Design of Dual Mode AVA with Enhanced Radiation Characteristics

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Abstract
This paper presents the design of a Dual mode antipodal Vivaldi antenna (AVA) with narrowband to wideband switching characteristics. The radiation characteristics are improved by loading the semi-circular slots on the radiator based upon the surface current analysis. This resulted in gain enhancement and the lower resonance frequency improvement. High-frequency switching is achieved via PIN diodes with proper biasing circuits. The proposed antenna is fabricated on a low-profile FR-4 substrate with the dimensions of 60 mm x 40 mm x 1.6 mm. The proposed antenna exhibits 8.3 GHz bandwidth in wideband mode with a peak gain of 6.9 dBi and 1.6 GHz bandwidth in narrowband mode with a peak gain of 7 dBi. Reference antenna is fabricated with the same dimension and utilized for the comparison with the proposed antenna. All the simulation results are carried out using CST full-wave simulator. The working principle of the antenna is explained through simulation and verified through measurements.

Keywords Antipodal Vivaldi antenna · FR-4 substrate · PIN diode · CST

1 Introduction
Rapid development in wireless communication demands the need for multifunctional antennas with cognitive functionalities. Reconfigurable antennas are the potential candidate to serve the demand. There are several reconfigurable antennas with several mechanisms available in the open literature. Depending on the application, it may be a frequency, pattern,
or polarization reconfigurable antennas. Among the implementation of such antennas, it is necessary to notch the unwanted bandwidth from the available spectrum to avoid intruders. Ultra-wideband technology is widely recommended for applications like satellite networks, biomedical detection, microwave imaging, military, and radar systems. Multifunctional characteristics can be obtained by embedding multiple antennas or implementing reconfigurable antennas. There were different reconfigurable mechanisms available and utilized in the literature. The antenna selection and the reconfigurable mechanism are equally crucial for efficient antenna implementation. At the same time, the reconfigurable mechanism should not affect the radiation characteristics of the antenna. Vivaldi antennas are among the end-fire antenna family, and it has been explored in many ways in many applications. In our research, we have implemented an antipodal Vivaldi antenna (AVA) to become a reconfigurable antenna with the help of PIN diodes.

A high gain Planar Vivaldi antenna is presented in [1] based on a grooves-based approach, which reduced the dimensions. Corrugated edges with the asymmetric parasitic patch are implemented in [2], which extend the lower bandwidth of the AVA. Miniaturization of AVA with improved radiation characteristics is observed in [3] with exponential strip arms. The fractal-shaped dielectric slab is placed on either side of the substrate [4], [6] for improved radiation. High-frequency antenna gain is improved by incorporating vias loaded with leaf-shaped structures [5]. Antipodal Vivaldi antenna with band notching is presented in [7] by implementing the resonant parallel strip. Narrowband -Wideband switchable antipodal antenna is realized [8] by PIN diodes for breast cancer detection and treatment.

To resolve the restriction, several techniques have been used and recorded to minimize the size of the Vivaldi antenna, and the slotted edge has been used [9]. Adding a high-permittivity dielectric director will significantly increase antenna gain at various operating frequencies [10]. Improved radiation characteristics can be obtained by inserting slots to its boundary, and it provides lightweight and reduced size [11]. Recently, the clustering of several networks in one antenna using antenna reconfiguration has gained a lot of coverage. The PIN diodes and slots are inserted in the antenna opening at different positions. This antenna is suitable for applications using UWB and narrowband switching [12, 13]. At the receiver side, the interference level can be reduced by applying antenna reconfiguration, and it can be used in cognitive radio applications [14, 15]. Frequency reconfiguration is typically accomplished utilizing lumped elements, such as PIN diodes and MEMS switches, in a particular location to monitor current distribution [16]. The slot antenna’s various designs are presented in [17, 18]. The proposed dual-mode antipodal Vivaldi antenna introduces rectangular slots to operate in the ultra-wide band and two narrow bands [19]. With the ground plane, input change and placing a slot resonator on the ground plane will provide a customized ultra wideband AVA [20]. Adding the lumped elements to the proposed miniaturized Vivaldi antenna will enhance impedance [21]. A small wideband AVA is created by loading convex lens and director in an arc-type radiator for high-frequency performance enhancement [22].

This article outlines the design and implementation of dual-mode antipodal Vivaldi antenna (AVA). Conventional AVA is taken as the reference antenna, and the proposed antenna is modified by loading the semi-circular slots on the radiating structure. Rectangular slits are loaded to the inner radiating profile to subtend the PIN diodes, and semi-circular slots are loaded to the outer radiating profile to improve the radiation characteristics. In open literature, there were many papers discussed with the radiation characteristics improvement.
Design of Dual Mode AVA with Enhanced Radiation Characteristics

by using modified radiating structures or adding the loading structures. For such instances, the lower end characteristics are improved with gain reduction. The novelty of the work is attributed to the improved radiation characteristics while incorporating the active PIN diodes. While implementing the diodes, we ensured uncompromised radiation characteristics with stable responses, suitable for practical implementations. The biasing circuits of the PIN diode and its equivalent circuit model are explained.

This paper is organized as follows. The antenna design with diode implementations is discussed in Sect. 2. Results and discussions are carried out in Sect. 3. Section 4 is the summary of our design and future potential.

2 Antenna Design

2.1 Antenna Geometry

The schematic of the proposed dual-mode AVA is shown in Fig. 1. The antenna is printed on a 1.6 mm thick FR-4 substrate with a 60 mm×40 mm footprint. The exponential profiles are designed by the Eqs. [1]–[3]. Antipodal Vivaldi antenna is an end-fire radiator whose characteristics are governed by the inner exponential profile.

\[
y = C_1 e^{Rx} + C_2
\]  

(1)

\[
C_1 = \frac{y_2 - y_1}{e^{Rx_2} - e^{Rx_1}}
\]  

(2)

Fig. 1 Schematic of the (a) reference and (b) proposed dual mode Antipodal Vivaldi Antenna. The dimensions are L=60 mm, W=40 mm, s=1 mm and r=10 mm
\[ C_2 = \frac{y_1 e^{Rx_2} - y_2 e^{Rx_1}}{e^{Rx_2} - e^{Rx_1}} \] (3)

Here \( C_1 \) and \( C_2 \) are constants. \( P(x_1, y_1) \) and \( P(x_2, y_2) \) are the starting point and ending point of the exponential profile, respectively.

2.2 Selection of Antenna Geometry

Vivaldi antenna is the category of tapered slot antenna, and it has highly directional radiation characteristics in the end-fire direction. The unmodified AVA is taken as the reference antenna, and its performance is compared with the proposed one. The antenna is comprised of two radiating structures printed on the same substrate. A simple microstrip line is used as a feed to excite the radiation from the antenna. The antenna is fed with the SMA connector in real-time implementation, and the antenna characteristics were studied. The aperture width is chosen to avoid the grating lobes, and it is responsible for the lower operating frequency of the AVA.

The antenna’s surface current distribution is shown in Fig. 2. The Figure shows that the current distribution is denser at the inner exponential profile and backward. This forward current is attributed to the directivity improvement of the antenna. If the current distribution is controlled on the inner radiating profile, the radiation characteristics could be modified and restored with high-frequency switching diodes. A small rectangular slit of 1 mm is placed on the inner profile of the antenna, and it is not extended to its outer radiating edges.

Fig. 2 Surface current distribution of the antenna at 5 GHz (a) Reference antenna and (b) Proposed antenna
The placement of the rectangular slot on the tapering profile is chosen to fix the narrowband operating frequency. This mode is termed narrowband mode. These slits are bridged with PIN diodes to restore the current flow on the edges for its wideband mode. The outer edges have a small current distribution as shown in Fig. 2. A semi-circular slot is placed on both sides of the radiating structure to improve the lower radiation characteristics. The antenna electrical length is increased, resulting in lower operating frequency, as shown in Fig. 3. It is evident from the Figure that the reference antenna is resonating from 4 GHz while the proposed antenna (when a diode is ON) resonates from 3.7 GHz. Bandwidth improvement of 300 MHz is witnessed due to the implementation of semi-circular slots.

Equivalent circuit model of BAR64-03WE6327 PIN diode is shown in Fig. 4. A DC variable power source with reverse polarity, ranging from 0 to 5 V is employed to bias the diodes. When the input voltage exceeds the biasing voltage, the diodes entered into the conduction state. Which caused the antenna to work in wideband. Alternatively, the diodes are OFF when the voltage is below the biasing voltage. The effective length of the current path on the radiator is reduced and operates in narrowband mode.

Fig. 3 Simulated reflection coefficient characteristics of the antenna(s)

Fig. 4 Equivalent circuit of the PIN diode

(a) ON state

(b) OFF state
To bias the PIN diodes, a 10 kohm resistor with 50nH RF choke is used in series for external RF isolation as shown in Fig. 5. PIN diodes in the ON condition are represented with a resistance of 4.7 ohms, whereas in OFF condition, it is a parallel combination of 10 kohm resistor and a 0.17 pF capacitor. The proposed AVA has been designed for narrowband to wideband switching applications; for this purpose two surface mount BAR64-03WE6327 PIN diodes are employed because their capacitance (CT) is nearly constant and their reverse resistance (RP) is around 100 kohm depending on reverse voltage (up to $-40$ V).

3 Result and Discussion

The fabricated reference antenna and proposed antenna are shown in Fig. 6. The performance metrics of the proposed AVA are compared with the reference antenna and discussed. The proposed antenna is fabricated and examined in an anechoic chamber. As a reference antenna, the Amkom horn antenna is used in the frequency range of 1–18 GHz with the impedance of 50 $\Omega$ in the distance of 1.5 m to verify the simulation results of the depicted antenna structure.

Field fox handheld network analyzer (N9917A) is used for reflection coefficient measurements. The measured reflection coefficient of the proposed dual-mode AVA is shown in Fig. 7. The red color line response corresponds to the OFF conditions of the diode. When both diodes are ON, the current distribution is towards the entire radiating structure and the antenna is operated in the wideband mode.

The bandwidth is measured to be from 3.7 to 12 GHz. When both diodes are OFF, the antenna works in narrowband mode and exhibits the bandwidth from 5 GHz. This is due to the diversion of current away from the radiating profile. The placement of the rectangular

![PIN diode biasing circuit](Fig.5 PIN diode biasing circuit)
slit decides the resonance at the narrowband mode, and it can be varied according to the application demand. Similarly, the length of the slot also influences the resonant frequency. In this work, the design parameters are optimized to have a resonance at 5 GHz for WLAN.
bandwidth. The measured results are in line with the simulated results, and the small discrepancy in the high frequency is attributed to the diode biasing, shown in Fig. 7.

Figure 8 exhibits the gain of the proposed antenna for its narrowband and wideband performance. Gain of the antenna is computed using the Friss transmission formula by inputting the received power of the reference antenna, proposed antenna, and gain of the reference antenna. A rectangular horn antenna is used as a reference antenna for these computations. The wideband mode exhibits good impedance matching between 3.7 and 12 GHz, and in narrowband mode, the matching is between 4.1 and 5.7 GHz. The negative values in the table are attributed to the notched characteristics of the narrowband mode. The measured radiation pattern of the antenna is given in Fig. 9. From Figure, it is evident that the directional characteristics of the antenna are preserved for both cases, viz. reference and the proposed antenna, respectively. Also, the cross-polarization of the antenna is well below the Co polarization. The radiation pattern shown here is taken only for the sample of 5 GHz. The directional characteristics are preserved, and the main beam is located in 0 degree for both cases of Fig. 9 (a) and 9 (b). In 9(b), the back lobe is higher than the reference antenna due to the backward current on the radiating profile still, the antenna exhibit uncompromised gain in the entire bandwidth.
4 Conclusions

This paper describes the design and implementation of dual-mode AVA with enhanced radiation characteristics. PIN diodes are utilized to obtain the switching between narrowband and wideband. The antenna exhibits a peak gain of 6.9 dBi in the wideband and 7 dBi in the narrowband. Also, the modified radiating fins provide 300 MHz additional bandwidth in the lower bandwidth. Wideband mode antenna exhibits a bandwidth of 8.3 GHz (3.7–12 GHz) and 1.6 GHz (4.1–5.7 GHz) in narrowband operating mode. PIN diodes are biased properly and ensure that it does not influence the antenna’s characteristics. In the future, the work will be extended for continuous reconfigurability using the Varactor diode.

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Declarations

Conflicts of Interest/Competing Interests. The authors declare that they have no conflicts of interest to report.

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