REPUBLIK INDONESIA
KEMENTERIAN HUKUM DAN HAK ASASI MANUSIA

SURAT PENCATATAN
CIPTAAN

Dalam rangka pelindungan ciptaan di bidang ilmu pengetahuan, seni dan sastra berdasarkan Undang-Undang Nomor 28 Tahun 2014 tentang Hak Cipta, dengan ini menerangkan:

Nomor dan tanggal permohonan : EC00202023566, 18 Juli 2020

Pencipta

Nama : **Dr. Nurhayati., ST., MT, Eko Setijadi., ST., MT., Ph.D dkk**

Alamat : Jl. Rungkut Barata Gang 17 No 11 RT/RW 0007/003 Kelurahan Rungkut Menanggal, Kecamatan Gunung Anyar, Surabaya, Jawa Timur, 60293

Kewarganegaraan : Indonesia

Pemegang Hak Cipta

Nama : **Dr. Nurhayati., ST., MT, Eko Setijadi., ST., MT., Ph.D,**

Alamat : Jl. Rungkut Barata Gang 17 No 11 RT/RW 0007/003 Kelurahan Rungkut Menanggal, Kecamatan Gunung Anyar, Surabaya, 10, 60293

Kewarganegaraan : Indonesia

Jenis Ciptaan : **Karya Tulis (Artikel)**

Judul Ciptaan : **Mutual Coupling Evaluation And Calculation For Coplanar Vivaldi Array**

Tanggal dan tempat diumumkan untuk pertama kali di wilayah Indonesia atau di luar wilayah Indonesia : 2 Desember 2019, di Surabaya

Jangka waktu pelindungan : Berlaku selama hidup Pencipta dan terus berlangsung selama 70 (tujuh puluh) tahun setelah Pencipta meninggal dunia, terhitung mulai tanggal 1 Januari tahun berikutnya.

Nomor pencatatan : 000195050

adalah benar berdasarkan keterangan yang diberikan oleh Pemohon.
Surat Pencatatan Hak Cipta atau produk Hak terkait ini sesuai dengan Pasal 72 Undang-Undang Nomor 28 Tahun 2014 tentang Hak Cipta.

a.n. MENTERI HUKUM DAN HAK ASASI MANUSIA
DIREKTUR JENDERAL KEKAYAAN INTELEKTUAL

Dr. Freddy Harris, S.H., LL.M., ACCS.
NIP. 196611181994031001

LAMPIRAN PENCIPTA

No	Nama	Alamat
1	Dr. Nurhayati., ST., MT	Jl. Rungkut Barata Gang 17 No 11 RT/RW 0007/003 Kelurahan Rungkut Menanggal, Kecamatan Gunung Anyar
2	Eko Setijadi., ST., MT., Ph.D	Jl. Raya Ngelom No 68 RT 0002/0003 Kel Ngelom Kecamatan Taman

LAMPIRAN PEMEGANG

No	Nama	Alamat
1	Dr. Nurhayati., ST., MT	Jl. Rungkut Barata Gang 17 No 11 RT/RW 0007/003 Kelurahan Rungkut Menanggal, Kecamatan Gunung Anyar
2	Eko Setijadi., ST., MT., Ph.D	Jl. Raya Ngelom No 68 RT 0002/0003 Kel Ngelom Kecamatan Taman

ARTICLE TYPE

Mutual Coupling Evaluation and Calculation for Coplanar Vivaldi Array

Nurhayati *[1] | Eko Setijadi[2]

[1]Department of Electrical Engineering, Universitas Negeri Surabaya, Surabaya, Indonesia
[2]Department of Electrical Engineering, Institut Teknologi Sepuluh Nopember, Surabaya, Indonesia

Correspondence
*Nurhayati, Email: nurhayati@unesa.ac.id

Present Address
Departement of Electrical Engineering, Faculty of Engineering, Universitas Negeri Surabaya, Indonesia

Abstracs

This paper discusses mutual coupling evaluation and calculation of the Coplanar Vivaldi antenna array. Mutual coupling of the Coplanar Vivaldi is evaluated by comparing several element widths, structure and size of configuration array in the E and H-plane. Mutual coupling calculation of two antenna elements in the E-plane is analyzed by multiplying the radiation pattern of its element and flux pointing. Mutual coupling in an array can be seen from mutual impedance that consists of mutual resistance and mutual reactance. The smaller the width of the antenna, the higher the mutual coupling so it advances the resistance and reactance. Coplanar Vivaldi Array with Exponential Corrugated Slot (CVA-ECT) shows better performance of return loss and gain than CVA with No Slot (CVA-NS) in the E-plane. But otherwise in the H-plane. For the same volume size of an array, the smaller the width of the element, the better the performance in gain than the wider ones. It shows that at 7 GHz, 3×2 array reaches a gain up to 13.69 dB. Otherwise, 2×2 CVA-NS grasps the gain 8.9 dB. There was a significant result between simulation and modeling results of the radiation pattern element and mutual coupling of the Coplanar Vivaldi antenna.

KEYWORDS:
Antenna array, vivaaldi antenna, mutual coupling, impedance, impedance

1 | INTRODUCTION

Vivaldi antenna is a tapered slot antenna [1] that has wide bandwidth and high gain. The previous study that describes return loss and radiation pattern performance of the Vivaldi element by changing the shape of the radiator has been discussed in [2][3][4][5], as well as the effect of the type of substrate on the antenna[6]. However, these explanations are just only for a single element antenna.

Vivaldi antenna can be arranged in an array to reach higher directivity and smaller beam width than a single element. In an array, the spacing between elements affects the result of the return loss and the performance of the total array pattern [7]. In wideband array, the wider element can improve return loss and mutual coupling performance in the low-end frequency, but it yields worse performance of radiation pattern in high-end frequency due to grating lobe and conversely. Vivaldi antenna as the wideband antenna has various applications in the array such as astronomy[8] and radar[9]. However, it has a problem in mutual coupling especially if the width of the antenna is less than one-half the wavelength of its low-end frequency. Furthermore, the existence of a mutual coupling disrupts phase vector [10]. Mutual coupling analysis was done as a previous study by Exponential Corrugated Truncated (CVA-ECT) Slot [6]. The discussion is only for two antenna elements in the E-plane. There is no discussion for H-plane and no discussion on some dimension of the array.

Mutual coupling reduction has been discussed in microstrip [11], monopole antenna [12], and Vivaldi antenna [7] by electromagnetic computation result. Mutual coupling in an analytical approach has been carried out in microstrip [13] and dipole [14] array. In that paper, the mutual coupling of the dipole antenna is shown from the mutual impedance which depends on the antenna element radiation pattern. Mutual coupling evaluation and analysis by the analytic method needs to be done because the influence of large mutual coupling will affect the performance of the antenna. The high mutual coupling can affect the antenna impedance and the total array of the pattern of the array. Therefore, it is important to analyze the mutual coupling of the Vivaldi antennas from simulation and calculation results.

The next part of this paper evaluates mutual coupling from scattering parameter S_{ij} (port j to i) performance and its radiation pattern in different sizes of an array, in the E and H plane. It is shown that mutual coupling in CVA-ECT is less than CVA without a slot (CVA-NS) in the E-plane, but the opposite is true in the H-plane. For wideband array, in the same dimension of array volume, the smaller width of the element yields better performance of radiation pattern at most of the frequency than larger widths of the element. We also consider the radiation pattern element and mutual coupling modeling of the Vivaldi array. The modeling result is compared and analyzed with the simulation result. This paper is organized as follows. Section 2 will discuss mutual coupling in coplanar Vivaldi Array. Section 3 will discuss mutual coupling calculation, and Section IV is the conclusion.

2 | MUTUAL COUPLING IN COPLANAR VIVALDI ARRAY

Coplanar vivaldi element with no structure is shown in Figure 1.(a) and (e), whreas Coplanar Vivaldi element with Exponential Corrugated Truncated (ECT) is shown in Fig 1(b). Antenna element in Figure.1 is designed on FR4 materials with dielectric constant of 4.6, substrate thickness of 1.6 mm, copper thickness of 0.035mm, L = 60 mm, W = 60 mm, W_t =30 mm, L_t = 42.5 mm, L_{sl} = 7.5mm, W_{sl} = 0.5 mm, r = 3 mm, W_f = 2.5 mm, D_f =3mm, x_f = 4 mm, y_f = 5 mm, R_2=0.001 mm, R_s=0.001 mm, N= number of corrugated and R=0.15 mm. The tapered slot of Vivaldi can be designed in [7]

$$y = C_1 e^{Rx} + C_2 , \qquad C_1 = \frac{y_2 - y_1}{e^{Rx_2} - e^{Rx_1}} , \qquad C_2 = \frac{y_1 e^{Rx_2} - y_2 e^{Rx_1}}{e^{Rx_2} - e^{Rx_1}} \tag{1}$$

where y denotes the tapered slot curve, while x_1, y_1, x_2, and y_2 are the coordinates of the start and end of tapered slot's slope.

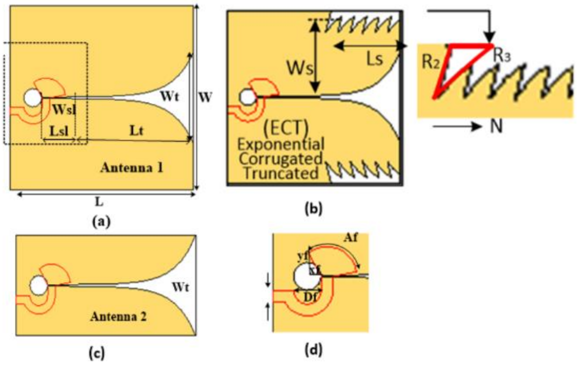


FIGURE 1. Coplanar Vivaldi Element: (a) Coplanar Vivaldi conventional, (b). Coplanar Vivaldi Antenna with ECT, (c) Vivaldi element with smaller width and (d) feeding shape

Figure 2(a) displays the performance of S_{11} (bottom side) and S_{21} (upper site) obtained for the 2x1 array with element width 40 mm, 50 mm, 60 mm. In an array configuration, the wider the element width, the larger spacing between elements. It reduces mutual coupling, especially in the lower frequency. The smaller element width yields higher fluctuation of resistance and reactance. At 2 GHz, an array with a continuous patch has a center-to-center spacing of 40 mm ≈ $0.26\lambda_0$, 50 mm ≈ $0.33\lambda_0$, 60 mm ≈ $0.4\lambda_0$. Except for spacing between elements, the structure of the antenna element could affect isolation between elements in an antenna array. Figure 2(b) shows the significant result of return loss from measurement and simulation results for CVA-NS and CVA-ECT. Although there is a slight discrepancy, the array antenna can work in UWB frequency from 2 GHz to more than 10 GHz. The effect on giving ECT structure to the array antenna performance will be explained in the next subsection.

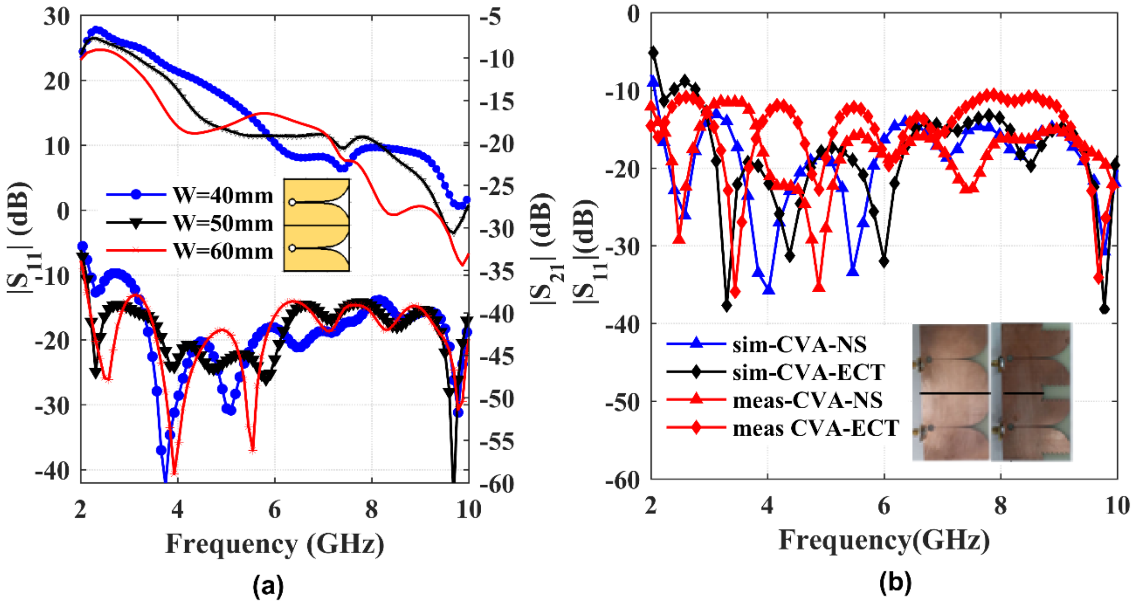


FIGURE 2. (a). S_{11} and S_{21} performance in different width of elements and (b). The simulation and measurement result of return loss for CVA-NS and CVA-ECT.

2.1 | Sij Contour Plot For Linear and Planar Array

S_{ij} performance of CVA-NS performed by contour plot has been discussed in [7] without comparison with CVA-ECT. However, in this subsection, we compare the S_{ij} performance of several dimensions of the array in the E and H-plane. At 3 GHz, CVA-ECT has a better performance of S_{ij} than CVA-NS for 2×1 array in the E-plane as shown in Figure 3(a)-(b). It shows that the S_{21} of CVA-ECT is -20 dB but CVA-NS is -11 dB. The corrugated truncated structure reduces the mutual coupling between array elements because the surface current will be trapped in the corrugated structure.

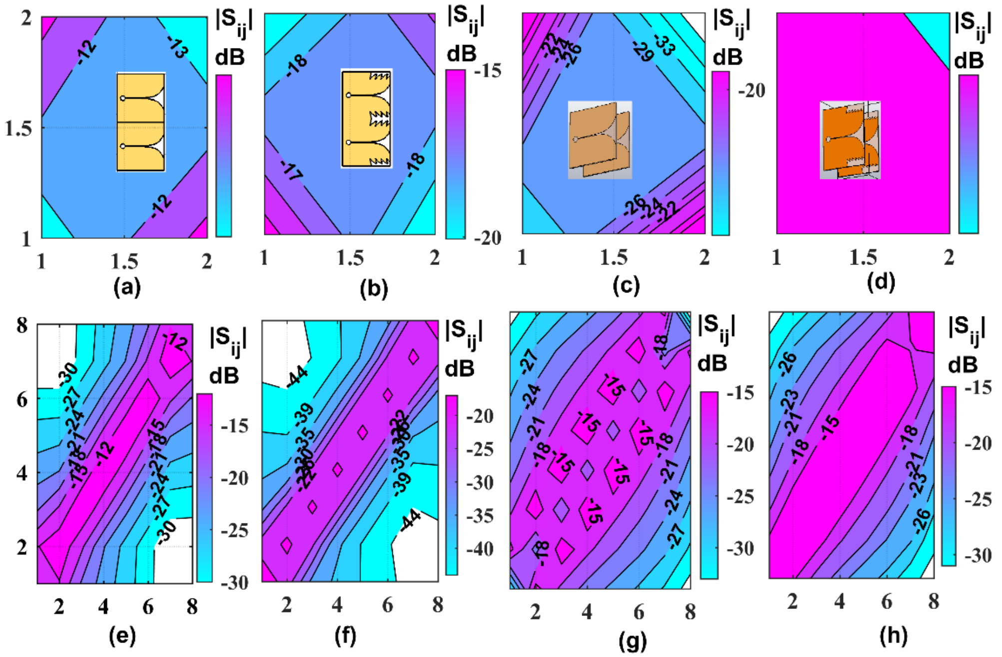


FIGURE 3. Contour plot of scattering parameter (S_{ij}) for j^{th} element to i^{th} element for (a) CVA-NS 2×1 in the E- plane, (b) CVA-ECT 2×1 in the E-plane, (c) CVA-NS 1×2 in the H-plane, (d) CVA-ECT 1×2 in the H-plane, (e) CVA-NS 8×1 in the E-plane, (f) CVA-ECT 8×1 in the E-plane, (g) CVA-NS 1×8 in the H-plane, (h) CVA-ECT 1×8 in the H-plane.

The performance S_{ij} of CVA-NS in Figure 3(c) with array dimension 2×1 in the H-plane has a better performance of S_{ij} than CVA-ECT in Figure 3(d) at 3 GHz with 40 cm spacing between elements. CVA-NS has more varieties of S_{ij} than CVA-ECT. It shows that the self scattering parameter in the H-plane is better than in the E-plane. Figure.3(e) and (f) show the performance of S_{ij} in the E-plane for 8×1 array. An increasing number of elements in the E-plane yields a decrease in S_{ij}. However S_{ij} performance of 1×8 array in the H-plane is shown in Figure 3(g) and (h). It can be concluded that in a linear array, CVA-ECT has better performance of S_{ij} than CVA–NS in the E-plane but the opposite is true in the H-plane. In the E plane, the movement of the surface current in the structure is obstructed to the next element in a continuous patch. In the H plane, the electric field with ECT structured gives more interference to the neighboring element from the air, but it depends on the spacing between elements.

2.2 | The Radiation Pattern of the Array

Figure. 4 compares the radiation pattern of 2×1, 8×1, and 2×2 of Vivaldi arrays. CVA-ECT has better gain than CVA-NS at 3 GHz. Gain performance in the ascending order is reached for 2×1, 2×2, and 8×1. An increasing number of the element, by giving ECT structure in 8×1 array, only slight produce increasing in gain performance of the antenna at the lower frequency. Figure.4 displays that the back lobe of CVA-ECT higher than CVA-NS for 2×1 and 2×2 arrays. whereas the back lobe for 8×1 CVA-ECT is less than CVA-NS. At 3 GHz, 2×1 CVA-ECT has a higher SLL than CVA-NS. This performance is the difference between other frequencies. There is a trade-off between increasing performance of gain, SLL and back lobe

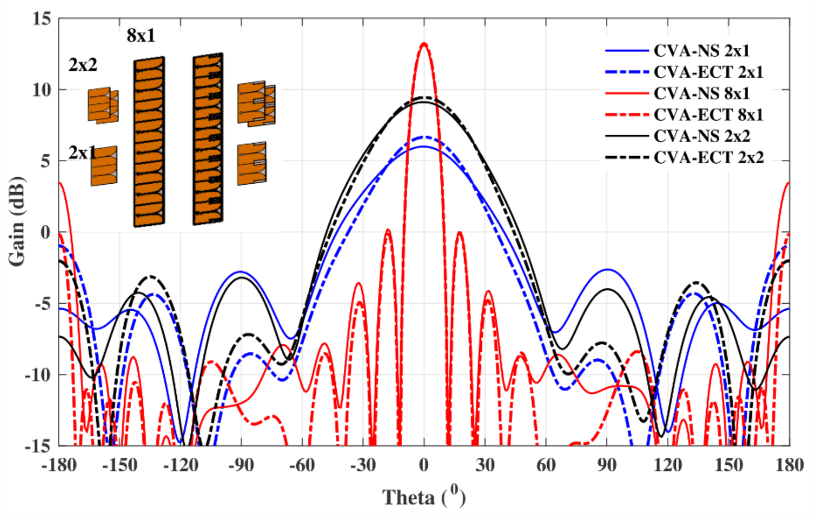
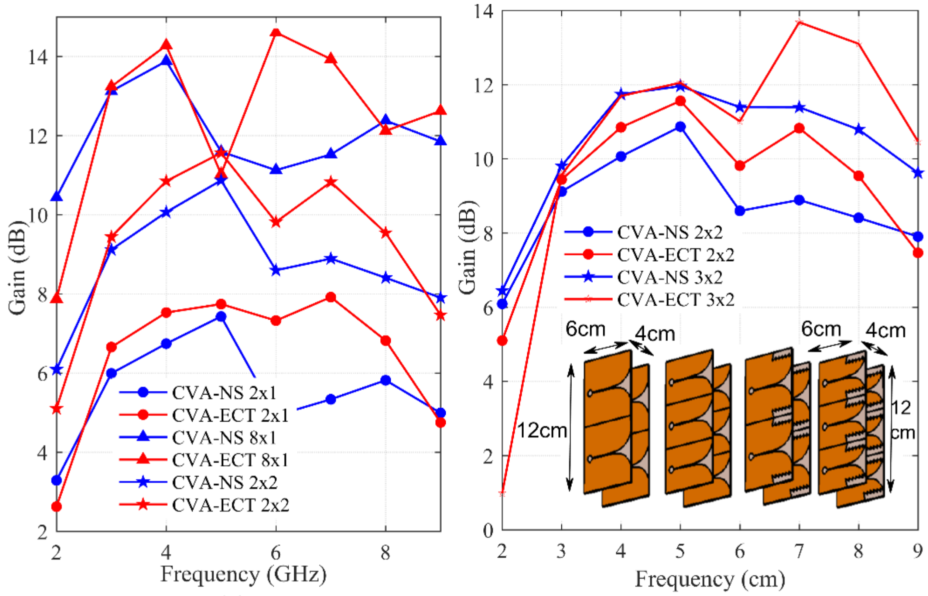


FIGURE 4 Gain OF CVA-NS and CVA-ECT for 2×1, 2×2 and 8×1 array at f = 3 GHz in the E-plane

The performance of gain in wideband frequency for 2×1, 2×2, and 8×1 array in the E-Plane is shown in Figure. 5(a). The increase of gain occurs in the most of frequency range for 2×1 CVA-ECT in the linear array and 2x2 CVA-ECT in the planar array in the E-plane. Whereas for 8x1 linear array, the increase of gain is only on some frequencies i.e. at 3, 4, 6, 7, and 9 GHz. The increasing number of the element not always the case increases the gain in all frequency band, especially in the linear array. The significant increase of gain for 2x2 happened in almost all band frequencies. Providing a corrugated slot can improve gain performance in a planar array, but for a linear array, it does not show an increase of gain at all frequencies.



(a)

(b)

FIGURE 5 Gain of CVA-NS and CVA-ECT : (a) 2×1, 2×2 and 8×1 array in the E-plane, and (b) The gain of CVA-ECT and CVA-NS in the planar array

Scattering parameter for 2×2 array with element dimension 6 cm x 6 cm x 1.6 cm and 3x2 array with element 4 cm × 6 cm ×1.6 cm are compared with ECT and No structure. Those comparisons are shown in Figure.5(b). Although both types of the array have the same volume dimension i.e 12 cm×6 cm ×4 cm, the smaller element has a higher performance of gain. At 7 GHz, Gain of CVA-ECT with 3×2 is 13.69 dB but CVA-NS with 2×2 has a gain of 8.9 dB. It shows increasing of gain as 4.79 dB. It can be concluded that for the same whole volume of an array, the smaller width of an element of the array, the better performance of gain than the bigger ones. Using smaller structured elements will decrease gain performance in lower frequency but for the whole frequency, the smaller structure is preferable.

3 | MUTUAL COUPLING CALCULATION

Mutual coupling of the antenna interferes with antenna performance due to its electromagnetic interaction. It can influence impedance and radiation pattern performance. Vivaldi antenna as a wideband antenna shows trade of the mutual coupling and radiation performance. The spacing between elements interferes with mutual coupling in the lower frequency but it also interferes with radiation pattern performance in the higher frequency. In the lower frequency, in the E plane, the antenna element has smaller spacing between elements than spacing at a higher frequency relative to its wavelength. Mutual coupling analysis can be found from mutual scattering S_{ij} or mutual impedance Z_{ij}. Calculation of mutual coupling for dipole and microstrip antenna has been discussed in [14]. It develops resistance modeling by pointing vector and reactance modeling by Kramers-Kronig relation. The integral through electric and magnetic field stated in that literature in equation (2) as power radiated from the radiator. Where *E* is an electric field, *r* is the distance between radiation center to surface, $\phi_i(\theta,\varphi)$ is the amplitude of the radiation pattern. Z_i is impedance parameter that interferes by free space characteristics impedance, radiation resistance and the directivity of radiator. These parameters are explained in detail in the reference[14]

$$\int_{S_0}\left(E\times H^*\right) dS = \frac{1}{120\pi}\int_{S_0}|E|^2 r_0^2 \sin\theta \, d\theta d\varphi \;=\mathrm{Re}\left\{\frac{Z_i Z_l}{120\pi}\sum_{l=1}^{m}\sum_{i=1}^{m} I_i I_l \int_0^{2\pi}\int_0^{\pi}\phi_i(\theta,\varphi)\varphi_l^*(\theta,\varphi)\sin\theta \, d\theta d\varphi\right\} \tag{2}$$

$$r_{12} = \frac{Z_1^2}{120\pi}\int_0^{2\pi}\int_0^{\pi}\left(\phi^2(\theta,\varphi)\cos\left(k\,d\sin\theta\sin\varphi\right)\sin\theta\right)d\theta\, d\varphi \tag{3}$$

$$x_{12} = -\frac{Z_1^2}{120\pi}\int_0^{2\pi}\int_0^{\pi}\left(\phi^2(\theta,\varphi)\sin\left(k\,d\sin\theta\right)\sin\theta\right)d\theta\, d\varphi \tag{4}$$

Impedance antenna consists of resistance and reactance can be seen in equation (3) and (4) by reference, where the wavenumber of $k = \omega / c$, d is the distance between the element in an array. From that equation, we found that there is radiation pattern modeling that is needed to model mutual resistance and mutual reactance. The radiation pattern modeling of the Coplanar Vivaldi element has been discussed [15]. However, it was complicated. As a result, we modeled simple radiation pattern modeling for Vivaldi element as shown in equation (5):

$$\phi(\theta,\varphi) = 0.4\left(\cos(1.8\theta)^2 + 0.6\exp\left(-2.5\left(1.4\theta/180\right)^2\right)\right) \tag{5}$$

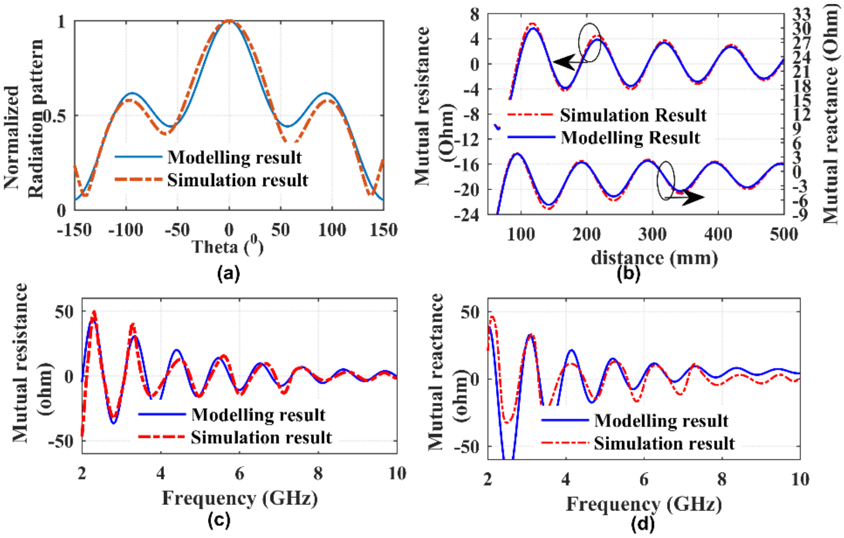


FIGURE 6. (a) Normalized radiation pattern of Coplanar Vivaldi element, (b) Mutual resistance and reactance vs distance, (c) Mutual resistance vs frequency, and (d) Mutual reactance vs frequency

Figure 6(a) displays radiation pattern the coplanar Vivaldi element in modeling result and simulation result in the E-plane at phi=90^0. This model can be developed for array analysis with factor array for coplanar Vivaldi in large volume and configuration of the array. Mutual resistance and reactance can be found by including the coplanar Vivaldi element modeling into equation (3) and (4). Mutual impedance vs distance of Coplanar Vivaldi array can be seen in Figure. 6(b). It exposes that there is consistency in mutual impedance using modeling results and simulation results. This article also purposes an equation for mutual impedance vs frequency of coplanar Vivaldi array that can be shown in equation (6) and (7).

$$r_{12} = \frac{Z_1^2 e^{-0.2f}}{120\pi} \int_0^{2\pi}\int_0^{\pi} \left(3*W*\left(\phi^2(\theta,\varphi)\right) \cos\left(\frac{2\pi f}{c} 4.75d \sin\theta \sin\varphi\right) \sin\theta \right) d\theta d\varphi \tag{6}$$

$$x_{12} = -\left(\frac{Z_1^2 e^{-0.35f}}{120\pi} \int_0^{2\pi}\int_0^{\pi} \left(12\left(\phi^2(\theta,\varphi)\right) \sin\left(\frac{2\pi f}{c}(4.75W) d \sin\theta \sin\varphi\right) \sin\theta \right) d\theta d\varphi + \frac{A}{1+(f \times B)} \right) + W \tag{7}$$

Where Z_i= impedance of element , W = element width, d = distance between element, A = the width of element and B = the length of the Coplanar Vivaldi element. Figure.6(c) and (d) display comparison mutual resistance vs frequency from equation (6) and mutual reactance vs frequency from equation (7) of modeling result and simulation result of coplanar Vivaldi. By using the modeling result we can approximately the mutual impedance of the array without simulation by including the radiation pattern modeling.

4 | CONCLUSION

Mutual coupling analyzed and calculation has been done for some array configuration i.e 2×1, 8×1, 2×2 and 3×2 of Coplanar Vivaldi array in E and H-plane. Exponential Corrugated Slot (CVA-ECT) has a better performance of mutual coupling and radiation pattern in the E-plane than Coplanar Vivaldi Array without slot (CVA-NS) but it is the opposite in the H-plane. In planar array, for the same volume of an array, the smaller width of element array yields better performance in gain than the wider ones in most operating frequencies. At 7 GHz, from the simulation result, 3x2 of CVA-ECT reach increasing in gain 4.79 dB, if it compares with CVA-NS, in the same volume of an array. Mutual coupling calculation of Coplanar Vivaldi array has been done to get mutual resistance and mutual reactance of Vivaldi array by including Coplanar Vivaldi element modeling in the calculation. The coplanar Vivaldi element modeling can be developed for array analysis with factor array in large volume and various configuration of the array. The calculation result of mutual coupling Coplanar Vivaldi array can be developed for mutual coupling analysis as validation with electromagnetic simulation.

References

[1] P. J. Gibson, “THE VIVALDI AERIAL,” in *Proc. 9th European Microwave Conference*, 1979, pp. 101–105.

[2] 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 Wirel. Propag. Lett.*, 2016, DOI: 10.1109/LAWP.2015.2457919.

[3] P. Fei, Y. C. Jiao, W. Hu, and F. S. Zhang, “A miniaturized antipodal Vivaldi antenna with improved radiation characteristics,” *IEEE Antennas Wirel. Propag. Lett.*, 2011, DOI: 10.1109/LAWP.2011.2112329.

[4] M. Abbak, M. N. Akıncı, M. Ç. Ayören, and ˙ I Akduman, “Experimental Microwave Imaging with a Novel Corrugated Vivaldi Antenna,” *IEEE Trans. Antennas Propag.*, vol. 65, pp. 3302–3307, 2017, DOI: 10.1109/TAP.2017.2670228.

[5] N. Nurhayati, A. M. De Oliveira, J. F. Justo, E. Setijadi, B. E. Sukoco, and E. Endryansyah, “Palm tree coplanar Vivaldi antenna for near field radar application,” *Microw. Opt. Technol. Lett.*, vol. 62, no. 2, 2020, DOI: 10.1002/mop.32127.

[6] S. Kasturi and D. H. Schaubert, “Effect of dielectric permittivity on infinite arrays of single-polarized Vivaldi antennas,” *IEEE Trans. Antennas Propag.*, vol. 54, no. 2, pp. 351–358, 2006, DOI: 10.1109/TAP.2005.863374.

[7] Nurhayati, G. Hendrantoro, T. Fukusako, and E. Setijadi, “Mutual Coupling Reduction for a UWB Coplanar Vivaldi Array by a Truncated and Corrugated Slot,” *IEEE Antennas Wirel. Propag. Lett.*, vol. 17, no. 12, pp. 2284–2288, 2018, DOI: 10.1109/LAWP.2018.2873115.

[8] E. W. Reid, L. Ortiz-Balbuena, A. Ghadiri, and K. Moez, “A 324-element Vivaldi antenna array for radio astronomy instrumentation,” *IEEE Trans. Instrum. Meas.*, vol. 61, no. 1, pp. 241–250, 2012, DOI: 10.1109/TIM.2011.2159414.

[9] J. B. Yan, S. Gogineni, B. Camps-Raga, and J. Brozena, “A Dual-Polarized 2-18-GHz Vivaldi Array for Airborne Radar Measurements of Snow,” *IEEE Trans. Antennas Propag.*, vol. 64, no. 2, pp. 781–785, 2016, DOI: 10.1109/TAP.2015.2506734.

[10] C. Yeh, M. Lee, and D. Ucci, “Bearing Estimations with Mutual Coupling Present,” *IEEE Trans. Antennas Propag.*, vol. 37, no. 10, pp. 1332–1335.

[11] C. Hao, H. Zheng, and X. Sun, “Mutual coupling reduction between patch antennas based on microstrip structures,” *Microw. Opt. Technol. Lett*, no. May, pp. 1–4, 2019, DOI: 10.1002/mop.32052.

[12] A. Isaac, H. Al-Rizzo, S. Yahya, A. Al-Wahhamy, and S. Abushamleh, “Decoupling of Two Closely- Spaced Planar Monopole Antennas Using Two Novel Printed-Circuit Structures,” *Microw. Opt. Technol. Lett*, vol. 2, no. 2, pp. 30–35, 2016, DOI: 10.1002/mop.31405.

[13] D. W. G. A. H. Mohammadian, N. M. Martin, “A Theoretical and Experimental Study of Mutual Coupling in Microstrip Antenna Arrays,” *IEEE Trans. Antennas Propag.*, vol. 31, pp. 1217–1223, 1989.

[14] O. G. Vendik and D. S. Kozlov, “A Novel Method for the Mutual Coupling Calculation between Antenna Array Radiators: Analysis of the radiation pattern of a single radiator in the antenna array.,” *IEEE Antennas Propag. Mag.*, 2015, DOI: 10.1109/MAP.2015.2481818.

[15] Nurhayati, E. Setijadi, and G. Hendrantoro, “Radiation pattern analysis and modeling of Coplanar Vivaldi antenna element for linear array pattern evaluation,” *Prog. Electromagn. Res. B*, vol. 84, 2019.

Mutual Coupling Evaluation and Calculation for Coplanar Vivaldi Array

by Nurhayati Nurhayati

Submission date: 10-Jun-2021 01:30PM (UTC+0700)

Submission ID: 1603914928

File name: Mutual_coupling_evaluation_and_calculation_Nurhayati.pdf (1.04M)

Word count: 3405

Character count: 16783

ARTICLE TYPE

Mutual Coupling Evaluation and Calculation for Coplanar Vivaldi Array

Nurhayati *[1] | Eko Setijadi[2]

[1]Department of Electrical Engineering, Universitas Negeri Surabaya, Surabaya, Indonesia
[2]Department of Electrical Engineering, Institut Teknologi Sepuluh Nopember, Surabaya, Indonesia

Correspondence
*Nurhayati, Email: nurhayati@unesa.ac.id

Present Address
Departement of Electrical Engineering, Faculty of Engineering, Universitas Negeri Surabaya, Indonesia

Abstracs

This paper discusses mutual coupling evaluation and calculation of the Coplanar Vivaldi antenna array. Mutual coupling of the Coplanar Vivaldi is evaluated by comparing several element widths, structure and size of configuration array in the E and H-plane. Mutual coupling calculation of two antenna elements in the E-plane is analyzed by multiplying the radiation pattern of its element and flux pointing. Mutual coupling in an array can be seen from mutual impedance that consists of mutual resistance and mutual reactance. The smaller the width of the antenna, the higher the mutual coupling so it advances the resistance and reactance. Coplanar Vivaldi Array with Exponential Corrugated Slot (CVA-ECT) shows better performance of return loss and gain than CVA with No Slot (CVA-NS) in the E-plane. But otherwise in the H-plane. For the same volume size of an array, the smaller the width of the element, the better the performance in gain than the wider ones. It shows that at 7 GHz, 3×2 array reaches a gain up to 13.69 dB. Otherwise, 2×2 CVA-NS grasps the gain 8.9 dB. There was a significant result between simulation and modeling results of the radiation pattern element and mutual coupling of the Coplanar Vivaldi antenna.

KEYWORDS:
Antenna array, vivaaldi antenna, mutual coupling, impedance, impedance

1 | INTRODUCTION

Vivaldi antenna is a tapered slot antenna [1] that has wide bandwidth and high gain. The previous study that describes return loss and radiation pattern performance of the Vivaldi element by changing the shape of the radiator has been discussed in [2][3][4][5], as well as the effect of the type of substrate on the antenna[6]. However, these explanations are just only for a single element antenna.

Vivaldi antenna can be arranged in an array to reach higher directivity and smaller beam width than a single element. In an array, the spacing between elements affects the result of the return loss and the performance of the total array pattern [7]. In wideband array, the wider element can improve return loss and mutual coupling performance in the low-end frequency, but it yields worse performance of radiation pattern in high-end frequency due to grating lobe and conversely. Vivaldi antenna as the wideband antenna has various applications in the array such as astronomy[8] and radar[9]. However, it has a problem in mutual coupling especially if the width of the antenna is less than one-half the wavelength of its low-end frequency. Furthermore, the existence of a mutual coupling disrupts phase vector [10]. Mutual coupling analysis was done as a previous study by Exponential Corrugated Truncated (CVA-ECT) Slot [6]. The discussion is only for two antenna elements in the E-plane. There is no discussion for H-plane and no discussion on some dimension of the array.

Mutual coupling reduction has been discussed in microstrip [11], monopole antenna [12], and Vivaldi antenna [7] by electromagnetic computation result. Mutual coupling in an analytical approach has been carried out in microstrip [13] and dipole [14] array. In that paper, the mutual coupling of the dipole antenna is shown from the mutual impedance which depends on the antenna element radiation pattern. Mutual coupling evaluation and analysis by the analytic method needs to be done because the influence of large mutual coupling will affect the performance of the antenna. The high mutual coupling can affect the antenna impedance and the total array of the pattern of the array. Therefore, it is important to analyze the mutual coupling of the Vivaldi antennas from simulation and calculation results.

The next part of this paper evaluates mutual coupling from scattering parameter S_{ij} (port j to i) performance and its radiation pattern in different sizes of an array, in the E and H plane. It is shown that mutual coupling in CVA-ECT is less than CVA without a slot (CVA-NS) in the E-plane, but the opposite is true in the H-plane. For wideband array, in the same dimension of array volume, the smaller width of the element yields better performance of radiation pattern at most of the frequency than larger widths of the element. We also consider the radiation pattern element and mutual coupling modeling of the Vivaldi array. The modeling result is compared and analyzed with the simulation result. This paper is organized as follows. Section 2 will discuss mutual coupling in coplanar Vivaldi Array. Section 3 will discuss mutual coupling calculation, and Section IV is the conclusion.

2 | MUTUAL COUPLING IN COPLANAR VIVALDI ARRAY

Coplanar vivaldi element with no structure is shown in Figure 1.(a) and (e), whreas Coplanar Vivaldi element with Exponential Corrugated Truncated (ECT) is shown in Fig 1(b). Antenna element in Figure.1 is designed on FR4 materials with dielectric constant of 4.6, substrate thickness of 1.6 mm, copper thickness of 0.035mm, $L = 60$ mm, $W = 60$ mm, $W_t = 30$ mm, $L_t = 42.5$ mm, $L_{sl} = 7.5$mm, $W_{sl} = 0.5$ mm, [illegible] = 3 mm, $W_f = 2.5$ mm, $D_f = 3$mm, $x_f = 4$ mm, $y_f = 5$ mm, $R_2 = 0.001$ mm, $R_s = 0.001$ mm, N= number of corrugated and $R = 0.15$ mm. The tapered slot of Vivaldi can be designed in [7]

$$y = C_1 e^{Rx} + C_2 , \quad C_1 = \frac{y_2 - y_1}{e^{Rx_2} - e^{Rx_1}} , \quad C_2 = \frac{y_1 e^{Rx_2} - y_2 e^{Rx_1}}{e^{Rx_2} - e^{Rx_1}} \tag{1}$$

where y denotes the tapered slot curve, while x_1, y_1, x_2, and y_2 are the coordinates of the start and end of tapered slot's slope.

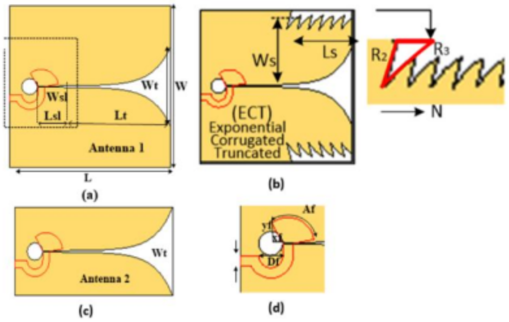
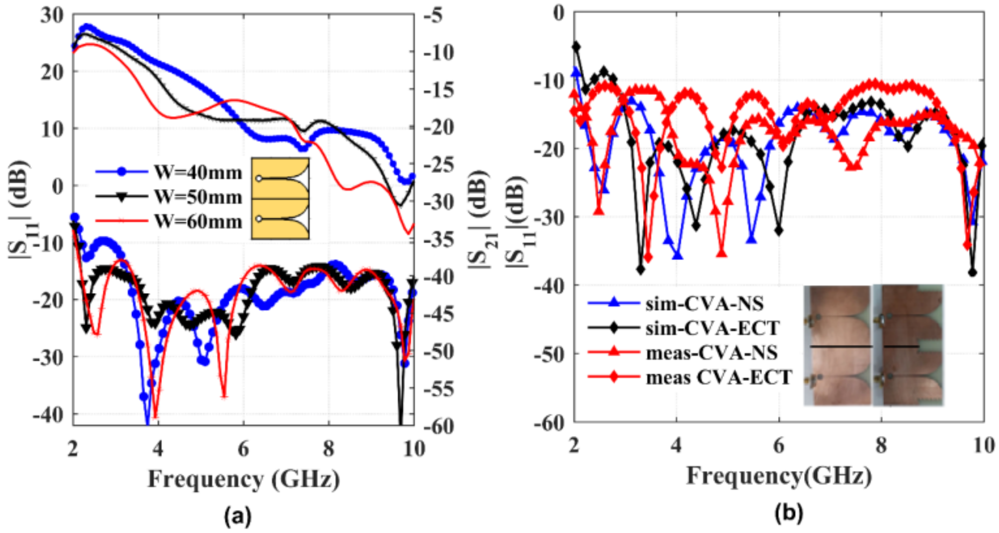


FIGURE 1. Coplanar Vivaldi Element: (a) Coplanar Vivaldi conventional, (b). Coplanar Vivaldi Antenna with ECT, (c) Vivaldi element with smaller width and (d) feeding shape

Figure 2(a) displays the performance of S_{11} (bottom side) and S_{21} (upper site) obtained for the 2x1 array with element width 40 mm, 50 mm, 60 mm. In an array configuration, the wider the element width, the larger spacing between elements. It reduces mutual coupling, especially in the lower frequency. The smaller element width yields higher fluctuation of resistance and reactance. At 2 GHz, an array with a continuous patch has a center-to-center spacing of 40 mm ≈ $0.26\lambda_0$, 50 mm ≈ $0.33\lambda_0$, 60 mm ≈ $0.4\lambda_0$. Except for spacing between elements, the structure of the antenna element could affect isolation between elements in an antenna array. Figure 2(b) shows the significant result of return loss from measurement and simulation results for CVA-NS and CVA-ECT. Although there is a slight discrepancy, the array antenna can work in UWB frequency from 2 GHz to more than 10 GHz. The effect on giving ECT structure to the array antenna performance will be explained in the next subsection.

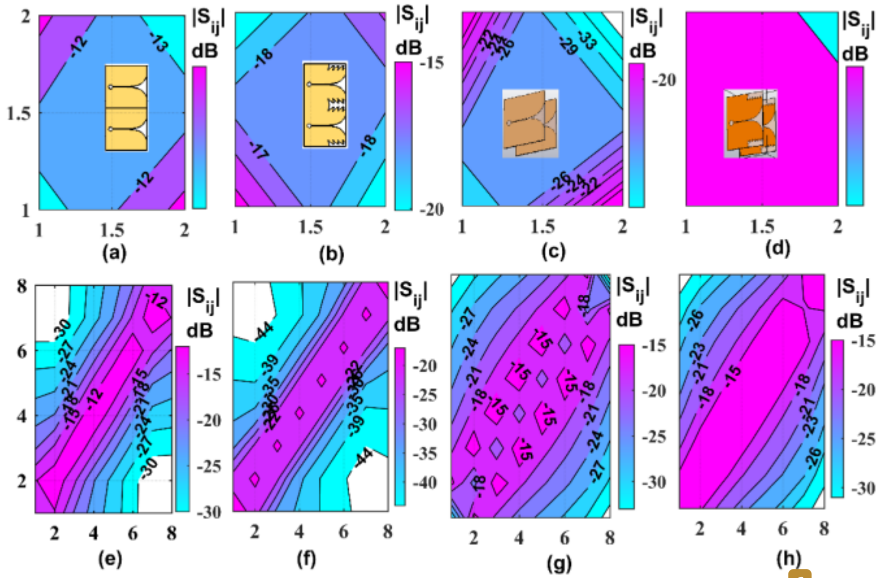


(a) (b)

FIGURE 2. (a). S_{11} and S_{21} performance in different width of elements and (b). The simulation and measurement result of return loss for CVA-NS and CVA-ECT.

2.1 | Sij Contour Plot For Linear and Planar Array

S_{ij} performance of CVA-NS performed by contour plot has been discussed in [7] without comparison with CVA-ECT. However, in this subsection, we compare the S_{ij} performance of several dimensions of the array in the E and H-plane. At 3 GHz, CVA-ECT has a better performance of S_{ij} than CVA-NS for 2×1 array in the E-plane as shown in Figure 3(a)-(b). It shows that the S_{21} of CVA-ECT is -20 dB but CVA-NS is -11 dB. The corrugated truncated structure reduces the mutual coupling between array elements because the surface current will be trapped in the corrugated structure.



(a) (b) (c) (d) (e) (f) (g) (h)

FIGURE 3. Contour plot of scattering parameter (S_{ij}) for j^{th} element to i^{th} element for (a) CVA-NS 2×1 in the E- plane, (b) CVA-ECT 2×1 in the E-plane, (c) CVA-NS 1×2 in the H-plane, (d) CVA-ECT 1×2 in the H-plane, (e) CVA-NS 8×1 in the E-plane, (f) CVA-ECT 8×1 in the E-plane, (g) CVA-NS 1×8 in the H-plane, (h) CVA-ECT 1×8 in the H-plane.

The performance S_{ij} of CVA-NS in Figure 3(c) with array dimension 2×1 in the H-plane has a better performance of S_{ij} than CVA-ECT in Figure 3(d) at 3 GHz with 40 cm spacing between elements. CVA-NS has more varieties of S_{ij} than CVA-ECT. It shows that the self scattering parameter in the H-plane is better than in the E-plane. Figure.3(e) and (f) show the performance of S_{ij} in the E-plane for 8×1 array. An increasing number of elements in the E-plane yields a decrease in S_{ij}. However S_{ij} performance of 1×8 array in the H-plane is shown in Figure 3(g) and (h). It can be concluded that in a linear array, CVA-ECT has better performance of S_{ij} than CVA–NS in the E-plane but the opposite is true in the H-plane. In the E plane, the movement of the surface current in the structure is obstructed to the next element in a continuous patch. In the H plane, the electric field with ECT structured gives more interference to the neighboring element from the air, but it depends on the spacing between elements.

2.2 | The Radiation Pattern of the Array

Figure. 4 compares the radiation pattern of 2×1, 8×1, and 2×2 of Vivaldi arrays. CVA-ECT has better gain than CVA-NS at 3 GHz. Gain performance in the ascending order is reached for 2×1, 2×2, and 8×1. An increasing number of the element, by giving ECT structure in 8×1 array, only slight produce increasing in gain performance of the antenna at the lower frequency. Figure.4 displays that the back lobe of CVA-ECT higher than CVA-NS for 2×1 and 2×2 arrays. whereas the back lobe for 8×1 CVA-ECT is less than CVA-NS. At 3 GHz, 2×1 CVA-ECT has a higher SLL than CVA-NS. This performance is the difference between other frequencies. There is a trade-off between increasing performance of gain, SLL and back lobe

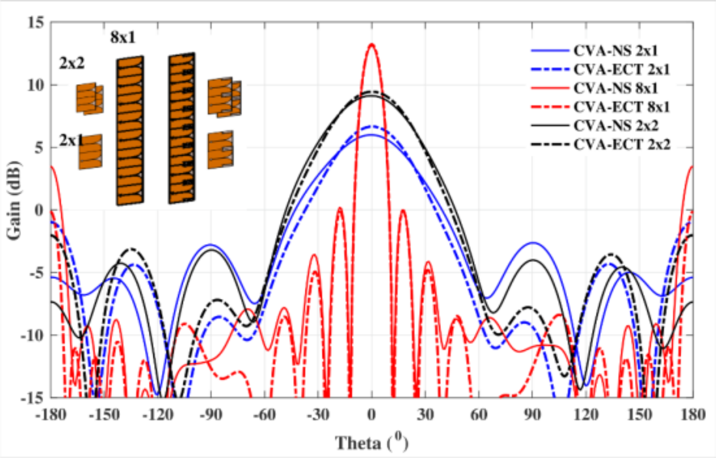


FIGURE 4 Gain OF CVA-NS and CVA-ECT for 2×1, 2×2 and 8×1 array at f = 3 GHz in the E-plane

The performance of gain in wideband frequency for 2×1, 2×2, and 8×1 array in the E-Plane is shown in Figure. 5(a). The increase of gain occurs in the most of frequency range for 2×1 CVA-ECT in the linear array and 2x2 CVA-ECT in the planar array in the E-plane. Whereas for 8x1 linear array, the increase of gain is only on some frequencies i.e. at 3, 4, 6, 7, and 9 GHz. The increasing number of the element not always the case increases the gain in all frequency band, especially in the linear array. The significant increase of gain for 2x2 happened in almost all band frequencies. Providing a corrugated slot can improve gain performance in a planar array, but for a linear array, it does not show an increase of gain at all frequencies.

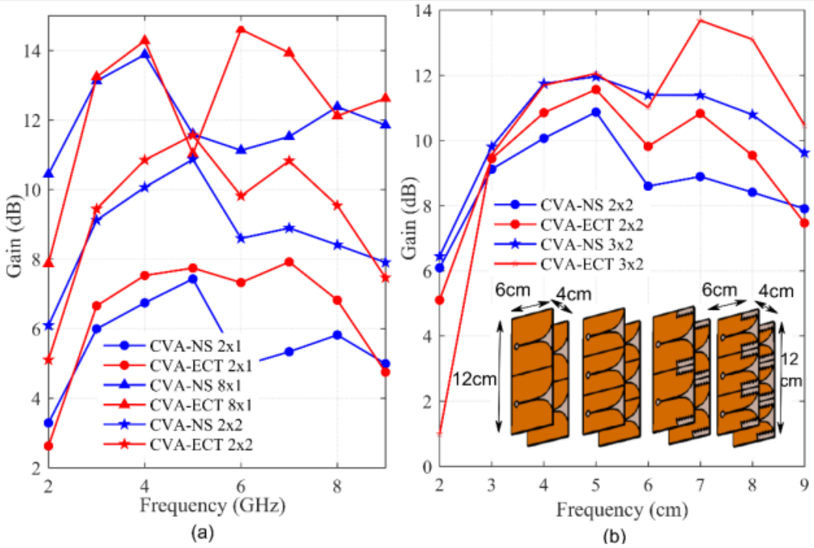


FIGURE 5 Gain of CVA-NS and CVA-ECT : (a) 2×1, 2×2 and 8×1 array in the E-plane, and (b) The gain of CVA-ECT and CVA-NS in the planar array

Scattering parameter for 2×2 array with element dimension 6 cm x 6 cm x 1.6 cm and 3x2 array with element 4 cm × 6 cm ×1.6 cm are compared with ECT and No structure. Those comparisons are shown in Figure.5(b). Although both types of the array have the same volume dimension i.e 12 cm×6 cm ×4 cm, the smaller element has a higher performance of gain. At 7 GHz, Gain of CVA-ECT with 3×2 is 13.69 dB but CVA-NS with 2×2 has a gain of 8.9 dB. It shows increasing of gain as 4.79 dB. It can be concluded that for the same whole volume of an array, the smaller width of an element of the array, the better performance of gain than the bigger ones. Using smaller structured elements will decrease gain performance in lower frequency but for the whole frequency, the smaller structure is preferable.

3 | MUTUAL COUPLING CALCULATION

Mutual coupling of the antenna interferes with antenna performance due to its electromagnetic interaction. It can influence impedance and radiation pattern performance. Vivaldi antenna as a wideband antenna shows trade of the mutual coupling and radiation performance. The spacing between elements interferes with mutual coupling in the lower frequency but it also interferes with radiation pattern performance in the higher frequency. In the lower frequency, in the E plane, the antenna element has smaller spacing between elements than spacing at a higher frequency relative to its wavelength. Mutual coupling analysis can be found from mutual scattering S_{ij} or mutual impedance Z_{ij}. Calculation of mutual coupling for dipole and microstrip antenna has been discussed in [14]. It develops resistance modeling by pointing vector and reactance modeling by Kramers-Kronig relation. The integral through electric and magnetic field stated in that literature in equation (2) as power radiated from the radiator. Where E is an electric field, r is the distance between radiation center to surface, $\phi_i(\theta,\varphi)$ is the amplitude of the radiation pattern. Z_i is impedance parameter that interferes by free space characteristics impedance, radiation resistance and the directivity of radiator. These parameters are explained in detail in the reference[14]

$$\int_{S_0}\left(E\times H^*\right)dS=\frac{1}{120\pi}\int_{S_0}|E|^2 r_0^2 \sin\theta\, d\theta\, d\varphi \;=\mathrm{Re}\left\{\frac{Z_i Z_l}{120\pi}\sum_{l=1}^{m}\sum_{i=1}^{m} I_i I_l \int_0^{2\pi}\int_0^{\pi}\phi_i(\theta,\varphi)\varphi_l^*(\theta,\varphi)\sin\theta\, d\theta\, d\varphi\right\} \tag{2}$$

$$r_{12}=\frac{Z_1^2}{120\pi}\int_0^{2\pi}\int_0^{\pi}\left(\phi^2(\theta,\varphi)\cos\left(k\, d\sin\theta\sin\varphi\right)\sin\theta\right)d\theta\, d\varphi \tag{3}$$

$$x_{12}=-\frac{Z_1^2}{120\pi}\int_0^{2\pi}\int_0^{\pi}\left(\phi^2(\theta,\varphi)\sin\left(k\, d\sin\theta\right)\sin\theta\right)d\theta\, d\varphi \tag{4}$$

Impedance antenna consists of resistance and reactance can be seen in equation (3) and (4) by reference, where the wavenumber of $k = \omega / c$, d is the distance between the element in an array. From that equation, we found that there is radiation pattern modeling that is needed to model mutual resistance and mutual reactance. The radiation pattern modeling of the Coplanar Vivaldi element has been discussed [15]. However, it was complicated. As a result, we modeled simple radiation pattern modeling for Vivaldi element as shown in equation (5):

$$\phi(\theta,\varphi) = 0.4\left(\cos(1.8\theta)^2 + 0.6\exp\left(-2.5\left({}^{1.4\theta}\!/_{180}\right)^2\right)\right) \tag{5}$$

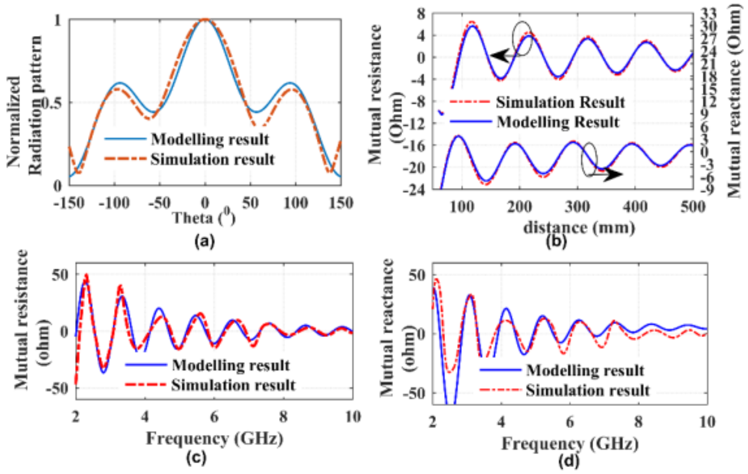


FIGURE 6. (a) Normalized radiation pattern of Coplanar Vivaldi element, (b) Mutual resistance and reactance vs distance, (c) Mutual resistance vs frequency, and (d) Mutual reactance vs frequency

Figure 6(a) displays radiation pattern the coplanar Vivaldi element in modeling result and simulation result in the E-plane at phi=90^0. This model can be developed for array analysis with factor array for coplanar Vivaldi in large volume and configuration of the array. Mutual resistance and reactance can be found by including the coplanar Vivaldi element modeling into equation (3) and (4). Mutual impedance vs distance of Coplanar Vivaldi array can be seen in Figure. 6(b). It exposes that there is consistency in mutual impedance using modeling results and simulation results. This article also purposes an equation for mutual impedance vs frequency of coplanar Vivaldi array that can be shown in equation (6) and (7).

$$r_{12} = \frac{Z_1^2 e^{-0.2f}}{120\pi} \int_0^{2\pi}\int_0^{\pi} \left(3 * W * \left(\phi^2(\theta,\varphi)\right) \cos\left(\frac{2\pi f}{c} 4.75d \sin\theta \sin\varphi\right) \sin\theta\right) d\theta d\varphi \tag{6}$$

$$x_{12} = -\left(\frac{Z_1^2 e^{-0.35f}}{120\pi} \int_0^{2\pi}\int_0^{\pi} \left(12\left(\phi^2(\theta,\varphi)\right) \sin\left(\frac{2\pi f}{c}(4.75W) d \sin\theta \sin\varphi\right) \sin\theta\right) d\theta d\varphi + \frac{A}{1+(f \times B)}\right) + W \tag{7}$$

Where Z_i= impedance of element , W = element width, d = distance between element, A = the width of element and B = the length of the Coplanar Vivaldi element. Figure.6(c) and (d) display comparison mutual resistance vs frequency from equation (6) and mutual reactance vs frequency from equation (7) of modeling result and simulation result of coplanar Vivaldi. By using the modeling result we can approximately the mutual impedance of the array without simulation by including the radiation pattern modeling.

4 | CONCLUSION

Mutual coupling analyzed and calculation has been done for some array configuration i.e 2×1, 8×1, 2×2 and 3×2 of Coplanar Vivaldi array in E and H-plane. Exponential Corrugated Slot (CVA-ECT) has a better performance of mutual coupling and radiation pattern in the E-plane than Coplanar Vivaldi Array without slot (CVA-NS) but it is the opposite in the H-plane. In planar array, for the same volume of an array, the smaller width of element array yields better performance in gain than the wider ones in most operating frequencies. At 7 GHz, from the simulation result, 3x2 of CVA-ECT reach increasing in gain 4.79 dB, if it compares with CVA-NS, in the same volume of an array. Mutual coupling calculation of Coplanar Vivaldi array has been done to get mutual resistance and mutual reactance of Vivaldi array by including Coplanar Vivaldi element modeling in the calculation. The coplanar Vivaldi element modeling can be developed for array analysis with factor array in large volume and various configuration of the array. The calculation result of mutual coupling Coplanar Vivaldi array can be developed for mutual coupling analysis as validation with electromagnetic simulation.

References

[1] P. J. Gibson, "THE VIVALDI AERIAL," in *Proc. 9th European Microwave Conference*, 1979, pp. 101–105.

[2] 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 Wirel. Propag. Lett.*, 2016, DOI: 10.1109/LAWP.2015.2457919.

[3] P. Fei, Y. C. Jiao, W. Hu, and F. S. Zhang, "A miniaturized antipodal Vivaldi antenna with improved radiation characteristics," *IEEE Antennas Wirel. Propag. Lett.*, 2011, DOI: 10.1109/LAWP.2011.2112329.

[4] M. Abbak, M. N. Akıncı, M. Ç. Ayören, and ˙ I Akduman, "Experimental Microwave Imaging with a Novel Corrugated Vivaldi Antenna," *IEEE Trans. Antennas Propag.*, vol. 65, pp. 3302–3307, 2017, DOI: 10.1109/TAP.2017.2670228.

[5] N. Nurhayati, A. M. De Oliveira, J. F. Justo, E. Setijadi, B. E. Sukoco, and E. Endryansyah, "Palm tree coplanar Vivaldi antenna for near field radar application," *Microw. Opt. Technol. Lett.*, vol. 62, no. 2, 2020, DOI: 10.1002/mop.32127.

[6] S. Kasturi and D. H. Schaubert, "Effect of dielectric permittivity on infinite arrays of single-polarized Vivaldi antennas," *IEEE Trans. Antennas Propag.*, vol. 54, no. 2, pp. 351–358, 2006, DOI: 10.1109/TAP.2005.863374.

[7] Nurhayati, G. Hendrantoro, T. Fukusako, and E. Setijadi, "Mutual Coupling Reduction for a UWB Coplanar Vivaldi Array by a Truncated and Corrugated Slot," *IEEE Antennas Wirel. Propag. Lett.*, vol. 17, no. 12, pp. 2284–2288, 2018, DOI: 10.1109/LAWP.2018.2873115.

[8] E. W. Reid, L. Ortiz-Balbuena, A. Ghadiri, and K. Moez, "A 324-element Vivaldi antenna array for radio astronomy instrumentation," *IEEE Trans. Instrum. Meas.*, vol. 61, no. 1, pp. 241–250, 2012, DOI: 10.1109/TIM.2011.2159414.

[9] J. B. Yan, S. Gogineni, B. Camps-Raga, and J. Brozena, "A Dual-Polarized 2-18-GHz Vivaldi Array for Airborne Radar Measurements of Snow," *IEEE Trans. Antennas Propag.*, vol. 64, no. 2, pp. 781–785, 2016, DOI: 10.1109/TAP.2015.2506734.

[10] C. Yeh, M. Lee, and D. Ucci, "Bearing Estimations with Mutual Coupling Present," *IEEE Trans. Antennas Propag.*, vol. 37, no. 10, pp. 1332–1335.

[11] C. Hao, H. Zheng, and X. Sun, "Mutual coupling reduction between patch antennas based on microstrip structures," *Microw. Opt. Technol. Lett*, no. May, pp. 1–4, 2019, DOI: 10.1002/mop.32052.

[12] A. Isaac, H. Al-Rizzo, S. Yahya, A. Al-Wahhamy, and S. Abushamleh, "Decoupling of Two Closely- Spaced Planar Monopole Antennas Using Two Novel Printed-Circuit Structures," *Microw. Opt. Technol. Lett*, vol. 2, no. 2, pp. 30–35, 2016, DOI: 10.1002/mop.31405.

[13] D. W. G. A. H. Mohammadian, N. M. Martin, "A Theoretical and Experimental Study of Mutual Coupling in Microstrip Antenna Arrays," *IEEE Trans. Antennas Propag.*, vol. 31, pp. 1217–1223, 1989.

[14] O. G. Vendik and D. S. Kozlov, "A Novel Method for the Mutual Coupling Calculation between Antenna Array Radiators: Analysis of the radiation pattern of a single radiator in the antenna array.," *IEEE Antennas Propag. Mag.*, 2015, DOI: 10.1109/MAP.2015.2481818.

[15] Nurhayati, E. Setijadi, and G. Hendrantoro, "Radiation pattern analysis and modeling of Coplanar Vivaldi antenna element for linear array pattern evaluation," *Prog. Electromagn. Res. B*, vol. 84, 2019.

Mutual Coupling Evaluation and Calculation for Coplanar Vivaldi Array

ORIGINALITY REPORT

17%	5%	15%	3%
SIMILARITY INDEX	INTERNET SOURCES	PUBLICATIONS	STUDENT PAPERS

PRIMARY SOURCES

1	Nurhayati, Gamantyo Hendrantoro, Takeshi Fukusako, Eko Setijadi. "Mutual Coupling Reduction for UWB Coplanar Vivaldi Array by Truncated and Corrugated Slot", IEEE Antennas and Wireless Propagation Letters, 2018 Publication	2%
2	Nurhayati Nurhayati, Alexandre Manicoba De-Oliveira, Warangkana Chaihongsa, Bagus Edy Sukoco, Akbar Kurnia Saleh. "A COMPARATIVE STUDY OF SOME NOVEL WIDEBAND TULIP FLOWER MONOPOLE ANTENNAS WITH MODIFIED PATCH AND GROUND PLANE", Progress In Electromagnetics Research C, 2021 Publication	2%
3	Guangwei Yang, Yiming Zhang, Shuai Zhang. "Wide-Band and Wide-Angle Scanning Phased Array Antenna for Mobile Communication System", IEEE Open Journal of Antennas and Propagation, 2021	1%

	Publication	
4	Submitted to Southern Taiwan University of Science and Technology Student Paper	1 %
5	Fitri Amillia, Eko Setijadi, Gamantyo Hendrantoro. "Subarray Design with Two Rectangular Elements for Massive MIMO System Development", 2019 International Conference on Advanced Mechatronics, Intelligent Manufacture and Industrial Automation (ICAMIMIA), 2019 Publication	1 %
6	P.L. Chin, A.Z. Elsherbeni, C.E. Smith. "Characteristics of coplanar bow-tie patch antennas", IEEE Antennas and Propagation Society International Symposium (IEEE Cat. No.02CH37313), 2002 Publication	1 %
7	"Substrate ‐ Integrated Millimeter ‐ Wave Antennas for Next ‐ Generation Communication and Radar Systems", Wiley, 2021 Publication	1 %
8	Nurhayati, Gamantyo Hendrantoro, Takeshi Fukusako, Eko Setijadi. "Mutual Coupling Reduction for a UWB Coplanar Vivaldi Array by a Truncated and Corrugated Slot", IEEE	1 %

	Antennas and Wireless Propagation Letters, 2018 Publication	
9	Submitted to Universitas Diponegoro Student Paper	1 %
10	Nurhayati, Gamantyo Hendrantoro, Eko Setijadi. "Mutual coupling and radiation pattern of vivaldi antenna with slit", Proceedings of the 3rd International Conference on Communication and Information Processing - ICCIP '17, 2017 Publication	<1 %
11	"Modern Antenna Handbook", Wiley, 2008 Publication	<1 %
12	"Proceedings of 2nd International Conference on Micro-Electronics, Electromagnetics and Telecommunications", Springer Science and Business Media LLC, 2018 Publication	<1 %
13	LI, W.L.. "DETERMINATION OF THE MUTUAL RADIATION RESISTANCES OF A RECTANGULAR PLATE AND THEIR IMPACT ON THE RADIATED SOUND POWER", Journal of Sound and Vibration, 20000203 Publication	<1 %
14	Hung Loui, J.P. Weem, Z. Popovic. "A dual-band dual-polarized nested vivaldi slot array	<1 %

	with multilevel ground plane", IEEE Transactions on Antennas and Propagation, 2003 Publication	
15	Kindt, Rick W., and Marinos N. Vouvakis. "Analysis of a Wavelength-Scaled Array (WSA) Architecture", IEEE Transactions on Antennas and Propagation, 2010. Publication	<1 %
16	Nurhayati, Eko Setijadi, Gamantyo Hendrantoro. "RADIATION PATTERN ANALYSIS AND MODELLING OF COPLANAR VIVALDI ANTENNA ELEMENT FOR LINEAR ARRAY PATTERN EVALUATION", Progress In Electromagnetics Research B, 2019 Publication	<1 %
17	R. Chair, A.A. Kishk, Kai-Fong Lee. "Comparative study on the mutual coupling between different sized cylindrical dielectric resonators antennas and circular microstrip patch antennas", IEEE Transactions on Antennas and Propagation, 2005 Publication	<1 %
18	Sharp, A.N., and R. Kyprianou. "Vivaldi antennas: wideband radar antennas simulation and reality", IET International Conference on Radar Systems 2007, 2007. Publication	<1 %

19	www.atlantis-press.com Internet Source	<1 %
20	www.findmeagift.co.uk Internet Source	<1 %
21	Nurhayati Nurhayati, Alexandre M. De Oliveira, Antonio. M. de Oliveira, Raimundo Eider Figueredo et al. "Comparison Study of Hilbert Sierpinski and Koch Fractal Structure on Coplanar Vivaldi Antenna for L/S band Application", 2020 Third International Conference on Vocational Education and Electrical Engineering (ICVEE), 2020 Publication	<1 %
22	mafiadoc.com Internet Source	<1 %
23	Nurhayati, G. Hendrantoro, E. Setijadi. "Total array pattern characteristics of coplanar vivaldi antenna in E-plane with different element width for S and C band application", 2017 Progress in Electromagnetics Research Symposium - Fall (PIERS - FALL), 2017 Publication	<1 %
24	emlab.utep.edu Internet Source	<1 %
25	epdf.tips Internet Source	<1 %

26	onlinelibrary.wiley.com Internet Source	<1%
27	www.jpier.org Internet Source	<1%
28	Shuangshuang Zhu, Haiwen Liu, Pin Wen. "A New Method for Achieving Miniaturization and Gain Enhancement of Vivaldi Antenna Array Based on Anisotropic Metasurface", IEEE Transactions on Antennas and Propagation, 2019 Publication	<1%
29	Charles MacWright Thomas, Huda A. Majid, Zuhairiah Zainal Abidin, Samsul Haimi Dahlan, Mohamad Kamal A. Rahim, Raimi Dewan. "A Study on V-Shaped Microstrip Patch MIMO Antenna", Indonesian Journal of Electrical Engineering and Computer Science, 2017 Publication	<1%
30	Roghieh Karimzadeh Baee, Keyvan Forooraghi. "Consideration of the isolated and mutual coupling among conformal hemispherical microstrip patch antennas", 7'th International Symposium on Telecommunications (IST'2014), 2014 Publication	<1%

Exclude quotes	Off	Exclude matches	Off
Exclude bibliography	On		