Different methods of antenna reconfiguration by switches: a review

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Article Info

Article history:

Received Aug 17, 2024
Revised Feb 24, 2024
Accepted Mar 29, 2025

Keywords:

Diode
Dipole
Slot
Stub
Switch
Triangular

ABSTRACT

The rapid advancement of wireless communication technology has focused researcher's attention on reconfigurable antennas with multiple input and output (MIMO) and cognitive radio operation in high-data-rate modern wireless applications. Reconfigurable antennas perform various functions in terms of operating frequency, radiation pattern, and polarization. Electronic, mechanical, physical, and optical switches are used in reconfigurable antennas as control elements to adjust the switching mechanism and accomplish dynamic tuning. Electronic switches are the most widely used component in reconfigurable antennas because of their effectiveness, dependability, and simplicity in integrating with microwave circuitry. In this paper, a review of various kinds of efficient implementation methods for electrically controlled frequency reconfigurable antennas are proposed. More electrical switches are being used for reconfiguration such as micro-electromechanical systems (MEMS), P-type, intrinsic, N-type (PIN), and varactor diodes. Even though PIN diodes are more frequently employed for reconfiguration due to their stability and constant variation in internal inductor and capacitor values. This study provides a deep analysis of the PIN diode usage in reconfigurable antennas and how to reduce the diodes in different microstrip reconfigurable antenna structures.

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1. INTRODUCTION

Printed antennas are frequently utilized in modern wireless and cellular communication systems because of their increased directivity, small size, affordability, and lightweight nature. Numerous investigations on printed antennas have been carried out since the technique was developed in the 1950s. The reconfiguration strategies and switching types will be covered in the following sections. Figure 1 shows the classifications of reconfigurable antennas. The antenna reconfigurations are frequency [1], [2], radiation pattern, and polarization. Hybrid recombination is the combination of any 2 reconfiguration methods [3], [4]. The antenna properties can be reconfigured by using active components and switches [5]-[7]. The most common switching elements are P-type, intrinsic, N-type (PIN) diode, photoconductor, varactor diode, and micro-electromechanical systems (MEMS) switches. The diode switches are the most cost-effective and reliable, whereas radio frequency (RF) MEMS switches are more complex and expensive. Both techniques allow for fast reconfiguration of the antenna characteristics, making them ideal for applications requiring frequent frequency band changes [8]. Optical reconfiguration is another approach that uses photoconductive switching [9] components to reconfigure the antenna's frequency. This approach has the advantage of being faster than electrical reconfiguration and requires less power to operate. Because both methods enable rapid reconfiguration of the antenna characteristics [10], they are perfect for applications requiring different frequency band changes. Optically controlled frequency reconfigurable antennas offer several advantages over conventional antennas. They offer greater flexibility in terms of frequency and radiation pattern control, and their compact size makes them suitable for radio over fiber applications. However, challenges such as power consumption and complexity of design need to be addressed to fully realize their potential. There have been reports of an optically feeding array antenna that uses high-voltage photodiodes for frequency reconfiguration as well as an E-structured patch antenna that operates at 2.4 GHz and 5.8 GHz with reflection co-efficient values of -12 dB and -40 dB [11], [12]. A low-power optical switch-equipped antenna has also been developed for X-band applications [13]. Two PIN photodiodes were used to show a planar (50×200) mm^2 Yagi-Uda antenna enabling pattern reconfiguration, with a maximum gain of 6.3 dBi [14]. A commercially available photodiode and phototransistor have been used in the example of an optically controlled antenna for antenna reconfiguration [15]. For each of these scenarios, wavelengths in the 850–1,550 nm range were chosen. This study suggests various reconfiguration approaches together with their switching strategies. This study examines the advantages of PIN diode switches over other types of diode switches and how the number of PIN diode switches can be reduced for the small reconfigurable antenna design. The second part of the paper contains the antenna reconfiguration with various innovative techniques and the third part of the paper provides the antenna reconfiguration techniques with different numbers of PIN diode switches.

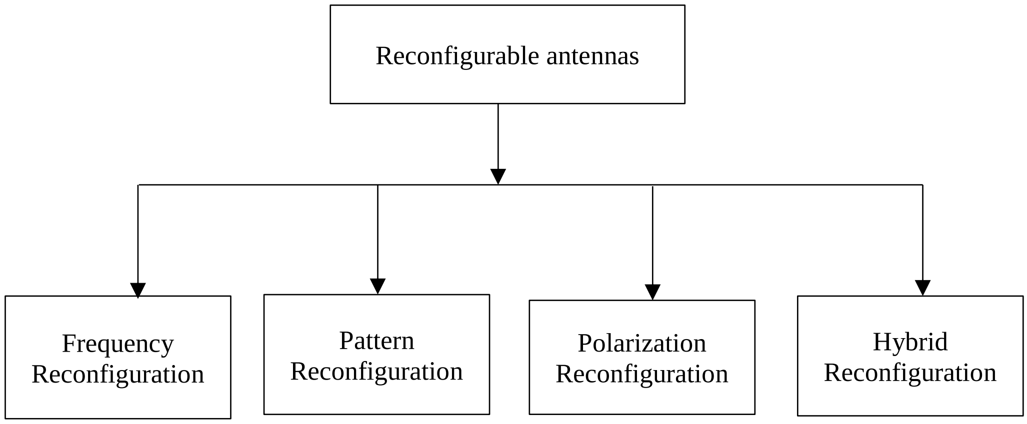

Figure 1. Classifications of reconfigurable antenna

2. ANTENNA SWITCHES

Reconfigurable antenna switches are critical components in modern wireless communication systems, enabling dynamic control of antenna parameters to optimize performance. These switches are employed to modify antenna characteristics such as frequency, polarization, radiation pattern, or impedance. The ability to reconfigure these parameters is essential in multi-band, multi-standard communication systems, where flexibility and efficiency are key. A reconfigurable antenna switch alters the signal path or electrical properties of an antenna system. By selectively connecting or disconnecting specific parts of the antenna, these switches can change its effective configuration. This is typically achieved using various technologies, including MEMS, PIN diodes, varactors, or field-effect transistors (FETs).

2.1. Radio frequency micro-electromechanical systems switches

Reconfigurable antenna research is now focusing on MEMS switches. When designing MEMS switches, researchers take several variables, including contact type, actuation mechanism, signal path, and structure type. There are several ways to generate the force needed to produce mechanical movement, such as electrostatic and magnetostatic actuation. Kingsley *et al.* [16] presented an antenna using RF MEMS switches with E-shaped patch slots. Similar to a shunt MEMS switch, this RF MEMS switch has two movable thin metal connections that are situated across the center conductor. The next model was developed by Jaafar *et al.* [17]. This switch can manage a maximum power of 20 W, and it can be used in satellite communication systems, radar systems, base stations, and network analyzers. A multilayer MEMS switch design was proposed to enable RF switching. The antenna is fed into an E-shaped radiation patch by a coaxial probe.

Kovitz *et al.* [18] examined the properties of a right-hand circular polarization/left-hand circular polarization (RHCP/LHCP) reconfigurable antenna with RF MEMS switches. Nadh *et al.* [19] created a different circular ring-shaped monopole antenna. The circular ring-shaped monopole was connected to coplanar waveguide feeding (CPW), and the reconfiguration was made feasible by integrating MEMS switches. Another dual-band antenna was proposed with RF MEMS switches capable of adjusting the frequency from 2.5 GHz to 5.4 GHz. Sravani *et al.* [20] created the RF MEMS capacitive switch. The primary and secondary patches on this antenna modify the wavelength at which the signal propagates. The specified switch had a quality factor of 0.3 and an operating voltage of 12 V. The MEMS switch capacitance ratio and switching time at a 34.6 KHz resonant frequency were found to be 12.72 and 12.06 s, respectively. A comparative analysis reveals that the RF switches and MEMS switches have a low switching speed, a short lifespan, and a high control voltage requirement. Nevertheless, MEMS switches continue to offer benefits like low power consumption, compact size, and integration potential. Researchers are looking into other designs, such as magnetic MEMS switches and MEMS-based varactors.

2.2. Varactor diodes

Varactor diodes are a common research topic because they may be used to modify the voltage levels and, consequently, the capacitance of reconfigurable antennas, which allows performance adjustments in antennas. Costa *et al.* [21] used chip-set varactor diodes to construct a low-profile adjustable scanning antenna in 2008. These diodes were connected to the supporting plane and patches through metalized vias. Five squares joined by five lines comprised the grid in which the patches were placed. A single tiny substrate was used to connect the varactor diodes by metal vias, and their bias circuit design was intricate. Huitema *et al.* [22] revealed an alternative design that had a complex active bias circuit connected for every surface of the varactor diode, enabling independent tuning of the reflection phases for orthogonal incident waves across a wide frequency range.

Liang *et al.* [23] designed a novel circularly polarised active electromagnetic bandgap antenna structure with a frequency and polarisation switching mechanism. This design makes more use of varactor diode switches. A frequency and pattern reconfigurable antenna design using varactor diode-loaded tuning stubs was reported by Zainarry *et al.* [24]. A 10% relative frequency tuning range between 2.15 and 2.38 GHz was the objective of the design optimization. Nevertheless, the antenna's overall frequency adjustment was very low. Yang *et al.* [25] developed a planar frequency-reconfigurable active artificial magnetic conductor (AMC) antenna on an FR-4 substrate. It has a unit cell compound ring nuzzling structure as its metal pattern. A metallic via loaded a single varactor diode into the ground area. Varactor diodes are less desirable for some applications, due to their low dynamic range and non-linear properties. To operate them, specialized bias circuitry is also required. Comparing varactor diode switches to other active elements like PIN diodes, they have constant tuning possibilities and less current flow. Therefore, to enhance their performance, varactor diodes require more effective bias circuits and control techniques [25].

2.3. Mechanical reconfiguration

Tawk *et al.* [26] and Ma *et al.* [27] have demonstrated the mechanical reconfiguration of antennas. The primary antenna radiator can provide various antenna properties without requiring switching processes, active element integration, or biassing systems. One suggestion is to use a liquid metal to accomplish the mechanical reconfiguration. A mechanically reconfigurable antenna is created by Huff *et al.* [28]. A vascular antenna with an equal side strip feed network and parallel strip feed lines was employed to reconfigure the antenna characteristics. The intended performance adjustment is accomplished by physically separating the liquid element's entry locations. Furthermore, there can be issues with long-term performance and dependability when using liquid metal [28].

2.4. Reconfigurable antenna by smart material

A reconfiguration technique utilizing a metal-insulator layer transition on vanadium dioxide was presented by Teeslink *et al.* [29]. A few smart materials were included in this design to change the substrate's characteristics. It is possible to alter the substrate's relative electric permittivity or magnetic permeability by injecting the fluid into the antenna’s resonating structure. Wang *et al.* [30] developed a coaxially-fed patch antenna that makes use of the pumping fluid concept. The working frequency is adjusted using a high-frequency, low-loss transformer oil. Table 1 shows the different methods of reconfiguration techniques. The comparison Varactor diode shows a maximum number of frequency reconfiguration bands compared with other reconfiguration methods. The PIN diode switch performance is analyzed in the upcoming chapters.

Table 1. Comparison of reconfigurable antennas with different switches and reconfiguration methods

Reference	Substrate material	Antenna structure	Size of the antenna (mm)	Reconfiguration method/switch used	Number of frequency bands
Borges *et al.* [12]	Silicon	Patch	3.7×5.2×0.4	RF MEMS	1 with 3 radiation patterns
Vian and Popovic [13]	Liquid crystal polymer	Ring-shaped monopole	40×28×0.1	MEMS	2
Da Costa *et al.* [15]	FR-4	Bow-tie	20×30×1.6	Varactor	4 (2.1-2.9) GHz
Kingsley *et al.* [16]	FR-4	Patch	230×30×43	Varactor	2
Jaafar *et al.* [17]	Roger-Duroid 5870	Metallic rectangular patch	171×171×0.787	Varactor	3 (1.4-1.52) GHz
Kovitz *et al.* [18]	Rogers-Duroid 5880	Rectangular patch	151.5×160.9×1.578	Varactor	3 (2.1-2.4) GHz
Nadh *et al.* [19]	FR-4	Unit cell	30×30×0.8	Varactor	2
Huitema *et al.* [22]	Template using sacrificial Vasctech filament	Dipole with meandering	0.6 mm diameter 0.6 mm height 0.02 mm width (printed by a 3D printer)	Liquid metal	10 MHz – 1 GHz
Liang *et al.* [23]	Sapphire	Bow-tie	10.26×11.77×1.6	Vanadium dioxide	3 (4.5-4.75) GHz
Zainarry *et al.* [24]	Water shed X $C_{11,122}$	Star patch	100.8×100.8×4.8	Transformer oil	1 with 4 radiation patterns

3. PIN DIODES

As mentioned in the above chapters antenna reconfiguration can be accomplished using a variety of methods, such as electrical, optical, mechanical, and intelligent materials. Using PIN diode switches to create reconfigurable antenna structures offers a flexible way to design antennas that can switch between different frequency bands. Based on the above comparison, MEMS switches and smart materials are more expensive and require more manufacturing complexity than the varactor diode and PIN diode switches. Although the internal inductance and capacitance values of PIN diode switches exhibit more stable variation than those of varactor diodes. The following study shows the antenna frequency band variations with the number of diode switches on various antenna structures. This study helps us to reduce the number of switches and increase the reconfiguration frequency band for small antenna structures.

3.1. Frequency reconfigurable antenna with 1-PIN diode

Some antenna has been designed with one PIN diode as shown in Figure 2. A microstrip slot antenna was created by Kulkarni and Sharma [31] for portable wireless DTV players. Through the use of PIN diode switch, the antenna can be operated for both direct TV bands and LTE bands. Jin *et al.* [32] have created a new solid-state device antenna based on a slot for plasma chips. An electromagnetic coupling was used to feed a microstrip line, and a surface-PIN diode was integrated into the antenna's radiation slot. The diode's logic state was switched by applying a forward bias voltage to implement the antenna's reconfigurable radiation slot. The substrate measures ten by ten millimeters. The suggested antenna can switch the frequency between 6.8 and 5.5 GHz [32].

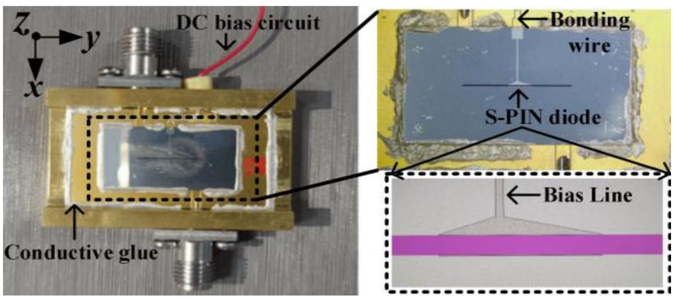

Figure 2. Antenna with one PIN diode

3.2. Frequency reconfigurable antenna with 2-PIN diodes

Figure 3 shows the antenna that uses two PIN diodes, Li *et al.* [33] demonstrated a reconfigurable antenna that could be electronically tuned over the lower ultrawideband frequency range of 5 to 6 GHz. The antenna was operated in two different modes by changing the state of the PIN diodes. Pandit *et al.* [34] developed a compacted frequency reconfigurable multiple input and output port (MIMO) slot antenna for C and S bands microwave sensing applications. The antenna-implanted sensor has a favorable frequency ratio for a wireless local area network and can be electronically shifted between the 3.5 GHz, 5.5 GHz, and 2.4 GHz frequency bands. A C-shaped meander line resonator is used with the radiator to increase the antenna microwave sensing capability from 2.45 GHz and 5.7 GHz respectively. Singh *et al.* [35] used two PIN diodes to create a small antenna for frequency diversity. The antenna could be used simultaneously for 5.35 GHz, 4.94 GHz, and C-band at 6 GHz applications. A flame retardant substrate (FR-4) with dimensions of (25×25) mm^2 and a dielectric constant of 4.4 and a substrate height of 1.6 mm was used for antenna fabrication. The antenna generated four frequency bands with an average gain of 3.91 dBi. A tri-band frequency-reconfigurable antenna for RF radio applications was reported by Bharadwaj *et al.* [36]. The given design includes a glass (wine) shaped slotted patch and a rectangular shaped ring type switchable slot in the ground plane. The antenna geometry was (30×30×0.762) mm^3 in size. The main radiating element and ground plane slots were employed to create multi-band resonances, and switching between these bands was accomplished by strategically placing two PIN diodes on the ground plane [36].

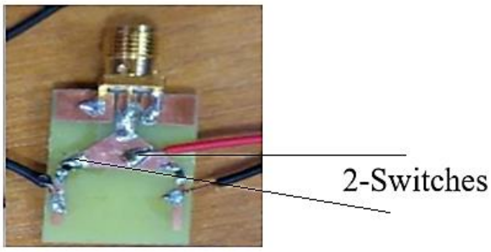

Figure 3. Fabricated antenna with two PIN diodes

Ullah *et al.* [37] reported a hexagon-shaped frequency-switchable antenna fed by a CPW. The antenna can be reconfigured to operate in four distinct frequency bands: Wi-Fi, 5G sub-6 GHz, 3G long term evolution, and WiMAX. An antenna with wide-band, dual-band, and single-band reconfiguration working modes was presented by Awan *et al.* [38]. Initially, a coplanar waveguide-fed triangular monopole antenna with a wide operating frequency range of 4.0 GHz to 7.8 GHz was achieved. The antenna's overall area was (0.27×0.16×0.017) λ_o. It can be used for a variety of wireless applications, including global interoperability for microwave access. The triangular monopole was then coupled to two more stubs using two PIN diodes.

3.3. Frequency reconfigurable antenna with 3-PIN diodes

Figure 4 provides the usage of three PIN diodes in an antenna. Majid *et al.* [39] used three PIN diodes to demonstrate three frequency-reconfigurable antennas. The original antenna was a slot-patch antenna that could switch between six different frequency bands, from 1.7 GHz to 3.5 GHz, coupled to a reflector at the back. The antenna consists of a microstrip patch antenna placed on the ground plane and a microstrip slot antenna. For the slot, there were three different frequency states. While the same slot antenna generated three more frequency bands with a bidirectional radiation pattern, the microstrip patch antenna produced three unique frequency bands with a directional pattern. The reflector located behind the antenna maintained the direction of the emission patterns in all frequency bands. A wideband switchable Yagi antenna array that could change the operational band by modifying the states of PIN diode switches was created by Nan *et al.* [40]. A 4×4 S-band array can be converted to a 2×2 L-band array with a fractional bandwidth of 66.7%/66.7% by using the separate L- and S-bands. At each reconfigurable mode, the distance between adjacent antenna elements was less than 0.72 λ_o [40].

3.4. Frequency reconfigurable antenna with 4-PIN diodes

Figure 5 shows how efficiently utilized four PIN diodes in an antenna. Haider *et al.* [41] presented a multiband phased array element. A pin-fed, planar antenna element capable of dual L/S band operation was introduced by them. Large scanning angles in the L and S frequency bands were possible because of their small size. Rayno and Sharma [42] reported the use of RF PIN diodes in the frequency-reconfigurable spirograph planar monopole antenna operating in the ultra-high frequency (UHF) band. The radiating element operated in three observed frequency ranges. It covered frequencies of 1.2 to 2.50 GHz with a 69.5%

impedance bandwidth, 1.07 to 2.92 GHz with a 92.7% impedance bandwidth, and 2.17 to 3.36 GHz with a 43% impedance bandwidth. The frequency range of 1.07-3.36 GHz was continually covered by the antenna.

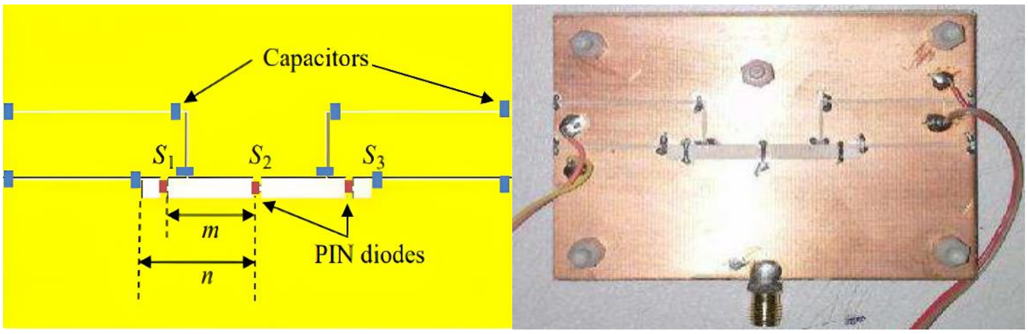

Figure 4. Three PIN diode usage in antennas

Sun *et al.* [43] introduced a novel reconfigurable antenna for multiband frequencies. The architecture allowed for dual frequency changes in the S-band and only one frequency band in the L-band by electronic modification. A broadband reconfigurable orthogonal network enabled the sawtooth patches and annular through a T-shaped slot in the ground plane. Nie *et al.* [44] presented a frequency and polarisation reconfigurable antenna with harmonic reduction for 5G applications. Two feeding structures with filtering divisions arranged in parallel, two pairs of frequency-reconfigurable dipole antennas polarised at 45°, and an AMC surface were all part of the proposed arrangement. The U-shaped structure was added to improve the effectiveness of impedance matching in two frequency bands. Jin *et al.* [45] have created a new differential reconfigurable antenna using dipole elements. The antenna's geometry is composed of two vertical arms, four PIN diodes, and the feeding structure. By flipping the PIN diodes "ON" and "OFF," the antenna could resonate in two modes, allowing operation centered at the resonant frequencies of 3.5 GHz and 5.5 GHz, respectively. Despite belonging to distinct resonant modes, the two states' effective radiation components were identical, and the mode switching structure did not contribute to the distant field [45].

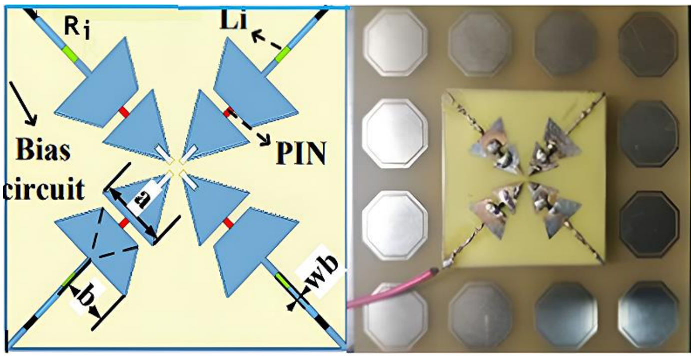

Figure 5. Antenna with four PIN diode switches

3.5. Frequency reconfigurable antenna with 6-PIN diodes

Qin *et al.* [46] showed a planar quasi-yagi antenna with a folded dipole driver element for frequency switching., The antenna was operated in the 5.8 GHz or 7.5 GHz band with independent tuning provided by six distinct PIN diodes. Boukarkar *et al.* [47] created a frequency-reconfigurable antenna with 36 switching states and six PIN high-frequency diodes. The frequency range of this antenna is 2.4 to 3.4 GHz. Figure 6 shows an example of six PIN diode antenna.

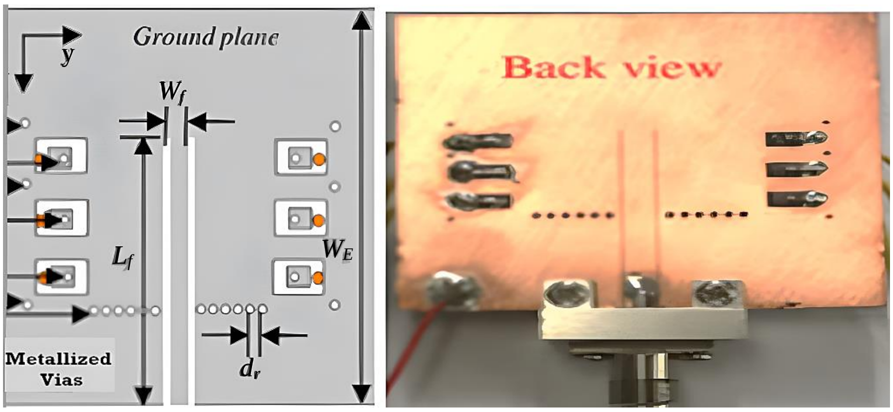

Figure 6. Antenna with six PIN diode switches

3.6. Frequency reconfigurable antenna with more than 6 PIN diodes

Shirazi *et al.* [48] has designed an antenna for frequency diversity in the L-band and C-band. The L-band circular slot antenna aperture was converted to a 2×2 C-band slot-ring antenna array by adjusting the states of 16 PIN diode switches. The antenna worked at frequencies of 1.76 and 5.71 GHz with fractional bandwidths of 8.6% and 11.5% in the L-band and C-band working modes. Table 2 shows the comparison of the antenna with multiple PIN diode switches, their frequency bands, structure, and size of the antenna.

Table 2. Comparison of electrically controlled frequency reconfigurable antennas

Reference	Substrate material	Antenna structure	Size of the antenna (mm)	Number of PIN diode switches	Number of frequency bands
Yang *et al.* [25]	FR-4	Microstrip slot	150×150×0.8	1	2
Tawk *et al.* [26]	Silicon	Chip antenna-based plane slot	20×10×0.35	1	2
Ma *et al.* [27]	Roger	Bow-tie antenna	50×45×1	2	6
Huff *et al.* [28]	FR-4	Slot with patch	30×20×0.8	2	3
Teeslink *et al.* [29]	FR-4	π-shaped slot	25×25×1.6	2	4
Wang *et al.* [30]	FR-4	Triangular patch	30×30×0.762	2	3
Kulkarni and Sharma [31]	FR-4	Hexagonal CPW structure	37×35×1.6	2	4
Jin *et al.* [32]	FR-4	Quarter wave monopole antenna	25×15×1.6	2	2
Li *et al.* [33]	Taconic RF-35	Slot patch	36×18.3×3.04	3	6
Pandit *et al.* [34]	FR-4	Monopole	22×13×0.8	3	8
Singh *et al.* [36]	Rogers	Spirograph planner monopole	69.3×13.3×1.8	4	3
Ullah *et al.* [37]	Rogers	Anular ring and sawtooth patch	124×124×10	4	3
Awan *et al.* [38]	FR-4	U-shaped structure	72×72×0.5	4	2
Majid *et al.* [39]	FR-4	Two vertical dipoles	50×50×1.6	4	2
Nan *et al.* [40]	FR-4	Bow tie	50×45×1	6	3
Haider *et al.* [41]	F4B	Rectangular patch	40×40×1.96	6	36 states

4. CONCLUSION

This work presents a comprehensive review of reconfigurable antennas, categorizing the many types of reconfigurable antennas with single and multiple reconfiguration properties. Several design strategies are thoroughly explained with examples, and the basic characteristics of various types of reconfigurable antennas are outlined. This review makes it evident that the usage of PIN diode switches in reconfigurable antennas is very effective and stable compared with other switching elements, especially varactor diodes. This study is useful for making a small-size frequency reconfigurable antenna with less number of PIN diode switches and more frequency bands for small electronic devices.

FUNDING INFORMATION

This research work was funded by "Visvesvaraya Ph.D. Scheme for Electronics and IT" Ministry of Electronics and Information Technology, the Government of India (unique awardee no is MEITY-Ph.D.-3061).

AUTHOR CONTRIBUTIONS STATEMENT

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C : **C**onceptualization
M : **M**ethodology
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R : **R**esources
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O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
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DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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