Switchable Square Ring Bandpass to Bandstop Filter ultra-ideband Applications

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SWITCHABLE SQUARE RING BANDPASS TO BANDSTOP FILTER
FOR ULTRA-WIDEBAND APPLICATIONS

Abstract:
Filters are the basic elements of transceivers that can be either pass-band or stop-band components. In this study, a switchable filter is upgraded such that it changes from bandpass to bandstop filter in the same ultra-wideband (UWB) range. The bandpass filter consists of four square ring resonators of quarter wavelength and a connecting stub of quarter wavelength. The main advantage of this microstrip filter is its capability to switch from bandpass to bandstop operation. The bandpass filter reconfigures to bandstop filter, when the gap was made in the corners of the square ring resonators, is open or short using Skyworks RF PIN diodes. Measured results of the BPF prototype exhibit three transmission zeros \((f_{z1} = 6.75\, \text{GHz}, f_{z2} = 15.67\, \text{GHz}, \text{and } f_{z3} = 16.68\, \text{GHz})\), and six transmission poles. The prototype has a rejection bandwidth of more than 2 GHz and an insertion loss of 1.5 dB within the transmission band from 11.225 GHz to 14.533 GHz. In addition, the BSF prototype shows a return loss response with ripple value of 1.5 dB in almost band, and three transmission zeros \((f_{z1} = 6.372 \, \text{GHz}, f_{z2} = 16.203 \, \text{GHz} \text{and } f_{z3} = 16.957 \, \text{GHz})\). The rejection band of the lower band is better than the upper band, which are 1.6 and 0.756 GHz at 10 dB, respectively. All the presented filters have been modeled and their corresponding performances have been evaluated using CST microwave studio. Finally, the PIN diode is modeled using CST microwave studio as a practical structure. Computed results of the proposed filters were compared with the measured results of the both prototype structures (BPF and BSF). The codes also showed good agreement between them. Other advantages include being small in size, and low in effective-cost.

1. Introduction
A single filter cannot investigate the filtering requirements of transceivers operating in wireless local area network (WLAN) and ultra-wide band, and the use of bank of filters occupy a large space [1]. Current applications, such as microwave and wireless systems, usually require small components to meet the required miniaturization. However, implementing both reconfigurable bandpass and bandstop filter banks would be unreasonable because of size constraints. Thus, a switchable bandpass-to-bandstop filter
constitutes a promising solution to this problem to miniaturize the entire wireless communication system. This kind of filter allows the selection of various frequency bands of operation by using a single filter with embedded switchable components [1]–[3] to not only reduce the area but also allow the system become flexible. In a broad sense, critical issues must be considered when selecting an exact technology to reconfigure microstrip switchable filters. Such issues include the frequency band of operation, tuning speed of electronic component, and resulting size. The latest wireless communication systems require low cost, high controllability, and miniaturized circuits with enhanced responses [4]–[6].

Naglish et al. presented bandpass-to-bandstop tunable filter in [7]. However, the observed narrowband frequency as well to high cost-effective and the complexity in his design were very clear. To the best of our knowledge, very few researchers have dealt with the switchable bandpass-to-bandstop [8]–[10]. An electronically reconfigurable filter was presented by [8] to achieve bandpass-to-bandstop response. An electronic band gap (EBG) design was used for the frequency-selective behavior of this filter. However, the use of low Q resonators resulted in spectrally wide responses. In addition, the filter was not tunable. The second design espoused the ring resonator with series-resonated varactor diode as perturbation component to achieve bandpass-to-bandstop characteristic. However, the resulting skirt of the narrow bandpass/bandstop filter was not very good [9]. Bended short stubs and half guided wavelength line connected to the terminals of the bent stub were adopted to configure the square ring resonator and obtain ultra-wideband (UWB) switchable bandpass/bandstop filter by PIN diode [10]. However, bad roll-off at the lower bandpass and increased critical transmission band characteristics were observed. This research aimed to design a new switchable bandpass-to-bandstop microstrip filter involving square ring resonators with new serial shunt configuration. Switchable bandpass-to-bandstop filter has exhibited many good properties in terms of high transmission band, and sharp roll-off led to high selectivity filter and UWB applications.

2. The proposed filter design

Figure 1 shows the proposed structure of the new filter topology. The target is to achieve the switchable bandpass-to-bandstop (BPF/BSF) responses with separate tuning electronic semiconductor device. The substrate Duroid Rogers RO5880 is used as a platform with
dielectric thickness $h = 0.787$ mm, relative effective dielectric constant $\varepsilon_{\text{eff}} = 2.2$, loss tangent $\delta = 0.0009$, and copper thickness $t = 0.0017$ mm. The ground plane of this filter occupies the whole back face of the substrate. The filter structure consists of a main ring resonator with a sidelength $\ell_{\text{ring}} = 11.8$ mm, which is equivalent to $(\approx \lambda_g / 2)$ at the center frequency of 11 GHz, with a line width $w_{\text{ring}} = 0.64$ mm. Every side is folded from its ends up to $\approx \lambda_g / 8$ and then connected to the other sides. The result in the main ring resonators is shown in Figure 1-a.

The corners of the main ring are replaced by the four small square ring resonators as shown in Figure 1-b. Each side of the small square ring resonator measures $\ell_{\text{pad}} = 5.8$ mm that is equivalent to $(\approx \lambda_g / 4)$ and shows line width $w_{\text{pad}} = 0.64$ mm at resonance frequency of 11 GHz calculated on basis of the Equation 1.

$$f_0 = \frac{nc}{\lambda_g \sqrt{\varepsilon_{\text{eff}}}} \quad \text{Equation1}$$

where $f_0$ the center frequency, $n$ is the number of modes, $c$ is the speed of light, $\lambda_g$ is the guided wavelength and $\varepsilon_{\text{eff}}$ is the effective dielectric constant. In addition, two-step impedance tuning open stubs were merged at $\theta = \mp 45^\circ$ and $\theta = \mp 135^\circ$ at all ring
resonators, as shown in Figure 2 with the parameters \(a = 0.35\) mm, \(b = d = 1.5\) mm, and \(c = 2.5\) mm, to obtain a broadened bandpass filter [11].

![Figure 2 The proposed microstrip BPF structure](image)

The input/output feed lines, with characteristic impedances of 50\(\Omega\) were coupled directly to the symmetric transmission line (\(\ell_{\text{ring}}\)) to reduce radiation and mismatch losses [11]. The feed lines measure \(W_{\text{fed}} = 1.79\) mm. A gap \(W_{\text{sice}} = 1.25\) mm was made opposite to corner, between the step impedance tuned open stubs in each resonator, as shown in Figure 3. This gap represents a critical point of the proposed filter to provide the stop-band characteristic with a similar center frequency and bandwidth.
PIN diodes of type HMPP3890 were connected to the terminals of these gaps to achieve switchable BPF-to-BSF characteristics [12]. In this regard, the PIN diode acts as a switchable on–off key that can be either open or short to exhibit the desired response. All diodes were modeled within the full-wave electromagnetic simulator (CST Microwave Studio, 2010) [13]. As in the practical case, the diodes will work either in forward or reverse bias, as clearly shown in Figure 4. To eliminate the possibility of short circuit at the PIN diode and DC supplier voltage, a DC blocking microstrip capacitor (cap) was used, as shown in Figure 4.
3. **Switchable bandpass to bandstop filter behavior**

The ring resonator shown in Figure 1-ahas been modeled using CST Microwave Studio. The current distribution and the resulting responses of the proposed ring resonator as are shown in Figures 5 and 6, respectively. Preliminary results of the S-parameters and surface current distribution clearly illustrate the bandpass characteristic with resonant pole frequencies in ultra-wide band.

![Figure 5](image1.png)

Figure 5: Surface current on the main ring resonator

![Figure 6](image2.png)

Figure 6: S-parameters of the main ring resonator
The corners of the main ring resonator were completed to become four square ring resonators on all main ring corners, as shown in Figure 1-b. This setup means that every two ring resonators were connected in series and then connected in parallel with each other to obtain a widened bandwidth in compact area. The side length of every square ring was designed to be equal to \( \frac{\lambda_g}{4} \). The resulting response of the new configuration reflects UWB-stop characteristics shown in Figure 7, as expected in [14].

![Figure 7 S-parameter of the square ring resonators](image)

Results shown in Figure 8 imply that surface current distribution of the square rings has explored the band-stop characteristics of the filter because of the orthogonality of the line side of the main ring to the small square rings [1], [11]. Thus, these lines were considered as input/output feed lines of every small square ring. In addition, the bandstop characteristic were realized as a result of the zero electric current distribution on the output line. In other words, the odd mode was exited and caused short circuit [1], [11].
Referring to Figure 1-b, two-step impedance tuned open stubs were added in the free small rings sides at $\theta = 45^\circ$ and $\theta = 135^\circ$ to obtain the bandpass characteristics, as presented in [11] and [16] and as shown in Figure 2. Figure 9 represents the UWB pass filter related to the bandpass filter structure illustrated in Figure 2. Inspection of the results showed fractional bandwidth of 70.11%, insertion loss of approximately 0.3 dB, three transmission zeros at $(f_{z1} = 6.75\,\text{GHz}, f_{z2} = 15.6\,\text{GHz}, \text{and } f_{z3} = 17.25\,\text{GHz})$ with rejection band of more than 35 dB, return loss over than 18 dB, and six transmission poles. In addition to being a new design, it also features a compact size, improved fractional bandwidth, reasonable return loss, low insertion loss, and wide stopband of more than 2 GHz. All these characteristics meet the requirements of the UWB systems [15].
Although the outcomes have shown good results, the design did not achieve the desired goal. In addition, this structure features only one characteristic (i.e., UWB bandpass filter). For this reason, Figure 2 was upgraded to a new proposed configuration by cutting the corners of each small ring resonator, as depicted in Figure 3. These cuts were made to transfer the response from bandpass to bandstop characteristic, as shown in Figure 10. Bandstop characteristic was achieved because each ring resonator—after cutting—resembled a transmission line electrically coupled to the quarter wavelength open stub resonators, which were spaced by a quarter-guided wavelength apart [14], [16].
In accordance with Figures 9, and 10, both the bandpass and bandstop responses can be achieved using two different configurations. In other words, the difference between these two configurations was made by short and open circuit in each small ring resonator. The main objective was to find a suitable design that can be used to obtain both responses within the same configuration. An appropriate electronic device was needed to get attain a short and open circuit that realizes these two configurations (i.e., Figures 2 and 3) in the same setup. Therefore, the switching PIN diode was used, as shown in Figure 4, to perform this function and to obtain switchable filter with both bandpass and bandstop responses.

4. **Electronically switchable filter results and discussion:**

The proposed filter structure, illustrated in Figure 2, was modeled and analyzed at the designed center frequency of 11 GHz using CST Microwave Studio and taking into account the dielectric and metallic losses. The conductivity of copper \( \sigma = 5.8 \times 10^7 \) S/m and the substrate loss tangent \( \tan \delta = 0.0009 \) were used in the simulation. At the resonance frequency, the side length of the small square ring resonator was set to 5.8 mm to be equivalent to the quarter of the guided wavelength \( \lambda_g \) given by Equation 2.

\[
\lambda_g = \frac{\lambda_c}{\sqrt{\varepsilon_{eff}}} \quad \text{Equation 2}
\]
where $\varepsilon_{\text{eff}}$ is the effective dielectric constant and $\lambda_o$ is the free space wavelength that can be calculated using the theoretical method presented in the previous work [16]. Tunable step impedance open stub resonator, with restricted length and width as shown in Figure 2 and overall length also equivalent to quarter waveguide wavelength mentioned above, was composed of the small square ring resonator. Transmission lines connecting two square ring resonators $\ell_{\text{ring}}$ (i.e., the side of main ring resonator) was also set to 5.9 mm to be equivalent to the quarter waveguide wavelength. The proposed microstrip BPF was fabricated on a microstrip substrate with both a relative dielectric constant of 2.2 and a thickness of 0.787 mm. A standard technology printed circuit board (PCB) and the SMA connectors were attached at the input/output feed lines.

Figure 11 shows a photograph of the fabricated filter structure design with the specified dimensions depicted in Figure 2. The total etched size of the proposed filter was miniaturized at 23 mm × 23 mm. In addition, the new configuration featured the established UWB, as well as reasonable return and transmission loss characteristics, which were disapproved as the authors claimed in previous works [17], [18]. One of the cited literatures has shown wide bandwidth by connecting three series square ring resonators [11]. However, the obtained bandwidth was not wide as compared with the achieved result shown in Figure 12.
Figure 11A photo of the fabricated BPF prototype based on Figure 2

Figure 12 shows the simulated and measured results of the BPF in terms of transmission and reflection characteristics. The measurement process was conducted in an ordinary room environment by vector network analyzer, (VNA model: Anritsu 37347D). The results showed that the simulated and measured responses were in good agreement with each other and thus validate the design process. The fabricated filter featured three transmission zeros ($f_{z1}=6.75\text{GHz}$, $f_{z2}=15.67\text{GHz}$, and $f_{z3}=16.68\text{GHz}$) and six transmission poles. It also has a fractional bandwidth of 69.227% at 3dB with wide stop band characteristics on both sides of more than 2 GHz. Finally, the roll-off obtained a very sharp response of 81.533 GHz/dB (calculated from 7.215 GHz with 29 dB to 7.477 GHz with 3 dB) and 81.47 GHz/dB (calculated from 15.474 GHz with 29 dB to 14.946 GHz with 3 dB). Such a response permits the proposed filter to be with high selectivity in the transmission band. The results exhibit good performance of $S_{21}$ of less than 1.5 dB within the transmission band from 11.225 GHz up to 14.533 GHz. However, $S_{21}$ showed degradation at the lower and upper transmission bands reaching 3.35 dB. The return loss has better than 12 dB across the passband from 8.528 to 14.561 GHz. $S_{11}$ featured smaller values at the lower and upper passbands up to 5 dB.
As mentioned earlier, a small gap $w_{ap}$ was made to get a bandstop filter, as shown in Figure 3 to get a bandstop filter. The same microstrip filter structure was practically fabricated on a PCB joining the input/output SMA connectors using a Duroid Rogers’s substrate, as shown in Figure 13. The same design parameters were also used in Figure 11, which used the BSF fabrication process. In other words, the BPF was recalled once again. However, a small aperture was engraved in all small resonator corners opposite the corner in between the step impedance open stubs to be an essential point of this design. The aperture was designed to be less than that size of the selected PIN diode in order to fix it on the two aperture sides. A full ground plane has covered the back side of the substrate, which means that no any additional structures were added to obtain the presented results. From a practical perspective, the proposed filter was designed with no complexity and lower cost effective as compared to liquid crystal polymer (LCP), and low temperature cofired ceramic (LTCC) [19], [20].
Both simulated and measured results were compared in terms of return loss and transmission responses, as shown in Figure 14. The results clearly reflect high compatibility between the simulated and measured results. In addition, the frequency band of the BSF almost resonated at the same center frequency and bandwidth, compared with the frequency band of BPF (11 GHz). Furthermore, the return loss response with ripple value of 1.5 dB in almost band featured three transmission zeros ($f_{z1}= 6.372$ GHz, $f_{z2}= 16.203$ GHz, and $f_{z3}= 16.957$ GHz). The rejection band of the lower band is better than the upper band, which are 1.6 and 0.756 GHz at 10 dB, respectively. Five transmission poles were observed at 7.3, 8.83, 10.62, 12.45, and 14 GHz. However, some degradation was noticed in the lower band of 1.8 dB, that is, variation was shown between the simulated and measured results. The deviation can be attributed to fabrication tolerance, the mismatching between the SMA connectors, and the feed lines as well as components and devices utilized in the measurement process. In comparison with the responses of recent literature presented, the proposed structure allows to miniature the size of UWB filter about 54.12% and 89.5% when compared to the works of [21] and [22], respectively. It shows also good characteristics in terms of size, responses and selectivity.
A- Forward bias of PIN diode

As seen in Figure 4, all PIN diodes were connected to the terminals of the cutting place gap \( w_{sce} \). Applying forward DC bias for all these PIN diodes will entail all diodes will function as ON (short circuit). In other words, a small resistive value was added to the model of the PIN diode resembling the ON state. A BPF response of the new proposed structure was tested using the CST Microwave Studio. The laboratory restrained the fixing of the PIN diode inside the structure because this type of PIN diode required high quality of operating machine. Thus, the simulated results were compared with the practical results related to Figure 11. Figure 15 illustrates the return loss and transmission responses of a modeled PIN diode in the simulated results of Figure 4 and the measured results of Figure 11 for BPF. The simulated and the measured results were in good agreement with each other, thus validating the proposed filter structure. In other words, the PIN diode indeed works as a switch on, or short circuit led to getting bandpass response. Degradation in performance was exhibited; PIN diode parasitic resistance of this device will result in power loss, so that total efficiency will be reduced.
Figure 15 Comparison of the BPF and proposed structure with PIN diode simulated results to validate the switchable filter

**B- Reverse bias of PIN diode**

A negative DC voltage was applied as a reverse bias for all PIN diodes and to work as an open circuit. Return to the limited laboratory ability, PIN diodes cannot practically be connected to the proposed filter structure. However, the simulated results were obtained and compared with the measured results of Figure 13. As shown in Figure 13 the cutting place gap at the corner of each small ring resonator was similar to the case in which the applied voltage for all PIN diodes was negative and the reverse bias can take place. In this case, high resistive value, on the basis of parallel connection of small capacitive value and resistor, for the PIN diode was observed, and the PIN diode can work as an open circuit as OFF state. In this context, the PIN diode works resemble open switch or OFF to get the gap as presented in Figure 13. To avoid the DC short circuit that happened on the PIN diode and DC-power supply, a DC microstrip capacitor was used and fixed inside the structure as presented in Figure 4.
Figure 16 shows the simulated result of the Figure 4 in which all PIN diodes in reverse bias states with the measured result obtained from Figure 13. Both the return loss and the transmission responses of both the simulated PIN diodes and the measured values were slightly near each other. However, the shifts in frequency band around 0.87 GHz was observed between the simulated and measured results that the PIN diode parasitic characteristic that cannot be avoided.

![Figure 16 Comparison of the BSF and proposed structure with PIN diode simulated results to validate the switchable filter](image)

The measured and simulated return loss in terms of $S_{11}$ and transmission responses in terms of $S_{21}$ for the three presented structures are summarized in Figures 17 and 18 respectively.
Figure 17 Comparison between simulated and measured S11 results to validate the switchable filter.

Figure 18 Comparisons between simulated and measured S21 results to validate the switchable filter.
Conclusions

A new switchable bandpass to bandstop UWB filter was designed in this paper. With a simple square ring resonator with quarter wavelength, open stub resonators were compiled into one structure to validate the proposed idea. In other words, a closed ring square ring resonator as series-shunt configuration is connected to offer the bandpass filter. By making a gap in each square ring resonator, a bandstop response according to the simple transmission line together with the open stub was observed. Simulated and measured results demonstrate that the presented microstrip filter offers a switchable response from bandpass to bandstop characteristic.

Measured results of the BPF prototype exhibited three transmission zeros ($f_{z1} = 6.75$GHz, $f_{z2} = 15.67$GHz, and $f_{z3} = 16.68$ GHz), and six transmission poles. The prototype also has a rejected bandwidth of more than 2 GHz and an insertion loss of 1.5 dB within the transmission band from 11.225 GHz to 14.533 GHz. Moreover, it has a fractional bandwidth of 69.227% at 3dB with roll-off response of 10 and 81.533 GHz/dB for the BPF skirt. This response lets the proposed filter to be with high selectivity in the transmission band. The BSF prototype shows three transmission zeros ($f_{z1} = 6.372$ GHz, $f_{z2} = 16.203$ GHZ, and $f_{z3} = 16.957$ GHz) and a return loss response with ripple value of 1.5 dB in almost band. Five transmission poles were observed at 7.3, 8.83, 10.62, 12.45, and 14 GHz. Finally, the rejection of the lower band is better than that of the upper band, which is 1.6 and 0.756 GHz at 10 dB, respectively. Measured results have been carried out on two filter prototypes to validate the reality of simulated results.
References:


