

A Compact Switchable and Tunable Bandpass Filter

Muhammad F. Karim* and Mohammed Y. Siyal

Abstract—In this paper, an integrated switchable and tunable bandpass filter is designed, simulated, and fabricated. This integrated bandpass filter is able to switch as well as tune in the ultra-wideband (UWB) as well as 2.4 GHz band. At first, a UWB bandpass filter is developed which consists of two bent shorted quarter-wavelength stubs and a connecting half-wavelength stub. Subsequently, a 2.4 GHz bandpass filter is realized by connecting another half-wavelength stub on top of the UWB filter. RF pin-diodes are used for switching the bands between UWB and 2.4 GHz bandpass filter. The switchable bandpass filter converts into a tunable filter by changing the inductance or the length of shorted stubs through the pin diodes. A detailed parametric analysis is done for calculating different stubs lengths of the UWB as well as 2.4 GHz bandpass filter. The simulation results show a high rejection level of > 40 dB at the lower frequency and a low insertion loss of 0.8 dB in the passband for UWB filter. For 2.4 GHz bandpass filter, the simulation results show an insertion loss of 0.42 dB and a 3 dB bandwidth of 796 MHz. The filter is fabricated on a Rogers 4003 substrate, and the measurement results of the switchable filter in the UWB band show an insertion loss of 2.1 dB and a 3 dB bandwidth of 7 GHz. In the case of 2.4 GHz bandpass filter, the insertion loss is 0.78 dB.

1. INTRODUCTION

Recent development in wireless communications systems demands radio frequency (RF) devices to operate in multiple and separated frequency bands. As such, a single filter cannot fulfill filtering requirements for receivers operating in the UWB and wireless local area network (WLAN) bands simultaneously. In addition, the use of multiple filters occupies a large surface area [1]. Tunable and switchable microwave circuits have allowed increased system functionality with lower weight and cost than existing systems. Therefore, switchable and tunable filters are of great interest [2, 3]. Tunable filters have been demonstrated with the use of semiconductor varactor diodes [4–6] and micro-electromechanical systems (MEMS) [7–10]. For frequencies below 10 GHz, PIN diodes and varactor diodes are able to demonstrate $Q > 50$ with reduced cost, easier packaging, and lower bias voltage. Significant research activities have been carried out to explore various UWB filters for indoor and handheld systems. Various UWB bandpass filters have been developed to achieve a fractional bandwidth of 110% at the central frequency of 6.85 GHz [11, 12]. Meanwhile, IEEE 802.11b/g WLAN standard at 2.4 GHz band has also been extensively incorporated into mobile and handheld devices, such as laptop, cell-phones, and PDAs. Bandpass filters operating at 2.4 GHz have been developed over the years with various configurations [13, 14].

The resonant frequency and coupling between resonators and input/output coupling were adjusted using MEMS switches in edge coupled filter topologies that was implemented in [15]. The filter response shows three distinct states at 8, 9, and 10 GHz, and preserves constant bandwidth over the switchable range [15]. Another switchable filter topology was demonstrated, which included two folded

Received 18 July 2019, Accepted 26 August 2019, Scheduled 14 September 2019

* Corresponding author: Muhammad Faeyz Karim (faeyz@ntu.edu.sg).

The authors are with the School of Electrical and Electronic Engineering, 50 Nanyang Avenue, Nanyang Technological University, NTU, Singapore.

resonator extensions switched by PIN diodes. It was able to switch between WiFi and universal mobile telecommunications (UMTS) transmit band standards [16]. A bandstop filter with the topology can be conveniently switched to have a bandpass response due to the presence of the inter-resonator coupling structures and has recently been reported. The filter was reconfigured by a pair of reflective MEMS switches, and it was demonstrated that the switchable filter can exhibit both bandstop and bandpass filter responses [17]. An integrated filter that is able to switch as well as tune has not been reported in literature.

In this paper, an integrated new switchable and tunable bandpass filter is presented. The proposed filter is able to switch and tune in the UWB and 2.4 GHz band. At first, a UWB bandpass filter consisting of two bent shorted quarter-wavelength stubs and a connecting half-wavelength stub is developed. It switches from UWB to 2.4 GHz bandpass filter by connecting another half-wavelength stub through RF pin diodes. Using pin diodes, the switchable filter becomes a tunable bandpass filter by changing the inductance or the length of the shorted stubs. The switchable and tunable bandpass filter has the merit of compact size and low insertion loss.

2. DESIGN OF SWITCHABLE AND TUNABLE BANDPASS FILTER

2.1. Design of Switchable Bandpass Filter

Figure 1 shows the schematic of a switchable and tunable bandpass filter. The UWB bandpass filter consisting of two bent short stubs l_2 of quarter wavelength and one bent connecting line in the form of a square loop. Unlike the conventional quarter-wave filter, the connecting line between the two shorted stubs has a length of half wavelength, l_1 , in order to obtain a wider bandwidth. The bending of the stubs also makes the design more compact than the conventional structure. The UWB bandpass filter is designed with the center frequency at 6.85 GHz and the lengths of stubs $l_1 = 12.4$ mm and $l_2 = 6.2$ mm, respectively. The gap between the folded stubs is $g = 0.3$ mm, and this helps in the optimization of the bandpass frequency characteristics. Figure 2 shows the simulation results for the UWB bandpass filter

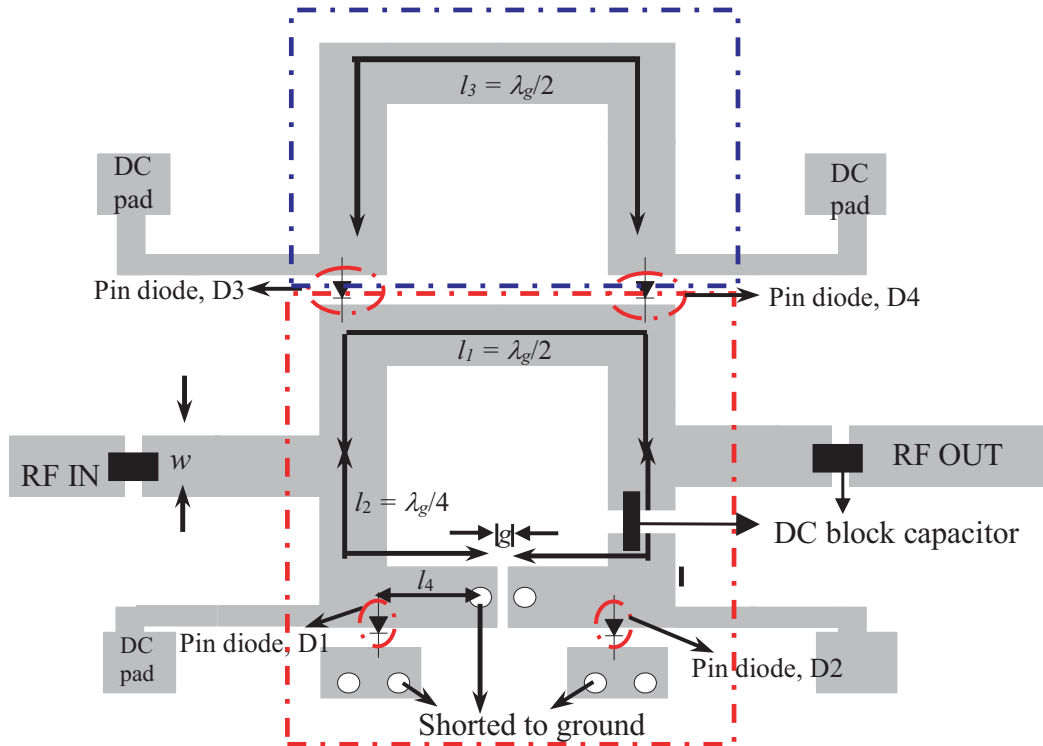


Figure 1. Schematic of an integrated switchable and tunable bandpass filter.

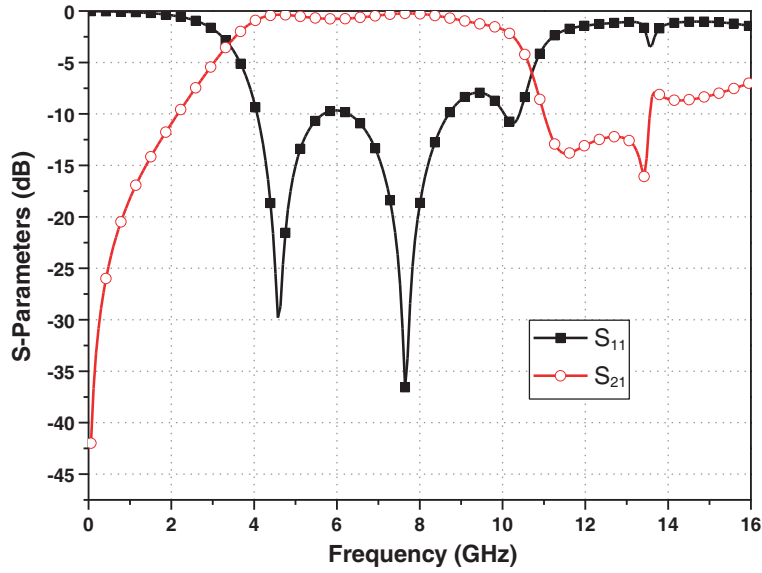


Figure 2. Simulation results of the UWB switchable bandpass filter.

using the commercial software IE3D. It shows a high rejection level of > 40 dB at the lower frequency and a low insertion loss of 0.8 dB in the passband.

The bandwidth of the UWB filter within the lower dotted red grid in Figure 1 depends on the centre connecting line l_1 as discussed previously. Using $ABCD$ parameters, an expression can be obtained:

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ Y & 1 \end{bmatrix} \begin{bmatrix} \cos \beta l_1 & jZ_0 \sin \beta l_1 \\ jY_0 \sin \beta l_1 & \cos \beta l_1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ Y & 1 \end{bmatrix} \quad (1)$$

$$S_{21} = \frac{2}{2 \cos \beta l_1 - 2jY Z_0 \sin \beta l_1 + 2Y Y_0 \cos \beta l_1 - jY_0^2 \sin \beta l_1 - jY \sin \beta l_1 - j \sin \beta l_1} \quad (2)$$

$$Y = -jY_0 \cot \beta l_2 \quad (3)$$

where Y is the admittance, and Z_o is the characteristics impedance. Eq. (3) is useful for determining

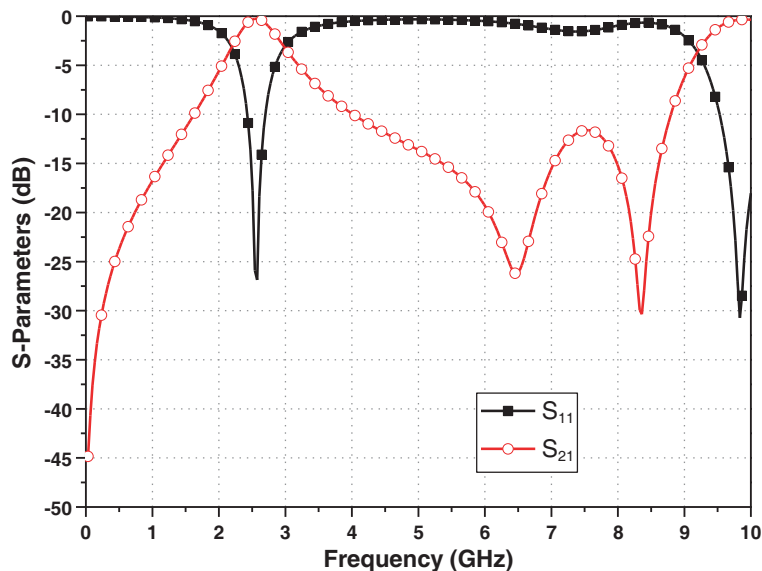


Figure 3. Simulation results of the 2.4 GHz switchable bandpass filter.

the bandwidth of the UWB bandpass filter.

When a stub of length $l_3 = \lambda_g/2$ is inserted into the filter as shown in the upper dotted blue grid in Figure 1, it becomes a switchable bandpass filter. It switches the band from UWB to 2.4 GHz band as shown in Figure 3. The insertion loss is 0.42 dB with a 3-dB bandwidth of 796 MHz. The out of band rejection is more than 4 dB on the lower and upper side bands of 2.4 GHz filter. The RF pin diodes D3 and D4 are placed to realize the switchable characteristics as depicted in Figure 1.

2.1.1. Varying the Length of Stub, l_1 , of UWB Bandpass Filter

In this case, suppose that the length of the stub, l_1 , of UWB bandpass filter changes from $\lambda_g/2$ to λ_g with other two lengths l_2 and l_3 fixed at $\lambda_g/4$ and $\lambda_g/2$. As depicted in Figure 4, the insertion loss for $l_1 = \lambda_g$ is quite high in the range of 4 dB with ripples appearing in the passband. With length $l_1 = \lambda_g/2$, the insertion loss is less than 1 dB, and it satisfies the requirement of the UWB band in terms of bandwidth.

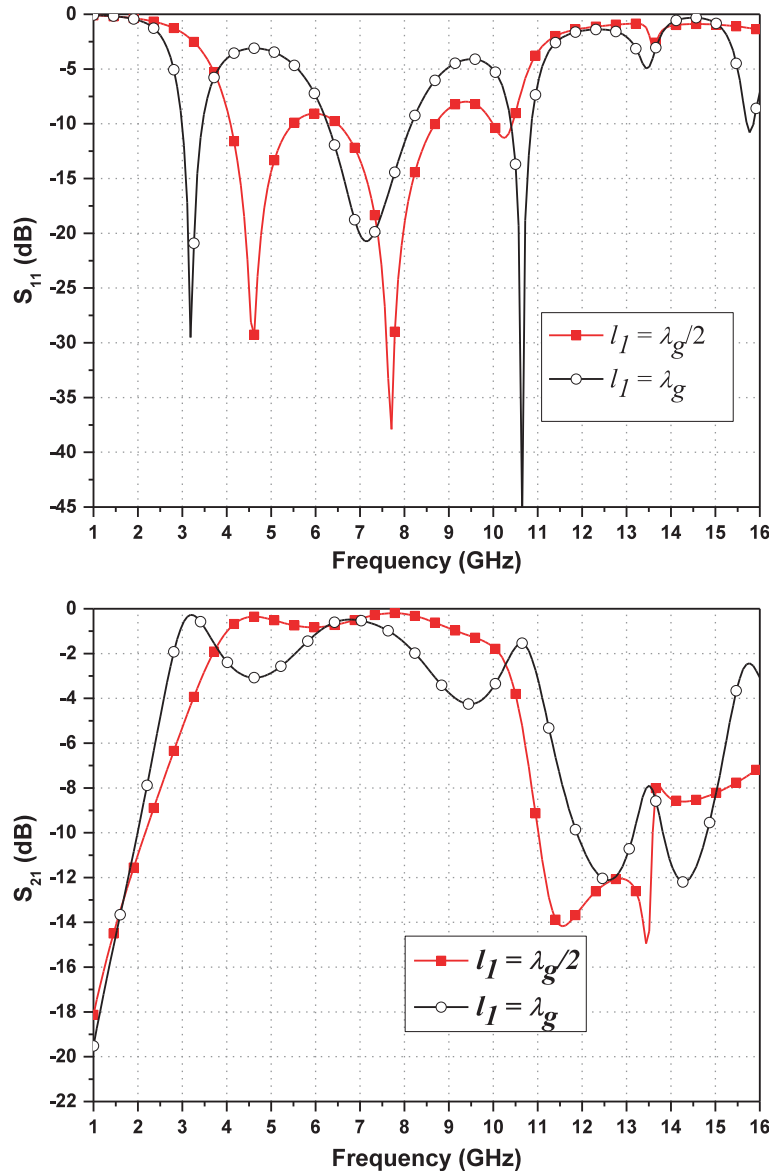


Figure 4. Simulation result for the variation in the length of stub, l_1 , of UWB bandpass filter.

2.1.2. Varying the Length of Stub, l_2 , of UWB Bandpass Filter

A parametric study is done by varying the length of the stubs, l_2 , for UWB bandpass filter. The other two lengths l_1 and l_3 are fixed at $\lambda_g/2$ and $\lambda_g/2$, respectively. The variation in the lengths also shows the tunability characteristics of around 600 MHz as shown in Figure 5. The results also show that for $l_2 = \lambda_g/6$ a high insertion loss is about 2 dB at 7 GHz. The 3-dB bandwidth is 9.8 GHz and is out of UWB. The return loss also decreases below 10 dB from 6 to 8 GHz. The length $l_2 = \lambda_g/2$ shows the minimum insertion loss of less than 1 dB and covers the UWB. The out of band rejection is more than 40 dB at lower frequency band and over 15 dB at higher band. Subsequently $l_2 = \lambda_g/8$ in Figure 5 shows the worst insertion loss of 3 dB at 7.2 GHz among the three, and the return loss drops below 10 dB from 6 to 9 GHz.

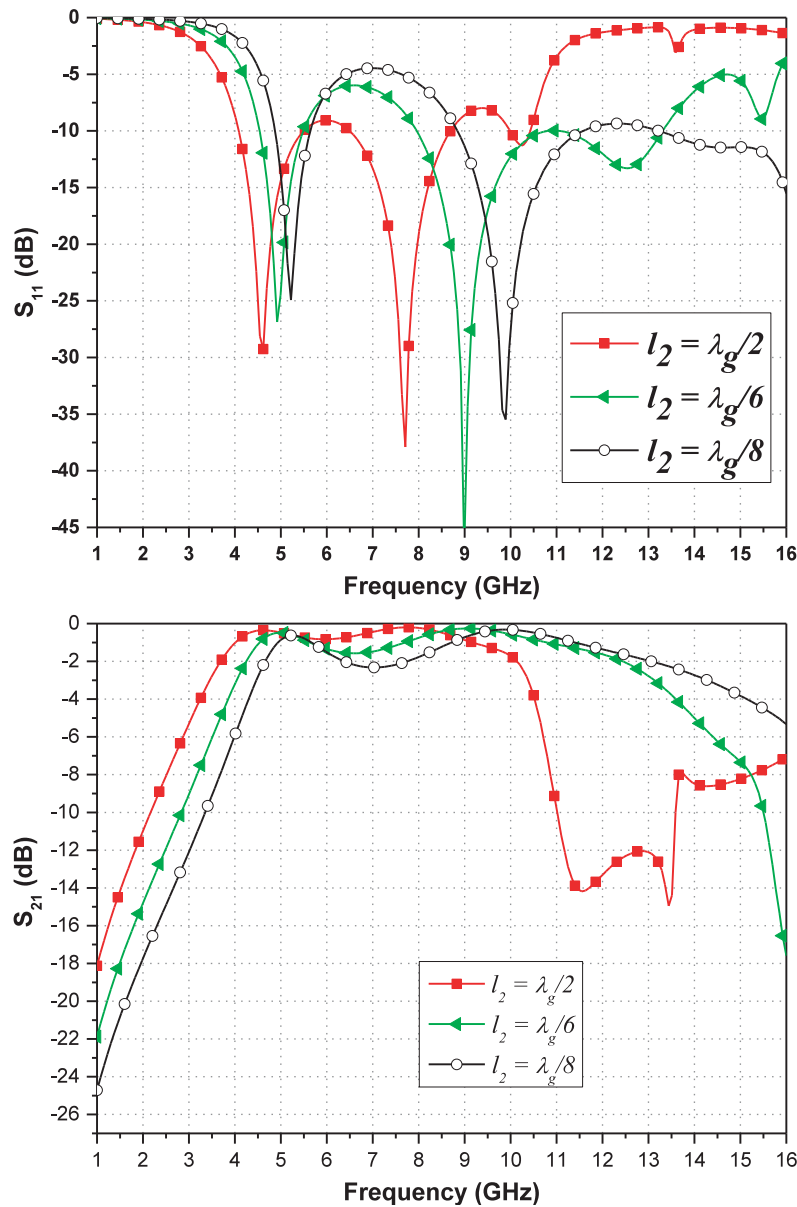


Figure 5. Simulation result for the variation in the length of stub, l_2 , of UWB bandpass filter.

2.2. Design of Tunable Bandpass Filter

The tunable bandpass filter is developed by changing the length of the stub, l_2 . The detailed analysis on the variation of the length is presented in the next subsection. Pin-diodes D1, D2, D3, and D4 are incorporated and turn ON or OFF simultaneously for tunability as shown in Figure 1. When diodes D3 and D4 are turned OFF and diodes D1 and D2 turned ON, the filter shows UWB characteristics as shown in Figure 6. This is because the inductance or the length of the stub changes. Similarly, when diodes D3 and D4 are turned ON and D1 and D2 turned ON and OFF respectively, it behaves as a tunable filter in the 2.4 GHz band as shown in Figure 7.

A transient response of the switchable filter at the UWB and 2.4 GHz band is also calculated using the Agilent ADS transient simulator controller in the co-simulation environment. The delay of the filter

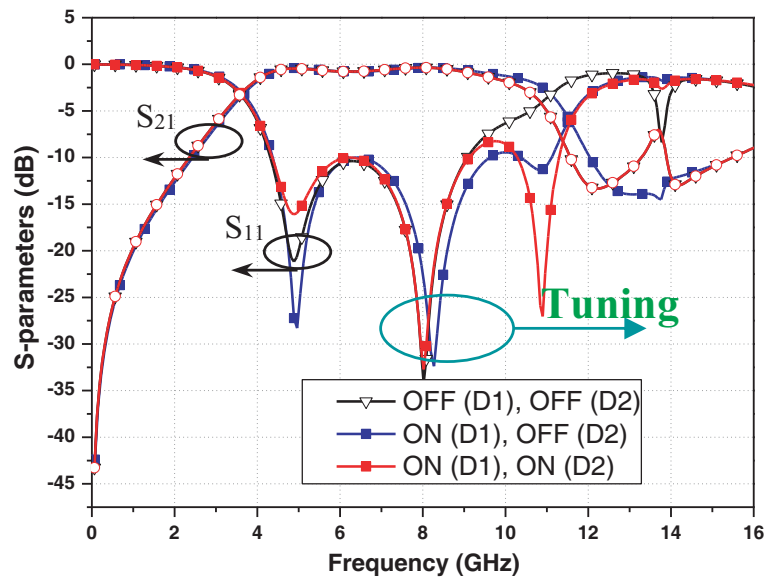


Figure 6. Simulation results of the tunable UWB bandpass filter.

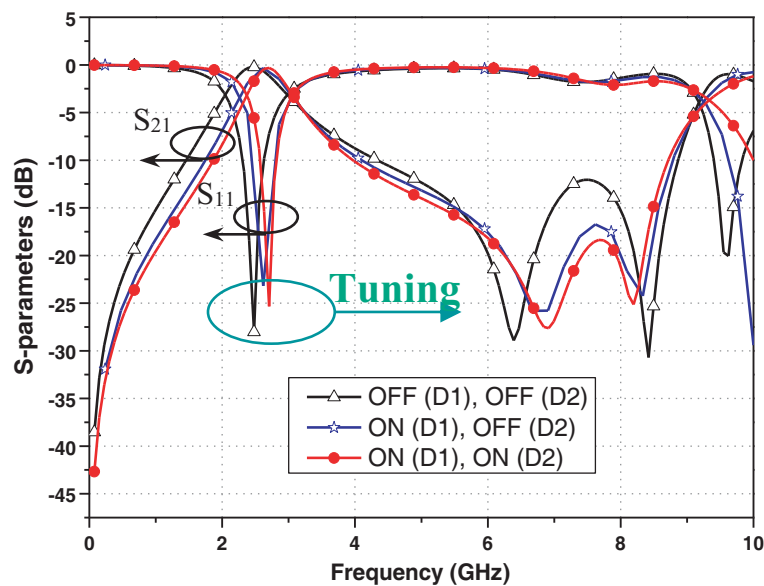


Figure 7. Simulation results of the tunable 2.4 GHz bandpass filter.

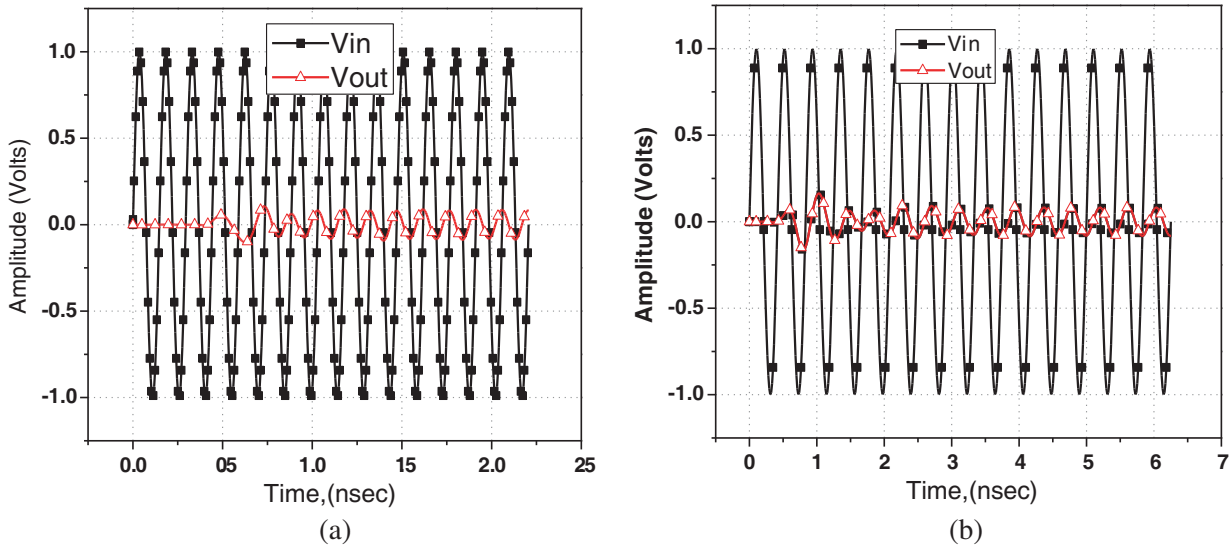
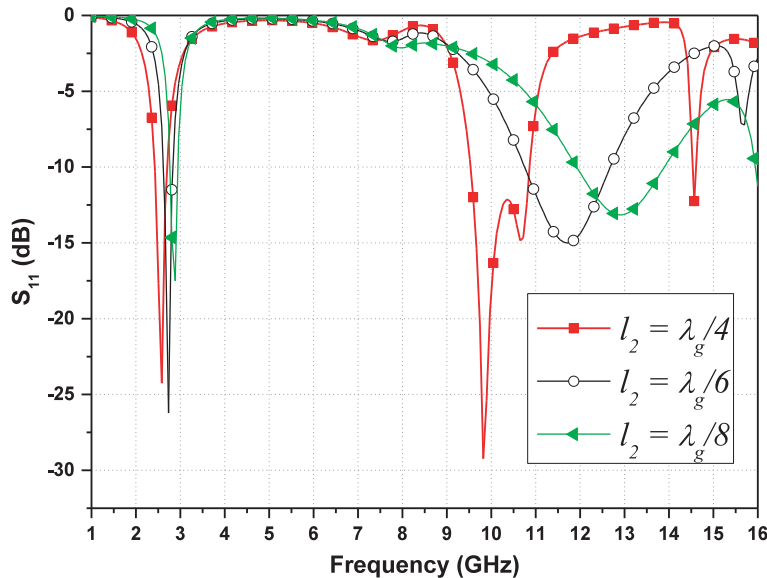


Figure 8. Transient responses of the filter (a) UWB and (b) 2.4 GHz filter.

is calculated and compared between the input voltage peak, V_{in} , and output voltage peak, V_{out} . The delay through the switchable filter in the UWB is 34 ps as shown in Figure 8(a). For 2.4 GHz band, it is 320 ps as shown in Figure 8(b).

2.2.1. Varying the Length of the Stub, l_2 , of 2.4 GHz Bandpass Filter

For a 2.4 GHz bandpass filter configuration, the length of the stub l_2 is varied from $\lambda_g/4$, $\lambda_g/6$ to $\lambda_g/8$, while the two lengths l_1 and l_3 are fixed at $\lambda_g/2$ and $\lambda_g/2$, respectively. Figure 9 shows that change in the length of the l_2 stub tunes the frequency from 2.4 GHz to 3.23 GHz. This in turn shows the change in the inductance value by varying the length of the stub. The insertion loss is 0.42 dB, and the 3-dB bandwidth is 796 MHz. The out of band rejection on lower frequency band is more than 45 dB and on the higher band is greater than 25 dB. The stub length of $l_2 = \lambda_g/4$ results in the generation of the second frequency band at 10 GHz. Its insertion loss is 0.6 dB with 3-dB bandwidth of 1.6 GHz.



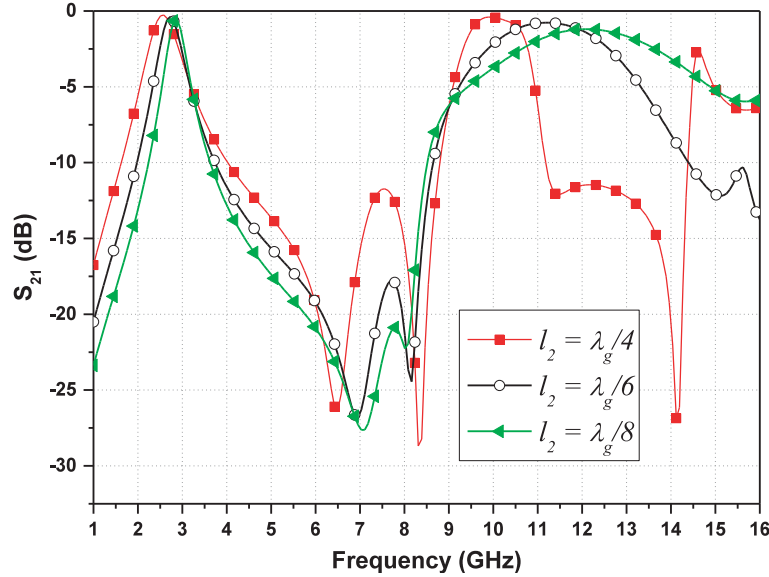


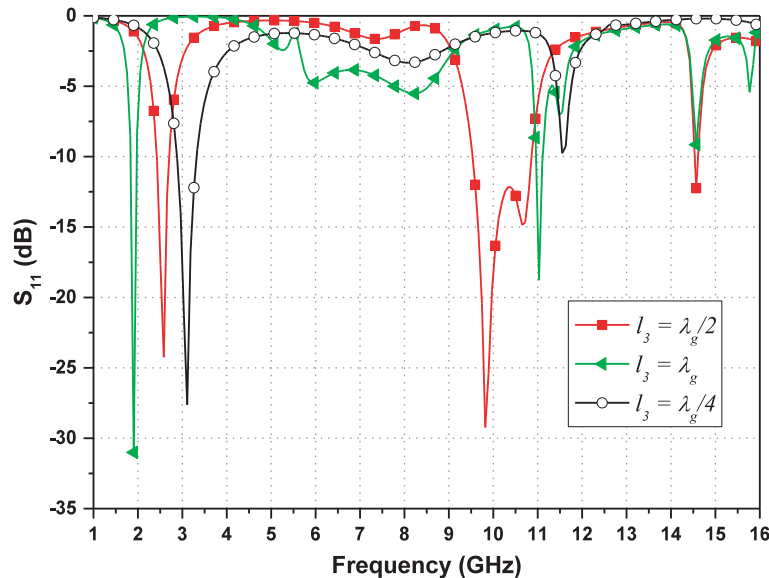
Figure 9. Simulation result for the variation in the length of stub, l_2 , of 2.4 GHz bandpass filter.

2.2.2. Varying the Length of the Stub, l_3 of 2.4 GHz Bandpass Filter

The final parametric study is for the length l_3 of 2.4 GHz bandpass filter. The lengths l_1 and l_2 are fixed at $\lambda_g/2$ and $\lambda_g/4$, respectively. The observation in this case is that there is a wide frequency shift if the lengths are changed from λ_g , $\lambda_g/2$ to $\lambda_g/4$. The shift in the frequency is more than 66% as the results in Figure 10. The rejection of $l_3 = \lambda_g$ stub length is very poor at the higher frequency band. However, the configuration $l_3 = \lambda_g$ is not realizable with the RF pin diodes.

3. EXPERIMENTAL RESULTS AND DISCUSSIONS

The switchable and tunable filter is fabricated on a Rogers substrate with dielectric constant, $\epsilon_r = 3.38$, and thickness of 0.8 mm as shown in Figure 11. The filter is designed with a $50\ \Omega$ signal line of width of 1.7 mm. Avago's HSMP 4890 dual anode pin diodes were used. The measurement results are shown



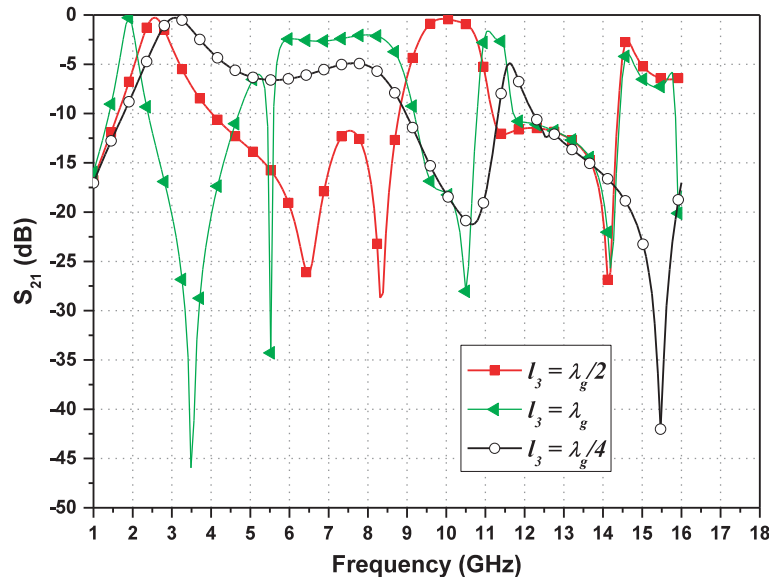


Figure 10. Simulation result for the variation in the length of stub, l_3 , of 2.4 GHz bandpass filter.

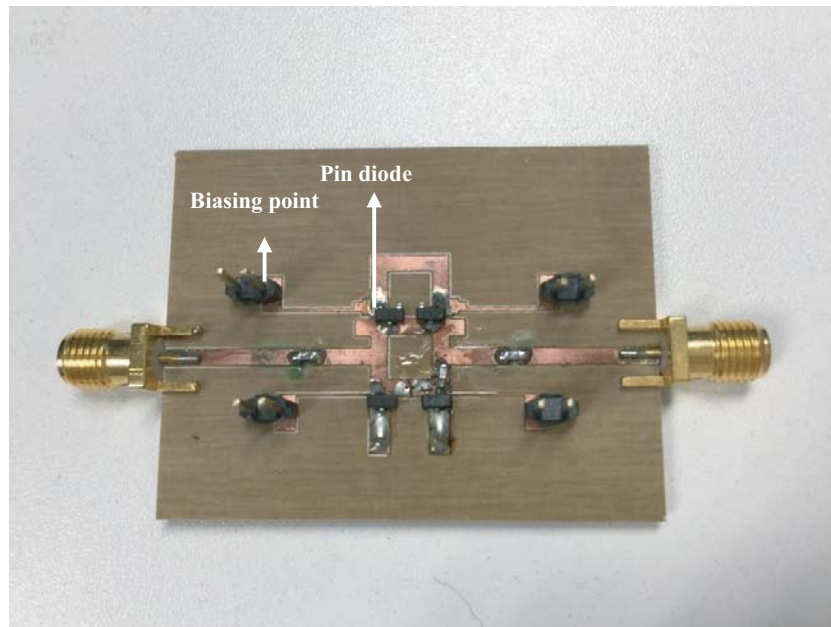


Figure 11. Fabricated structure — The switchable and tunable filter.

in Figure 12. Figure 12(a) shows that when diodes D1, D2, D3, and D4 are switched OFF, it exhibits UWB bandpass filter characteristics. However, when D1 and D2 are switched ON at 0.8 V, the length of stub l_2 changes, which results in the tunability of UWB. The UWB filter has shown an insertion loss of 2.1 dB and 3 dB bandwidth of 7 GHz. The tuning range is about 150 MHz, which is small because of the wide bandwidth of the filter. When diodes D3 and D4 are turned ON, length of stub l_3 changes. However, when diodes D1 and D2 are OFF, the filter switches to the 2.4 GHz band. Tuning in the 2.4 GHz band occurs when diodes D3 and D4 are turned ON one by one, i.e., length of stub l_3 changes. For the filter operating at the 2.4 GHz band, it has very low insertion of 0.78 dB, and the 3 dB bandwidth is 400 MHz as shown in Figure 12(b). The tuning range is more than 600 MHz.

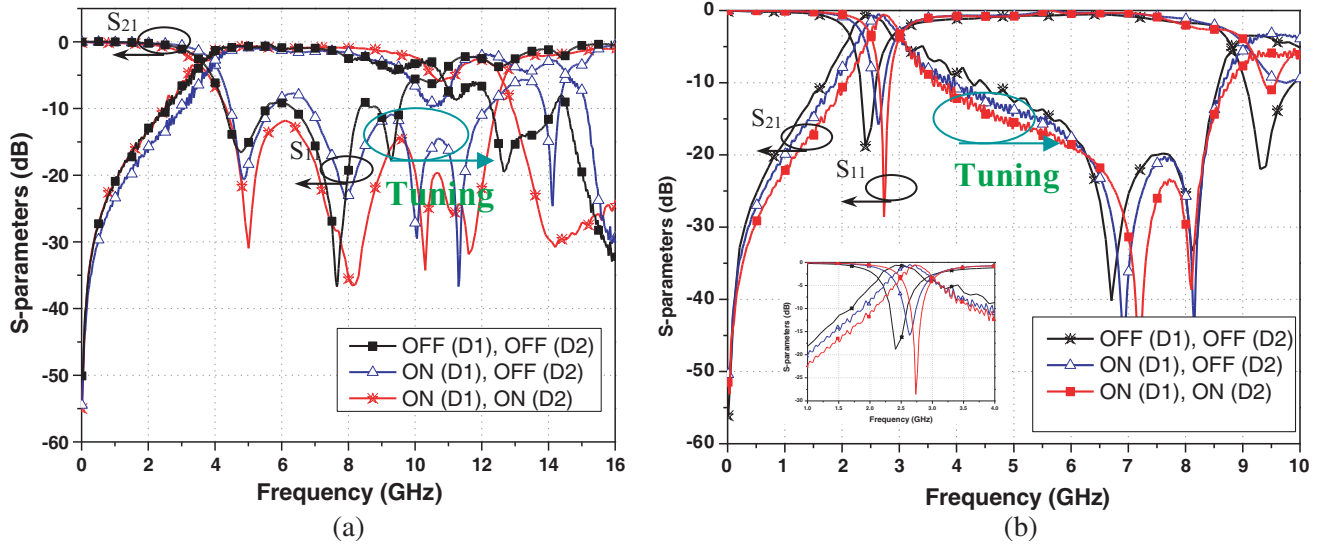


Figure 12. Measurement result. (a) Tuning — UWB band. (b) Tuning —2.4 GHz band.

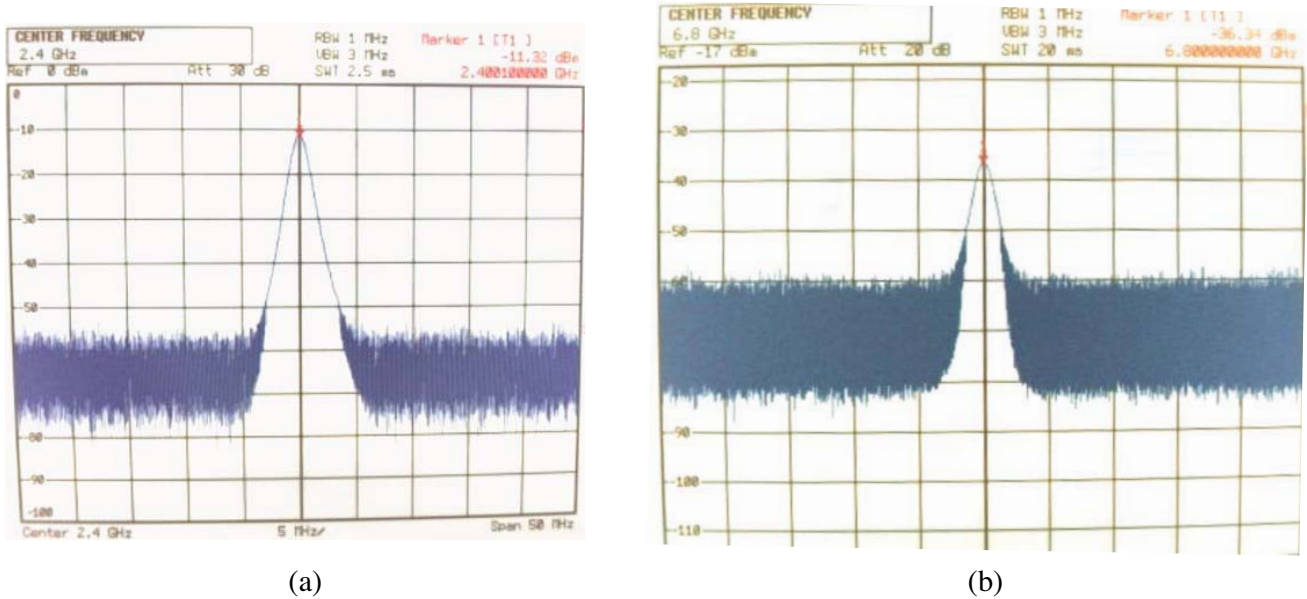


Figure 13. Measured isolation of the bandpass filter at (a) 2.4 GHz and (b) 6.8 GHz.

The isolation of the switchable filter is measured when the filter operates in the UWB while the isolation is calculated at 2.4 GHz and vice versa. Thus, the measured isolation is -11.32 dB at 2.4 GHz and is -35 dB at 6.8 GHz, respectively as shown in Figure 13.

4. CONCLUSIONS

An integrated switchable and tunable filter in the UWB and 2.4 GHz band has been designed, fabricated, and tested. A UWB filter consisting of two bent shorted quarter-wavelength stubs and a connecting half-wavelength stub is first developed. It switches to a 2.4 GHz band pass filter by connecting another half-wavelength stub through RF pin diodes. The switchable filter becomes a tunable filter by changing the inductance or the length of the shorted stubs by using pin diodes. The measurement results of the

switchable filter in the UWB show an insertion loss of 2.1 dB and a 3 dB bandwidth of 7 GHz. The tuning range is 150 MHz. For the 2.4 GHz filter, the insertion loss is 0.78 dB, and the tuning range is more than 600 MHz. The isolation of filter is -11.32 dB at 2.4 GHz and -35 dB at 6.8 GHz, respectively.

REFERENCES

1. Tamjani, A. A., L. Dussopt, and G. M. Rebeiz, "Miniature and tunable filter using MEMS," *IEEE Trans. Microwave Theory Tech.*, Vol. 51, 1878–1885, 2003.
2. Karim, M. F., A. Q. Liu, A. Arokiaswami, and A. B. Yu, "A tunable bandstop filter via the capacitance change of micromachined switches," *Journal of Micromechanics & Microengineering*, Vol. 16, 851–861, 2006.
3. Karim, M. F., Y.-X. Guo, Z. N. Chen, and L. C. Ong, "Miniaturized reconfigurable and switchable filter from UWB to 2.4 GHz WLAN using PIN diodes," *International Microwave Symposium, IEEE Microwave Theory and Techniques Society (MTT-S)*, 509–512, Boston, USA, 2009.
4. Brown, A. R. and G. M. Rebeiz, "A varactor tuned RF filter," *IEEE Trans. Microwave Theory Tech.*, Vol. 48, 1157–1160, 2000.
5. Pal, B. and S. Dwari, "Microstrip dual-band bandpass filter with independently tunable passbands using varactor-tuned stub loaded resonators," *AEU — International Journal of Electronics and Communications*, Vol. 73, 105–109, March 2017.
6. Supavarasuwat, P., M. Kumngern, S. Sangyaem, W. Jaikla, and F. Khateb, "Cascadable independently and electronically tunable voltage-mode universal filter with grounded passive components," *AEU — International Journal of Electronics and Communications*, Vol. 84, 290–299, February 2018.
7. Fourn, E., A. Pothier, C. Champeaux, P. Blondy, et al., "MEMS switchable interdigital coplanar filter," *IEEE Trans. Microwave Theory Tech.*, Vol. 51, 320–324, 2003.
8. Kraus, G. M., C. Goldsmith, C. D. Nordquist, et al., "A widely tunable RF MEMS end coupled filter," *IEEE MTT-S Int. Microwave Symp. Dig.*, 429–432, 2004.
9. Karim, M. F., A. Q. Liu, A. Arokiaswami, and A. B. Yu, "A reconfigurable micromachined switching filter using periodic structures," *IEEE Trans. Microwave Theory Tech.*, Vol. 55, 1154–1162, 2007.
10. Potrebić, M., D. Tošić, and A. Plazinić, "Reconfigurable multilayer dual-mode bandpass filter based on memristive switch," *AEU — International Journal of Electronics and Communications*, Vol. 97, 290–298, December 2018.
11. Ishida, H. and K. Araki, "Design and analysis of UWB bandpass filter with ring filter," *IEEE MTT-S Int. Dig.*, 1307–1310, 2004.
12. Wong, S. W. and L. Zhu, "EBG-embedded multiple mode resonator for UWB bandpass filter with improve upper stop band performance," *IEEE Wireless Component Lett.*, Vol. 17, 421–423, 2007.
13. Gozhenko, V., A. Przada, and P. Hagn, "Multilayer LTCC bandpass filter design," *IEEE 37th European Microwave Conference*, 540–543, 2007.
14. Matsuge, K., S. Him, M. Ishida, T. Kitaham, and T. Yamamoto, "Full RF module with embedded filters for 2.4 GHz and 5 GHz dual band WLAN applications," *IEEE MTT-S Int. Dig.*, 629–632, 2004.
15. Chan, K. Y., S. Fouladi, R. Ramer, and R. Mansour, "RF MEMS switchable interdigital bandpass filter," *IEEE Wireless Component Lett.*, Vol. 22, 44–46, 2012.
16. Brito, Z., I. Llamas-Garro, G. Navarro-Munoz, J. Perruisseau-Carrier, L. Pradell, F. Giacomozzi, and S. Colpo, "Precise frequency and bandwidth control of switchable microstrip bandpass filters using diode and microelectro-mechanical system technologies," *IET Microwaves, Antennas & Propagation*, Vol. 6, 713–719, 2012.
17. Lee, J., E. J. Naglich, H. H. Sigmarsson, et al., "New bandstop filter circuit topology and its application to design of a bandstop-to-bandpass switchable filter," *IEEE Trans. Microwave Theory Tech.*, Vol. 61, 1114–1123, 2013.