Design of a Novel Miniaturized Vivaldi Antenna with Loading Resistance for Ultra Wideband (UWB) Applications

Yongzhong Zhu [*1], Daoyi Su [2], Wenxuan Xie [1], Zihao Liu [1], and Kaiwei Zuo [1]

[1] Department of Information Engineering
Engineering University of PAP, Xi'an, Shanxi, 710086, P. R. China
*bsbs1980@sina.com, 184753211@qq.com, 33591232@qq.com, zkwcapf@163.com

[2] Guangdong Mikwave Communication Tech. LTD
Guangzhou, Guangdong, 510700, P. R. China
510727155@qq.com

Abstract ─ A compact improved Vivaldi antenna working on 0.8-3.8 GHz was designed by using resistance-loaded and slotting technology. Resistance-loaded can reduce the plane size of antenna and three symmetrical unequal rectangular slots in the antenna radiation part can increase the gain. The improved Vivaldi antenna size is 150×150×0.508 mm^3, which can be used in ground penetrating radar. The simulation results and experimental results are presented to validate the performance of the proposed improved structure of Vivaldi antenna.

Index Terms ─ ETSA, loading resistance, UWB antenna, Vivaldi antenna.

I. INTRODUCTION

An exponentially tapered slot antenna (ETSA), which was firstly described by Gibson in 1979 [1], has been widely studied and applied due to its simple structure, light weight, wideband, high efficiency and high gain. It has been utilized in many ultra wideband (UWB) applications such as ground penetrating radar, UWB communication systems, UWB imaging system, etc. Theoretical and experimental analysis of various Vivaldi antenna characteristics can be found in [2]–[16].

In the tapered slot-line antenna, Vivaldi antenna has infinite bandwidth in theory [2], and therefore it gets wide application and research. However, the actual prepared Vivaldi antenna always has limited bandwidth. There are two main reasons: one is its feed structure limits that it can only achieve resonance in a limited bandwidth; the other is the maximum exponential type slot width of Vivaldi antenna determines the maximum electric length of antenna, and limits the lowest working frequency. Therefore, currently a lot of studies focus on the design of Vivaldi antenna above 3 GHz.

According to the structure of the radiating element, Vivaldi antenna can be divided into three categories: Vivaldi antenna [3, 4], antipodal Vivaldi antenna [6], and balance antipodal Vivaldi antenna [7]. In [3], it adopted coplanar waveguide feed to improve the VSWR of low frequency. In [4], in order to make miniaturization, it also improved the feeding part. It increased the area of feeding part and adopted feed with stepped structure. In [5] and [6], they made improvement on radiation part. The antenna in [5] opened unequal semicircle slots while that in [6] opened multiple rectangular slots on the edge of the radiation part, so as to improve antenna gain. The antenna in [7] adopted the method of increasing the length of the dielectric substrate to improve the directivity, and so on. Compared with several antennas, the antennas in [3] and [4] do better in miniaturization, but somewhat lacking in direction and gain, the antennas in [5-7] have higher antenna gain, while make some sacrifices in miniaturization.

In order to further reduce the size of the Vivaldi antenna, some scholars have put forward many new ways to improve the miniaturization of these structures. A tapered slot edge with resonant cavity (TSERC) structure is adopted to improve the design of a planar printed conventional Vivaldi antenna in [8], the low-end cutoff frequency of the TSERC structure is further reduced with the same antenna size. In [9], the gain and the impedance bandwidth are significantly improved by using two pairs of eye-shaped slots, especially at the low frequencies. In [10], structural modifications in the radiating fins of the antipodal Vivaldi antenna can reduce the lower operating frequency from 5.2 GHz to 3.7 GHz and achieve 28.8% size reduction without altering the dimensions. In [11], an UWB miniaturized antipodal Vivaldi antenna (AVA) with two pairs of tapered slot and two circularly shaped conductor is presented, its feed structure adopts the transition from broadside parallel stripline to CPW which makes it easily being integrated with RF circuit. The antenna in [12] adopts the method of modifying corrugated balanced antipodal Vivaldi structure with director to improve the directivity and

Submitted On: June 12, 2017
Accepted On: August 12, 2017

impedance matching of low frequency.

This paper proposes an improved structure of Vivaldi antenna, which loads resistance at the bottom of exponential type antenna to improve voltage standing wave ratio (VSWR) at low frequency, and opens three symmetrical unequal rectangular slots in the antenna radiation part to increase the gain. The proposed antenna has the impedance bandwidth of 0.8-3.8 GHz and is proper for UWB applications. Also, the improvement of antenna gain at 0.8-1.5 GHz band is very obvious. The maximum gain at 3.8 GHz is 8.1 dB. The simulation and analysis of the proposed antenna is performed by using HFSS. The simulated and measured results are in good agreement and validate the design approach.

II. ANTENNA DESIGN

Traditional Vivaldi antenna can be divided into three parts: feeding part, transition part and radiation part. Figure 1 (a) shows the structure of traditional Vivaldi antenna.

Based on the traditional Vivaldi antenna, Fig. 1 (b) shows a Vivaldi antenna with loading resistor. A chip resistor is loaded on the new antenna, and a short circuit pin is utilized at the one end of the feeding line. The Vivaldi antenna in this paper loads resistance at the bottom of the exponential-type slot in the feeding part, and opens three unequal rectangular slots on both sides in the radiation part. Among them, loading resistance is to improve the feeding structure, so that the antenna can better match in low frequency band and increase the degree of miniaturization. Slotting is to improve the low frequency gain and to strengthen the directionality. Figure 1 (c) shows the structure of resistive loaded and three unequal rectangular slotted Vivaldi antenna. The dielectric substrate used in the designed antenna is FR-4, whose relative dielectric constant is 4.4 and thickness is 0.508 mm. The size of the substrate is 150×150 mm^2 (L×B). Feeding mode adopts microstrip line feed, which is located under the substrate.

The equivalent circuit model of the proposed new antenna is given in Fig. 2, where jX_m denotes the equivalent inductance of the pin; jX expresses the equivalent reactance brought by the discontinuity of the slotline. All of the circuit elements are transformed to the input of the microstrip, and the following equations can be deduced:

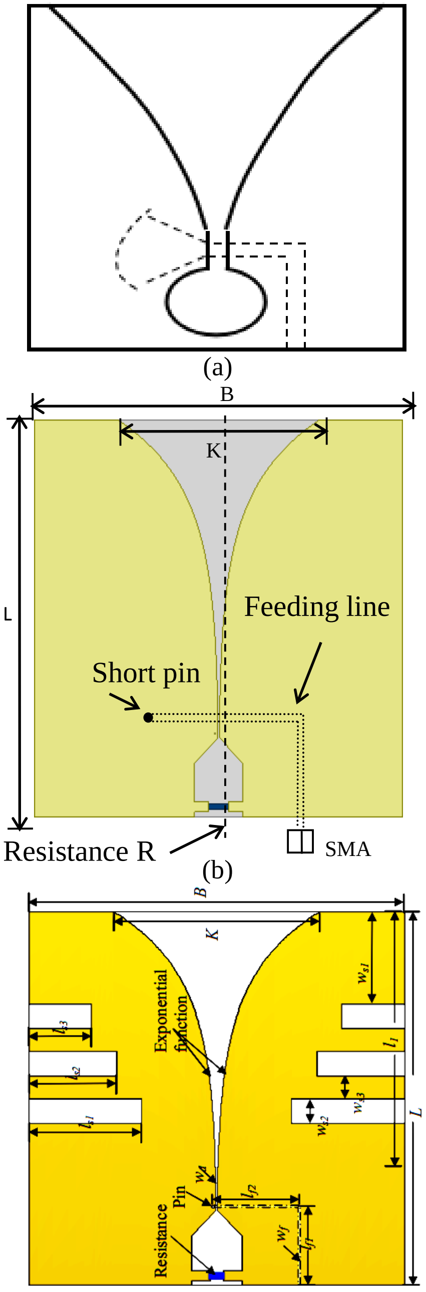
$$R_S = n^2 \frac{R^2 + Z_{Ant} R + X^2}{(R + Z_{Ant})^2 + X^2} Z_{Ant}, \tag{1}$$

$$X_S = n \frac{Z_{Ant}^2 X}{(R + Z_{Ant})^2 + X^2}. \tag{2}$$

It is indicated by (2) that the value of X_S can be greatly reduced if $R \gg Z_{Ant}$. On the other hand, the inductance of the short circuit pin is so small that it can be neglected. Therefore, the reflection coefficient can be expressed as:

$$\Gamma_{in} \approx \frac{R_s - Z_{om}}{R_s + Z_{om}}. \tag{3}$$

At the aspect of energy distribution, the power consumed by the chip resistor is little while it is far higher than radiation impedance, for the resistance is parallel with the antenna radiation part.



(a)

(b)

(c)

Fig. 1. Modification process of designed antennas: (a) traditional Vivaldi antenna (Ant.0); (b) a Vivaldi antenna with a chip resistor (Ant.I); (c) a novel Vivaldi antenna with a chip resistor and three unequal rectangular slots (Ant.II).

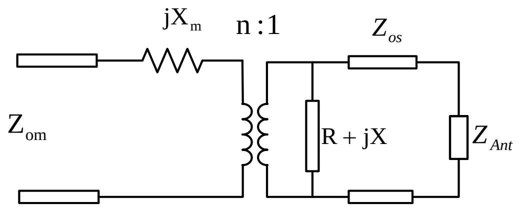


Fig. 2. Equivalent transmission line model of Fig. 1.

III. SIMULATION AND TEST OF ANTENNA

Ansoft HFSS15 is used to simulate, analyze and optimize the parameters of the antenna. When other parameters are constant, the effects of a single parameter on antenna performance are observed.

A. The influence of dielectric substrate thickness h on antenna performance

The change of substrate thickness *h* will directly affect the radiation conductance of antenna and the quality factor Q changes accordingly. The greater of the *h*, the smaller of Q value it is, the wider of frequency band is, but at the same time the surface wave will be more intensified. So only choosing appropriate thickness can ensure the comprehensive performance of the antenna.

Figure 3 is the influence of substrate thickness *h* on antenna return loss (S_{11}). It can be known from Fig. 3 that, when the thickness of *h* increases, the lowest frequency will be decreased. Therefore, the optimal value $h = 0.5$ mm is obtained.

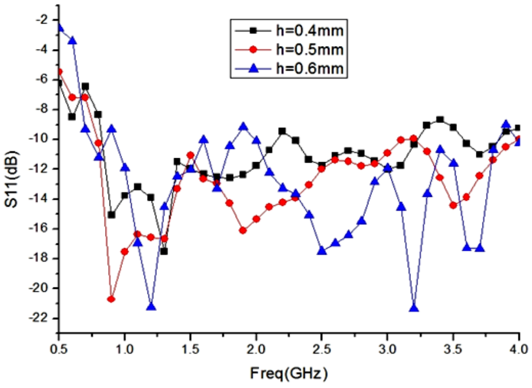


Fig. 3. The influence of substrate thickness h on S_{11}.

B. The influence of loading resistance R on antenna performance

Figure 4 shows the influence of the loading resistance value *R* on S_{11}, when Resistance value *R* respectively is 200 Ω, 300 Ω and 400 Ω. It can be known from the figure that, the lowest frequency basically remains unchanged when the resistance of the loading resistance changes. When $R = 200$ Ω, the performance will be worsen sharply at around 1.5 GHz and 2.7 GHz, this is caused by impedance mismatching at the higher frequency due to the small resistance. When $R = 300$ Ω or 400 Ω, the performances are very similar. However, when the bottom resistance value is greater, the antenna current will be decreased and the radiation efficiency is lower. Moreover, this paper selects SMD resistor with specifications of 2512, resistance of 331 Ω.

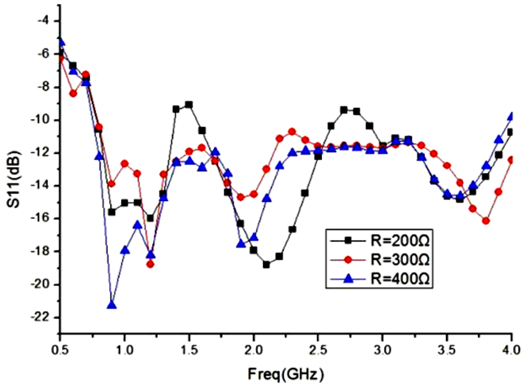


Fig. 4. The influence of resistance R on S_{11}.

C. The influence of the position of rectangular slots in radiative part on antenna performance

There are many parameters of rectangular slots. This paper is focused on its location. In Fig. 5 it shows that when the slot position is closer to the top of the exponential-type slot, the bandwidth of the antenna is more quickly decreased. If the slot position reaches a certain distance, the performance of the antenna will not change much. But with the continuing increase in distance, the performance of antenna working on about 3.2 GHz will decline. Therefore, the optimal value $w_{s1} = 37$ mm is obtained.

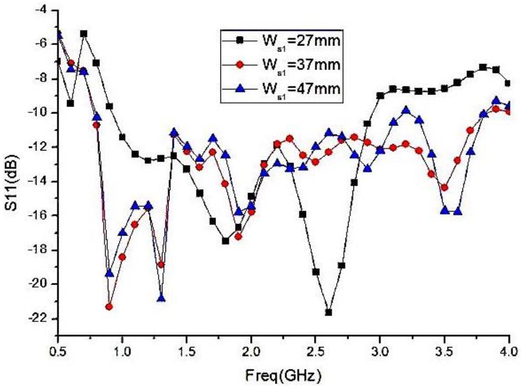


Fig. 5. The influence of slot position w_{s1} on S_{11}.

In addition to the above parameters optimized in the process of simulation experiment, other parameters also make further optimization such as feeding line width w_f, three rectangular slot lengths l_{s1}, l_{s2}, l_{s3}, three rectangular slot width w_{s2} and spacing distance w_{s3} between the rectangular slots. The final optimization results of the various parameters of antenna are shown in Table 1.

Antenna I is a Vivaldi antenna that only loads resistance at the bottom and antenna II is a Vivaldi antenna that both loads resistance and rectangular slots. After improvement, the antenna II improves the current distribution. First, the structure suppresses the edge current of the antenna, resulting in an increase in the current density of the antenna, and the current is more concentrated in the vicinity of the exponential-type slot. Second, reducing the current through the resistor in the low frequency band of the antenna, the performance has been improved. Thirdly, near the open gradient slot line, the original surface current is changed to be distributed along the trough line, so that the equivalent size of the antenna is relatively increased; thereby these methods result in declining the low frequency cutoff frequency and playing a miniaturization effect.

Table 1: Final optimization results of the parameters of antenna (Unit: mm)

L	150	w_f	0.8	l_{s1}	45	w_{s1}	37
B	150	l_{f1}	32	l_{s2}	35	w_{s2}	10
K	82	l_{f2}	30	l_{s3}	25	w_{s3}	9
l_1	103	w_d	0.8	h	0.5	R (Ω)	331

Figure 6 shows a comparison of the simulated radiation efficiency of antenna 0, antenna I and antenna II. Antenna II optimizes the antenna's low frequency band (0.8 to 1.5 GHz) performance by using the method of slotting. Especially at the frequency of 0.8 GHz, the radiation efficiency improves from the original 48% to 59%.

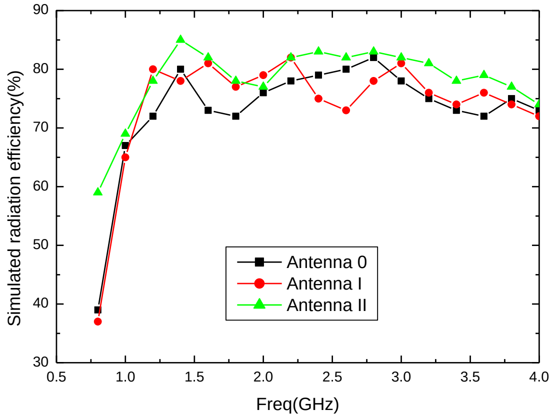


Fig. 6. The comparison of the simulated radiation efficiency of antenna I and antenna II.

In order to further verify the working performance of antenna, it prepares material object through accurate processing according to the optimal data. Figure 7 shows the picture of the antenna. The curves of the measured and simulated results are shown in Fig. 8 and Fig. 9.

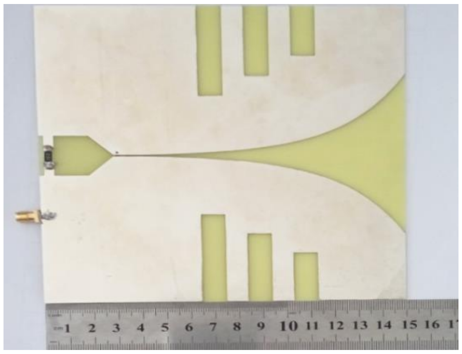


Fig. 7. Picture of the antenna.

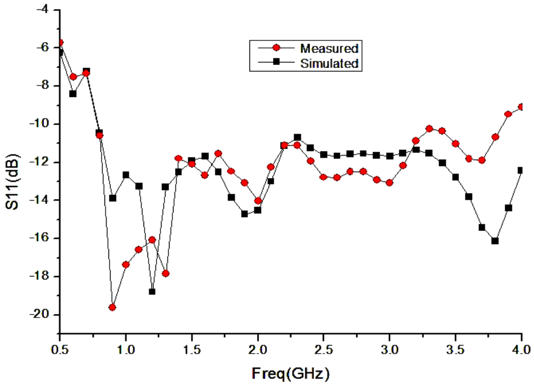


Fig. 8. Measured and simulated results for S_{11} of the antenna.

Table 2: The size and performance of the Vivaldi antennas

Ref.	Dimensions (mm^3)	O.W.B. (GHz)	Length/ λ_L	Width/ λ_L	Freq. (GHz)/ Gain (dB)
4	41×48×0.8	3-15.1	0.41	0.48	3.5/5 14/5.5
5	52×145×0.508	3.1-10.6	0.52	1.45	3/3.5 11/12.5
6	50×66.4×1	4-30	0.67	0.89	4/5 30/5
7	50×166×3.15	3-18	0.50	1.66	3.5/2 18/12
This work	150×150×0.508	0.8-3.8	0.40	0.40	0.8/2.4 2.8/6.1 3.8/8.1

Note: "O.B.W." states the operating bandwidth; " λ_L " is the wave length of minimum frequency in bandwidth.

It can be known from Fig. 8 that, the measured antenna impedance bandwidth is 0.8-3.8 GHz. The measured and simulated curves are almost identical. Compared with the simulation results, the measured curve will be slightly up at high frequencies around 3.5 GHz. Figure 9 shows the simulated and measured antenna pattern. It can be known from figure that the simulation results are consistent with the measured results, so the antenna has stronger directivity within the scope of the bandwidth. Because of the inevitable effects of factors such as process error and test environment, measured results are not as ideal as simulation results, but on the whole, error is within the allowed range. The proposed novel Vivaldi antenna maintains realized gain between 2.4 dB to 8.1 dB. The parameters performance of the Vivaldi antennas in [4-7] and the designed antenna in this work parameters performance is roughly summarized in Table 2. Implementation of this method does not require any additional layers and simple structural modifications are used to achieve better performance.

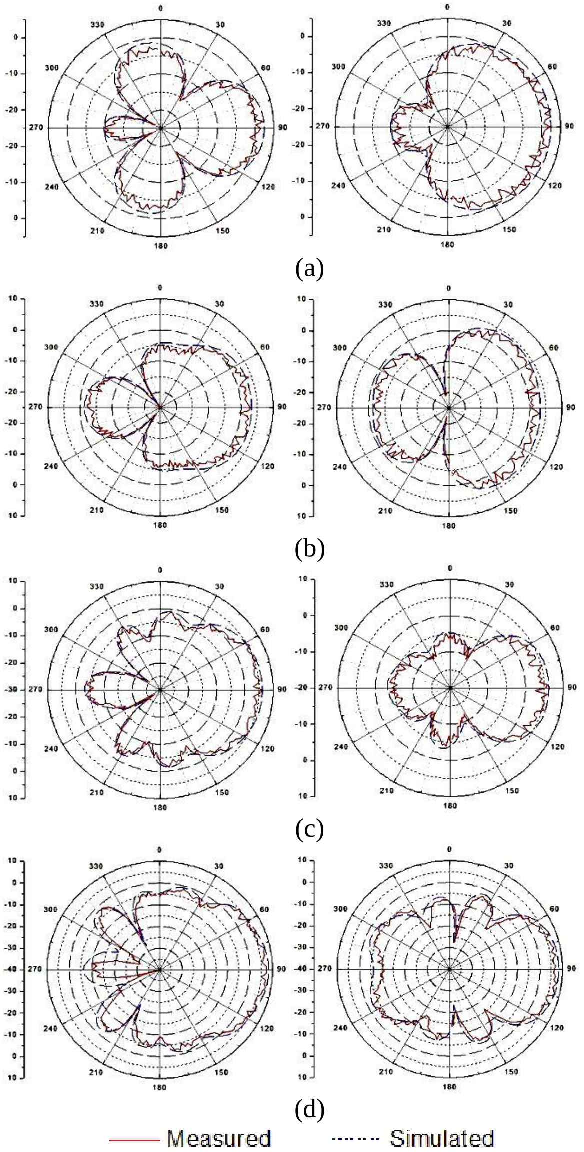


Fig. 9. The radiation patterns of the antenna at E-plane (left) and H-plane (right) at: (a) 0.8, (b) 1.8, (c) 2.8, and (d) 3.8 GHz.

IV. CONCLUSION

This paper designs and prepares a new type of Vivaldi antenna with the dimensions of 150×150×0.508 mm^3. The antenna adopts the loading resistance and opening unequal rectangular slots to optimize traditional Vivaldi antenna, which realizes the design objective of ultra-wideband, good directionality, and low frequency. In addition, it can be known from simulation and measure that the impedance bandwidth of the antenna is 0.8-3.8 GHz. Moreover, the measured results show that the antenna has good work performance and certain practical values.

ACKNOWLEDGMENT

This work was supported by the National Natural Science Foundation of China (No. 61302051 and No. 61771490), the Basic Research Program of ENGG University of the Chinese People Armed Police Force (No. WJY201606).

REFERENCES

[1] L. Lewis, M. Fassett, and J. Hunt, “A broadband stripline array element,” *IEEE Antennas and Propagation Society International Symposium*, pp. 335-337, June 1974.

[2] M. Chiappe and G. L. Gragnani, “Vivaldi antennas for microwave imaging: Theoretical analysis and design considerations,” *IEEE Transactions on Instrumentation and Measurement*, vol. 55, no. 6, pp. 1885-1891, Nov. 2006.

[3] J. Shao, G. Fang, Y. Ji, K. Tan, and H. Yin, “A novel compact tapered-slot antenna for GPR applications,” *IEEE Antennas and Wireless Propagation Letters*, vol. 12, no. 1, pp. 972-975, Aug. 2013.

[4] J. Wu, Z. Zhao, Z. Nie, and Q. H. Liu, “A printed UWB Vivaldi antenna using stepped connection structure between slotline and tapered patches,” *IEEE Antennas and Wireless Propagation Letters*, vol. 13, no. 1,pp. 698-701, Apr. 2014.

[5] D. M. In, S. Pyo, H. S. Lee, M. J. Lee, and Y. S. Kim, “Antipodal linearly tapered slot antenna using unequal half-circular slotted sides for gain improvements,” *Microwave Conference Proceedings (APMC), 2010 Asia-Pacific*, Yokohama, pp. 2036-2039, Mar. 2010.

[6] G. Teni, N. Zhang, J. Qiu, and P. Zhang, “Research on a novel miniaturized antipodal Vivaldi antenna with improved radiation,” *IEEE Antennas and Wireless Propagation Letters*, vol. 12, no. 2, pp. 417-420, Mar. 2013.

[7] A. Molaei, M. Kaboli, S. A. Mirtaheri, and M. S. Abrishamian, “Dielectric lens balanced antipodal Vivaldi antenna with low cross-polarisation for ultra-wideband applications,” *IEEE Microwaves,*

Antennas & Propagation, vol. 8, no. 14, pp. 1137-1142, Nov. 2014.

[8] M. OstadRahimi, L. Shafai, and J. LoVetri, “Analysis of a double-layered Vivaldi antenna inside a metallic enclosure,” *Progress In Electromagnetics Research*, vol. 143, pp. 503-518, 2013.

[9] K. Ma, Z. Zhao, J. Wu, S. M. Ellis, and Z.-P. Nie, “A printed Vivaldi antenna with improved radiation patterns by using two pairs of eye-shaped slots for UWB applications,” *Progress In Electromagnetics Research*, vol. 148, pp. 63-71, 2014.

[10] Y. Zhang, E. Li, C. Wang, et al., “Radiation enhanced Vivaldi antenna with double-antipodal structure,” *IEEE Antennas & Wireless Propagation Letters*, vol. 16, no. 7, pp. 561-564, July 2017.

[11] D. Wu, X. Wang, Y. Xie, et al., “A novel hybrid loaded Vivaldi antenna with broadened relative bandwidth,” *Microwave & Optical Technology Letters*, vol. 58, no. 9, pp. 2037-2041, June 2016.

[12] M. Moosazadeh and S. Kharkovsky, “A compact high-gain and front-to-back ratio elliptically tapered antipodal Vivaldi antenna with trapezoid-shaped dielectric lens,” *IEEE Antennas & Wireless Propagation Letters*, vol. 15, no. 7, pp. 552-555, July 2016.

[13] M. Abbak, M. N. Akinci, M. Cayoren, et al., “Experimental microwave imaging with a novel corrugated Vivaldi antenna,” *IEEE Transactions on Antennas and Propagation*, vol. 65, no. 6, pp. 3302-3307, June 2017.

[14] J. Wu, Z. Zhao, and Q. Liu, “A novel Vivaldi antenna with extended ground plane stubs for ultra-wideband applications,” *Microwave & Optical Technology Letters*, vol. 57, no. 4, pp. 983-987, Feb. 2015.

[15] G. K. Pandey, H. Verma, and M. K. Meshram, “Compact antipodal Vivaldi antenna for UWB applications,” *Electronics Letters*, vol. 51, no. 4, pp. 308-310, Feb. 2015.

[16] R. Natarajan, J. V. George, M. Kanagasabai, et al., “A compact antipodal Vivaldi antenna for UWB applications,” *IEEE Antennas & Wireless Propagation Letters*, vol. 14, no. 3, pp. 1557-1560, Mar. 2015.