Design of Low RCS Vivaldi Antenna Based on Differential Evolution Algorithm

Ge Zhao [1], Zi-Yu Pang [1], Xiao-Yu Ma [1], Guan-Long Huang [1]*, Luyu Zhao [2]*, Jia-Jun Liang [3], and Chow-Yen-Desmond Sim [4]

[1] College of Electronics and Information Engineering, Shenzhen University, Shenzhen, Guangdong 518060, China
*guanlong.huang@ieee.org

[2] National Key Laboratory of Antennas and Microwave Technology,
Xidian University, Xi'an, Shaanxi, 710071, P.R. China
*lyzhao@xidian.edu.cn

[3] School of Physics and Telecommunication Engineering, Yulin Normal University, Yulin, P.R. China

[4] Department of Electrical Engineering, Feng Chia University, Taichung 40724, Taiwan

Abstract **─** A novel method to reduce antenna radar cross section (RCS) is proposed in this paper. A wideband Vivaldi antenna is adopted for demonstration, the shape of which is optimized by the differential evolution algorithm (DEA) under Python and HFSS co-simulation environment. By utilizing this simple and efficient design approach, no additional structure is required for RCS reduction while other electromagnetic performance of the antenna can be well maintained. Results show that the designed Vivaldi antenna achieves a good RCS reduction from 4 GHz to 9 GHz, validating the possibility and feasibility of this method for further radar target application.

Index Terms **─** Differential evolution algorithm (DEA), radar cross section (RCS) reduction, Vivaldi antenna.

I. INTRODUCTION

With the development of detection technology and stealth technology, the radar cross section (RCS) reduction of the antenna is undoubtedly of great military significance. RCS is a physical indicator that quantitatively describes the effective scattering area of the incident wave from a certain direction. Obviously, different kinds of antennas have different RCS response [1]-[7]. Vivaldi antenna, as a typical ultra-wideband (UWB) antenna, is often used in the military field due to its advantages of good directivity, wide frequency band and high gain. Therefore, to enhance its practical versatility in practical application, it is of significance to reduce the Vivaldi antenna's RCS.

The RCS reduction of Vivaldi antenna has been studied in many literatures. Basically, reducing the RCS of Vivaldi antenna can be categorized to two groups. One is to load specially-designed structures on the Vivaldi antenna to achieve antenna RCS reduction. In [8], ultrathin microwave-absorbing materials (MAMs) are placed at the side edges of a Vivaldi antenna, which can absorb the reverse currents at the outer side edges so that the RCS can be reduced. A half-mode substrate integrated waveguide (SIW) structure proposed in [9] is used in antenna design for RCS reduction while a phase-switched screen (PSS) is designed for the same purpose in [10]. In addition, a photonic band gap (PBG) structure is applied to a bilateral Vivaldi antenna to realize antenna's RCS reduction [11].

The other group is to modify the shape of the Vivaldi antenna so as to achieve low RCS response. In [12], an antipodal Vivaldi antenna with low RCS characteristic is demonstrated, which is realized by removing a portion of the metal from the antenna and placing periodic slots near the edges of the radiating element. Vivaldi antennas are modified in [13] by three pairs of arcs to realize wideband RCS reduction. In [14], an approach to implement annular slot along with exponential curves in the antenna is proposed to achieve RCS reduction. Moreover, a flat corrugated slotline is designed in [15] to replace the exponential gradient curve of antenna, which results in RCS reduction when the incident wave is perpendicular to the antenna.

However, regarding to the approaches of either introducing extra structures or modifying the shape of the antennas, all of these above-mentioned design methods still have to take a long and customized simulation process, which is not a universal methodology for RCS reduction. Therefore, it is necessary to have a

Submitted On: February 1, 2020
Accepted On: March 16, 2020

1054-4887 © ACES

new and highly efficient method so that researchers can specify design goals and then use an optimization tool to find and select the most reasonable result and obtain the desired performance. From the mathematical point of view, the optimization method should be a fast way to find extreme values, i.e., under the constraints of a set of equations or inequalities, the system's objective function reaches its extreme value of maximum or minimum.

In this paper, in order to alleviate the aforementioned problems, a low RCS Vivaldi antenna is designed by a highly efficient optimization method. The co-simulation of the commercial electromagnetic tool, HFSS, and Python program is adopted, and the differential evolution algorithm (DEA) is utilized to find the optimal antenna pattern that satisfies both radiation and scattering requirements.

II. PRINCIPLE OF DEA METHOD

The DEA is a random parallel direct search algorithm proposed by Storm Rainer and Price Kenneth in 1995 [16]. It has the characteristics of simple operation and global search, which not only can avoid the shortcomings of classic and local optimization methods such as low convergence accuracy and easy convergence to local extreme values, but also has been successfully applied to complex electromagnetic optimization problems such as array synthesis and filter design. In this work, the DEA is applied to the RCS reduction of the antenna for the first time. Figure 1 shows the flowchart of optimizing the RCS of Vivaldi antenna with DEA method.

In this paper, Vivaldi antenna is separated into small rectangles, and low RCS Vivaldi antenna is obtained by controlling the presence or absence of the rectangles in each position. Each column of the Vivaldi antenna is considered as a variable. Before the optimization, the number of rectangles (denoted as N) contained in each column of the Vivaldi antenna needs to be calculated. For each variable, the value ranges from 0 to 2^N-1. When the Vivaldi antenna is optimized by the DEA, the individuals of population number are randomly generated to form the first generation population, and then the HFSS software is called by Python script, where the antenna model is simulated by Finite Element Method (FEM) to realize the calculation of antenna radiation and scattering characteristics and then each individual fitness value can be obtained. The fitness function here is the RCS of the antenna. The fitness value will be compared with the target value afterwards. Once the fitness value is less than the target value, the optimal pattern of the low RCS Vivaldi antenna can be obtained. Otherwise, mutation and crossover operations are then performed to obtain crossover individual. Next, the target individual is compared with the crossover individual. If the fitness value calculated by the crossover individual is less than the fitness value calculated by the target individual, the crossover individual is inherited to the next generation. Otherwise, the target individual will be given to the next generation. This is going to repeat until the fitness value is less than the target value or the number of iterations reaches the specified maximum number of iterations, the whole optimization process will be terminated.

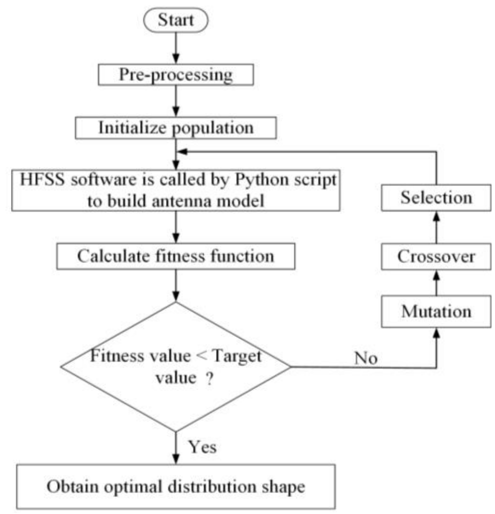


Fig. 1. Flowchart of DEA method for Vivaldi antenna RCS reduction.

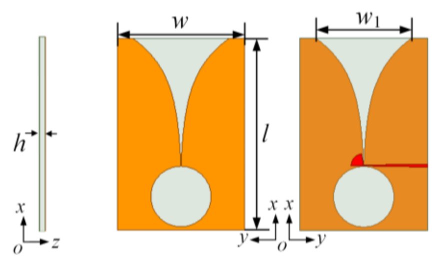
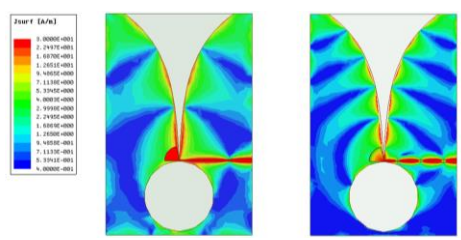


Fig. 2. Geometry of the reference Vivaldi antenna.



(a) (b)

Fig. 3. Surface radiating current of the reference Vivaldi antenna at: (a) 4.5 GHz and (b) 8.5 GHz.

It is worth noting that for the design of low RCS Vivaldi antenna, both radiation and scattering characteristics must be taken into account. Therefore, as long as the reflection coefficient of the Vivaldi antenna is less than -10 dB, a series of subsequent steps such as the comparison between the fitness value and the target value would be performed.

III. DESIGN AND DISCUSSION OF LOW RCS VIVALDI ANTENNA

A. Low RCS Vivaldi antenna design

In order to illustrate the RCS reduction effect, a conventional Vivaldi antenna is taken as the reference antenna, and its geometry is shown in Fig. 2. It can be known that the Vivaldi antenna is composed of a stepped microstrip feeding line and a radiating tapered slot.

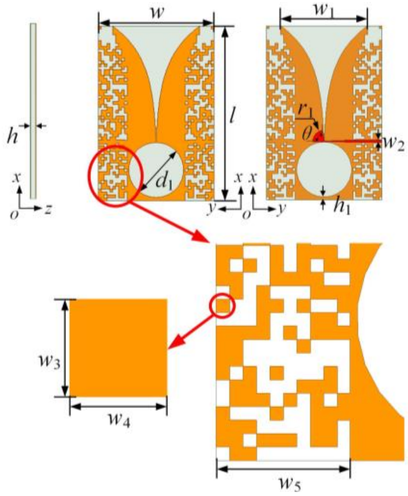


Fig. 4. Geometry of the proposed Vivaldi antenna.

The surface radiating current distributions of the reference antenna at 4.5 GHz and 8.5 GHz are shown in Fig. 3, which can be observed that the radiating current of the Vivaldi antenna is mainly concentrated on both sides of the tapered slot and the microstrip line, so DEA method can be applied to optimize the remaining part of the Vivaldi antenna with relatively weak radiating current, which can in turn help reduce the antenna's RCS. The proposed antenna optimized by DEA method is shown in Fig. 4. Both antennas are printed on Rogers 5880 substrate with dielectric constant of 2.2, loss tangent of 0.0009 and thickness of 0.508 mm. The detailed dimensions of the proposed antenna are shown in Table 1.

Table 1: Parameters of the proposed Vivaldi antenna

Parameter	Value	Parameter	Value
w	80 mm	w_4	2 mm
l	120 mm	w_5	20 mm
h	0.508 mm	d_1	38 mm
w_1	60 mm	h_1	2 mm
w_2	1.65 mm	r_1	7.8 mm
w_3	2 mm	θ	80°

B. Radiation performance

In order to verify the radiation characteristics of the proposed antenna, the VSWRs, maximum radiation gains, and radiation patterns of the reference antenna and the proposed antenna are discussed in this section.

The simulated VSWRs and gains are depicted in Fig. 5. It can be seen that the VSWR of the proposed antenna is less than 2 in the frequency range of 4~9 GHz, which is similar to that of the reference antenna. By observing the gain response in Fig. 5, it can be found that the gain of the proposed antenna is slightly lower than the reference antenna but within an acceptable range, the phenomenon of which can be understood that the effective radiation aperture of the proposed antenna is slightly smaller than the reference antenna.

The *E*-plane and *H*-plane normalized radiation patterns of the two antennas at 4.5 GHz and 8.5 GHz are plotted in Fig. 6, from which one can observe that the proposed antenna has comparable radiation performance as the reference one.

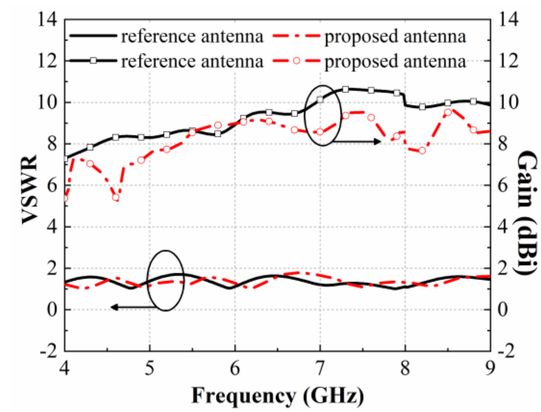


Fig. 5. Simulated VSWRs and gains of the reference and the proposed antennas.

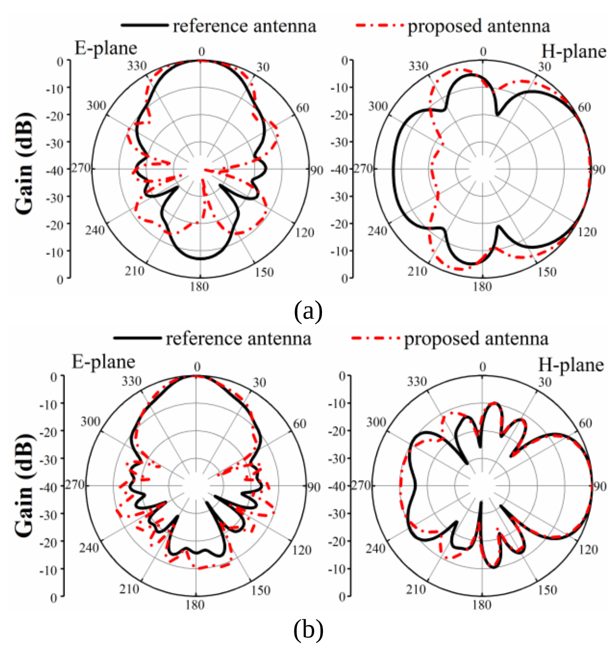
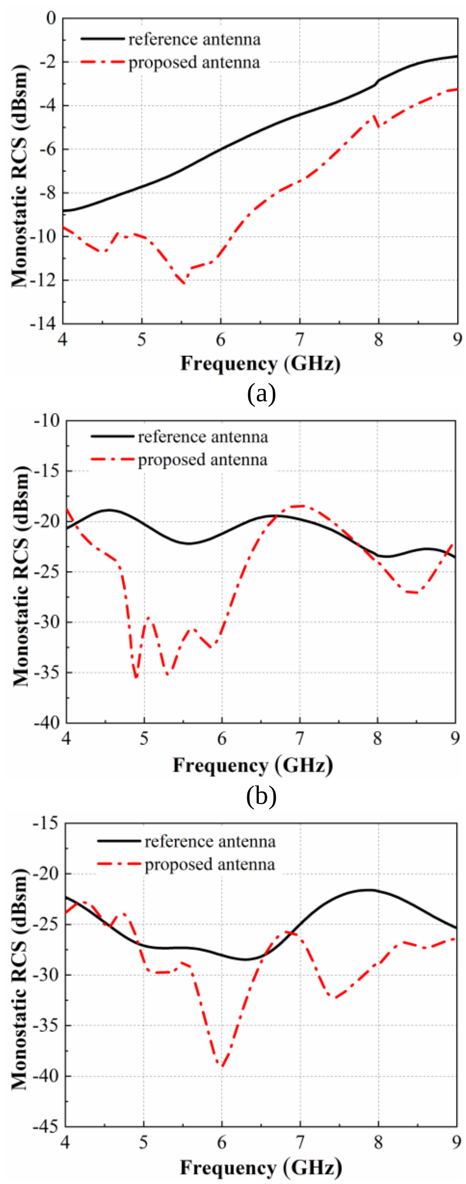


Fig. 6. Radiation patterns of the reference and the proposed antennas at: (a) 4.5 GHz and (b) 8.5 GHz.

C. Scattering performance

In order to evaluate the scattering characteristics of the proposed antenna, planar incident wave is uniformly illuminated on the antenna surface, and the monostatic RCS at different incident angles can be calculated in HFSS when the incident wave is θ-polarized. According to Fig. 7 (a), when the incident wave is perpendicular to the Vivaldi antenna, i.e., φ = 0°and θ= 0°, the monostatic RCS of the proposed antenna in the whole frequency band is significantly reduced compared with the reference antenna. In particular, the monostatic RCS of the proposed antenna is reduced by 5.24 dB at 5.5 GHz.



(a) (b) (c)

Fig. 7. Simulated monostatic RCS at different incident angles: (a) φ = 0°, θ= 0°; (b) φ = 0°, θ= 60°; (c) φ = 90°, θ= 60°.

Figures 7 (b) and (c) show the monostatic RCS performance when the angle of incident wave θ increases to 60°. It can be seen that, though the incident direction varies to a large angle, the monostatic RCS reduction of the proposed antenna can still maintain in a satisfactory range in most frequency bands of 4~9 GHz. Especially, when φ = 0°and θ= 60°, the monostatic RCS of the proposed antenna can be reduced more than 6 dB in the band of 4.75~6.2 GHz; and at 4.85 GHz, 14.4 dB RCS reduction is achieved. At the case of φ = 90° and θ= 60°, the proposed antenna obtains more than 6.5 dB RCS reduction in both 5.8~6.2 GHz and 7.25~8.05 GHz bands, particularly 11 dB RCS reduction is achieved at 6 GHz. Therefore, it can be concluded that the average monostatic RCS of the proposed antenna in the whole frequency band is much lower than that of the reference antenna while the proposed one still possesses other good radiation performance similar to the reference one.

IV. CONCLUSION

A low RCS Vivaldi antenna for UWB communication system application is proposed in this paper. Numerical results show that satisfactory radiation performance of the proposed antenna has been obtained. Compared with the reference antenna, the operational bandwidth of the proposed antenna can cover a wide range from 4 GHz to 9 GHz with VSWR less than 2, while its radiation patterns still maintain directional performance. The scattering characteristics when the incident wave is θ-polarized are also analyzed. Results show that when the incident wave is perpendicular to the antenna, the monostatic RCS of the proposed antenna has been reduced in the whole frequency band, particularly when the incident wave angle increases to 60°, the monostatic RCS still maintain a good reduction in most frequencies of 4~9 GHz.

ACKNOWLEDGMENT

This work was supported partially by the National Taipei University of Technology-Shenzhen University Joint Research Program under Grant No. 2020011, the Fok Ying-Tong Education Foundation, China under Grant No. 171056, the National Natural Science Foundation of China under Grants 61801300 and 61701320, and the New Teacher Natural Science Research Project of Shenzhen University under Grant No. 860-000002110627.

REFERENCES

[1] J. Jiang, Y. Xia, and Y. Li, "High isolated X-band MIMO array using novel wheel-like metamaterial decoupling structure," *Applied Computational Electromagnetics Society Journal*, vol. 34, no. 12, pp. 1829-1836, 2019.

[2] F. Liu, J. Guo, L. Zhao, G. L. Huang, Y. Li, and Y. Yin, "Dual-band metasurface-based decoupling method for two closely packed dual-band antennas,"

IEEE Transactions on Antennas and Propagation, vol. 68, no. 1, pp. 552-557, Jan. 2020.

[3] G.-L. Huang, J. Liang, L. Zhao, D. He, and C.-Y.-D. Sim, "Package-in-dielectric liquid patch antenna based on liquid metal alloy," *IEEE Antennas and Wireless Propagation Letters*, vol. 18, no. 11, pp. 2360-2364, Nov. 2019.

[4] J. Li, X. Zhang, Z. Wang, X. Chen, J. Chen, Y. Li and A. Zhang, "Dual-band eight-antenna array design for MIMO applications in 5G mobile terminals," *IEEE Access*, vol. 7, pp. 71636-71644, 2019.

[5] F. Liu, J. Guo, L. Zhao, G. Huang, Y. Li, and Y. Yin, "Ceramic superstrate-based decoupling method for two closely packed antennas with cross-polarization suppression," *IEEE Transactions on Antennas and Propagation*, Submitted.

[6] J. Guo, F. Liu, L. Zhao, Y. Yin, G. Huang, and Y. Li, "Meta-surface antenna array decoupling designs for two linear polarized antennas coupled in H-plane and E-plane," *IEEE Access*, vol. 7, pp. 100442-100452, 2019.

[7] L. Zhao, G. Jing, G.-L. Huang, W. Lin, and Y. Li, "Low mutual coupling design for 5G MIMO antennas using multi-feed technology and its application on metal-rimmed mobile phones," *IEEE Transactions on Antennas and Propagation*, Submitted.

[8] P. Zhang and J. Li, "Compact UWB and low-RCS Vivaldi antenna using ultrathin microwave-absorbing materials," *IEEE Antennas and Wireless Propagation Letters*, vol. 16, pp. 1965-1968, 2017.

[9] Y. Jia, Y. Liu, Y. Hao, and S. Gong, "Vivaldi antenna with reduced RCS using half-mode substrate integrated waveguide," *Electronics Letters*, vol. 50, no. 5, pp. 345-346, Feb. 2014.

[10] G. Zhang, L. Xu, and A. Chen, "RCS reduction of Vivaldi antenna array using a PSS boundary," *2008 8th International Symposium on Antennas, Propagation and EM Theory*, Kunming, China, pp. 345-347, 2008.

[11] W. Jiang, Y. Li, S. Gong, and W. Wang, "Novel UWB vivaldi antenna with low RCS," *2014 Asia-Pacific Microwave Conference*, Sendai, Japan, pp. 1405-1407, 2014.

[12] N. Rajesh, K. Malathi, S. Raju, V. Abhai Kumar, S. Deepak Ram Prasath, and M. G. N. Alsath, "Design of Vivaldi antenna with wideband radar cross section reduction," *IEEE Transactions on Antennas and Propagation*, vol. 65, no. 4, pp. 2102-2105, Apr. 2017.

[13] Y. Jia, Y. Liu, S. Gong, T. Hong, and D. Yu, "Printed UWB end-fire Vivaldi antenna with low RCS," *Progress in Electromagnetics Research Letters*, vol. 37, 2013.

[14] R. Natarajan, M. Kanagasabai, and J. V. George, "Design of an X-band Vivaldi antenna with low radar cross section," *IET Microwaves, Antennas & Propagation*, vol. 10, no. 6, pp. 651-655, 2016.

[15] T. Luo and Z. Nie, "RCS reduction of antipodal Vivaldi antenna," *2015 Asia-Pacific Microwave Conference (APMC), Nanjing*, pp. 1-3, 2015.

[16] S. Rainer and P. Kenneth, "Differential evolution–a simple and efficient heuristic for global optimization over continuous spaces," *Journal of Global Optimization*, vol. 11, no. 4, pp. 341-359, 1997.