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Miniaturized Metamaterial-Loaded Antipodal Vivaldi Antenna with Enhanced Bandwidth for 5G System

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ABSTRACT: The increasing need for fast wireless communication in 5G networks means that antennas must offer broad bandwidth, strong signal strength, and small size to work well on mobile devices. This study introduces a small antipodal Vivaldi antenna combined with metamaterial designs to improve its radiation performance for use in 5G mobile systems. The antenna uses a tapered slot design that allows it to work over a very wide range of frequencies while keeping its size small. To better enhance the electromagnetic performance, a unit cell inspired by metamaterials is added to the antenna design. This helps change how the surface currents spread out and makes the antenna match better with the desired frequency range. So, the new antenna performs better than older Vivaldi types by offering a wider range of frequencies, stronger signal strength, and better use of power. The antenna is created and studied using a full-wave electromagnetic simulation tool, and its performance is checked based on reflection coefficient, radiation pattern, gain, and bandwidth. Simulation results show that adding metamaterial components greatly enhances the performance of antennas.

KEYWORDS: Antipodal Vivaldi Antenna, Metamaterial, 5G Communication, Wideband Antenna, Compact Antenna Design, Gain Enhancement

I. INTRODUCTION

Due to the vast expansion of wireless communication, the necessity of high frequency spectrum is in greater demand [1]. The improvement of modern wireless technologies including Wi-Fi 5, Wi-Fi 6, 4G LTE and 5G have presented better innovations and merits over the industry [2]. The present 4G LTE communication in case of mobile phones generate a moderate data rate and capacity that influences from spectrum limitation. The 5G technology is an advanced form of 4G LTE with rapid connections, additional capacity and increased throughput [3]. For a better outcome, the 5G communication system needs higher data rate, larger bandwidth and wider capacity.

Nowadays, the 5G technology are highly affected due spectrum shortage problems [4]. The major requirement for the 5G application is to provide sub-6 frequency of range 2-5GHz and for manipulating above 6GHz, the frequency range must be compatible to provide 24-71GHz [5]. Normally, the mm wave have the frequency range of 30-300GHz and it is integrated with 5G applications capable of handling above 6GHz frequency range [6]. To comply diverse necessities of 5G technology, an efficient antenna with huge bandwidth, steady radiation pattern and enhanced gain are needed [7]. The researchers have designed diverse antenna types including monopole antenna, patch antennas, dipole antennas, loop and antipodal Vivaldi antenna (AVA) in case of 5G applications [8].

From these types, AVA can be utilized for larger frequency spectrum and shows outstanding performance especially in mm wave 5G applications [9]. The AVA is invented by Dr. Gibson and later it is changed into antipodal shape for improving the directivity, gain and bandwidth of the Vivaldi antenna [10]. The AVA consist of several parameters like antenna length, width, tapered length, rate, slot line length, back wall offset (BWO) and opening mouth (OM) that plays an important role in minimizing the bandwidth consumption and refection coefficient [11]. Due to increased band spectrum, the parameters of the AVA gets affected. For improving the parameters of the AVA, dielectric lens, parasitic patch, balanced AVA, metamaterial, array and MIMO are utilized [12]. In this, the dielectric lens is one of the material that can be utilized instead of substrate having varying relative permittivity. But it highly depends upon the antenna size and is cost effective [13].

In existing studies [14], utilized elliptical shape parasitic patch for increasing the bandwidth and gain of the antenna. However, this material suffers from high hardware complexity. For the balanced AVA (B-AVA), three basic layers are present namely double ground patches and single patch radiators that acts as a sandwich between patch grounds [15]. The B-AVA can produce a cross view beamforming but it is complex structure. Recent studies [16] utilizes array

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antenna for maximizing the diversity gain and avoids the antenna to take multi-path fading. Several researchers have investigates the different antenna performance for enhancing the communication performance [17]. In [18], 1×4 array AVA used with substrate integrated waveguide (SIW) and corrugations to generate gain of 23dBi. However, the determination of dimension and position of the antenna remains the complex task [19]. To overcome this issue, slots are integrate at the ground plane that can normalize meander lines (ML) between different micro-strip patch antennas [20]. There are different slot shapes for reducing the MC between the each antenna namely circular, rectangular, H-shaped, U-shaped, L-shaped slot etc. [21]. The size of the antenna can be reduced using corrugation and it may be triangular, rectangular or square shape etc. Most of the existing works utilizes rectangular corrugations of maximizing the antenna efficiency [22]. In addition to the slots and metamaterial, defected ground structure (DGS) and asymmetrical co-planar strip wall also play an integral role in reducing the MC between the antenna elements. Moreover, electromagnetic band-gap (EBG) and split-ring resonator (SRR) structures are inserted between two antennas to improve the MC. Utilization of EBG in the feeding network for eliminating the wave surfaces and MC in the antenna [24].

Recently, the metamaterial play an important role in reducing the size of the antenna and have the capability to produce multi-band frequencies effectively. There are many different kinds of metamaterial are present that provides varying permittivity based on its nature [24]. The metamaterial having negative permittivity then it is said to be epsilon negative (ENG) permittivity [25] and if the relative permittivity is negative then it is considered as the mu negative permittivity (MNG) [26] and if both are negative then it is double negative (DNG) [27] permittivity. Based on their behaviour, the metamaterial are separated into different types as anisotropic, photonic, isotropic, chiral, and frequency selective-surface [28]. The metamaterial have numerous advantages like increasing bandwidth, reduces MC and improves gain effectively [29]. Traditional AVA, the antenna is contemplated between double metamaterial slabs for maximizing the directivity and for generating fixed radiation performance. The conventional meander-line, W-shaped metamaterial structure can provide enhanced half power beam-width especially in 5G applications [30].

II. RELATED WORKS

Some of the recent works done by different authors:

Amruta S. Dixit & Sumit Kumar [31] suggested antipodal vivaldi antenna (AVA) using metamaterial for enhancing gain in 5G applications. The dimensions of the suggested AVA were $24mm\times 50mm\times 1mm$. The property of negative relative permittivity was exhibited by 'V' meta-material and so it was called epsilon negative metamaterial (ENG). To transmit more energy in end-fire direction, the ENG unit cells were organized in between the two AVA flares. The gain of the antenna differs between 10.9 and 13.82 dBi in 24-30 GHz frequency range, which made it appropriate for 5G applications.

Amruta S. Dixit & Sumit Kumar [32] introduced a low profile AVA with substantial enhancement in front-to-back ratio as well as sidelobe levels (SLL) in order to tackle adverse effect in 5G communication system. This AVA had modelled by integrating corrugations and substrate integrated waveguide (SIW) for 38 GHz band of communication system and it comprised of 36 to 48.43 GHz of impedance bandwidth. Besides, the antenna efficiency was above 94% over the desired range of frequency and the usage of SIW enhanced SLL and bandwidth.

Amruta S. Dixit & Sumit Kumar [33] described AVA based on fermi-dirac function for millimeter wave (mmWave) application to accomplish broadband performances. This model had offered an outstanding fractional bandwidth, which ranges between 10.45 and 300 GHz. The outer exponential curve was initially modelled by fermi-dirac function whereas, the inner curve was quarter part of circle. Besides, the rectangular shaped corrugations improvement scheme was integrated in AVA in order to improve gain and bandwidth.

Innocent Kadaleka Phiri & Kumaresh Sarmah [34] presented AVA array with enhanced ground plane as well as slotted radiators for 5G mmWave applications. In the beginning, single element AVA was modelled, and further an array with elements of 4×1 AVA and a 3dB power divider was modelled on $28\times 32\times 1.6mm^3$. The operating bandwidth of array antenna was improved by the addition of cuts. On the feeding section, the structural enhancement of ground plane enhanced array antenna gain, operating bandwidth, and impedance matching.

K. Nishanth Roa et al. [35] offered an optimization-based AVA for ultra-wide band (UWB) communication to improve the performance. Here, the antenna was modelled with optimal-tuning of antenna parameters such as aperture width, taper length, slot line width, opening rate, ground plane width, etc., correspondingly. More specifically, an enhanced

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grey wolf optimization algorithm (EGWO) with update evaluation based on fitness was employed to fine-tune the parameters. As a result, this model had accomplished directivity, gain, current distribution etc.

Parthasarathy Ramanujam et al. [36] suggested a modified AVA array with surpassed mutual coupling for 5G mmWave application. By utilizing eight radiating elements, the configuration was assembled with single 1-8 power divider networks. The mutual coupling between the array elements were intimidated by including various notch structures. Thus, the radiating system had extended impedance, enhanced gain and maximal additional isolation.

Ziye Wang et al. [37] presented a modified metamaterial slabs enhanced AVA (MMSEAVA) for improving gain and directivity. In MMSEAVA, the metamaterial slabs, which encompassed a unit cell comprising of metal ellipse ring had loaded to effectively enhance the performance. The presented metamaterial slabs had maximum permittivity while comparing with substrate. Besides, MMSEAVA could effectively minimize the H-planes and E-planes half-power beamwidth. Subsequently, it was perceived that this MMSEAVA had benefits of maximal directivity, maximal gain and ultra-wide band.

Houyuan Cheng et al. [38] suggested a maximum gain AVA with a compound optical lens (COL) encouraged by metamaterials. The unit cell of metamaterials was a closed symmetric S-type resonator (CSSR). COL, comprised of double-convex lens and plano-convex lens, could construct a narrow bean with 11.2^0 half-power beamwidth at 12 GHz. It also concentrated on plane wave converted from spherical wave, which creates an extremely narrow radiation beam. As a result, the obtained narrow band was about 11.2^0 at 12 GHz.

Peyman Mahouti et al. [39] offered a multi-layer frequency selective surface (FSS) architecture to enhance the performance of Vivaldi antenna model. This Vivaldi model utilized a data-driven surrogate method along with the optimization algorithm, which was known as honey-bee matching optimization. Besides, the optimally modelled antenna had prototyped as well as their performance characteristics were evaluated. Experimental outcomes revealed that the presented structure had maximum gain with no performance losses the characteristics of return loss.

Jia Liu et al. [40] recommended a miniaturized ultra-wide band AVA array by integrating low-scattering characteristics with hybrid diffusive-absorptive meta surface. For antenna element, a dielectric lens and periodic elliptical slots at outer edges were employed to enhance the performance. The 4×4 array realized a radar cross section (RCS) with no degration of radiation performance by loading an optimized Minkowski-shaped metasurface as ground reflector. The results verified the feasibility of enhancing the antenna performance and low-scattering functionality of ultra-wide band.

Table 1: Contribution and Limitations of existing models

Authors	Technique	Contribution	Result	Limitation
Yue-jun Zheng,Jun Gao,Yu –Long Zhou,Xiang –Yu Cao,Si-Jia Li,Huan HuanYang	Metamaterial based patch antenna with wideband RCS reduction and gain Enhancement using improved loading method	Wideband radar Cross section reduction and gain enhancement are both achieved for patch antenna by Loading Metamateria**l.**	Gain of the proposed antenna is enhanced	Deteriorations in radiation pattern is observed
Yuejun Zheng,Jun Gao,Xiangyu Cao,Zidong Yuan ,Huan Huan yang	Wideband RCS reduction of a Microstrip Antenna using Artificial Magnetic Conductor structures	RCS reduction of microstrip antenna has been obtained by loading a planar modified chess board structure	RCS reduction of proposed antenna has been validated	Cross polarization of of proposed antenna is little larger then reference antenna
Amruta S. Dixit & Sumit Kumar [31]	AVA+ V-shaped metamaterial	To provide AVA suitable for applying in 5G communication devices	Better compactness, enhanced gain and wide bandwidth	Need to improve return loss.
Amruta S. Dixit & Sumit Kumar [32]	Low profile AVA with front-to-back ratio and SLL	To resolve the adverse effect on the components of communication system with gain	Improved gain, reduced size, and enhanced SLL	Need to enhance the efficiency.

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		enhancement and antenna size reduction		
Amruta S. Dixit & Sumit Kumar [33]	AVA based on fermi-dirac function	To introduce a wideband AVA for attaining broadband performance in mmWave range	Stable radiation patterns and enhanced efficiency	Need to improve gain performance.
Peyman Mahouti et al. [39]	Multi-layer FSS architecture	To boost the performance of Vivaldi antenna model with maximum gain	Higher gain	More complexity

III. MOTIVATION AND PROBLEM FORMULATION

In recent years, the growth of 5G applications has increased exponentially for wireless communication system. This immersive growth of 5G technology have witness by providing high capacity and high network speed. Practically, the pros of the 5G system can be utilized completely only when multiple antennas are integrated at the time of antenna design. However, utilization of several antennas can cause high hardware complexity and low gain. To overcome this issue, mm wave band is contemplated with the 5G technology that can provide high frequency band by reducing physical complexities of the antenna. The use of high frequency spectrum can affect the transmission path badly hence the latency also gets increased. For overcoming this issue, antenna array is utilized in which the antenna are designed in array manner to maximizing the gain of the antenna. But the major problem with the array antenna it can maximize the mutual coupling between the antenna elements that can decrease the gain and directivity of the system.

For past few years, 4G LTE system is utilized for many wireless applications. But it lacks the communications speed and this is the reason behind the development of 5G technology. The utilization of 5G with IoT can increase the bandwidth and consumes low power for data transmission. However, the increase in negative ad positive permittivity can cause high path loss and failed data transmission. One of the most common factor that can supress the pros of the antenna efficiency is that multipath fading. For integrating 5G applications with MIMO antenna requires less mutual coupling and high frequency spectrum. These kinds of major drawbacks motivate us to develop an efficient antenna design for various 5G applications. To the best of the knowledge, the proposed study address all the issues faced by the existing techniques and shows the outstanding performance effectively.

IV. RESEARCH OBJECTIVES

- To design an Antipodal Vivaldi antenna (AVA) with split ring resonator (SRR) for 5G application for improving directivity and gain of the antenna.
- To design a corrugation based 1x4 antipodal Vivaldi antenna (AVA) arrayfor 5G applications for increasing the bandwidth and gain of the antenna.
- To design an epsilon near zero metamaterial (ENZ) based Antipodal Vivaldi antenna (AVA) for the better bandwidth and less reflection coefficient.
- To design a negative index metamaterial (NIM) based antipodal Vivaldi antenna (AVA) for achieving low mutual coupling and better diversity gain.

V. WORK PLAN IMPLICATIONS

Problem Formulation (Objective 1)

In mobile communication, the fifth generation (5G) has been plays a major role because of the high data rates. 5G networks can provide high capacity and high data rates. These requirements are analysed by using antennas comprises of microstrip patches at the terminals and base station. This 5G technology utilizes a large frequency bands at 28 GHz to 37 GHz. There is a huge requirement for high performance networks and efficient cellular devices which requires more efficiency in the design of antennas. Minimizing the number of antennas for various applications in the single system is suggested because of physical limits. Therefore, it is possible to design a single antenna which can be used in different applications. High data rates are achieved at millimetre band; but the frequencies in this band suffer due to severe path loss. To tackle this challenge, high gain antennas, small size and high bandwidth are needed. 5G antennas should operate at high frequencies and the propagation losses occurs at highfrequencies. Hence, the Antipodal Vivaldi antenna (AVA) is the better choice for 5G applications for minimizing the propagation losses at high frequencies and also to achieve better gain.

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Work plan (Objective 1)

This work presents antipodal Vivaldi antenna (AVA) which operates at ***28-39 GHz for 5G applications***. The metamaterial based AVA is introduced in this work for improving directivity and gain of the antenna. Initially, the standard AVA is designed and then ***split ring resonator (SRR) based metamaterial with rectangular corrugation i***s designed.The AVA with SRR based rectangular corrugation enhances the gain of antenna. The substrate used is ***Roger RT/duroid 5880***and here the aperture width and taper length are optimized by the ***metaheuristic Marine Predators optimization (MPO).***The designed antenna will be in compact size and it will be suitable for 5G applications. The performance of the antenna is carried out by with and without SRR and with SRR based corrugation.

Problem Formulation (Objective 2)

Present cellular communication band below 3 GHz undergoes severe shortage and can't manage with rapid demand of the communication speed. The use of mm-Wave bands for improving the communication quality is the major for 5G applications. For overcoming the high propagation loss in the mm-Wave, the antenna should have high gain and stable radiation properties. Due to the light weight and ease of fabrication, the antipodal Vivaldi antenna (AVA) is most preferable for mmWave applications. Moreover, the array structures are utilized for achieving the better gain. However, the problem is occur between the side-lobes and mutual coupling also increases. Large side-lobes may affect the radiation performance of the antenna. Hence, there is a need of design which reduces the mutual coupling and enhances the gain and bandwidth of antenna array.

Work plan (Objective 2)

The 5G frequency is becoming one of the major bands for the up-coming generation communication. It offers better quality of service, high capacity, high data rate and low latency. To overcome the issues of 4G communications, this work presents a compact size ***1x4 antipodal Vivaldi antenna (AVA)array*** for 5G applications. This design operates in the range of ***28-39 GHz for 5G millimeter wave applications.*** To reduce mutual coupling between the antenna elements, the ***defective ground structure (DGS)*** is introduced and designed on the ***FR-4 substrate.***Further, the***gradient tilted corrugation*** is designed for increasing the bandwidth and gain of the antenna. The performance of the 1x4 antenna array is analyzed by with and without DGS and with DGS based corrugation.

Problem Formulation (Objective 3)

The mobile communication has been evaluated from 1G to 4G and brings revolution in the technology. 4G technology is utilized in several applications like remote sensing, machine to machine communication and video call data. Though, this 4G technology has advantages, it has some issues of more energy consumption, poor quality, bad interconnectivity and poor coverage. However, this technology is not suitable for fast communication growth. Hence, there is a need of 5G technology which integrates the internet of things (IoT) into device to device to device (D2D) with large bandwidth, better coverage and low power consumption. Recently, antipodal Vivaldi antenna (AVA) is utilized for mm-wave application and several enhancement approaches are investigated in existing works. The designs like parasitic patch and dielectric lens are utilized; but these designs increased the size of antenna and leads to high design complexity. Hence, the performance of antenna is enhanced by using metamaterialsbased AVA. These material has better electromagnetic characteristics like negative permittivity and negative permeability. Hence, this objective focus on the integration of metamaterial based AVA for 5G application.

Work plan (Objective 3)

A compact size and low design complexity ***antipodal Vivaldi antenna (AVA)array*** is designed for 5G mobile applications. The proposed antenna design has three layers: the initial layer has ***eight element array*** and is connected by ***1 to 8 power divider network***. The second layer has the substrate of ***Roger RT/duroid 5880*** and the bottom layer has the ***defective ground structure.*** Then, for enhancing the gain of the antenna***the metamaterial epsilon near zero metamaterial (ENZ)*** is placed between the antenna elements. These ENZ cells have the benefits of suppressing the radiation fields. Further, this design resonates at the frequency of 28-38 GHz. This antenna provides better bandwidth and less reflection coefficient. The performance of theeight element array is compared with four element array, two element array and single elementwith the measures like Gain, return loss, VSWR, radiation pattern, and directivity.

Problem Formulation (Objective 4)

During the last two decades, wireless communication system have shown high growth and 5G antenna is gaining more attention. Though, the 5G technology have significant benefits like high data rate, high communication capacity and low cost, they undergo various issues of multi-path fading and reliability. To tackle this issue, multiple input multiple output (MIMO) is integrated with 5G applications for achieving the better gain, improving data transmission efficiency and also for suppressing the multi-path effect. Several research works were introduced for gain enhancement and for reducing the mutual coupling using band notched MIMO antenna. It is proved that the MIMO antenna for 5G

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applications needs small size and less mutual coupling. The mutual coupling may increase when the antenna size is reduced. However, only less research works are carried out using band notched Vivaldi MIMO antenna. Hence, this research work focus on band notched Vivaldi MIMO antenna for 5G applications.

Work plan (Objective 4)

For the need of low mutual coupling for MIMO antenna for 5G application, a new design based on ***negative index metamaterial (NIM) based antipodal Vivaldi antenna (AVA)*** is introduced in this work. The proposed design has ***two orthogonal polarized antennas on the FR4 substrate***. Then, the ***slots*** are provided in the antennas for obtaining the frequency range of ***28-39 GHz.*** For minimizing the isolation between the elements of MIMO antenna with low cost and low complexity the antenna elements are distributed in the z-direction. Then, the elements are spacing between half wavelength and ***two electromagnetic band gap (EBG) cells*** are placed along the feedline of the antenna. The size of the antenna is compact and the performance will analyzed on the measures like directivity gain, reflection coefficient, gain, radiation pattern, VSWR, envelope correlation coefficient (ECC), Total active reflection coefficient (TARC), and Mean effective gain (MEG) are measured. As well as the proposed design is compared with existing design to prove the efficiency of the designed antenna.

Implementation Tool: HFSS

VI. CONCLUSION

The utilization of high frequency spectrum have gained much attention towards the researchers due to fast growing wireless communication. Recently, the 5G applications are utilized with mm wave that can provide greater frequency spectrum with low latency. However, 5G applications operates on larger frequency bands and also requires high number of antennas for achieving high performance. The need of multiple antenna in 5G system causes high hardware complexity and cost effective. This article brings novel metamaterial based compact antipodal Vivaldi antenna as a single antenna to achieve high directivity and gain for 5G applications. The proposed methodology undergoes four major objectives to address the bandwidth consumption, low gain, high latency and fixed radiation response. In the first objective, the proposed method introduces a novel design of AVA with SRR for maximizing the gain and directivity in 5G application. This study helps to enhance the gain and directivity of the antenna effectively. In the second objective, a novel design of corrugation based AVA array for processing with 5G application. This research study aids to enhance the bandwidth and the gain of the antenna. In the third objective, the article proposes a novel design of ENZ based AVA for 5G technology. This study aims to provide high bandwidth and reduces the reflection coefficient efficiently. In the fourth objective, an effective NIM based AVA design is studied to enhance the communication in mobile applications. The main aim of this study is reduce the mutual coupling and to enhance the diversity gain of the antenna.

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