Regular Article

A New Linear Printed Vivaldi Antenna Array with Low Sidelobe Level and High Gain for the Band 3.5 GHz

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Abstract– **This paper proposes a new design of a low sidelobe level (SLL) and high gain linear printed Vivaldi antenna array. The array composes of two parts, which are a linear Vivaldi antenna array and a back reflector. The array consists of 10 single Vivaldi antennas and a new series-fed network, those are based on Rogers RO4003C substrate (ε = 3.55) with the dimension of $450 \times 140 \times 1.524$ mm^3. Bat algorithm with the amplitude-only control technique has been applied to optimize the output coefficients of the series-fed network for gaining a low SLL. The simulation results indicate that the proposed antenna provides a low SLL of -29.2 dB in E-plane with a high gain of 16.5 dBi at the frequency of 3500 MHz. A prototype of the proposed antenna array has been fabricated. The measured data has agreed well with the simulated data.**

Keywords– **Vivaldi antenna, low sidelobe level, linear antenna array, Bat algorithm application.**

1 Introduction

Vivaldi antennas have been introduced for several decades. Some typical structures of Vivaldi antennas such as a 3D array or multi-layer antennas have been used in wireless systems. They have a high directivity and a large bandwidth. However, these antennas are not convenient to be integrated into small wireless systems due to their large sizes. This problem has been overcome when printed Vivaldi antennas have been developed. Printed Vivaldi antenna arrays usually have simple structures and easy to be fabricated, while they still have a high gain and a wide bandwidth. Several designs of these antenna arrays have been proposed in [1–6]. A Vivaldi antenna array has been proposed for 5G handsets in the mmWave based on a corporate-fed network in [1] and [2]. In [1], notch structures have been used to reduce mutual coupling of about 37 dB between adjacent elements to improve the radiation pattern. In [2], an end-fire antenna array has been designed with a high gain of 12 dB. Works in [3] and [4] have proposed Vivaldi antenna arrays for ultra-wideband applications in the L, S or X bands. The common drawback of these studies is that the reduction of SLLs has not been studied yet. The effect of the Vivaldi element pattern on the pattern of a uniform linear array in the frequency range of 2-4 GHz has been investigated in [5]. The results show that the gain of 13 dB can be achieved, but the SLL is too high with -6 dB when the number of elements is 10. In [6], the design of a Vivaldi antenna using director elements has been proposed. This antenna has a SLL of -19.9 dB, but the gain is only 10 dBi.

A high SLL causes serious problems for wireless systems. It produces electromagnetic radiation in unwanted directions in transmitting and receive undesired signals in receiving systems. Therefore, several attempts have been studied to reduce the SLL of linear antenna arrays. The most usual approach is to use a Chebyshev amplitude taper [7–10]. A linear microstrip patch antenna array, which consists of twelve rectangular patches and a corporate-fed network, has been proposed in [7]. This antenna array can provide a low SLL of -26.5 dB at the frequency of 5.8 GHz. However, the back lobe level is quite high at -15 dB. In [8], a series-fed linear dielectric resonator antenna (DRA) array with eight patches has been proposed. The antenna has a low SLL of -23 dB and a gain of 15.7 dBi at the frequency of 7 GHz. Another DRA array with ten patches has been presented in [9]. This antenna achieves -27.7 dB of SLL and a gain of 15.7 dBi in the V-Band. Even though it is complicated to design and fabricate the DRA structure. A double-sided printed dipole array with ten elements has been proposed in [10]. This antenna provides a high gain of 17.5 dBi, and the SLL is about -26 dB in E-plane.

Another approach for gaining a low SLL of linear antenna arrays is to use optimization algorithms. This method's advantage is that it allows setting any specific demand of SLLs by synthesizing the array factor. Several algorithms have been investigated in [11] such as

Gravitational search, Genetic algorithm (GA), Particle swarm optimization (PSO), Ant Lion, Modified invasive weeds and Cat swarm. In simulation results, these algorithms can provide a wide range of SLL suppression.

A new inspired-nature algorithm, the Bat algorithm (BA), has been proposed for SLL suppression and null placement of a linear antenna array in [12–15]. In these works, BA has been demonstrated that it is better than famous algorithms such as PSO or GA in term of convergence, robustness and precision. However, there is still a lack of proposals for antenna array designs using the above algorithms. There are few works which have used optimization algorithms in design low SLL antenna arrays. The author in [16] has used the differential evolution algorithm in the design of an array of ten patch antennas. This antenna has a SLL as low as -25.3 dB at the frequency of 9 GHz. The PSO has been used in the design of a 4D Vivaldi antenna for UWB in [17]. The SLL can be reduced 27.8 dB at the frequency of 15.1 GHz and 44.9 dB at the frequency of 10.1 GHz. However, this study uses the switching time technique, which is complicated to be deployed in reality.

The frequency band of 3.5 GHz has been using for fixed satellite and radar systems for a long time. However, the band has also been allocated to fixed wireless systems and International Mobile Telecommunications (IMT) systems such as 4G/5G worldwide since recent years [18, 19]. Therefore, it raises the issue of studying on protecting the existing satellite and radar systems from harmful interference of new wireless systems in areas where these systems are sharing the 3.5 GHz band. In reality, one of the solutions of handling radio interference, which has been using in fixed wireless systems or mobile base stations, is to install high directivity and low SLL linear antenna arrays.

In this paper, BA has been used to calculate an optimized amplitude excitation weight distribution of a linear array antenna for a low SLL of -30 dB. Then a new series feeding-network has been designed to deploy this amplitude distribution. An array of ten printed Vivaldi antennas has been developed based on the proposed feeding-network for fixed or mobile wireless systems operating in the band 3.5 GHz. The proposed array Vivaldi antenna can provide a low SLL of -29.2 dB while the maximum gain can be reached by 16.5 dBi.

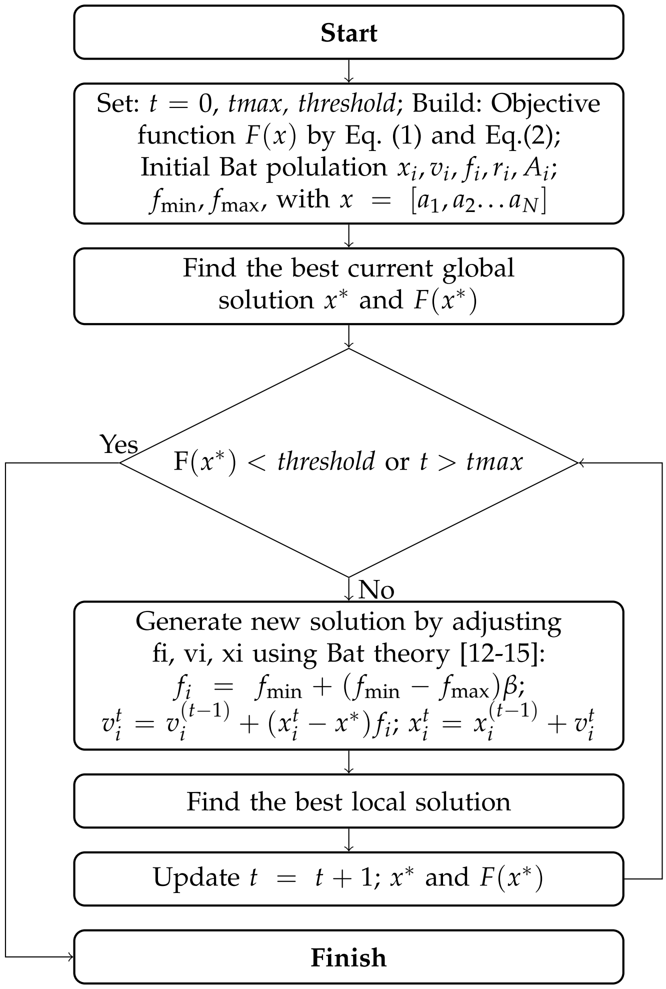


Figure 1. Flow chart of BA algorithm.

2 Antenna Array Design and Structure

2.1 Design of a Feeding Network

2.1.1 Amplitude Distribution of the Array Factor for Low Sidelobe Level: In this work, a uniform linear array has been studied. The array has ten elements, which are equally separated by a half of a wavelength. The array factor AF of the array can be expressed as:

$$F(\theta) = \sum_{n=1}^{N} a_n e^{j\left(n\frac{\lambda}{2}k\sin(\theta)+\delta_n\right)}, \quad (1)$$

where $N = 10$, the excitation weight of the n^{th} element has the amplitude of a_n and the phase of δ_n, and k is the wavenumber, $k = 2\frac{\pi}{\lambda}$. With the amplitude-only control technique, this work assumes $\delta_n = 0^0$ and $a_n = a_{N+1-n}$ to keep the main lobe direction at $\theta = 0^0$. For the purpose of gaining a low SLL, the BA has been used to find out a distribution of the amplitude (a_n) through the optimization progress of the AF. The theory of the BA has been investigated in [12–15]. The objective function, F, has been designed as:

$$F = \sum_{\theta=-90^0}^{90^0} \left[\left| AF_o(\theta) - AF_d(\theta) \right|^2 \right] \quad (2)$$

AF_o is the output array factor for a low SLL. AF_d is the reference array factor. In this study, AF_d has been preset with the maximum SLL of -30 dB. The BA can be re-written to solve the problem of SLL suppression as shown in Figure 1. The optimization progress has been done in the following condition: the number of bats $n = 50$; $f_{\min} = 0$, $f_{\max} = 2$; *threshold* is 0.001; A_i and r_i are initiated by 0.5; the maximum number of searching rounds is 20. The amplitude distribution for a low SLL has been calculated and shown in Table I.

2.1.2 Design of a Feeding Network: A series-fed network has been proposed to implement excitation amplitude weights for a low SLL of a 10×1 linear antenna

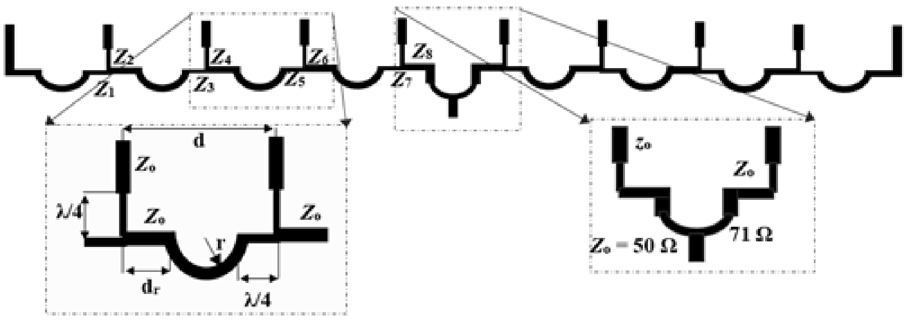


Figure 2. Design of the proposed series-fed network.

Table I
Amplitude Distribution for SLL of -30 dB.

n	1 and 10	2 and 9	3 and 8	4 and 7	5 and 6
a_n	0.2066	0.4203	0.6506	0.8679	1.0000

array. The series-fed network has two characteristics. The first one is that the output power distribution is corresponding to the distribution of amplitude, which is presented in Table I. The second one is that all output phases are uniform. Because this amplitude distribution is symmetric, the series-fed network consists of two identical and symmetrical arms on each side of the centerline. The design of the proposed series-fed network is depicted in Figure 2. T-junctions have been proposed to control the power flow to outputs. The impedance of the input and all outputs, Z_0, has been designed equally to 50Ω. Transmission lines of a quarter-wavelength $(Z_1, \ldots, Z_8)$ have been used to match the impedance between T-junctions and the outputs. If the output phases between adjacent output ports are in-phase, the phase delay Φ between them must be 2π. However, the phase delay Φ of a signal passing through a transmission line with a length of l can be calculated by the expression [20]:

$$\Phi = \frac{2\pi}{\lambda_g} l, \tag{3}$$

where λ_g is the effective wavelength, l is a constant and $l < \lambda$. Thus, Φ usually is smaller than 2π. A new solution has been proposed in this study to control Φ. A circular arc is added to the transmission line which connects two adjacent outputs. The radius of the circular arc, r, is approximately calculated to achieve $\Phi = 2\pi$ by expressions:

$$d_p = d_r + 2r + \frac{\lambda_g}{4}, \tag{4}$$

$$2\pi = \frac{2\pi}{\lambda_g}(d_r + \pi \mathrm{r}) + \frac{\pi}{2}. \tag{5}$$

Because $Z_1, \ldots, Z_8$ have the lengths of $\frac{\lambda_g}{4}$, the phase delays of them are approximately $\frac{\pi}{2}$. The weights of the proposed series-fed network have been calculated with the requirement of the amplitude distribution in Table I, as presented in Table II. Where w_i is the width of Z_i. The output coefficients of the proposed feeding network have been simulated. The simulation results of the amplitude and phase distribution have been presented in Table III. It is obvious that there is not much difference between the simulation results and the theoretical one. The response of the array factor with simulated amplitude weights has been compared to that one with the theoretical amplitude weights, as presented in Figure 3. Clearly, this network can be used to gain a low SLL of the linear antenna array in this study.

Table II
The Series-Fed Network's Weights (*mm*)

w_0	w_1	w_2	w_3	w_4	w_5
3.41	0.93	2.64	0.76	2.76	1.86
w_6	w_7	w_8	r	d_p	d_r
1.86	2.14	1.56	10.2	41.26	9.3

Table III
Simulation of the Output Coefficients of the Proposed Series-Fed Network

Output	1 and 10	2 and 9	3 and 8	4 and 7	5 and 6
Amplitude (theory)	0.2066	0.4203	0.6506	0.8679	1.0000
Amplitude (simulation)	0.1905	0.3935	0.6025	0.8317	1.0000
Phases [degree]	-106.55	-108.16	-107.70	-108.19	-106.90

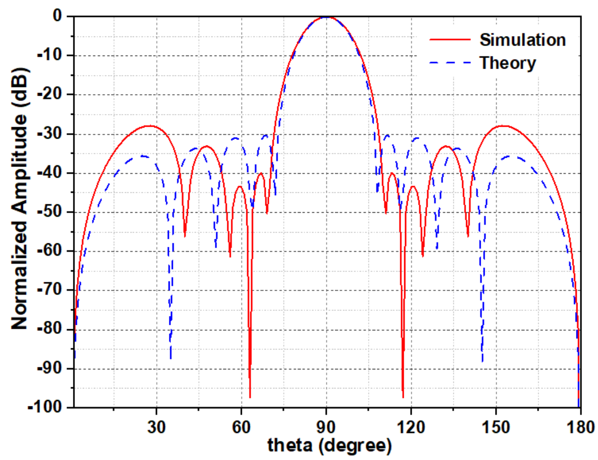


Figure 3. The AF with simulated amplitude coefficient and with theoretical one.

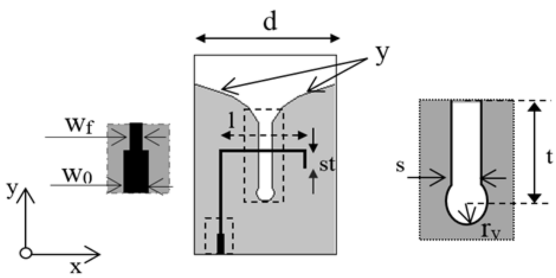


Figure 4. The geometry of a Vivaldi antenna element, top view (black) and bottom view (gray).

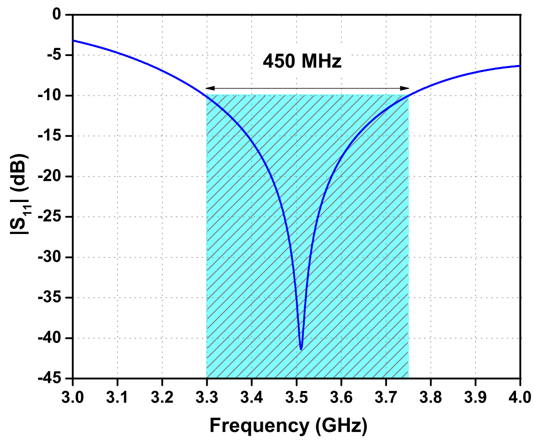


Figure 5. S_{11} Simulation of a Vivaldi antenna element.

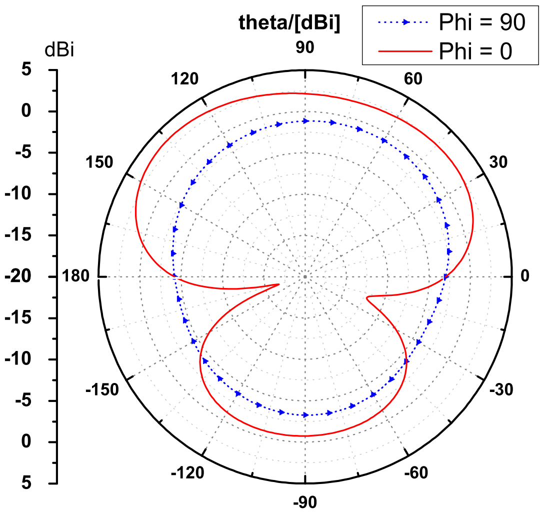


Figure 6. Radiation pattern simulation in E-plane (solid line) and H-plane (dash line).

2.2 Design of a Vivaldi Antenna Element

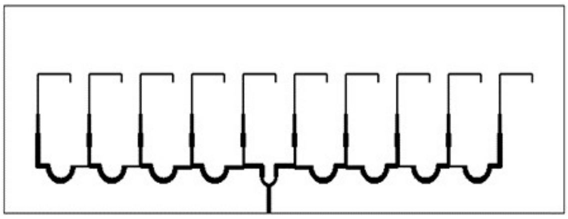
A Vivaldi antenna element has been designed on both the top and the bottom layers of a Rogers substrate RO4003C, as shown in Figure 4. On the top, there is a microstrip line, which plays the role of a taper to a slot on the bottom. This line consists of two interconnected segments, a quarter of a wavelength of 50Ω transmission line and an open line of the width of w_f. On the bottom, there is a rectangular slot with the width of $s = 2\alpha$ and the length of t located at the center. This slot is connected to a circle of radius of r_v and an exponential planar horn which is designed based on expressions:

$$y = \alpha e^{-px}, \tag{6}$$

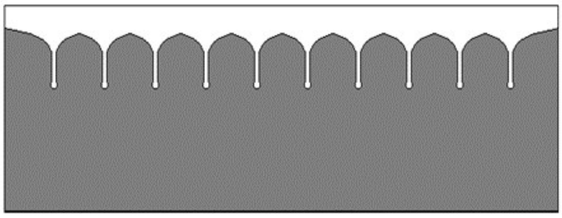
where $x = 0 \rightarrow \frac{t}{2}$; $\alpha > 0$ and $p > 0$. The parameters of the Vivaldi antenna element have been calculated, as presented in Table IV. The Vivaldi antenna has been simulated, and the simulation results are presented in Figures 5 and 6. As indicated in Figure 5, the antenna has a bandwidth of 450 MHz (3300 - 3750 MHz) at the reflection coefficient (S_{11}) of -10 dB. Figure 6 shows the radiation pattern in E-and H-plane. This antenna provides a gain of 4.4 dBi. From the simulation results, the Vivaldi antenna element can be well used in the proposed array of this work.

Table IV
Parameters of a Vivaldi Antenna Element (mm)

w_0	w_f	d	t	α	r_v	l	s_t	p
3.41	0.7	41.26	20	1.9	2.6	23.3	5.5	0.06



(a) Top view



(b) Bottom view

Figure 7. View of the Vivaldi antenna array.

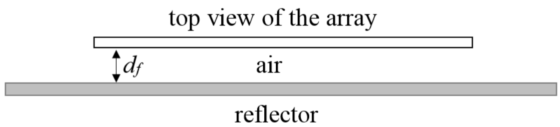


Figure 8. Configuration of the proposed antenna.

2.3 Construction of the Proposed Antenna Array

The linear Vivaldi array antenna has been designed by arranging 10 Vivaldi antenna elements along the x-axis. Each element is connected to an output of the series-fed network by a transmission line. Inter-element spacing is approximately half of the wavelength of 3.5 GHz. The Vivaldi array is constructed on Rogers RO4003C substrate (ϵ = 3.55) with a total size of 450 × 140 × 1.524 mm^3. Figure 7 shows the top view and the bottom view of the Vivaldi antenna array. A reflector has been placed at the backside of the array, as shown in Figure 8. This reflector is based on FR4 substrate (ϵ =

Table V
Computer Configuration for Simulation in this Work

Computer	ACPIx64 based PC
Disk drivers	Kington SUV500120G
Display adapters	ANVIDIA GeForce GT 1030
Processors	Intel(R) Core(TM)i-8500CPU @3.00GHz (x8)
RAM	8 GHz

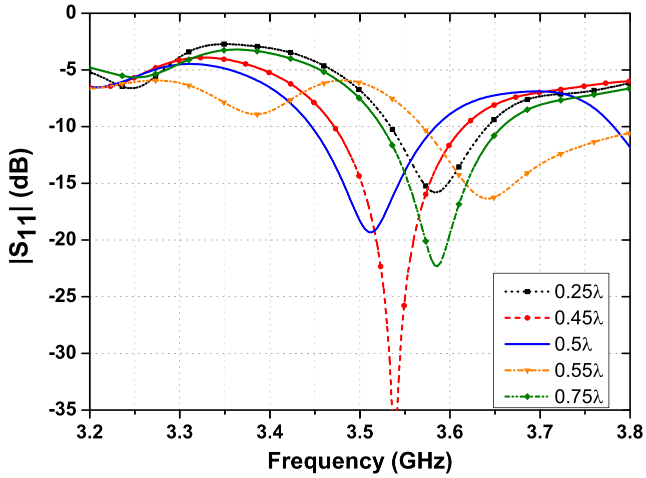


Figure 9. Reflection coefficient simulation with different distances of the back reflector.

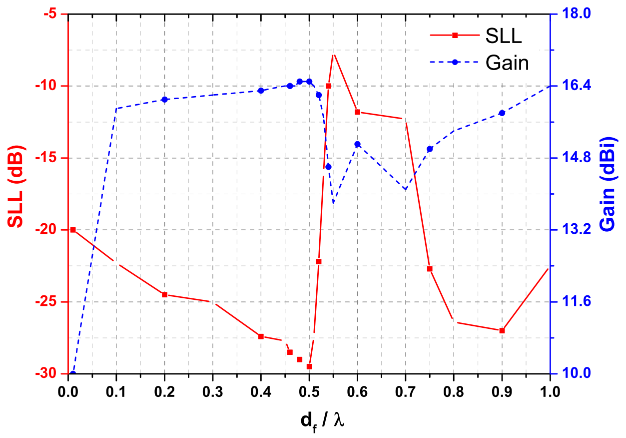


Figure 10. SLL and gain simulation with different distances of the back reflector.

4.4) with the overall dimensions of $503 \times 192 \times 1.6$ mm^3. The back reflector plays a role as a mirror reflecting the electromagnetic wave according to the image theory [21]. With the presence of the reflector, the electromagnetic wave has been removed from the bottom side of this array and has been forwarded to above the top side. Thus the maximum gain can be improved. However, the gain and the radiation direction depend on the distance d_f. In this work, all simulations have been done by using CST Microwave Suite 2018 with the computer configuration as presented in Table V. The Vivaldi antenna array has been simulated and optimized its elements and feeding-network parameters. The influence of the distance from the antenna array to

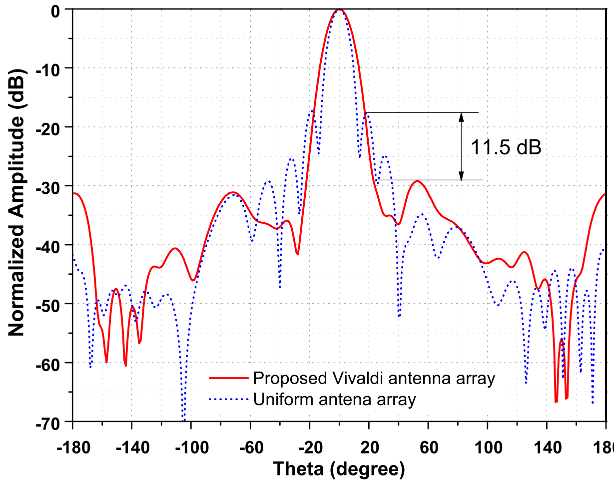


Figure 11. Simulation result of radiation pattern with proposed and uniform weights.

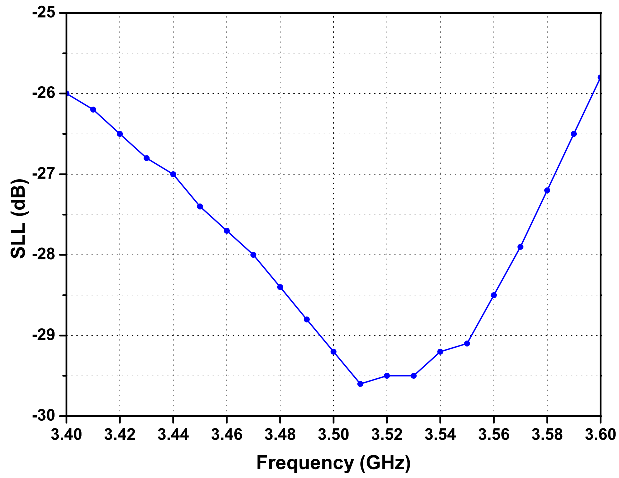


Figure 12. Simulation result of SLL over frequency when $d_f = 0.5\lambda$.

the reflector has also been investigated. Figures 9 and 10 show the variation of the bandwidth, maximum gain and SLL when d_f is changed. The maximum bandwidth can be achieved at the frequency of 3500 MHz while the distance is about 0.5λ. As presented in Figure 10, the distance df can be determined equal to 0.5λ in terms of having both a low SLL (-29.2 dB) and the highest gain (16.5 dBi). The simulation result of the radiation pattern with $d_f = 0.5\lambda$ has been presented in Figures 11 and 12. As presented in Figure 11, the maximum SLL of the array with the proposed amplitude excitation weights is 11.5 dB better than that one with uniform excitation weights. Figure 12 shows that the SLL over the frequency range of 3400-3600 MHz always is better than -26 dB, the maximum SLL suppression has been achieved by more than 29 dB in the frequency range of 3490-3550 MHz. Thus, the distance d_f has been finally chosen equal to 0.5λ in this design.

3 Experimental Results

A prototype of the proposed Vivaldi array antenna has been fabricated and measured. Figure 13 shows the

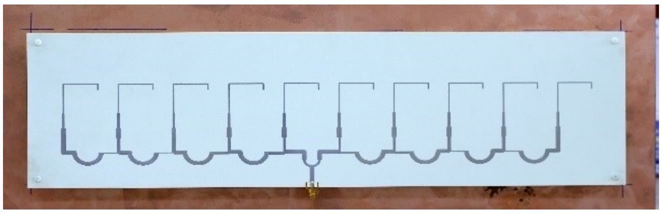


Figure 13. Fabricated Vivaldi antenna array.

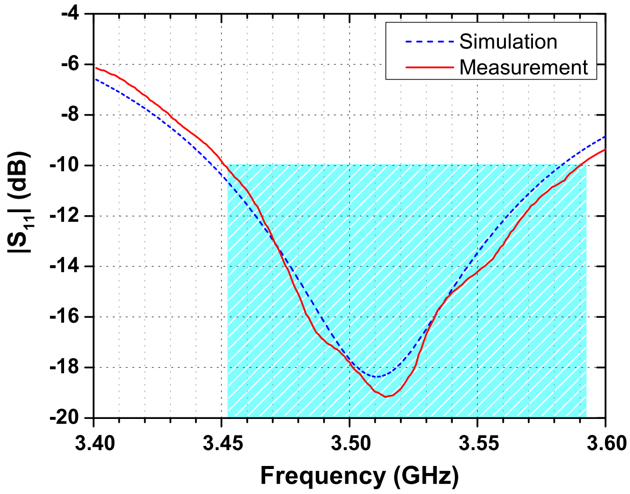


Figure 14. Simulation and measurement results of reflection coefficients.

fabricated antenna.

The reflection coefficient (S_{11}) has been measured by using the device Anritsu BTS Master 8222A. Radiation patterns have been measured in the far-field region by using a test antenna chamber, which has the size of 26 × 10 × 10 m^3. The measurement has been set with the frequency step size of 10 MHz and the resolution of the radiation pattern of 1°. The measurement data has been collected and compared to that of the simulated one. It is noted that in all figures, the coordinate axes (Oz) have been aligned with the maximum direction of the main lobe for the comparison of the simulation and measurement results.

The measurement and simulation of the reflection coefficient are presented in Figure 14. The antenna has the bandwidth of 140 MHz (from 3450 to 3590 MHz) at -10 dB of S_{11}.

The measured radiation patterns at the frequencies of 3450 MHz, 3500 MHz, 3520 MHz, 3550 MHz and 3590 MHz have been presented in Table VI and Figure 15. According to the measurement data, SLLs at those frequencies have been suppressed by more than 25 dB. The best SLL suppression has been achieved by approximately 27.0 dB at the frequency of 3500 MHz.

The simulated and measured radiation patterns at the frequency of 3500 MHz have been compared in detail, as shown in Figure 16. Both co-polarization and cross-polarization data are considered in the E-plane and H-plane. Obviously, measurement results agree well with simulation data. The proposed antenna array has the direction of maximum radiation in E-plane.

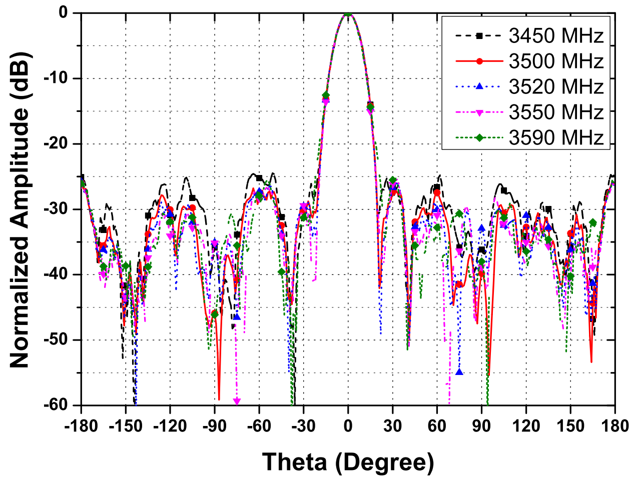


Figure 15. Measurement results of the radiation pattern in E-plane at different frequencies.

Table VI
The Maximum Measured SLL (dB)

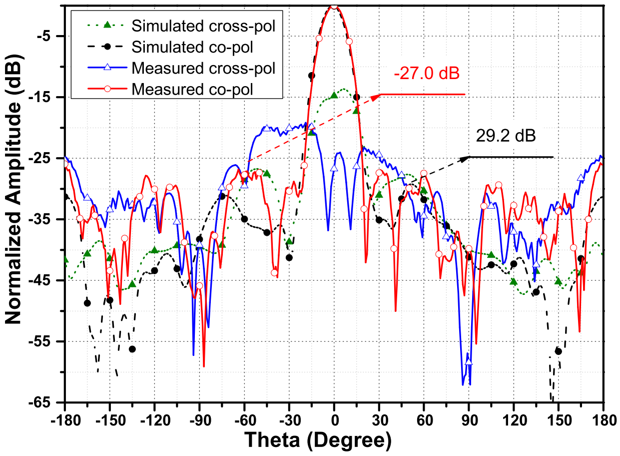
Frequency (MHz)	3450	3500	3520	3550	3590
SLL (dB)	-24.5	-27	-26.5	-25.5	-25

Table VII
Comparison with Other Works

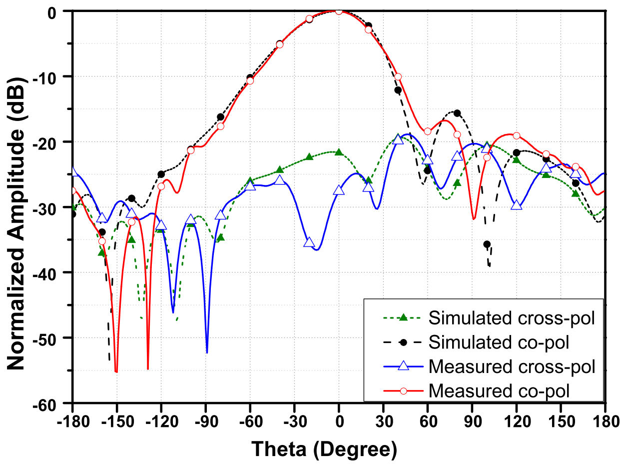
References	[16]	[10]	[8]	This work
Element No.	10	10	8	10
Frequency (MHz)	9000	5500	7300	3500
SLL (dB)	-25.3	-26.0	-23.0	-27.0
Cross-polarization (dB)	-25	-20	-30	-20
Maximum gain (dBi)	14.5	17.5	15.7	16.5
Substrate	RO4350	RT/5870	RT/5880	RO4003C

The maximum measured SLL is approximately -27.0 dB, while the simulation result with co-polarization is -29.2 dB. On the other hand, neither SLL measurement nor simulation results is above -20 dB with cross-polarization.

As indicated in Figure 16, the measurement results still have a slight difference from the simulated ones. It may be caused by some reasons. Firstly, SLLs is normally very low; thus, it can be changed by interference, such as refecting signals from other directions in the measurement process. Secondly, array fabrication may have errors, which is also a factor leading to inaccuracy measurement of the radiation pattern. However, the error of -2.2 dB may be an acceptable level. For comparison, the measurement data in this work has been compared with that of [8], [10] and [16] as shown in Table VII. The proposed Vivaldi antenna array has a SLL of -27.0 dB that is better than SLLs in [8], [10] and [16]. The antenna gain in this work is about 16.5 dBi that is 1 dB lower than the gain in [10]. The proposed antenna in this work has better gain and SLL suppression than those in [8] and [16]. The cross-polarization in this work is equivalent that in [10] and worse than those in [8] and [16].



(a) E-plane



(b) H-plane

Figure 16. The Radiation simulation and measurement results at the frequency of 3500 MHz.

4 Conclusions

A new linear printed Vivaldi antenna array has been developed. The BA has been used to optimize the output amplitude distribution of the series-fed network of this array. Simulation results show that the SLL has been suppressed to -29.2 dB, and the bandwidth is 140 MHz in the frequency of 3500 MHz with the reflection coefficient of -10 dB, while the maximum gain can be achieved at 16.5 dBi. A prototype of this antenna has been fabricated and measured to verify simulation results. The measured data has agreed well with simulated ones.

References

[1] S. Zhu, H. Liu, P. Wen, and Z. Chen., "A compact gain-enhanced vivaldi antenna array with suppressed mutual coupling for 5G mmwave application," *IEEE Antennas and Wireless Propagation Letters*, vol. 17, pp. 776–779, 2018.

[2] N. Ojaroudiparchin, M. Shen, and G. Pedersen, "Design of vivaldi antenna array with end-fire beam steering function for 5G mobile terminals," in *Proceedings of the 23rd Telecommunications Forum Telfor (TELFOR)*. IEEE, 2016, pp. 587–590.

[3] X. Li, Z. Zhang, K. Xu, Y. Li, L. Sang, and K. Dai, "Design of structural-reliable x-band high-gain vivaldi array antenna," in *Proceedings of the 12th International Symposium on Antennas, Propagation and EM Theory (ISAPE)*. IEEE, 2018, pp. 1–4.

[4] Y. Yue, Y. Dong, and J. Zhou, "An ultra-wideband vivaldi antenna array in l and s bands," in *Proceedings of the 5th Asia-Pacific Conference on Antennas and Propagation (APCAP)*. IEEE, 2016, pp. 301–302.

[5] Nurhayati, E. Setijadi, and G. Hendrantoro, "Effect of vivaldi element pattern on the uniform linear array pattern," in *Proceedings of the International Conference on Communication, Networks and Satellite (COMNETSAT)*. IEEE, 2016, pp. 42–47.

[6] S. M. Umar, W. R. Khan, S. Ullah, and F. Ahmad, "Gain enhancement technique in vivaldi antenna for 5G communication," in *Proceedings of International Conference on Computing, Mathematics and Engineering Technologies – iCoMET*. IEEE, 2019, pp. 1–3.

[7] S. Koziel and S.Ogurtsov, "Surrogate-assisted desing of low-sidelobe microstrip linear arrays with corporate feeds," in *Proceedings of MTT-S International Conference on Numerical Electromagnetic and Multiphysics Modeling and Optimization (NEMO)*. IEEE, 2018, pp. 1–3.

[8] J. Lin, W. Shen, and K.Yang, "A low side lobe and wide band series fed linear dielectric resonator antenna array," *IEEE Antennas and Wireless Propagation Letters*, vol. 16, pp. 513–516, 2016.

[9] W. Shen, J. Lin, and K. Yang, "Design of a v-band low sidelobe and wideband linear DRA array," in *Proceedings of the Progress in Electromagnetic Reseach Symposium*, 2016, pp. 477–480.

[10] T. T. Toan, T. V. B. Giang, and N. M. Tran, "A novel chebyshev series fed linear array with high gain and low sidelobe level for WLAN outdoor systems," *The Applied Computational Electromagnetics Society Journal*, vol. 34, pp. 1143–1151, 2019.

[11] J. Kaur and S. Goyal, "A comparative study on linear array antenna pattern synthesis using evolutionary algorithms," *International Journal of Advanced Research in Computer Science*, vol. 8, pp. 1582–1587, 2017.

[12] Q. Yao and Y. Lu, "Efficient beamforming using bat algorithm," in *Proceedings of the IEEE MTT-S International Conference on Numerical Electromagnetic and Multiphysics Modeling and Optimization (NEMO)*, 2016.

[13] T. V. Luyen and T. V. B. Giang, "Interference suppression of ULA antennas by phase-only control using bat algorithm," *IEEE Antennas And Wireless Propagation Letters*, vol. 16, pp. 3038–3042, 2017.

[14] ——, "Bat algorithm based beam former for interference suppression by controlling the complex weight," *REV Journal on Electronics and Communications*, vol. 7, pp. 87–93, 2017.

[15] ——, "Null-steering beam former using bat algorithm," *The Applied Computational Electromagnetics Society Journal*, vol. 33, pp. 23–29, 2018.

[16] G. Yin, Q. Wu, C. Yu, H. Wang, and W. Hong, "Low sidelobe-level series-fed microstrip antenna array of unequal inter-element spacing," *IEEE Antennas and Wireless Propagation Letters*, vol. 16, pp. 1695–1698, 2017.

[17] A. Reyna and L. I. Balderas, "4D antenna array of UWB vivaldi elements with low side lobes and harmonic suppresion," in *Proceedings of the IEEE International Symposium on Antennas and Propagation & USNC/URSI National Radio Science Meeting*. IEEE, 2018, pp. 1505–1506.

[18] *Radio Regulations*, International Telecommunication Union, Geneva, 2016.

[19] *Terrestrial wireless communications: Identifying, managing and harmonizing radio-frequency spectrum*, ITU-R News Magazine, Geneva, 2019.

[20] D. M. Pozar, "Chapter 3: Transmission lines and waveguides," in *Microwave Engineering*, 4th ed. New York: John Wiley & Sons, Inc, 2011.

[21] C. A. Balanis, "Chapter 15: Reflector antennas," in *Antenna Theory Analysis and Design*, 3rd ed. New York: John Wiley & Sons, Inc, 2011.

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