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COMPARATIVE STUDY OF SWITCHABLE FILTERS AND A NEW TECHNIQUE OF BANDSTOP TO BANDPASS FILTER USING LOSSY RESONATORS

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ABSTRACT

In this paper, the comparative studies of switchable bandstop to bandpass (or bandpass to bandstop) are presented. It shows that by using microstrip technology, high-Q bandstop to bandpass responses is difficult to achieve. Therefore, this paper proposes a new technique of matched bandstop to bandpass filter using two lossy low-Q resonators. The proposed technique is implemented based on perfectly-matched bandstop topology which is not only produced high-Q bandstop filter, but also easy to switch from bandstop to bandpass response. The PIN diodes (as switching element) that used in this proposed technique are incorporated into the topology to exhibit either matched bandstop response or bandpass response by turning "ON" and "OFF" of the PIN diodes. The proposed technique based on simulation result was carried out. As a result, it was found that the proposed technique was able to switch the microstrip filter from matched bandstop to bandpass filter using two lossy low-Q resonators.

Keywords: switchable filter, lossy resonator, bandstop filter, bandpass filter.

INTRODUCTION

There have been widely developed switchable bandstop to bandpass (or bandpass to bandstop) filter for wireless communication and cognitive radio system. For example, in a cognitive radio environment, this filter is used in the radio system to select signals of interest or attenuate interfering signals. It depends on the environment or mode of operation of the radio. In (Zhengzheng *et al*., 2011), a reconfigurable and cognitive radio requires frequency agile radio front-end modules to cover a wide range of wireless communication spectrum. Therefore, switchable filters are very important components in cognitive radios and have been focusing on recent research and development (Rebeiz *et al*., 2009), (Abunjaileh *et al*. 2010), (Adoum *et al*., 2012), (Naglich *et al*., 2012), (Anand *et al*., 2013), (Juseop *et al*., 2013), (Sánchez-Soriano *et al*., 2013), Pu-Hua *et al*., 2014), (Rabbi *et al*., 2014), (Young and Rebeiz, 2014), (Adoum *et al*., 2014).

In this paper, the comparative study of switchable bandstop to bandpass (or bandpass to bandstop) is discussed and a new technique of switchable filter with the ability to switch between matched bandstop to bandpass filter based on lossy resonator is proposed. The proposed switchable filter was designed using microstrip technology. The switchable bandstop to bandpass filter response using low-Q lossy resonator was investigated based on simulated results. The switchable filter was realized on L-shape matched bandstop filter (which is a lossy resonator). PIN diodes or varactor diodes were used to control the switching operation between bandstop and bandpass response.

COMPARATIVE STUDY OF SWITCHABLE BANDSTOP TO BANDPASS FILTER

Introduction of switchable filter

There are a few studies on bandpass-to-bandstop (or bandstop-to-bandpass) filter that have been reported. In paper (Yi-Ming *et al*., 2009), the author demonstrated a bandpass-to-bandstop filter with a closed-ring resonator, where reconfigurability results from the perturbation effect on degenerate modes. Figure-1 shows the schematic diagram of the reconfigurable bandpass-to-bandstop filter.

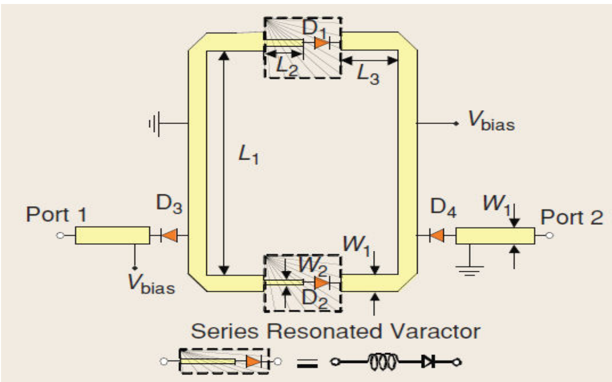

Figure-1. Schematic diagram of the reconfigurable bandpass-to-bandstop filter. D1 and D2 series-resonated (Yi-Ming *et al*., 2009).

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The filter consisted of one-wavelength closed-ring resonator with series-resonated varactors D_1 and D_2. The filter then connected at the symmetry plane with the coupling varactors D_3 and D_4 which are connected at the input and output ports respectively. By appropriately controlling the D_1 and D_2 reactance, bandpass or bandstop filter can be achieved.

The simulated and measured results of the reconfigurable bandpass-bandstop filter are shown in Figure-2. The bandpass and bandstop states are reconfigured based on the varactor bias voltage. The bandpass response is achieved when the bias voltage is at 5.5 V, and the simulated insertion loss is 0.5 dB at 2.45 GHz, the 3-dB bandwidth is 360 MHz, and two transmission zeros exist at 2.2 GHz and 3.2 GHz, respectively. Bandstop response is achieved when bias voltage is at 0 V and has 20 dB rejection frequencies of 2.4-2.7 GHz.

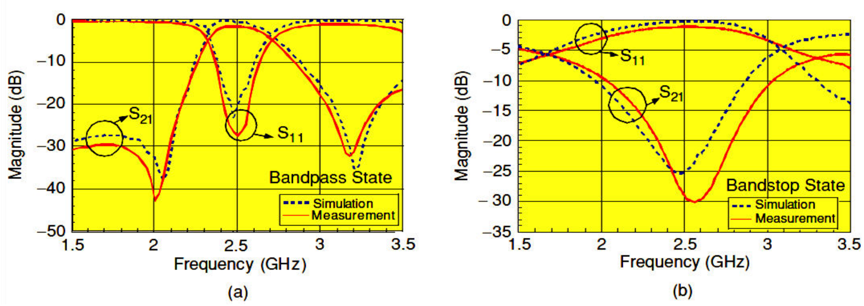

Figure-2. Simulated and measured results of the reconfigurable bandpass-to-bandstop filter at 2.45 GHz, (a) Bandpass state, (b) Bandstop state (Yi-Ming *et al.*, 2009).

A novel reconfigurable switched bandpass to bandstop filter using electromagnetic bandgap structures (EBG) at the same frequency has been reported in (Karim *et al.*, 2006). The authors derive the unit model for the reconfigurable filter by using an equivalent circuit approach and full wave electromagnetic simulation for extracting the values of the lumped elements. The Dispersion characteristics are obtained by using a Floquet's theorem to analyze the behavior within the unit cell. PIN diode is used to switch bandpass to bandstop filter where the unit cells are cascaded to form a bandpass filter. Figure-3 shows the fabricated structure of the reconfigurable filter.

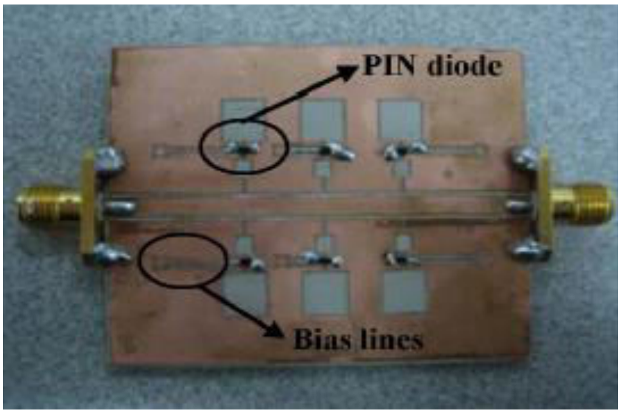

Figure-3. Fabricated structure of the reconfigurable filter (Karim *et al.*, 2006).

Figure-4 shows the measurement result. It shows that when the diode is off, a band pass filter is operating at 7.3 GHz with an insertion loss of 2.1 dB. It has 3 dB bandwidth of 5.2 GHz and rejection greater than 35 dB. When the diode is switched ON, it will show a bandstop response. The measurement results for a bandstop show the resonant frequency at 7.3 GHz and it has insertion loss of 1.6 dB. The 20 dB rejection bandwidth is 5.3 GHz (Karim *et al.*, 2006).

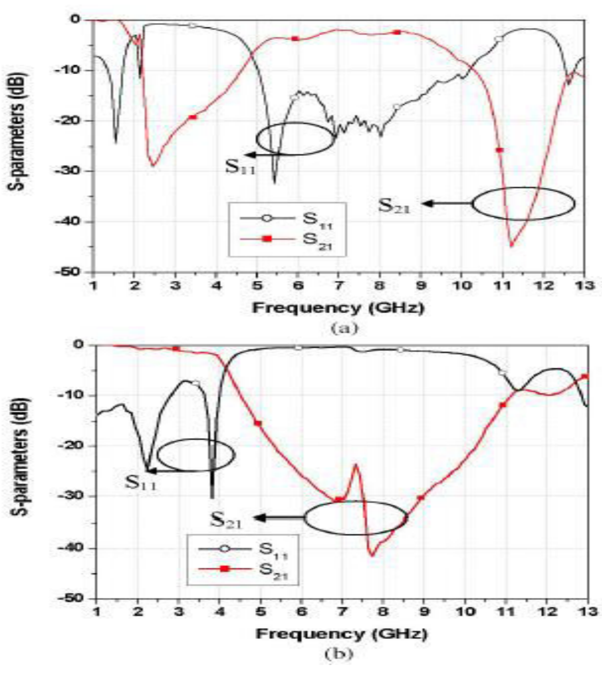

Figure-4. Measurement results of the reconfigurable filter (a) PIN diode is 'OFF', bandpass filter (b) PIN diodes is 'ON', bandstop filter (Karim *et al.*, 2006).

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A tunable bandstop-to-bandpass filter with reconfigurable 2- and 4-pole responses have been reported by Young and Rebeiz (2014). The filter performances are achieved based on the change of the coupling paths using the zero-valued couplings. In this filter, the authors state that a coupled line with series capacitor is employed to obtain the zero-valued coupling between the adjacent resonators. Figure-5 shows the fabricated of the filter.

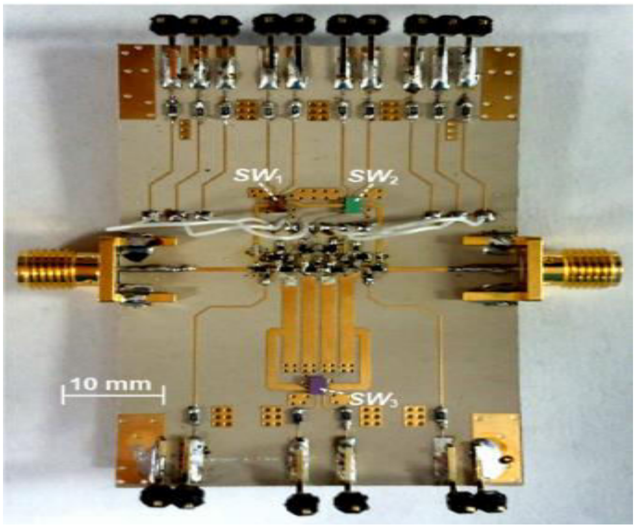

Figure-5. The fabricated filter for 2-pole and 4-pole responses (Young and Rebeiz, 2014).

Figure-6 shows measured result of S_{21} bandstop response. As shown in Figure-6(a), the 2-pole bandstop rejection level and the 20-dB bandwidth are measured as 24-28 dB and 15-24 MHz for center frequencies of 0.64-0.96 GHz. On the other hand, the rejection level and the 20-dB bandwidth for the 4-pole bandstop mode are 32-41 dB and 25-45 MHz, respectively, for center frequencies of 0.71-0.96 GHz as shown in Figure-6(b).

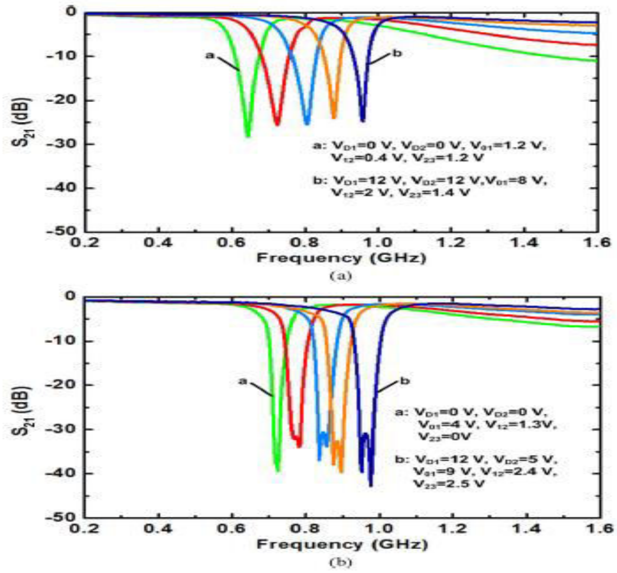

Figure-6. Measured S_{21} responses for (a) 2-pole (b) 4-pole bandstop modes (Young and Rebeiz, 2014).

Figure-7 shows the measured center frequency for bandpass modes. The 2-pole bandpass mode covers 0.71–0.99 GHz with an insertion loss and 1-dB bandwidth of 4.9–2.9 dB and 34-63 MHz, respectively. The 4-pole bandpass mode covers 0.72-1.01 GHz with an insertion loss and 1-dB bandwidth of 6.1–4.8 dB and 41-70 MHz, respectively. The 2-pole bandpass mode has 1.2 dB better insertion loss compared to the 4-pole filter at almost the same bandwidths.

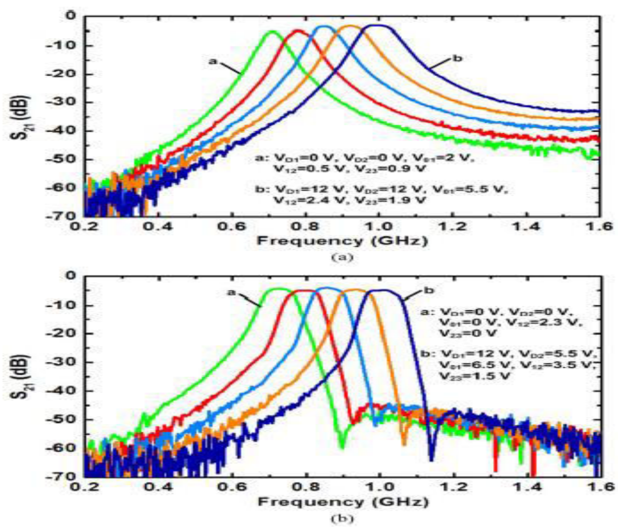

Figure-7. Measure S_{21} responses for (a) 2-pole bandpass mode, (b) 4-pole bandpass mode (Young and Rebeiz, 2014).

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Table-1 shows the comparative of switchable bandstop to bandpass (or bandpass to bandstop) in term of technique and insertion loss (S_{21}). Based on these literatures, it is found that there is a potential study on the lossy resonator (Guyette *et al.*, 2005) for switchable high-Q bandstop to bandpass with small and compact size. These will be described and discussed in details in the next sub-topic.

Table-1. Comparative of technique and insertion loss (S21).

Technique	Bandpass characteristic	Bandstop characteristic
	S_{21}	S_{21}
A closed-ring resonator (Yi-Ming *et al.*, 2009)	0.5 dB	> 20 dB
Electromagnetic bandgap structures (EBG) (Karim *et al.*, 2006)	2.1 dB	>35 dB
Reconfigurable 2- and 4-pole (Young and Rebeiz, 2014)	2-pole: 4.9-2.9 dB 4-pole:6.1-4.8 dB	2-pole: > 20 dB (24-28 dB) 4-pole: >20 dB (32-41 dB)

SWITCHABLE MATCHED BANDSTOP TO BANDPASS FILTER USING LOSSY RESONATOR

Introduction of matched bandstop filter

In 2005, (Guyette *et al.*, 2005) were successfully demonstrated an ideal infinite stopband attenuation of the matched bandstop where high notch depth and selectivity can be produced with only two lossy low-Q resonators in microstrip technology. This idea was from (Jachowski, 2004) that builds upon the perfectly-notch concept where it consists of two identical lossy resonators connected to the 90° hybrid coupler or directional coupler as shown in Figure-8. This technique enables the use of two low-Q lossy resonators for high attenuation of bandstop filter applications. Thus, its advantages are not only to produce higher stopband attenuation but also being perfectly matched in the passband and stopband as well as compact in size.

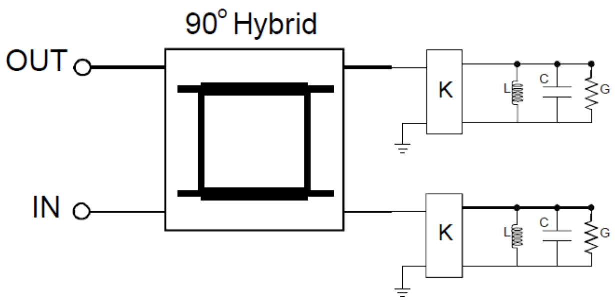

Figure-8. Conceptual diagram of an enhanced Q notch filter employing a 3-dB, 90° hybrid coupler (Guyette *et al.*, 2005).

The overview of the matched bandstop filter using lossy resonators was reported by Shairi, *et al.*, (2014), where the lossy resonator was applied in matched bandstop filter (Guyette *et al.*, 2005), (Jachowski, 2004), (Guyette *et al.* 2009), tunable filter (Guyette, 2010), (Phudpong and Hunter, 2007), (Jachowski and Guyette, 2009), (Peng *et al.*, 2007), switchable bandstop to Allpass filter (Adoum *et al.*, 2013), (Zahari *et al.*, 2011) (Zahari *et al.* 2012) and RF switches (Shairi, *et al.*, 2012) (Shairi, *et al.*, 2015).

The matched bandstop filter has a characteristic of Allpass network where an ideal lossless Allpass network has the property of passing all frequencies with zero attenuation, and thus must present a perfect match at all frequencies (Guyette *et al.*, 2009). The perfectly notched concept (Guyette *et al.*, 2005) was applied to improve the Q factor of bandstop limiter in the filter design. Based on a reflection mode filter, this concept makes use of two identical lossy resonators coupled to a 3-dB 90° hybrid coupler with correct coupling factors. At the center frequencies, the incident signals are critically coupled to the resonators and absorbed in the resistive part of the resonator leaving no reflected signals at the output, thus achieving a theoretically infinite attenuation (Guyette, 2010). Figure-9 shows a practical matched notch filter and Figure-10 shows the bandstop response of perfectly-matched bandstop filter.

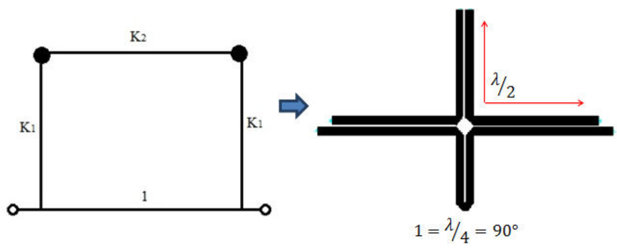

Figure-9. Realization of matched bandstop filter using two L-shape resonators.

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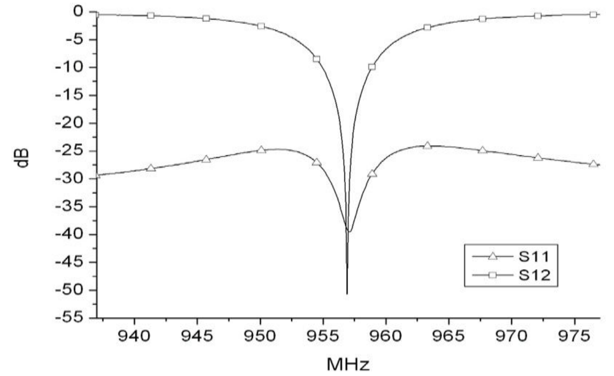

Figure-10. Perfectly-matched bandstop response (Guyette, 2005).

This topology has a symmetrical structure of two-port network defined by utilizing the conventional method for odd and even mode analysis. Odd and even mode admittances of the circuit structure depicted below:

$$S_{11} = \frac{1-Y_O Y_e}{(1+Y_O)(1+Y_e)} \quad (1)$$

$$S_{12} = \frac{Y_O - Y_e}{(1+Y_O)(1+Y_e)} \quad (2)$$

As stated by (Hunter *et al.*, 2005), if $Y_o = 1/Y_e$ for all frequencies, then $|S_{11}| = 0$ for all frequencies, and the network possesses the Allpass property. If $Y_o = Y_e$ at a certain frequency, then $|S_{12}| = 0$, and the network produces infinite attenuation at that frequency. Based on Figure-11, the network consists of two identical resonators with an unloaded Q of $\omega C/G$, and four admittance inverters. The circuit shown that both Allpass and the perfect notch property are met when $K_1 = \pm\sqrt{2G}$ and $K_2 = G$. The power at stopband frequencies is absorbed by the losses of the present resonators and is not reflected as in conventional filters.

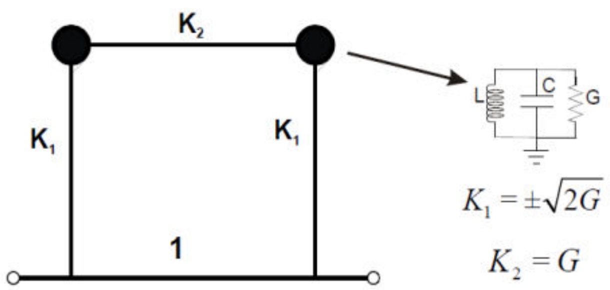

Figure-11. A coupled-resonator model of a matched bandstop filter (Guyette *et al.*, 2005).

The proposed of switchable matched bandstop to bandpass filter

As described above, the proposed of switchable filter was designed at center frequency of 2.4 GHz. The filter provided two modes of operation under two conditions, where the filter can be switched either matched bandstop or bandpass response. The switching element (PIN diodes) in this filter was incorporated into the filter topology as shown in Figure-12. In the first condition, the PIN diodes were turned "ON" to produce a matched bandstop response. During this condition, the PIN diodes act like a variable resistor R_s. In the second condition, the PIN diodes were turned "OFF" to produce a bandpass response.

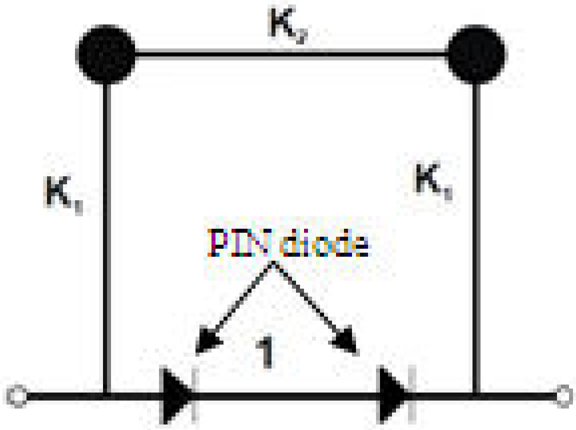

Figure-12. Generalized model of switchable matched bandstop to bandpass filter.

The new switchable filter with the ability to switch between matched bandstop and bandpass filter is proposed. It was designed using L-shape lossy resonators as shown in Figure-13.

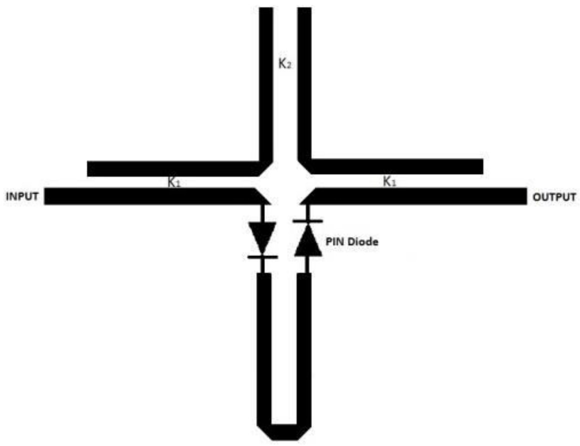

Figure-13. The proposed switchable matched bandstop to bandpass filter.

The PIN diodes as a switching element were integrated into the L-shape matched bandstop filter to switch from matched bandstop to bandpass responses. Figure-14 shows the simulated matched bandstop response when the PIN diodes were turned "ON". The simulated attenuation was 64 dB and the return loss was below than 13 dB. From the simulated result at the center frequencies, the incident signals were critically coupled to the resonators and absorbed in the resistive part of the resonator leaving no reflected signals at the output, thus achieving a theoretically infinite attenuation (Phudpong, 2009). The filter was having high-Q factor matched bandstop response while being perfectly matched in both the passband and stopband (Hunter *et al.*, 2005). In Figure-15 shows the simulated bandpass response, where the insertion loss was around 9 dB. Further improvement of higher insertion loss of the bandpass filter can be done by enhancing the coupling resonator or tuning the length of each resonator.

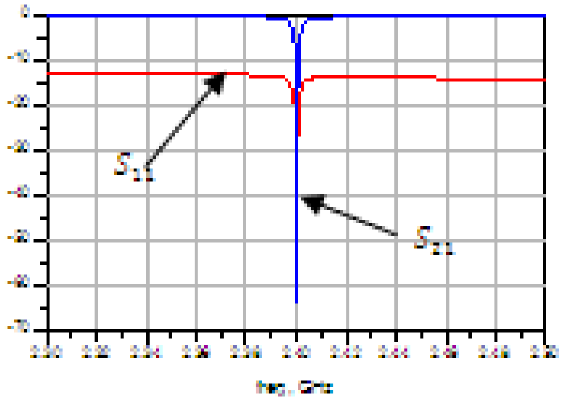

Figure-14. Simulated matched bandstop response.

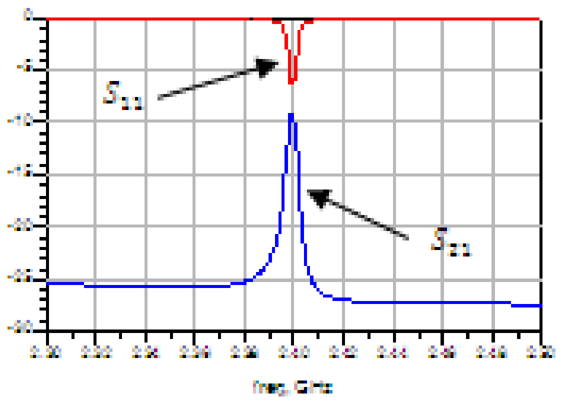

Figure-15. Simulated bandpass response.

The frequency resonance of the bandpass response can be enhanced by tuning the resonator using PIN diodes.

CONCLUSIONS/FUTURE WORK

In this paper, the comparative study of switchable bandstop to bandpass (or bandpass to bandstop) and a new technique of switchable bandstop to bandpass filter are presented. The comparative study has shown that by using microstrip technology, it is difficult to achieve high-Q bandstop to bandpass responses. The proposed new technique of matched bandstop to bandpass filter using lossy resonators also are reported. By implementing perfectly-matched bandstop topology in the filter, it is not only producing high-Q factor of bandstop response, but also able to switch to bandpass response. Thus, PIN diodes are incorporated into the topology to exhibit either matched bandstop or bandpass response by turning “ON” and “OFF”. The simulated result showed that the matched bandstop filter can be switched to bandpass. Further improvement of higher insertion loss of the bandpass filter can be done by enhancing the coupling resonator or tuning the length of each resonator. Potential future works will be focused on the enhancement of the bandpass response and realized in the fabrication stage for verification.

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