Review on Recent Trends and Applications of Vivaldi Antenna in the Range of 1 GHz – 40 GHz

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***Abstract*— This paper reviews several recently used methods to ameliorate the performance of Vivaldi antennas working in the vital frequency range of 1 - 40 GHz. In recent years, numerous researchers have suggested various methods to improve Vivaldi antenna's performance. Some of the techniques include the use of dielectric lens, metamaterial, Electromagnetic Band Gap, Corrugations, Slot, Parasitic patch between radiators, Substrate shape and choice of permittivity etc. Moreover, this paper reviews various major applications of Vivaldi antennas in recent times e.g., 5G/mmWave communication, Satellite communication (SATCOM), MIMO, UWB, Vehicular communication, etc.**

Keywords- Vivaldi antenna; 5G/mmWave; SATCOM; RADAR; UWB; MIMO; Wireless Communication.

I. INTRODUCTION

The need for an antenna with characteristics like wide bandwidth and high directivity has grown due to the enormous surge in broadcast and wireless communication technologies. Broadband antennas find use in various applications such as SATCOM, RADAR, remote sensing, microwave imaging, etc. A Vivaldi antenna is a type of Tapered Slot Antenna (TSA) that was first discovered and studied by Gibson in 1979 [1]. The conventional design of a TSA antenna is a tapered slot engraved on the metal over the dielectric substrate which is also an end-fire radiator. TSA has some models depending on the variations of the tapered-shaped slot. The most used are: Linear TSA (LTSA) [2], Constant TSA (CTSA) [3] and Exponentially TSA. Exponentially TSA design is also known as Vivaldi antenna. The Antipodal Vivaldi antenna, also known as the dual exponentially tapered slot antenna (DETSA) forms part of the end-fire tapered slot family of antennas Figure 1 is an illustrative representation of the generalized form of a Vivaldi antenna. By tapering the microstrip line, the feeding structure transition is accomplished [4].

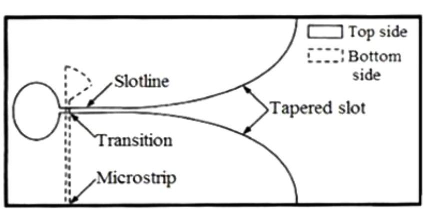

Figure 1. Structure of Vivaldi antenna [5].

The structure of this paper is as follows: A brief description of basic design and characteristics of Vivaldi antenna are given in Section I. Section II discusses various optimized Vivaldi antenna designs for various applications, e.g., (a) SATCOM/Radar/5G (b) UWB application (c) Wireless and Vehicular communication (d) Other miscellaneous applications. Finally, conclusions are given in Section III, followed by references.

II. VARIOUS APPLICATIONS OF VIVALDI ANTENNA

Vivaldi antennas are finding applications in all the major areas of communication systems. Some of them are listed as follows, along with their design methodology:

A. SATCOM/Radar/5G

Ullah et al. [6] proposed the design of an Antipodal Vivaldi Antenna (AVA) for 5G communication and Ku-band usages, as shown in Figure 2. The top layer of the design contains an array of eight elements having split-shaped leaf design fed by a power divider and the bottom layer contains truncated ground. Puskely et al. [7] proposed a dielectric loaded antipodal SIW Vivaldi antenna with high gain operating in the Ka band (25 - 40 GHz), as shown in Figure 2. An improved impedance matching with better directional radiation pattern is attained by the combination of dielectric loading, printed transition and corrugated ripples fabricated on the arms of antenna.

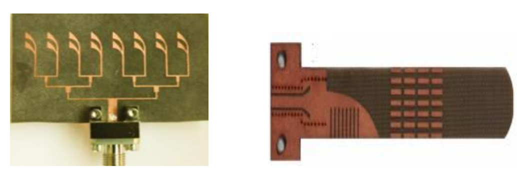

Figure 2. Fabricated prototypes [6][7].

Emre et al. [8] proposed a high gain UWB Vivaldi antenna array for Synthetic Aperture Radar (SAR) applications as shown in Figure 3. First, the Vivaldi antenna's single element is designed for ultra-wide band operation in the X-band and Ku-band frequency range. Subsequently, edge grooves are created on the sides of exponential etched patch surface in order to shield the proposed antenna from surface currents. Furthermore, the parasitized element is complemented to increase the antenna gain. Kähkönen et al. [9] proposed an 18–30 GHz dual–polarized Vivaldi antenna array design for satellite communication as shown in Figure 3. The array consists of 4×4 dual-polarized antenna elements and RF module. The RF module comprises amplifiers and phase shifters to control the antenna elements. Zhang et al. [10] suggested a miniaturized, wide band dual-polarized Vivaldi antenna with reduced Radar Cross Section (RCS), as shown in Figure 3. Two single-polarized Vivaldi elements are arranged in a cross-shape to create the dual-polarized antenna with S11<-10 dB covering the spectrum from 1.8 to 6 GHz. The RCS of the antenna can be reduced over a wide frequency band by creating symmetric rectangular slots and curving metallic portion from the radiating surfaces.

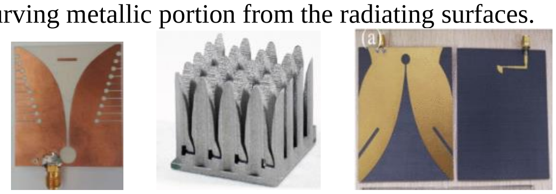

Figure 3. Fabricated prototypes [8][9][10].

Dixit et al. [11] proposed a 1 × 4 AVA array for various 5G services as shown in Figure 4. The proposed antenna operates over 24 – 29 GHz and 30 – 40 GHz frequency ranges and possesses high gain. The size of antenna is miniaturized with help of corrugations which also improve front-to-back ratio augmenting the gain. To increase the bandwidth, optimized corporate feeding is used. Moosazadeh et al. [12] proposed an AVA antenna Surrounded by Dielectric (AVA-SD) with operating frequency, ranging from 5 to 40 GHz for mmWave imaging, radio astronomy, etc., as shown in Figure 4. The conventional AVA is enclosed by dielectric material (Teflon) to suppress higher-order modes and also to enhance antenna gain at higher frequency. The surrounding dielectric area is slightly expanded beyond the antenna to contain most of the energy. Kuriakose et al., [13] proposed a high gain UWB Vivaldi antenna for Through-Wall Radar (TWR) applications with operating frequency ranging from 1.8 GHz to 12 GHz, as shown in Figure 4. First, a broadband Vivaldi antenna is designed using exponentially tapered slot. Then, corrugations and periodic grating elements are introduced along the length of the antenna arm to enhance the gain.

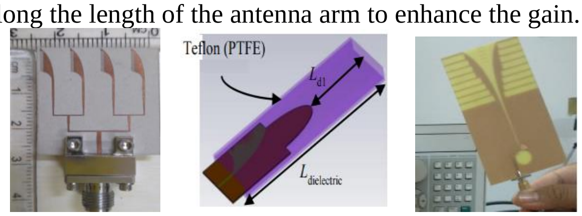

Figure 4. Fabricated prototypes [11][12][13].

Cheng et al. [14] proposed a small sized Vivaldi Antenna for Ground Penetrating Radar (GPR) system as shown in Figure 5. In the proposed design, a Side Lobe Suppressor (SSR) and Artificial Materials Lens (AML) are inserted to increase the gain and radiation capabilities of the GPR antenna. SSR mostly affects low-frequency EM waves, while AML primarily affects high-frequency EM waves. Ramanujam et al. [15] proposed the design of upgraded and compact AVA array for 28 GHz 5G millimeter wave (mm-wave) application with reduced coupling. The design as shown in Figure 5 consists of eight radiating elements with slots on the ground plane and the radiating arm to increase gain and reduce mutual coupling.

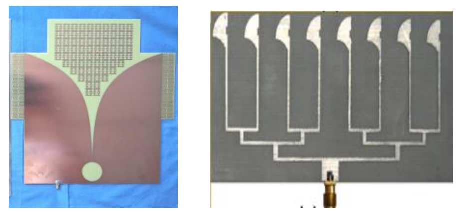

Figure 5. Fabricated prototypes [14][15].

Elabd et al. [16] proposed a broadband MIMO Vivaldi 5G base station antenna for frequency bands (28 GHz and 38 GHz) as shown in Figure 6. The proposed antenna consists of two orthogonally polarized antennas with better isolation using a novel EBG structure. Hence, the final design consists of a two-element beam switch MIMO Vivaldi antenna with electromagnetic band gap structure. Paul et al. [17] proposed a wide band (2 - 28 GHz) Vivaldi antenna, as shown in Figure 6, for satellite and 5G bands in Sub-6 GHz applications using optimization technique. To upgrade the performance, particularly the bandwidth and gain of the antenna, it includes ten corrugated side slots on radiating arm, two circular slots, and one via near feed point.

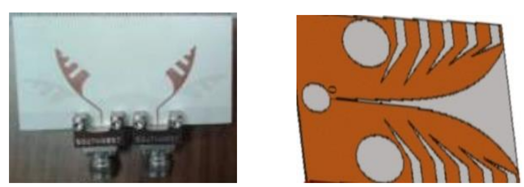

Figure 6. Fabricated prototypes [16][17].

Kumar et al. [18] proposed a wideband (15 - 40 GHz) AVA by integrating a V shaped Negative Index Metamaterial (NIM). The 'V'-shaped MTM unit cells are positioned at the upper surface amidst two radiators in order to radiate a strong electric field in the end-fire direction.

B. *Ultra-Wide Band (UWB) Applications*

Yin et al. [19] projected a compact, wideband Vivaldi antenna comprising a half leaf-shape radiating arm with row of metallized vias making a HM-Vivaldi design, as shown in Figure 7. Further, when it is combined with truncated ground plane, it improves the impedance matching of HM-Vivaldi and hence the bandwidth. An UWB ranging from 5.3 - 40 GHz with S11< -10 dB is accomplished. Wang et al. [20] proposed removal of the redundant substrate from the metallic flares of the proposed antenna and applying dual slotted edges, as shown in Figure 7, to enhance the radiation characteristics. Also, a microstrip-to-stripline transition is incorporated for better impedance matching. The design functions well over 10–40 GHz with S11 < -10dB providing good bandwidth and can be used for a wide range of applications for wireless communication. Li et al. [21] proposed an UWB metamaterial slab (meta-slab) loaded AVA with high gain and stable radiation pattern, as shown in Figure 7. The energy is transmitted to the end fire direction with help of the high permittivity meta-slab, which absorbs it from the tapered slot. Antenna S11 has a measured value of less than -10 dB between 3.6 and 40 GHz.

Figure 7. Fabricated prototypes [19][20][21].

Nassar et al. [22] proposed a unique method for enhancing the bandwidth and directivity of a wide band (2-32 GHz) antipodal Vivaldi antenna structure as shown in Figure 8. The technique is based on inserting a parasitic elliptical patch on the aperture to augment the field coupling amid the arms and create more radiation towards the end fire direction. Mazhar et al. [23] proposed a compact and wideband (5-40 GHz) circular Vivaldi antenna, as shown in Figure 8. The circular Vivaldi antenna is embedded with configuration of log periodic slots and achieves advantages of high gain and low side lobe levels at higher frequencies. Chen et al. [24] proposed a dual-band and dual-polarized nested Vivaldi antenna in frequency range 2 - 40 GHz. The proposed Vivaldi antenna comprises of a 2–8 GHz section along with a 8–40 GHz section nested together. These two nested Vivaldi antennas are arranged in a cross-shape to achieve the antenna's dual-polarized radiation.

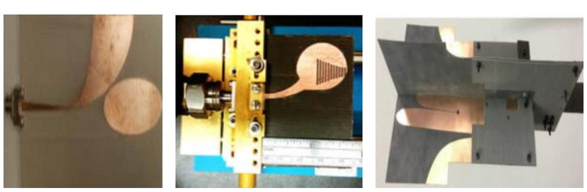

Figure 8. Fabricated prototypes [22][23][24].

Wan et al. [25] proposed design of ultra-wideband Vivaldi antenna with frequency band 3.3–40 GHz, as shown in Figure 9. A trapezoidal dielectric substrate is embedded in the direction of the major axis centred around conventional antipodal Vivaldi antenna, which enhances the directional radiation performance, e.g., high efficiency, low cross polarization ratio and high Front to Back Ratio (FBR). For UWB communications, Natrajan et al. [26] proposed an improved AVA with compact size and large bandwidth by adding another petal to conventional AVA as shown in Figure 9. Through this development, it increases the electrical length of the radiator and thereby reduces the lower operating frequency. Hence, adding another petal results in small size and increased bandwidth (2.4 - 20 GHz). Alhawari et al. [27] proposed a Multiple Input Multiple Output (MIMO) antenna on denim substrate exhibiting dual polarization and low mutual coupling with UWB bandwidth of 5–40 GHz. The antenna, as shown in Figure 9, is integrated with staircase meander line; thereafter, it is embedded with the metamaterial structure that reduces mutual coupling, increasing the gain and efficiency.

Figure 9. Fabricated prototypes [25][26][27].

Natarajan et al. [28] proposed a low cross-polarized and small sized antipodal Vivaldi antenna operating in the frequency range from 3.7 GHz to over 18 GHz as shown in Figure 10. The miniaturization in size is achieved by structurally modifying the radiating fins without changing the dimensions of antenna. Altering the fin's structure results in the diminution of lower operating frequency and hence the size is reduced. Zhang et al. [29] proposed a compact and wide-band Antipodal Vivaldi Antenna (AVA) for UWB applications, as shown in Figure 10. The radiator's conventional exponential tapering edge is substituted with an arc curve in the design to make the AVA more compact. In order to enhance its gain at high-frequency, the AVA is additionally equipped with a "director" and a "convex lens." The proposed antenna is compact with an operating frequency range from 3.01 to 10.6 GHz.

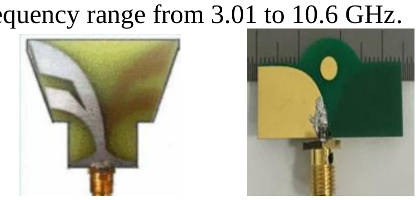

Figure 10. Fabricated prototypes [28][29].

C. *Wireless and Vehicular Communication*

For vehicular communications, a three-port diversity antenna generating three-directional radiation pattern was proposed by Natarajan et al. [30]. It comprises of three Vivaldi antennas interconnected on a single PCB as shown in Figure 11. The second radiating wing is supplemented with the primary with twin line transition. It provides ultra-wideband features with end-fire radiation pattern and bandwidth ranging from 5 to 11 GHz. Jeon et al. [31] proposed a dual-polarized Vivaldi antenna for the Over-The-Air (OTA) testing and measurement of communication devices which are used in the frequency band of 3 – 7 GHz. By vertically interconnecting two planar Vivaldi antennas, the dual-polarization capability is achieved. For the broadband impedance matching of the antenna, a λ/4 long balun is used. Shan et al. [32] proposed a developed Vivaldi antenna with planar directors near the tapering slot's aperture and transverse slots are etched on the edges for vehicular wireless communication Systems. An antenna with planar directors and transverse slots is designed for IEEE 802.11a (4.9 – 5.93 GHz) vehicular communication, as shown in Figure 11.

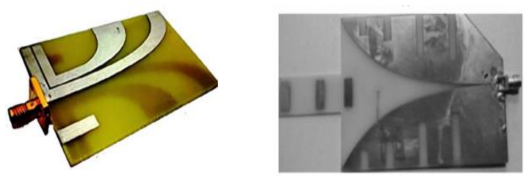

Figure 11. Fabricated prototypes [30][32].

For Vehicle-to-Vehicle (V2V) communication, a switching beam antenna system using four Vivaldi antennas is proposed by Ameen et al. [33], as shown in Figure 12. Vivaldi's operation is decided by switches which make particular antenna active. Tiwari et al. [34] proposed a slotted Vivaldi antenna for the wireless communication applications in the range of 3.5-8.4 GHz for WLAN, WiMAX and HiperLAN applications. Circular and triangular slots are etched on radiating arm of antenna for miniaturization and creating various frequency bands. Güneş et al. [35] proposed a tri-band AVA for WLAN and IoT applications. The antipodal Vivaldi antenna is made up of a Frequency Selective Surface (FSS) inspired director made up of an array of sub-wavelength rectangular patches and meander slotted lines etched on the edges of tapered metallic parts. FSS is used to reduce side lobe level. Bulgaroni et al. [36] proposed a novel design made by an array of two AVAs placed opposite to each other and fed via a microstrip to Coplanar Strip (CPS) transition, as shown in Figure 12. The feed in both antennas is out of phase. The proposed antenna shows four bands in frequency range of 1.85 - 6.9 GHz covering all important frequency bands for wireless technologies e.g, WLAN, Bluetooth, WiMAX, ISM band.

Figure 12. Fabricated prototypes [33][35][36].

Saleh et al. [37] proposed a non-uniform transmission line (NTL) based Vivaldi non-uniform slot profile antenna, as shown in Figure 13. Reduction in the taper slot length by 33% was achieved by this. The proposed antenna provides S11 < −10 dB through 2.4 –13.55 GHz and finds use in various wireless communication applications. Kapoor et al. [38] proposed a vehicular antenna, as shown in Figure 13, to cover the frequency bands for LTE and the mid-band fifth-generation (5G) systems by modifying the Vivaldi antenna which is in form of tapered slot structure. The antenna effectively connects mobile cellular networks and Internet on Vehicle (IoV) systems by virtue of its excellent directional radiation capability.

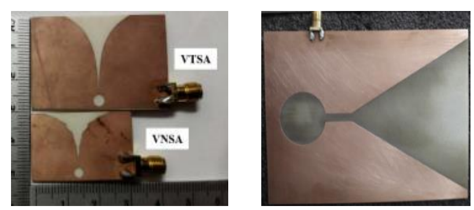

Figure 13. Fabricated prototypes [37][38].

D. *Miscellaneous*

Biswas et al. [39] proposed a compact and wide band fractal Vivaldi antenna by implementing the nature fern inspired fractal leaf structure, as shown in Figure 14. The impedance bandwidth of the proposed antenna is around 18.7 GHz ranging from 1.3 - 20 GHz. Zhang et al. [40] proposed the design of a novel Double-Slot Vivaldi Antenna (DSVA) with impedance bandwidth from 4.7 to 20 GHz, as shown in Figure 14. In comparison with former DSVAs, proposed antenna's radiation characteristics and gain finds great improvement by inserting the double-antipodal structure, director (lens) and corrugated edges in antenna aperture. Moosazadeh et al. [41] proposed an UWB AVA for civil engineering purposes. The inner edges of the upper and bottom radiators of the Conventional AVA (CAVA) have been suitably bent to enhance impedance bandwidth. Further, comb-shape slits have been applied to the edges of the radiators to improve F-to-B ratio and its gain. The result shows an impedance bandwidth between 1.65 - 18 GHz.

 ISBN: 978-1-68558-035-3

Figure 14. Fabricated prototypes [39][40][41].

Wang et al. [42] proposed a compact coplanar waveguide fed AVA embedded with two pairs of elliptically shaped loads and tapered slots for improving the radiation performance, as shown in Figure 15. The wide measured impedance band width achieved is from 1.3 GHz to 17 GHz. Moosazadeh et al. [43] proposed a modified UWB AVA for frequency range (3.4–40 GHz), as shown in Figure 15. The slit edge method is used to enhance the gain at lower frequencies, forming a Periodic Slit Edge AVA (PSEAVA). Thereafter, to further improve the directivity, a Trapezoid-shaped Dielectric Lens (TDL) is added as an addendum to the substrate. Moosazadeh et al. [44] proposed a compact AVA operating from 1 to 30 GHz for assessment of construction material. The conventional AVA's inner edges have been bent to extend the lower frequency range. Further, slit edge method is utilized to enhance the gain and lastly an elliptical-shaped dielectric lens is added to the substrate to attain high front-to-back ratio and gain.

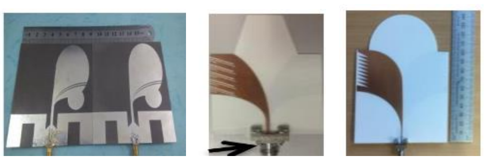

Figure 15. Fabricated prototypes [42][43][44].

Deng et al. [45] proposed an AVA integrated with Double-Ridged Substrate Integrated Waveguide (DRSIW), as shown in Figure 16. DRSIW can attain a lower cut-off frequency as compared to usual SIW due to the inserted ridge. Therefore, DRSIW-fed AVA achieves a decrease in cut-off frequency with improved bandwidth as compared to Vivaldi antennas fed by SIW. The bandwidth with $|S11|\leq -10$ dB lies in the range of 11.0 GHz to 40 GHz. Recently, [46] has proposed Vivaldi antenna array using Ceramic LTCC substrate materials for low loss, high frequency circuit carriers for 6G wireless communication technology and millimeter wave radar.

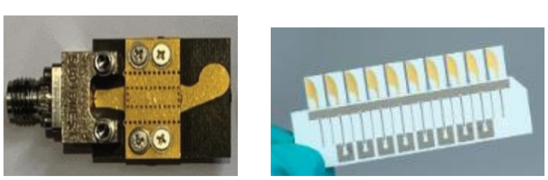

Figure 16. Fabricated prototypes [45] [46].

Vivaldi antenna has several advantages e.g., broadband characteristics, easy impedance matching to the feeding line, compact size, etc. In spite of many advantages of the Vivaldi antenna, it still suffers from a few drawbacks, such as tilted beam, moderate gain and mostly being costlier due to the complex fabrication process.

III. CONCLUSION

In this paper, various techniques for improving the performance of Vivaldi antenna along with their application areas are presented. The basic ideas behind the working principle of Vivaldi and various optimizing techniques are discussed. Further, several recent works using Vivaldi antenna for various areas of communication e.g., Satellite communication, Vehicular communication, Wireless application, RADAR, UWB, MIMO etc. are briefly reviewed.

ACKNOWLEDGEMENT

This work was carried out during the tenure of an ‘ERCIM (The European Research Consortium for Informatics and Mathematics) Alain Bensoussan Fellowship’ programme Founded in 1988.

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 ISBN: 978-1-68558-035-3