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Design of metamaterial based antipodal Vivaldi antenna

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The advanced devices for Ultrawide Band (UWB), 5G, and Millimeter-wave communication demand an antenna that can handle massive data rates and provide high gain and better radiation patterns as a solution for most current wireless communication complications. Many different antennas have been designed. The Antipodal Vivaldi Antenna (AVA) has drawn the attention of most of the researchers because of its high gain, wider bandwidth, less radiation loss, and consistent radiation pattern. Different methods have been presented to enhance the performance of AVA. These different methods include varying the substrate material, radiating element's flaring shape, slots, and feeding techniques. Further, AVA performance can be enhanced by incorporating corrugation, dielectric lens, patch in between two flares, balanced AVA (BAVA), metamaterial, and AVA array. Implementing enhancement techniques in AVA modifies the electrical and physical properties, which in turn improves its performance. This paper discusses a detailed review of Metamaterial-based Antipodal Vivaldi Antennas and a comparison of the antenna parameters.

Keywords: Metamaterial, Millimeter-wave communication, Tapered slot antenna, Ultrawide B, 5G

1 Introduction

The rapid increase has been perceived in the use of the UWB frequency spectrum, and quite a number of UWB antenna designs have been proposed in both academia and the industry, following the commercial licensing of the UWB frequency spectrum by the Federal Communication Commissions (FCC). The recent advancements in wireless communication need an antenna with high bandwidth, low profile, and enhanced efficiency[1]. There has been a quick increase in the use of this spectrum by industry, military, and space wireless communication applications as UWB covers S, C, and X bands[2]. UWB antennas such as Log-periodic, bow-tie, TEM horn, fractal, spiral, conical, and Vivaldi antennas have been scrutinized and proposed. Required features such as planar, low profile, lightweight, and symmetric beam in both radiating planes, conformity with mounting host surfaces and others have been combined to make the Vivaldi antenna more competitive in UWB applications compared with Log periodic and Horn antennas which were large and non-planar[3]. Compared to multiple antennas or reconfigurable antennas in a broadband system, a UWB antenna has less complexity, low power consumption, and a more compact footprint. Vivaldi antenna is a wideband antenna that allows the UWB operation. Vivaldi antennas are widely used for Military applications. Vivaldi, also known as a tapered slot antenna, is a simple planar broadband antenna that possesses linear polarization. It has the radiating element which is tapered conically. Figure 1 shows the Vivaldi antenna along with its radiation pattern.

The structure of the antenna consists of a substrate coated with conducting material at the top of it. The conducting material is a tapered structure with any different shape[3,4]. Vivaldi antennas are categorized into three types based on their structure as Coplanar Vivaldi Antenna, Antipodal Vivaldi Antenna (AVA), and Balanced Antipodal Vivaldi Antenna (BAVA).

2 Materials and Methods

2.1 Antipodal Vivaldi antenna

The antipodal version of the Vivaldi antenna overcame the problem of bandwidth limiting transitions[4]. The AVA antenna used a clever tapered feed to gradually transform an unbalanced coaxial microstrip transmission line into a balanced microstrip line. This was achieved by gradually reducing the width of the ground plane until it matched the width of the microstrip. This then gradually merged into an overlapped slot-line as the throat of the Vivaldi opens up. So, as long as these tapers are modified gradually with respect to the wave length they do not generate

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significant reflections. This results in the highest bandwidth as compared to conventional Vivaldi antenna. Figure 2 shows the AVA structure.

2.1.1 Design equations

The design of AVA was initialized by creating a taper to stretch a structure of curved flares. The feed was given as a base and the flares were designed by placing two ellipses and intersecting them. The patch was designed on the top and bottom side of the Substrate.

The design equations are given below[3],

$$f_{min} = \frac{c}{2W\sqrt{\mathcal{E}_{eff}}} \quad \ldots (1)$$

where,

f_{min} is the minimum frequency, W is the width of the antenna and $\mathcal{E}_{eff}$ is the effective permittivity and also called as effective dielectric constant. This can be found using Eq. (2).

$$\mathcal{E}_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left(1 + \frac{12}{W}\right)^{-0.5} \quad \ldots (2)$$

The exponential flare of the AVA is constructed by two ellipses using the following Eqs 3 and 6,

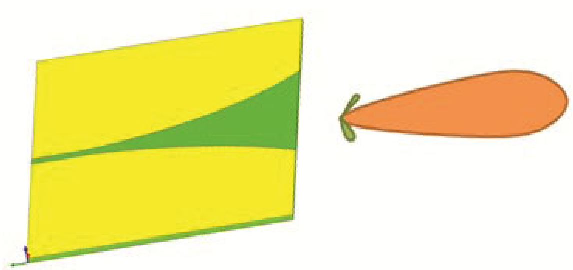

Fig. 1 — (a) Structure of Vivaldi antenna[7] and (b) radiation pattern.

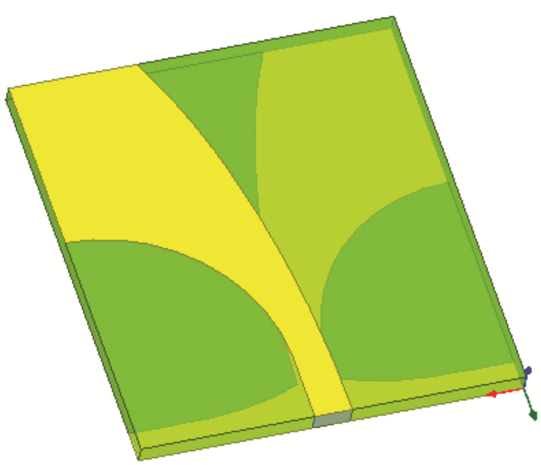

Fig. 2 — Structure of AVA[3].

$$a_1 = \frac{W - W_f}{2} \quad \ldots (3)$$

$$a_2 = 1.68 b_2 \quad \ldots (4)$$

$$b_1 = 0.48 a_1 \quad \ldots (5)$$

$$b_2 = \frac{W}{2} \quad \ldots (6)$$

where, a_1 and b_1, are the minor and major axis of the first ellipse i.e. the big flare and a_2 and b_2, are the minor and major axis of the second ellipse (i.e.) the expurgated portion down the flare respectively.

2.2 Metamaterials

A material which tends to have a property that is not found naturally is called a metamaterial. Generally, they are beyond matter which means it should be artificially made from associations of multiple elements created from many materials. Using metamaterial, it is possible to have an antenna with low mutual coupling, high gain, wide bandwidth, and compact size. Their preciseshape, size and orientation gives them their extraordinary properties capable of operatingelectromagnetic wavesto provide better performance that go beyond what was only possible with the conventional materials[2,3].

2.3 Literature review

This section presents a detailed review on planar design and performance AVA when incorporated with different types of metamaterials. The AVA based on Meta surface (MS), Anisotropic Meta surface, Zero Index Metamaterial (ZIM), Negative Index Metamaterial (NIM) and AVA array using metamaterials along with the obtained antenna parameters are clearly discussed.

A UWB Antipodal Vivaldi Antenna with Meander-line shaped Zero Index Metamaterial (ZIM) units were presented[3]. Since metamaterial improved the antenna gain, ZIM was placed on the antenna aperture to improve the antenna gain and directivity within a compact size. The antenna was printed on FR4 substrate with permittivity of 4.7 and 0.76-mm thickness. The operating frequency range of the antenna is 2 to 12 GHz except a tiny region of negative permittivity over the frequency range from 8.44 GHz to 8.8 GHz. The dimensions of the antenna were $140 \times 96 mm^2$. For both AVA and AVA with ZIM, the reflection coefficients were less than − 10dB. Therefore, we could understand that, printing of metamaterial units keep the ultra-wide-band property of the AVA. The radiation performance of the antenna with and without ZIM was noted at 5GHz, 7GHz and 10GHz. Loading ZIM units had enriched the radiation of the antenna, where the gain varied between 9.5 dB and 12.3 dB within the operating range. Almost equal radiation patterns at different frequencies in both E and H planes were achieved.

An Ultrawide B and metamaterial slab covered AVA was presented[4]. The AVA was printed on a Rogers RO4003C, 0.508 mm thick substrate with dielectric constant of 3.38 and loss tangent of 0.0027. The total size is $60 \times 40mm^2$. The AVA consisted of three major parts, an elliptically tapered ground, a microstrip feed line, the 50 Ω coaxial line and two dual exponentially tapered radiators printed on the top and bottom sides of the substrate. From the simulated results, it was observed that the AVA has a broad bandwidth from 3.74 to 44 GHz, and a slight mismatch occurs between 5 and 6.25 GHz. To enhance the gain of AVA a parallel line unit cell is printed on the Rogers RO4350B substrate with a relative permittivity of 3.48 and a thickness of 0.101 mm. To enhance the antenna performance into a broad band especially at high frequencies, metamaterial Slabs covered Antipodal Vivaldi Antenna (MSAVA) was designed and fabricated. The meta-slabs consisting of 10 × 25 array of high permittivity metamaterial unit cell could significantly increase gain and directivity, narrow beam width and reduce side lobe level without altering the length of the antenna. The measured gain was up to 17.7 dBi in the frequency band of 3.68 to 43.5 GHz. The measured results confirmed that the proposed antenna achieved a gain >10 dBi in the range of 10–20 GHz, >15 dBi in the range of 20 to 32 GHz, and >17 dBi in the range of 32 to 40 GHz[4].

The gain enhanced AVA was realized for 5G communication applications[5]. At first the AVA was designed and it was enhanced by introducing metamaterial and rectangular corrugations. The designed antenna covered 25 to 29.5 GHz and 31.8 to 33.4 GHz 5G frequency bands. The substrate used was FR4 with thickness of 1.6mm and the size of the antenna is $40 \times 24mm^2$. The epsilon negative metamaterial was used to enhance the performance of AVA. This metamaterial was designed by placing multiple V-shaped unit cells in between the two flares. Further, the design was enhanced by introducing corrugations. The effect of metamaterial corrugations had improved the antenna bandwidth to 9.75 GHz with slight reduction in return loss. The AVA with metamaterial corrugations played a vital role in back lobe reduction and thus the design possessed good radiation characteristics as well as better results by having wider bandwidth and reduced return loss at 5G frequencies, it suited well for 5G Communication devices.

A compact and efficient modified leaf shaped Antipodal Vivaldi antenna was designed for UWB and band notched characteristics for WLAN applications was presented[6]. It was attained by incorporating three split ring resonators in different positions of the antenna. The AVA was designed on a 1.6 mm thick FR4 substrate, with size of 36×28 mm^2. It was observed that, for position-1(top), the band rejection was not reasonable. In position-2 (bottom), there was band rejection in WLAN frequency (5.15 to 5.725 GHz), impedance matching was not satisfactory for frequency bands from 2 to12 GHz. In addition to that, position-3 (surface of flare) the concept of band-notching was fully justified and the impedance matching for other frequency bands was satisfied. From the results, broadside radiation pattern was observed with the placement of SSRR (Square Split Ring Resonator). Maximum directivity in main lobe and minimum directivity in the back and side lobe was observed, making it ideal as a dual-functionality antenna. It was also observed that the design of AVA with SSRR had improved the overall performance of the antenna. It provided the ultra-wide bandwidth from 2 to 12 GHz and it notched WLAN from 5.15 GHz to 5.72 GHz. The average gain was 8.8 dBi. Thus, this technique provided better results.

A planar AVA array with better performance for future 5G millimeter (mm) wave communication applications was presented[7]. The proposed structure is an 8 × 1 array with eight elements in E-plane, which was fed by a 1-to-8 power divider network. In order to reduce its size and to improve its gain, an anisotropic meta surface was placed at the aperture, without changing the overall dimension or compromising the performance of AVA array. The AVA was designed on a thin $0.787\ mm^2$, Rogers 5880 substrate with ε_r of 2.2, loss tangent of 0.001. The overall size was $6.11\ \lambda_g \times 2.93\ \lambda_g \times 0.08\ \lambda_g$. It contained two metal layers, eight left and eight right arms of the AVA array were printed on the top and bottom layers, respectively. A 1-to-8 power divider network on the top layer and a ground plane on the bottom layer were incorporated and which acted as a balun. A two-stubs-loaded split-ring resonator was placed in between the two flares. Due to this, most of the radiated power would get transmitted from the AVA array within a wide frequency range. From the simulations, the designed AVA with meta surface has the impedance bandwidth of 24.1 to 28.5 GHz, which could be used for future 5G mm wave communication applications, a higher gain of 9.35 to 12 dB in comparison with the AVA array, whose gain was 8.5–11.2 dB in the frequency band of 24.75 to 28.35 GHz. Thus, implementing Meta surface in AVA array provided better results.

A novel AVA was designed for UWB frequency range 3.1 to 10.6 GHz[8]. The AVA was designed on the top and bottom of FR4 substrate. The Vivaldi antenna was modified by incorporating Electromagnetic band gap (EBG) structures in the form of SSRR which are the constituent part of metamaterials. The operating frequency of the designed antenna was 2 to 15 GHz. The overall size of the antenna was 100 × 100 mm^2. The EBG structure was in the form of SSRR which were incorporated in the ground. By this, the bandwidth of the antenna got improved by covering X, S, C bands. The gain of the proposed antenna was 10.3dB. The modification by including EBG structures had improved the bandwidth and gain of the antenna.

A corrugated AVA with Negative Index Metamaterial (NIM) was presented[9]. The metamaterial was made of archimedean spiral design. The single layer NIM was placed on the middle of the two flares of proposed antenna. The size of the antenna was 30 × 60 mm^2. Initially, the AVA was designed on the top and bottom of RT-Duroid-5880 which had the dielectric constant of 2.2 and loss tangent of 0.0009. The thickness of the substrate was 0.787. The spiral NIM cell layer of 5×5mm^{2}was placed perpendicular in between the two flares. From the results, the ultra wideband was obtained from 4.7 GHz to 11GHz.

The AVA was designed and incorporated with Anisotropic Zero Index Metamaterial[10]. The main aim of using AZIM is to improve the directivity of the antenna. The antenna design was done on FR4 substrate with dielectric constant of 4.4 and thickness of 1.6mm. The size of the antenna was 60 × 70 mm^2. The antenna was initially modified by placing slots at the edges and then a set of AZIM cells which were placed in between the two flares. As a result, the antenna provided a gain of 7.4 dB.

3 Results and Discussion

The usage of metamaterials in the antenna was able to improve the antenna parameters in terms of gain, ultra wide bandwidth and better radiation characteristics[11]. The Table 1 shows the comparison of the antenna parameters obtained by incorporating different metamaterials in AVA.

Table 1 — Comparison of results[3-10]

Size	Substrate	Bandwidth	Gain
140 × 96 mm^2	FR4	9.3 GHz	9.5 – 12.5 dB
60 × 40 mm^2	Rogers RO4003C	39.82 GHz	17 dB
40 × 24 mm^2	FR4	9.75GHz	9.53dB
36 × 28mm^2	FR4	6GHz	9dB
6.11 λg × 2.93 λg	Rogers 5880	4.35 GHz	9.35 – 12 dB
100 × 100 mm^2	FR4	13 GHz	10.3dB
30 × 60 mm^2	RT Duroid 5880	6.3GHz	1dB
60 × 70 mm^2	FR4	225MHz	7.4dB

Table 1 compares the dimensions of metamaterial incorporated AVA in terms of the substrate used, operating frequency and the obtained gain. The gain of the antenna got increased by using metamaterial. FR4 was widely used for fabrication as it was cost efficient but it had the drawback that it changed with respect to temperature[12]. But the Rogers had less loss and it withstood when there was change in temperature. An efficient substrate was necessary since it was the base for the improvement of bandwidth and efficiency of an antenna[13]. The gain and bandwidth were better in all the methods used. Further, concentrating on size reduction could make the design more effective.

4 Conclusion

In this paper, a comprehensive review of different metamaterial based AVA's has been presented with the comparison and analysis of their performance enhancement techniques. The designed AVA's with metamaterials enhances the performance of the antenna in terms of gain, radiation characteristics, and UWB. AVAs are widely used for military, RADAR, and space applications as it provides UWB characteristics, stable radiation patterns and enhances the gain. Further enhancement in AVA can be carried out to expand its signature and make it usable for the applications such as microwave imaging, SAR, and stealth applications.

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