



Reconfigurable Antenna for Wireless Communication: Recent Developments, Challenges and Future

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Abstract

The growth in the popularity of reconfigurable antennas has been observed recently. Because of the fast progress of wireless communication technology in current wireless applications with large data rates, multimode and cognitive radio operations are implemented with reconfigurable antennas. These antennas are well-suited for wireless applications, including 4G and 5G mobile devices, due to their versatile capabilities. These include requiring minimal front-end processing, providing strong isolation, and effectively rejecting signals outside the desired frequency bands. In this article, we reviewed some of the latest reconfigurable antenna designs that have recently been proposed for use in wireless communications, including cognitive-radio, MIMO, ultra-wideband, and 4G and 5G mobile terminals. It investigated the fundamental properties and characteristics of reconfigurable antennas with single and multiple reconfigurability modes. This study examines related publications on reconfigurable antennas across a variety of platforms to determine methodologies. In the present year, the examination of reconfigurable antennas involves addressing various complexities in their development and analysis. The existing methodologies exhibit certain advantages and constraints, which are studied upon. Furthermore, emerging research hurdles in this domain are identified and proposed. Each concept and its design techniques are analysed, with merits, limitations, and future improvement highlighted.

Keywords 4G · 5G · Cognitive radio · MIMO · Reconfigurable antenna · Wireless communications · UWB

1 Introduction

Antenna design in the future generation must be smart and flexible to changing conditions and the environment. Antennas must be able to recover from failures and respond quickly to new developments. Reconfigurable antennas can be flexible, reliable, and

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efficient so they will be used for many applications like Cognitive radio, multiple input-multiple-output (MIMO), on-body networks, satellites, wireless and space communication systems [1]. This antenna is currently under investigation due to its numerous benefits, such as multi-band capability, polarization diversity, and adaptable radiation patterns. These attributes lead to compactness, reduced complexity, lower costs, and improved overall performance of radio frequency systems [2]. Microstrip array antennas in design [3] are widely used in modern wireless communication and radar systems due to their compact size, lightweight, and ease of integration.

With a proper selection of reconfiguration mechanisms, we can achieve the required functionality and property of reconfiguration. Several reconfiguration techniques can be included in antenna design beneficial to distribute its antenna. An antenna's operation frequency, radiation pattern, and polarisation can all be changed using various approaches using active elements like switches or capacitors [4]. Electrical techniques are used for reconfiguration to connect and disconnect antenna parts and to distribute antenna current which is based on the switches. RF MEMS is used which is dependent on mechanical movement to achieve reconfiguration. RF MEMS need less power consumption and high isolation. The switching speed of RF MEMS is 1–200 s, which may be insufficient for some applications [5]. PIN diodes and varactor diodes are quickly generating electrical reconfiguration techniques. These switches can be more compact and faster than RF MEMS. A PIN diode's switching speed is between 1 and 100 ns. PIN diode-based reconfigurable antennas provide a higher dynamic reconfiguration capability [6, 7]. Alternatively, Varactors were used in reconfigurable antennas to vary the capacitance of equivalent varactor by altering the biasing voltage. These antennas have a large tuning range due to the incorporation of a variable capacitance into the antenna structure [8]. While electrical switching components can exhibit an efficient reconfiguration, it is necessary to note that the design of biasing network should be proper. Features of a reconfigurable antenna can be single and multiple reconfigurations. The reconfigurable feature can be increased using several switches or on the amount of active elements use [9, 10]. The designed [11] triple-band rectangular microstrip antenna loaded with notches and slots offers a versatile solution for wireless communication applications. The integration of notches and slots allows the antenna to achieve resonance in three different frequency bands, making it adaptable to various wireless standards. The antenna is designed [12] to cover the frequency bands of both WLAN (2.4–2.4835 GHz) and WiMAX (2.5–2.69 GHz) standards. Slot structures are introduced to improve impedance matching and broaden the antenna's bandwidth. By adjusting the slot dimensions and positions, the antenna's impedance matching is improved, leading to a wider bandwidth that covers both the WLAN and WiMAX frequency bands in design [13].

The literature mainly focuses on all types of reconfigurable antenna for wireless communications applications. The sub-6 GHz band of the 5G wireless communication technology is used in current wireless communication technologies to meet the growing need for good connectivity, faster speeds, and increased data rates with low latency and improved spectral efficiency in the available spectrum. All these types of reconfiguration cover higher-than-frequency bands along with 1 GHz using different types of actuators like PIN, varactor diode, and RF MEMS which is a more attractive area of research. It aims to offer a comprehensive analysis of recent advancements, design factors, and emerging research prospects in the reconfigurable antenna field. The review includes a detailed examination of various switching mechanisms and potential applications where reconfigurable antennas can be applied. Additionally, it incorporates a summary

of findings and existing design challenges that can be addressed to improve the performance of reconfigurable antennas. In this study, we give a comprehensive analysis of all forms of antennas that may be reconfigured for mobile or wireless systems, including single and multiple reconfigurability functionalities.

Therefore, this survey aims to assist antenna researchers in familiarising themselves with reconfigurable antenna designs and enhancing existing designs. The paper is organized to explore antennas with both single and multiple reconfiguration features, searching into the evolution and conceptual foundations of different reconfigurable antenna types in Sect. 2. Section 3 examines diverse switching methods adapted for different reconfigurations. In Sect. 4 reconfigurable antenna's different applications are discussed in detail. Section 5 concludes the paper. Different approaches used in previous research to improve the effectiveness of the radiating component are explored in the literature, and the design challenges detail is presented in Sect. 6. Section 7 concludes the paper.

2 Single and Multiple Reconfigurable Antenna

The reconfigurable antennas can achieve frequency altering, radiation pattern switching, and polarisation switching with active elements to change the antenna shape and size of the radiators. The many forms of reconfigurable antennas with a particular reconfigurable function are discussed in this section. The issue of band interference arises due to the over allocation of wireless frequencies to various applications. As a solution, modern wireless applications, which demand multiband and multimode compact antennas, primarily utilize this type of antenna. Design [14] antenna's ability to cover S and C frequency bands with optimized geometry and feed techniques makes it a valuable solution for various communication and radar systems.

2.1 Design Flow for the Development of Reconfigurable Antenna

Create a flowchart outlining the development process for a reconfigurable antenna that allows for subsequent shown in Fig. 1. To initiate the antenna design process, the following steps need to be sequentially followed:

1. **Design specification:** The process involves determining the resonance frequency for each specific frequency band, as well as outlining the reconfiguration elements necessary for its operation and the intended application.
2. **Specify reconfigurability methodology:** Define resonance frequency and operating band. Select the appropriate material and design approach based on the provided specifications.
3. **Antenna design:** Create the RF structure utilizing software and simulation tools, and validate the expected outcomes.
4. **Reconfigurability:** Identify the necessary switching mechanism to incorporate reconfigurability as a feature.
5. **Testing:** Design a prototype for the structure and conduct testing in a suitable environment. If the results do not meet the requirements, iterate the development process until the desired outcome is achieved.

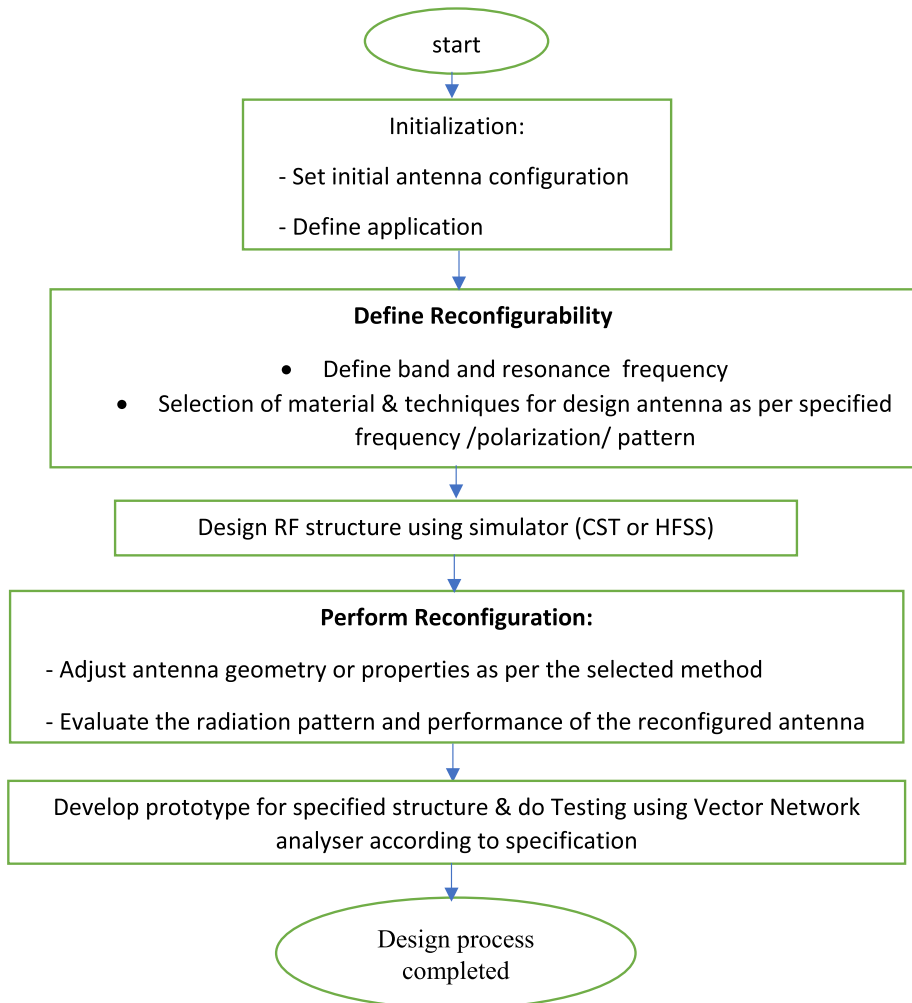


Fig. 1 Reconfigurable antenna development process flow chart

2.2 Frequency-Reconfigurable Antennas

Scientists and industry executives are interested in frequency reconfigurable antennas because of its ability to minimize the size of front-end systems, remove interfere with other wireless applications, and increase throughput [15].

In different wireless systems, PIN diodes are mostly used as a switching component. For a reconfigurable antenna, size for RF and direct current blocks are essential for antenna design [16]. In a narrowband mode, varactor diodes can control operational band in a broadband or ultra-wideband mode (UWB) [17]. The UWB antenna provides sensing, while the reconfigurable antenna provides communications. The focus on UWB capabilities and compact design [18] addresses the demand for versatile and efficient antennas in modern wireless communication systems. Hybrid optimization strategy combines multiple optimization techniques, which could include heuristic algorithms, machine learning, or

evolutionary methods. This approach aims to improve the efficiency and effectiveness of the antenna design process in design [19].

The use of a pin diode and MEMS switch limits frequency reconfigurability to certain frequencies, whereas varactor diodes provide continuous ranges of frequency reconfigurability. Photoconductive switches are preferred over MEMS (micro-electromechanical system), PIN diodes, and lumped elements because of their higher performance. The photoconductive method eliminates the need for bias lines, which are generally located in the antenna's plane and can degrade the antenna's electromagnetic function. Photoconductive switches also have exceptionally high switching speeds in the range of nanosecond [20]. However, because of their lossy behaviour and the necessity for a sophisticated activation mechanism, they are not popular [21]. The CPW fed slotted circular patch antenna design [22] is compact, flexible and it is used for multiband operation. With Two slots etching on the circular radiator structure multi-mode and multi-band behaviour is achieved using two diode. A CPW-fed triangular patch antenna [23] is radiated at a maximum of 8 separate bands and a wideband with two PIN diodes coupled to two different serpentine stubs. In the H-plane, the antenna has a steady Omni-directional radiation pattern, while in the E-plane, it has an octagonal radiation pattern. In the two operating situations with PIN diodes, 2 elements MIMO PIFA antenna design [24] is suggested to achieve triple-band operation and dual-band operation. At all operational frequencies, good isolation of 20 dB is obtained between the frequency reconfigurable antenna elements to decoupling circuits. The design [25] has undergone optimization to achieve the desired wideband performance while maintaining effective notch features at the specified frequency bands for WiMAX and WLAN.

Figure 2 depicts the performance and design of the antenna [26]. The resonant frequency of the triangular monopole antenna is shifted from 5 to 3.5 GHz by inserting a rectangular sleeve. A symmetric sleeve is inserted at the other side of the radiator, and the insertion of this open-ended stub mitigates the higher resonance, and the antenna becomes a wide band antenna, as shown in Fig. 2a. To provide frequency reconfigurability in multi-band, narrowband, and dual-band modes, rectangular stubs fed were loaded to an inverted triangular patch antenna [26]. The suggested multi-mode frequency reconfigurable antenna was put together by joining the two antennas together. This antenna has a 2 to 9 GHz wideband mode. CPW feeding technique is added in this monopole antenna which is generating wideband operational mode. In switching mode 111 antenna is operated for 3 different bands with a max 3.1 dBi gain mentioned in Fig. 2b. Compared to other existing frequency-adjustable antennas in the literature, the described multimode antenna offers a

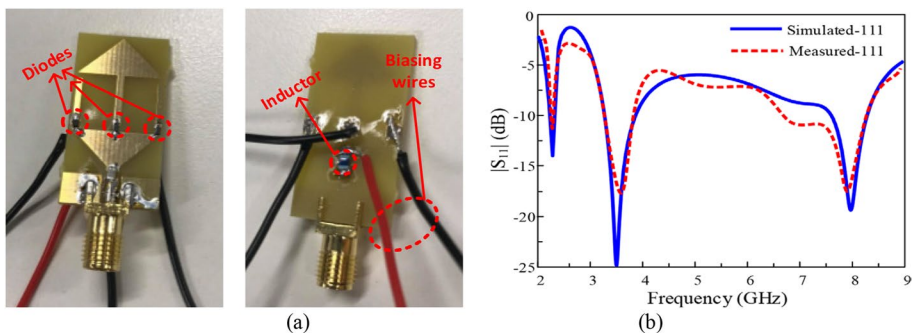


Fig. 2 Fabricated prototype **a** fabricated design **b** return loss comparison states at Case-111 [26]

smaller ratio of the number of operating bands to the number of pin-diodes. To increase bandwidth, the author used the approach of truncating the radiator corner in the suggested work.

The frequency reconfigurable antenna type that have recently been proposed and published in the literature are summarised in Table 1. Fundamental antenna features such as the type of antenna, number of switches utilised, the operational frequency range, the antenna's total size and limitations have been studied. The table suggests that the majority of the listed studies have employed the slotting approach to achieve frequency reconfiguration. Additionally, many of them have utilized PIN diodes to switch between multiple frequencies. This is meant to assist readers in determining which frequency reconfigurable antennas are most suited to their needs.

The antenna in paper [27] was compact and achieved frequency reconfiguration with a single varactor diode and a low bias voltage. This antenna was tuned from 1000 to 1150 MHz, with 15% tuning. By controlling the states of four PIN diode switches through bias networks, the design can function at either 2.45 GHz or 3.50 GHz which is mentioned in reference [28]. Design [29] cover sub-6 GHz and 5G bands and has a wide range of applications including GSM, UMTS, LTE, WIMAX, Wireless LAN, Internet of Things-enabled wireless systems in smart cities, and 6 GHz Fixed Satellite Services. This antenna offers efficiency 84% and gain ranges from 1.2 to 3.6 dBi, respectively at corresponding resonant frequencies. Frequency diversity was achieved in the reference [30] by adjusting the bias voltage while keeping the antenna, feed probe, and shape of the patch at same. The article [31] design was operated between 0.43 and 5 GHz and exhibits approximately omnidirectional emission patterns. The designed antenna has a simple structure and compact size of 60 mm × 100 mm which is suitable for mobile wireless devices. Without increasing the size of an antenna mentioned in reference [32], the narrower band of 0.69 GHz was obtained. Reference antenna [34] had the best combination of compact size, multi-mode functioning, wide operating region, good gain, and a simple geometrical structure.

2.3 Pattern-Reconfigurable Antennas

Pattern reconfigurable antennas are often utilized to improve the quality and coverage of transmission signal [35] of present communication systems. These antennas are useful in detecting and tracking applications because they provide higher directivities in radiation patterns in the same frequency band [36].

Pattern reconfigurable antenna design approaches can be split into three groups. The 1st option is to use extra parasitic elements as directors or reflectors in stacked [37] or planar design [38] to achieve various beam shapes and directions due to their varying operational states. The 2nd method is to choose and excite various single antenna's functioning modes [39] and to produce pattern diversity, Various current distributions of these modes are used. The 3rd is to alter the antenna's electrical structure [40] to produce the desired radiating apertures. The radiation main beam was deflected by angles of +30° and -27° in the E-plane ° with two metamaterial configurations [41] are arranged near the dipole radiating elements to guide the main beam in desired directions. Design [42] analyse how the slotted array technique enhances the antenna's bandwidth and gain compared to conventional designs.

The design of dual band proposed antenna [43] is illustrate in Fig. 3. The arrangement is symmetrical around the Y-axis. The long and short bands, alternately responded to frequencies of 2.45 and 5.5 GHz. The design used the FR4 substrate. Figure 4a shows

Table 1 Comparison of frequency reprogrammable antennas mentioned in the literature

References	Antenna type	Reconfiguration mean	Range of frequency (GHz)	No. of switch	No. of operating band	Antenna size (mm ²)	Limitation
Ghaffar et al. [26]	Triangular monopole	PIN	2–9	3	12	15 × 30 × 1.6	Limited gain up to 2 dBi
Ahmad et al. [27]	Patch	Varactor	1–1.15	1	5	22 × 21 × 1.57	Cover limited band, Complex Biasing Circuit
Jin et al. [28]	2-Layer patch	PIN	2–4	4	2	0.8λ × 0.8λ × 0.02λ	Cover limited band
Dildar et al. [29]	Monopole	PIN	1–8	5	9	40 × 32 × 1.2	Limited gain
Boufritoua et al. [30]	Slot	PIN	4–5.5	1	5	55 × 55	Size is more
Kantemur et al. [31]	Monopole	Varactor	0.43–8	1	3	60 × 100	Large bias voltage
Subbaraj et al. [32]	Loop	Varactor	0–6	4	4	25 × 10 × 0.2	Independent tuning of bands
Rao et al. [33]	Circular patch	RF MEMS	0–49	2	2	6.52 mm diameter	Operating band is less
Ghaffar et al. [34]	Triangular-shaped monopole	PIN	1.8–4.5	2	8	30 × 30	Limited gain

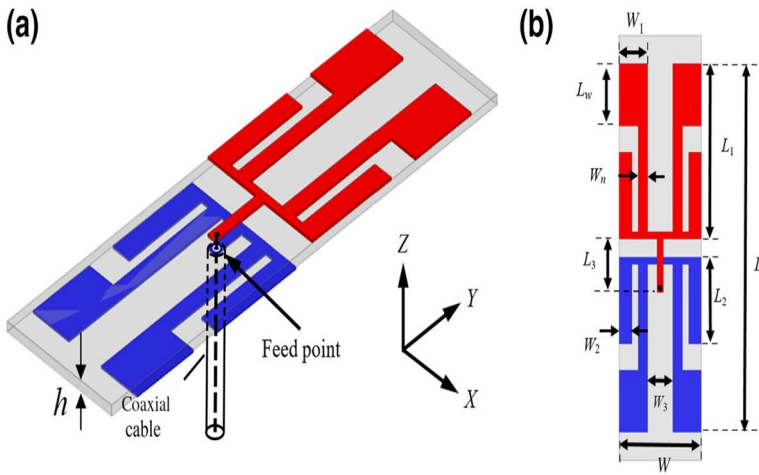


Fig. 3 Design of array antenna [43]: **a** 3D view, **b** XY -plane view

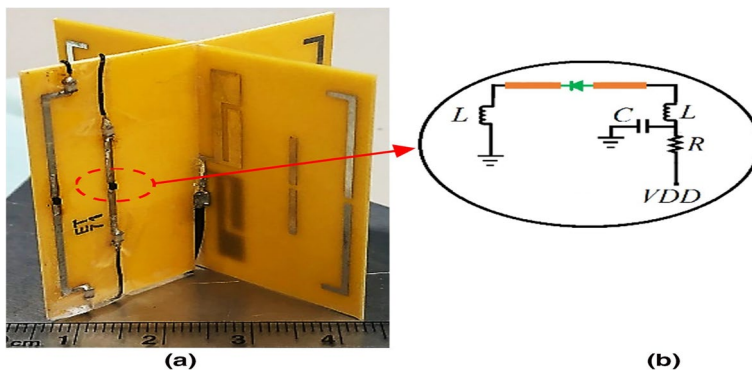


Fig. 4 **a** Fabricated dipole antenna array **b** DC bias for diode switches [43]

fabricated dipole array antenna and Fig. 4b shows DC biases for diodes. As director parasitic metallic strips were used and the reconfiguration feature was fulfilled by using a diode which was used to reconstruct the radiation pattern of the proposed antenna in the 0° , 90° , 180° , and 270° directions and support complete coverage in the horizontal plane. In this design, the author has achieved a maximum gain of 5.3 dBi and 17.3 dB front-to-back ratio using 4 switches.

The pattern reconfigurable antenna types that have recently been proposed and published in journal article are summarised in Table 2. Some key characteristics, such as the type of antenna used, Front to back ratio, no. of diode used, operation bandwidth, beam steering of antenna, and limitations have been compared. The development of radiation patterns with a large switching angle was induced in numerous research. This is meant to assist readers in determining which pattern reconfigurable antennas are most suited to their needs.

The goal of the paper [44] was to increase coverage by relocating the main lobe and optimising the main beam angle to avoid signal interference from nearby signals. The

Table 2 Pattern-reconfigurable antennas are compared in terms of performance mentioned in the literature

References	Antenna type	Front to back ratio (dB)	Operating band	Number of diodes	Max. bandwidth (S11<−10 dB)	Steering	Limitation
Su et al. [43]	Dipole array	17	2.45/5.5 GHz	8 PIN	30%/46%	0°, 90°, 180°, 270°	Cost will increase due to no. of diode
Rahmani et al. [44]	Circular patch	Not given	5.15/5.5 GHz	5 PIN	16%	18°, 143°, 161°	Less bandwidth
Faizal Ismail et al. [45]	Patch with EBG	Not given	2.4/5.8	14 PIN	2.46%/1.46%	−26°, 0°, +26°	Size is more, costly
Shamsinejad et al. [46]	Cubic slot	10	2.4 GHz	2 PIN	21%	360°, −50°	Only use for single band
Santamaria et al. [47]	4 wire-patches	6.5	2.44 GHz	1 SP4T	Not given	230°	Limited beam steering
Zhang et al. [48]	Circular patch	10	2.08 GHz	4 PIN	2.5%	0°, 90°, 180°, 270°	Cover only azimuth plane, less bandwidth
Tarun Prakash et al. [49]	Curved printed dipole	9.5	2.45 GHz	4 PIN	Not given	320°, 90°, 210°, 30°, 270°, 150°	Limited gain
et al. [50]	Stacked patch	Not given	2.45/2.65 GHz	2 PIN	11%	0°, 30°, ±60°	Less bandwidth

pattern reconfiguration was recorded in reference [45] using an EBG structure with three different angles (-26° , 0° , $+26^\circ$). In this case, PIN diodes are integrated with EBG (Electromagnetic Band Gap) structures to achieve pattern reconfiguration. In reference [46], a reliable feeding mechanism was proposed that uses electrical switches to switch between the two available radiation pattern such as omnidirectional and directional. Radiation pattern steering is achieved in design [47] using a single low-power, low-insertion loss SP4T switch. This method eliminates the need for multiple electronic components in the reconfiguration process, making it suitable for the limited resource constraints of IOT micro-controllers. At 2.08 GHz, The FBR was measured to be 10 dB, and the 3-dB beam width in azimuth plane in reference [48] was switched from 82° to 190° . Pattern reconfiguration was offered in six different directions in a 360° azimuth plane in the reference [50], and it has a broad operating bandwidth while maintaining a low profile and minimal amount of cross-polarization.

2.4 Polarization-Reconfigurable Antennas

Multipath fading can be significantly reduced with polarisation reconfigurable antennas. Using this kind of antenna [51], we may change the mode of an antenna. Most polarization-reconfigurable antenna research focuses on turning among right and left-hand circular polarisation at a specific frequency [52]. Linear polarisation (vertical and horizontal modes) was also investigated in the article [53] using PIN diodes or RF-MEMS have been employed in most cases to switch the polarisation states of antenna arrays. Several approaches for switching the polarisation states of antenna array have been presented in [54], with Electrical control devices like PIN diodes or RF-MEMS being used in most. Antennas with circular polarisation [55] have significant advantages when it comes to multipath scattering and fading, as well as channel interference in crowded environments.

The polarisation reconfigurable antennas were executed using FR-4 substrate [56]. The metal reflector was mounted 30 mm just below the substrate to improve the antenna's directivity. As illustrated in Fig. 4, on the upper side of the FR-4 substrate, the first and second group of parasitic elements were manufactured, while the third set was created on the bottom side shown in Fig. 5a. The parasitic element and the reflector have little effect upon reflection coefficient S_{11} , as seen in Fig. 5b. The parasitic element has the greatest impact on antenna's 3 dB axial ratio performance, indicating that the parasitic element has positive impact on antenna Axial ratio. The reflector can also alter the 3 dB AR bandwidth and increase the antenna's directionality. The majority of the proposed antenna consists of three sets of parasitic elements and two pairs of crossed dipoles. The suggested antenna has a broad overall measured effective operating bandwidth of 48.6% (2.40–3.94 GHz) as well as a significant measured peak gain of 8.2 dBi compared to the majority of its prior work.

The list comprises a summary of different research focused on the development of polarization reconfigurable antennas in Table 3. The fundamental antenna features such as antenna type, no. of diode used, maximum bandwidth, types of polarization, Axial and Impedance Bandwidth, and limitations have been compared. This is meant to assist readers in determining which polarization reconfigurable antennas are most suited to their needs.

In [54], the four polarisation states were achieved: two orthogonal linear (horizontal as well as vertical) and two circular polarisations (right hand and left hand circular polarization). The measured overlapping bandwidth and axial ratio in the fabricated prototype of reference [57] was 25.6%, with a maximum broadside gain of 7.3–7.9 dBi. The wideband capability is achieved by the author in this design by combining multiple

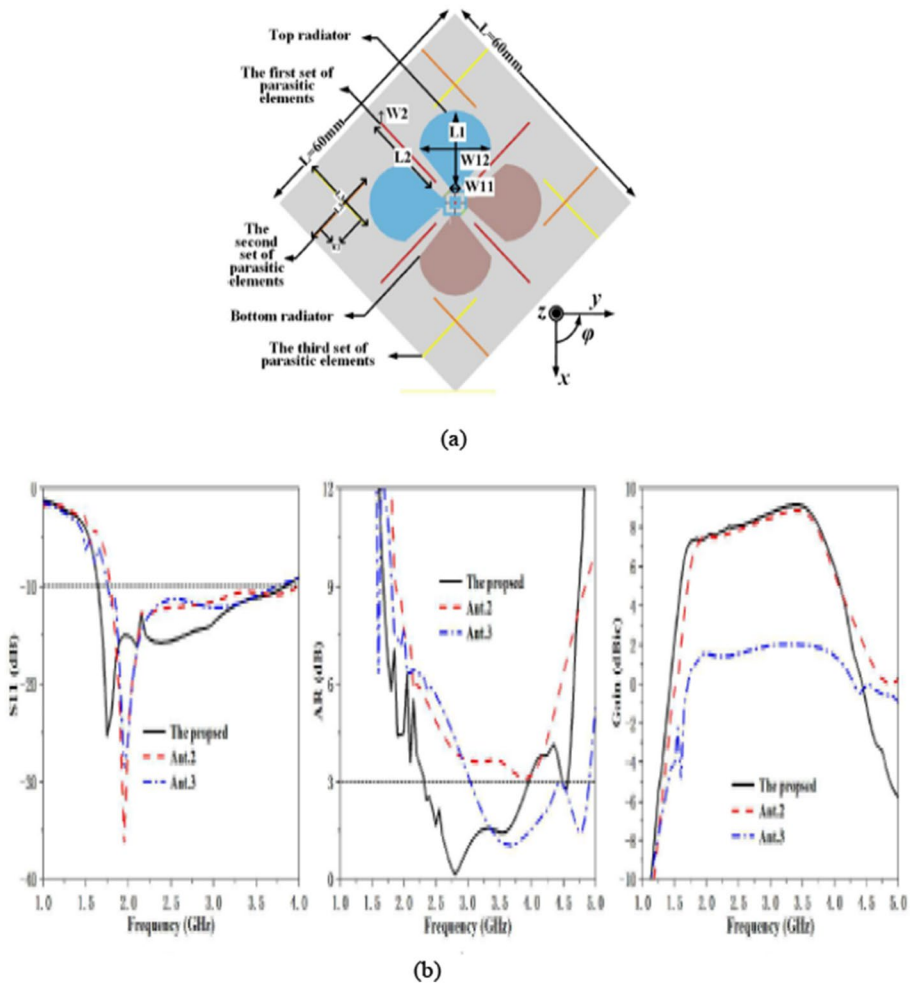


Fig. 5 **a** Representation of parasitic element and **b** characteristics of the antenna [56]

operating modes generated through the use of a microstrip patch and a non-uniform microstrip structure. The main components of the proposed antenna [56] consist of two pairs of crossed dipoles and three sets of parasitic elements. The antenna is constituted of a $3/4$ square ring supplies with two crossed dipoles, two microstrip feeding elements were etched in the middle of the top and lower sides of the dielectric substrate, and three sets of microstrip parasitic elements which help to extend the AR bandwidth. In [58], a switchable fractal slot inside the ground plane generating circular polarisation was used to create a dual polarization reconfigurable antenna. The antenna [60] has the largest impedance bandwidth, larger axial ratio bandwidth for both Circular and linear Polarization, and the smallest size. The F-shaped feedline produces the first circular polarised band, while the polarised band produces the second. The proposed antenna design [62] covers the entire UHF RFID range, spanning from 840 to 960 MHz. It consists of a CPW—fed square slot antenna with an F-shaped feeding structure, an embedded

Table 3 Polarization-reconfigurable antennas are comparison in terms of their performance

References	Antenna type	Overall size (mm ²)	Type of polarization	Axial B.W. (%)	No. of state/ no. of diode	IMPEDANCE B.W. (%)	Limitation
Huyh et al. [57]	Truncated-corner patch	0.88 × 0.88 × 0.05	RHCP, LHCP	25.6	2/PIN	25.6	Overall bandwidth is less
Jin et al. [56]	Crossed dipole	60 × 60	LP, RHCP, LHCP	54.5	4/PIN	63.5	Overall bandwidth is less
Saraswat et al. [58]	Fractal slot	0.29 λ × 0.29	RHCP, LHCP	17.61	4/PIN	15.44, 13.16	Dual-band polarisation
Chenna et al. [59]	Inverted L	70 × 70 × 18	RHCP, LHCP	1.2	Not given	6	Very less Axial ratio
Bhattacharjee et al. [60]	Circular	30 × 33	LP, RHCP, LHCP	> 69.6	2/PIN	> 93.7, 51.9	Effective BW is limited up to 60%
Dhara et al. [61]	Monopole	55 × 55 × 1.6	RHCP, LHCP	< 3	Not given	80.53	Very less Axial ratio
Tang et al. [54]	Huygens Dipole	Not given	2 orthogonal LP, LHCP, RHCP	0.19	6/PIN	< 1.1	Operated for limited band only
Virothu et al. [62]	Square slot	114 × 114 × 0.8	2 LP, LHCP, RHCP	29.44	3/PIN	221/23.26	Site is more

inverted L-shaped stripline to the ground, three PIN diodes, and an additional strip line connected to the feed.

Multi-reconfigurable antennas can have two or more characteristics modified independently.

1. Frequency and Radiation Pattern
2. Frequency and Polarization
3. Radiation Pattern and Polarization
4. Frequency, Radiation Pattern, and Polarization (Hybrid RA)

2.5 Frequency and Radiation-Pattern Reconfigurable Antennas

In this category, reconfigurable antennas were constructed for frequency and radiation pattern reconfigurability [63]. The radiation pattern can be reconfigured between broad-side, end-fire, and Omni-directional modes [64]. By enhancing signal directions, radiation pattern reconfigure can improve system performance, minimize noise, and also save the power. Reconfigurable antennas offer several advantages over wideband antennas, including compactness, consistent radiation patterns across various frequency bands, efficient utilization of the electromagnetic spectrum, and frequency adaptability. These features aid in mitigating the adverse effects of co-channel interference and jamming [65]. The antenna presented in [66] has a compact size and a wide bandwidth coverage, as well as a discrete RF switch type that offers flexibility, frequency and pattern reconfigurability. This antenna's frequency can be varied from 2.1 GHz to 1.8 GHz. Frequency diversity is a technique used to combat the effects of multipath fading and interference in wireless communication systems by transmitting the same data on multiple carrier frequencies. Antenna design [67] incorporates a Rectangular SRR structure along with switched slotted microstrip patch elements to achieve improved frequency diversity characteristics.

In [68], a microstrip patch antenna design with frequency and pattern reconfigurable through a single switch was presented. A single switch was used in this design which minimized the distortions that were seen in the radiation pattern of reconfigurable antennas because of usage of numerous switches. In paper [69], a new frequency reconfigurable antenna and directional radiation pattern based on graphene pads has been proposed for a microstrip monopole construction. Using lumped RLC component frequency and pattern reconfigurable antenna was simulated in [70]. In this design, the antenna resonated at two distinct frequencies including WiMAX and WLAN, i.e., 3.5 GHz and 5.2 GHz was tilt from $\pm 170^\circ$ in the yz plane. The metallic ground plane was truncated to offer maximum gain, directivity, and radiation efficiency in the proposed work. A frequency reconfigurable patch antenna design was presented in [71]. The proposed antenna can adequately excite three resonant modes, and their resonance frequencies can be altered using varactors integrated in radiating patch. As a result, the reconfigurable antenna's operating frequency has a large tuning range. Furthermore, all modes produce radiation patterns with a conical shape, and they were stable. The design is for a wideband slot antenna with reprogrammable frequency and pattern, as seen in reference [72]. It includes three different radiation patterns that cover the frequencies of 3.4–3.8 and 3.7–4.2 GHz. To obtain pattern reconfigurability in [72], two PIN diodes were placed into a sickle-shaped ground slots to form two independent frequencies, and two more PIN diodes were placed into the fork-shaped feed line. The integration of SIW with the microstrip array aims to improve the overall antenna

performance in terms of impedance matching, radiation pattern, and efficiency in design [73].

The fork-shaped antenna, which may be modified in terms of frequency and pattern proposed in [74]. To alter the frequency and pattern of the proposed antenna, four PIN diodes were used. This Antennas was resonated at 3 GHz (radio navigation), 3.1 GHz (weather radar and satellite applications), 3.2 GHz (radiolocation), 3.72 GHz (5G wireless receiver applications), 4.9 GHz (public safety band), 5 GHz (wireless applications), 5.2 GHz, and 5.5 GHz (WLAN) in various PIN diode switching modes With various switching modes of the PIN diode, the radiation pattern tilts from $\pm 170^\circ$ in reference [72]. Figure 6 depicts the antenna's top view, which shows the radiating structure is made up of slots with various resonance lengths and is responsible for a specific frequency [72]. As a result of the additional distance travelled by current, a phase difference occurs, causing the pattern to reconfigure in various switching states. Figure 7 depicts the pattern reconfiguration procedure at various frequencies for ease of reference. By adjusting switching states, the pattern reconfigurability process shown in Fig. 7 can be produced at other frequencies. The gain levels of the proposed antenna are suitable for the applications. To reduce the impact of radiation on performance, biasing wires are connected in various switching modes as needed. By altering the radiating element's present path, the pattern reconfiguration is achieved. In various modes, it can be seen that the radiation pattern is tilted from -170° to $+170^\circ$ in the yz plane which is depicted in Fig. 6. In all switching state direction of the main lobe is at $\theta = 90^\circ$ for the same frequency.

The frequency and pattern reconfigurable antenna types that have recently been proposed and published in the literature are summarised in Table 4 which shows the comparison of proposed work with previously published work in terms of size, gain and number of actuators used to reconfigure frequency and pattern. This is meant to assist readers in determining which frequency and pattern reconfigurable antennas are most suited to their needs.

The design [75] has a 340 MHz tunability and 700 MHz bandwidth, and beam tilting capabilities of 30° , 40° , $+35^\circ$, 90° , and 120° , making it suitable for wideband applications in two different bands S and C. The antenna [76] consists of a hexagonal patch antenna featuring four slits: two slits positioned diagonally (longitudinal) and two slits positioned horizontally (latitudinal). This design allows the antenna's pattern to be reconfigurable in four different directions, all without the need for a servo system. The antenna [77] has a

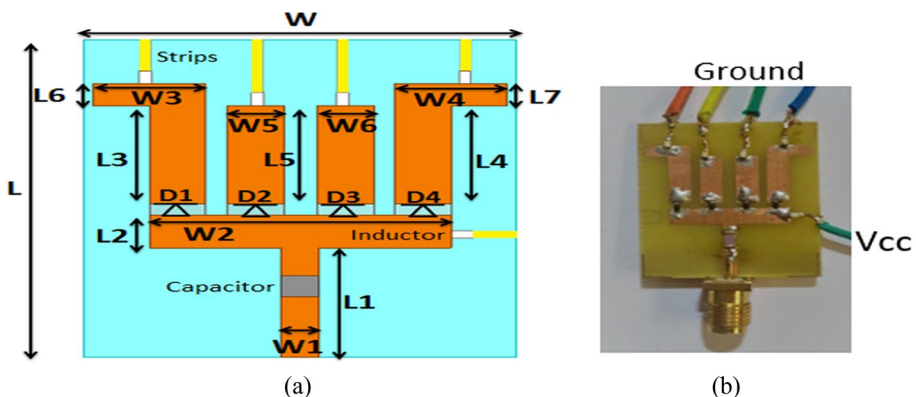


Fig. 6 a Schematic of fork antenna b fabricated antenna [74]

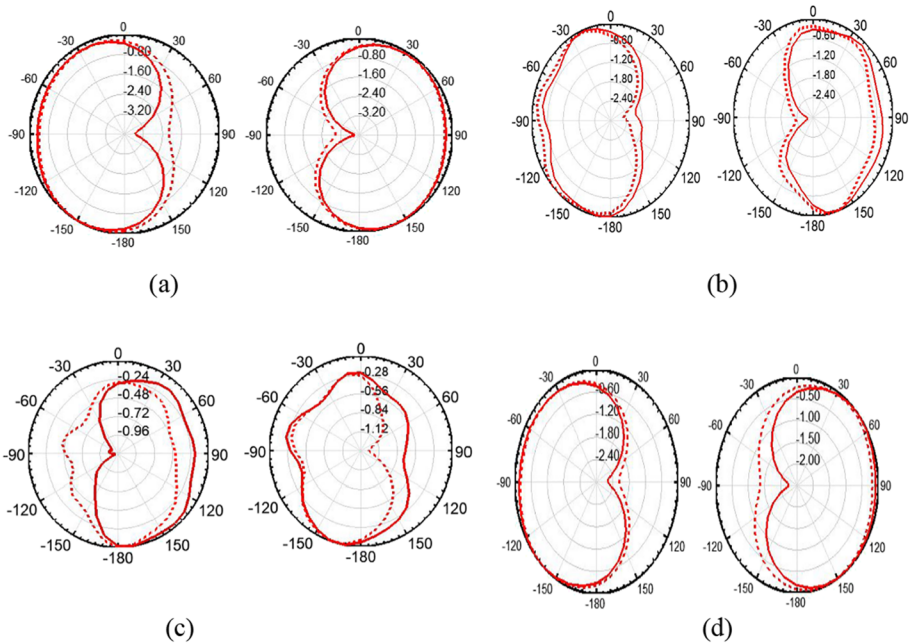


Fig. 7 Normalized radiation pattern in dB [74] **a** mode 1 and mode 4 at 3.1 GHz, **b** mode 1 and mode 4 at 5.5 GHz **c** mode 2 and mode 3 at 4.9 GHz **d** mode 1 and mode 10 at 3.2 GHz

small number of switches, which reduces switch losses and the design's complexity. This antenna [77] has a small footprint and a wide bandwidth coverage, as well as a discrete RF switch type that offers flexibility and frequency and pattern reconfigurability. In the 3.4–3.8 GHz and 3.7–4.2 GHz frequency bands, the antenna described in paper [74] offers beam-steering of 25° and 20°, respectively. The impedance bandwidth 12.8% was obtained in the operating bands. The antenna [70] has a pattern inclination of ± 170 in the yz plane and resonates in two distinct frequency bands. This antenna is compact and has fewer actuators compare to other designs discussed.

2.6 Frequency and Polarization Reconfigurable Antennas

Operational frequency and polarisation parameters can be reconfigured in this category. An antenna with frequency and polarisation flexibility is becoming more desirable in smart technology. Reconfigurable antennas with frequency flexibility and polarisation variation offer several advantages, including better spectrum usage, enhanced system ability due to polarization variability, and enhance communication security due to random mode selection [78]. In a flexible wireless system numerous reconfigurable parameter, such as stable gain for all different configurations is must require, which improves system efficiency, reduces system cost, and achieves a good signal to noise ratio. Using different RF switches like varactor diodes, PIN diodes, microelectromechanical systems (MEMS) switches, and Liquid metal eutectic gallium indium (EGaIN) a variety of implementations with integrated frequency and polarisation reconfigurability have been accomplished recently. An

Table 4 Frequency and pattern reconfigurable antennas are compared in terms of performance described in the literature

References	Type of antenna	Actuators	Bandwidth (MHz)	Peak gain (dBi)	Size of antenna	Limitation
Lavadiya SP et al. [75]	Microstrip patch	2 PIN	450/570/750/700	Not given	31 × 23	Bandwidth is limited
Thanki et al. [74]	Fork shaped	4 PIN	190–1260	1.14–4.27	29 × 23	Due to 4 PIN diode design cost is more
Iqbal et al. [65]	Patch	3 PIN diode	1700/1200	4.01/4.60	23 × 31	Operated at only two frequencies
Chandra et al. [76]	Hexagonal patch	4 PIN diode	360/260/260/200/200/300	6.4/2/2/3.6/3.6/1.9	40 × 40	No. actuator are more
Han et al. [72]	Sickle-shaped slot	2 PIN diode	17.4/15.3/15.3/16.2/14.8/14.8 (in %)	2.24/2.45/2.8/2.2/2.53/2.76	40 × 40	Provide < 30° beam-steering
Ghaffar et al. [77]	Triangle monopole	2 PIN diode	410	2.2	40 × 50	Antenna design was for limited freq. rang (1.5–2.75 GHz)
Thanki et al. [70]	I shaped	1 PIN diode	440/1250	1.07/2.96	25 × 15	Antenna resonates at only two distinct frequencies

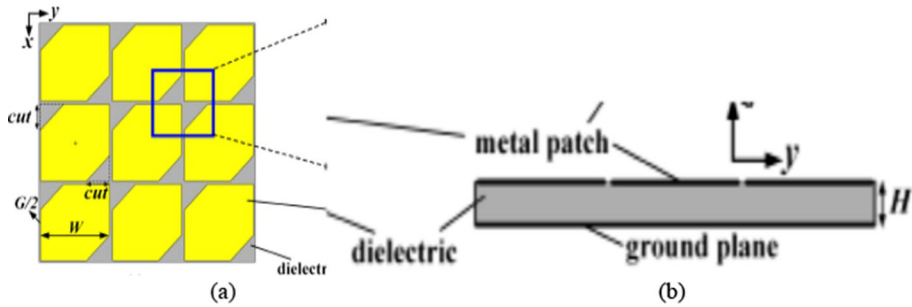


Fig. 8 **a** Schematic of PRAMC structure and **b** side view [80]

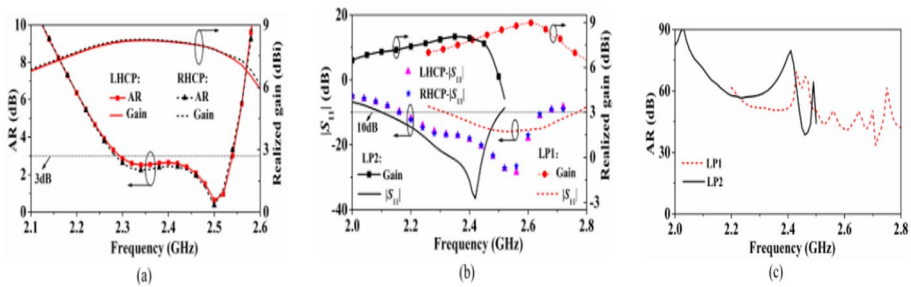


Fig. 9 Antenna [80] simulation results: **a** axial ratio and gains for CP states **b** S parameters and gain for LP states, and **c** axial ratio for LP states

active artificial magnetic conductor (AMC) and metasurface structure [79, 80]. One good way is to use switches on the front of the antenna resonator.

Two such designs were introduced in [79, 80]. By moving the metasurface around the axis of the slot antenna, the presented antenna was achieved linear polarisation, left and right-hand circular polarization [79]. The spacing between the slot antenna and the metallic reflector can be adjusted to obtain the operational frequency of a circular polarisation antenna. A polarisation and frequency reconfigurable antenna with a double layer MS was responsible for frequency and polarisation reconfiguration in [80]. In linear polarization (LP) frequency of operation can be constantly altered from 4 to 4.35 GHz (8.4%) by turning the frequency reconfiguration MS, while the circular polarisation operating frequency was around 5 GHz. Design [81] focuses on maintaining a compact antenna size which is more essential in application such as mobile devices or small communication terminals.

Another design was introduced in [80]. The active AMC unit cell in this design includes four corner-cut patch and triangles loaded with four varactors. By altering the capacitance of the varactors, polarization-reconfigurable and frequency tunable reflection characteristics was achieved. A multi-functional antenna with reconfigurability polarisation and frequency-tuning features was well designed by using the surface of a pair of linearly polarised dipole antennas. Schematic polarization-rotation AMC (PRAMC) was first analyzed and evaluated to generate a multi-functional AMC structure, shown in Fig. 8. LHCP radiation can be obtained when $C1 \ll C2$ (illustrate in Fig. 9a). The 3-dB Axial ratio BW was approximately 11%, which was shorter than the impedance operating band and perfectly overlapped (which is shown in Fig. 9b). Furthermore, throughout the whole band, a

stead gain response of the left-hand circular along the z-axis is less than 1 dB, with a peak gain of around 8.26dBi at 2.34 GHz was achieved. The three polarization states of right-/left-handed circular polarization (R/LHCP) and linear polarization (LP) can be switched, respectively, by adjusting the DC bias of the varactors. Each tuning state of the antenna has a very broad operating bandwidth; for example, the 3-dB AR bandwidth (ARBW) of CP states can reach 8.7%, while the IMBW of LP states can get close to 17%.

PIN diodes were used for frequency reconfiguration, while switchable truncated corners of the patch antenna were used for linear-to-circular polarisation conversion. Switch diodes were placed in the antenna to alter the surface current distribution, enabling frequency and polarisation reconfiguration [79]. By appropriate switching shorting pins, eight distinct operational frequency bands were created, and by modifying perturbation segments, three polarisation states, including left and right hand circularly polarisation, and linearly polarisation was achieved simultaneously [82]. PIN diodes were used for frequency reconfiguration, while switchable truncated corners of the patch antenna were used for linear-to-circular polarisation conversion was proposed in [83].

The summary highlights multiple research studies that focus on developing polarization-reconfigurable antennas in Table 5. Fundamental characteristics in terms of the element type, reconfigurable frequency band, no of active component and type of active component used, types of system polarization, frequency range, and limitation have been compared. This is meant to assist readers in determining which frequency and polarization reconfigurable antennas are most suited to their needs.

The antenna [79] offers the flexibility to operate in either a single-band or dual-frequency band mode, depending on the state of its lumped switches. One of the switches connects the semi-circular patch with an extended feed, enabling frequency reconfigurability. Out of 10 switches two switches are connected to the ground to achieve polarization reconfigurability specifically at 2.4 GHz. The active Artificial Magnetic Conductor (AMC) unit cell consists of an inner patch with four corner cuts and four triangles equipped with varactor diodes. Through adjustments in the varactor diodes capacitance in design [80], this unit cell achieves both polarization-reconfigurable and frequency-tunable reflection characteristics. By appropriately switching shorting pins, eight different operating frequency bands were achieved, and three polarisation states, such as left and right hand circularly polarisation, and linearly polarisation, were simultaneously produced by altering perturbation segments in the antenna [82]. The antenna [84] emitted circularly polarised radiation in four separate bands, which was one of its distinguishing characteristics. In [86], antenna was design to achieved 3 different operating frequency bands for left and right hand circularly polarisation. PIN diodes were used for frequency reconfiguration, while switchable truncated corners of the patch antenna [83] were used for linear-to-circular polarisation reconfiguration.

2.7 Radiation Pattern and Polarization Reconfigurable Antennas

Antennas with changeable radiation patterns and polarizations have features such as pattern variation and support for multiple polarizations. For the L1 band frequency range is (1.575 GHz), a helix antenna using mechanically operated liquid metal in a helical channel was presented in [87]. Radiation pattern switching can adjust the antenna design to meet system requirements [88] and increase channel capacity without adding more radiator space. Many similar antennas have recently been proposed in [88, 89].

Table 5 Frequency and polarization reconfigurable antennas are compared in terms of performance described in the literature

References	Element type	Reconfigurable band	Active component	System polarization	Freq. range (GHz)	Limitation
Patriotis et al. [84]	Microstrip patch	4	2 PIN	Circular	23.75–30.01	Reconfigure only single polarization
Ranjana Kumari et al. [79]	Patch	5	10 PIN	Linear-to-circular	0–4.5	Due to more pin diode use design is costly
Jun et al. [82]	Element	8	16 PIN	LP, RHCP, LHCP	1.883–2.65	Due to more pin diode use design is costly
Chen et al. [80]	Dipole antenna	2	4 Varactor	LP, RHCP, LHCP	2–3.5	Operating band are less
Liu et al. [85]	Printed monopole	5	2 PIN	LP, RHCP, LHCP	1.5–3.5	Design is operated with limited range
George U et al. [83]	Patch	6	10 PIN	LP, CP	0–4.5	No. of diode are more so design is costly
Liu et al. [86]	Slot	3	EGain	LP, CP	1.6–3.23	Operating band are less

Two sets of back-to-back planar complementary dipoles were used to create a front as well as back pattern-reconfigurable circularly polarized antenna mentioned in [90]. This antenna was a good fit for ISM device, which were widely used in portable medical equipment as well as signal detection. Antenna Presented in [91], is a broad microstrip patch antenna having customizable radiation patterns that incorporates two equally inverted U-slots and two coaxial probes with the patch's resonant length. Within the achieved bandwidth, proposed antennas that have been sustain polarisation and symmetry radiation patterns for broadside and conical radiation patterns. The bottom layer of the antenna has a feeding line, the middle ground layer has a cross-slot, and the top layer has a meta surface (MS). PIN diode switch states on the Meta surface and the ground plane were changed to reconfigure the system. It was conceived in [92]. One of the radiation pattern's antennas can generate transition between left and right-handed circular polarisation along the Z-axis. The antenna's low profile, ease of handling, and reconfiguration functions made it suited for practical applications in the continuous band. In [93], a mode tunable feed network was designed that contains a set of eight L-probes which supports the appropriate excitation of the patch's in TM₁₁ or TM₂₁ mode and produces symmetry radiation patterns. Second, an annular slot was inserted into this patch to enable their functioning bands to overlap. This antenna's CP pattern reconfigurability, combined with its excellent performance qualities, works perfectly for a wide range of RFID and satellite communication applications.

The antenna made up of a centre-fed 4-way Gysel power divider, delay lines, inside Lamina Emergent Torsion (LET) joints, and four thick flat dipole antennas presented in [94] based on spatial-mapping origami theory. Figure 10 illustrate the constructed antenna. The antenna's overall width and length are both 100 mm and the effect of non-zero transmission line lengths are represented in Fig. 11. In an ideal situation, the physical length of a star-connected transmission line is zero. In an ideal situation, the electrical length of a star-connected transmission line is zero. The insertion loss was 6.2 decibels (IS₂₁). The antenna's planar model, like a monopole antenna, emits a linearly polarised omnidirectional radiation pattern, whereas the folded mode emits

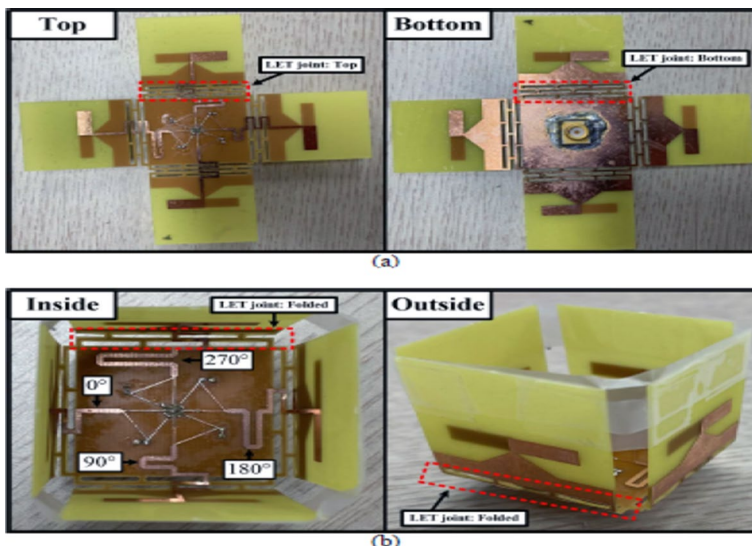


Fig. 10 Fabricated antenna [94]: a planar, b folded, and inactive modes

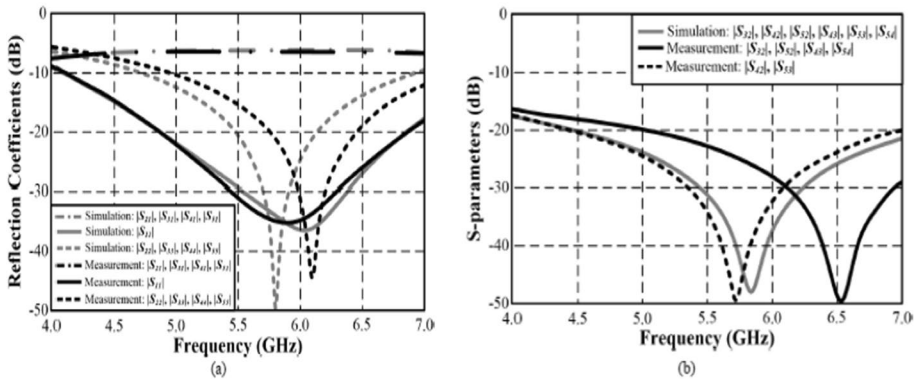


Fig. 11 Simulated and tested S-parameters of antenna [94]

a circularly polarised radiation pattern. The proposed antenna could enable new satellite-based communication systems, such as 6G connection, while also addressing volume issues with CubeSat antennas. The inside of the antenna has a Lamina Emergent Torsion (LET) joint structure that was utilized in the origami process. The antenna can be folded and unfurled using the space-mapping equivalent of the origami method. At 5.8 GHz, the measured axial ratio (AR) value is 1.13 dB, and the cross—polarization suppression ratio is approximately 25 dB.

The electrical length of a star-connected transmission line is zero in an ideal case. Insertion loss ($|S_{21}|$) was 6.2 dB. The planar model of the antenna, like a monopole antenna, has a linearly polarised omnidirectional radiation pattern, but the folded mode has a circularly polarised radiation pattern. The proposed antenna could have the new path satellite-based communication systems such as 6G connectivity, as well as solve the volume problems with CubeSat antennas.

The pattern and polarization reconfigurable antenna types that have recently been proposed and published in the literature are summarised in Table 6. Fundamental characteristics in terms of CP bandwidth, overall area, no. of the diode, and type of diode and limitation have been compared. This is meant to assist readers in determining which pattern and polarization reconfigurable antennas are most suited to their needs.

A flat CP end-fire antenna with configurable polarisation, omnidirectional patterns that can be alter between left and right-hand circularly polarised is described in this article [95]. A WLAN antenna article [89] was built for 2.4 GHz applications and could steer its beam in three directions based on the condition of PIN diodes installed in the ground plane. It could also transition between horizontal, vertical, and linear polarisation states. To achieve polarization reconfiguration in design [89], the square ring patch utilizes PIN diodes positioned in the diagonal spacing, which can be switched ON/OFF. On the other hand, for pattern reconfiguration, the PIN diodes are employed in the ground plane and can also be turned ON/OFF. In a compact package, the antenna [98] achieved high impedance and AR bandwidths of 36.2% and 22%, respectively. The antenna offers two additional advantages. Firstly, it provides wide impedance and axial ratio (AR) bandwidths. Secondly, it achieves a compact size without the need for large ground or reflectors.

Table 6 Polarization and pattern reconfigurable antennas are compared in terms of performance mentioned in the literature

References	Antenna type	CP bandwidth (%)	Overall area (mm ²)	No. of diode/type of diode	Limitation/challenges
Yan et al. [95]	Complementary dipoles	3	0.87 $\lambda_0 \times 0.87 \lambda_0$	24/PIN	Design is costly due to max. use of diode
Niture et al. [89]	Square ring patch	8	60 \times 65	2/PIN	Freq. Band Is Limited
Xiao et al. [96]	Circular ring patch	1.2	Not given	3/PIN	Freq. Band Is Limited
Sun et al. [97]	Stacked-patch antenna	Up to 40	42 \times 37	4/PIN	Axial bandwidth is very small (up to 3.3%)
Yi et al. [98]	Helical	36.2	79 \times 70	2 group of PIN diode	Frequency band is limited

2.8 Frequency, Radiation Pattern and Polarization Reconfigurable Antennas

There are only a few factors that can be changed in above designs presented. There is only one design for independently three-parameter reconfiguration in the literature, which was proposed in [99]. In the article [100], another frequency, radiation pattern, and polarisation reconfigurable antenna design was described, although it had limitations such as a narrower frequency tuning range, a narrower beam forming range in two major planes, and a larger number of switches than the design in [99].

The antenna design and prototype [99] are shown in Fig. 12. An orthohexagonal patch and six parasitic patches constitute the radiating patch. The six parasitic patches were placed around the orthohexagonal patch, with a varactor diode connecting each parasitic patch to the orthohexagonal patch. For the 14-array antenna along with four feeding probes were used. Figure 12 shows an array antenna prototype (b). The operating frequency can be continuously tuned and the polarization altered between left-handed CP (LHCP) and right-handed CP (RHCP) simultaneously by properly changing the DC voltage given to the three groups of varactor diodes. The radiation beam of the array antenna can be dynamically adjusted among five different beam states by appropriately switching feeding probes for the four elements. The antenna can constantly vary the working frequency from 2 to 3 GHz, beam scan in five beam modes with a beam range of 50° , and change the polarisation from LHCP to RHCP.

Table 7 summarised with various research works that contributed to the realization of combined reconfiguration and the notable observations are as follows. Fundamental features in terms of reconfigurability, antenna dimensions, type of the antenna and type of switch used, and how many switches are used have been compared. This is meant to assist readers in determining which compound reconfigurable antennas are most suited to their needs.

Because the working frequency of the article [99] antenna can be continually changed, it's an excellent fit for current communication systems like wireless sensor networks and RFID readers. It can control the polarisation and guide the radiation pattern between five beam states with a beam coverage of 50° , and the polarisation can be switched between left and right-handed CP. The antenna [101] was capable of switching polarisation between

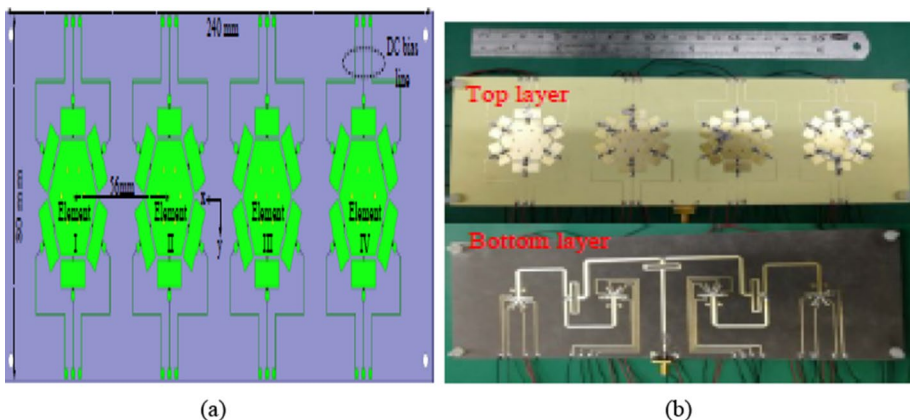


Fig. 12 Schematics and the prototype of antenna [99]

Table 7 Compound reconfigurable antennas are compared in terms of performance described in the literature

References	Antenna type	Reconfigurability		Polarization	Total size	Switches
		Freq. tuning range	Pattern			
Hu et al. [99]	Patch array	33%	Five beam states with beam coverage of $\pm 50^\circ$	LHCP, RHCP	$2\lambda_0 \times 0.67\lambda_0 \times 0.018\lambda_0$	24 varactor diodes, 32 PIN diode
Ge et al. [101]	Slot	Not given	Not given	LHCP, RHCP, LP	$0.86\lambda_0 \times 0.78\lambda_0 \times 0.01\lambda_0$	48 PIN diode
Zhang et al. [102]	Patch	Not given	Six beam states with beam coverage of $\pm 46^\circ$	LHCP, RHCP	$1.2\lambda_0 \times 1.2\lambda_0 \times 0.04\lambda_0$	10 PIN diodes and 8 Varactors

two orthogonal linearly and circularly polarized states, tune across three frequency bands for all this states, and for all 20 states this design maintaining appropriate unidirectional radiation patterns. In The article [102] polarization (LHCP/RHCP), resonant frequency (1.96 to 2.03 GHz), and radiation pattern reconfiguration were rotated between five different situations in the yz -plane and the xz -plane. By dynamically adjusting the frequency, polarization, or radiation characteristics of this design signal-to-noise ratio was enhanced and optimized spectrum utilization in wireless communication.

3 Reconfigurable Switching Methods

The utilization of switching techniques is crucial in the design of reconfigurable antennas, as it enables the modification of the current distribution within the radiating structure by connecting or disconnecting different components of the structure or by changing the physical structure of the antenna, by changing the feeding technique or by changing edges of antenna. Various types of switches, such as electrical, optical, and mechanical switches, as well as external adjustments and the use of reconfigurable materials (as depicted in Fig. 13, can be employed as switching mechanisms. If the designer changes any one parameter in antenna characteristics it may affect other parameters of that antenna. So designers should be careful whenever designing reconfigurable antenna to achieve reconfigured properties [5].

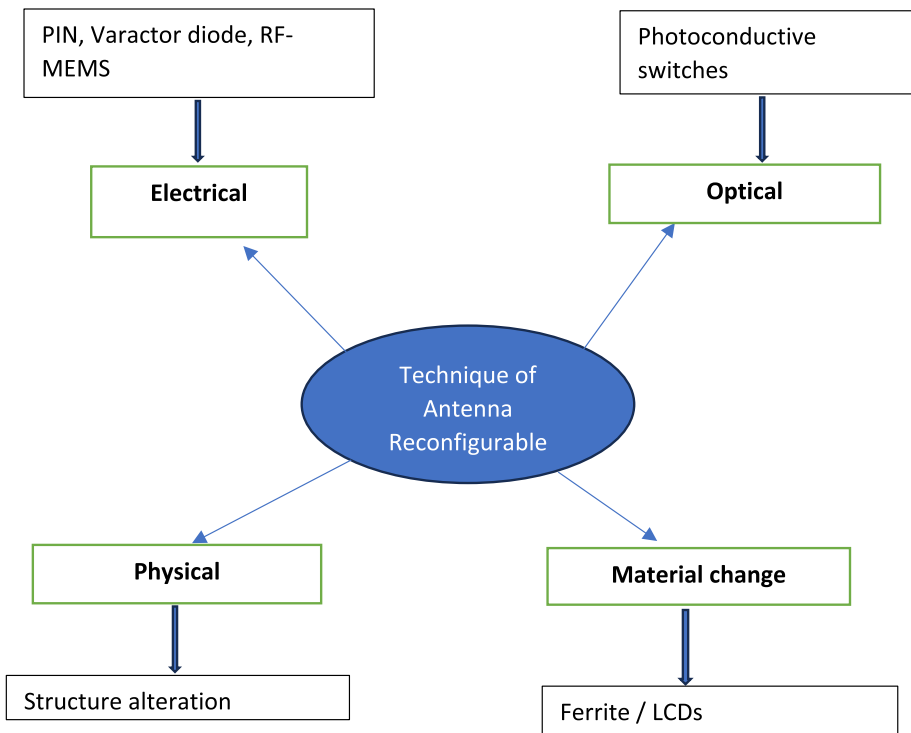


Fig. 13 Various techniques of reconfigurable antenna

3.1 Electrically Reconfigurable Antennas

The electrical system utilizes both discrete and continuous tuning techniques, which involve the utilization of p-i-n (PIN) diodes, varactor diodes, and field-effect transistors (FETs). To operate these electronic components in the antenna circuit, it is necessary to have direct current (DC) sources and biasing circuits. Consequently, an electrical reconfigurable antenna depends on a DC power source and electronic switches, which can negatively impact the antenna's operation and performance. The integration of switches into the antenna structure makes it easier for designers to reach the desired reconfigurable functionality [5]. The drawbacks associated with electronic reconfigurability include non-linear impacts of switches, reduction in signal quality due to interference losses, and adverse consequences arising from biasing lines. The benefits of using this type of technique are in terms of simplified integration. However, drawbacks of this method include non-linear impacts of switches, losses due to interference, and adverse effects of biasing lines.

The PIN diode possesses a broad intrinsic region situated between the p and n junctions, resulting in a high breakdown voltage suitable for applications requiring high voltages. Figure 14a illustrates its equivalent circuit [103]. The use of PIN diodes for reconfiguration

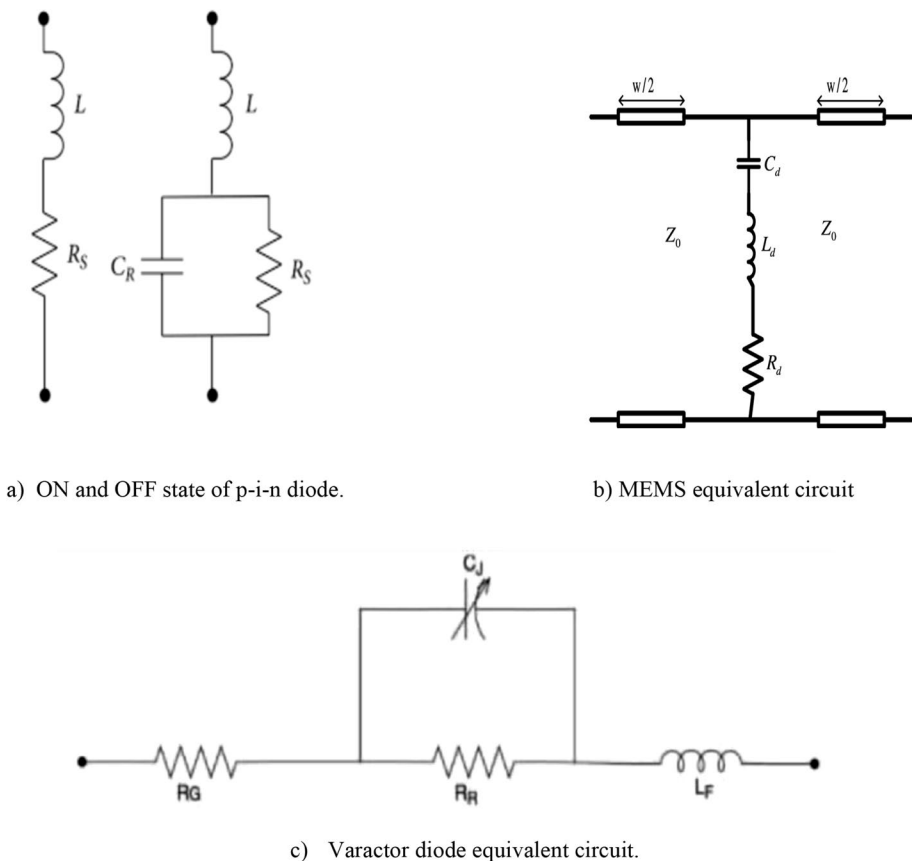


Fig. 14 Equivalent circuits of electrical switches

at microwave frequencies is advantageous due to their ability to manage high RF signal power using a low control voltage. Additionally, PIN diodes are less prone to Electrostatic Discharge (ESD) damage and possess a higher Figure of Merit (FOM) compared to Field Effect Transistors (FETs). Applying forward bias to the PIN diode creates an ON state by establishing a short circuit, while reverse biasing creates an OFF state by creating an open circuit. In both states, the inductor maintains a constant value and functions as a choke, allowing DC signals to pass through while blocking RF signals [104].

Primarily, it functions as an optimal radio frequency switch, offering a rapid switching speed of 100 ns. On the other hand, RF-MEM (radio frequency microelectromechanical systems) is a switch composed of actuators, sensors, and mechanical components integrated on a substrate using an IC (integrated circuit) fabrication process [97]. It has several advantages over other switching diodes, including low insertion loss and power consumption, as well as high reliability and isolation. However, its switching speed is relatively slower at around 200 microseconds. Figure 14b demonstrates the equivalent of the RF-MEM's. When the frequency is lower than the resonant frequency of the LC series, the switch behaves like capacitive. Conversely, when the frequency exceeds the LC series resonant frequency, the switch behaves as an inductor. At the resonant frequency, the switch transforms into a purely resistive element.

The varactor diode serves as a tuning diode, and its equivalent circuit is depicted in Fig. 14c [105]. Where R_R is the reverse bias resistance and R_G is the geometric resistance of the varactor diode. C_J is the junction capacitance which is dependent on the reverse bias voltage. L_F is the effective inductance and it depends on the frequency limits under which a varactor diode should be operated. Table 8 presents different research studies that have contributed to achieving combined reconfiguration using electrical switches.

In the antenna [74] slight difference between the results obtained from the simulation and actual measurements is because of the insertion loss introduced by the PIN diode (Skyworks SMP 1345-079LF). To achieve the desired extensive frequency range, the proposed approach utilizes both discrete switching and continuous tuning methods in design [31]. In this paper, Two discrete switches are utilized to achieve the switching capability between the wideband range of 1 to 5 GHz and the reconfigurable region spanning from 430 MHz to 1 GHz. Design [49] Provides different 6 radiation patterns in the azimuth plane at the same angle interval. In design [34] slots are mounted to achieve desired frequency as well as For reconfigurability PIN diode were utilized. In Table 9 advantages and disadvantages of electrical switches are summarized. It is inferred from the comparison that, the PIN diode possesses high switching speed and RF MEMS offers reduced power consumption, high isolation, and low loss.

3.2 Optical Switching

Optically reconfigurable antennas belong to a category of radiating elements that can modify their radiation properties through the utilization of switches. These switches can be optically activated, such as silicon switches or reactive elements. The advantage of optically controlled devices is that they eliminate the need for metal wires that could interfere with the antenna's radiation characteristics. By using optically controlled reconfigurable antennas, the complexity arising from the inclusion of additional metallic microstrip or wired biasing lines can be overcome. Moreover, the interference among the desired radiation patterns, which is a significant issue in DC-controlled microstrip antennas, can be mitigated. Optical switches are recognized for their higher reliability compared to other

Table 8 Electrically reconfigurable antenna are compared in terms of performance

References	Radiating structure	Reconfiguration mean	Type of reconfiguration	No. of electrical switch	Antenna size (mm ²)	Substrate
Thanki et al. [74]	Fork shaped	PIN	Freq. and pattern	4	29×23	FR4
Chen et al. [80]	Dipole antenna	Varactor	Freq. and polarization	4	0.04 λ ₀ (height)	FR4-slab
Niture et al. [89]	square ring patch	PIN	Pattern and polarization	2	60×65	FR4
Hu et al. [99]	Patch array	Varactor diodes, PIN	Freq., Polarization, and Pattern	24-PIN, 32 Varactor	2λ ₀ ×0.67λ ₀ ×0.018λ ₀	FR4
Kantemur et al. [31]	Monopole	Varactor	Frequency	1	60×100	RT/Duroid 5880
Virothu et al. [62]	Square slot	PIN	Polarization	3	114×114×0.8	FR4_epoxy
Tarun Prakash et al. [49]	Curved printed dipole	PIN	Pattern	1	90 mm diameter	Taconic: TLY
Ghaffar et al. [34]	Triangular-shaped monopole	PIN	Frequency	2	30×30	ROGERS RT/droid 6010
Rao et al. [33]	Circular patch	RF MEMS	Frequency	2	6.52 mm diameter	Silicon

Table 9 Advantage and disadvantage of electrical switches reconfiguration techniques [106, 107]

Electrical switch	Advantage	Disadvantage
PIN diode	They provide improved insulation for the switching components and offer a significant advantage of low loss	The integration of switches introduces added complexity to the antenna structure, as it requires the inclusion of extra bypass capacitors and inductors. Consequently, this leads to an increase in the overall power consumption of the system
Varactor diode	Varactors contribute to the scalability of reconfigurable antennas by enhancing their adaptability. These switches can be easily integrated into the antenna structure, allowing for seamless integration	The process of activating these switches involves the utilization of biasing lines, which have the potential to negatively impact the antenna's radiation pattern. Additionally, this can introduce further losses and nonlinearity effects, including capacitive and resistive elements
RF-MEMS	Provide good isolation and Low-loss property	In comparison to PIN diodes and varactors, the response time of these switches is relatively slower, typically on the scale of nanoseconds

types of switches. When these switches are controlled using laser light, the level of distortion is significantly reduced. Additionally, optical switches demonstrate linearity and do not necessitate the inclusion of partition lines for integration into antenna designs. Consequently, there is no need for optical fibers to transmit light to the switches, as highlighted in the research [108]. Implementing optical switches in reconfigurable antennas can involve complex optical designs, alignment, and calibration, which might increase the overall system complexity. There are 3 optically reconfigurable antennas with different activation techniques.

3.2.1 First Activation Technique: Non-integrated Optical Fiber

In this configuration, the control of optical receiver switches relies on optical fiber cables. The study [109] introduces a novel approach where an LED bulb, small LEDs, and LED-mounted optical fiber cables are employed to activate two readily available photodiodes operating within the range of 600 nm to 1010 nm. The antenna exhibits excellent reconfiguration, gain, and bandwidth when utilizing 950 nm LEDs as a source, in comparison to other LED sources. When red LEDs are employed as the optical source for the antenna, it achieves a maximum bandwidth of 21%.

3.2.2 First Activation Technique: Integrated Optical Fiber

A new planar monopole antenna [110] with optical frequency reconfigurability is introduced for cognitive radio applications. The antenna design incorporates two silicon samples, which function as optical switches. The fundamental concept underlying the antenna design involves modifying the distribution of surface current on the antenna by optically transitioning the Si switches from high resistance to low resistance. This compact antenna design utilizes only two switches to achieve multiband polarization reconfiguration and pattern agile antennas. To the best of the authors' understanding, this planar monopole antenna represents the first instance of a multiband antenna that is optically reconfigurable.

3.2.3 Third Activation Technique: Integrated Laser Diode

Laser diodes are used in this design to emit light onto the photoconductive switches, which establish connections between various radiating components within the antenna framework. To activate the silicon switches, laser diodes are incorporated into the antenna substrate. To facilitate the delivery of light from the laser diode to the silicon switches, a 1 mm hole was drilled through the substrate. The type of antenna investigated in this study [111] is a stripline-fed structure. It has been observed from this article that the antenna maintains its ability to radiate in all directions while adjusting its operating frequency in both the E and H planes. Table 10 presents different research studies that have contributed to achieving combined reconfiguration using optical switch.

3.3 Structural Alteration and Mechanical Based Switching

Another method to achieve antenna reconfiguration involves physically modifying the radiating structure. The tuning process is accomplished by making structural changes to the antenna's radiating components. The significance of this approach lies in its independence from switching mechanisms, biasing lines, or the integration of optical fiber/

Table 10 Optically reconfigurable antenna are compared in terms of performance

Reference	Type of reconfiguration	Antenna area	No. of diode use	Application	Substrate
Reji et al. [109]	Frequency	$0.58 \times 0.37 \times 0.02$	2 photodiode	5G, 5 GHz band, 6 GHz Wi-Fi applications	Roger
Ali et al. [110]	Frequency	30 mm \times 30 mm	2 SI diode	Cognitive radio and wireless applications	Rogger
Tawk et al. [111]	Frequency and pattern	45 mm \times 20 mm	2 laser diode	–	Rogers 5880
Lin et al. [112]	Frequency	148.13 \times 78 \times 1.23 mm ³	3 photodiode	Communication and radar integration	FR-4

laser diodes. However, this technique is dependent on the device's capability to be physically reconfigured.

The complete structure [113] was created by designing individual patches for each mode of operation. These antenna patches were then positioned on a circular disk, which was cut from the square substrate. Behind the rotatable circular disk, a stepper motor was installed. The strategic placement of the motor at the back of the antenna helps minimize interference between the components. The ability to reconfigure the antenna [114] is attained through the rotational movement of a specific section of the patch antenna. This rotating part takes the shape of a circle and encompasses four distinct shapes, each corresponding to a different antenna structure. As the circle rotates, it feeds different antenna structures sequentially, resulting in the generation of various sets of resonant frequencies. In Table 11 advantages and disadvantages of different reconfiguration techniques are summarized.

3.4 Material Based Switching

Various research has been conducted to explore the implementation of reconfiguration using reconfigurable materials. This approach eliminates the need for structural alterations in the radiating structure to achieve reconfiguration. Reconfiguration in THz applications can be accomplished using reconfigurable materials such as graphene and liquid crystals as substrates.

An article [115] presents a wideband beam reconfigurable directional antenna designed for THz wireless communication systems, utilizing graphene-based parasitic elements. The individual adjustment of surface conductivity is achieved by applying a bias voltage through the chemical potential of the graphene. By using the unique properties of graphene, the shape of the patch in this study [116] can be altered among three different configurations: triangle, rectangle, circle, and slotted patches. The antenna design being proposed exhibits the capability of reconfiguring both polarization and frequency. This is made possible by utilizing graphene as the primary radiation patch within the structure.

Table 11 Advantages and disadvantages of different reconfiguration techniques [106, 108–113]

Reconfigurable switching technique	Advantage	Disadvantage
Optical switches	Do not require a metallic biasing wire, which might interfere with radiation patterns	Lossy behaviour
	Does not require any metallic elements to feed the structure	Need of complex mechanism
Mechanical switch and structural alteration	Does not require biasing circuitry	Create an impedance mismatch that degrades the antenna's performance
	No need of active elements	Slow response Required power source
Material base	More versatile	Low efficiency
	Lighter weight	Limited applications

4 Applications

The ability to adjust various parameters of a radiating structure has provided reconfigurable antennas for a wide array of applications. The following sections discussed the role of reconfigurable antennas in applications like cognitive radio, MIMO technology and 5G systems.

4.1 MIMO Technology

To attain enhanced data transmission capabilities, the concept of multiple-input-multiple-output (MIMO) addresses this challenge while preserving RF specifications. Reconfigurable MIMO antennas, capable of adapting from wideband to narrowband frequencies, show great promise as a potential solution for the aforementioned issue. MIMO antennas are required to be characterized with standard values of major parameters like isolation, envelope correlation coefficient (ECC), diversity gain, and total reflective coefficient. Ensuring effective isolation between antenna elements is crucial when integrating MIMO antennas into compact-sized devices.

EBG structures are engineered periodic arrays in design [117] that exhibit unique electromagnetic properties, often used to improve antenna performance. The implementation of decoupling structures using Electromagnetic Band Gap (EBG) or meta-materials can enhance the isolation between MIMO antenna elements [118]. The process of converting each monopole element from wideband to narrowband is achieved by employing PIN diodes positioned between the fed line and stepped-impedance resonating stubs (SIRS) in design [119]. The antenna [120] is intentionally designed without any decoupling structure, simplifying its overall structure. Instead, it utilizes perpendicular feeding, which ensures high isolation between its components. The performance of the MIMO antenna's diversity is evaluated using metrics such as the envelope correlation coefficient (ECC), diversity gain (DG), and total active reflection coefficient (TARC). The ECC between any two antennas is determined by using the measured radiation pattern, as per the given equation [121],

$$ECC = \frac{\left| \iint E_{\theta_i} \cdot E_{\theta_j}^* + E_{\phi_i} \cdot E_{\phi_j}^* d\Omega \right|^2}{\iint E_{\theta_i} \cdot E_{\theta_i}^* + E_{\phi_i} \cdot E_{\phi_i}^* d\Omega \iint E_{\theta_j} \cdot E_{\theta_j}^* + E_{\phi_j} \cdot E_{\phi_j}^* d\Omega} \quad (1)$$

where i and j represents the port numbers. The DG is calculated using the measured ECC of MIMO antenna array using [122] the equation

$$DG = 10 \times \sqrt{1 - |ECC|} \quad (2)$$

TARC is calculate using the measured S-parameters of the MIMO antenna using the equation [123]

$$TARC = \frac{\sqrt{\sum_{i=1}^2 |b_i|^2}}{\sqrt{\sum_{i=1}^2 |a_i|^2}} \quad (3)$$

The ECC value ranges from 0 to 1. A low ECC is generally desired in MIMO systems to ensure that the antennas provide diverse spatial channels that can be independently

exploited for improved signal quality and system performance. MIMO antenna designs often aim to achieve low envelope correlation coefficients by considering factors such as antenna spacing, polarization, radiation patterns, and other design parameters. Maintaining effective isolation between the various components of an antenna is vital to preserving the benefits of amplified MIMO (capacity in antenna design. A threshold of 10 dB isolation between ports is considered an acceptable standard for MIMO devices [120]. This isolation level ensures that signals transmitted or received through different ports remain sufficiently separate, minimizing interference and enabling the complete utilization of the MIMO system's capacity-enhancing advantages.

4.2 Cognitive Radio Application

Cognitive Radio is a technology that enables dynamic and intelligent utilization of the radio spectrum. CR systems can sense the available spectrum, identify unused or underutilized frequency bands, and opportunistically access those bands to improve spectrum efficiency. Cognitive radio applications span various domains and offer numerous benefits, including efficient spectrum utilization, improved communication reliability, and enhanced wireless services. The antenna [124] adapts to varying frequency bands as required by cognitive radio systems to exploit unused or underutilized spectrum.

The main contribution of design [125] involves incorporating tunable components or structures that can modify the resonance frequency of the antenna. This adaptability allows the antenna to operate efficiently across various frequency bands, maximizing spectrum utilization. The use of PIN diodes allows the antenna [126] to change its resonance characteristics, enabling it to efficiently operate across different frequency ranges. This adaptability is a crucial feature for cognitive radio systems, where the ability to access unused or underutilized frequency bands is essential for spectrum efficiency. Compact MIMO (Multiple-Input Multiple-Output) slot antenna [127] capable of frequency reconfiguration which is focused on creating an antenna suitable for interweave cognitive radio (CR) applications, where the antenna can adjust its operating frequency to avoid interference with primary users.

Developing a hexagon-shaped printed antenna [128] that is suitable for cognitive radio applications. The specific geometric characteristics of the hexagonal shape are likely chosen to enable desirable radiation patterns and frequency properties. A novel antenna design [129] that is compact, reconfigurable, and broadband. These features align well with cognitive radio principles and applications.

4.3 5G Systems

Reconfigurable antennas offer numerous advantages for 5G technology by providing adaptive beamforming, improved coverage, increased capacity, and enhanced interference management. Their ability to adapt to changing network conditions and user demands makes them a valuable tool for optimizing the performance and efficiency of 5G communication systems. 5G operates across a wide range of frequency bands, including both traditional cellular frequencies and higher-frequency millimeter-wave (mmWave) bands. Frequency reconfigurability plays a significant role in 5G antenna design [130] as it greatly impacts data throughput by expanding bandwidth and capacity. Reconfigurable antennas can adjust their resonance frequencies to operate efficiently across different frequency bands, maximizing spectrum utilization and enabling seamless communication in various deployment

scenarios. 5G operates across a range of frequency bands, including both sub-6 GHz (mid-band) and mmWave (millimeter-wave) frequencies.

Recent research progress is on creating an uncomplicated, cost-effective, adaptable, flexible, and shape-conforming antenna for 5G communication. In different situations, the transmission of millimeter-wave signals through wireless channels faces challenges such as significant free space path loss and signal attenuation caused by obstructions in the communication path or alterations in atmospheric conditions. To address issues like path loss and signal weakening while sustaining high data rates, it is necessary to utilize directional antennas characterized by broad bandwidth, various polarization options, and substantial gain [131]. The adaptability to switch between multiple frequencies, the capacity to modify spatial arrangements, and the capability to adjust the transmitting RF signal's orientation render reconfigurable antennas well-suited for 5G communications. Additionally, the appeal of advanced 5G antenna design is enhanced by features such as an effective feeding network, minimized mutual interference, heightened gain, and improved efficiency [132].

5 Observations, and Research Challenges

This section provides a summary of the findings from the literature regarding different techniques employed in reconfigurable antenna design to improve the performance of radiating structures. It also discusses the research challenges that can be focused in the future antenna designs.

6 Summary of Observations

Reconfigurable antennas offer a versatile and efficient solution for addressing the diverse and evolving communication needs of modern wireless systems. Some reconfigurable antennas can be adjusted remotely through software control, enabling operators to optimize network performance without physically accessing the antennas. The achievement of combined reconfiguration involves multiple radiating components and switching elements. PIN-based switching is well-suited for discrete switching scenarios, while varactor-based switching is better suited for continuous scanning applications [133]. The choice of switching mechanisms is heavily contingent on the specific demands of the application and the operational frequency. Using a single reconfigurable antenna instead of multiple fixed antennas can reduce manufacturing costs and complexity in devices and systems. PIN diodes have the advantage of fast switching speeds, enabling rapid changes in the antenna's configuration. This can be important for real-time adaptation to varying signal conditions.

In various studies, a multitude of methods were utilized to enhance the efficacy of reconfigurable antennas. Beyond reconfiguration, crucial factors to contemplate during the design of such antennas encompass bandwidth, mutual coupling, isolation, gain, and size. Expanding bandwidth can be achieved by facilitating energy exchange between the patch and the ground plane. Frequency-reconfigurable antennas provide a flexible and efficient solution to the challenges posed by the dynamic and evolving landscape of wireless communication technologies and spectrum allocations. Pattern reconfigurability [71] enables dynamic beamforming, allowing the antenna to focus its radiation towards specific users, devices, or sectors, improving signal strength and quality. As user devices may have varying polarization orientations, polarization-reconfigurable antennas can adapt to maximize

signal reception and transmission quality. Design [36] is used for pattern reconfigurability which involves the use of switching elements, and phase shifter to achieve the desired radiation pattern adjustments.

Mechanical switches have a proven track record of reliability and long operational lifetimes. This is important in critical applications where the antenna's performance must be consistent over time [113]. Integrating optical switches with antenna structures and electronic control circuits might pose challenges in terms of design and fabrication. Optical components and switches can be expensive to manufacture and integrate, potentially impacting the cost-effectiveness of the reconfigurable antenna system [112].

The SIW can be designed in [73] to provide good impedance matching between the feed network and the antenna elements, ensuring efficient power transfer and minimizing signal reflections. The SIW structure can help in reducing the electromagnetic field leakage and losses associated with conventional microstrip feed lines. The antenna's radiation pattern should be designed to minimize interference to other users and systems sharing the same spectrum. This involves achieving good isolation from adjacent channels or frequency bands [124]. By introducing slots or gaps in the microstrip patch or the ground plane, electromagnetic coupling occurs, which can lead to a wider bandwidth. These slots can be strategically placed to enhance bandwidth and achieve wideband operation [13], and also by placing a dielectric resonator on the patch or near it can create additional resonances and broaden the bandwidth. The EBG structure can be used as a reflector or a director to enhance the directivity and gain of the microstrip patch antenna. By strategically placing the EBG structure behind or in front of the antenna, it can manipulate the radiation pattern and improve the antenna's gain in the desired direction [117].

7 Research Challenges

Simple reconfigurations may involve straightforward control algorithms, while more advanced and adaptive reconfigurations might require more sophisticated algorithms, which can increase the computational load. The complexity of these simulations depends on factors like the antenna's geometry, the number of reconfigurable elements, and the materials used. Simulating antennas with a large number of reconfigurable elements or complex geometries can be computationally demanding.

8 Conclusions and Future Work

This study presents an in-depth analysis of reconfigurable antennas with single and multiple reconfiguration features, as well as a classification of all antennas that can be reconfigured. Some design strategies are described with examples, and a comparison of the fundamental attributes of various antennas that can be reconfigured is shown. Previous research has used several methods to explain and analyse the antennas they've created. The complexity of an antenna increases as the number of reconfigurable increasing proportion, according to this article. The key contributions of this paper include a complete review and classification of studies regarding the evaluation of reconfigurable antenna applications, as well as the methodology used. A design requirement, such as the ability to design an antenna is also mentioned in the demonstration that can reconfigure antenna frequency, radiation patterns, and polarisation qualities simultaneously and independently.

8.1 Future Scope

A reconfigurable antenna with a large frequency tuning range, as required by cognitive radio systems, is still difficult to obtain. Characterization of new flexible materials with low-moderate loss at mm-wave is still challenging. Due to the integration of the MIMO system and various antenna elements to support several wireless communication protocols, existing cell phones face huge difficulties due to mutual coupling issues.

We have identified the following open research topics and potential directions for future research:

- There will be a growing demand for smaller and more compact reconfigurable antennas that can be integrated into various devices, including wearables, Internet of Things (IoT) devices, and even bio-implantable systems.
- Exploring the potential of reconfigurable antennas in emerging technologies, such as 5G and beyond, wireless power transfer, and autonomous vehicles, will be an area of interest.
- There are still challenges to investigate a new technique for reducing the size and increasing the bandwidth of reconfigurable antennas for use in mobile and portable devices.

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