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Multiband reconfigurable antennas for future wireless communication systems

Kusum Dalal*, Tejbir Singh & Pawan Kumar Singh

Electronics & Communication Engineering Department, SRM University, Sonipat, Haryana 131 023, India

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Evolution in wireless technology has resulted in remarkable capabilities, but ever increasing user demand and limited bandwidth spectrum has always instigated the researchers to think of new techniques that can improve network efficiency in terms of size, power and bandwidth consumption. Antenna designing is one of the key factors in achieving this goal and as a result plethora of research work has been conducted in past for crafting sustainable reconfigurable multiband antennas for different wireless services. The concept of combining the wideband-narrowband reconfiguration functionality into a single antenna has created an effective solution for optimizing antenna size and enhancing flexibility in antenna designing. Moreover; this combination has offered the advantage of pre-filtering, which has helped in mitigating the level of interference at the receiver end and has provided an edge over the fixed or non-reconfigurable transceivers. This paper has presented a detailed outlook about reconfigurable antennas and the various techniques involved in attaining reconfigurability in antenna design. The review has been supported by some antenna designs and simulation results that have provided an insight into reconfiguration features. Some new technologies employed in antenna design have also been briefly presented.

Keywords: Wideband antennas, Multiband antennas, Reconfiguration techniques for antennas, Switching devices, Radiation pattern, Feeding structures

1 Introduction

The antenna has been in use for transmitting and receiving radio signals for more than the last 100 years, and still a significant scope exists for further research in this area. Hein-rich Hertz in 1887 devised some experiments in order to test some hypothesis of J.C. Maxwell, as a consequence of which the first antenna came to the limelight. A flat dipole is used by Hertz as a radiating antenna and for reception purpose a single turn loop antenna is utilized in his experimental setup. Later the antenna technology was dedicated to the use of wires for making radiating structures that were supported by wooden poles and this was continued for almost fifty years or so. The initial time antennas were characterized by narrow band features in which array synthesis principles were adopted to enhance the directivity of resulting radiation patterns. H. Yagi and S. Uda in 1926 proposed Yagi-Uda antenna that offered high directivity and found many applications in communication industry.

In traditional fixed RF/microwave wireless communication systems operating on predefined frequency bands, the antennas and filters acts as the main components for the front-end circuitry. Bandwidth, radiation pattern, gain, reflection coefficients and polarization are some of the parameters that define these circuit components. In recently developed technologies such as satellite, radar, unmanned airborne vehicles, microwave imaging, cognitive radio system there is an utmost requirement for flexibility that can aid in accommodating variable number of wireless standards such as: Bluetooth, UWB, WiMAX, Wi-Fi, WLAN, UMTS etc. According to Jackson *et al.*[1] the antenna, as a front-end circuit in RF/microwave system, is a very useful device for selecting or rejecting the signals at various frequencies in various modern wireless application systems. Due to the limitation of the frequency spectrum, designing of RF/microwave reconfigurable antenna with linear phase, low insertion loss, lightweight, small size, high selectivity and lower cost, pose a continuous challenge to the researchers and developers[1-2].

The reconfiguration attribute can be claimed as the capability of an individual radiator system to vary its operating characteristics by making changes in its electrical, mechanical, or material characteristics. Reconfigurable antennas have potential of altering operating frequencies, radiation pattern, polarization

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*Corresponding author (E-mail: kusumdalal@gmail.com)

and impedance bandwidth independently as per the desired application. The types of reconfigurations possible are illustrated in Fig. 1.

Frequency reconfiguration eliminates the need for having multiple antennas for providing different services operating on different frequencies and thereby helps in reducing circuit complexity and cost. The frequency reconfigurable antenna has been categorized into two types: one which follows continuous frequency tuning that permits smooth transformations among operating frequencies without noticeable hiccups; the second type follows switched tuning, in which, the antennas work in distinct frequency bands on the basis of switching mechanism. In general, both the categories share a common theory of reconfigurable operation[3-6]. Over the years, large numbers of reconfigurable antennas have been designed that showed switching capabilities among two particular narrowband frequencies[7-8].

The compact wideband-narrowband reconfigurable antenna is extremely useful in terms of its capability to operate on multiband frequencies. This approach has significant advantages over fixed or non-reconfigurable transceivers[9-11], by offering pre-filtering feature. The multiband reconfigurable antenna is a viable solution for the challenges posed in antenna designing such as accommodating ever increasing number of users in limited frequency spectrum[12]. In applications involving surveillance or tracking, pattern reconfiguration can be used for producing desired radiation patterns with variable directivity without introducing any shift in frequency. Diverse radiation patterns also help in mitigating problems resulting from random noise sources and electronic jammers; thereby improving security, reliability and energy efficiency. Polarization reconfiguration can be achieved by initiating switching among horizontal and vertical linear polarizations or among right-hand circular polarization (RHCP) and left-hand circular polarization (LHCP) and among elliptical polarizations[13]. Hybrid reconfiguration employs combination of above mentioned reconfiguration types to enhance the network performance for desired service. A detailed review about the reconfiguration techniques (that helps in attaining the goal of reconfiguration in terms of frequency, pattern, polarization or their combination) is provided in section 2. The use of some emerging technologies in antenna design is briefed in section 3. Section 4 highlights the future prospects of reconfigurable antennas and section 5 present summary of the paper.

2 Classifications of reconfiguration techniques

Various techniques have been developed over the years to introduce reconfiguration capabilities in an antenna system as reflected in Fig. 2 and Fig. 3. One such technique exploits electronic switches (PIN diodes, Varactor diodes, RF-MEMS switches etc.) for modifying the length of radiating structure.

Antennas that employ photoconductive switches for reconfiguration purpose are called optically reconfigured antennas and in those antennas where reconfiguration is achieved by structural variation are called mechanically reconfigurable antennas. Special categories of materials (having ferroelectric and ferromagnetic properties) like liquid crystals and ferrites are also sometimes used to create reconfigurability in antenna design and such type of reconfiguration is called as material reconfiguration. The selection of technique for introducing reconfigurability depends on application. This section provides an exhaustive review of various reconfigurable techniques used in antenna design.

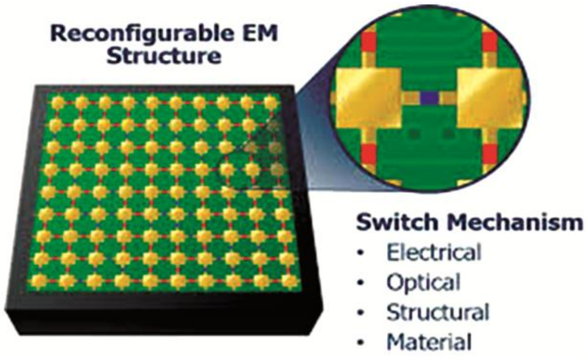


Fig. 2 — Reconfiguration mechanism[14].

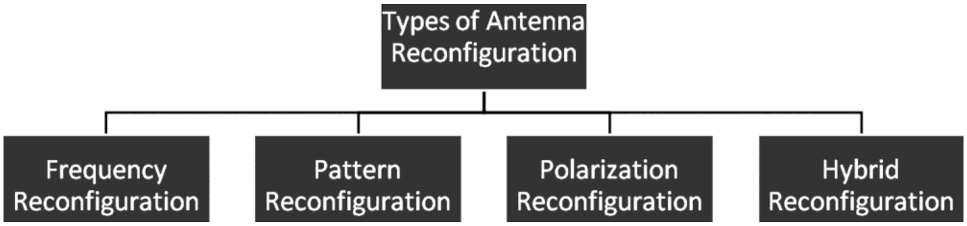


Fig. 1 — Various types of reconfigurations available for antenna design.

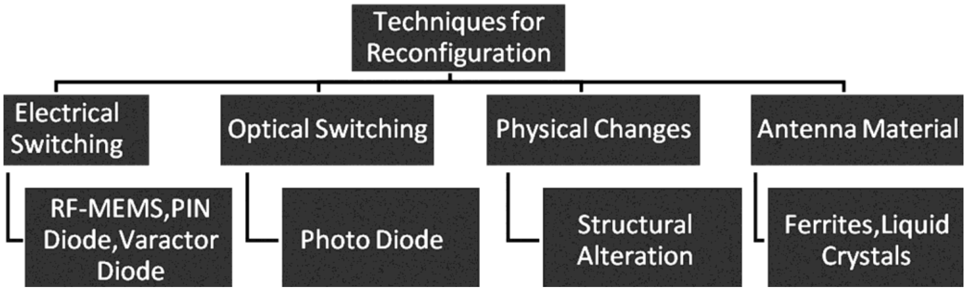


Fig. 3 — Techniques used for antenna reconfiguration.

Table 1 — Performance comparison of different electronic switches[13].

Switch Type	Merits	Demerits
PIN Diode	• Very reliable • Extremely low-cost • Work at tenths of MHz to over 100 GHz • Low losses	• High tuning speed • Large DC bias voltage • Bias tees and blocking capacitors limit usable bandwidth in the UWB applications
Varactor Diode	• Limited current flow • Uninterrupted tuning • Unproblematic integration in antenna design	• Nonlinearity • Limited dynamic range • Complex bias circuitry
RF-MEMS	• Suitable for high frequencies • Very high isolation • Linearity • Wide impedance bandwidth • Low power consumption • Low noise figure	• High actuation voltage • Sluggish switching • High packaging cost
GaAs FET	• Work at DC to mm-wave frequencies • No bias tee and blocking capacitors are needed to separate DC bias from RF signal • Switching speed higher for GaAs FET (< 10 ns) • Low cost	• Isolation degrades at higher frequencies • High insertion loss at high frequencies • High losses • Noise problems • Non-linear at high frequencies.

2.1 Reconfiguration technique using electrical switching

In such type of reconfiguration technique, the electrical length of the antenna structure is customized by utilizing electronic switches like Radio Frequency Micro-Electro Mechanical System (RF-MEMS), PIN diode, Varactor diode, GaAs FET switch etc. The change in electrical length results in change of frequency, radiation pattern and polarization thereby, introducing reconfigurability in system. This technique offers high efficiency and reliability and can be easily integrated with microwave circuitry. Each electronic switch used in this technique has its own set of advantages and disadvantages as mentioned in Table 1.

2.2.1 Reconfiguration using PIN diode

Due to various merits offered by PIN diodes as mentioned in Table 1, they are widely used by researchers for designing frequency, pattern or polarization reconfigurable antennas. Some of the reputed works employing PIN Diodes are enlisted in this section.

A compact antenna design is presented by Iqbal *et al.* [15], having 23 mm × 31 mm × 1.6 mm dimensions and frequency and pattern reconfigurability features. The design comprise of three PIN Diode switches where one switch (Switch 1) is used for controlling operating frequency and other two switches (Switch 2 and 3) are used for beam switching. PIN Diode in its ON/OFF states is represented in Fig. 4 in form of equivalent RL and RLC circuits respectively along with its biasing circuit. As value of R is reduced in RL circuit, more current flows to the radiating structure and increased value of RC in RLC circuit inhibits current flow to the radiating structure. For simplification, RL circuit configuration is adopted for simulation in this paper. Operating frequency lies in

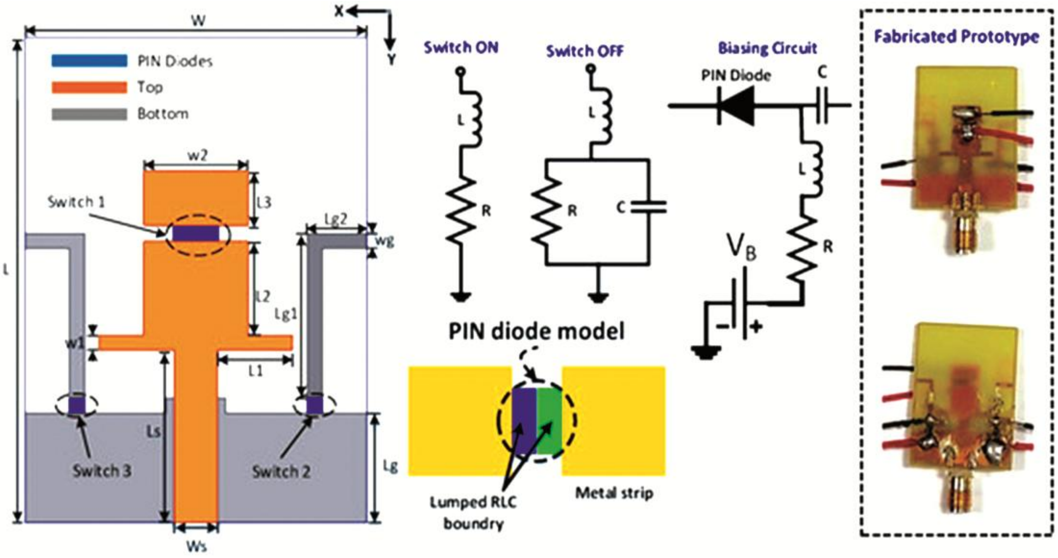


Fig. 4 — Proposed antenna design, biasing circuit and antenna prototype[15].

range of 2.5–4.2 GHz and 6.2–7.4 GHz bands. Gain values of 3.7 dBi and above are obtained for all switch combinations.

The length of the radiating element is given as:

$$L_{f_r} = \frac{c}{4 f_r \sqrt{\epsilon_{eff}}} \quad \dots (1)$$

$$\mathcal{E}_{eff} = \frac{\mathcal{E}_r+1}{2} + \frac{\mathcal{E}_r-1}{2}\left[\frac{1}{(1+12\frac{h}{W})^{\frac{1}{2}}}\right] \quad \dots (2)$$

where, λ_g is the guide wavelength, c is the speed of light in a vacuum, w is the substrate width, ϵ_{eff} is the effective dielectric constant and h is substrate thickness. Diverse stubs are attached with the ground plane for observing the antenna's S-parameter response for all switching states. Antenna efficiency and gain performance of designed antenna are shown in Fig. 5.

Another magnificent work employing PIN diodes was presented by Rajeev *et al.*[16]. A low profile quadrilateral patch antenna was designed having triangular slot and feedline on either side of FR4 substrate. The proposed antenna offered 12 different frequency bands in 2.46-3.90 GHz range using six PIN diodes. The parasitic effects in circuit were reduced by incorporating the biasing circuit into ground plane as represented in Fig. 6. The complexity of biasing circuit was reduced by using small number of PIN diodes and also by utilizing triangular slot structure as illustrated in Fig. 7. The designed antenna has appreciable gain and radiation efficiency performance over frequency bands of interest as portrayed in Fig. 8.

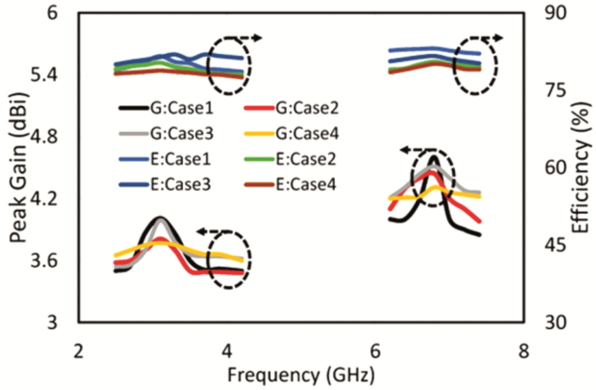


Fig. 5 — Peak gain and efficiency performance for all switching cases[15].

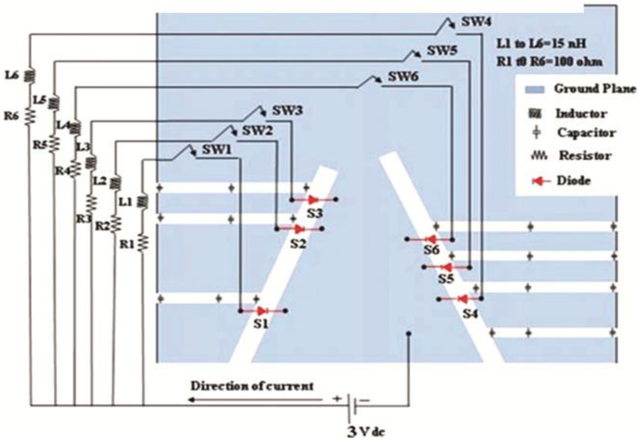


Fig. 6 — Biasing network for proposed design[16].

In order to improve frequency reconfigurability range along with respectable gains and low profile, Anilkumar *et al.*[17] proposed a frequency reconfigurable antenna that operates in S-band of 2-4 GHz range and C-band that is in range of 4-8 GHz, having circular ring- shaped radiating patch attached to a pair of connected circle using two PIN Diodes as shown in Fig. 9. Such antenna has showed application for vehicular communication in an Internet of Things (Vehicles) environment. The FR4 substrate is used for antenna fabrication having dimensions 40×30×1.6 mm^3. Peak gain of more than 1.3 dB in S-band and more than 3.5 dB in C-band were obtained. Reflection coefficient performances for various diode state combinations are shown in Fig. 10.

A novel antenna design was presented by Ye *et al*.[18] which showed pattern and frequency reconfiguration characteristics. The proposed antenna was a back-to-back F (BTBF) semicircular antenna with centre feed. Four PIN diodes were connected with four BTBF elements to produce three operating states. Two states operate in frequency range of 2.51 GHz to 2.76 GHz and one state operates in 3.01 GHz-3.23 GHz range. Different radiation patterns were achieved for all three states as noticed from Fig. 11(b). Also as can be seen from Fig. 11(a), the semicircular BTBF antenna was obtained by half-cutting a circular BTBF antenna and due to symmetry the native radiation characteristics of circular BTBF were retained with appreciable reduction in structure size and cost.

A compact, efficient and electronically tunable antenna has been designed and presented by Peroulis *et al*.[19]. The proposed fundamental structure has a single-fed slot resonator. The reconfiguration feature is provided using four PIN diodes such that the radiating structure can be tuned to an overall frequency range of 540MHz to 950 MHz. A better return loss (-20 dB) has been observed which proves the best impedance matching for the operating frequency band along with measured gain of 11 dBi, which reflect an antenna efficiency of 47%.

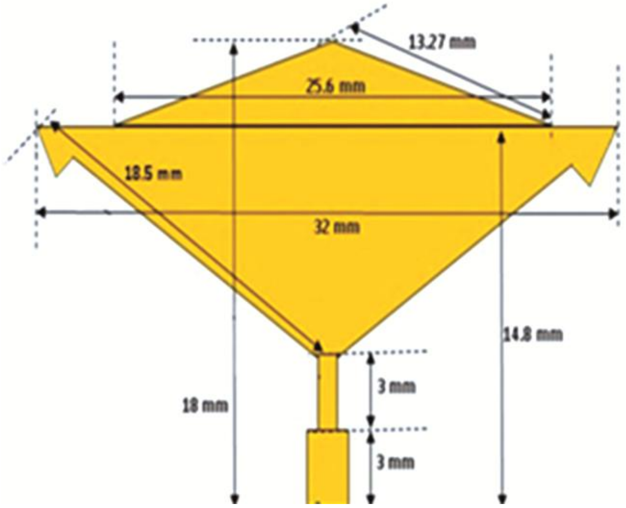


Fig. 7 — Proposed antenna front view[16].

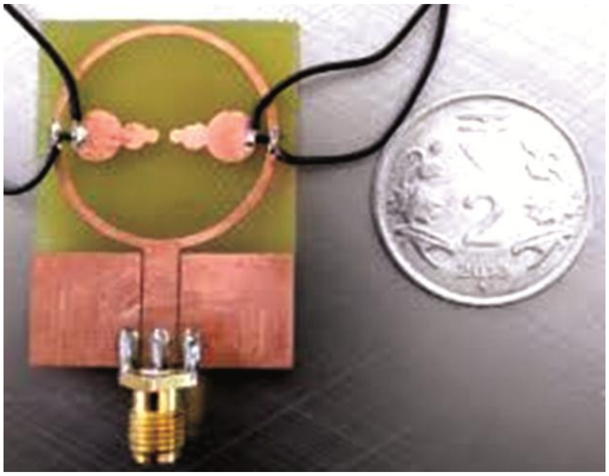


Fig. 9 — Prototype of proposed circular ring- shaped radiating patch antenna[17].

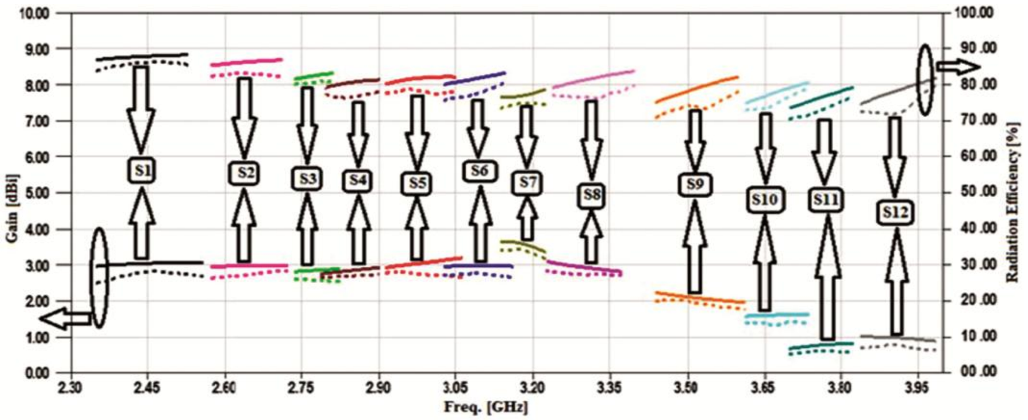


Fig. 8 — Measured and simulated results for gain and radiation efficiency[16].

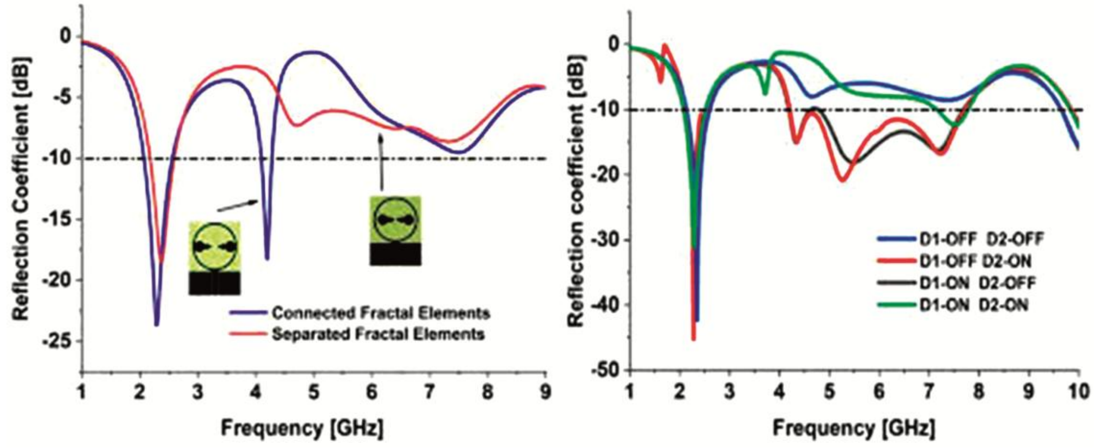


Fig. 10 — Reflection Coefficient Performance for various diode state combinations[17].

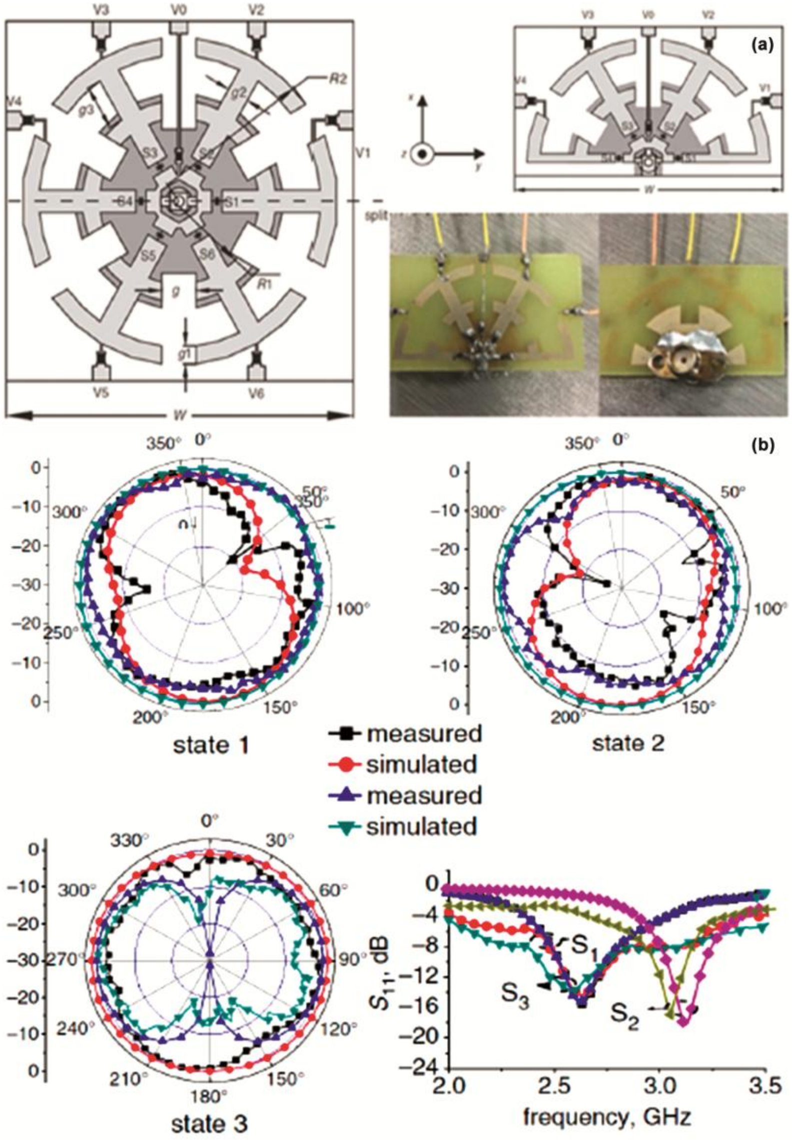


Fig. 11 — (a) BTBF antenna design and (b) Performance characteristics of antenna[18].

A novel antenna design was presented by Lugo *et al.*[20] which offered frequency reconfigurable feature and used a band-pass filter comprising of six-states as means of providing the reconfiguration. The proposed design claimed a bandwidth having average tunable passband ratio of 1.73:1 and showed filter responses at centre frequencies of 9 GHz, 10 GHz, and 11 GHz. The structure used PIN diodes as switching elements. The gain achieved for tones (separated by 1MHz around f_0) was greater than 48 dBm and the insertion loss due to filters lies between 1.74 and 1.92 dB. A patch antenna design showing frequency reconfigurability using PIN diodes has been presented by Piazza *et al.*[21]. The above mentioned design is suitable for multi-standard personal communication systems. The proposed design is executed using two different configuration showing dual-band behaviour: the first configuration have two slots cut in patch antenna connected by switches, the second configuration have a rectangular patch with a switchable parasitic element. In the proposed design on average 10% (i.e. 10dB) improvement in SNR and 8% (i.e. 20dB) improvement in SNR with respect to a fixed antenna configuration have been achieved. A patch antenna design having slots in the ground plane is presented by Wang *et al.*[22]. PIN diode acts as switching element for providing dual-frequency operation. Slots introduced in the ground plane increases the electrical length and thereby reduce the system size by 53%.

PIN diode in its OFF state results an operating frequency in K-PCS (1.85 GHz) band with a bandwidth of 60 MHz. A microstrip patch antenna with compact size and having polarization reconfiguration feature has been proposed by Qin *et al*.[23]. U-slot has been cut in this structure and the effective length of U-slot arms has been made variable by using PIN diodes that result in polarization reconfiguration. Two PIN diodes are responsible for introducing two circular polarizations in this design. The designed antenna operates over entire WLAN band from 5.725 GHz to 5.85 GHz and has measured bandwidth of 5.7 GHz to 5.86 GHz with axial ratio of 3 dB.

2.2.2 Reconfiguration using Varactor Diode

Some researchers have exploited the merits of Varactor diodes such as continuous and hassle-free tuning and ease of integration for designing proficient reconfigurable antenna designs.

To enhance the tuning capabilities of reconfigurable antennas, a novel small size patch antenna using Varactor diodes was designed by Cai *et al.*[24] which depicts frequency reconfigurability with high gain. The designed structure comprised of a grid-slotted patch which was loaded with Varactor diode switches that can be tuned for obtaining a unidirectional radiation pattern. By altering the bias voltages of Varactor diodes a continuous variable frequency of operation was obtained in the frequency range of 2.45 GHz-3.55 GHz. Experimental results displayed a rise in gain from 4.25 dBi to 8.49 dBi as frequency is raised from 2.45 GHz to 3.55 GHz. Another work that reflects the antenna reduction feature was proposed by Zhao *et al.*[25]. In this study a novel slotted-patch antenna with MIMO (Multiple-Input Multiple-Output) characteristics is designed. The proposed antenna has microstrip feedline and provides for dual-band frequency reconfiguration feature. A dual-purpose hexagonal-shaped defected ground structure (DGS) is utilized in the proposed design for achieving antenna dimensions of $120 \times 60 \times 1.6$ mm^3. FR4 is used as substrate material in this work and Varactor diodes are used for providing frequency reconfiguration. The designed antenna showcases the reconfigurability property in the range of 1.3 GHz to 2.6 GHz and shows isolation above 12 dB for complete frequency band.

In some cases a combination of both PIN diodes and Varactor diodes are used for enhancing the antenna performances.

Qin *etal*.[26] reported a novel monopole microstrip antenna, which is in form of circular disc and shows both wideband and narrowband reconfigurability features. The proposed antenna utilizes a BPF (Band Pass Filter) in the path of feed-line to introduce the reconfiguration. A PIN Diode was used to reconfigure the impedance bandwidth from wideband to narrowband. Varactor diodes were used for tuning the narrowband states to achieve antenna response from 3.9 GHz to 4.82 GHz frequency range.

Tang *et al.*[27] presented a frequency reconfigurable filtenna for cognitive radio applications. It offers wideband sensing services in 2.35-4.98 GHz band with narrowband services in 3.05-4.39 GHz range. To accomplish switching between wideband and narrowband services PIN Diodes are used and to continuously change frequencies in narrowband range Varactor diodes are utilized. The structure of filtenna have size of $0.235\ \lambda_L \times 0.392\ \lambda_L$($\lambda_L$corresponds to the lower bound of its operational frequencies) and its reflection coefficient performance is shown in Fig. 12.

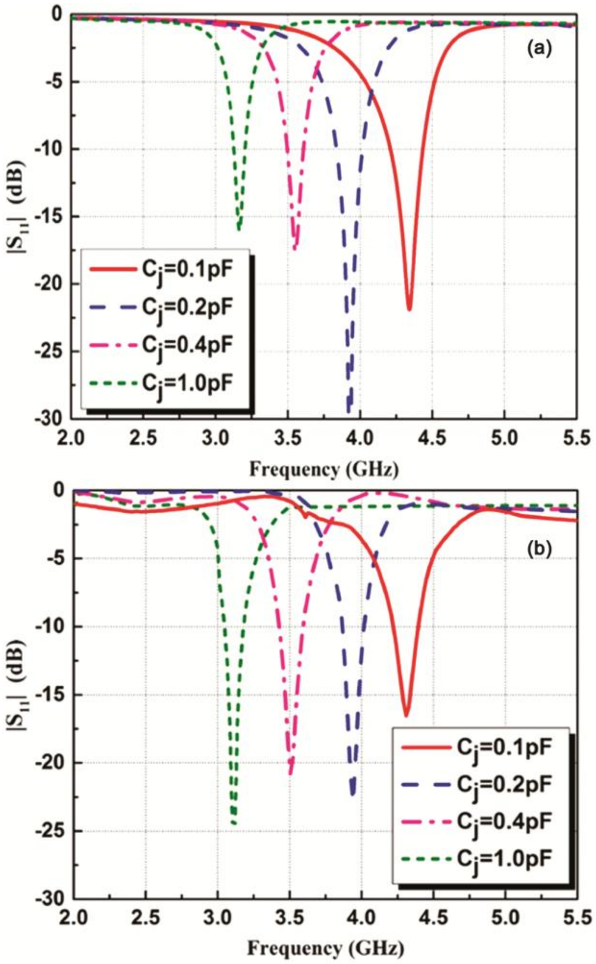


Fig. 12 — S-parameter (a) simulated results and (b) measured results[27].

Another work related to multiband antenna operation was presented by Zhao *et al.*[28]. The designed antenna exhibited both multi-mode and ultra wideband reconfigurable characteristics along with MIMO feature. In this study, two printed monopole antenna elements were used that are modified into triangular-shape and were used with amalgamation of PIN and Varactor diode switches to provide reconfigurability. The low profile antenna has dimensions of 120 × 60× 1.5 mm^3 with minimum 12.5 dB isolation.

2.2.3 Reconfiguration using RF-MEMS switch

Contemporary era has witnessed a sudden inclination towards RF-MEMS (Radio Electro Mechanical System) actuators due to their significant advantages[29] such as high switching speeds, low insertion loss and low power requirements. They can operate on the principle of electrostatic, electromechanical, thermal or piezoelectric. Also, RF-MEMS switch can be used in any of the following configurations:

(i) Shunt capacitive
(ii) Series capacitive
(iii) Shunt resistive
(iv) Series resistive

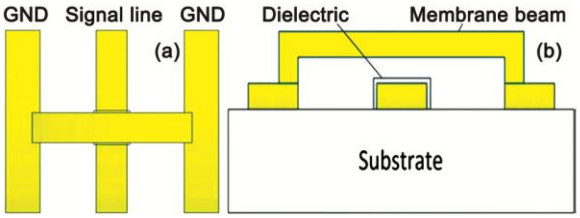


Fig. 13 — Schematic of a shunt capacitive type RF MEMS switch (a) top view and (b) section view [30].

Among these Shunt capacitive is widely used configuration and its schematic is shown in Fig. 13.

The actuation voltage needed to accomplish the switching function in this configuration is given as:

$$V_{\text{PI}} = \sqrt{\frac{8K_{eff}g_0^3}{27A\varepsilon_0}} \qquad \dots (3)$$

where, K_{eff} is the effective spring constant of the bridge, g_0 is the in-between gap of membrane and actuation pad and A is actuation pad area.

$$K_{eff} = 4Ew\left(\frac{t}{l}\right)^3 \qquad \dots (4)$$

$$K_{eff} = K' + K'' \qquad \dots (5)$$

$$K' = 32Ew\left(\frac{t}{l}\right)^3 \left(\frac{27}{49}\right) \qquad \dots (6)$$

$$K'' = 8\sigma\sigma_0(1-v)w\left(\frac{t}{l}\right)\left(\frac{3}{5}\right) \qquad \dots (7)$$

where, K_{eff} is the effective spring constant of the metal bridge, *K'* is the stiffness caused by the restoration force of the metal bridge, and *K''* is the stiffness resulting from the mean residual stress of the metal bridge, *E* and *t* are the Young's Modulus and membrane thickness respectively; *v*, *l* and *w* are Poisson's ratio, total length and width of the gold (metal) beam respectively[31].

A plenty of research work has been done in this field and still there are research gaps that needs to be worked upon such as reducing the actuation voltage. In this section some relevant work in the area is presented.

Dey*et al.*[32] presented a RF-MEMS based lateral switching network that is electrostatically actuated for broadband application (1-30GHz) as shown in Fig. 14. The return loss (>21 dB), insertion loss

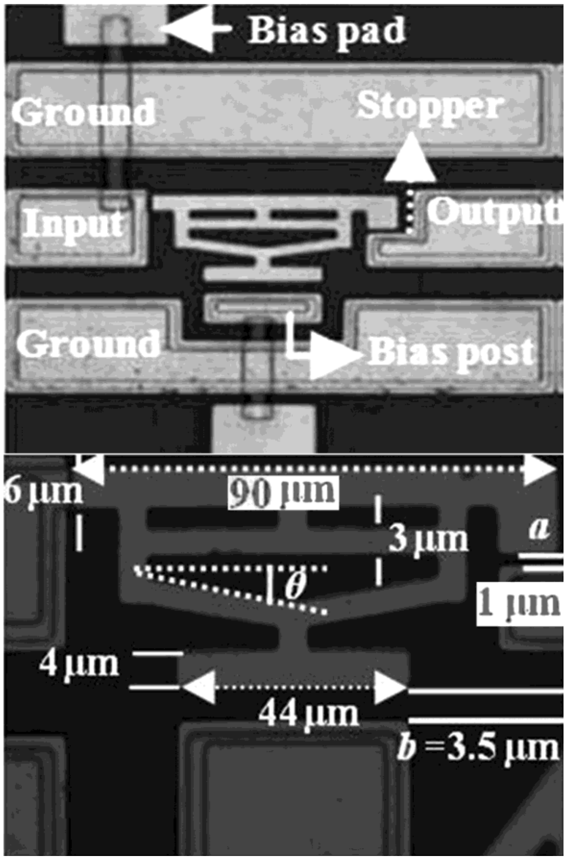


Fig. 14 — SEM image of the fabricated lateral MEMS switch where all optimized structural parameters are marked[32].

(<0.67 dB) and isolation (>31 dB) were achieved in this work at 3.5 GHz as depicted in Fig. 15. Maximum fabricated switch (SP6T) area was ~0.7mm^2 including bias lines and pads. If the total length (L) of the cantilever beam is divided in $l1$, $l2$, and $l3$, then total electrostatic force can be defined as:

$$F_e = \int_{l_1}^{l_1+l_2} \frac{\varepsilon_0 t V a dx}{2\,(b-a)^2} \qquad \ldots (8)$$

where, ε_0 is the absolute permittivity, t the thickness, and V_a the actuation bias voltage.

In another work a novel Vee-antenna structure has been proposed by Chiao*et al.*[33] with pattern reconfiguration feature. This design employs Radio Frequency Micro-Electro Mechanical System (RF-MEMS) switch to produce reconfigurable pattern. At 17.5 GHz operating frequency this design provides a maximum directivity of 5.6 dB with optimal angel of 82.5^0 and a beamwidth of 37.9^0 with antenna directivity of 3 dB. In another work a antenna design is reported by Cetiner*et al.*[34] that have a microstrip feedline and a RF-MEMS actuator (having single and double-arm cantilever type DC-contact) that is used as a switching element for introducing frequency reconfiguration feature. In this work two frequency reconfigurable modes of operation have been observed, one at high frequency f_h = 5.2 GHz and one at low frequency f_l = 2.4 GHz with the

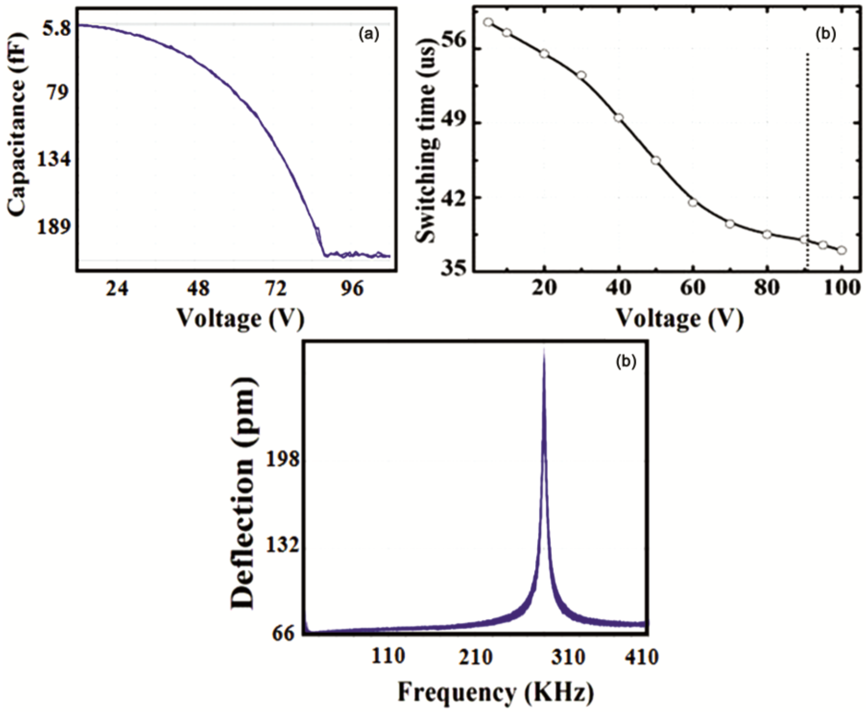


Fig. 15 — Measured (a) actuation voltage, (b) switching time and (c) mechanical resonance frequency of the single lateral MEMS switch[32].

frequency bandwidths of 100 MHz and 650 MHz respectively.

Guo *et al.*[35] described the behavior of a triangular shaped Sierpinski fractal antenna having multiband. A comparison was also drawn among proposed antenna and bow-tie antenna which is inherently single band. The numerical and empirical results have shown the similar fractal property transfer in the form of electromagnetic behavior. Also for controlling the antenna components RF-MEMS switches were used. Kingsley *et al.*[36] proposed a Sierpinski multiband fractal antenna design in which RF-MEMS switches were used in set of three for activating and deactivating the antenna as per applied voltage conditions. Using such method of feeding the signal directly using electrostatic action present in RF-MEMS switches eliminated the requirement of individual bias lines for switching by compromising the different bias voltages applied.

Some correlated work of RF-MEMS switches with microstrip antenna has been judiciously carried out in a work presented by Zhou *et al.*[37]. A low-voltage RF-MEMS switch contact has been designed to drive reconfigurability using a rectangular microstrip antenna coil, which provides a frequency tuning capability. In order to optimize the electromechanical design, micro-fabrication was done using commercial poly-MUMPS and results were derived using RF simulations. The designed RF-MEMS based frequency tunable microstrip coil antenna has been investigated using the electromagnetic simulation tool, which is based on full wave analysis.

In a work done by Pourziad *et al.*[38] a multi-state RF-MEMS switch was used in association with microstrip antennas as depicted in Fig. 16. The main feature of proposed switch design is its simple DC biasing mechanism and its amalgamation in antenna structure. Apart from this, the proposed switch operates in seven different states. In this work, three designed RF-MEMS switches are used on a U-slotted antenna for providing the pattern reconfigurable property in various state combinations.

2.2.4 Reconfiguration using miscellaneous electronic devices

Sometimes capacitors or semiconductor diodes such Schottky diode or GaAs Field Effect Transistor (FET) switch can also be used for providing reconfigurability feature. In this section some of the concerned work is reproduced.

The antenna, shown in Fig. 17, is a polarization diversity antenna proposed by Saghati *et al.*[39] having wideband (UWB)/narrowband switching capability. The proposed structure consists of two uniplanar ports with two open annular slots which are excited orthogonally through identical coplanar waveguide feed line from the center, to result in polarization reconfiguration feature in UWB band that extend from 2.9 GHz to 11 GHz range and in narrowband

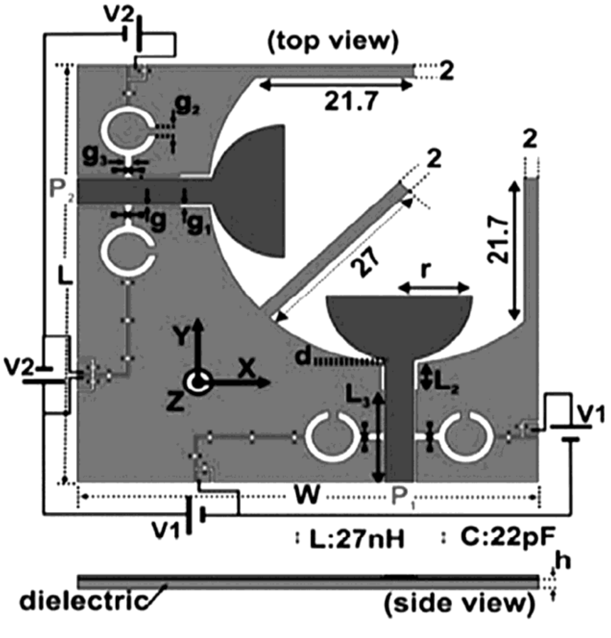
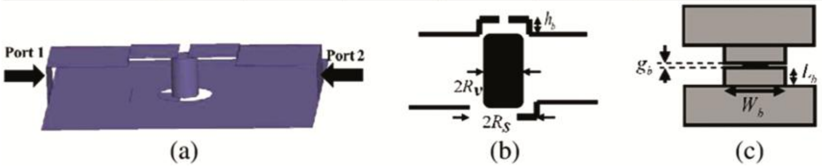


Fig. 17 — Polarization diversity antenna[39].

State	1	2	3	4	5	6	7
T. Beam 1	Up	Down	Down	Down	Up	Up	Down
T. Beam 2	Up	Up	Down	Down	Down	Down	Up
B. Beam	Up	Up	Up	Down	Up	Down	Down
Schematic diagram							



(a) (b) (c)

Fig. 16 — Switch states (1 to 7) and the simulation model of the switch: (a) 3-D view, (b) side view and (c) top view[38].

that exist from 4.9 GHz to 5.5 GHz range. A slot resonator-based filter was used to achieve UWB/NB switching. The length of both the resonators is $l_g/4$. The Schottky Diode has been used for electronic control at the entrance of the slot. The gain values for proposed design have variation from 3.2dBi to 6.5dBi for UWB and from 4.5dB to 5.1dB for narrowband.

A microstrip antenna, having polarization and frequency reconfigurability feature has been proposed by Nishamol *et al.*[40]. X-slot is introduced in the antenna structure for producing dual band operation and the effective length of slot is varied by incorporating a capacitor at the central position of the slot. The designed antenna can be tuned from 1.594 GHz to 1.748 GHz frequency range by escalating the capacitor values from 2.2 pF to 100 pF and this clearly shows good impedance matching effect. The maximum radiation direction provides peak gain value of 3.39 dBi and frequency ratio of 1.66 and 1.09 were obtained at first and second resonances of linearly polarized radiation. Also at resonant frequencies a respectably high tuning range of 34.48% and 14.3% were detected.

Aboufoul *et al.*[41] presented a compact micro-strip monopole antenna that is configured with two GaAs FET switches as shown in Fig. 18. Simple biasing was used for switches that do not cause any adverse effect in antenna performance and the switches used have low insertion loss that does not hamper the radiation patterns. Using this antenna design for multiband frequency operation enhanced the gain by 20 % as compared to UWB operation and efficiency remained appreciably same. The gain and efficiency performance for simulated and measured results has been tabulated in Table 2. Also, the pre-filtering feature is offered as observed from reduced out-of-band total efficiency. Another feature of this design is the low power consumption of less than 33 μW, making it suitable for cognitive radio application. The reflection coefficient performance is depicted in Fig. 19.

As witnessed in this section, plenty of work has been done in the field of reconfigurable antennas using electronic switching devices. Each switch design has its own share of merits and demerits, some of which are enlisted in Table 1. Depending on the application desired and constraints encountered, a particular switching mechanism can be selected for antenna design. Most of the existing works have shown preference for PIN diodes or RF-MEMS switches due to their more pros and less cons characteristics.

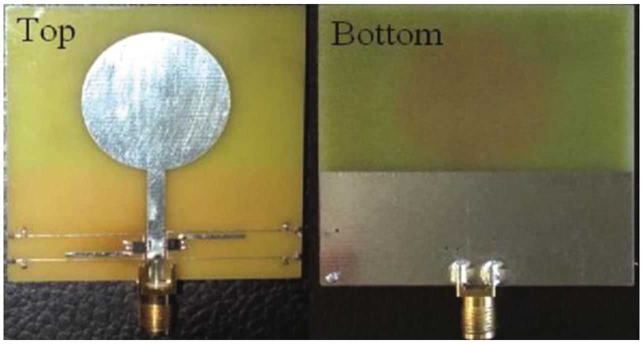


Fig. 18 — Proposed antenna prototype[41].

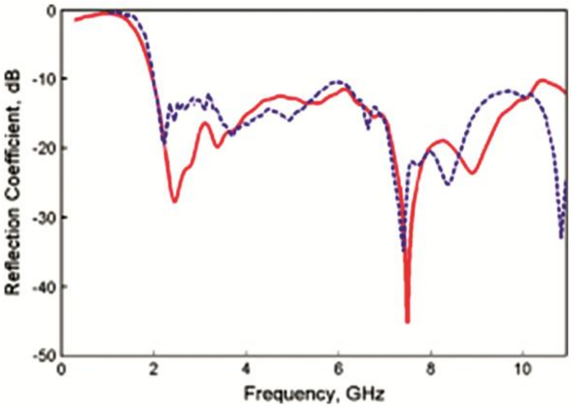


Fig. 19 — S-parameter performance of proposed antenna[41].

Table 2 — Simulated and measured values for gain and total efficiency (re-drawn)[41].

Frequency (GHz)	Gain (dBi)		η_t(%)	
	Simulated	Measured	Simulated	Measured
2.4	2.2	1.8	90	72
4.2	2.7	2.2	91	80
3.3	2.3	2.0	88	77
5.4	3.9	3.6	89	78

The details of the various antennas designed using different reconfiguration technique have been summarized in the Table 3, which also depicts information related to bandwidth, different reconfiguration modes and the key features of the different designs. In Table 4, the various antenna designs have been summarized for providing the readers with an option to select the antennas on the basis of different switching methods used, the number of reconfigurable frequency bands attained and the design challenges encountered in various designs.

2.2 Reconfigurable antenna based on optical switching

This reconfigurable technique employs photo-conductive switches (made up of Silicon or Gallium

Table 3 — The design specifications and key features of some of the designed antennas.

References	Design Specifications and features
Yang *et. al*[42]	1- The proposed design shows reconfigurability feature in terms of polarization and frequency and also features bandwidth enhancement. 2- The design achieves 3% CP bandwidth (for both RHCP & LHCP pattern. 3- As per the state of switch (ON or OFF), the axial ratios achieved are 2.9 dB and 1.6 dB at 4.0 GHz and 4.37 GHz frequencies respectively.
Jung *et. al.*[43]	1- A novel antenna design having two rectangular patches and showing frequency reconfigurable property has been proposed. 2- Both patches have been printed on the PCB substrate and connected via 4-bridges to obtain the dual frequency band operations at 2.4 GHz (IEEE 802.11b) and 5.5 GHz (IEEE 802.11a) WLANs respectively. 3- With $\theta = 0$, the gains achieved are 5 dBi and 3.7 dBi at 2.4 GHz and 5.5 GHz frequency band respectively.
Cetiner *et. al.*[44]	1- The proposed spiral antenna shows polarization reconfiguration characteristics by using RF-MEMS switches and offers applications in adaptive MIMO systems. 2- The design obtains the average half power beam width (HPBW) of around 105^0. 3- The axial ratio of 0.9 dB is achieved for the circularly polarized wave and a gain value of 5.3 dB is observed. 4- The bandwidth of 11% is obtained with axial ratio$\leq$ 3 dB and also the gain variation of the antenna over the complete band is 4.9 dB.
Zhang *et. al.* [45]	1- A fractal microstrip patch antenna, which shows polarization and pattern reconfiguration features, has been presented. 2- The reconfiguration is achieved by using RF-MEMS switches at 10 GHz frequency. The return loss of -20 dB is obseved.
Wu *et. al.*[46]	1- A frequency reconfigurable patch antenna design is proposed and shows to have application in personal communication systems. 2- PIN diodes are used for providing frequency reconfiguration. 3- With this design impedance bandwidths of 0.48% and 2.45% are obtained at 1.89 GHz and 2.37 GHz frequencies respectively.
Nikolaou *et. al.*[47]	1- A novel annular slot antenna design is proposed with pattern and frequency reconfigurability features. 2- Pattern reconfiguration is achieved at 5.2 GHz, 5.8 GHz and 6.4 GHz frequencies using PIN diodes and stub network.
Fankem *et. al.* [48]	1- A novel patch antenna with frequency reconfigurable feature is proposed that can be utilized in wireless communication systems and offers wide operational bandwidth. 2- The states of integrated switches (ON/OFF) provides reconfiguration to this E-shaped patch structure at 9.2 GHz to 15.0 GHz and 7.5 GHz to 10.7 GHz frequency bands with 48% and 35% relative bandwidths respectively.
Yang *et. al.*[49]	1- A novel microstrip patch antenna design is presented with frequency reconfigurable property. 2- This design offers a tunable frequency range from 2.6 GHz to 3.35 GHz by inserting a varying capacitor and inductor in the input gateway of radiating structure having a U-shaped slot. 3- Such design arrangement provides a broad bandwidth accompanied by flat input resistance and linear input reactance.
Weily *et. al.*[50]	1- A novel high gain antenna design with partially reflective surface (PRS) and showing frequency reconfigurability characteristic is proposed. 2- This design comprises an array of phase changing reflection cells placed on a thin substrate above the ground plane of the antenna structure. 3- Variable bias voltage of Varactor diodes helps in controlling the reflection phase of each cell. The variation in bias voltage from 6.49 V to 18.5 V results in variation in operating frequency from 5.2 to 5.95 GHz. 4- In this operating frequency band the gain also varies from 10 dBi to 16.4 dBi accordingly with a tuning range of 3.5 %.
Perruisseau-Carrier *et. al.*[51]	1- A novel patch antenna is proposed that utilize three pairs of Varactor diodes for producing frequency reconfigurability in the design. 2- Such design has a broad bandwidth and is adaptable in terms of available antenna states. 3- Variation of tuning capacitance in 0.1pF - 2.0 pF range leads to a variable operating frequency in range of 1.859 GHz to 3.672 GHz along with frequency ratio of 2 and reflection coefficient value below -10 dB. 4- Measurements show a moderate efficiency in range of 50% to 70% for 2.0 GHz to 4.25 GHz frequency range.
Artiga *et. al.*[52]	1- A novel Vivaldi antenna is proposed, having frequency reconfiguration feature. Such design has ability of rejecting dynamic interference and cover principle standard like WiMAX , Wi-Fi , Bluetooth, WLAN (802.11a) etc. 2- This design has operating frequency band from 2.5 GHz to 8 GHz with a stop band from 1.8 to 5.8 GH which is useful for vehicle to vehicle communication.

(*Contd.*)

Table 3 — The design specifications and key features of some of the designed antennas (*Contd*.).

References	Design Specifications and features
Sanchez-Escuderos *et. al.* [53]	1- A reconfigurable slot-array antenna has been presented which employs RF-MEMS switch. 2- An isolation factor of 12 dB is achieved between two states of the switch. The radiation efficiencies are for ON and OFF state is observed as 36% and 93% respectively.
Abutarboush *et. al.*[54]	1- A novel patch antenna is presented which have dual patch radiating structures on which C-slot is cut. The complete design offers two dual-band modes and one wideband mode using PIN diodes as switch element. 2- The overall dimension of designed structure, including ground plane is 50×50×1.57 mm^3. 3- The operating frequency for this antenna system extends from 5 GHz to 7 GHz range with gain values varying from 3.72 dBi to 4.92 dBi. The impedance bandwidth obtained is around 33.52%.
Majid *et. al.*[55]	1- A novel microstrip slot antenna has been presented with frequency reconfiguration characteristics. 2- The proposed antenna uses five RF-PIN diodes to generate six variable frequency states in 2.2 GHz to 4.75 GHz range. 3- The designed antenna shows a size reduction of 33% and average gain of 1.9 dBi.

Table 4 — Performance comparison of various antenna designs along with challenges posed.

Antenna Specifications	Number of Switches used	Resulting Number of Frequency bands	Challenges
Yagi-Uda antenna with single port[56]	12 (Varactor diodes)	6	Very high ohmic losses because 1 MΩ resistors are used to bias 12 Varactor diodes.
Stub-Loaded Microstrip Patch Antenna[57]	4 (Varactor diodes)	2	Low quality factor (Q-factor); MEMS switches are suggested for tuning purpose
Microstrip radiator with four frequency band reconfigurations[58]	4 (RF-MEMS Switches)	4	Need filters to remove noise and have poor isolation between switches
Microstrip antenna for UWB applications[59]	4 (RF- MEMS Switches)	Wideband	Though provides fast transitory switching between UWB and narrow band but cover less bandwidth.
C-Shaped Circular Patch Antenna[60]	2 (RF- MEMS Switches)	2	Polarization reconfiguration is achievable but only at fixed frequency bands.
Monopole antenna with Coplanar microstrip fed-line[61]	2 (Electronic switches)	3	Same substrate arrangement of feed line causes difficulty in suppressing coupling effect.
Metamaterial based low profile antenna[62]	1 (PIN diode)	2	Low gain with superior reconfigurable features and reduced structure size
E-shaped Patch Antenna with frequency reconfigurable feature[63]	1 (PIN diode)	3	Respectable reconfigurable features with trade off with size

Arsenide) for optically controlling the operational frequency, radiation pattern and bandwidths. The photoconductive switches are operated using light illuminations, hence they obviate the need of metallic biasing lines (as used in electronic switches) to alter the radiating structure and thereby reduces the complexity of design. The switching speeds for these photoconductive switches are very fast and lie in nanosecond range[13].

Zheng *et al.*[64] presented an optically reconfigurable antenna design resulting in UWB/narrowband features for cognitive radio applications. The complete antenna prototype is structured in two parts. For UWB characteristic, a U-shaped monopole antenna was used for sensing purpose. For communication purpose an open-annulus antenna was used that have four photoconductive switches. The combination of ON/OFF states for these four switches results in four different operating frequencies around 6, 7, 8 and 9 GHz.

In another work, an optically controlled reconfigurable antenna has been reported by Li *et al.*[65]. This design offers services in area of cognitive radio by integrating wideband and narrowband functionalities into single entity. The reconfiguration is achieved by using four conductive silicon switches. The switch behaved as a short circuit conductor or will be in ON state when the light illuminates the switch and will behave as an insulator or will have an OFF state when there is no beam of light. The reconfiguration in terms of frequency was achieved by altering the structure or the ground of inner portion of antenna by variably combining different slender ring parts via optically controlled switches. The four reconfigurable frequency bands were obtained from 5.8 GHz to 6.8 GHz, 6.7 GHz to 7.3 GHz, 7.0 GHz to 8.4 GHz, and 7.9 GHz to 9.2 GHz. For UWB band the gain varied from 2.6 dBi to 4.1 dBi and for narrowband the values range from -0.1 dBi to 4.5 dBi.

2.3 Reconfigurable antenna using physical alteration technique

This reconfiguration technique involves mechanical variation in radiator structure in order to accomplish variation in different characteristics. This technique obviates the use of active elements and their related biasing circuit, but there is big challenge to design such kind of antennas that encompasses actuation mechanism and still maintains other characteristics with significant structural changes.

A novel antenna system is presented by Tawk *et al.*[66] and is suitable for cognitive radio applications. The designed antenna works on wideband (UWB) range with frequency reconfigurable characteristics. The proposed UWB antenna scans the complete wideband from 2 GHz to 10 GHz range and the rotation of antenna patch achieves frequency agility feature by tuning to various bands within this range. For various antenna positions, the measured gain values of 6.2 dB, 6.67 dB, 7.4 dB, 7.77 dB and 8.4 dB are achieved. The ground plane structure of the antenna is separated in three sections, one is moving plane and other two are fixed. The two actuators are used to control the moving ground plane that allows vertical movement and variable tilting positions. The controlling actuators are based on pulse width modulation and are governed by Arduino board.

Zheng *et al.*[67] proposed a novel antenna system as shown in Fig. 20, for cognitive radio application. The proposed system comprises of two separate antennas dedicated individually for sensing and communication purpose. For sensing purpose a printed monopole patch antenna is designed with its plane perpendicular to the plane of reconfigurable communication antenna and some distance apart from it as shown in Fig. 20. Such placement of antennas ensures a good isolation between the two antennas. The wideband sensing antenna is fed via strip line of width 0.4 cm and has a partial ground plane of dimension 4.7X0.75 cm^2, while the dimension for radiating monopole patch antenna is 3.75X2.79 cm^2.

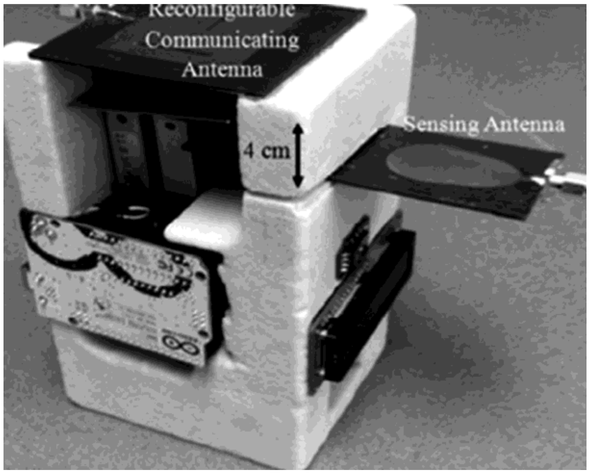


Fig. 20 — Reconfigurable antenna using structural alteration[67].

Tawk *et al.*[68] presented design of reconfigurable antennas that employ actuators for introducing physical alteration in radiating parts. In this work reconfiguration is achieved in three antenna designs. Frequency reconfiguration is accomplished in a quadrifilar helix antenna by varying number of turns in helical arms and in a monopole antenna by extending and tilting ground plane. Reconfiguration in terms of radiation pattern is achieved in a quasi-U-shaped patch antenna by rotating the L-shaped microstrip line feed structure.

2.4 Reconfigurable antenna based on material change

Altering the material characteristics of the antenna design, can provide variable frequency tuning options for the antenna system. The values of relative permeability and permittivity of the ferromagnetic and ferroelectric materials can be altered by varying the applied static magnetic fields and static electric fields respectively. Such variation in material property leads to a variable change in the effective length of antenna structure which in turn causes variable frequency tuning of the antenna system. Apart from biasing issues, this technique may also result in degradation of antenna efficiency due to the high conductivity feature of ferrite bulk materials over other substrates.

A reconfigurable structure based on smart materials has been presented by Mazlouman *et al.*[69]. The proposed design can be used as an adaptive antenna in various budding communication devices. A helical antenna in axial mode is designed in this work which shows frequency reconfigurability feature by utilizing a shape memory alloy spring actuator for varying antenna height as shown in Fig. 21. As the height of helix is altered, the pitch spacing and pitch angel varies (total length of helix being fixed), resulting in variable radiation patterns. The measured and simulated results have been compared for some helix height of the proposed antenna (60 mm, 70 mm and

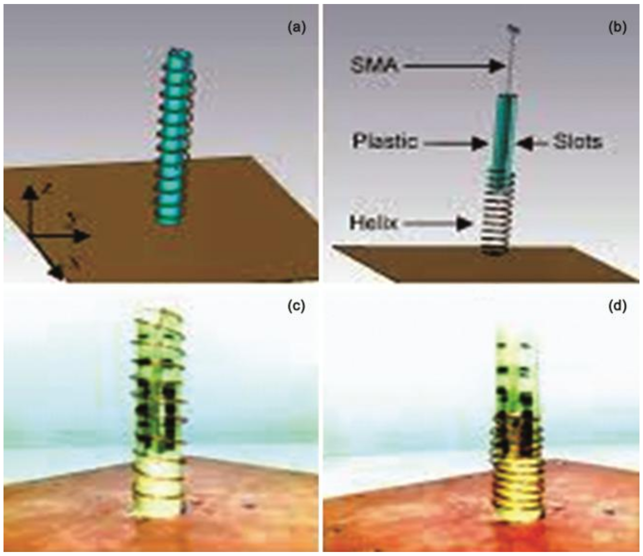


Fig. 21 — (a),(c) The proposed antenna at original height, when no current is applied, and (b), (d) the compressed helix antenna when DC current is passed through the SMA[69].

80 mm). A good impedance matching was observed from 4 GHz to 4.5 GHz for all sweep points of the conical helix. A maximum radius of 18 mm was achieved with 6 turns of conical helix and radius ratio of 0.55. In this mode the variation in conical helix height was made from 50 mm to 90 mm which showed the sensible matching for a wideband frequency in 3 GHz range. Also for the cylindrical helix, different patterns were obtained by changing the height of the helix from 40 mm to 95 mm. The gain values obtained ranged from 10 dB to 11.5 dB and the HPBW varied from 65^0 to 50^0 with a fixed helix length. Experimental results are shown in Fig. 22.

Material properties can also be exploited to reduce the antenna size as is shown by Pradeep *et al.*[70]. In this work a low electrical profile antenna is designed having metamaterial as its base material that exhibits zeroth order resonance. A spiral resonator is used and embedded into an asymmetric coplanar stripline, for designing such antenna. Combination of spiral and microstrip line demonstrated CRLH property (equivalent circuit as shown in Fig. 23). The series resonance frequency is given by:

$$w_{se} = 1/\sqrt{L_R C_L} \quad \text{... (9)}$$

and shunt resonance is given by:

$$w_{sh} = 1/\sqrt{L_L C_R} \quad \text{... (10)}$$

A frequency reconfigurability of 1:1.47 was achieved using such design.

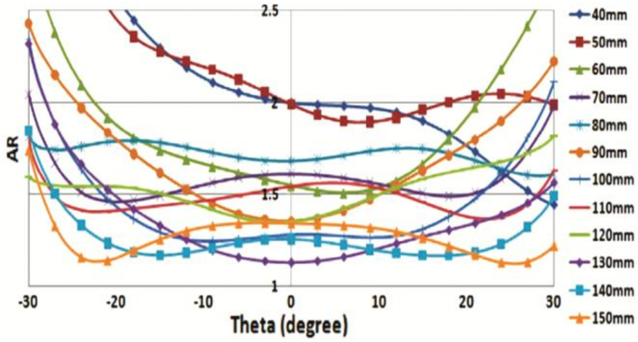


Fig. 22 — Experimental results of $\varphi = 0^0$AR of the prototype vs height variations within HPBW[69].

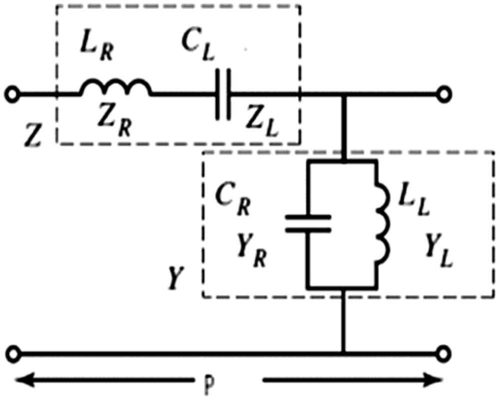


Fig. 23 — Equivalent circuit of CRLH transmission line unit cell[70].

In Table 5, a comparative summary is provided for some of the antenna designs proposed in recent times. From the table, the characteristic analysis can be made depending on type of antenna design, types of reconfiguration offered by the proposed design, the technique and means of attaining the reconfiguration, the number of switches used for achieving the reconfiguration, the operating frequency and the antenna profile. The table provides the readers with an opportunity to select the best antenna type for required application.

3 Use of emerging technologies in antenna design

Besides using different conventional methods of reconfiguration in antenna design, various advanced technologies are being used these days to further enhance the functionalities and characteristics of antennas. Artificial Neural Network (ANN) and Internet of Things (IoT) are two such technologies that have captivated the researchers the most. Some relevant work is mentioned in this section.

Rajeev *et al.*[78] proposed a ANN model based on back propagation algorithm, for determining resonant frequency of a hexagonal shaped slot antenna based on stub length (L) and slot height (H) parameter.

Table 5 — Comparative summary for reconfigurable antennas.

Type of Antenna Proposed	Type of Reconfiguration Provided	Technique for Reconfiguration	No. of Switches Employed	Operating Frequency (GHz)	Antenna Profile (mm^2)
Patch[71]	F/P/R	PIN-diode	60	2.4–3	31 × 31
Slot [72]	F/R	PIN-diode	2	3.6/3.95	30 × 40
Monopole [73]	F/B	PIN/Varactor diode	3	3.9–4.82	25 × 75
Slot [74]	P/R	PIN-diode	36	5	78 × 78
Helical[75]	P/R	PIN-diode	32	0.9	81 × 81
Monopole [76]	F/P	Varactor diode	112	1–1.6	88 × 114
Patch[77]	F/R	Varactor diode	2	2.15/2.25/2.38	151.5 × 160.9

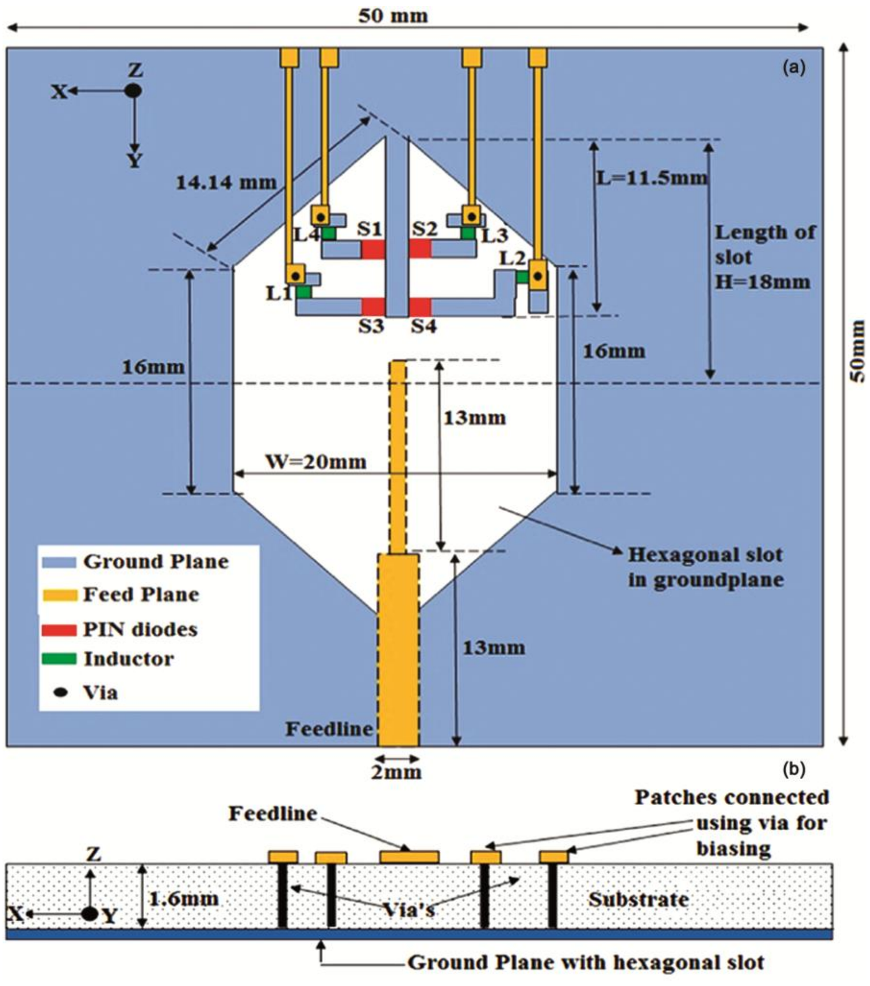


Fig. 24 — Design of proposed antenna (a) back view and (b) side view[79].

In another work Rajeev *et al.*[79] proposed a frequency reconfigurable antenna whose dimensions are optimized using back propagation network (BPN) and this antenna resonates at eight different frequency bands in 2.36-3.92 GHz range using four PIN diodes as shown in Fig. 24. In order to minimize the parasitic effects, the biasing circuit was incorporated in ground plane as presented in Fig. 25.

For decreasing the dependency of antenna performance on biasing circuit of switches, various methods and switching circuits were introduced. One such arrangement was presented by Arun *et al.*[80]. In this work, an antenna was designed that can achieve frequency reconfiguration by employing PIN diode switches that were biased through IoT method. In designed antenna as shown in Fig. 26, two rings

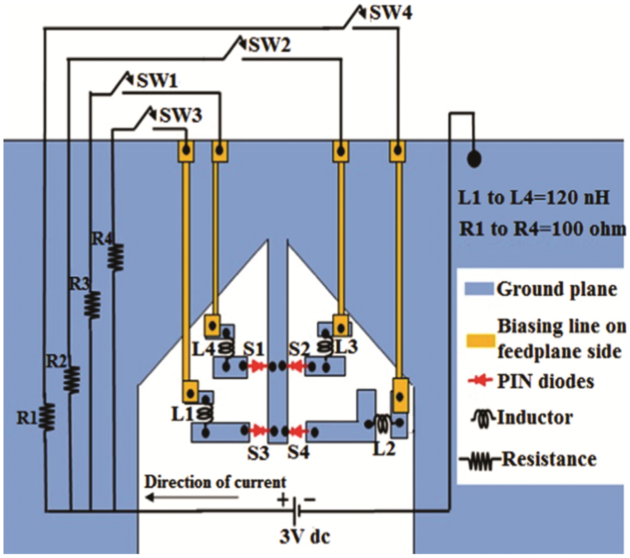


Fig. 25 — Biasing network[79].

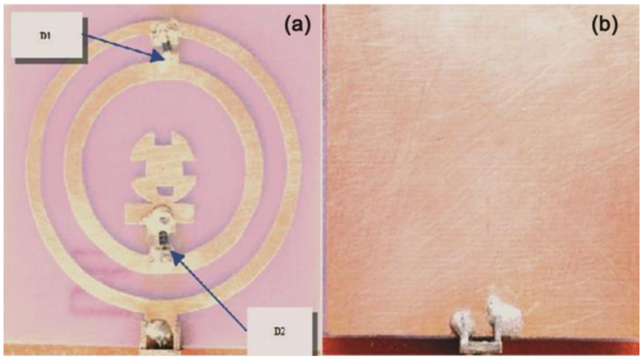


Fig. 26 — Fabricated Antenna (a) Front view and (b) Back view[80].

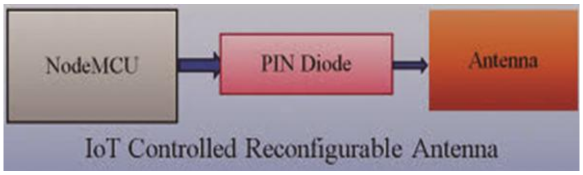


Fig 27 — Model for IoT controlled reconfigurable antenna[80].

were considered which can be joined through these switches. Proposed antenna was fabricated on epoxy-Fr4 substrate and have dimension of 50×50 mm^2. As depicted in Fig. 27, IoT device (NodeMCU) is used for obtaining four frequency bands of order 4.5 GHz, 3.5 GHz, 2.4 GHz and 1.8GHz. Return loss greater than -10dB is achieved along with a maximum gain of 2.7 dB that is obtained at 3.5 GHz as shown in Fig. 28.

4 Future prospects of reconfigurable antennas

The future prospects of reconfigurable antennas lies in self-adaptation and self-improvement, for the purpose of attaining the maximum energy efficiency with minimum losses and low power requirements, in order to sustain the communication link with the highest reliability in the dynamic and unpredicted environment. The future reconfigurable antennas should have attributes of providing multiple functions simultaneously and without any evident hiccups. The reconfiguration techniques should be more inclined towards emerging areas like software controlled IoT gateway or machine learning models related with ANN technology in order to sense and respond to dynamic RF changes. Novel wireless technology trends such as cognitive radio system, MIMO systems, emerging cellular systems etc. should act as building block for designing of reconfigurable antennas.

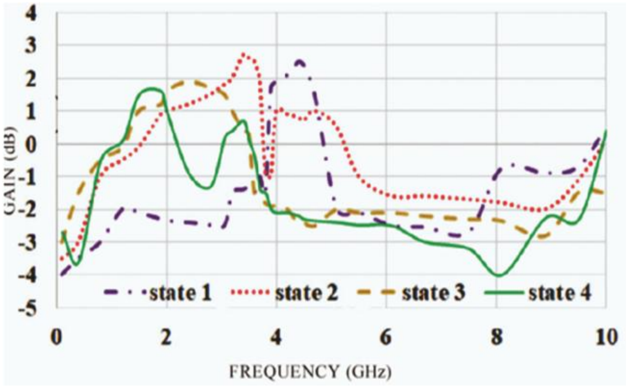


Fig. 28 — Measured gain plot of proposed antenna[80].

5 Conclusions

The above work presents an exhaustive review about the reconfigurable antennas used in multiband communication systems. Various reconfiguration techniques are discussed at large and escorted by their respective merits and demerits. The paper has meticulously presented the application areas of reconfigurable antennas, covering an extensive range of operating frequency bands. The review work is complemented by various antenna designs and prototypes along with their simulated and measured results that help in drawing inferences about various reconfigurable antennas and outline foundation for selection of suitable antenna design technique as per requirement. While presenting antenna designs various factors affecting the performance of antenna are highlighted and investigated such as biasing circuits, antenna shape and size, number of switches employed etc. It is observed in some cases that while working towards attainment of low profile, the antenna efficiency is affected and circuit complexity increases. It is also noted that most of the work is conducted at high frequencies and little attention is given to low frequency wireless applications. It is can be concluded that design of antenna employing all possible reconfigurations such as frequency, pattern, polarization and bandwidth, simultaneous incorporated in a low profile antenna is the area which still needs investigation and making use of emerging technologies such as ANN and IoT can help in achieving this goal.

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