Pattern-reconfigurable antenna in azimuth plane using SP3T reconfigurable switching network

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Abstract
This paper presents a new pattern-reconfigurable antenna. This antenna has been designed, fabricated, and measured for 2.45 GHz band application. It provides six different radiation patterns in the azimuth plane at the same angle interval. First, a new single-pole three-throw switching network with one input and three outputs has been built on the circuit simulator and afterward validated by structural simulation. This reconfigurable switching network provides six switching conditions by the combination of turning ‘ON’ and ‘OFF’ states of the used four radio frequency p-i-n diode switches. Second, three curved printed dipole antennas are designed with an equal interval of 120° in the azimuth plane. Finally, switching network and curved printed dipole antennas are simultaneously simulated for 2.45 GHz band applications followed by fabrication. Maximum half-power beamwidth and average gain are obtained as 110° and 4 dBi, respectively, and the radiation efficiency is always better than 90.2%.

1 | INTRODUCTION

Alteration in the direction of the antenna radiation pattern can enable a system to save energy, improve security, and enhance the signal quality [1]. It can be made possible by restricting the propagation of the signal in an unintended direction. Therefore, pattern-reconfigurable antennas are highly demanded in the field of wireless communications [1,2].

Phased-array antennas have traditionally been a common beam-steering system [3]. By changing the feeding phase of antenna elements in the array, the main beam direction of the antenna is controlled. In comparison, the phased-array antenna faces extreme problems, such as limited scanning angle, higher side-lobe level (SLL), and high variations in gain [4–7]. This is due to the rise in mutual coupling between the antenna elements when scanning is performed at lower elevation angles.

On the other hand, by using monopole- or dipole-based antennas surrounded by reconfigurable parasitic directors or reflectors [8–13], pattern reconfiguration is also reported. These antennas are designed differently to achieve radiation pattern reconfiguration in azimuth, elevation, or both planes. These antennas are bulky and complicated in nature because of the 3D form and higher numbers of p-i-n diodes in the switching networks.

Some other planar antennas are also designed for radiation pattern reconfiguration in elevation or azimuth plane based on reconfigurable pixels [14–16]. In these antennas, rectangular pixels are designed at the front or surrounding of the radiating antenna element and connected to the p-i-n diode switching network. Due to the use of a large number of p-i-n diodes with many switching conditions, these designs are extremely complicated and expensive.

Apart from these, such antennas have also been designed in which end-fire radiating elements are placed at various angles in the azimuth plane [1,2,17]. But it has been reported that increasing the number of discrete directions of radiation leads to an increase in the number of the end-fire radiating antenna elements, which also increases the design complexity and required number of p-i-n diodes.

In this study, these issues were first addressed by introducing the concept of concurrently switching the multiple antennas to cover the 360° azimuth plane. In this proposed design, three antenna elements are used at an interval of 120° that can produce six radiation patterns. So, compared to the traditional antennas, the requirement of antenna elements in

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the proposed design is reduced by half. Second, to feed the proposed antenna, a new reconfigurable single-pole triple-throw (SP3T) switching network is developed.

It enables to switch the multiple output ports simultaneously to feed the proposed antenna. It is made possible by connecting an open matching stub in the switching network [18,19]. Figure 1 shows the proposed antenna design which produces radiation patterns in the six discrete directions in 360° azimuth plane. In Table 1, the proposed antenna design is compared with recently published works. It shows that the proposed antenna has reduced the requirement of antenna element by half as compared to [1,2]. At the same time, the number of p-i-n diodes are also reduced by using the proposed SP3T switching network.

So, the antenna designing steps are mainly organized in sections, as follows. It starts from the second section by designing of the SP3T switching network on Advanced Design System (ADS) software. Later on, this proposed SP3T switching network is validated by 3D electromagnetic simulation on Computer Simulation Technology (CST). After that, in the third section, the curved printed dipole (CPD) antenna design is discussed where the concept of increasing half-power beamwidth (HPBW) has been demonstrated. The fourth section discusses the simultaneous simulation of the SP3T switching network and CPD antennas and validated for the required antenna performance. In the same section, measured results and discussion on this antenna are also given. Finally, the fifth section is the conclusion.

2 DESIGNING OF AN SP3T RECONFIGURABLE SWITCHING NETWORK

A new reconfigurable SP3T switching circuit is designed and simulated on ADS and CST software. It is a four-port switching circuit as shown in Figures 2 and 3. Among all, port 1 is dedicated to excite the radio frequency (RF) input power to the switching network and the remaining parts are needed to feed the antennas. In order to design the switching network, four BAR64-02V low-signal distortion RF p-i-n diodes are used. The individual biasing circuit is provided to switch all p-i-n diodes. Their circuit switching operation is given in Table 2. For switching arrangements, it addresses the two

![Figure 1](image.png)

**FIGURE 1** Three different layers: top (copper), middle (Taconic: TLY-03, εr: 2.33, thickness: 0.51 mm), and bottom layer (copper). The value of $G = 1.5$, $T = 1.45$, $D1 = 91$, $L1 = 28.66$, $L2 = 50.5$, $L3 = 7.18$, $L4 = 25.8$, $L5 = 4 (\theta = 84^\circ)$, $Ra = 25.27$, $C = 1.425$ (all dimensions are in millimetres).

| TABLE 1 Comparing the proposed antenna with the recently published pattern reconfigurable antennas |
|---------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|---------|
| Ref. no. | Frequency (GHz) | HPBW (in degrees) | Beam dir. | Gain (dB) | No. of p-i-n diodes | Pola. status | Switching type | Type of antenna |
| [1]      | 5.2             | 60              | 6        | 4       | 6                | HP           | Single O/P      | Planar parasitic patch |
| [2]      | 2.25–3.16      | >120            | 4        | 4.11    | 4                | HP           | Single O/P      | Printed arc dipole     |
| [8]      | 2–3            | 123             | 4        | 5.08    | 4                | VP           | Switchable director/reflector | Vertical monopole |
| [9]      | 1.575          | >60             | 8        | 7.1–3   | 8                | VP           | Switchable parasitic strips | Vertical monopole |
| [13]     | 2.45           | 90–124          | 5        | 5.2–6.5 | 20               | HP           | Parasitic strip lines and reflecting metal pieces | Radiating dipole |
| [16]     | 5.35–6.45      | ~               | 4        | 5.7–6.3 | 52               | HP           | Single O/P and RAS | Vivaldi-shaped slots and printed pixel |
| This work | 2.45           | <110            | 6        | 3.85–4.2 | 4                | HP           | Single/dual O/P mode | Curved printed dipole |

Abbreviations: Dire., direction; HP, horizontal polarization; No., number; Pola., polarization; VP, vertical polarization.
distinct modes, namely single O/P mode and dual O/P mode. The characteristic impedance ($Z_0$) of this switching network is chosen as 50 $\Omega$ for all transmission lines. Therefore, there is no impedance mismatch in the single O/P mode since one of the output ports (between 2, 3, and 4) connects to the input port 1. Whereas, in dual O/P mode, any two output ports (among 2, 3, and 4) connect through the input port 1. Thus, it faces extreme impedance mismatch at the power dividing point in dual O/P mode condition, since the load impedance ($R_L$) is 25 $\Omega$.

Few feasible strategies are common to prevent such impedance mismatch, for example, short- or open-stub link to transmission line before power dividing point [19]. Both types of stubs are having their own merits and demerits. Short stub needs additional via connection with the ground, but does not support radiation through it. Whereas, open stub does not need additional via connection with the ground, but it supports small radiation through the stub. In the proposed design, open-stub matching is chosen due to the easiness in fabrication. The open stub is connected by a p-i-n diode switch just before the power dividing point. This p-i-n diode becomes ‘OFF’ in single O/P mode and ‘ON’ in the dual O/P mode by changing the DC supply at the bias point ‘P4’.

Two parameters are expected to be computed to design an open stub. First, the distance, ‘L3’ from the power dividing point to the stub position. Second, the value of susceptance provided by the stub. The distance ‘L3’ is calculated by the admittance ‘Y’, seen looking into the line at a distance ‘L3’ from the power dividing point is of the form $Y_0 + j\beta$. Then, the susceptance of the stub is chosen as $-j\beta$, resulting in a matched condition. The load impedance ($R_L$) for single and dual O/P mode is considered as 50 $\Omega$, and 25 $\Omega$, respectively. Finally, ‘L3’ is calculated by the relation $t = \tan(\beta L3)$, where the value of $t$ can be calculated [19] by solving the quadratic equation given in Equation (1). In this design, the value of reactance ‘$X_L$’ is considered as zero. Similarly, ‘D2’ is calculated [19] directly from Equation (2). The values of ‘L3’ and ‘D2’ are calculated as $\approx 0.19 \lambda_g$ for both, where $\lambda_g$ corresponds to 2.45 GHz. The reflection coefficient in dual O/P mode is shown in Figure 4 which represents with and without matching stub connection. In Table 2, all possible six bias states of the biasing point ‘P1’, ‘P2’, ‘P3’, and ‘P4’ are represented by either ‘0’ or ‘1’.

$$Z_0(R_L - Z_0)t^2 - X_LZ_0t + (R_LZ_0 - R_L^2 - X_L^2) = 0 \quad (1)$$

$$D2 = (\lambda_g/2\pi)\tan^{-1}(B/Y_0) \quad (2)$$

Here ‘0’ represents 0 V DC supply and ‘1’ represents +9 V DC supply. Two instances are considered as examples from Table 2 in order to explain the antenna biasing techniques. The bias state is initially considered to be ‘1000’ from a single O/P mode. The bias point ‘P1’ is connected with +9 V DC and remaining bias points ‘P2’, ‘P3’, and ‘P4’ with 0 V DC supply. Port 1 is fed with RF input power in this state, and almost total power is redirected to port 2. Next, the bias state ‘1101’ is

![Figure 2](image-url)  
**FIGURE 2** P-i-n diode equivalent circuit for both switch ‘ON’ and ‘OFF’ condition and design of single-pole three-throw switching network on Advanced Design System software. Value of $Ld = 0.6$ nH, $Rs = 1.38$ $\Omega$, $Rp = 3$ k, and $CT = 0.12$ pF: Three different layers: top (copper), middle (Taconic: TLY-03, $\epsilon_r = 2.33$, thickness: 0.51 mm), and bottom layer (copper).

![Figure 3](image-url)  
**FIGURE 3** Design of single-pole three-throw switching network on Computer Simulation Technology software. Three different layers: top (copper), middle (Taconic: TLY-03, $\epsilon_r = 2.33$, thickness: 0.51 mm), and bottom layer (copper).

**TABLE 2** State of the output ports of the switching network concerning the biasing

| Mode       | Bias state (P1 P2 P3 P4) | O/P port     |
|------------|--------------------------|--------------|
| Single O/P | 1000                     | Port 2       |
|            | 0100                     | Port 3       |
|            | 0010                     | Port 4       |
| Dual O/P   | 1101                     | Port 2 and Port 3 |
|            | 0111                     | Port 3 and Port 4 |
|            | 1011                     | Port 2 and Port 4 |
and overall power is equally split and redirected to ports 2 and 3. It should be noted here that the bias at 'P4' is associated with 0 V DC and +9 V DC supply, respectively, in both single O/P and dual O/P modes. The simulated S-parameter responses of the bias state ‘1000’ and ‘1101’ are plotted in Figure 5(a,b), respectively.

3 | DESIGNING OF CURVED PRINTED DIPOLE ANTENNA

To realize an end-fire radiation pattern, a quasi-Yagi structure is adopted with two arms. A metallic via with 0.6 mm diameter is placed to connect one arm of the dipole antenna to the microstrip ground as shown in Figures 2 and 6(a). Initially, it is designed with straight arms as shown in Figure 6(a) and simulated. The reflection coefficient of this antenna is plotted in Figure 6(b) which shows matching better than -10 dB at 2.45 GHz. It is folded inside from the edge end of the dipole antenna after optimization of the straight arms and has become a slight curved portion of the circle. The center of this circle is shifted upside by 1.425 mm from the upper edge of the triangular-shaped ground plane as shown in Figure 2. This CPD is simulated along with switching network for the bias condition ‘0100’. In Figure 6(c), the normalized radiation pattern is plotted for both kinds of dipole antenna arms. It can be found here in this plot of radiation patterns that HPBW has been raised from 64° to 108.7°. This is because, when the

considered from a dual O/P mode. The bias point ‘P1’, ‘P2’, and ‘P4’ are connected with +9 V DC and ‘P3’ with 0 V DC supply. So, RF input power is fed to port 1 in this condition,
dipole arm starts folding inside, the electric field also starts moving obliquely on both sides of the forward direction.

4 | MEASUREMENT OF THE PROPOSED ANTENNA

In this step, the proposed switching network of Section 2 and CPD antenna of Section 3 are simultaneously simulated. After achieving the desired radiation parameters, the antenna is fabricated and measured in an anechoic chamber for far-field measurement. It was observed that the reconfigurable switching network would not greatly impact the pattern of antenna radiation in the direction of maximal radiation. It is because of the switching network being placed at the backside of the CPD antenna for all possible switching conditions. The front and the backside views of the fabricated antenna are shown in Figure 7(a,b), respectively. In Figure 8, simulated and measured reflection coefficient parameters are plotted which shows better matching at 2.45 GHz. The simulated and measured results of the radiation patterns in the azimuth plane is depicted in Figures 9 and 10. The difference between the normalized co- and cross-polarization radiation is always better than 17 dB. The radiation patterns of all six directions can keep consistent. Therefore, the proposed antenna can be applied in the communication systems for the 2.45 GHz band applications, which requires the same pattern in different directions. In Figure 11, the current distribution is shown for both switching modes. This can be found in Figure 11(a), at the open stub line, there is no current distribution, but it exists in Figure 9(b). The proposed antenna can cover six different directions by changing the switching bias conditions. The measured results of the radiation pattern match with the simulated ones. The measured front-to-back ratio is better than 9.5 dB. The simulated and measured gain and simulated efficiency is plotted in Figure 12. The measured average gain is reported 4 dBi and a minimum efficiency of 90.2% at 2.45 GHz. Here the direction of the maximal radiation, HPBW, and antenna gain are given in Table 3.

5 | CONCLUSION

A pattern reconfigurable antenna is presented in this study for 2.45 GHz applications. Pattern reconfiguration is provided in six discrete directions in 360° azimuth plane. The SP3T switching network is designed in ADS software and also validated by 3D electromagnetic simulation software CST. For six different directions, six switching conditions are provided by a
A combination of four RF p-i-n diode switches. Moreover, three CPD antennas are designed in the azimuth plane with 120° of rotation. Lastly, the switching network and CPD antennas are simultaneously simulated and fabricated. The measured maximum HPBW and average gain are obtained as 110° and 4 dBi, respectively.

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