A Novel Dielectric Loaded Vivaldi Antenna with Improved Radiation Characteristics for UWB Application

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Abstract **─**In this paper, a compact (40×50×0.8mm^3) Vivaldi antenna with trapezoidal corrugation and a triangular director element is proposed for high gain performance. The exponential slot with diamond slot stub is designed to broaden the bandwidth. The measured bandwidth is 11.3 GHz from 2.9 to 14.2 GHz under the condition of Voltage Standing Wave Ratio (VSWR) less than 2. The simulated gain is 5.5-9 dBi at the full bandwidth. The measured gain is 5-7.6 dBi from 3 to 5.8 GHz. In addition, the measured group delay of the proposed antenna is around 2±0.8 ns. The simulated and measured results agree well.

Index Terms **─** Diamond cavity, dielectric loaded, gain enhancement, Vivaldi antenna.

I. INTRODUCTION

Since the Federal Communications Commission (FCC) declaration of the frequency band 3.1 to 10.6 GHz for commercial communication applications in 2002, inexpensive realization of ultra-wideband (UWB) systems have become one of the key topics in the industry worldwide [1]. Vivaldi antenna has been designed and researched due to its natural wide impedance bandwidth, low cross polarization and end-fire radiation characteristic [2-4]. However, Vivaldi antenna is facing many challenges including miniaturization, good radiation performance, high gain and stable group delay through the entire band.

Facing the above challenges, there have been quite a few reported methods. In [5], two pairs of eye-shaped slots at outer edges is used to concentrate the current along the inner edges to improve the performance. In [6, 7], dielectric is loaded to enhance the gain and improve the radiation performance. In [8], the artificial material with lower effective refractive index acts as a regular lens in beam focusing. In [9], six periodic metallic strips in middle of tapered slot are added to improve gain. In [10], resistive loading Vivaldi antenna is designed to enhance bandwidth by the high chip resistor and short pin. In [11], a hybrid loaded with patches, resistors and the split-ring resonator (SRR) structure is used to extend the low-end bandwidth limitation. The resistor loaded method can effectively broaden the bandwidth but reduce the gain.

In this paper, a compact and high gain Vivaldi antenna is proposed for UWB application. The four kinds of Vivaldi antennas are designed and compared in this paper. Antenna B is obtained by loading trapezoidal corrugation at outer edges of original antenna (antenna A). Antenna C is achieved by extending the substrate of antenna B and adding a triangular metallic element as director to enhance the gain. Finally, antenna D is proposed by designing a diamond slot stub instead of circular one to broaden the impedance matching at low-end frequency band. The measured bandwidth of proposed antenna is 2.9 GHz to 14.5 GHz under the condition S_{11} < -10 dB. The simulated gain of antenna D has been increased by 2-4 dB over full UWB compared with original antenna.

II. DIELECTRIC LOADED ANTENNA DESIGN AND SIMULATION

A. Dielectric loaded Vivaldi antenna

The configurations of three types of Vivaldi antennas are shown in Figs. 1 (a)-(d). The original antenna (antenna A) consists of exponential slot, microstrip feeding line, and the microstrip line to slotline transition, as shown in Figs. 1 (a)-(b). In Fig. 1 (c), symmetrical trapezoid-shaped slots are etched on the outer edges, which formed antenna B to concentrate the current along inner edge. In Fig. 1 (d), the dielectric substrate is extended 10 mm and the triangular metallic element is added in the middle of radiating slot as a director to enhance the gain in antenna C.

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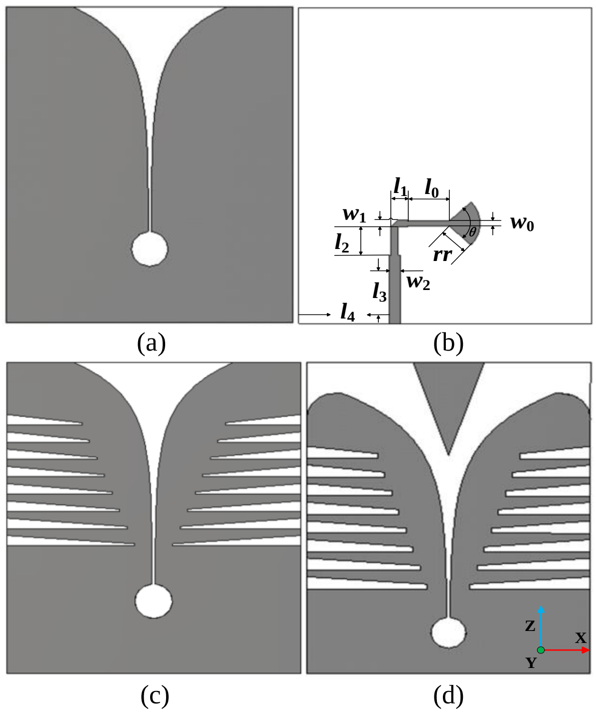

Fig. 1. Geometry of the Vivaldi antenna: (a) bottom view of antenna A, (b) top view of antenna A, (c) tottom view of antenna B, and (d) bottom view of antenna C.

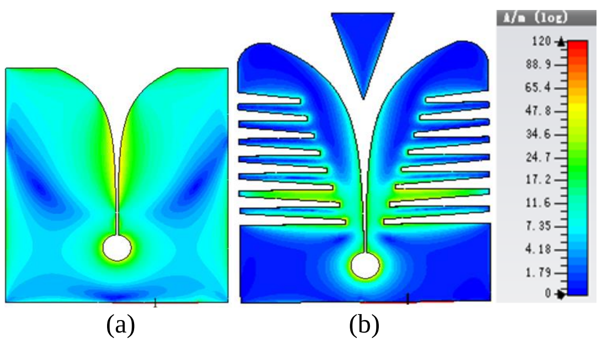

Fig. 2. Simulated surface current distribution at 3.5 GHz of (a) antenna A and (b) proposed antenna.

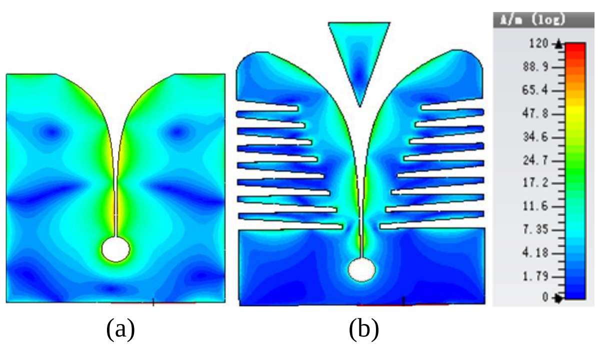

Fig. 3. Simulated surface current distribution at 10 GHz of (a) antenna A and (b) antenna C.

The performance of the designed antenna is simulated using the simulation tool HFSS v16. In order to further understand the operating characteristic of the antenna C at the low frequencies, surface current distribution of both the original (antenna A) and antenna C at 3.5 GHz and 10 GHz are given in Figs. 2-3, respectively. We can see that the surface current concentrated along the inner edges of exponential slots and the trapezoid-shaped slots. However, for the antenna A, the current is mostly distributed around the exponential slots. This phenomenon indicates that lower frequency resonance is formed because of the trap ezoid-shaped slots. In Fig. 3 (b), the surface current distribution is stronger at the triangular metallic element, which acts as director at high-end frequency to improve the gain.

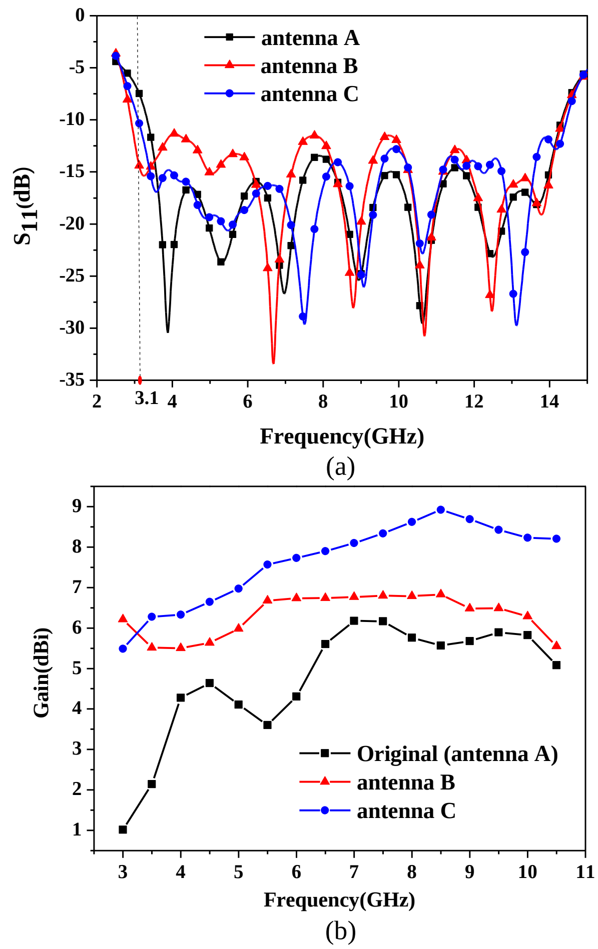

Fig. 4. The simulated performance of three Vivaldi antennas: (a) simulation of peak realized gain versus frequency, and (b) simulation of S_{11} versus frequency.

Figure 4 (a) illustrates the S_{11} variation of the antenna A, antenna B, and antenna C. As shown in the figure, the lower end $S_{11} < -10$ dB limitation of antenna A is 3.5 GHz, while the antenna B is to 2.9 GHz. It means that the antenna B is able to miniaturize the size of Vivaldi antenna by lower frequency. In Fig. 4 (b), then we can see that the simulated gain of antenna C has been enhanced by 1-3 dB compared with antenna B and has been enhanced by 2-4 dB compared with antenna A. That caused by extending the substrate which acts as a regular lens in beam focusing. The triangular metallic element is effectively concentrated the currents to improve gain at high-end frequency. But extending the dimension of the substrate deteriorates the bandwidth at low-end frequency band. Compared to antenna B, the low-end frequency band of antenna C is shifted from 2.9 to 3.1 GHz.

B. Dielectric loaded Vivaldi antenna with the diamond cavity

The gradient slot line can achieve a wide impedance bandwidth characteristics. So the microstrip line to slotline transition is the main limit of impedance bandwidth in Vivaldi antenna. Aiming for broaden the impedance matching bandwidth at low-end frequency, the diamond slot stub is designed to replace circular one in transition structure, as shown in Fig. 5 (the blue dashed rectangle). And its equivalent circuit of microstrip line to slotline transition is shown in Fig. 4. In Fig. 6 (a), Z_{om} and Z_{os} are the characteristic impedance of microstrip line and slotline, respectively. C_{oc} represents the equivalent capacitor of the microstrip open end and L_{os} represents inductance of the slot line short end. θ_m and θ_s are the electrical length of extension of the opened microstrip and shorted slotline at central frequency, respectively. The open-circuit microstrip stub and the short-circuit slotline are represented as:

$$X_m^{in} = jX_m = Z_{om}\frac{1/jw\cdot C_{os} + jZ_{om}\tan\theta_m}{Z_{om} + \tan\theta_m / wC_{oc}}, \tag{1}$$

$$X_s^{in} = jX_s = Z_{os}\frac{jL_{os} + jZ_{os}\tan\theta_s}{Z_{os} - L_{os}\tan\theta_s}. \tag{2}$$

When $3.8 \le \varepsilon_r \le 9.8$, $0.006 \le d/\lambda_0 \le 0.06$, and $0.0015 \le ll/\lambda_0 \le 0.075$, the characteristic impedance of the slotline is [12]:

$$\begin{aligned} Z_{os} &= 73.6 - 2.15\varepsilon_r + (638.9 - 31.37\varepsilon_r)(ll/\lambda_0)^{0.6} \\ &+ (36.23\sqrt{\varepsilon_r^2 + 41} - 255)\frac{ll/h}{(ll/h + 0.876\varepsilon_r - 2)} \\ &+ 0.51(\varepsilon_r + 2.12)(ll/h)\ln(100h/\lambda_0) \\ &- 0.753\varepsilon_r(h/\lambda_0)/\sqrt{ll/\lambda_0}, \end{aligned} \tag{3}$$

ll and λ_0 is the width of the slot, substrate height and free space wavelength.

The simplified equivalent transmission line model of transition structure is shown in Fig. 6 (b), where,

$$R = n^2 Z_{os} X_s^2 / (Z_{os}^2 + X_s^2), \tag{4}$$

$$X = n^2 Z_{os}^2 X_s / (Z_{os}^2 + X_s^2). \tag{5}$$

Γ of the antenna can be expressed as:

$$\Gamma = \frac{R - Z_{om} + j(X_m + X)}{R + Z_{om} + j(X_m + X)}. \tag{6}$$

In Equation (6), the value of X_m and X_s affects the antenna bandwidth, and X_m is close to zero. If we increase the value of X_s, both the value of X and Γ will be reduced. The antenna bandwidth will be improved. From Fig. 7 we can see that X_s of diamond slot stub is larger than the circular one. In this paper the circular slot stub is replaced by diamond slot stub to enhance the low-end frequency bandwidth. The final optimized dimensions of the proposed antenna are given in Table 1.

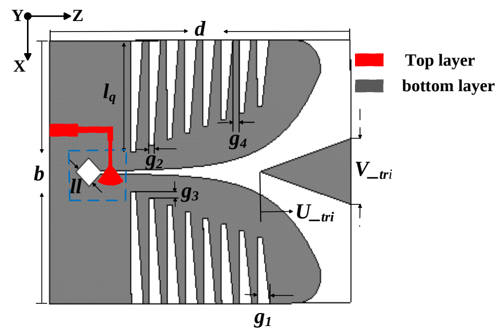

Fig. 5. Bottom view of the proposed antenna.

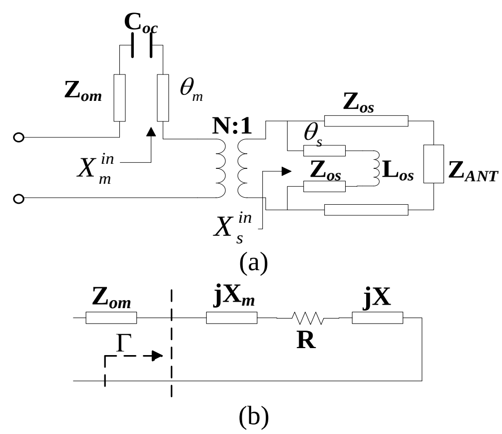

Fig. 6. Equivalent circuit of the microstrip line to slotline transition: (a) equivalent circuit, and (b) simply circuit.

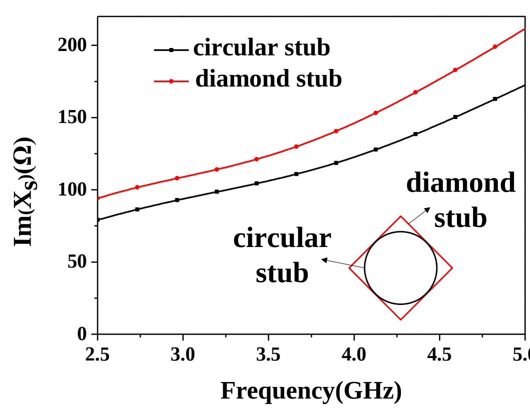

Fig. 7. Simulated Im (X_s) of the diamond and circular slot stub.

Table 1: The optimal dimensions of the proposed antenna (Unit: mm)

Parameters	Value	Parameters	Value
b	40	d	50
W_0	0.8	W_1	1
W_2	1.5	W_3	0.4
rr	4.5	ll	3
L_q	17	L_0	5.6
L_1	1.2	L_2	4
L_3	3.8	L_4	12.6
g_1	1.5	g_2	0.8
g_3	1	g_4	1
$U_{\_tri}$	15	$V_{\_tri}$	10
θ	86°		

III. RESULTS AND DISCUSSIONS

The proposed coplanar fed broadband antenna has been prototyped for the verification and measured using Keysight PNA-X network analyzer. The fabricated prototype of the proposed antenna is shown in Fig. 8. The simulated reflection coefficients for the antenna C and the proposed antenna are compared in Fig. 9. It can be seen that the simulated impedance bandwidth of proposed antenna and antenna C are 11.6 GHz (2.9-14.5 GHz) and 11.4 GHz (3.1-14.5 GHz), respectively. The measured impedance bandwidth is 11.4 GHz (2.8-14.2 GHz). The simulated and measured results agree well. From Fig. 10, it can be seen that the simulated gain of proposed antenna stably varies from 5.5 to 8.9 dBi, which has been increased by 2-4 dB compared with original (antenna A). Due to the test frequency limitation of the anechoic chamber, the gain is measured only in 3-5.8 GHz. It is observed that the measured gain is 5-7.6 dBi and the simulation and measurement results agree well.

The group delay is measured by using two proposed antennas placed in end-to-end orientation in far field at a distance of 40 cm, as shown in Fig. 11. It is observed that the group delay of the proposed antenna is about 2±0.8 ns in the operating UWB frequency band, as shown in Fig. 12. The simulation and measurement results agree well. The proposed antenna have good end-fire radiation at 3 GHz and 5 GHz.

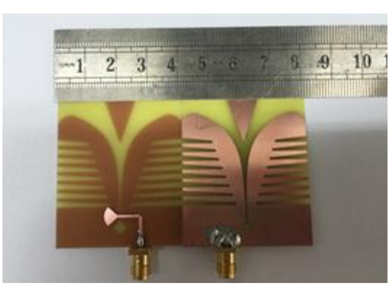

Fig. 8. Photographs of the fabricated proposed antenna.

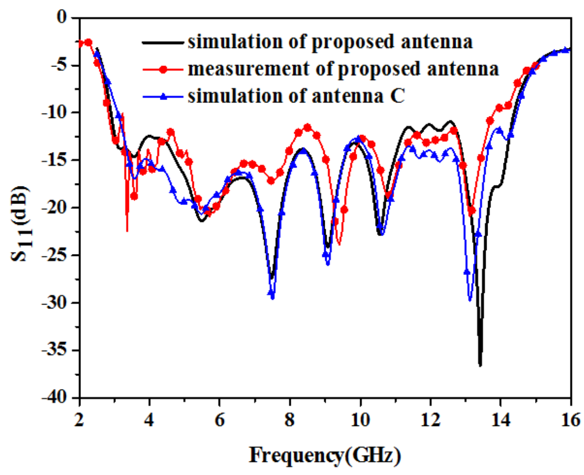

Fig. 9. S_{11} results of proposed antenna and antenna C.

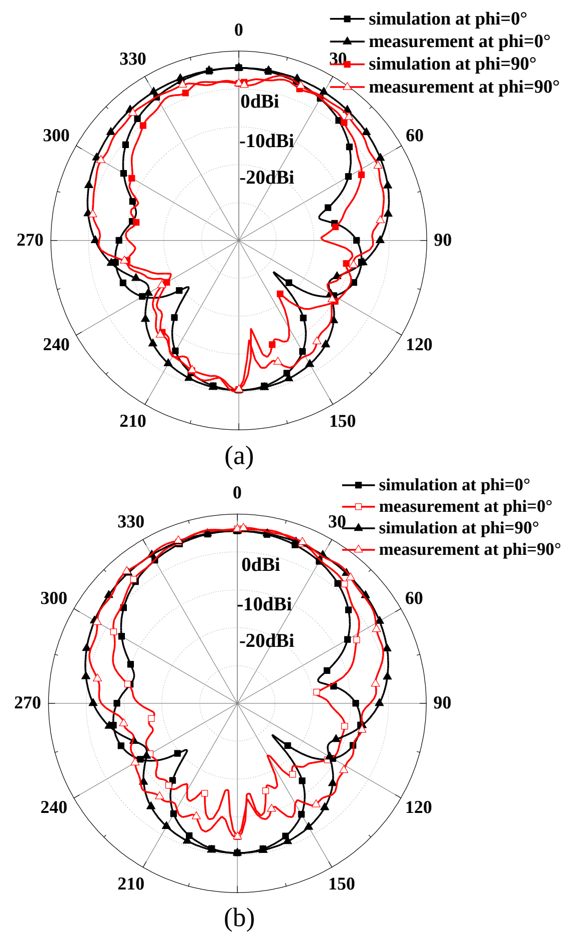

Fig. 10. The simulation and measurement of the radiation pattern: (a) 3 GHz and (b) 5 GHz.

From Table 2, it's demonstrated that the proposed antenna provides compact size and good radiation performance.

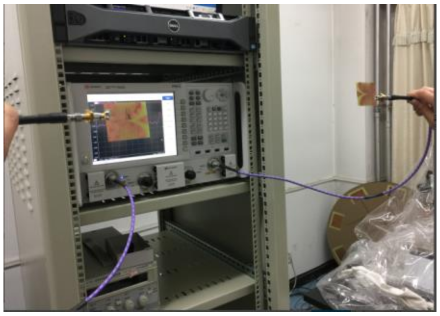

Fig. 11. The group delay measured environment.

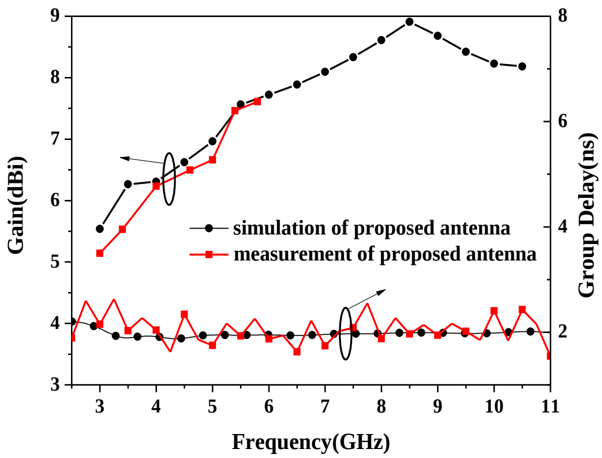

Fig. 12. Measured and simulated results of peak realized gain and group delay for proposed antenna.

Table 2: Performance comparison of the proposed antenna with references

Reference		Dimensions (mm^3)	Bandwidth (GHz)	Gain (dBi)
[5]		36×36×0.8	3-12.5	4-8
[6]		42×77×1	6-19	7.2-12
[7]		40×90×0.508	3.4-40	6-14
[8]		62×70×0.5	1-20	0.9-7.8
[9]		40×82×1	0.58-6.72	-
This work	Antenna A	40×40×0.8	3.5-14.2	1-5.2
	Antenna B	40×40×0.8	2.9-14.5	5-5.5
	Antenna C	40×40×0.8	3.1-14.2	5.5-9
	Proposed antenna	40×50×0.8	2.8-14.2	5.5-9

VI. CONCLUSION

A compact UWB antenna is proposed by loading dielectric and triangular metallic element, etching trapezoidal corrugations to enhance the gain. The low-end frequency band is improved by replacing circular slot stub with diamond one. The proposed antenna yields an impedance bandwidth of 11.4 GHz (2.8-14.2 GHz) under the condition of S_{11} less than -10 dB. The simulated peak gain varies from 5.5 to 9 dBi from 3-10.6 GHz. The measured peak gain varies from 5 to 7.6 dBi from 3-5.8 GHz. The measured group delay of the proposed antenna is around 2±0.8 ns. Both the simulated and measured results agree well. The proposed antenna has good potential for UWB communication applications.

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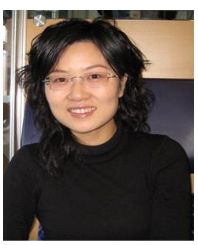

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