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Review On Gain and Directivity Enhancement Techniques of Vivaldi Antennas

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Abstract— Continued developments in wireless communication technologies have necessitated the demand for antennas with ultra wide bandwidth. Aside from this feature, the Vivaldi antenna also has many other advantages that made it the favorite of ultra-wide band communication system. These class of antennas, however, also suffer from some drawbacks such as low or inconsistent gain and directivity which tend to limit their wide spread utilization. Different techniques and methods have generally being proposed over the years by researchers in a bid to overcome these limitations. This paper therefore provides a review on some of the various techniques utilized for enhancing the gain and directivity of the Vivaldi antenna.

Index Terms— Antenna, Array, Corrugation, Dielectric, Directivity, Gain, Metamaterial

1 INTRODUCTION

The design and implementation of UWB system has become a highly competitive topic in both academic and industrial communities of telecommunications after the approval by the federal communication commission (FCC) of 3.1 to 10.6 GHz frequency band for commercial use in February 2002 [1]. The ultra-wideband (UWB) radio transmission technology having a minimum bandwidth of 500MHz or at least 20% of the center frequency has many antenna types and designs [2], [3].
Unlike most UWB antennas which are not fully planar [4], the Vivaldi antenna has planar and simple structure, light weight, compactness, ultra-wide bandwidth, high efficiency and symmetric beam in *E*-plane and *H*-plane [5], [6], [7], [8]. But despite the many advantages of the Vivaldi Antenna, it still suffer from some drawbacks, such as tilted beam , and low or inconsistent directivity and gain among others [9], [10], [11]. Several techniques have being reported in literature for overcoming these drawbacks including the use of split-ring resonators (SRR) [12], I-shaped (ISR) and H-shaped (HSR) resonator structures [13], [14], substrate end shaping technique [15], multi-slot structure [16], [17], [18], [19] as well as substrate elongation as dielectric load [20], [21].

Other reported methods include the use of profiled dielectric directors, radiating arm slots (corrugations), array structure, photonic band gap structure, negative index metamaterial (NIM), zero index metamaterial (ZIM) for which a survey and review will be provided in this paper.

2REVIEW OF RELATED LITERATURE

2.1 Gain Enhancement using dielectric director

Researchers have found that adding a piece of high permittivity dielectric director in the aperture center of theVivaldi antenna drives the radiating wave of the antenna in the direction of its top and thus improve its directivity and gain [22], [23]. As shown in Fig. 1, the high permittivity material called the director acts as a wave guiding structure that direct most of the energy toward the aperture center and thus significantly increasing the antenna directivity and gain.

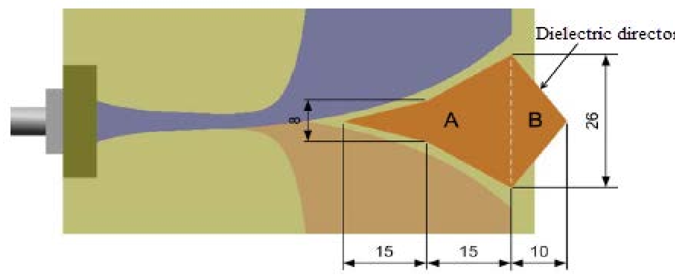

Fig. 1: Antipodal Vivaldi antenna with dielectric director [24].

Using this method [25] presented the Antipodal Vivaldi antenna (AVA) loaded with a high permittivity triangular dielectric director in the end of the antenna aperture. This resulted in a maximum gain increase of 4.4 dB at 7.5 GHz in the 2 – 15 GHz operating frequency band when compared to the conventional AVA without the director while radiation beamwidth was also narrowed by about 12.4^{o} (52.5^{o} – 40.1^{o}).

Similarly [26, 27] presented the gain enhancement of the antipodal Vivaldi antenna. In [26] a novel elliptical slot edge (ESE) structure was employed on the radiating arm of the modified antipodal Vivaldi antenna which lowered the low-end operating frequency by 570 MHz (2.26 – 1.69 GHz) and help improved the radiation characteristics in the lower frequencies. Then a pair of planar dielectric directors was used which improved the value of gain at high frequency bands by a maximum 1.4 dB (9.8 – 11.2 dB) at 7 GHz in the 1.69 GHz to 11 GHz operating frequency range of the antenna. On the other hand [27] used a parasitic elliptical patch in the flare aperture of the antenna as a director to achieve gain enhancement by improving the field coupling between the arms and producing stronger radiation in the endfiredirection. This resulted in a maximum gain increase of 5.5 dB at 15 GHz in the 2 – 32 GHz operating frequency band with directivity and HPBW as well as the front-to-back (F/B) ratio also significantly enhanced over 5 – 12 GHz and 2 – 20 GHz respectively.

H. Hong et al [28] also used triangular parasitic elements to the flared slot between radiators of an AVA, a maximum gain enhancement of 0.5 dB at 9 GHz was achieved for the antenna frequency band of 2 – 10.6 GHz. As against the AVA without the triangular parasitic element, the radiation patterns of the antenna equally had narrow beamwidth with increasing frequency when simulated using the CST MWS studio v2012. A. Elsherbini et al [29] had presented the enhancement of gain and narrower H-plane beamwidth of a UWB antipodal Vivaldi antenna with protruded dielectric rod. The protruded dielectric rod acting as a travelling wave antenna produced a 3.3dB increase in gain over the 4 – 8 GHz operating frequency band of the proposed antenna while the larger aperture size of the rod in the H-plane compared to the conventional Vivaldi antenna also lead to a narrower H-plane beamwidth of the overall radiation patter.

Incorporation of a diamond-shaped metal director was found to have enhanced the gain of a wideband end-fire conformal Vivaldi antenna mounted on a dielectric cone at high frequency. The gain of the proposed antenna was enhanced by 1 dB (9.4 – 10.4 dB) at 9.5GHz in the frequency band of 2 – 11 GHz due to the effect of the metal director in the antenna aperture [30]. L. Li et al. [31] on the other hand presented enhanced radiation parameters of a wideband BAVA using a parasitic elliptical-shaped metal director compounded in the center of the antenna aperture. A maximum gain increase of 4.8 dB (8.2 – 13 dB) was achieved at middle-high frequency with the metal director length of 50mm. Beam squinting of the proposed antenna was also reduced to less than 5^{o} in the E-plane compared to the conventional BAVA without the director.

Table 1: Summary of Gain Enhancement Using Dielectric Director

	Conventional Vivaldi		**Proposed Vivaldi**		
Literature Ref.	BW (GHz)	Gain (dB)	BW (GHz)	Gain (dB)	% Gain Enhancement
[25]	2 – 15	7.2	2 – 15	11.6	61%
[26]	2.26 – 11	9.8	1.69 – 11	11.2	14.3%
[27]	2 – 32	6.5	2 – 32	12	84%
[28]	2 – 10.6	8.7	2 – 10.6	9.2	5.7%
[29]	4 – 8	5	4 – 8	8.3	66%
[30]	2 – 11	9.4	2 – 11	10.4	10.6
[31]	2 – 40	8.2	2 – 40	13	58.5%

2.2 Gain enhancement Using Corrugations

Corrugations are shaped alternating parallel grooves or ridges which form modification to the radiating arm of the Vivaldi antenna as shown in Fig. 2. These modifications enabled significant currents to be observed along the slot edges which lengthened the effective length of the current path there by improved the radiation directivity [32 – 34].

According to A. M. De Oliveira et al [36], using an exponential slot edge (ESE) corrugation the gain of an antipodal Vivaldi antenna was enhanced by 66% (5 – 8.3 dB) at 6 GHz with reduction of lower limit of the reflectioncoefficient from 5.28 GHz to 5.08 GHz when compared with the conventional antipodal Vivaldi antenna working at 5.28 – 16 GHz frequency band.

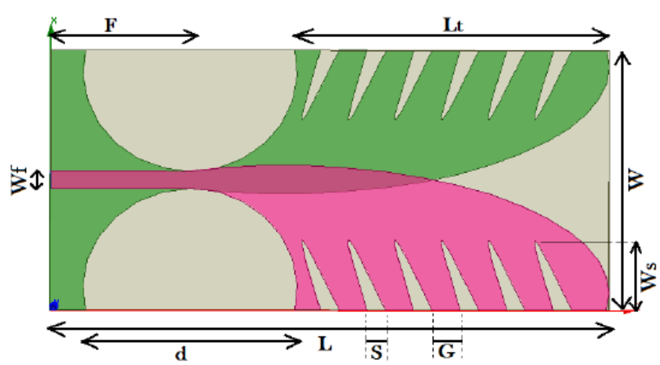

Fig. 2: Antipodal Vivaldi antenna with corrugations [35].

A squint correction of 0 degrees was also achieved against 5 degrees of the conventional AVA which led to improved directivity. An improved AVA with rounded corners and metallic background plane presented by [37] achieved a gain increase from 7 to 8.4 dB when compared with a conventional AVA and improved AVA without the back plane. The H-plane directivity of the proposed antenna operating at 6 – 18 GHz frequency band was significantly improved while a maximum VSWR less than 2 (VSWR < 2) was recorded over the desired frequency range compared to 2.2 of the conventional AVA.

A combination of corrugations on the edges of exponential metallic flaring section and some periodic grating elements consisting of small metallic strips on the slot area [38], improved the gain of a compact Vivaldi antenna by a maximum of 68.3 % (4.1 – 6.9 dB) at 5.2 GHz in the 2.9 – 11 GHz frequency range with lower side lobe and back lobe levels resulting in improved radiation in the bore sight direction and hence improved directivity. Y. Cao [39] proposed a miniaturized balanced antipodal Vivaldi antenna with a corrugated edge (BAVA-CE) which improved the gain of the conventional AVA by 3 dB (5 – 8 dB) in the mid and high frequency region of the 2.1 – 10 GHz operating frequency band. The lower frequency limit of the conventional AVA was also extended from 2.8 to 2.1 GHz resulting in better impedance matching.

The gain of the conventional Vivaldi antenna was also improved by 75% (4 – 7 dB) at 5.5 GHz within the 2 – 14 GHz operating frequency band by using a pairof symmetrical array of trapezoid-shaped slots etched on theouter edges as corrugation and some metallic strips as grating elements in the slot area as reported by L. Yao et al [40], while [41] achieved a gain improvement of 45% (6.2 dB – 9 dB) over the operating frequency range of 2.3 – 18 GHz of the antipodal Vivaldi antenna using the comb-shaped corrugations.

T. J. Huang et al [42] realized a 3.09 dB (5.58 – 8.67 dB) maximum gain enhancement at 3 GHz with a stepped edge corrugations for the antipodal dual exponentially tapered slot antenna operating at 3 - 18 GHz when compared to the conventional DETSA without corrugations. The E-plane and H-plane HPBW were also improved by 35^{o} (42%) and 18.9^{o} (14.8%) respectively which led a corresponding increase in directivity at the bore sight direction. H. Sato and Y. Katagi [43] also reported gain enhancement by incorporating corrugations on an antipodal Fermi antenna with low cross-polarization. A 4.8 dBi (10.7 – 15.5 dBi) increase was achieved at 13 GHz over the broad frequency band of 2 – 18 GHz.

Table 2: Summary of Gain Enhancement Using Corrugations

	Conventional Vivaldi		**Proposed Vivaldi**		
Literature Ref	BW (GHz)	Gain (dB)	BW (GHz)	Gain (dB)	% Gain Enhancement
[36]	5.28 – 16	5	5.08 – 16	8.3	66%
[37]	6 – 18	7	6 – 18	8.4	20%
[38]	2.9 – 11	1.1	2.9 – 11	6.9	68.3%
[39]	2.8 – 10	5	2.1 – 10	8	60%
[40]	2 – 14	4	2 – 14	7	75%
[41]	3.3 – 18	6.2	2.3 – 18	9	45%
[42]	3 – 18	5.58	3 – 18	8.67	55.4%
[43]	2 – 18	10.7	2 – 18	15.5	44.86%

2.3 Gain enhancement using zero and negative index metamaterial

Metamaterials are made from assemblies of multiple elements fashioned from composite materials such as metals or plastics. They are normally engineered to exhibit properties not usually found in natural materials such as a negative refractive index [44]. These materials with zero/negative index of refraction can be used to enhance the directivity of printed antennas using the principle of directive emission [45, 46]. Thus different researchers have proposed the use of metamaterials to realize directive emission by matching the wave impedance of air and the metamaterial such that high efficiency of radiating and receiving electromagnetic waves is achieved [47]. As shown in Fig. 3, the metamaterial are loaded at the

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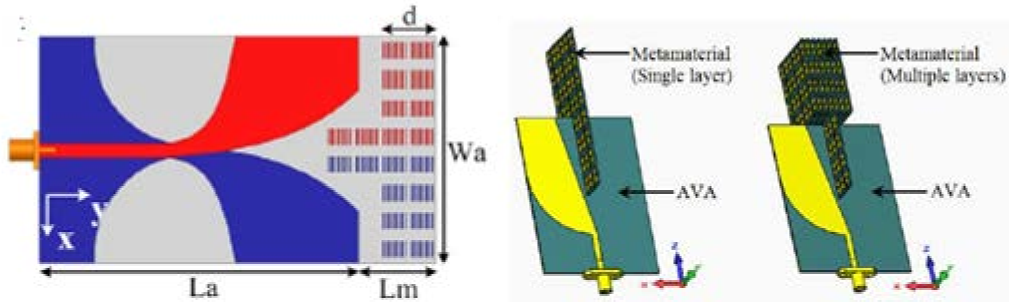
open aperture region or snugged-in between the radiating arms of the conventional Vivaldi antennas.

An anisotropic zero-index metamaterial (AZIM) designed at 9.5 – 10.5 GHz was used to improve the directivity and gain of a conventional Vivaldi antenna by [50]. Single layer and multiples layers of the AZIM with zero permittivity point around 10 GHz, incorporated in the aperture of the Vivaldi antenna operating at 3 – 14 GHz frequency band, improved the measured gain of the conventional Vivaldi antenna by 41 % (9.92 – 13.97 dB) at 10 GHz using the multiple layers of the AZIM. Directivity was enhanced with reduced half power beamwidth (HPWB) from 48.4° to 22.8°. Adopting similar method and using a creative ZIM unit cell with zero permittivity point at 0.584 GHz, [51] achieved a maximum gain enhancement of 3.1 dB (4.38 – 7.48 dB) at 0.584 GHz,



(a) (b)

Fig. 3: Antipodal Vivaldi antenna with metamaterial (a) loaded at the open aperture region [48] and (b) single and multiple layer snugged-in between radiating arms [49].

using multilayer ZIM unit cell in the 0.45 – 0.95 GHz TSA operating frequency band. The HPBW was equally reduced by 26.8° (92.4° – 65.6°) compared with the typical TSA.

The incorporation of the meander-line anisotropic zero-index metamaterial (AZIM) unit cell operating at 4.4 – 10 GHz achieved a 2.51 dBi increase in directivity at 5.5 GHz and a decreased the HPBW by 54.3° when compared with the conventional operating at 1 – 10 GHz [52].

In the same vain, using an array of anisotropic artificial material (AAM) unit cells with zero permittivity point at 9 GHz in the frequency range of 8 GHz – 12 GHz, laid-out in the extended aperture of a conventional Vivaldi antenna (CVA) [53], the gain of the antenna was enhanced by a maximum of 2 dBi at 12 GHz in the frequency range of 3 GHz – 12 GHz while H-plane beamwidth was significantly decreased compared to the E-plane throughout the frequency band. In [54] the gain and directivity of conventional TSA operating at 3.1 – 12 GHz were enhanced by up to 2 dBi and 24° in the H-plane at 7 GHz respectively using an inhomogeneous anisotropic artificial metamaterial (IA-AM) with dual broadband property in the frequency band of 5.5 – 12 GHz.

A. R. H. Alhawari et al [49] and R. Singha and D. Vakula [55] presented the use of snugged-in negative index metamaterial (NIM) unit cells integrated perpendicularly in the middle of the two radiating arms of a conventional AVA for gain enhancement. The proposed structure in [49] achieved a maximum gain enhancement of 4 dB (11.5 – 15.5 dB) a multiple layer NIM within the 6 to 20 GHz operating frequency band of the proposed AVA. Maximum directivity enhancement of 4 dB (11.7 – 15.7 dB) with a corresponding decrease in HPBW of 17° (40° – 23°) was also recorded. On the other hand [55] achieved a gain and directivity enhancement of 1.2 dB (7 – 8.2 dB) and 1 dB (7 – 8 dB) respectively in the 4.7 – 11 GHz operating frequency band of the proposed antenna by the NIM with negative refractive index from 4.6 - 8.4 GHz and 9.4 – 12 GHz.

Table 3: Summary of Gain Enhancement Using Metamaterial

Conventional Vivaldi	Proposed Vivaldi

ISSN 2229-5518

Literature Ref	BW (GHz)	Gain (dB)	Direct. (dB)/ HPBW (o)	BW (GHz)	Gain (dB)	Direct. (dB)/ HPBW (o)	% Gain Improvement	% Direct./ HPBW Improv.
[49]	6 – 20	11.5	11.7	6 – 20	15.5	15.7	35%	34
[50]	3 – 14	9.92	48.4^{o}	3 – 14	13.97	22.8^{o}	41%	53
[51]	0.45 – 0.95	4.38	92.4^{o}	0.45 – 0.95	7.48	65.6^{o}	70.8%	29%
[52]	1 – 10	NR	7.49	1 – 10	NR	10	33.5%	-
[53]	3 – 12	5.5	NR	3 – 12	7.5	NR	36.4%	-
[54]	3.1 – 12	7	105^{o}	3.1 – 12	9	81^{o}	28.6%	23%
[55]	4.7 – 11	7	7	4.7 – 11	8.2	8	17%	14.3%

*NR – Not Reported

2.4 Gain enhancement using array structure

An array is a set of two or more antennas connected together from which signals are combined to realize an improve performance against that of a single antenna as shown in Fig 4. Antenna array are generally used to provide diversity reception, interference cancelling, beam steering as well as gain and directivity improvement [56, 57]. The radiation from individual antennas in an array is coherently added in space to form the antenna main beam.

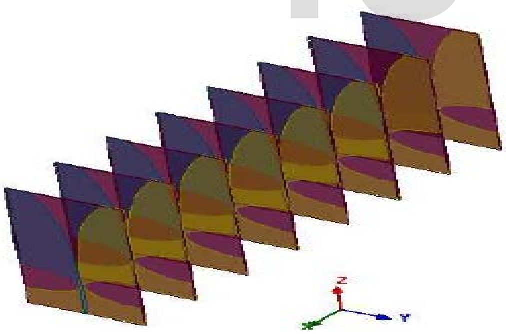


Fig. 4: 1 x 8 Antipodal Vivaldi antennas linear array [58].

Two element and four element arrays were investigated for gain enhancement of an AVA by [59]. A maximum gain and HPBW improvement of 19% (5.287 – 6.29 dBi) and 43.5^{o}(139.5^{o} – 96^{o}) was achieved with the two-element array in the H-plane configuration within the 1 – 4 GHz operating frequency band. C. Liu et al [60] achieved improvement in gain by presenting 2 x 2 element circularly polarized antenna array. The single element antipodal Vivaldi antenna with tapering serrated structure achieved a maximum gain of 10.2 dBi at 5 GHz as against 7.6 dBi for the conventional AVA. The array structure however achieved a maximum gain enhancement of 4.5 dBi (7.6 – 12.1 dBi) at 5 GHz within the 2.5 – 11 GHz operating frequency band.

M. Strackx et al. [61] investigated gain improvement of a two elements dual elliptically tapered antipodal slot antenna (DETASA) array in stack configuration where a maximum of 3.2 dB (7.8 – 11 dB) increase in gain at 6 GHz and 45^{o} (76^{o} – 31^{o}) reduction in HPBW at 7 GHz were realized by the array compared to a single element antenna operating in 3 – 11 GHz UWB band. C. K. T. Ormeno et al [62] reported a gain enhancement of 61% (9.8 – 15.8 dB) in a conventional Vivaldi antenna operating frequency band of 3.18 – 10.5 GHz and an improved lower frequency limit from 3.18 to 2.9 GHz with a five-element linear array designed based on the balanced antipodal Vivaldi antenna. Z. Changfei et al. [63] presented a 1 x 5 E-plane array of a novel antipodal Vivaldi antenna with slot edge modification operating in 8 – 20 GHz which achieved a maximum gain enhancement of 4 dB (9.7 – 13.7 dB) over the single element having improved the lower frequency band limit from 7.7 – 20 GHz.

Table 4: Summary of Gain Enhancement Using Array Structure.

	Conventional Vivaldi	**Proposed Vivaldi**

Literature Ref	BW (GHz)	Gain (dB)	Direct. (dB)/ HPBW (°)	BW (GHz)	Gain (dB)	Direct. (dB)/ HPBW (°)	% Gain Improvement	% Direct./ HPBW Improv.
[59]	1 – 4	5.287	139.5°	1 – 4	6.26	96°	19%	31.2%
[60]	2.5 – 11	7.6	NR	2.5 – 11	12.1	NR	59%	-
[61]	3 – 11	7.8	76°	3 – 11	11	31°	41%	59%
[62]	3.18 – 10.5	9.8	NR	2.9 – 10.5	15.8	NR	61%	-
[63]	7.7 – 20	9.7	NR	8 – 20	13.7	NR	41%	-

*NR – Not Reported

3 DISCUSSION

Detailed knowledge of the working and complexity of the Vivaldi antenna as a travelling wave antenna whose lower frequency limit is determined by the width of its aperture is desirable in the overall analysis of its operations. However, recently a lot of attention has being given to the Vivaldi antenna because of advancement in communication systems. Thus a number of methods for overcoming the limitations of the Vivaldi antenna have being investigated. Generally from the survey reported hereof, a general summary can be drawn as follows:

- Using the method of loading a high permittivity dielectric material in the antenna's aperture a gain improvement up to 84% was achieved by [27] with the least improvement of 5.7% achieved by [28].
- Based on the techniques of inserting slots on the radiating arm of the antenna the best reported gain enhancement of 75% was achieved by [40] while 20% improvement was achieved by [37].
- Highest and lowest gain enhancement of 70.8% and 17% were recorded respectively by [51] and [55] using ZIM/NIM metamaterial unit cells in the aperture of the Vivaldi antenna.
- Implementation of the array structure technique to enhance the gain of the Vivaldi antenna yielded a maximum of 61% improvement by [62] and a minimum of 19% as reported by [59].

Table 7 summarizes the best results achieved by the techniques reviewed in this work.

Table 5: Summary of Best Results for Reviewed Techniques

		Conventional Antenna			**Proposed Antenna**				
Enhancement Technique	Paper Ref.	Operating Freq. Band (GHz)	Gain (dB)	Dir./ HPBW (dB/deg)	Operating Freq. Band (GHz)	Gain (dB)	Dir./ HPBW (dB/deg)	% Gain Enhanc't	% Dir./ HPBW Enhanc't.
Dielectric Director	[27]	2 – 32	6.5	NR	2 – 32	12	NR	84%	-
Corrugations	[40]	2 – 14	4	NR	2 – 14	7	NR	75%	-
Metamaterial (ZIM/NIM)	[51]	0.45 – 0.95	4.38	92.4°	0.45 – 0.95	7.48	65.6°	70.8%	29%
Array Structure	[62]	3.18 – 10.5	9.8	NR	2.9 – 10.5	15.8	NR	61%	-

*NR – Not Reported

4 CONCLUSION

One of the major limitations of the Vivaldi antenna is the low or inconsistent gain and directivity. A number of techniques have being proposed by researchers to overcome this limitation. This paper presented a review of four techniques used in improving the gain and directivity of this class of antennas. Each section provided a review of at least five papers with varying degree of reported result.

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