A Four-Element Patch Array Antenna for Direction of Arrival (DOA) Estimation with Beam Switching Applications

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***Abstract*—In this study, a four-element patch array on a Teflon substrate is constructed and simulated for Direction of Arrival (DOA) estimation with a variety of applications. The compact Magic-T's even mode and odd mode analysis favors achieving DOA estimation. Also, depending on the input signals and the configurations of the diode states, the antenna has the capacity to switch its beam as well as it can detect signal of wide angle range. The antenna has the ability to alter the direction of its radiated beam in two dimensions. The beam can change direction up to $\pm 17^\circ$ along $\Phi = 90^\circ$ plane and up to $\pm 30^\circ$ along $\Phi = 0^\circ$ plane. Additionally, it provides a large angle range of detection of $\pm 50^\circ$ for $\Phi = 90^\circ$ plane and $\pm 60^\circ$ for $\Phi = 0^\circ$ plane. In the operating frequency ranges, the antenna's overall gain of greater than 13 dBi, and return loss of less than -30 dB indicates that the antenna is well-matched.**

***Keywords*—Four Element Array, Beam Switching, DOA Estimation, Microstrip Patch, Wide Angle Detection**

I. Introduction

An antenna's ability to perform multiple functions simultaneously is advantageous in the communication sector, according to recent significant advancements in antenna design technology [1]–[3]. Microstrip patch antenna in communication technology has already claimed its prevalence as it can offer very simple design process along with light weight, easy installation as well as incorporating both sided microwave integrated circuit (MIC) into design gives them the ability to make them compact and easy to operate with planar circuit [4]–[7].

In wireless communication, such as radar and satellite antennas, the ability to switch the radiation beam in a specific direction without moving the antenna is required, as well as the ability to determine the source of an object, and recent advancements in direction of arrival (DOA) antennas and beam steering antennas have been made by a number of researchers shows that using microstrip antennas for DOA estimation or beam switching has ease in design process [8]–[10].

In [11], disk-based patches are constructed with twin ports to build four separate directed beam patterns by stimulating two different fundamental patch modes, although it has a very low gain of about 4 dB. A typical way for creating beam switchability is to use pin diodes to guide beam in a specified direction in a patch array. Utilizing diodes in a three element patch array allows for a ± 12 degree broadside beam shift [12]. Beam switching by diodes in reflectarray antenna can increase the overall gain, however has a limited switching capability up to only ± 5 degrees [13]. And the procedure for DOA estimation involves receiving the arriving signal and figuring out its direction so that source localization can be determined [14]. For DOA estimation, a variety of microstrip antennas including conformal arrays [15], uniform circular arrays [16], and semicircular patch arrays [17] have been constructed.

On the basis of the array antenna suggested in [18], a four element patch array antenna is constructed and simulated utilizing both sided MIC in this study using the Advanced Design System (ADS). In contrast to [18], which attached port #2 to the outside of the patch elements, the suggested work's design is more compact since it places two ports in between the array components. This reduces the antenna's total size. When a diode is inserted into Port #2 of the proposed antenna, it can separately excite two patches one at a time, providing beam switchability orthogonal to the plane determining DOA. The remaining portions of the work are further elaborated as follows: section II outlines the design process along with the DOA concept, section III analyzes the simulated outcomes of the suggested work, and section IV sums up the study as a whole.

II. Antenna Design Procedure

A. Antenna Geometry

Four patches, numbered #1, #2, #3, and #4, have been placed on a Teflon dielectric substrate with a relative dielectric constant of ϵ_r = 2.15 and a thickness of 0.8 mm. A quarter wavelength transformer connects patch #1 and patch #3, and patch #2 and patch #4, which are subsequently linked to port #1 via a microstrip line. A 0.2 mm wide slot line in the ground plane links the patches to port #2. As in both situations, the patches are linked to ports #1 and #2 through microstrip and slot lines, respectively. The dotted circle in Fig. 1 forms two Magic-Ts via which sum and difference signals may send to both ports. Additionally depicted in the picture is a cross-sectional view of the designed antenna along AA'.

Two microstrip lines from port #2 has two diodes namely D1 and D2 to realize beam switching function in the design. Microstrip lines from port #1 must be linked to the quarter

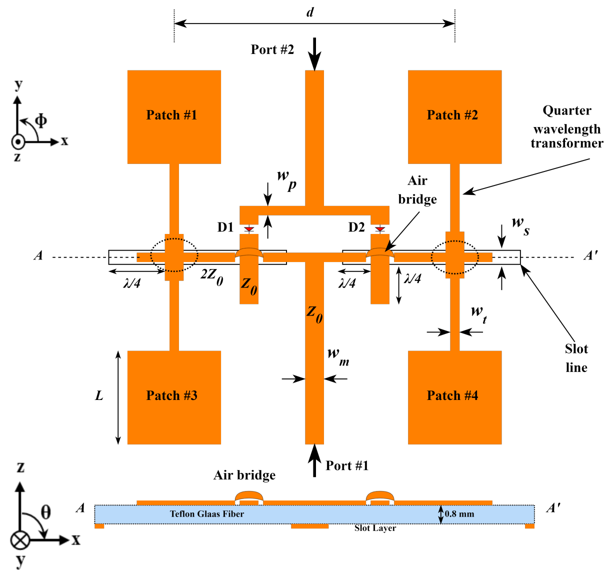

Fig. 1: Antenna structure of proposed four element patch array antenna.

wavelength transformer through an air bridge because lines from port #2 become interconnected if not routed through air bridges. Two microstrip lines from port #2 are connected via two microstrip-slot junctions and two slot-microstrip junctions, respectively, to receive signals from patches via a quarter wavelength transformer or to provide signals to patches. The $\lambda/4$ slot length extending from the junctions provides isolation for the junctions, and a little extension of microstrip line from the junctions provides impedance matching for port #1. Fig. 2

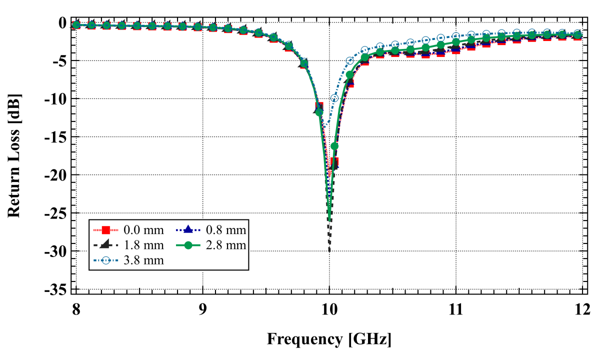

Fig. 2: Impedance matching for several extended microstrip line lengths in the junction for port #1.

depicts the input impedances for port #1 at various lengths of the extended microstrip line. The graphic clearly shows that length solely affects impedance matching and has no effect on resonance frequency or impedance bandwidth. The antenna's dimensions and parameters are listed in Table I.

TABLE I: Design parameters of the proposed microstrip antenna array

Parameter	Value
Substrate Material	Teflon Glass Fiber
Relative dielectric constant, ϵ_r	2.15
Patch length , L	9.7 mm
Microstrip line width, w_m	2.1 mm
Microstrip line width, $w_p = w_t$	0.8 mm
$\lambda/4$ slot line length	4.8 mm
Slot line width, w_s	0.2 mm
Microstrip line impedance , Z_0	50 Ω
Element to element distance , d	30 mm

B. DOA Conceptualization

Fig. 3 and Fig. 4, which show a block diagram of the idea and the Magic-T developed in the junctions of the array antenna, respectively, as indicated by the dotted circle in Fig. 1, can both be used to illustrate the idea behind DOA estimation. A DOA estimation concept is described in terms of receiving

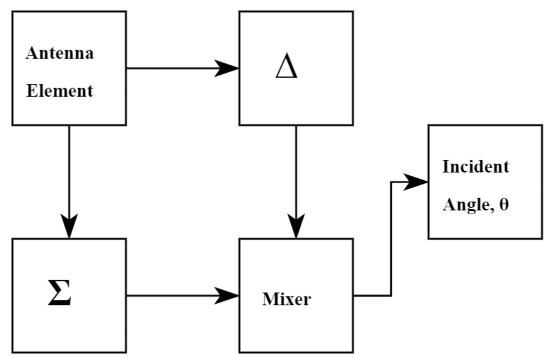

Fig. 3: Block diagram of basic behaviour of the DOA estimation.

signal components in Fig. 3. When an antenna receives a signal, two ports on the antenna can separate the signal into sum (Σ) and difference (Δ) signals, which are then supplied to a mixer to calculate the incident angle using (1) [18], where d is the distance between elements.

$$\theta = sin^{-1}\frac{\lambda\Delta\phi}{2\pi d} \tag{1}$$

The Magic-T produced in the junction and vector analysis of the signal on the proposed array elements is shown in Fig. 4 as its working principal. When performing mode analysis on H plane signals (even mode) and E plane signals (odd mode), magic-T's primary operation is to take two input ports from a four port device. When combined, the slot line and the microstrip line in Fig. 4(a) form a modified coplanar waveguide transmission line, with the slot line standing in for the E port and the microstrip line for the H port. The signals arriving from Patches #1 or #3 and Patches #2 or #4 are received by the additional ports denoted by 1 and 2 in the figure. The vector analysis for the sum and difference signals is displayed in Fig. 4(b), where $\Delta\phi$ represents the angle between the patches' receiving signals. The angle between the

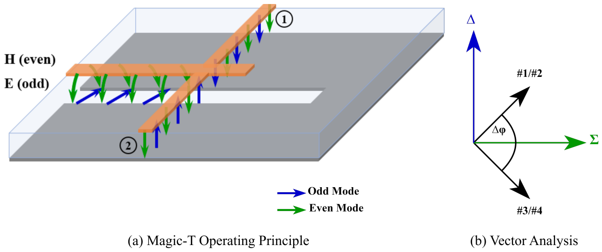

Fig. 4: DOA estimation (a) Operating principle of the Magic-T (b) vector analysis.

sum and difference vectors is thus defined as $\frac{\Delta\phi}{2}$. Therefore, (1) becomes,

$$\theta = sin^{-1}(\frac{\lambda}{\pi d} tan^{-1}\frac{\Delta}{\Sigma}) \quad (2)$$

Equation (2) [18] can be used to determine the incident angle of the incoming signals for estimating the direction of arrival. It is important here to mention that for DOA estimation, both diodes in port #2 are kept on. The schematic diagram for DOA estimation for the array antenna is shown in Fig. 5. The figure's arrows depict the electric field for in-phase and out-of-phase signals, with green arrows for in-phase signals and blue arrows for out-of-phase signals.

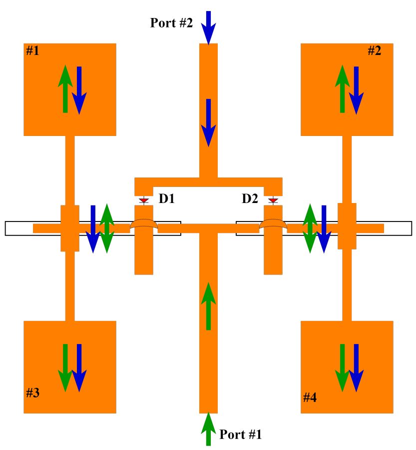

Fig. 5: Schematic diagram of the proposed design for DOA estimation.

C. Beam Switching and Wide Angle Detection

The antenna should be in the receiving end for DOA estimation, but when it is used as a transmitter, it has the ability to switch the beam in a particular direction based on the port signals and diode arrangement. Patch #1, #2, and Patch #3, #4 receive signals with a phase difference when signals are concurrently sent through Ports #1 and #2 due to the Magic-T circuit in the transmission line. As a result, the antenna's beam is angled in that direction. Additionally, if signals fed into ports #1 and #2 with a phase difference between them, the beam will be tilted in the opposite direction of how it was previously aligned when there was no phase difference between the input ports. Additionally, only patches #1, #3, or #2, #4 can be individually excited when only port #2 is active as an input port and one of the diodes is ON, tilting the emitted beam in the direction orthogonal to the beam switching plane when two inputs were provided concurrently.

Furthermore, the ability of ports #1 and #2 to produce bidirectional and broadside directional radiation beams when both diodes are turned on in response to individual RF signal provides insight into the wide angle scanning or wide range detection of signals by the proposed array antenna.

III. Simulated Performance Analysis

This section discusses the simulation findings and basic behavior of the suggested design. In order to determine if the antenna is matched in resonance frequency, the antenna is first generated and then simulated using ADS simulation software with both diodes kept ON (in this paper, copper lines are used in place of the diode to represent ON state of the diode). Next, DOA estimation is examined. The beam switching is then examined by turning the diodes ON and OFF, and the broad angle detection is ultimately determined by sending each individual RF signal to the ports.

A. Return Loss

The input impedance and port isolation of the suggested antennas are depicted in Fig. 6. The graph unequivocally demonstrates that the antenna is properly matched for both input ports at the resonance frequency. Due to the unbalancing

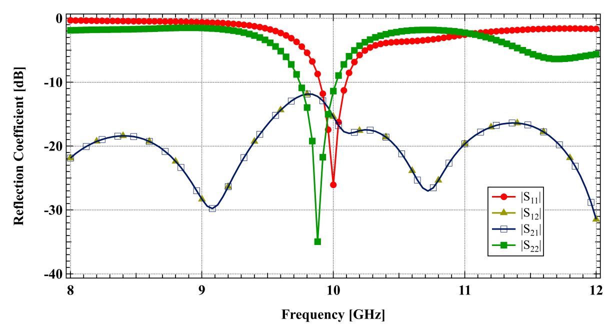

Fig. 6: Simulated impedance matching and input ports isolation of the proposed design.

at the microstrip lines caused by the inclusion of diodes in the transmission lines, port #2's input impedance exhibits a tiny shift in the resonance. For ports #1 and #2, the antenna displays return losses of less than -20 dB and less than -30 dB, respectively. The signals from the input ports are very effectively isolated because the isolation for both ports are less than -10 dB for the simulated frequency range.

B. DOA Estimation

The ratio of the difference and sum signals are necessary for DOA estimation, and for that purpose, the two signals are retrieved from two ports of the proposed antenna and sent to a mixer. The simulated received power graph for port #2

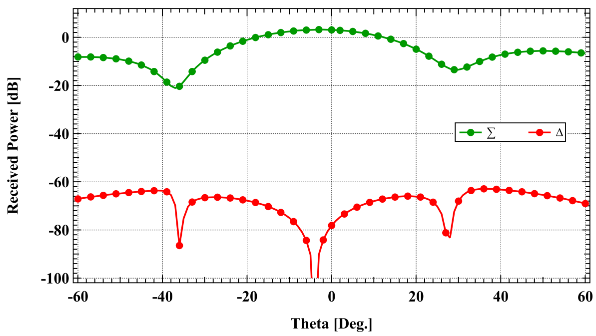

Fig. 7: Simulated radiation pattern of sum and difference signal.

is shown in Fig. 7. The difference in level between those two signals is greater than 70 dB, which shows that when sum signals are received by port #2, no difference signal is received by that port. Hence, it can be said that sum signals are being received by port #2 while the difference signal is being received by the other port.

C. Beam Switching

The antenna can alter its radiated beam to $+17°$ along the $\Phi = 90°$ plane when it is thought of as a transmitting antenna and two simultaneous signals are provided to its two input ports without any phase difference between them. And the beam is altered to $-17°$ along the same plane when fed with a 90 degree phase difference between the two input signals. Fig. 8 depicts the proposed antenna's 2D radiation pattern after

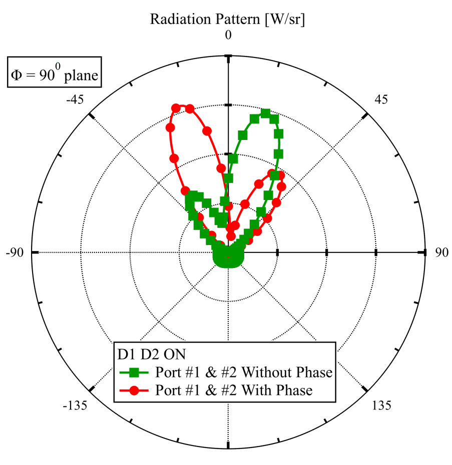

Fig. 8: Simulated 2D radiation pattern of the proposed four element patch array antenna along $\Phi = 90°$ plane.

simulation with two input signals running simultaneously.

The diodes' ON and OFF states can cause the antenna to radiate in the phi = 0 degree plane when the input signal is only sent to port 2. The configuration's 2D radiation pattern is depicted in Fig. 9. Moreover, it is evident from the figure that the antenna can tilt the beam by around 30 degrees along the phi = 0 degree plane. So, The antenna can switch its radiated

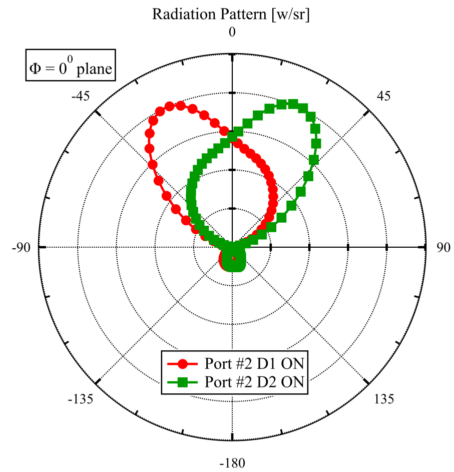

Fig. 9: 2D radiation pattern of the proposed four element patch array antenna along $\Phi = 0°$ plane.

beam to four particular directions i.e. θ = -17°, +17°, -30°, and +30° along two dimensional plane ($\Phi = 0°$ and $90°$ plane) , as is seen from both figures.

D. Wide Angle Detection

The antenna is capable of producing a broadside, bidirectional radiation beam when signals are separately provided to both inputs while maintaining both diode states in ON states. The beam for port #1 is bidirectional, whereas the beam for port 2 is radiated in a broadside direction as seen from Fig. 10. The diagram shows that the antenna's bidirectional beam is

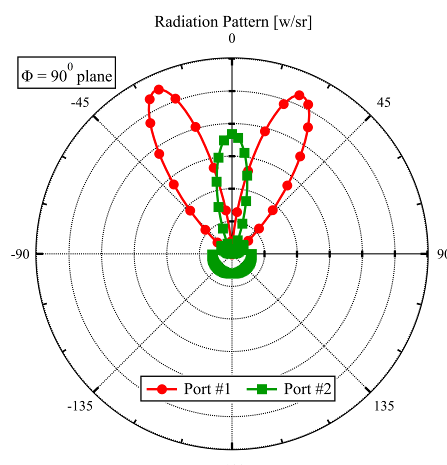

Fig. 10: Radiation pattern for individual port excitation when D1 and D2 are in ON state.

formed in the direction of $\pm 24°$, and that it radiates broadside beam for port #2 excitation. And, also the beams are well directive.

According to Fig. 11, the antenna may scan over a range of -50° to +50° for $\Phi = 90°$ plane and -60° to +60° for $\Phi = 0°$ plane if the lower value of directivity of 10 dB is taken into account, for which the antenna can transmit as well as receive signals. Thus, at the X-band operating frequency, it can be claimed that the antenna has the ability to scan a broad area.

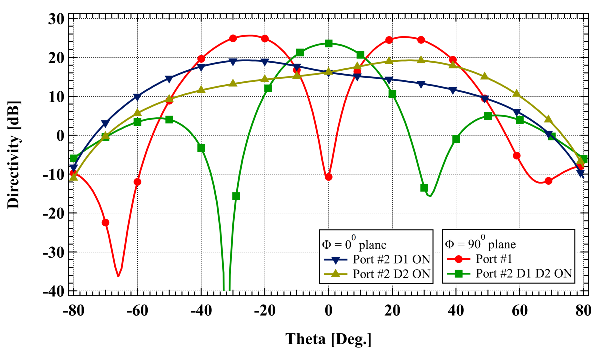

Fig. 11: Simulated directivity for different configuration of the array antenna.

E. Gain

The suggested patch array antenna not only has many uses but also a strong gain over the operational frequency range. The demonstration is shown in Fig. 12, where the antenna exhibits more than 8 dBi gain over the X-band frequency range and a maximum gain of 13.67 dBi.

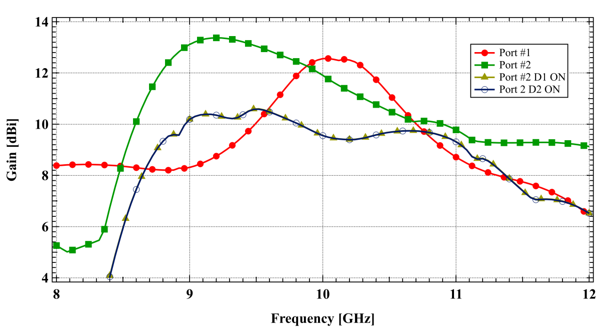

Fig. 12: Simulated Gain for different configuration of the array antenna.

IV. Conclusion

In this study, a four-element microstrip patch array for beam switching, wide-range detection, and direction of arrival estimation is presented. The antenna's performance in certain application areas is outstanding. It has a large range of directivity of approximately $\pm 50°$ and a beam switching capability of about $\pm 17°$ along the 90 degree plane, and a range of about $\pm 60°$ and beam switching of about $\pm 30°$ along the 0 degree plane. Moreover, The antenna can be used for radar applications because it is tuned to operating frequency in the X-band with a gain more than 12 dBi.

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