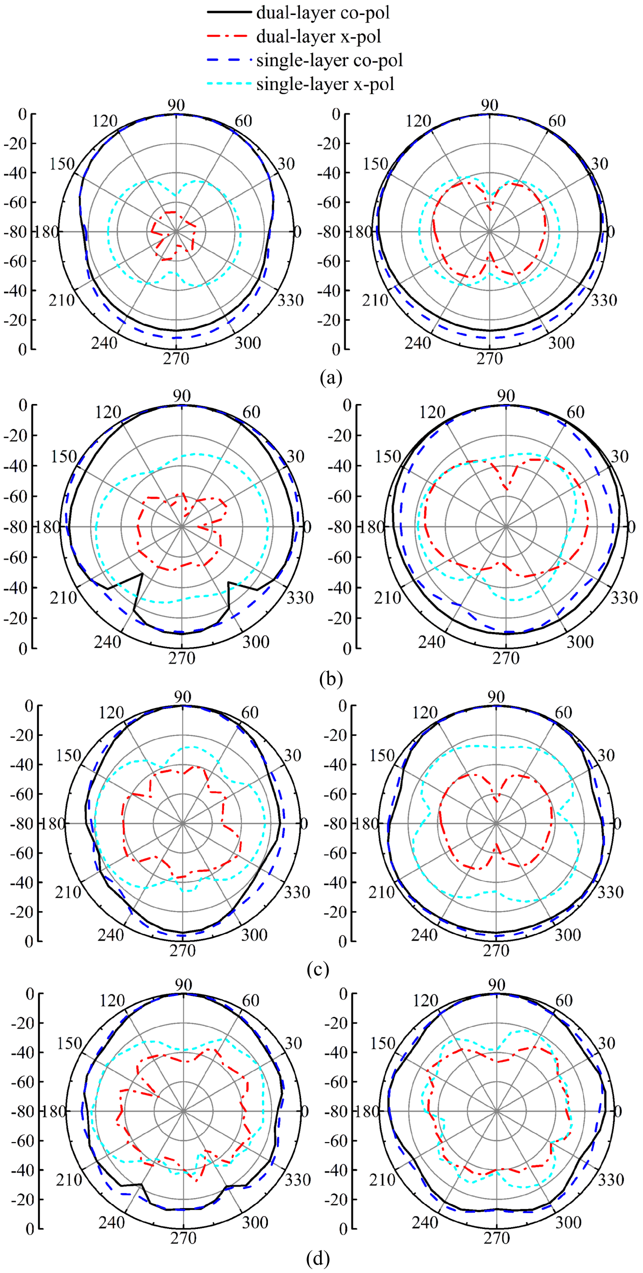

FIGURE 6. Measured normalized far-field radiation patterns for the E-plane (yoz, left side) and H-plane (xoz, right side) at (a) 2.5 GHz, (b) 5 GHz, (c) 7.5 GHz, and (d) 10 GHz.

antenna is 3.5 GHz, while the single-layer Vivaldi antenna and dual-layer Vivaldi antenna extend to 2.5 GHz. It is clear that the modified structure of the proposed Vivaldi antenna could reduce the size of the Vivaldi antenna by lowering the minimum resonance frequency. Furthermore, the impedance bandwidth of the proposed Vivaldi antenna is up to 126% for $S_{11} < -10$ dB, with a range from 2.5 GHz to 11 GHz, which is wide enough to cover the entire UWB band. To demonstrate the radiation performance of the Vivaldi antenna, the normalized far-field radiation patterns of the single-layer Vivaldi antenna and the dual-layer Vivaldi antenna are also measured. Fig. 6 shows the measured normalized far-field

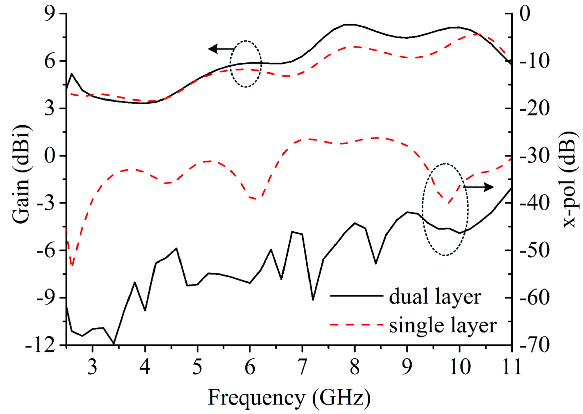

FIGURE 7. Gain and cross-polarization level of single layer- and dual layer- Vivaldi antenna.

radiation patterns for the E-plane (*yoz*) and H-plane (*xoz*) at 2.5 GHz, 5 GHz, 7.5 GHz, and 10 GHz. The single-layer- and dual-layer- Vivaldi antennas have similar co-polarization far-field radiation patterns. Over the operating frequency band, the main lobes of the radiation patterns are fixed in the end-fire direction. At high frequencies, the higher order modes cause a narrowing of the beam width. However, for cross-polarization far-field radiation patterns, the differences are large.

Fig. 7 gives the gain and cross-polarization levels of both the single-layer and dual-layer Vivaldi antennas. It is observed that the gain of both the single-layer- and the dual-layer Vivaldi antennas is up to 4 dBi over the impedance bandwidth. However, the cross-polarization levels of the dual-layer Vivaldi antenna are far lower than those of the single-layer Vivaldi antenna. The cross-polarization levels of the single-layer Vivaldi antenna are below −25 dB over the entire UWB band, while the dual-layer Vivaldi antenna reduces the cross-polarization to −40 dB. At most of the operating frequencies, the cross-polarization levels of the dual-layer Vivaldi antenna are significantly lower than −50 dB. The cross-polarization levels are significantly reduced due to the dual-layer structure.

B. TIME-DOMAIN BEHAVIOR

The IR-UWB system uses very short pulses in time that cover a very broad frequency spectrum. Compared with frequency-domain characterization, time-domain characterization is equally important to the UWB antenna.

Waveform relative cross-polarization in this paper can be defined as the time domain cross-polarization. It describes how the polarization mismatch loss affects the peak of the waveform's amplitude. The waveform relative cross-polarization is written as

$$XPD_{time} = 20\log\left(\frac{\max|v_{x-pol}(t)|}{\max|v_{c-pol}(t)|}\right) \quad (4)$$

where v_{co-pol} represents the receiver antenna output waveform for co-polarization and v_{x-pol} represents the receiver antenna output waveform for cross-polarization.

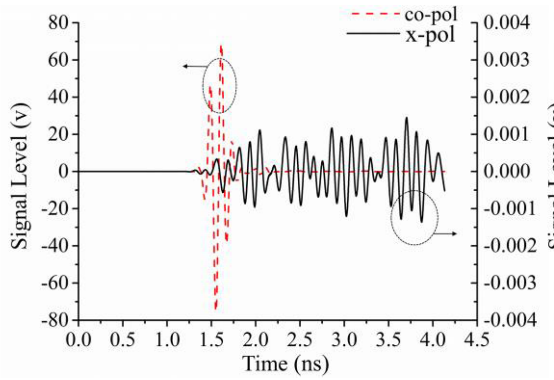

FIGURE 8. Received waveform for co-polarization and cross-polarization.

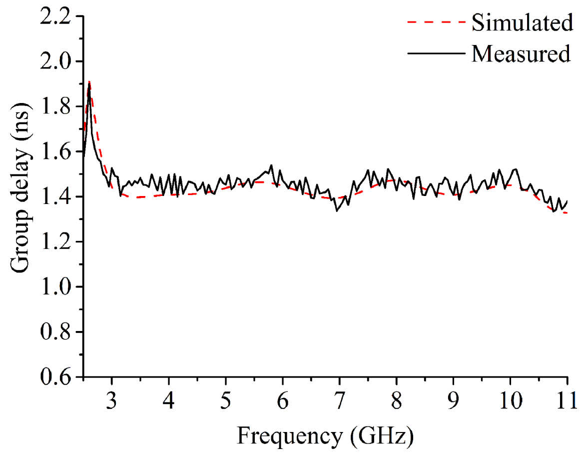

FIGURE 9. Simulated and measured group delay of the proposed antenna.

To analyze the waveform relative cross-polarization performance of the proposed Vivaldi antenna, the input pulse is selected as the Gaussian pulse, which generates a typical UWB pulse. The received waveforms for co-polarization and cross-polarization are shown in Fig. 8. Observing the received signal for cross-polarization, some ringing phenomena exist. The ringing phenomena should result in power loss, which is one way of reducing the waveform relative cross-polarization. In this case, the waveform relative cross-polarization level is reduced to -90 dB.

The group delay describes the pulse distortion from one antenna to the other. Two identical dual-layer Vivaldi antennas are placed face to face separated by 300 mm, and their group delay characteristics are shown in Fig. 9. As shown in the figure, the group time delay is approximately 1.4 ns with a variation of less than 0.5 ns in the UWB band.

The System Fidelity Factor (SFF) is a number that quantifies some types of correlation and dependence, meaning the statistical relationships between the transmission and received pulse signals. It is used to quantify the signal distortion produced by a system composed of two antennas [18]. The SFF can be written as

$$\mathrm{SFF} = \max_{n} \int_{-\infty}^{\infty} v_t(t) v_r(t+\tau) dt \tag{5}$$

Where $v_t(t)$ represents the normalized input pulse and $v_r(t)$ represents the normalized received pulse.

The results of the SFF are between 0 and 1. A value of SFF=1 indicates that the input and received pulse signal are perfectly aligned., while SFF values close to 0 show little to no linear relationship.

The SFF of the proposed antenna is simulated and measured in the axial direction. The simulation result shows that the SFF is 0.92, and the measured result shows that the SFF is 0.86. The results indicate that the proposed antenna has an acceptable waveform distortion.

IV. CONCLUSION

A miniaturized UWB antenna was designed and fabricated in this paper. By inserting slots on the radiation patches, a low frequency resonance is formed. In this way, the relative size of the Vivaldi antenna can be reduced. To achieve a lower cross-polarization characteristic, a dual-layer structure is utilized. Experimental and simulation results demonstrate that the proposed antenna can achieve an impedance bandwidth of approximately 126% ranging from 2.5 GHz to 11 GHz. The size of the proposed antenna is $0.3\lambda_0 \times 0.26\lambda_0 \times 0.02\lambda_0$. The cross-polarization is under -40 dB over the bandwidth. The time-domain response of the proposed antenna is also studied. The results of waveform relative cross-polarization indicate that the proposed antenna has low cross-polarization in the time domain. The results of the group delay and SFF show that the proposed antenna has admirable time domain responses.

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