FACTA UNIVERSITATIS
Series: **Electronics and Energetics** Vol. 38, Nº 4, December 2025, pp. 681 - 695
https://doi.org/10.2298/FUEE2504681B

Original scientific paper

DESIGN OF A RECONFIGURABLE MICROSTRIP FILTENNA USING π-SHAPED FILTER

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Abstract. *In this paper, a novel proposal is presented for the design features of a compact reconfigurable circular patch antenna capable of switching between different frequency bands. The filtenna or filtering antenna comprises of a circular patch antenna offering ultra-wideband (UWB) performance and a π-shaped RF filter integrated with feed line to provide filtering functionality and reconfigurability. Additionally, three switches are incorporated into the filter at the intersections of the stubs with the feed line and at the connection point between the feed line and the patch antenna. When considering a system with three switches, there are a total of eight distinct various configurations of switch states. Each of these combinations is associated with unique frequency and pattern properties. The proposed antenna exhibits excellent compatibility with Wi-Max, Wireless LAN, and ultra-wide band applications, ensuring minimal disturbance from neighboring systems. The circular patch antenna, featuring a circular shape, exhibits exceptional performance within the UWB frequency spectrum spanning from 2 GHz to 10 GHz, all the while operating without the inclusion of a filtering network. The π-shaped RF filter is designed to target specific frequencies: 4.27 GHz 3.51 GHz, 3.93 GHz, 5.185 GHz, and 2.93 GHz. The radiation characteristics further elucidate the substantial gain observed at the central frequencies that correspond to distinct switching states (ON and OFF). The proposed antennas have been successfully fabricated and subsequently subjected to meticulous measurements using network analyzer MS2037C. Based on careful observation, it is anticipated that there will be an excellent degree of agreement between the measured and simulated results.*

Key words: *Reconfigurability, Filtenna, π-shaped RF filter, Ultra-Wide Band (UWB).*

Received December 15, 2024; revised April 02, 2025 and April 10, 2025; accepted April 12, 2025
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1. Introduction

In ultra-wide band wireless communication systems, which are utilized in many different wireless applications, filters and antennas are essential components. It is necessary to scale the most modern UWB antennas to fit into tiny devices. Microstrip Patch Antennas (MPAs) printed directly onto the circuit board are ideal for many electromagnetic applications. Microstrip antennas are ideal in several UWB applications because they are narrow, inexpensive, and simple to incorporate on a number of VLSI circuits. A wide range of antenna configurations and categories have been widely stated to demonstrate the fundamental capabilities of ultra-wide band operation [1]. The most common challenges faced by UWB antennas are interference from nearby devices and insertion loss. To minimize interference from neighbouring circuits, implement an RF filter with band-selecting capabilities. In modern applications, there is an increasing tendency to combine RF filters with antennas into a one unit to minimize insertion-loss and decrease the overall dimension of the system.

There are different techniques available for filtennas design; however, their appropriate choice depends on their particular application. The various techniques like co-design, synthesis approach, multilayer structure, slot/slit, or parasitic elements are used for filtenna design. More specifically, in the co-design technique, the antenna and filter are combined without inter-stage impedance matching. Thus, reducing mismatch losses and size and provide improved performance. In contrast, the synthesis technique, the last resonator of the filter, is integrated into the antenna, which acts as a load for the filter. Although high selectivity and bandwidth are the key advantages of the synthesis technique due to the large numbers of resonators, making the design is more cumbersome. However, in both methods (i.e., co and synthesis), an additional and extra filter is required in the filtenna design which in turn increases the overall size of the design. Therefore, in the recent literature a new design approaches are developed like, use of multilayers and parasitic elements where the extra filter is not required. With these, multilayer structure, both filter and antenna properties are integrated into the same structure. On the other hand, parasitic elements suppress harmonics and increase selectivity. But, these designs are bulky in nature. To reduce the complexity in the design and reduce the overall size of the system a novel method is proposed in this article, i.e., defected microstrip structure. In this technique, filter is directly connected to the feed line of the patch. The proposed method avoids the usage of the extra filter, no need of using resonators, reduces the size and also increases the overall performance of the design in terms of bandwidth and radiation characteristics.

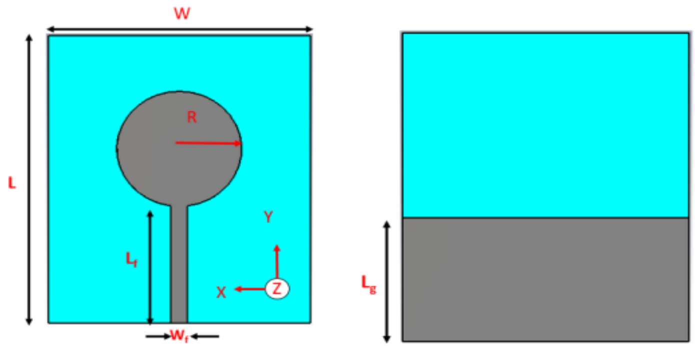
2. Related Work

In the context of this study, it has been observed that filtering antennas exhibit band-selective frequency operation within the range of references [2-9]. In [2], parallel coupled microstrip lines used with printed inverted-L-shaped filtering antenna is reported. A filtering dielectric resonator antenna is proposed in [3], fed by microstrip-coupled slot. A combined ring slot and shorting vias are used to design an omnidirectional filtering patch antenna in [4]. The feed network using microstrip-to-slot line transition is used to design a planar dipole filtenna in [5]. In [6], switchable filtenna is designed for various networking applications. In [7], hairpin bandpass filter is used to design printed elliptical filtenna. The design of a wideband and high-gain metasurface antenna is presented in [8]. The design of a compact semi-circular patch antenna is reported in [9]. In recent years, several proposals have been put towards the utilization of horn antennas equipped with filtering circuits [10–11], UWB antennas integrated with filters [12–14], filtering antennas based on substrate integrated waveguide (SIW) technology [15–16], and balanced filtering notch antennas [17]. All of these structures have been developed with the filter synthesis methodology. This methodology offers a reliable filtering process, but with consequential impacts on antenna gain and far-field radiation characteristics as a result of filter noise and insertion loss. Another option is to create a filtering antenna by incorporating a basic parasitic element or resonator into the patch or its feed line. This approach allows for a reduction in antenna size and minimization of insertion loss.

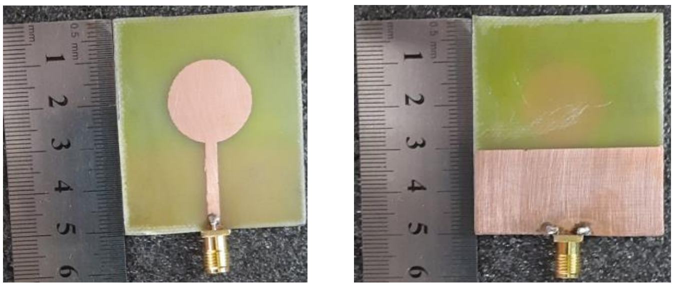
This paper presents the design and analysis of frequency switchable filtering microstrip antenna. The substrate used for the antenna has a ε_r=4.7 and a height of 1.6mm. The antenna is enhanced by attaching microstrip discontinuities and stubs [18]. Moreover, the introduction of reconfigurability in the structure is achieved by incorporating three switches. These switches, when in their ON or OFF states, result in distinct pass band and pattern properties. Using the recently developed new planar filters [19-21], the performance of planar filtennas may be improved. There are four sections to the current research.

3. Design and Implementation

The filtering antenna features a substrate with ε_r = 4.4 and a height of 1.6 mm. The implementation of the reconfigurable filtering microstrip antenna is executed in a 2-phase approach.



(a) Front & Rear view of the simulated circular patch antenna



(b) Top & bottom views of the fabricated circular patch antenna

Fig. 1 Structure of the proposed circular patch antenna

In phase-1 approach, circular patch antenna is implemented with transmission line feed. The circular monopole patch antenna is selected due to its ability to support Ultra-Wideband (UWB) operation, while minimizing metallization on the radiating surface. Its symmetrical geometry facilitates uniform current distribution, resulting in consistent radiation patterns and reliable impedance matching over a broad frequency spectrum. Fig.1 depicts the simulated and constructed designs for the UWB monopole antenna, as well as the top and bottom perspectives. The optimal specifications of the circular monopole disc antenna are shown in Table 1. The suggested ultra-wide band circular antenna is successfully fabricated and subsequently subjected to meticulous measurements using network analyzer MS2037C. The measurement setup with VNA is depicted in Fig. 2.

Table 1 Optimized measurements of the proposed circular patch Antenna

SI. No	Dimensions	size (mm)
1.	Substrate length (L)	50.0
2.	Substrate Width (W)	42.0
3.	Microstrip line length (L_f)	20.30
4.	Feed Width (W_f)	2.60
5.	Patch Radius (R)	10.0
6.	DGS length (L_g)	24.0

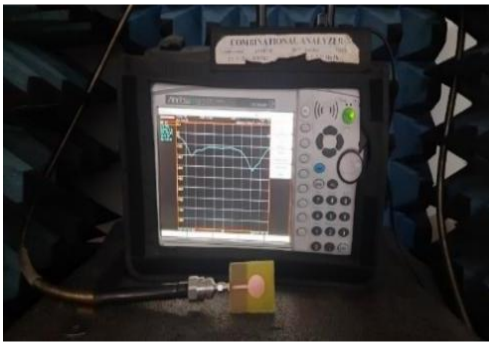


Fig. 2 Measurement setup for the circular patch antenna

In phase-2, a π-filter is added to provide the filtering functionality. A π-filter is a type of passive filter which is widely used in RF and power supply applications. It is named for its resemblance to the Greek letter π when represented schematically. The filter design consists of two conductors spaced by an appropriate distance. The π-filter is formed by cascading 2 T-junctions (with parallel stubs) and a microstrip line. Typically, it consists of a combination of capacitors and inductors configured to achieve desired filtering characteristics. The π-filter is designed with following specifications.

Impedance Z_0 = 50 Ω
Cut-off frequency f_c = 3 GHz
Equi-ripple = 0.5 dB.
Rejection band = 20 dB at 2*f_c
The normalized frequency = W / W_c = 2

The Chebyshev band pass filter prototype is chosen with equi-ripple response of 0.5 dB. The ripple is controlled in the passband, and a steep roll-off ensures significant attenuation in the stop band. The Chebyshev attenuation is given by [23-24]

$$A_S = 10\log_{10}\left(1+\in^2 \cdot T_n^2\left(\frac{W}{W_c}\right)\right). \quad (1)$$

The Ripple factor:

$$\in = \sqrt{10^{\frac{Ripple}{10^{-1}}}}. \quad (2)$$

The ripple value is 0.5 dB, then the Ripple factor is ∈ = 0.3317. As A_S = 20dB, W / W_C = 2, $T_n\ (W / W_C)$ is nth order Chebyshev polynomial

$$T_n\left(\frac{W}{W_c}\right) = \sqrt{\frac{10^{\frac{A_S}{10}-1}}{\in^2}} \quad (3)$$

The Chebyshev polynomial $T_n\ (x)$ for x = 2 is

$$T_n(2) = \cosh(n.\cosh^{-1}(2)) \quad (4)$$

The normalized frequency is 2, with an attenuation of 20 dB. Using the filter response curve for a Chebyshev filter with 0.5 dB ripple, the required filter order (N) for the design is determined. Based on a 20 dB attenuation and a normalized frequency of 2, the filter order is found to be 4. For a 4th-order Chebyshev low-pass filter with 0.5 dB Equi-ripple, the corresponding normalized low-pass prototype element values are g_i listed in Table 2.

Table 2 Chebyshev filter coefficients with 0.5dB ripple

N	g_1	g_2	g_3	g_4	g_5
1	0.6986	1.0000			
2	1.4029	1.1256	1.0000		
3	1.5408	0.7071	1.9841	1.0000	
4	1.7058	1.2296	2.5408	1.2296	1.7058

For filter order N=4 and using filter coefficients from Table-2 the filter coefficients are determined as g_1=1.70580, g_2=1.22960, g_3=2.54080, g_4=1.22960 & g_5=1.70580. Using these values, the capacitor and inductor values are calculated for the equivalent circuit shown in Fig. 3. Fig. 3 illustrates the equivalent circuit of the π-shaped filter with order N=4, utilizing discrete L and C components. In the π-topology g_1, g_3 and g_5 corresponds to shunt capacitors and g_2 and g_4 corresponds to series inductors respectively.

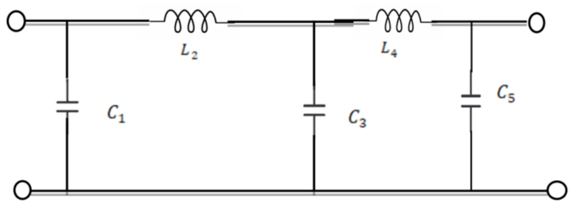


Fig. 3 π- section filter with order N=4

The component scaling equations are based on the impedance (Z_0 = 50 Ω) and cutoff frequency (f_c = 3 GHz). The normalized capacitance (shunt elements) and inductance (series elements) of the prototype is

$$C_n = \frac{g_n}{2\pi f_c Z_0} \tag{5}$$

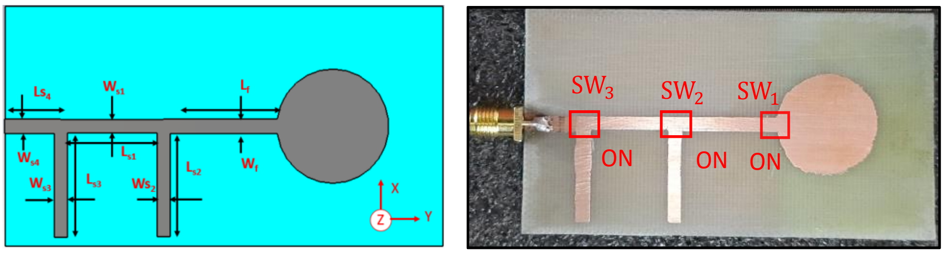
$$L_n = \frac{g_n Z_0}{2\pi f_c} \tag{6}$$

The inductor and capacitor values are determined by using the above equations. The optimized values for the capacitors and inductors are provided in Table 3.

Table 3 The final component values of the π- section filter

S. No	Element	Value
1.	C_1	1.81pF
2.	L_2	3.26nH
3.	C_3	2.70pF
4.	L_4	3.26nH
5.	C_5	1.81pF

Now, the proposed π-shaped filter is added to the feed line of the circular patch antenna to attain frequency selectivity. To enable frequency reconfiguration, 3 switches are coupled at the filter and feed line junctions to design a microstrip filtering antenna. The design of the circular patch antenna at a particular resonance frequency is started with the formula, given in [22]. The complete dimension of the filtering antenna, after simulation, is 80x42x1.6 mm^3. The front view of the simulated and fabricated filtering antenna is depicted in Fig.4. The optimized dimensions of the filtering antenna structure are tabulated in Table 4 and the equivalent circuit of the microstrip filtering antenna is depicted in Fig. 5.



(a) Simulated Filtering antenna (b) Fabricated filtering antenna

Fig. 4 Simulated and fabricated design of filtering antenna

Table 4 Optimized dimensions of the microstrip filtering antenna

S. No	Parameter	Value (mm)
1.	L_{s1}	18.36
2.	W_{s1}	2.31
3.	L_{s2}	19.4
4.	W_{s2}	2.31
5.	L_{s3}	19.2
6.	W_{s3}	2.31
7.	L_{s4}	10.0
8.	W_{s4}	2.60

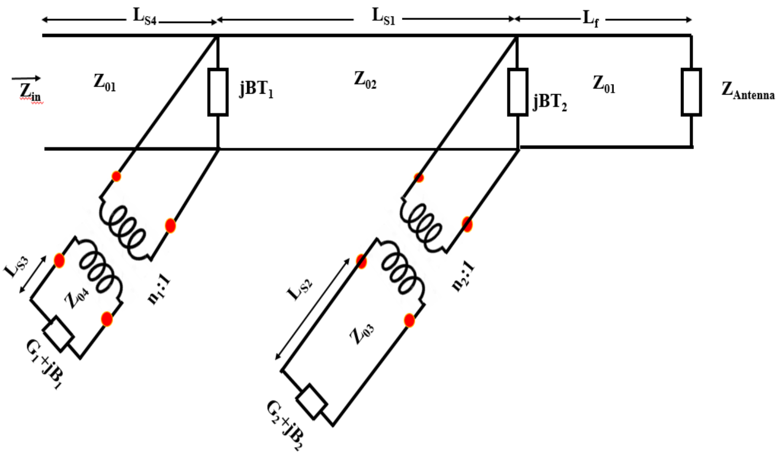


Fig. 5 Circuit model of an antenna with filtering capabilities

In the suggested microstrip filtering antenna configuration, depicted in Fig. 5, three switches are presumed at specific locations to accomplish the frequency reconfigurability. From the antenna side, SW-1 is positioned among the feed line and the antenna; SW-2 is positioned at the 1st T-intersection; and SW-3 is positioned at the next T-intersection. The filtering antenna with switch positions is depicted in Fig. 6.

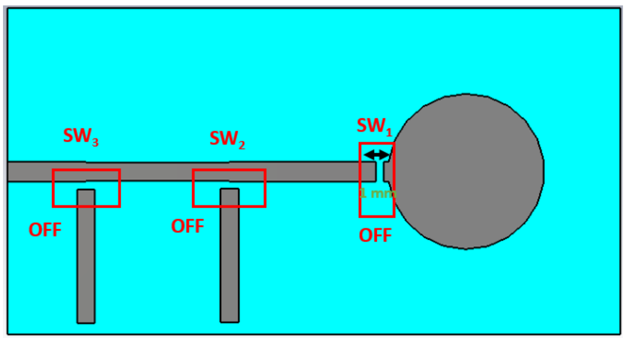


Fig. 6 Filtering microstrip antenna at 000 Boolean combination

To simplify modeling, switches are represented as ideal open or short circuits. A switch in the ON state is equivalent to a continuous conductive path, while the OFF state represents a discontinuity in the path.

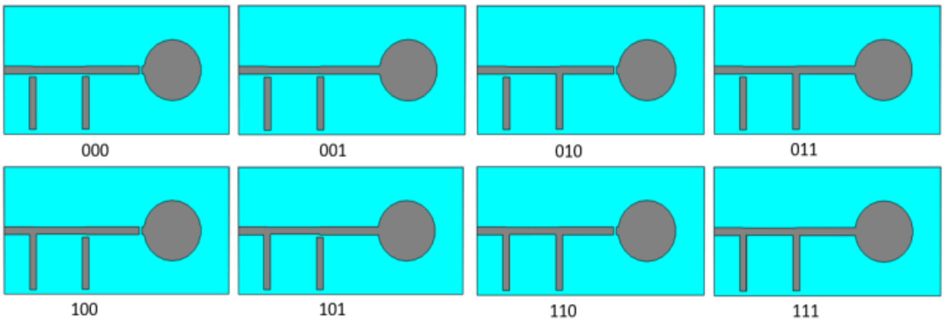


Fig. 7 All eight possible combinations of switches

The two-state switches are represented in Boolean form as 1 (ON) and 0 (OFF). There are eight different state combinations for three of the switches in the suggested configuration. For example, suppose each of the 3 switches is in the open circuit or OFF state. Fig. 7 depicts simulations of all eight switching combinations.

4. Results and Discussion

The filtenna is simulated using 3D EM tool CST MWS Studio. Then the filtenna is fabricated and measurement is done using vector network analyzer.

4.1. Impedance Characteristics

Fig. 8 illustrates the parametric sweep analysis of the ground plane. The Lg of the ground plane is varied from 20 mm-26 mm and it is optimized to 24 mm. For Lg = 24mm the minimum S_{11} of -54 dB at 8.5 GHz.

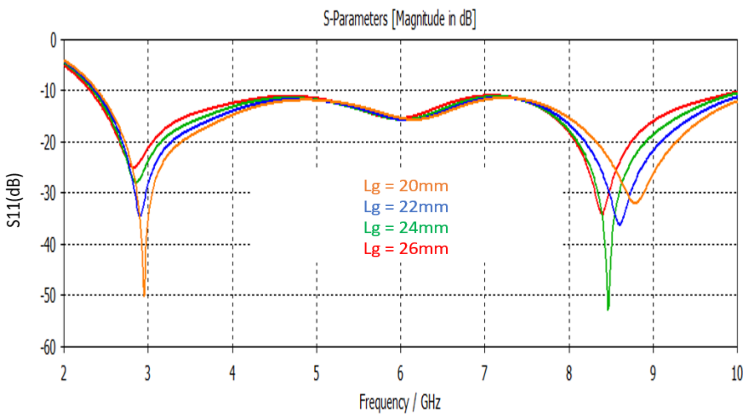
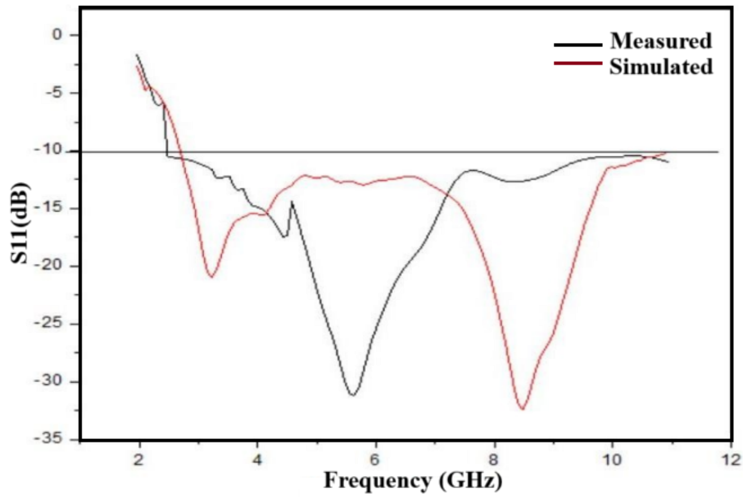
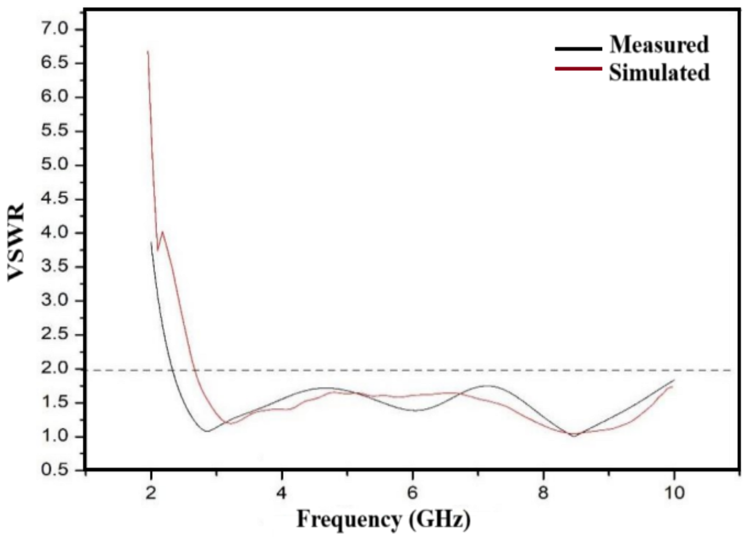


Fig. 8 Variation of S11 with the length of the ground plane

The simulated and measured S_{11} and VSWR characteristics of the planar circular patch antenna after simulation using Finite Integration Technique is presented in Fig.9. The proposed circular patch antenna demonstrates ultra-wideband (UWB) operation, spanning 2.4 GHz to 12 GHz. The S_{11} plot confirms UWB performance, with minor variations in S11 attributed to fabrication losses. Fig. 9(b) shows the simulated and measured VSWR plot, revealing a VSWR value below 2 across the entire UWB frequency range.



(a) Simulated and measured S_{11} plot



(b) Simulated and measured VSWR plot

Fig. 9 Variation of S_{11} & VSWR with frequency for the circular monopole antenna

The proposed microstrip filtering antenna achieves frequency selective characteristics by incorporating three switches with the filter in design phase-2. The resulting simulated and measured S_{11} plot is shown in Fig.10. By operating these three switches the filtering antenna can be used to operate at different applications like Bluetooth, Wi-Fi, WLAN and also X-band applications. Due to the filter the sharp operating band are also achieved by rejecting the out of band frequencies.

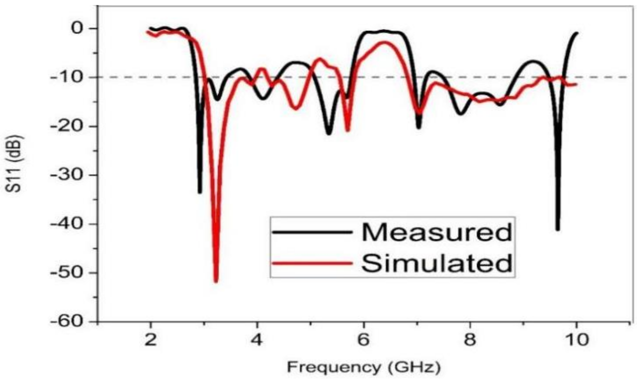


Fig. 10 Simulated and measured return loss plot of the filtering antenna

To provide frequency reconfigurability, the filtering antenna is equipped with three switches. Fig. 11 displays the S_{11} parameters of the filtering microstrip antenna, featuring a π-shaped filter, for four switching conditions (identified in Fig. 7). In the 000 switch state, the antenna functions as a narrowband filter centered at 4.28 GHz with an S_{11} of -16.92 dB. Switching to the 001 state enables multi-frequency operation at 3.51 GHz, 4.31 GHz and 8.91 GHz, with S_{11} values of -29.23 dB, -23.92 dB & -32.18 dB, respectively, making it suitable for Wi-Max applications.

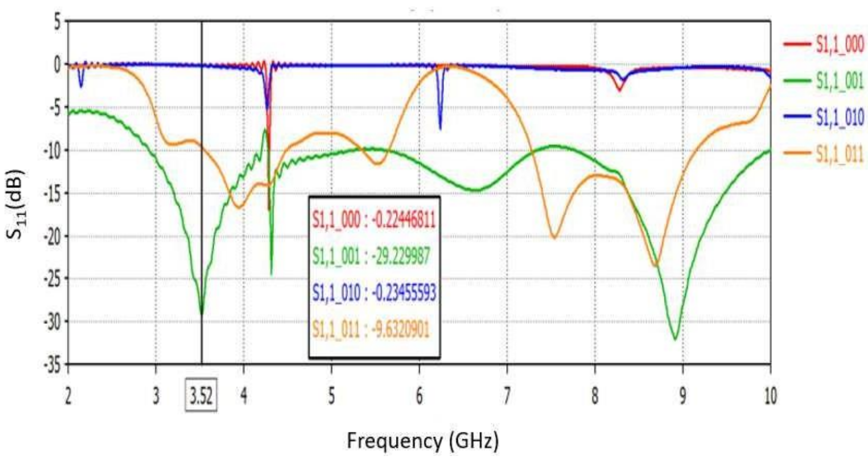


Fig. 11 S_{11} Vs Frequency plot for switching combinations 000, 001, 010, and 011

When SW-2 is on and SW-1 and SW-3 are OFF, the antenna rejects signals across the full ultra-wide band frequency range. Conversely, when SW-1 OFF and SW-2 and SW-3 are on, the antenna supports dual-band operation, covering 3.55-4.49 GHz and 7.28-9.15 GHz, making it suitable for W-Max and (8-12GHz) (X-band) applications.

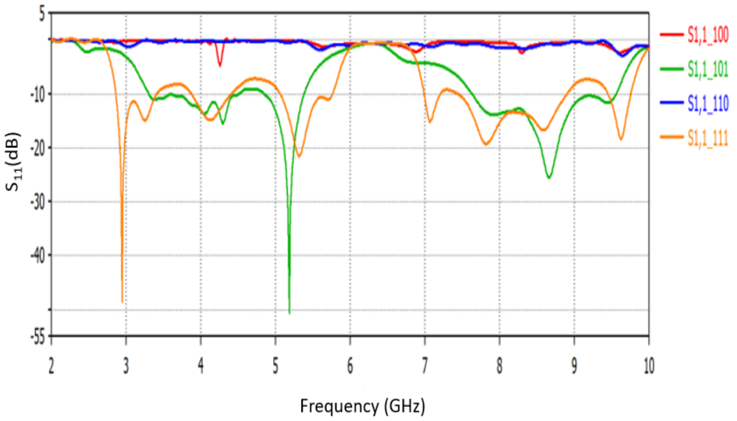


Fig. 12 S_{11} Vs Frequency plot for switch conditions 100, 101, 110, and 111

As shown in Fig.12, the S_{11} parameters for the last four switch combinations reveal that the intended antenna acts as a Band Rejection Filter (BRF) for the whole UWB spectrum when in the 100 and 110 switch states. With SW-1 and SW-3 on and SW-2 OFF (101), achieves excellent narrowband performance at 5.183 GHz, with an S_{11} of -50.61 dB, suitable for WLAN applications. When all switches are activated, the antenna functions as a narrowband antenna at 2.94 GHz, with an S_{11} of -48.57 dB, making it suitable for Bluetooth and W-Max applications.

4.2. Radiation Characteristics

The circular patch filtenna far field realized gain plot is displayed in Fig. 13. The monopole antenna operates at 2.94 GHz with a max. Gain of 4.41dBi.

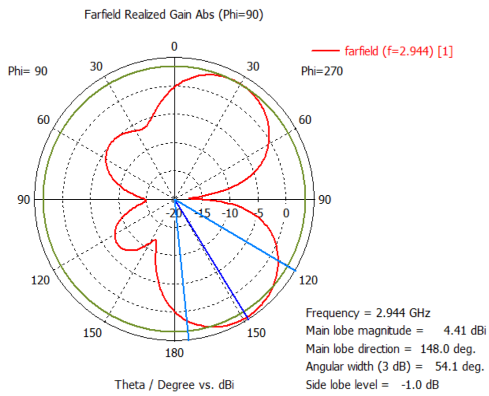


Fig. 13 Far-filed gain plot for the circular patch filtenna

The Gain patterns of the filtering antenna are illustrated in Fig.14, showcasing its performance at multiple frequencies and switching states. The above plot indicates that the antenna achieves adequate gain values across all operating frequencies.

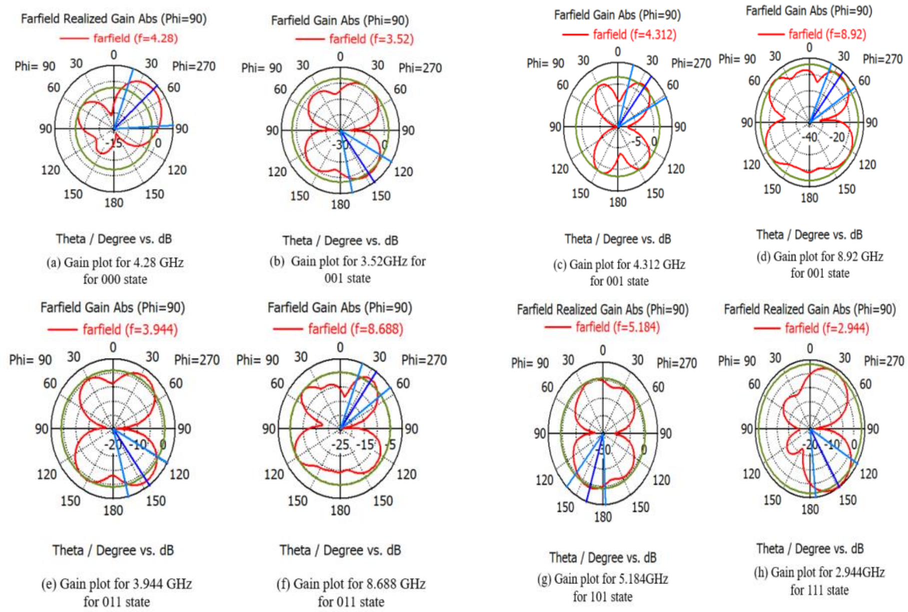


Fig. 14 Far-field gain plots of the filtering antenna in 2D for various switch states

As illustrated in Fig. 14(d), the filtering antenna reaches maximum gains of 5.8 dBi at 8.91 GHz in the (001) switch state, and 3.38 dBi at 4.27 GHz in the (000) switch state. Peak gains of 3.51 dBi, 3.06 dBi, and 5.80 dBi are found at 3.51 GHz, 4.3 GHz, and 8.91 GHz, respectively, in the (001) switch state. The (011) state exhibits peak gains of 2.88 dBi and 5.66 dBi, while the (101) state has a peak gain of 3.08 dBi. For 111 condition, a peak gain of 4.58 dBi is recorded at 2.92 GHz.

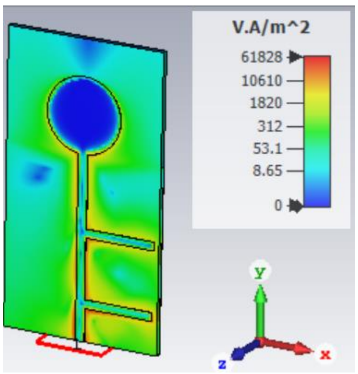


Fig. 15 Current distribution plot of the proposed microstrip filtenna

Fig. 15 shows the current distribution plot of the proposed microstrip filtenna at a frequency of 8.92 GHz. From the current distribution plot it is clearly observed that the maximum current is distributed at the edges of the π-shaped filter. Conversely the minimum value of the current is distributed at the center of the patch. Except the edges there is a uniform current distribution is observed through the entire substrate. Table 4 provides a comprehensive summary of all switch configurations.

Table 4 Summary of the operating characteristics of the filtering antenna

SI. No	Sw1	Sw2	Sw3	Frequency (GHz)	S_{11} (dB)	Bandwidth (MHz)	Maximum Gain (dBi)
1.	OFF (0)	OFF (0)	OFF (0)	4.28	-16.93	176.3	3.386
2.	OFF (0)	OFF (0)	ON (1)	3.52, 4.31 & 8.92	-29.22, -24.40 & -31.97	1284, 960 & 2223	3.516, 3.064 & 5.808
3.	OFF (0)	ON (1)	OFF (0)	Band rejection filter (BRF)			
4.	OFF (0)	ON (1)	ON (1)	3.94 & 8.68	-16.93 & -23.42	937 & 1875	2.89 & 5.665
5.	ON (1)	OFF (0)	OFF (0)	Band rejection filter (BRF)			
6.	ON (1)	OFF (0)	ON (1)	5.184	-50.6	544	3.07
7.	ON (1)	ON (1)	OFF (0)	Band rejection filter (BRF)			
8.	ON (1)	ON (1)	ON (1)	2.93	-48.50	542	4.59

Table 5 Performance comparison of π-filtenna with other filtering techniques

Ref. No	YoP	Size (mm^2)	Type of the filter	Resonance frequency	Bandwidth	Peak Gain (dBi)
[25]	2012	120X12	SIW inductive window BPF	14.4 GHz	380 MHz	3.6
[26]	2016	90.3X83.8	Open-loop resonator filter	900 MHz & 1900 MHz	60 MHz & 70 MHz	1.1 & 2.7
[27]	2019	136.09X50	Four rectangular cavities	5.025 GHz & 5.125 GHz	50MHz & 65MHz	6.2 & 2.5
[28]	2018	187.2X92.6	Reconfigurable SIW filter	2.07 GHz	210MHz	2.03
[29]	2018	310X36	Substrate integrated waveguide	4.5 GHz & 6.4 GHz	155 MHz & 950MHz	4.08
[30]	2017	170X140	Split-Ring Resonator (SRR)	10 GHz	4.2GHz	3.68
[31]	2019	212.73X127.65	Mechanically tunable filter with dual-post resonators	3.03GHz & 20.75GHz	940MHz & 6.5GHz	2.6 & 3.5
[32]	2017	80X60	Ring slot Resonator Filter	2.875GHz	650MHz	2.2 & 3.1
- -		78X42	π- shaped filter	2.93GHz, 3.52GHz, 4.31GHz, 5.18GHz & 8.68GHz	542MHz, 1.28GHz, 960MHz, 544MHz & 1.87GHz	4.59, 3.516, 3.064, 3.01 & 5.66

The performance comparison of the current work is compared with other recent works and presented in Table 5. From the comparison, the overall dimension of the proposed filtenna is reduced with improved performance in terms of impedance bandwidth and gain characteristics.

6. CONCLUSION

This research presents the design and analysis of a compact, reconfigurable π-shaped microstrip filtenna with adaptable spectrum choosing capabilities. Reconfigurability is achieved through the incorporation of three switches, simulated using equivalent short-circuited and open-circuited circuits. Simulation results reveal that when all switches are activated, the filtering antenna selectively operates within a limited frequency range within the UWB band, mitigating potential interference with adjacent communication systems. The S_{11} properties reveal that the proposed structure can operate across multiple frequency bands, centered at 2.93 GHz, 3.51 GHz, 3.93 GHz & 4.29 GHz, 4.30 GHz, 5.17 GHz, 8.67 GHz, and 8.91 GHz, depending on the specific switch conditions. The proposed filtering antenna is capable of operating as a BRF across the complete ultra-wide band for particular switch combinations. It also demonstrates peak gain values spanning 2.88 dBi to 5.80 dBi, with distinct pattern features.

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