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Diode Based Reconfigurable Microwave Filters for Cognitive Radio Applications: A Review

HASHINUR ISLAM[1], (Graduate Student Member, IEEE), SAUMYA DAS[1], TANUSHREE BOSE[1], AND TANWEER ALI[2], (Senior Member, IEEE)

[1]Department of Electronics and Communication Engineering, Sikkim Manipal Institute of Technology, Sikkim Manipal University, Gangtok 737136, India
[2]Department of Electronics and Communication, Manipal Institute of Technology, Manipal Academy of Higher Education, Manipal 576104, India

Corresponding author: Tanweer Ali (tanweer.ali@manipal.edu)

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ABSTRACT The cognitive radio paradigm for developing next-century wireless communication systems is rapidly entering the mainstream, and various aspects of it are currently being applied in 5G technology, aeronautical engineering, military communications, emergency, and public safety applications, satellite communication, and healthcare. Cognitive radio focuses on the existence of software defined radio architectures that allow dynamic reconfiguration. Many researchers have taken initiatives in the last decade to achieve the reconfiguration ability in cognitive radio systems to support the concept of dynamic spectrum access. As cognitive radio adapts dynamic spectrum allocation for its users, the physical implementation requires reconfigurable filters that can alter the carrier frequencies and bandwidth. Although there are many ways to reconfigure filter operation, diode based reconfiguration has received utmost attention among researchers because of its shorter response delay and easy implementation. In the last decade, researchers have reported several diode-based reconfigurable filters, including their characteristics such as filter function, filter combination, tuning range, variation in bandwidth, isolation, and resonance. However, to examine the potential of these filters in the application of cognitive radio, a comprehensive review needs to be pursued. In this review article, the descriptions of several diode based reconfigurable filters are illustrated with their exhibiting characteristics. The detailed information provided in this article has disclosed that primarily three different types diode based reconfigurable filters have been reported by researchers: Tunable, Switchable, and Hybrid (Both Tunable and Switchable). It is also found that each type of reconfiguration can further be segregated in terms of filter function, centre frequency variation, and bandwidth variation. The detailed categorization of the reconfiguration presented in this paper provides a systematic approach to select the correct reconfigurable filter for the desired frequency reconfiguration in cognitive radio.

INDEX TERMS Cognitive radio, reconfigurable filter, tunable filter, switchable filter, hybrid reconfigurable filter.

I. INTRODUCTION

Cognitive Radio (CR) is considered to have tremendous potential to alleviate the spectrum scarcity problem in wireless communication [1]–[3]. It exploits underused spectrums to find a new way of spectrum access. CR systems are capable of reconfiguring themselves depending on spectrum availability, traffic congestion, channel interference, etc. The intelligence of CR systems is widely being explored by 5G technology [4], [5], military communication [6], healthcare [7], aeronautical applications [8], RADAR [9], emergency and public safety applications [10], and satellite communication [11], as depicted in Fig. 1. Further, the use of cognitive radio is expected to grow exponentially through the different vertical sectors in the coming years. By 2022, the scale of the cognitive radio industry is projected to exceed USD 7.44 billion, with a compound annual growth rate (CAGR) of 16.6 percent [12].

In CR system, two types of spectrum users are present: 1) Primary user who owns the spectrum and has the highest priority for using it. 2) Secondary user who can access the spectrum when the primary user is not in operation. Spectrum utilization measurement has shown that many primary user bands are left unused and underused over different space and

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FIGURE 1. Cognitive Radio Applications.

time and can be adaptively utilized by the secondary user with the implementation of CR technology. CR can sense the spectrum holes that are not occupied by primary users and allows secondary users to capture that spectrum to start communication. At any frequency, if the primary communication gets affected by secondary, then secondary has to stop its operation over that band and needs to find another inactive primary user band to continue its communication. Hence the secondary user has to be adaptive as spectrum holes are dynamic, and it must be reconfigurable to maintain its communication all the time.

From the hardware aspect, reconfigurability of secondary user system can be achieved with the use of reconfigurable filters. Reconfigurable filters can provide the secondary user the ability to adapt to the dynamic nature of spectrum holes and avoid the interference caused by congested communication applications. So reconfigurable filter is an inevitable hardware for the CR applications.

Reconfigurable microwave filters are the filters which can adapt multiple bands of operation with a single filter structure [13]. It will be highly desirable in future wireless communication with the increase in number of multifunctional devices. Multiple bands of a bandpass filter and bandstop filter can enable the secondary user of CR to select the desired spectrum and reject the interference in an opportunistic approach. Thus, a cognitive approach would pave the way for multiple applications to be introduced without spectrum constraints.

Two different types of filter reconfiguration are considered by researchers. Continuous variation or tuning and discrete variation or switching. The continuous variation or tuning technique exhibits continuous change of centre frequency and/or bandwidth of filter response and is achieved by using varactor diodes [14], Micro-Electrical Mechanical Systems (MEMS) capacitors [15], phase shifters [16], ferroelectric materials [17], photonic microwave filters [18], optical delay line, and ferromagnetic materials [19], [20] etc. In contrast, discrete variation or switching can be generally obtained by PIN diodes [21], MEMS switches [22], optical frequency comb [23] etc. In addition, there are research work where both continuous and discrete variation have been reported.

Although there are many ways to reconfigure filter operation, diode based reconfiguration has gained the utmost attention from researchers for its shorter response delay and easy implementation. Therefore, a study on diode based reconfigurable filter has been considered in this article for exploring spectrum reconfiguration in CR implementation.

A varactor diode is advantageous in continuous variation or tuning over other methods because of its small dimension, low cost, and high tuning speed. PIN diode is also inexpensive and small in dimension. In addition, it exhibits very low loss, good isolation, low parasitic reactance, and high switching speed. PIN diodes can also control large radio frequency signals using low power levels. PIN diodes need a simple DC bias network for acting as a switching circuit. These qualities of PIN diodes make them superior to other methods for achieving discrete variation or switching in reconfigurability.

In this article, three categories of diode based reconfigurable filters have been discussed, mentioning their specifications and specialties. The first category includes varactor based continuous variation or tunable reconfigurable filters. Second is PIN diode based discrete variation or switchable reconfigurable filters. Third is a hybrid approach where both varactor and PIN diodes have been included in a single structure to explore more working options. All three categories are precisely able to adapt reconfigurability for CR systems and thereby have the potential to become the enabling hardware technology for next generation wireless communication. To assist the reader in choosing the suitable method for designing appropriate reconfigurable filters as per the requirement, a well-organized summary diagram of diode based filter reconfiguration and a probable research direction on diode based reconfigurable filter designing for the implementation of CR is also presented.

II. VARACTOR DIODE BASED RECONFIGURABLE FILTERS

Varactor diodes are semiconductor diodes whose capacitance varies with varying bias voltages. Varactor diode is essentially a p-n junction diode that exhibits the characteristics of variable capacitance under the influence of reverse bias voltage. The junction capacitance decreases with the increase in reverse bias voltage, as depicted in Fig. 2. Thus, if a varactor diode is integrated with the filter structure, tuning of resonating frequency is possible with the varying reverse

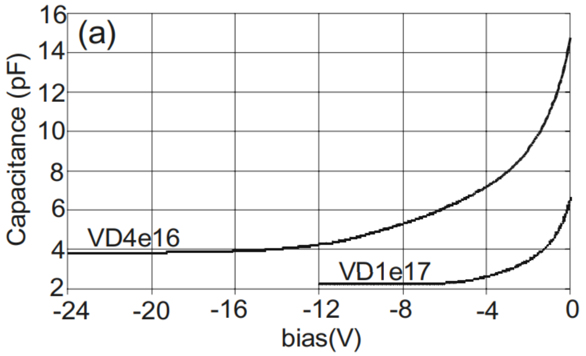


FIGURE 2. Variation in capacitance with bias voltage in varactor diode [24].

bias voltage. So reconfigurability can be attained with the use of varactor diode in the filter circuit.

Table 1 includes underlying information on the number of tunable elements, filter dimensions, tuning range, bandwidth variation, and the value of insertion loss within the stated band from few recent research works on varactor diode based reconfigurable filter. This table finds that tunability of varactor diode can explore mainly three possible combinations of reconfigurable filter characteristics: 'Variable centre frequency constant bandwidth', 'Constant centre frequency variable bandwidth', and 'Variable centre frequency variable bandwidth'. The three categories of varactor diode based reconfigurable filters are explicitly illustrated in Fig. 3 referring their related research papers from Table 1. Discussions on each of the three categories depicting examples are included in the following subsections.

A. VARIABLE CENTRE FREQUENCY CONSTANT BANDWIDTH

In this case, tuning operation in diode changes the central resonating frequency without affecting bandwidth of the filter. This can be seen in a research work [30] where four varactor diodes are engaged to achieve a dual band reconfigurable bandpass filter. Fig. 4 shows the geometric configuration and frequency response to the filter. Reflection coefficient and transmission coefficient curve of this dual band BPF illustrates the centre frequency tuning from 0.98-1.22 GHz in lower band and 1.63-1.95 GHz in upper band with constant absolute bandwidth of 76 MHz and 100 MHz respectively under the influence of two bias voltages.

B. CONSTANT CENTRE FREQUENCY VARIABLE BANDWIDTH

In this case of reconfiguration, tuning affects the bandwidth of the filter but keeps the centre frequency constant. Fig. 5 shows a geometric configuration and frequency response characteristics diagram for a research work [41] where six varactor diodes are used to vary the bandwidth from 440 to 680 MHz keeping the centre frequency constant at 2 GHz.

C. VARIABLE CENTRE FREQUENCY VARIABLE BANDWIDTH

This causes both centre frequency and bandwidth of filter variable under the influence of variable bias voltage. An example of this type [43] where centre frequency tuning from 2.17-2.72 GHz and 3 dB BW tuning range 140-208 MHz around 2.17 GHz, 231-355 MHz around 2.45 GHz, and 314-435 MHz around 2.72 GHz is achieved with the use of varactor diodes. Fig. 6 presents the necessary graph depicting the scattering parameters for variable centre frequency variable bandwidth tunable filter.

It is noteworthy that the capacitance variation in varactor diode does not cause any transformation in filter characterization. So BPF remains BPF, and BSF remains BSF under varactor diode based filter reconfiguration.

III. PIN DIODE BASED RECONFIGURABLE FILTERS

The PIN diode acts as a variable resistance diode under the control of bias voltage. Under reverse bias conditions, a small series junction capacitance causes high impedance to restrict the current from flowing through junction. A forward biasing in PIN diode removes that junction capacitance to exhibit very low impedance and thereby a sharp increase in flowing current through the junction. This behaviour of PIN diode makes it appropriate for switching function. Fig. 7 depicts the characteristics graph for PIN diode where current flow increases with the increase in bias voltage.

PIN diode explores a wide range of reconfiguration in filter characteristics. A large change of centre frequency of reconfigurable filter can be achieved with the use of PIN diodes. Additionally, this reconfiguration technique can transform the filter characteristics exploring the ON and OFF state of PIN diode. So a BPF can be transformed into BSF or vice versa by changing the biasing voltage of PIN diodes. Similarly, BPF can be reconfigured as LPF or HPF or vice versa with the use of PIN diode reconfiguration.

Table 2 includes information on the number of switchable elements, filter dimensions, possible combinations, centre frequency of each combination, bandwidth of each combination, and the value of insertion loss within the stated band from few recent research articles on PIN diode based reconfigurable filters. This table reveals that the biasing voltage of PIN diodes is varied to meet one of the four possible combinations: 'Variable centre frequency constant bandwidth', 'Constant centre frequency variable bandwidth', 'Variable centre frequency variable bandwidth' and 'Filter mode transformation.' These four categories are explicitly illustrated in Fig. 8 referring their related research papers from Table 2.

The first three cases seem to be same as cases of varactor diode based reconfigurable filter. However, in the PIN diode reconfiguration, all the cases are the outcome of switching action instead of tuning action. Because of the switching action, there is a long hop in centre frequency and/or in bandwidth of the filter.

TABLE 1. Varactor diode based tunable filters of different reconfigurable categories.

Ref.	Dimensions	Number of Varactor diodes	Performance/Outcome			
			Filter Type	Tuning range (GHz)	Bandwidth variation	IL (dB)
[25]	$0.09\lambda_g \times 0.1\lambda_g$	7	BPF	0.97-1.53	5.5% (1 dB FBW)	4.2-2
[26]	$0.12\lambda_g \times 0.16\lambda_g$	4	BSF	0.66-0.99	18% (3 dB FBW)	30.0-38.0
[27]	$0.25\lambda_g \times 0.18\lambda_g$	2	BPF	0.542-0.926	105 MHz (3 dB ABW)	1.5-2.56
[28]	$0.005\lambda_g^2$	2	LPF	1.15-2.15	Constant BW	0.2-0.4
[29]	$0.19\lambda_g \times 0.19\lambda_g$	3	BPF	0.6-1.015	15.5% (3 dB FBW)	1.1-2.8
[30]	$0.21\lambda_o \times 0.17\lambda_o$	4	Dual BPF	0.98-1.22 (Lower), 1.63-1.95 (Upper)	76 MHz (Lower), 100 MHz (Upper) (3 dB ABW)	2.1-3.0 (Lower), 2.8-4.0 (Upper)
[31]	$0.29\lambda_o \times 0.19\lambda_o$	2	Dual BSF	1.47-1.84 (Lower), 2.76 (Upper)	370 MHz (Lower), 730 MHz (Upper) 3 dB ABW	More than 33.0 (Lower), More than 10.0 (Upper)
[32]	60 mm × 42 mm	4	BPF	1.60-2.27	137 MHz (3 dB ABW)	4.17-1.99
[33]	65 mm × 20 mm	4	BPF	1.5-1.9	85 MHz (1 dB ABW)	6.2-6.7
[34]	$0.12\lambda_o \times 0.08\lambda_o$	6	BPF	0.5-0.825	56 MHz (3 dB ABW)	2.2-3.3
[35]	$0.065\lambda_g \times 0.065\lambda_g$	3	BPF	0.9-1.5	290 MHz (3 dB ABW)	2.3-1.2
[36]	$0.125\lambda_g \times 0.125\lambda_g$	2	Notch filter	0.71-3.04	450 MHz	More than 20.0
[37]	$0.0189\lambda_g^2$	4	Dual BPF	0.80-1.02 (Lower), 2.02-2.48 (Upper)	170 MHz (Lower), 240 MHz (Upper) 3 dB ABW	1.12-2.93 (Lower), 1.45-4.89 (Upper)
[38]	$0.395\lambda_g \times 0.197\lambda_g$	4	BSF	1.73-2.2	50 MHz (20 dB ABW)	More than 10.0
[39]	$0.029\lambda_g^2$	6	Dual BPF	2.2-2.7 (Lower), 3.45-4.2 (Upper)	500 MHz (Lower), 750 MHz (Upper)	Less than 6.0
[40]	120 mm × 40.2 mm	11	BPF	1.0	46-482 MHz (1 dB BW)	17.7-3.12
[41]	34 mm × 21 mm	6	BPF	2.0	440-680 MHz (3 dB BW)	0.3-0.8
[42]	$0.0088\lambda_g^2$	2	Dual BPF	0.69-0.88 (Lower), 2.67-3.78 (Upper)	23.5%-40.27% (Lower), 30%-14% (Upper) 3 dB FBW	1.83-0.78 (Lower), 1.76-2.02 (Upper)
[43]	$0.24\lambda_g \times 0.189\lambda_g$	5	BPF	2.17-2.72	140-435 MHz (3 dB BW)	1.7-4.8
[44]	28 mm × 65 mm	4	BPF BPF BPF BPF	1.5 1.29-1.71 1.20-1.74 1.37-1.72	87-165 MHz (3 dB BW) 132-137 MHz (3 dB BW) 7.9%-8.0% (3 dB FBW) 161-142 MHz (3 dB BW)	2.4-4.8 2.7-3.2 2.9-4.4 2.5-3.1
[45]	17.6 mm × 10.9 mm	2	BPF	0.61-2.39	150-260 MHz (Lower), 290-520 MHz (Upper) 3 dB ABW	2.1-4.4
[46]	$0.19\lambda_g \times 0.11\lambda_g$	3	BPF	1.52-2.76	240-350 MHz (3 dB BW)	2.4-4.8
[47]	$0.1\lambda_g \times 0.03\lambda_g$	6	BPF	0.56-1.15	65-180 MHz (1 dB BW)	1.4-4.5
[48]	$1.87\lambda_g \times 0.43\lambda_g$	3	BPF	3.75-4.0	140-280 MHz (3 dB BW)	Less than 6.0
[49]	$0.11\lambda_g \times 0.08\lambda_g$	4	BPF	0.8-1.52	63-140 MHz (3 dB BW)	2.4-5.8
[50]	$0.65\lambda_g \times 0.164\lambda_g$	6	BPF	1.11-1.5	46-130 MHz (3 dB BW)	2.62-7.0
[51]	$0.35\lambda_g \times 0.62\lambda_g$	6	BPF	2.45-3.02	630-1500 MHz	0.75-1.1
[52]	$0.09\lambda_g \times 0.20\lambda_g$	4	BPF	1.3-1.6	120-420 MHz (1 dB BW)	Less than 0.9
[53]	$0.12\lambda_g \times 0.08\lambda_g$	10	BPF	0.58-1.22	65-180 MHz (3 dB BW)	1.8-4.6
[54]	$0.138\lambda_g \times 0.131\lambda_g$	8	BPF	0.84-1.15	9.6-12% (3 dB BW)	2.7-1.6
[55]	$0.12\lambda_g \times 0.07\lambda_g$	6	BPF	1.7-2.7	50-110 MHz (1 dB BW)	4.9-3.8
[56]	$0.41\lambda_g \times 0.12\lambda_g$	7	BPF	0.58-0.91	115-315 MHz (1 dB BW)	1.53-1.19
[57]	$0.24\lambda_g \times 0.18\lambda_g$	6	BPF	0.669-1.215	140-644 MHz (3 dB BW)	1.0-2.0
[58]	37 mm × 26 mm	6	Dual BPF	0.77-1.0 (Lower), 1.57-2.0 (Upper)	20.3%-24.7 (Lower 3 dB FBW), 120 MHz (Upper 3 dB ABW)	0.7-1.4 (Lower), 2.74-3.93 (Upper)
[59]	40 mm × 30 mm	4	BPF	0.43-0.6	16-55 MHz (1 dB BW)	1.4-4.63
[60]	11.9 mm × 17.2 mm	10	BPF	1.55-2.1	40-120 MHz (1 dB BW)	6.0-4.5
[61]	$0.19\lambda_o \times 0.04\lambda_o$	3	Dual BPF	0.79-0.86 (Lower), 1.20-1.33 (Upper)	4%-4.5% (Lower), 9%-10.5% (Upper) 3 dB FBW	2.6-3.1 (Lower), 1.8-2.7 (Upper)
[62]	29 mm × 16 mm	5	BPF	2.9-3.5	4%-12% (3 dB FBW)	1.0-3.0
[63]	38 mm × 26 mm	6	Dual BPF	1.48-1.8 (Lower), 2.40-2.88 (Upper)	5.76%-8.55% (Lower), 8.28%-12.42% (Upper) 3 dB FBW	1.99-4.4 (Lower), 1.60-4.2 (Upper)
[64]	10.4 mm × 14.8 mm	5	BPF	1.75-2.25	70-100 MHz (1 dB BW)	7.2-3.2
[65]	$0.18\lambda_g \times 0.21\lambda_g$	9	BPF	1.5-2.2	50-170 MHz (1 dB BW)	5.1-3.2
[66]	48 mm × 36 mm	6	BPF	0.8-1.43 (Lower), 3.0-5.6 (Upper)	25 MHz (Lower), 45-33 MHz (Upper) 1 dB BW	Less than 3.1 (Lower), Less than 2.8 (Upper)

IL: Insertion loss, BPF: Bandpass Filter, BSF: Bandstop Filter, FBW: Fractional bandwidth, LPF: Lowpass Filter, BW: Bandwidth, ABW: Absolute bandwidth

The PIN diode action for each of the four cases of reconfiguration is depicted in the following subsections with appropriate examples.

A. VARIABLE CENTRE FREQUENCY CONSTANT BANDWIDTH

This case of reconfigurability can be explained with a recent research work [69] where in first combination, two PIN diodes are used to get the dual band BPF with centre frequency at 1.2 GHz and 3.5 GHz keeping fractional bandwidth almost constant as 3.5% and 4% respectively. Further, the biasing voltages of two PIN diodes are controlled to stop 1.2 GHz or 3.5 GHz in other combinations. Fig. 9 provides necessary reflection coefficient and transmission coefficient graph of this PIN diode based reconfigurable filter for different combinations.

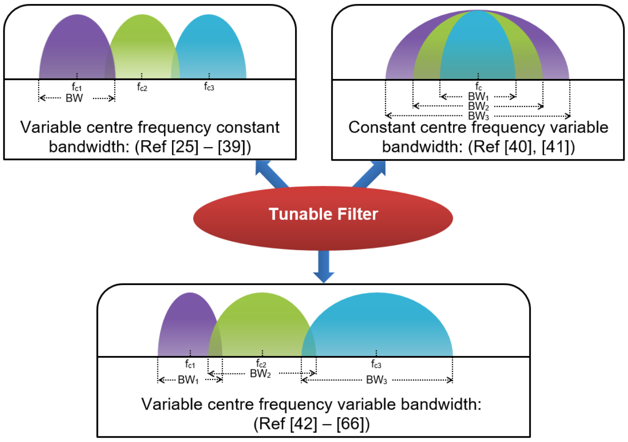


FIGURE 3. Varactor diode based tunable filter of different reconfigurable categories.

B. CONSTANT CENTRE FREQUENCY VARIABLE BANDWIDTH

This type of reconfiguration displays change in bandwidth keeping centre frequency constant. Fig. 10 illustrates the frequency response of an example [70] where fractional bandwidth is varied from 58.5% to 75% maintaining centre frequency constant at 2.4 GHz by controlling the biasing voltages of 4 PIN diodes.

C. VARIABLE CENTRE FREQUENCY VARIABLE BANDWIDTH

In this case, Both centre frequency and bandwidth of the filter vary under the control of PIN diodes bias voltages. This can be viewed in research work in Fig. 11 where two PIN diodes are used to reach three centre frequencies 2.4/3.5/5.2 GHz with their fractional bandwidth percentage 7.9/6/9.1, respectively [74]. Fig. 12 depicts four different combinations of filter output depending on the ON and OFF states of PIN diodes.

D. FILTER MODE TRANSFORMATION

This can only be achieved with the use of PIN diode in diode based reconfiguration circuit. This can change the filter characteristics from BPF to BSF, BSF to BPF, BPF to LPF, and BSF to LPF, etc. Fig. 13 shows an example of filter transformation [86] where different bandpass and bandstop options are explored with biasing of two PIN diodes in three different modes. In first mode, bandpass filter (Passband: 2.8-5.4 GHz) with a notch at 3.5 GHz is obtained, keeping PIN1 at ON state and PIN2 at OFF state. Second mode provides a bandstop filter (Stopband: 3.2-7.0 GHz) keeping PIN1 at OFF state and PIN2 at ON state while the third mode brings a full bandpass filter (Passband: 2.8-5.4 GHz) holding PIN1 at OFF state and PIN2 also at OFF state. The necessary reflection coefficient and transmission coefficient diagram for three different modes are shown in Fig. 13. Further, an almost constant group delay in bandpass region (Fig. 13 (d)) satisfies the linear phase requirement of the filter.

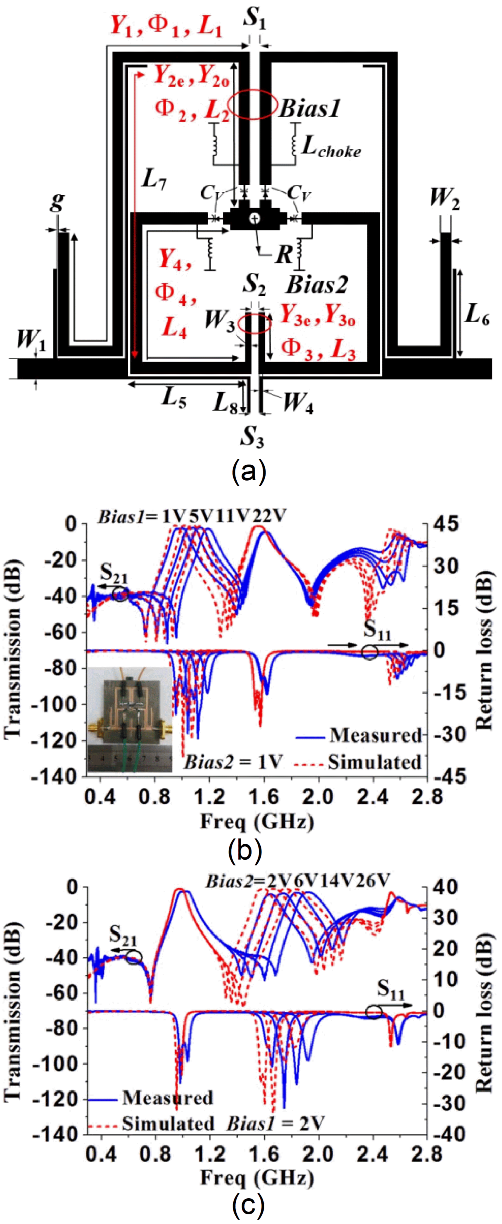


FIGURE 4. The varactor diode based dual band tunable BPF for 'Variable centre frequency constant bandwidth' [30] (a) geometric configuration (b) frequency responses of lower band (c) frequency response of upper band.

Because of its four possible reconfigurable options, PIN diodes are widely used in many applications of reconfigurable filters.

IV. HYBRID DIODE BASED RECONFIGURABLE FILTER

In many recent research works, hybrid structure of reconfigurable filters is proposed in order to bring advantages of both tuning and switching action. These filters include both varactor and PIN diodes in its configuration. The varactor diode causes the filter response to varying gradually while the PIN diode can transform the filter function, e.g., BPF to BSF or BPF to LPF, as well as can change the centre frequency

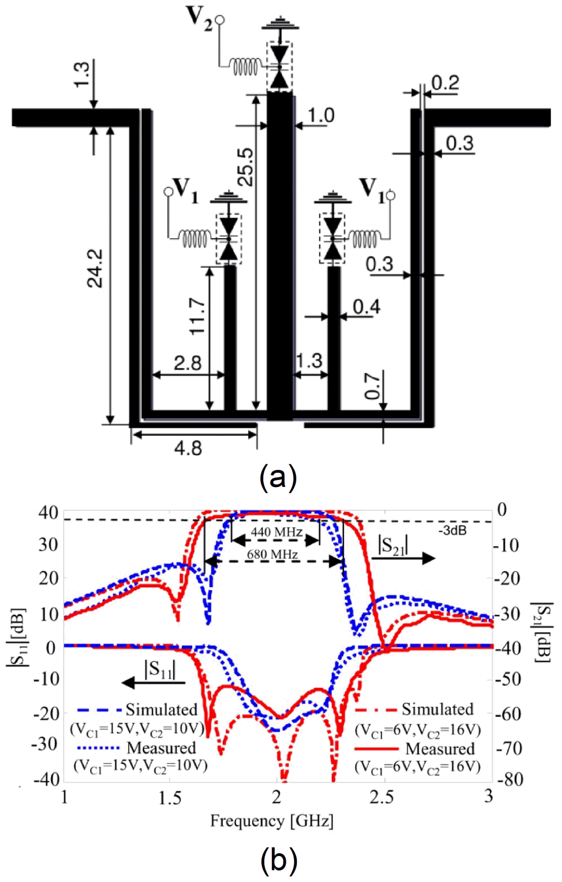


FIGURE 5. The (a) geometric configuration, and (b) frequency responses of varactor based tunable filter for 'Constant centre frequency variable bandwidth' [41].

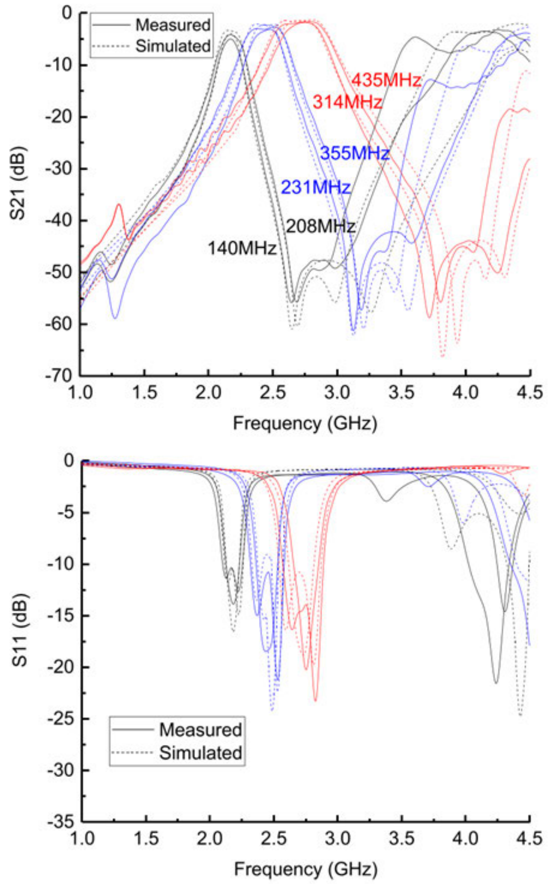


FIGURE 6. The frequency responses of varactor based tunable filter for 'Variable centre frequency variable bandwidth' [43].

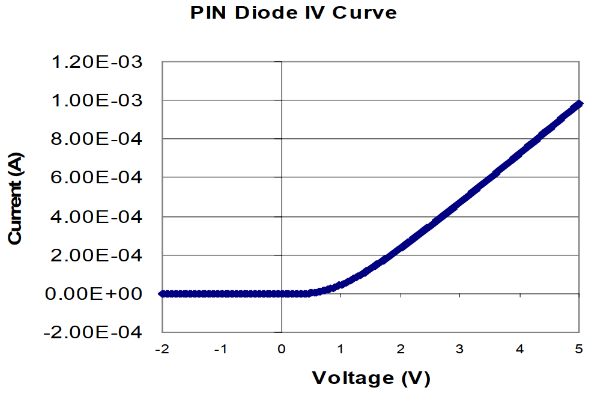


FIGURE 7. Current-Voltage relation for PIN diode [67].

and bandwidth significantly. Table 3 includes information on the number of different diode elements, effect of PIN and varactor diodes on filter characteristics, tuning range, bandwidth variation, and the value of insertion loss within the stated band from few recent research works on hybrid reconfigurable filter. Presence of both varactor and PIN diodes results in three different categories of filter characteristics: 'Variable centre frequency constant bandwidth,' 'Variable centre frequency variable bandwidth,' and 'Multimode filter transformation'. These three categories are explicitly illustrated in Fig. 14 referring their related research papers from Table 3. The action of varactor diode and PIN diode for each of the three cases of hybrid reconfiguration are depicted in the following subsections with appropriate examples.

A. VARIABLE CENTRE FREQUENCY CONSTANT BANDWIDTH

In this case of hybrid reconfigurable filter, gradual shifting of centre frequency under the influence of varactor diode biasing has been implemented at lower and upper range of frequencies keeping bandwidth constant. The function of PIN diode is to switch between lower and upper range of frequencies. A recent research [93] can be considered for its illustration. Five varactor diodes and two PIN diodes are used to bring a tuning range from 255 MHz to 455 MHz and from 455 MHz to 725 MHz at lower and higher band respectively. Bandwidth is kept constant as 75 MHz for both the bands. Lower band and higher band are achieved keeping PIN diodes are OFF and ON, respectively. Tuning in both bands is obtained by controlling three biasing voltages: V_L, V_{od}, and V_{in}. Fig. 15 illustrates the geometric configuration and frequency response of the reconfigurable bandpass filter.

TABLE 2. PIN diode based switchable filters of different reconfigurable categories.

Ref.	Dimensions	Number of PIN diodes	Performance/Outcome			
			Combination with Characteristics	Center Frequency (GHz)	Percentage Bandwidth (%)	IL (dB)
[68]	50 mm × 13 mm	5	i. Five BSFs ii. BSF with no rejection iii. Four BSFs iv. Three BSFs v. Three BSFs	2.412,2.422, 2.437,2.457, 2.484 … 2.412,2.422, 2.437,2.484 2.422,2.457, 2.484 2.412,2.422, 2.484	4% (3 dB FBW)	More than 10.0
[69]	$0.21\lambda_g \times 0.064\lambda_g$	2	i. Dual band BPF ii. BPF iii. BPF	1.2/3.5 3.5 1.2	3.5%/4% (3 dB FBW) 3.5% (3 dB FBW) 4% (3 dB FBW)	2.79/2.96 2.96 2.79
[70]	$0.514\lambda_g \times 0.514\lambda_g$	4	i. BPF ii. BPF	2.4 2.4	58.5% (3 dB FBW) 75% (3 dB FBW)	Less than 1.1
[71]	29.4 mm × 29.4 mm	4	i. BPF ii. BPF iii. WB-BPF	5.69 5.68 5.66	34.8% (FBW) 48.4% (FBW) 56.5% (FBW)	Less than 1.4
[72]	68 mm × 68 mm	2	Dual BPF	2.4, 2.4	4.8%, 1.5% (3 dB FBW)	1.2, 1.5
[73]	$0.54\lambda_g \times 0.15\lambda_g$	1	i. WB-BPF ii. NB-BPF	1.5 1.5	50% (3 dB FBW) 29% (3dB FBW)	1.1 0.9
[74]	$0.20\lambda_g \times 0.15\lambda_g$	2	i. Tri Band BPF ii. Dual Band BPF iii. Dual Band BPF	2.4/3.5/5.2 3.5/5.2 2.4/3.5	7.9%/6%/9.1% (3 dB FBW) 6%/9.1% (3 dB FBW) 7.9%/6% (3 dB FBW)	Less than 1.9
[75]	30×18 mm^2	3	Multiband BPF	1.2, 1.5, 1.8, 1.9, 2.4, 2.45, 3.2	4.5% for GPS, 5.4% for GSM, 9% for ISM, 27.5% for WiMAX	Less than 3.0
[76]	29.8 mm × 30.8 mm	4	i. Dual band BPF ii. Tri band BPF iii. Quad band BPF	1.71, 1.94 1.71, 1.94, 2.75 1.71, 1.94, 2.75, 2.85	12%, 13% (3 dB FBW) 12%, 13%, 25% (3 dB FBW) 12%, 13%, 25%, 11% (3 dB FBW)	Less than 1.0 Less than 2.5 Less than 3.0
[77]	$0.26\lambda_{g_o} \times 0.13\lambda_{g_o}$	2	i. Tri band BPF ii. Dual band BPF	1.87/2.62/3.95 2.06/3.95	19.6%/8%/24% (3 dB FBW) 30%/24% (3 dB FBW)	Less than 1.5 Less than 3.0
[78]	20 mm × 20 mm	3	i. BPF ii. BPF iii. BPF	2.4 3.5 1.65-1.89	20% (3 dB FBW) for WLAN 11% (3 dB FBW) for WiMAX 14% (3 dB FBW)	#
[79]	$0.75\lambda \times 0.50\lambda$	4	Dual BPF	1.5, 2.0	11.4%, 10.8% (3 dB FBW)	3.05, 3.1
[80]	24 mm × 30 mm	2	Dual band BPF BPF	2.45, 5.2 5.2	6.2%, 5.4% (3 dB FBW) 7% (3 dB FBW)	2.45, 2.1 2.1
[81]	30×30 mm^2	2	Dual BPF BPF	1.8, 3.5 3.5	9%, 7% (3 dB FBW) 7% (3 dB FBW)	Nearly 3.0
[82]	$0.50\lambda \times 0.25\lambda$	6	i. UWB-BPF ii. NB-BPF iii. UWB-BSF	2.57 2.9 2.54	95.7% (3 dB FBW) 25.3% (3 dB FBW) 106% (3 dB FBW)	0.94 0.8 More than 10.0
[83]	$0.41\lambda_g \times 0.76\lambda_g$	2	Bandpass to bandstop	2.4 with 5.0 stopband 5.0 with 2.4 stopband	100.76% (10 dB BW) 45.78% (10 dB BW)	0.47 1.28
[84]	22.5 mm × 24.3 mm	4	i. SB-BSF ii. ASF iii. SB-BPF iv. DB-BSF	2.0 dc to 4.3 1.92 1.61/2.36	50.2% (10 dB FBW) 4.3 GHz 9.7% (3 dB FBW) 21.1%/20% (10 dB FBW)	More than 10.0 12.0 1.95 More than 25.0
[85]	$0.41\lambda_g \times 0.24\lambda_g$	5	i. BPF ii. BSF iii. UWB BPF iv. UWB with notched band v. Narrow band BPF	1.83 1.95, 1.88, 1.83, 1.77 1.84-3.43 1.80-1.85 & 3.43-3.50 1.77	14.8% (FBW) 9.7% for UMTS, 9.8% for PCS, 11% for GSM, 12.5% for DCS 63% (FBW) 2% (FBW) 18%(FBW)	1.01 25.5 25.0 40.0 21.0 0.25 27 0.15
[86]	$0.15\lambda_g \times 0.13\lambda_g$	2	i. BPF with one notch band ii. BSF iii. BPF	4.15 with notch at 3.56 4.73 4.15	2.8-3.52 GHz and 3.63-5.4 GHz with 3.2% (5 dB FBW) for notch band 3.2-7.0 GHz (80% 3 dB FBW) 2.8-5.4 GHz (63% 3 dB FBW)	0.9 for BPF 16.0 for notch band More than 20.0 0.9
[87]	$0.75\lambda \times 0.50\lambda$	4	i. Dual band lowpass bandpass filter ii. LPF iii. BPF iv. All reject	1.5, 2.4 1.5 2.4 …	1.5 GHz BW, 9%(3 dB BW) 1.5 GHz BW 9% (3 dB BW) …	0.37, 3.3 0.37 3.3 33.0, 26.0
[88]	5.0×4.4 mm^2	2	Passband Stopband	5.5 …	5% (FBW) …	2.35 More than 20.0

B. VARIABLE CENTRE FREQUENCY VARIABLE BANDWIDTH

This case includes a change in both centre frequency and bandwidth. Involvement of both tuning and switching action enables the filter reconfigurability to be implemented in a wide frequency range. Fig. 16 illustrates an example of this case [99], where four varactor diodes are used to tune the centre frequency from 1.25 GHz to 1.45 GHz, and one PIN

TABLE 2. ***(Continued.)*** **PIN diode based switchable filters of different reconfigurable categories.**

Ref.	Dimensions	Number of PIN diodes	Performance/Outcome			
			Combination with Characteristics	Center Frequency (GHz)	Percentage Bandwidth (%)	IL (dB)
[89]	21.8 mm × 22 mm	1	i. BPF ii. Band notched	1.7 2.4	118% (3 dB FBW) 15% (3 dB FBW)	0.8 More than 20.0
[90]	$0.25\lambda_g \times 0.23\lambda_g$	1	i. Band notched ii. BPF	3.52 3.1-5.0	3.2% (5 dB rejection FBW) 60% (3 dB FBW)	16.0 0.7
[91]	8.3 mm × 7 mm	1	i. Notch band ii. UWB BPF	5.67 3.0-10.9	2.3% (10 dB BW) 138% (3 dB BW)	More than 10.0 0.2
[92]	39.2 mm × 6 mm	2	i. UWB BPF ii. Notch at 5GHz iii. Notch at 2.4GHz iv. Dual notches	1.8-7.8 5.15 2.4 5.15, 2.4	160% (3 dB FBW) 4% (3 dB FBW) 21% (3 dB FBW) 4%, 21% (3 dB FBW)	0.5-7.0 27.0 38.0 27.0, 38.0

IL: Insertion loss, BSF: Bandstop Filter, FBW: Fractional bandwidth, BPF: Bandpass Filter, WB-BPF: Wide-band bandpass filter, NB-BPF: Narrow-band bandpass filter, #: Not mentioned, UWB: Ultra wideband, SB-BSF: Single-band bandstop filter, ASF: All-stop filter, SB-BPF: Single-band bandpass filter, DB-BSF: Dual-band bandstop filter, LPF: Lowpass Filter

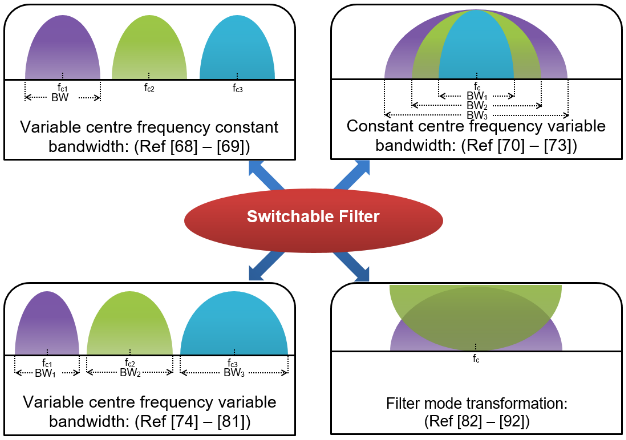


FIGURE 8. **PIN diode based switchable filter of different reconfigurable categories.**

diode is used to switch the FBW in two discrete states of 8% and 12%. The varactor biasing voltages are varied from 0 to 20 V.

C. MULTIMODE FILTER TRANSFORMATION

Multimode transformation in reconfigurable mechanism enables gradual tuning as well as filter characteristics transformation. An illustration of this case can be viewed in a recent research work [103]. A geometric configuration of this reconfigurable filter is shown in Fig. 17. In this work, six varactor diodes and one PIN diode have been utilized to explore two different modes: dual bandpass mode and dual bandstop mode. In the dual bandpass mode, the lower passband tuning range is from 1.7 to 2.2 GHz, and the higher passband tuning range is from 2.2 to 2.7 GHz. For the dual bandstop mode, the lower stopband tuning range is from 1.7 to 2.3 GHz, and the higher stopband tuning range is from 2.3 to 2.9 GHz. A picture of reflection coefficient and transmission coefficient under the control of PIN diode and varactor diode biasing is shown in Fig. 18 for depicting the filter responses at different modes.

V. DIODE BASED RECONFIGURABLE FILTER FOR CR APPLICATIONS

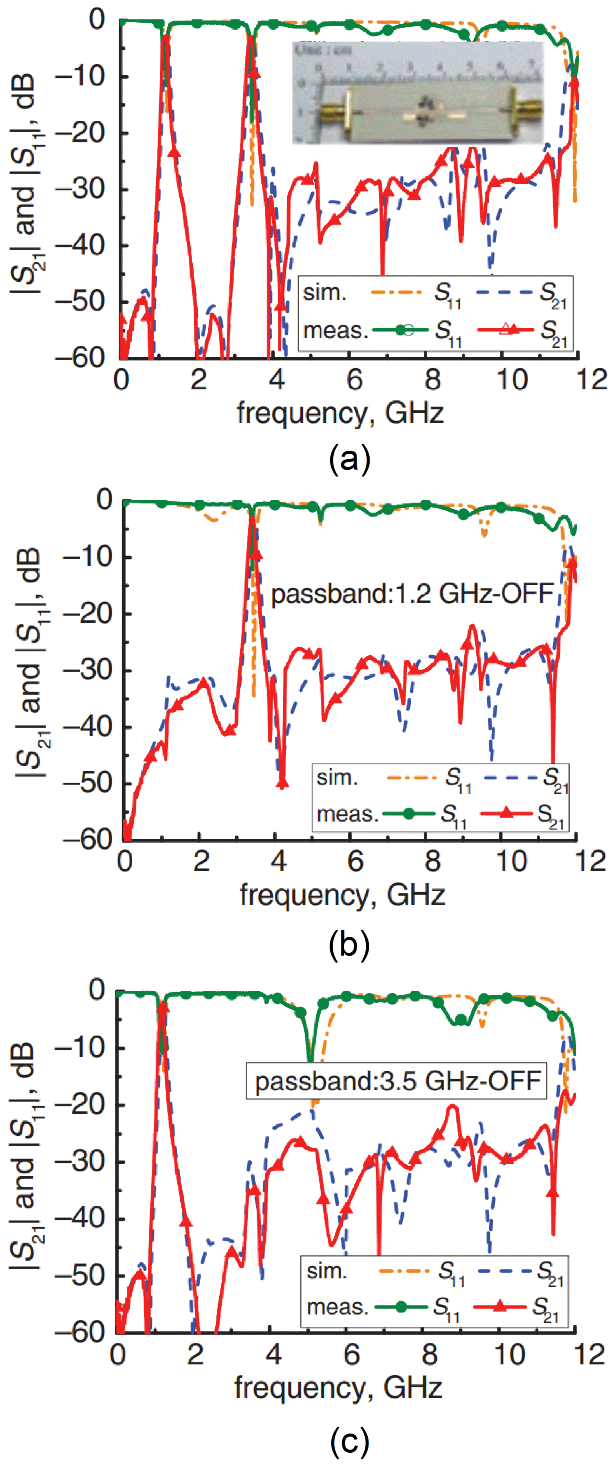
So far, three different categories of reconfigurability in the design of diode based filters have been discussed: Tunable filters, Switchable filters, and Hybrid reconfigurable filters. Based on reflection coefficient, and transmission coefficient value in the frequency band, each category of reconfigurability again explored multiple options of their possible applications. Fig. 19 summarizes all the possible combinations explored by the researchers in the domain of diode based reconfigurable filter designing.

The main aim of the CR framework is to bring various heterogeneous devices and systems together to provide smart services with minimal device resonance requirements, i.e., power, hardware complexity, cost etc. [106]. Under all circumstances, to attain this objective, the communication between devices should always be continued. This demands cyclic execution of four routine phases of cognitive radio: sensing, decision-making, sharing, and mobility (Fig. 20). The cognition process starts with the step of spectrum sharing (SS), in which various SS methods are used to identify the available spectrum resources across the specified spectrum band. Depending on the results of the detection, the decision is made for sharing the band concurrently, or to cease transmission within that band.

Once a CR takes a decision to use the band, a proper Medium Access Control (MAC) protocol is utilized, and power allocation should be reasonably considered to protect the primary user. Finally, the mobility process is performed by switching applications from one band to another.

The authors in [107] proposed the expansion of four traditional cognition phases by introducing certain additional CR modules, as shown in Fig. 21. The diagram also offers a briefing on the role of each module.

Diode based reconfigurable filters can contribute to the physical implementation of reconfigurable modules or the mobility phase of cognition cycle for CR. Out of several reconfigurable parameters, as shown in Fig. 21, frequency, and bandwidth can be cognitively controlled by the reconfigurable filters presented in this article.

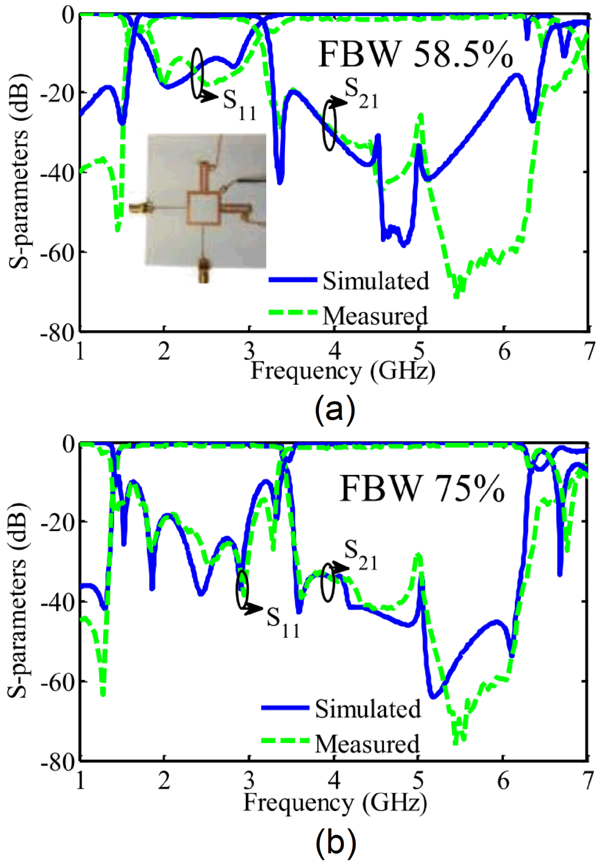


(a)

(b)

(c)

FIGURE 9. The four different frequency responses of PIN diode based switchable filter for 'Variable centre frequency constant bandwidth' [69] (a) dual band BPF (1.2/3.5 GHz) (b) BPF (3.5 GHz) (c) BPF (1.2 GHz).



(a)

(b)

FIGURE 10. The frequency responses of PIN diode based switchable filter for 'Constant centre frequency variable bandwidth' [70] (a) BPF (2.4 GHz) with BW 58.5% when PIN diodes are at OFF state (b) BPF (2.4 GHz) with BW 78% when PIN diodes are at ON state.

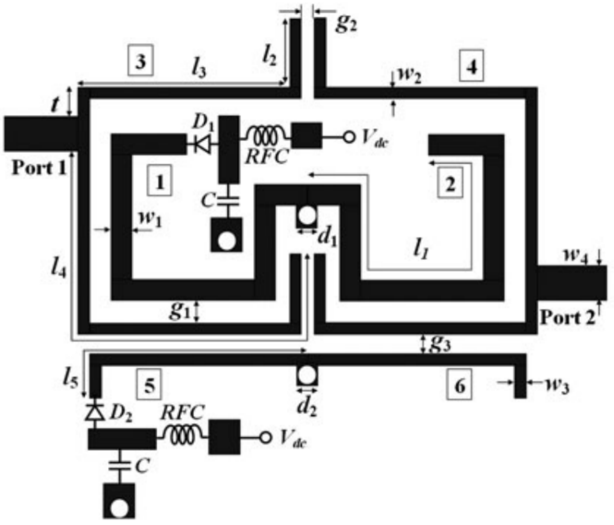


FIGURE 11. Geometric configuration of PIN diode based reconfigurable filter for 'Variable center frequency variable bandwidth' [74].

VI. FUTURE PERSPECTIVE

In the upcoming domain of wireless communication, certain application possibilities of reconfigurable filters could create opportunities in the implementation of cognitive systems. A brief discussion on future perspective of different categories of reconfigurable filters are presented in this section.

TABLE 3. Hybrid Diode Based Reconfigurable Filters.

Ref.	Dimensions	Number of diodes	Performance/Outcome				
			Combination with Characteristics	PIN effect	Varactor effect (Centre frequency tuning, GHz)	Bandwidth	IL (dB)
[93]	$0.2\lambda_g \times 0.14\lambda_g$	5 Varactor, 2 PIN	i. BPF ii. BPF	i. Lower BPF when PIN OFF ii. Higher BPF when PIN ON	0.255-0.455 0.455-0.725	75 MHz (3 dB ABW) 75 MHz (3 dB ABW)	1.4-1.8 2.5-2.9
[94]	60 mm × 46 mm	4 Varactor, 2 PIN	BPF	i. Frequency tunable passband with constant ABW when PIN ON ii. In band isolation is optimized when PIN OFF	0.785-0.566	51 MHz (3 dB ABW)	2.52-4.08
[95]	$0.06\lambda_g \times 0.27\lambda_g$	7 Varactor, 2 PIN	i. BPF ii. BPF	i. Lower BPF when PIN ON ii. Higher BPF when PIN OFF	1.1-1.5 1.5-2.1	40 MHz (3 dB ABW)	4.4-6.1
[96]	25 mm × 55 mm	1 Varactor, 1 PIN	i. BPF ii. BPF	i. BPF BW 36 MHz when PIN ON ii. BPF BW 45 MHz when PIN OFF	0.72-0.82 0.72-0.82	36 MHz (3 dB ABW) 45 MHz (3 dB ABW)	2.8 2.8
[97]	35 mm × 47 mm (2-pole) 36 mm × 58 mm (3-pole)	4 Varactor, 4 PIN (2-pole) 6 Varactor, 4 PIN (3-pole)	i. BPF (2-ploe) ii. BPF (3-pole)	i. low band when Sw 2 ON and Sw 1 OFF ii. high band when Sw 2 OFF and Sw 1 ON iii. low band when Sw 2 ON and Sw 1 OFF iv. high band when Sw 2 OFF and Sw 1 ON	0.55-0.99 0.99-1.9 0.54-1.006 0.96-1.8	92 MHz ($3dB$ BW) 91 MHz (3 dB BW) 89 MHz (3 dB BW) 91 MHz (3 dB BW)	3.2-4.4 3.2-4.0 4.2-5.4 4.0-5.4
[98]	6.12 mm × 4.12 mm (unit cells)	16 Varactor or 16 PIN	i. Notch ii. Notch	i. When OFF BW is 5.7% ii. When ON BW is 6.75%	5.09-5.43	450 MHz 340 MHz	More than 10.0
[99]	40 mm × 40 mm	4 Varactor, 1 PIN	i. BPF ii. BPF	i. BPF with narrow BW when PIN OFF ii. BPF with wide BW when PIN ON	1.25-1.45 1.25-1.45	8% FBW 12% FBW	Nearly 3.0 Nearly 3.0
[100]	$0.16\lambda_g \times 0.11\lambda_g$	4 Varactor, 1 PIN	i. BPF ii. BSF	i. BPF when PIN OFF ii. BSF when PIN ON	0.79-1.59 0.7-1.47	22% (3 dB FBW) 7% (15 dB FBW)	1.3-2.1 More than 20.0
[101]	$0.52\lambda_g \times 0.42\lambda_g$	4 Varactor, 4 PIN	i. BPF ii. BSF	i. BPF when PIN ON ii. BSF when PIN OFF	1.8-2.5 1.0-1.5	127-29 MHz . . .	2.5-3.2 28.0
[102]	$0.14\lambda_g \times 0.12\lambda_g$	3 Varactor, 2 PIN	i. BSF ii. BPF	i. BSF when PIN ON ii. BPF when PIN OFF	0.95-1.35 0.95-1.35	3%-7% (3 dB FBW) 15% (3 dB FBW)	More than 13.0 4.7-5.6
[103]	$0.333\lambda_g \times 0.346\lambda_g$	6 Varactor, 1 PIN	i. Dual BPF ii. Dual BSF	i. BPF when PIN ON ii. BSF when PIN OFF	1.7-2.2 (lower), 2.2-2.7 (upper) 1.7-2.3 (lower), 2.3-2.9 (upper)	200 MHz (lower), 400 MHz (upper) 200 MHz (lower), 500 MHz (upper)	4.6-5.0 (lower), 4.6-5.6 (upper) More than 20.0
[104]	$0.084\lambda_g \times 0.084\lambda_g$	5 Varactor, 3 PIN	i. LPF ii. BPF I iii. BPF II	i. LPF when PIN OFF ii. BPF when PIN ON iii. BPF when PIN ON	0.59-1.48 0.85-1.25 1.04-1.6	NA 550-800MHz 140-215MHz	0.82-0.43 1.65-1.16 2.84-1.47
[105]	58 mm × 54 mm	4 Varactor, 3 PIN	i. BPF ii. BSF	i. Bandstop mode when D1 ON and D2-D3 are OFF ii. Bandpass mode when D1 is OFF and D2-D3 are ON	0.805-1.032 0.760-1.228	92-166 MHz (3 dB) 52-85 MHz (3 dB)	3.1-5.9 More than 40.0

IL: Insertion loss, BPF: Bandpass Filter, BSF: Bandstop Filter, ABW: Absolute bandwidth, FBW: Fractional bandwidth

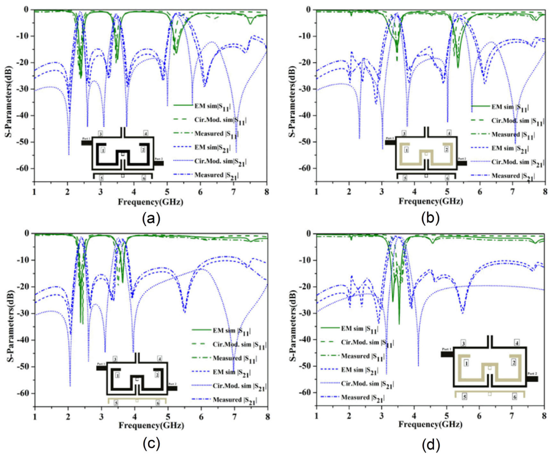


FIGURE 12. The frequency responses of PIN diode based switchable filter for 'Variable centre frequency variable bandwidth' [74] (a) Tri Band BPF (2.4/3.5/5.2 GHz) with FBW 7.9%/6%/9.1% when diode D1 and D2 are OFF (b) Dual Band BPF (3.5/5.2 GHz) with FBW 6%/9.1% when diode D1 is ON, and D2 is OFF (c) Dual Band BPF (2.4/3.5 GHz) with FBW 7.9%/6% when diode D1 is OFF, and D2 is ON (d) BPF (3.5 GHz) with FBW 6% when diode D1 and D2 are ON.

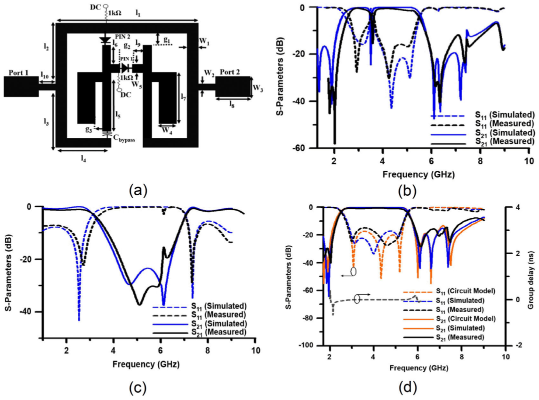


FIGURE 13. The geometric configuration and frequency response of PIN diode based switchable filter for 'Filter mode transformation' [86] (a) filter structure (b) BPF with notch band at 3.56 GHz response when PIN1 is ON, and PIN2 is OFF (c) BSF when PIN1 is OFF, and PIN2 is ON (d) BPF when PIN1 and PIN2 are OFF.

The three reconfiguration abilities of tunable filters, 'Variable centre frequency constant bandwidth', 'Constant centre frequency variable bandwidth', and 'Variable centre frequency variable bandwidth' can be involved in different forms of cognitive radio implementation. 'Variable centre frequency constant bandwidth' can facilitate the secondary

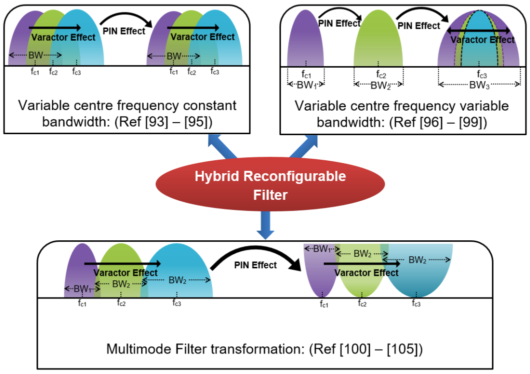


FIGURE 14. Hybrid reconfigurable filter categories.

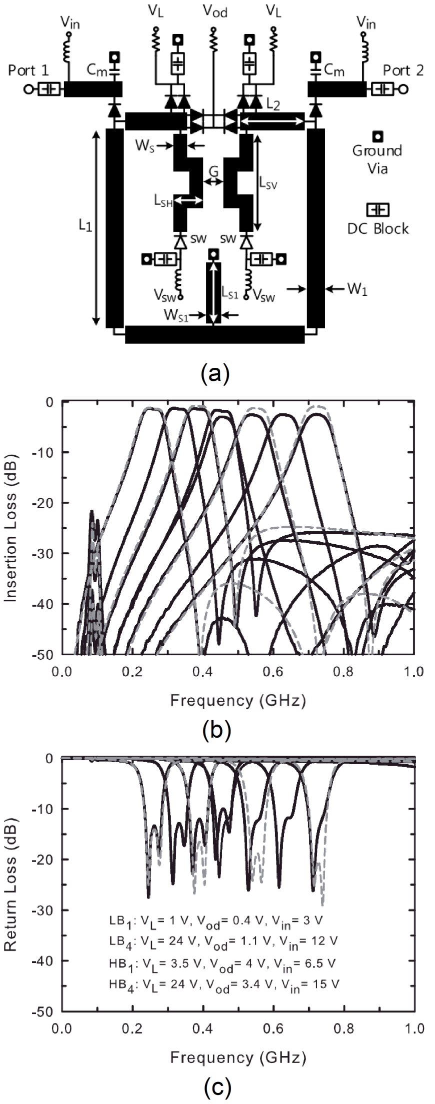


FIGURE 15. The hybrid reconfigurable filter for 'Variable centre frequency constant bandwidth' [93] (a) geometric configuration (b) insertion loss of both lower band (Both PIN diodes are OFF) and higher band (Both PIN diodes are ON) under the control of biasing voltages of varactor diodes (c) return loss of both lower band (Both PIN diodes are OFF) and higher band (Both PIN diodes are ON) under the control of biasing voltages of varactor diodes.

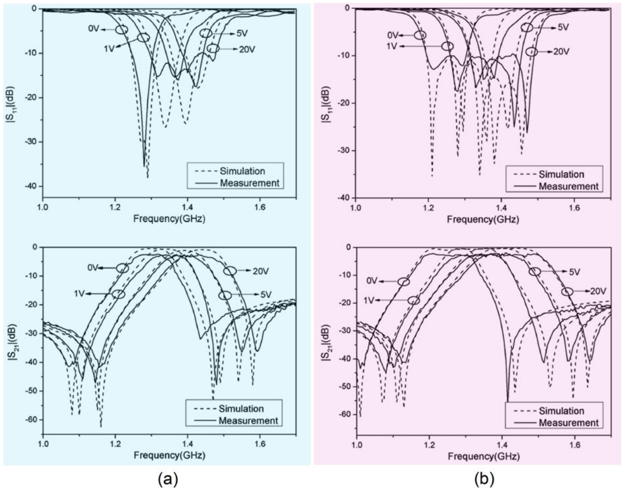


FIGURE 16. The frequency responses of hybrid reconfigurable filter for 'Variable centre frequency variable bandwidth' [99] (a) return loss and insertion loss BPF (Centre frequency tuning 1.25-1.45 GHz) with 8% FBW when PIN diode is OFF (b) return loss and insertion loss BPF (Centre frequency tuning 1.25-1.45 GHz) with 12% FBW when PIN diode is ON.

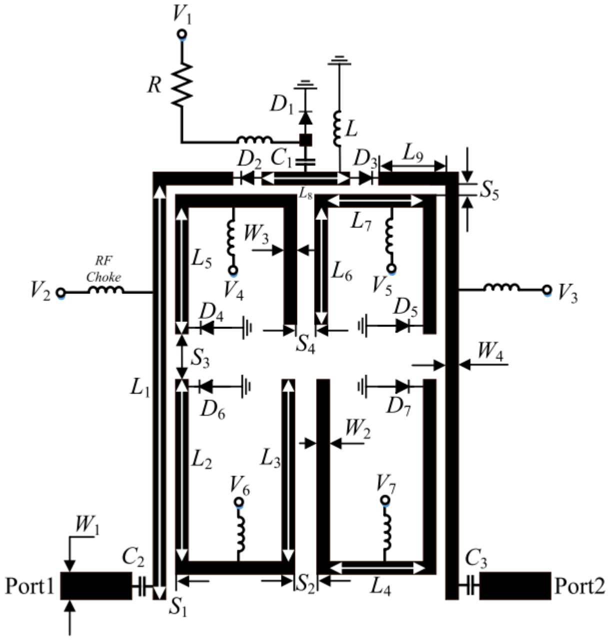


FIGURE 17. Geometric configuration of hybrid reconfigurable filter for Multimode transformation [103].

user to continue the communication by altering the carrier frequency as per the spectrum availability without changing the required bandwidth while the 'Constant centre frequency variable bandwidth' can enable the CR to adapt the rate of data transfer as per the availability of bandwidth following Shannon's theorem on channel capacity. This is extremely useful in the implementation of cognitive radio of variable bandwidth. 'Variable centre frequency variable bandwidth' can explore the opportunity of implementing secondary user communication with cognitive centre frequency and cognitive bandwidth approach.

The switchable filter uncovers 'Filter mode transformation' in addition to possibilities explored by tunable filters. CR may be in need to restrict the secondary user to

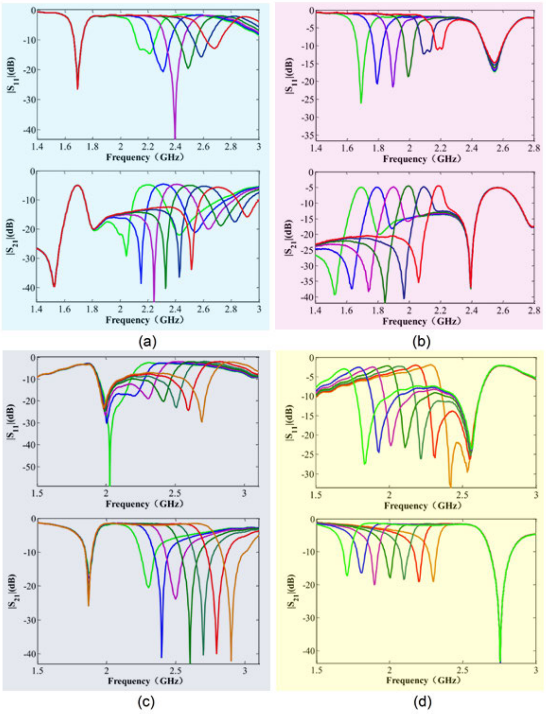


FIGURE 18. The frequency responses of hybrid reconfigurable filter for multimode transformation [103] (a) Dual Bandpass with fixed lower band but variable higher band when PIN diode is ON and V2=V3=30V, V4=V5=0∼6V, V6=V7=0V (b) Dual Bandpass with variable lower band but fixed higher band when PIN diode is ON and V2=V3=30V, V4=V5=3V, V6=V7=0∼30V (c) Dual Band stop with fixed lower band and variable higher band when PIN diode is OFF and V2=V3=0V, V4=0∼18V, V5=0.4∼30V, V6=1.9V, V7=1.6V (d) Dual Bandstop with variable lower band and fixed higher band when PIN diode is OFF and V2=V3=0V, V4=7.6V, V5=12V, V6=0.1∼30V, V7=0∼26V.

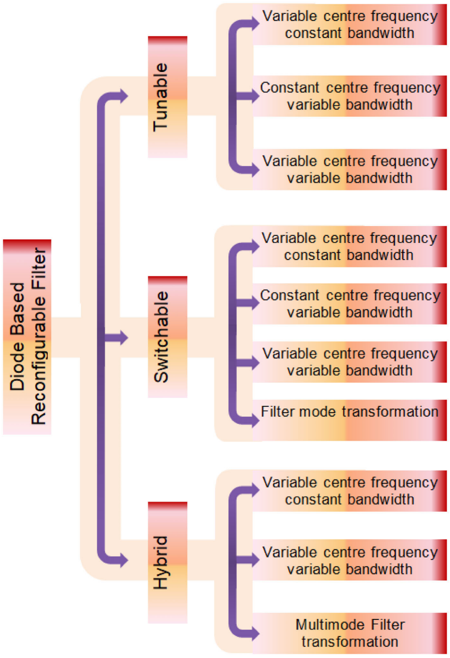


FIGURE 19. Summary for diode based reconfigurable filter categories.

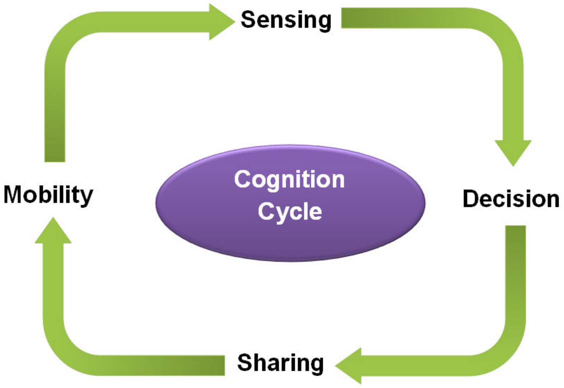
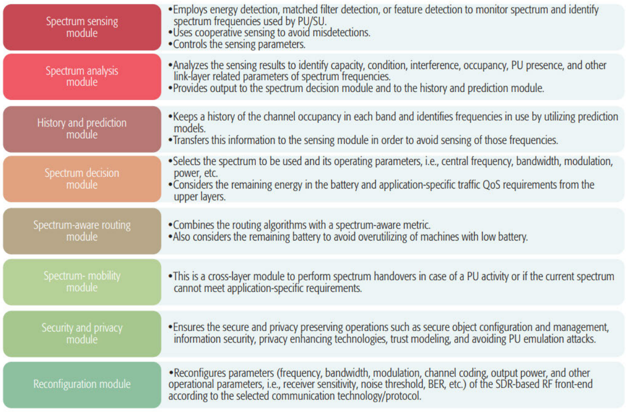


FIGURE 20. Common cognition cycle.



Spectrum sensing module	•Employs energy detection, matched filter detection, or feature detection to monitor spectrum and identify spectrum frequencies used by PU/SU. •Uses cooperative sensing to avoid misdetections. •Controls the sensing parameters.
Spectrum analysis module	•Analyzes the sensing results to identify capacity, condition, interference, occupancy, PU presence, and other link-layer related parameters of spectrum frequencies. •Provides output to the spectrum decision module and to the history and prediction module.
History and prediction module	•Keeps a history of the channel occupancy in each band and identifies frequencies in use by utilizing prediction models. •Transfers this information to the sensing module in order to avoid sensing of those frequencies.
Spectrum decision module	•Selects the spectrum to be used and its operating parameters, i.e., central frequency, bandwidth, modulation, power, etc. •Considers the remaining energy in the battery and application-specific traffic QoS requirements from the upper layers.
Spectrum-aware routing module	•Combines the routing algorithms with a spectrum-aware metric. •Also considers the remaining battery to avoid overutilizing of machines with low battery.
Spectrum- mobility module	•This is a cross-layer module to perform spectrum handovers in case of a PU activity or if the current spectrum cannot meet application-specific requirements.
Security and privacy module	•Ensures the secure and privacy preserving operations such as secure object configuration and management, information security, privacy enhancing technologies, trust modeling, and avoiding PU emulation attacks.
Reconfiguration module	•Reconfigures parameters (frequency, bandwidth, modulation, channel coding, output power, and other operational parameters, i.e., receiver sensitivity, noise threshold, BER, etc.) of the SDR-based RF front-end according to the selected communication technology/protocol.

FIGURE 21. An enhanced version of cognitive radio modules [107].

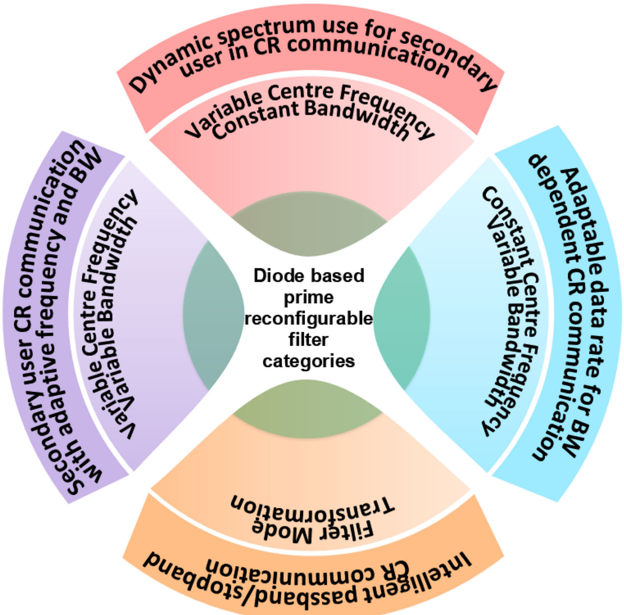


FIGURE 22. Prospective CR applications of diode based prime reconfigurable filter categories.

allow the primary in some particular frequency band. 'Filter mode transformation' can convert the filter from bandpass to bandstop to limit the secondary from participating in any licensed band communication.

The hybrid approach brings both tuning and switching action in filter characteristics with the use of both varactor diode and PIN diode. One new possibility has been explored with this complex approach as 'Multimode filter transformation.' This can enable the CR to adapt multiband acceptance or multiband rejection for fulfilling the need of a collaborative CR network.

Fig. 22 illustrates some prospective applications of prime reconfigurable filter categories for CR implementation. All of these possible outcomes could pave a new research path for the implementation of CR in the use of different customized wireless communication requirements.

VII. CONCLUSION

This article has addressed a comprehensive survey on diode based reconfigurable filters for cognitive radio applications. Three different types of reconfigurable filters based on diode were primarily reviewed: Tunable filter, Switchable filter, and Hybrid reconfigurable filter. Each type is further divided into subgroups. Filter response and controlling action of each subgroup have been illustrated with examples. Several research papers of each type, including the recently published ones, have been enlisted for exploring possibilities for CR implementation. A summary has been drawn to show the potential use of three types of reconfigurable filters for realizing CR systems. The work presented here may be of assistance to the researchers working on reconfigurable filter development for CR devices. Some application possibilities of reconfigurable filters may open up new opportunities in the implementation of cognitive systems in the future arena of wireless communication.

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HASHINUR ISLAM (Graduate Student Member, IEEE) received the B.Tech. degree in electronics and telecommunication engineering from the Institute of Electronics and Telecommunication Engineers (IETE), India, in 2014, and the M.Tech. degree in digital electronics and communication engineering from the Sikkim Manipal Institute of Technology, Sikkim Manipal University, in 2018. He is currently pursuing the Ph.D. degree with Sikkim Manipal University.

He has published over 12 refereed papers in journals and conference proceedings. His research interests include multiband antennas, fractal antenna, circular polarization on antennas, feeding mechanism for antenna, PIFA antenna, wearable antenna, antenna for embedded systems, microstrip filters, and so on. He is an Associate Member of IETE, India.

SAUMYA DAS received the B.Tech. degree in electronics and telecommunication engineering from the Institute of Electronics and Telecommunication Engineers (IETE), India, and the M.E. degree in electronics and communication engineering from the Delhi College of Engineering, University of Delhi.

He has more than 15 years of teaching experience with expertise in various subjects, such as electromagnetic field theory, antenna theory, microwave devices and circuits, signals and system, digital signal processing, and adaptive signal processing. He is currently an Assistant Professor with the Department of Electronics and Communication Engineering, Sikkim Manipal Institute of Technology, India. He has published several articles in reputed peer-reviewed international journals and conferences. His research interests include different feeding techniques for microstrip and dielectric resonator antennas, flexible and wearable antenna for tracking and medical application, computational mathematics for antenna designing, RF exposure testing on human-bodies, electromagnetic compatibility, and ultra wideband antenna designing. He is an Associate Member of IETE, India. He serves as a Reviewer for *Microwave and Optical Technology Letters (MOTL)* (Wiley), and *IETE Journal of Research* (Taylor & Francis).

TANUSHREE BOSE received the Ph.D. degree in design of printed antennas using neural network from the Department of Electronics and Communication Engineering, BIT, Mesra, India, in 2011.

She worked in RF and microwave antennas with soft computation. She is currently an Associate Professor with the Sikkim Manipal Institute of Technology, India. She has published over 30 refereed papers in journals and conference proceedings. She has completed one Government (AICTE) Sponsored Research Project on Patch Antenna Designing Using Artificial Neural Network and successfully guided her research scholars. Her current research interests include multiband antennas for handsets and networks, miniature antennas, reconfigurable antennas, EBG application on conformal antennas, flexible and wearable antennas, smart antennas, and so on. She served on many national and international technical committees.

TANWEER ALI (Senior Member, IEEE) is currently an Assistant Professor-Senior Scale with the Department of Electronics and Communication Engineering, Manipal Institute of Technology, Manipal Academy of Higher Education, Manipal. He is also an Active Researcher in microstrip antennas, wireless communication, and microwave imaging. He has published more than 90 papers in reputed peer-reviewed international journal and conferences. He is a member of the IEEE Antenna and Propagation Society and an Associate Member of IETE, India. He serves on the board of reviewers of journals, such as the IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION, the IEEE ANTENNAS AND WIRELESS PROPAGATION LETTERS, IEEE ACCESS, the IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES, the IEEE SENSORS, *IET Microwaves, Antennas and Propagation*, *Electronics Letters* (IET), *Wireless Personal Communication (WPC)* (Springer), *AEU-International Journal of Electronics and Communications*, *Microwave and Optical Technology Letters (MOTL)* (Wiley), the *International Journal of Antennas and Propagation* (Hindawi), *Advanced Electromagnetics*, *Progress in Electromagnetic Research (PIER)*, *KSII Transactions on Engineering Science*, Korea, the *International Journal of Microwave and Wireless Technologies*, *Frequenz*, *Radioengineering*, and so on.

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