

A Simplified Method to Synthesize UWB Compact Bandpass Filter with Dual Notch Bands

Arvind Kumar Pandey and R. K. Chauhan

Department of Electronics and Communication Engineering, M.M.M.U.T., Gorakhpur
arvindmknk@gmail.com

Abstract— This paper presents a simplified method to synthesize a new and compact UWB bandpass filter with good selectivity, wide bandwidth and two notched frequencies at 5.2GHz and 7.8GHz. UWB bandpass is created by cascading highpass and lowpass filters. The proposed work uses network synthesis techniques to design highpass and lowpass filters with Chebyshev transfer function using insertion loss method. The optimized low pass and high pass circuits are implemented with the help of hairpin line and interdigital structure (IDS), respectively. The open ended stub and spurline are loaded on the outermost fingers of IDS to create notches at 5.2GHz and 7.8GHz frequencies, respectively. The size of the filter is highly miniaturized and compact in shape when compared with the other existing structures. The insertion loss in the pass band of the filter is smaller than 0.4dB and stop band is wide. Filter is fabricated on FR4 with dielectric constant 4.4 and thickness of 1.6mm.

Index Terms— Bandpass Filter; Hairpin; Interdigital; Spurline; Stubline; UWB.

I. INTRODUCTION

The research interest in the design of Ultra Wide band filters increases since 2002 after the approval of unlicensed use of frequency range 3.1-10.6GHz for the commercial purposes [1]. Because of this the requirement of band pass filter with ultra wide band was noticeably increased. The designing method of such wide band filter has not been accurately defined in the literature. Although the design theory of microwave design has been well developed but anyhow most of the techniques are only useful for narrow or moderate bandwidth, not suitable for wideband. The parallel-coupled transmission-line resonator filters in [2], shows accuracy only on center frequency. Furthermore some better synthesis methods based on parallel coupled lines were proposed, but there was limitation on bandwidth enhancement due to its dependency on separation between coupled lines [3], [4]. Some more synthesis methods based on MMR structures and coupled lines were proposed to improve insertion loss in pass band and selectivity from pass band to stop band [5-6]. But these methods do not give direct solution and are only effective for lower frequency ranges. The highpass and lowpass filter are cascaded to design UWB filter by some researchers but size of filter was increased and due to mismatching between structures ripples were also seen in the pass band [7].

Earlier many filters proposed by researchers for the UWB frequency range were based on structures such as cascaded band pass filters, ring resonator, multimode resonators etc. [8-10]. Most of these structures were based on the quarter-wavelength and couplings between resonators, which limits the miniaturization of structure. This limitation in

miniaturization was resolved up to some limit by using concept of zero order resonance (ZOR) in composite right- and left-handed-transmission line (CRLH-TL). The size of a CRLH-TL is much smaller than the quarter-wavelength due to its property of ZOR and so is used for miniaturization of the structures [11-13]. However, they suffer from the use of via in the structure that makes the fabrication complex and costly.

For last one decade due to vast development in communication systems the use of many frequencies such as WiMax, WLAN etc. is increased in the UWB range. To avoid the interference of these frequencies with UWB filters, many structures have been tried by the researchers [15-18]. But, most of these filters uses extra structures such as via or defected ground structures that make the filter costly and of bigger size.

In view of the above discussions, followings are the major challenges in the design of UWB BPF (a) Lack of easy and direct design methods of UWB BPF (b) Size reduction of filter without using via or defected ground structure and (c) Technique to create notch in the pass band for current requirement of UWB BPF without using via or defected ground structure. In this paper a simple design method of UWB band pass filter is used in such a way that via or defected structure is not required, and size is reduced to a maximum value with less ripples in the passband.

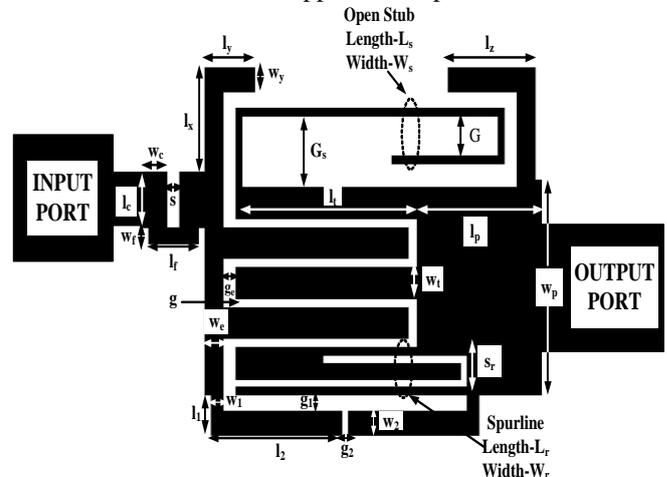


Figure 1(a): Geometry and dimensions of proposed filter



Figure 1(b): Fabricated structure of proposed filter

II. DESIGN AND ANALYSIS

The geometry of proposed filter is shown in Figure 1(a). It consists of stepped impedance hairpin resonator (SIHR) cascaded with IDS to create bandpass in UWB frequency range. SIHR responses as a low pass and IDS as a high pass filter. An open stub is loaded on uppermost finger and a spurline on lowermost finger of IDS to create notches at 5.2GHz and 7.8GHz respectively.

A. Design of Lowpass Filter

The geometry of SIHR is shown in Figure 2(a). It is a stepped impedance resonator folded like a hairpin. The SIHR can be represented as a combination of single transmission line of length l_f and a symmetric coupled line with a length l_c , as shown in Figure 2(a), [19]. The width of folded transmission line and coupled lines are w_f and w_c respectively. The gap between coupled lines is s . The characteristics impedance of the single transmission line of the length l_f is Z_f and the even and odd mode characteristics impedances of symmetric coupled lines of length l_c are Z_{oe} and Z_{oo} .

The single transmission line is represented by a LC π -network including inductor L_f representing inducting effect of transmission line and capacitor C_{pf} representing capacitive effect of dielectric material on which line is designed. Moreover, as shown in Figure 2(a) the parallel coupled lines are modeled as a capacitive π -network.

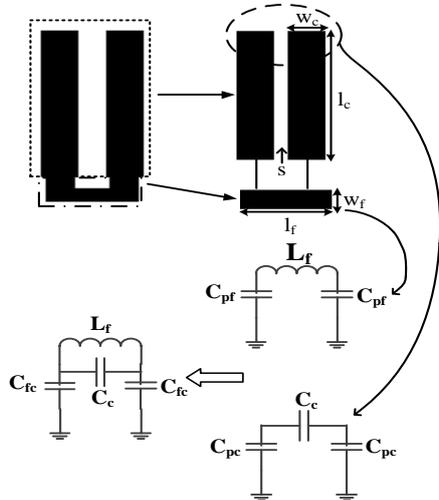


Figure 2 (a): Geometry and equivalent circuit of SIHR

The ABCD matrix of transmission line and its L-C equivalent circuit can be expressed as [20]

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix}_{\text{Line}} = \begin{bmatrix} \cos(\beta_f l_f) & jZ_f \sin(\beta_f l_f) \\ jY_f \sin(\beta_f l_f) & \cos(\beta_f l_f) \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix}_{\text{Equivalent}} = \begin{bmatrix} 1 + Z_{fL} Y_{fC} & Z_{fL} \\ Y_{fC} (2 + Z_{fL} Y_{fC}) & 1 + Z_{fL} Y_{fC} \end{bmatrix} \quad (2)$$

Where β_f is the phase constant of the transmission line of length l_f and Y_f is characteristics admittance of the folded transmission line. The Z_{fL} and Y_{fC} are impedance and admittance of inductor L_f and capacitor C_{pf} at frequency ω , respectively.

The ABCD parameter of symmetric parallel coupled line and its equivalent circuit can be written as [21]

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix}_{\text{PC}} = \begin{bmatrix} \frac{Z_{oe} + Z_{oo}}{Z_{oe} - Z_{oo}} & \frac{-j2Z_{oe}Z_{oo} \cot(\beta_c l_c)}{Z_{oe} - Z_{oo}} \\ \frac{j2}{(Z_{oe} - Z_{oo}) \cot(\beta_c l_c)} & \frac{Z_{oe} + Z_{oo}}{Z_{oe} - Z_{oo}} \end{bmatrix} \quad (3)$$

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix}_E = \begin{bmatrix} 1 + Z_{cL} Y_{cC} & Z_{cL} \\ Y_{cC} (2 + Z_{cL} Y_{cC}) & 1 + Z_{cL} Y_{cC} \end{bmatrix} \quad (4)$$

Where, Z_{cL} and Y_{cC} are impedance and admittance of capacitor C_c and capacitor C_{pc} at frequency ω , respectively. Z_{oe} and Z_{oo} are even and odd mode characteristics impedances of the parallel coupled lines.

From equation (1) the values of equivalent inductance and capacitance can be related to dimensions of the folded transmission line as

$$L_f = \frac{Z_f \sin(\beta_f l_f)}{\omega} \text{ (H)} \quad (5)$$

$$C_{pf} = \frac{1 - \cos(\beta_f l_f)}{\omega Z_f \sin(\beta_f l_f)} \text{ (F)} \quad (6)$$

From equation (2) the equivalent capacitances of parallel coupled line are related to dimensions are

$$C_c = \frac{Z_{oe} - Z_{oo}}{2\omega Z_{oe} Z_{oo} \cot(\beta_c l_c)} \text{ (F)} \quad \text{and} \quad (7)$$

$$C_{pc} = \frac{1}{\omega Z_{oe} \cot(\beta_c l_c)} \quad (8)$$

The length of folded transmission line and coupled lines can be expressed as

$$\text{Length of folded transmission line, } l_f = \frac{\sin^{-1} \frac{\omega L_f}{Z_f}}{\beta_f} \quad (9)$$

$$\text{Length of coupled transmission line, } l_c = \frac{\tan^{-1} [\omega Z_{oe} (C_{fc} - C_f)]}{\beta_c} \quad (10)$$

The low pass prototype components of Chebyshev method in insertion loss method are used to design low pass filter of order three for 12GHz center frequency [21]. By using equations (1) to (10) the dimensions of SIHR are approximately synthesized as a low pass filter with 12GHz cutoff frequency. The low pass prototype Chebyshev values, L-C values of Chebyshev lowpass filter for 12GHz and approximated L-C values of SIHR are tabularized in Table 1.

 Table 1
L-C values and respective dimensions of SIHR LPF

Lowpass prototype values (for Chebyshev order three)	Lowpass filter (LC π -network) for 12GHz	L-C values of SIHR lowpass filter for 12GHz (for Figure 2)	Dimensions of SIHR	Characteristics Impedances of SIHR
$g_1=1.5963$	$C_1=0.423\text{pF}$	$C_{fc}=0.31\text{pF}$	$l_f=0.82\text{mm}$	$Z_f=150\Omega$
$g_2=1.0967$	$L_2=0.73\text{nH}$	$C_c=0.03\text{pF}$	$w_f=0.22\text{mm}$	$Z_{oc}=104.9\Omega$
$g_3=1.5963$	$C_3=0.423\text{pF}$	$L_f=0.71\text{nH}$	$l_c=0.9\text{mm}$	$Z_{oe}=187.1\Omega$
		$C_{fc}=0.31\text{pF}$	$w_c=0.4\text{mm}$	$Z_{oo}=58.93\Omega$
			$s=0.2\text{mm}$	

The Chebyshev lowpass prototype lumped components values are here only used to find the approximate dimensions of the SIHR as a lowpass filter for 12GHz cutoff frequency. The frequency response of the LPF filter using L-C lumped

components and SIHR are analyzed on ADS and found approximate lowpass behavior of both, shown in Figure 2(b).

From Figure 2(b) it can be seen that the performance of LPF designed by using SIHR is not good because only one cell of SIHR is used. The performance of lowpass filter is improved by using a tri-section stepped impedance resonator (SIR) loaded on finger of IDS, as shown in section 3. The lowpass section is used to achieve wide stopband for frequencies greater than 12GHz.

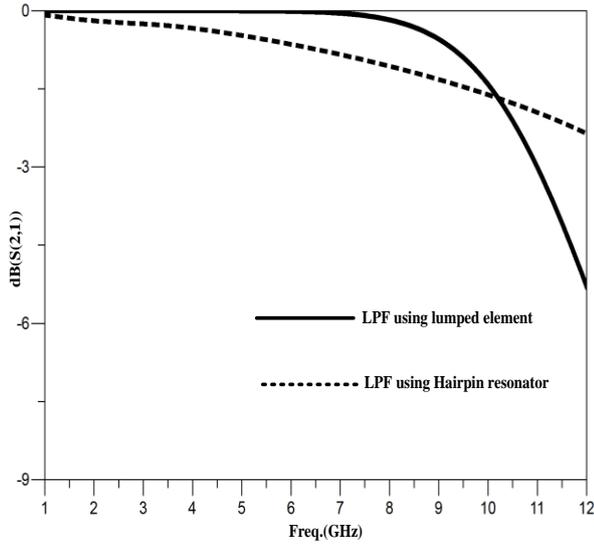


Figure 2(b): Frequency response of SIHR

B. Design of High-Pass Filter Circuit

The geometry of planar IDS is shown in Figure 3(a). It consists of parallel coupled lines called fingers. The length of fingers creates inductive effect, L, and gaps between the fingers create capacitive effect, C, as shown in equivalent circuit of IDS in Figure 3(a) [20].

The inductance and capacitances in equivalent circuit of IDS can be expressed as [20]

$$L = \frac{Z_0 \sqrt{\epsilon_{re}}}{c} l_t, \quad C_{p1} = C_{p2} = \frac{1}{2} \frac{\sqrt{\epsilon_{re}}}{Z_0 c} l_t \quad (11)$$

$$C = \left(\frac{\epsilon_r + 1}{W'} \right) l_t [(N - 3)A_1 + A_2] \left(\frac{\text{pF}}{\mu\text{m}} \right) \quad (12)$$

$$\text{Where } A_1 = 4.409 \tanh \left[0.55 \left(\frac{h}{w} \right)^{0.45} \right] \times 10^{-6} \left(\frac{\text{pF}}{\mu\text{m}} \right)$$

$$A_2 = 9.92 \tanh \left[0.52 \left(\frac{h}{w} \right)^{0.5} \right] \times 10^{-6} \left(\frac{\text{pF}}{\mu\text{m}} \right)$$

The L is inductance due to finger of IDS and capacitances C_{p1} and C_{p2} are due to dielectric material on which IDS is designed. The capacitor C represents capacitive effect of gap between fingers of IDS. The length of the finger is l_t , Z_0 is the characteristics impedance of IDS, c is speed of light and ϵ_{re} is the effective dielectric constant. The thickness of dielectric material and width of finger is shown by h and w respectively. W' is the total width of IDS, l_t is length of fingers and N is number of fingers.

By using insertion loss method with Chebyshev function, the L-C components of highpass filter for 2GHz cutoff frequency are calculated [21]. The L-C components are then used to synthesize HPF using IDS. The values of L-C components and their respective dimensions of IDS for HPF are listed in Table 2.

Table 2
L-C components and dimensions of IDS for HPF

Highpass filter(LC π -network) for 2GHz cut-off frequency	Dimensions of IDS
$L_1=0.423\text{pF}$	$l_t=2.9\text{mm}$, $w_f=0.39\text{mm}$,
$C_2=0.727\text{nH}$	$g=0.12\text{mm}$, $g_c=0.2\text{mm}$,
$L_3=0.423\text{pF}$	Number of fingers=5,
	$w_c=0.3\text{mm}$

The Chebyshev prototype values are used to design highpass filter using lumped components. The values of lumped components are used to find the approximate dimensions of IDS as a highpass filter with 2GHz cutoff frequency. The IDS layout and HPF circuit are designed and simulated. The frequency response of the IDS and respective HPF with L-C components both shows high pass behavior, as shown in Figure 3(b).

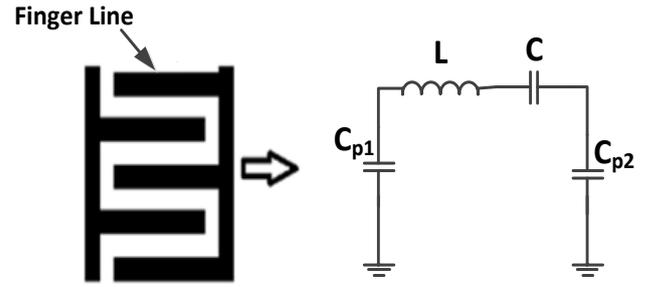


Figure 3(a): Geometry and equivalent circuit of IDS

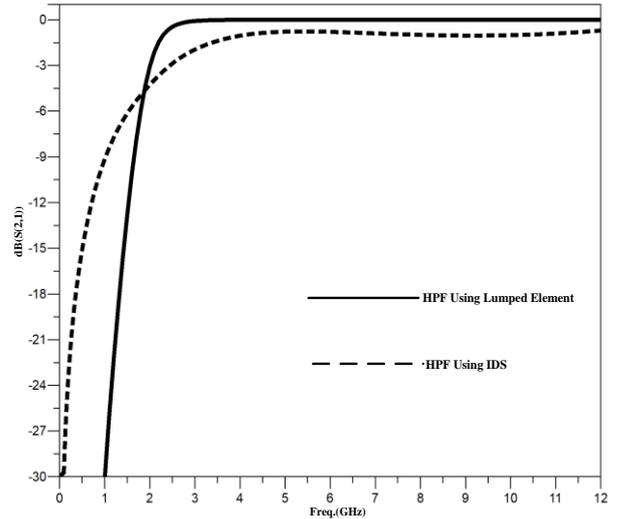


Figure 3(b): Frequency response of IDS

C. Creation of Notch Bands

In the pass band of proposed filter two notched bands at 5.2GHz and 7.8GHz are created. The notch band at 5.2GHz and 7.8GHz is achieved by loading open stub at the top most finger and spurline at the bottom most finger of IDS respectively, as shown in Figure 4(a).

1) Creation of notch at 5.2GHz

A band stop filter can be designed by loading quarter wavelength stub on the main line. Stub is a transmission line connected in shunt of main line. The geometry of stub is shown in Figure 4(b). The width and length of stub is w_s and l_s respectively. If stub is open and of quarter wavelength long at a particular frequency it creates notch at that frequency.

The bandwidth, B, of notch is related to characteristic impedances of the mainline and stub as

$$B = 2 \tan^{-1} \frac{Z_1}{Z_2} \quad (13)$$

where Z_1 and Z_2 are characteristics impedance of main line and loaded stub respectively [22].

To create sharp notch at any frequency bandwidth (B) should be as small as possible and it can be possible by small ratio of Z_1/Z_2 . In the proposed filter a stub is loaded on the outer finger of IDS. To create sharp notch at any frequency the ratio of characteristics impedances of outer finger of IDS and stub at that frequency should be as small as possible. For constant finger width of IDS, the bandwidth of notch will be inversely proportional to stub width, W_s . To create sharp notch, W_s should be as small as possible and it can be minimum 0.1 mm due to limitation of PCB printing technique. The response of stub loaded IDS is studied on simulation tool and found that stub creates a sharp notch at 5.2GHz frequency for quarter wavelength stub length. The entire frequency of notch can be varied by varying stub length, L_s . The frequency characteristics of stub with different L_s are simulated and found center frequency is inversely proportional to L_s , as shown in Figure 4(c).

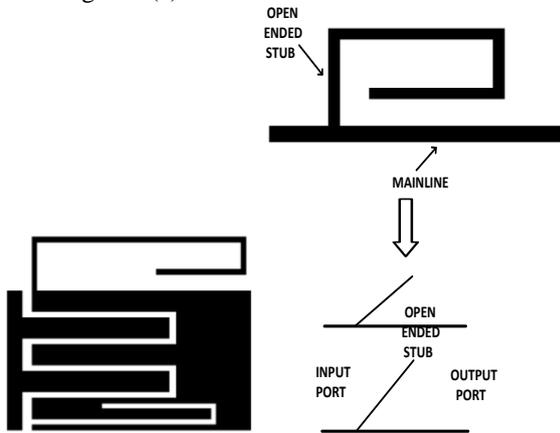


Figure 4(a): IDS loaded with open stub and spurline

Figure 4(b): Geometry of stub line as its equivalent model

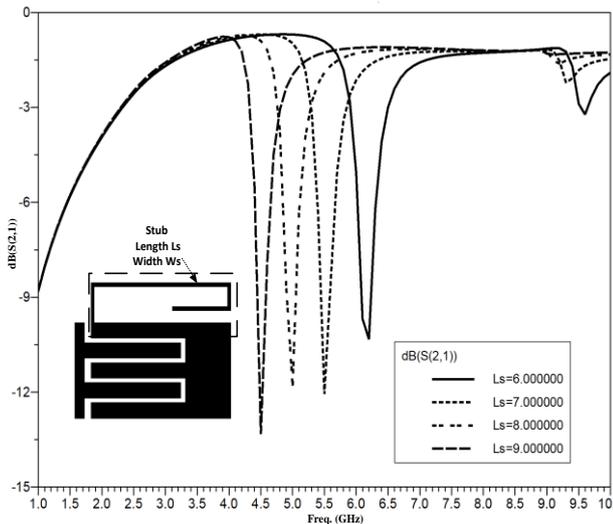


Figure 4(c): Frequency characteristics of stub loaded IDS with different L_s

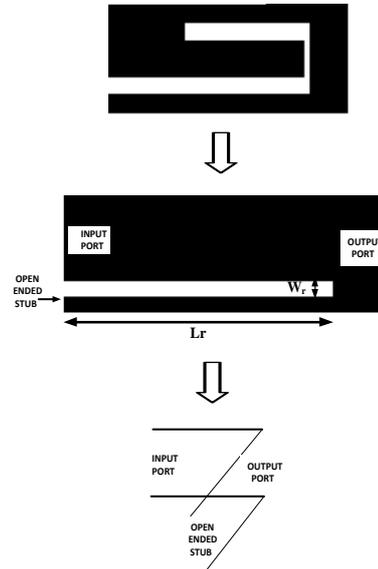


Figure 4(d) Geometry of spurline and its equivalent model

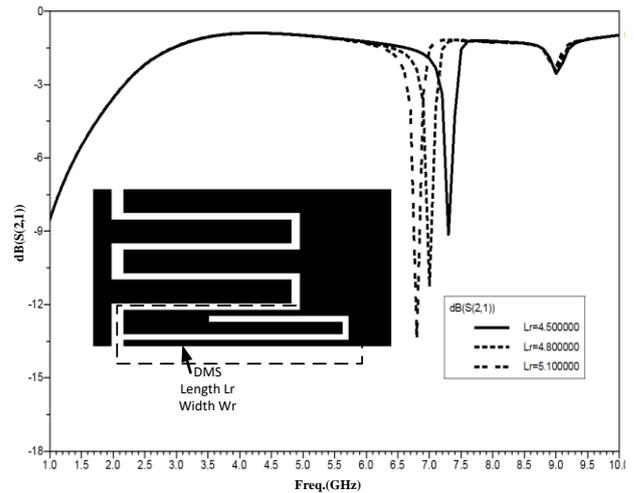


Figure 4(e): Frequency characteristics of DMS loaded IDS for different values of L_r

2) Creation of notch at 7.8GHz

A notch band can be created by spurline on the mainline of the signal. Spurline is a type of defected microstrip structure which creates open stub line on the mainline of the filter. The length and width of spurline is W_r and L_r respectively. The spurline structure can be modeled as an open stub loaded mainline as shown in Figure 4(d) [23]. The spurline creates notch according to the length of the slot and it is related as quarter wavelength for a particular frequency. In the proposed filter a spurline is created on the lower finger of the IDS and its behavior is studied on the simulation tool. The center frequency of notch is inversely proportional to length L_r of spurline. The characteristic of filter with respect to length of spurline is studied as shown in Figure 4(e).

III. OPTIMIZATION AND RESULTS

The geometry of proposed filter consists of an IDS cascaded with hairpin resonator and trisection SIR. The trisection SIR behaves as a lowpass filter [24], so it is loaded on finger of IDs to widen the stop band. Open stub and spurline are loaded on the finger of IDS to create notch in the pass

band of the filter. The proposed filter is designed and simulated on the HFSS. The frequency response of the filter is shown in the Figure 5(b). In the response of the filter insertion loss is around 1.5dB and some ripples are also present in the pass band of the filter. To improve frequency response of the filter structure is optimized on HFSS using gradient method and parametric analysis with respect to matching conditions between different cascaded structures. The output port of the filter is become wider and stubs are loaded at input and output ports in the geometry of the filter after optimization. The shape and dimensions of the proposed filter after the optimization is shown in Figure 1(a).

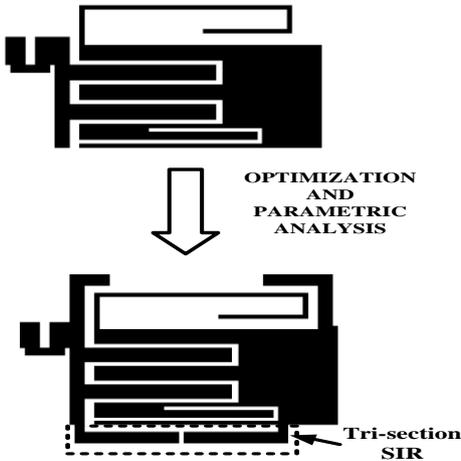


Figure 5(a): Change in Geometry of proposed filter to improve response

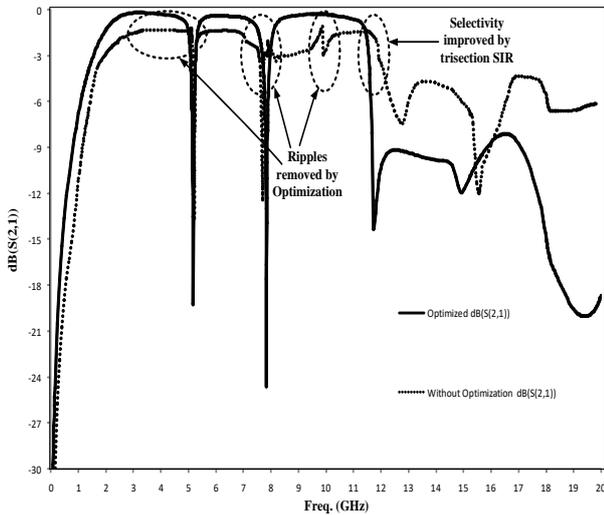


Figure 5(b): Effect of optimization and tri-section SIR on frequency response of filter

The dimensions of the optimized proposed filter shown in Figure 1(a) are $l_c=0.9\text{mm}$, $w_c=0.4\text{mm}$, $l_f=0.8\text{mm}$, $s=0.2\text{mm}$, $w_f=0.2\text{mm}$, $l_r=2.9\text{mm}$, $w_r=0.39\text{mm}$, $g=0.12\text{mm}$, $g_e=0.2\text{mm}$, $w_e=0.3\text{mm}$, $s_r=0.6\text{mm}$, $L_r=6.4\text{mm}$, $W_r=0.1\text{mm}$, $g_1=0.2\text{mm}$, $l_1=0.5\text{mm}$, $l_2=2.1\text{mm}$, $w_1=0.2\text{mm}$, $w_2=0.3\text{mm}$, $g_2=0.1\text{mm}$, $L_s=7.8\text{mm}$, $W_s=0.1\text{mm}$, $G=0.5\text{mm}$, $G_s=0.9\text{mm}$, $l_x=1.5\text{mm}$, $l_y=0.8\text{mm}$, $l_z=1.4\text{mm}$, $w_y=0.3\text{mm}$, $l_p=1.9\text{mm}$, $w_p=2.6\text{mm}$. The proposed filter is implemented on FR4 with dielectric constant of 4.4 and with height 1.6mm. The photograph of fabricated filter is shown in Figure 1(b) which occupies $6.4\text{mm}\times 4.6\text{mm}$. The filter is tested on the vector network analyzer.

The simulated and measured results of proposed UWB BPF are shown in Figure 6. The measured results are in good

agreement with simulated results except the passband between two notches. Some small differences between measured and simulated results may be due to less accuracy in fabrication. The simulated 3-dB lower and upper cutoff frequencies of proposed filter are 1.99GHz and 11.5GHz respectively. The 3-dB cutoff frequencies of proposed filter in measured result is seen very closed to simulated response as 2.1GHz at lower edge and 11.4GHz at higher edge. The insertion loss in passband is seen more than 0.4dB in simulated and more than 1.3dB in measured response of the proposed filter. The group delay of the proposed filter is less than 0.4ns except at notches. The simulated and measured response of the proposed filter shows wide stop band from 11.5GHz to more than 30GHz (stopband between 11GHz to 20GHz is only shown in Figure 6).

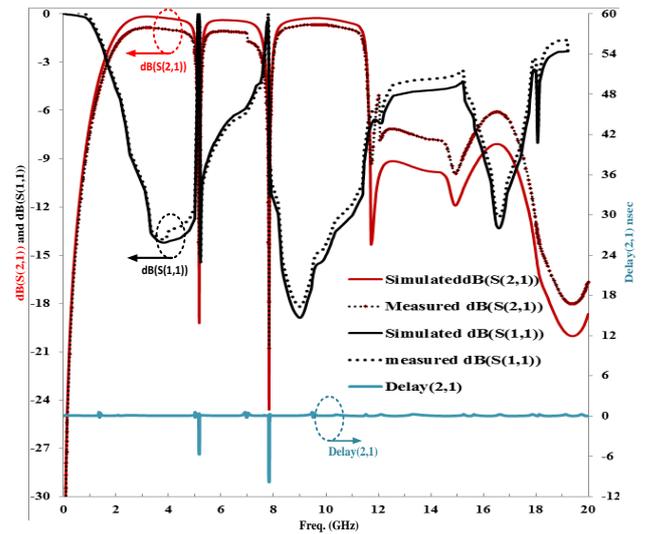


Figure 6: Simulated and measured S-parameters of the proposed UWB BPF

The response of proposed filter is also compared with some previously reported filters and found much smaller size with better performance such as good insertion loss, selectivity and wide stop band as reported in the Table 3.

Table 3
Comparison of proposed filter with some previously reported UWB BPF with notch.
FBW-Fractional Band width, λ_g - Guided wavelength at 6.85 GHz

Ref.	$\epsilon_r/h(\text{mm})$	Inse rtion loss (dB)	Notch freque ncy (GHz)	% 3-dB FBW at notch	Use of Via/ DGS	Size: in term of ($\lambda_g \times \lambda_g$)
[14]	2.2/0.78	<0.5	5.22	3.0	Yes	0.61×0.5
[15]	3.38/0.508	<0.5	5.9/8.0	3.6/3.6/4.1	Yes	0.92×0.45
[16]	2.2/0.78	<0.5	-	-	Yes	0.49×0.31
[17]	2.65/1.0	<2	5.3/7.8	4.0/3.2	Yes	1.02×0.54
[18]	2.2/0.78	<1	5.9/8.0/9.0	2.1/1.8/2.8	Yes	0.64×0.17
This work	4.4/1.6	<0.4	5.2/7.8	3.7/3.5	No	0.27×0.19

IV. CONCLUSION

A highly miniaturized UWB bandpass filter with dual notch band is proposed. The design method is very simple without any tedious calculation. The insertion loss of the filter is less than 0.4 dB in the pass band and greater than 15dB in stop band. The group delay of the proposed filter is less than 0.4ns

except at two notch frequencies. The stop band of the filter is very wide with sharp selectivity. The ripples in the output due to mismatching are removed by using optimization in HFSS. The filter is highly miniaturized without using via or DGS in the geometry of the proposed design. The response of the filter is compared with reported results available in the literature. The proposed design was smaller in size with better performance. The measured results of proposed design were found in good agreement with simulated results.

REFERENCES

- [1] "Revision of Part 15 of the commission's Rules Regarding Ultra-Wideband Transmission Systems," FCC, Washington, DC Tech. Rep. ET-Docket, 8, pp. 1–118, Apr. 2002.
- [2] S. B. Cohn, "Parallel-coupled transmission-line-resonator filters," *IRE Trans. Microw. Theory Tech.*, vol. 4, pp. 223–231, Apr. 1958.
- [3] K.S. Chin, L.Y. Lin, and J.T. Kuo, "New formula for synthesizing microstrip bandpass Filters with relatively wide bandwidths," *IEEE Trans. Microwave and Wireless Components Letters*. vol. 14, pp. 231–233, May 2004.
- [4] K. S. Chin and J.T. Kuo, "Insertion loss function synthesis of maximally flat parallel-coupled line bandpass Filters," *IEEE Trans. Microwave Theory Tech.* vol. 53, pp. 3161–3168, Oct. 2005.
- [5] C.P. Chen, Z. Ma and T. Anada, "Synthesis of ultra-wideband bandpass filters employing parallel-coupled stepped-impedance resonators. *IET Microwaves Antennas Propag.* , vol. 2, pp. 766–772, 2008.
- [6] R. Li, S. Sun and L. Zhu, "Synthesis design of ultra-wideband bandpass filters with designable transmission poles," *IEEE Microwave Compon. Lett.*, vol. 19, pp. 284–286, 2009.
- [7] R.G. Garcia, and J. I. Alonso, "Systematic Method for the Exact Synthesis of Ultra-Wideband Filtering Responses Using High-Pass and Low-Pass Sections," *IEEE Transactions on Microwave Theory and Techniques*. Vol. 54, pp. 3751–3764, October 2006.
- [8] G. Yang, W. Kang and H. Wang, "An UWB bandpass filter based on single ring resonator and shorted stubs loaded without coupled feed lines," *J. Electromagnetics Waves. Appl.*, vol. 25, pp. 2159–2167, 2011.
- [9] Z. Zhang and F. Xiao, "An UWB bandpass filter based on a novel type of multi-mode resonator," *IEEE Microwave Wireless Compon. Lett.* vol. 22, pp. 506–508, 2012.
- [10] K. Song and Y. Fan, "Compact ultra-wideband bandpass filter using dual-line coupling structure," *IEEE Microwave Wireless Compon. Lett.*, vol. 19, pp. 30–32, 2009.
- [11] S. Kahng and D. Lim, "A center-tapped CRLH ZOR UWB bandpass filter with improved stopband," *Microw. J.*, vol. 55, pp. 86–92, Jun. 2012.
- [12] S. Kahng and S. Jang, "A novel compact metamaterial zeroth order resonant bandpass filter for a VHF band and its stopband improvement by transmission zeros," *J. Electromagn. Eng. Sci.* , vol. 13, pp. 263–266, 2013.
- [13] Y.C. Yun, S.H. Oh, J.H. Lee, K. Choi, T. K. Chung and H. S. Kim, "Optimal Design of a Compact Filter for UWB Applications Using an Improved Particle Swarm Optimization," *IEEE Transactions on Magnetics*, vol. 52, pp. 1–4, March 2016.
- [14] R. Ghatak, P. Sarkar, R.K. Mishra and D.R. Poddar, "A compact UWB bandpass filter with embedded SIR as band notch structure," *IEEE Microwave Wireless Compon. Lett.* vol. 21, pp. 261–263, 2011.
- [15] J. Zhao, J. Wang, G. Zhang, J.L. Li, "Compact microstrip UWB bandpass filter with dual notched bands using E-shaped resonator," *IEEE Microwave Wireless Compon. Lett.* , vol. 23, pp. 638–640, 2013.
- [16] S. Khalid, W.P. Wen and L.Y. Cheong, "Synthesis design of UWB bandpass filter using multiple resonance resonators (MRR)," *Electron. Lett.* vol. 50, pp. 1851–1853, 2014.
- [17] Y. Song, G.M. Yang and W. Geyi, "Compact UWB bandpass filter with dual notched bands using defected ground structures," *IEEE Microwave Wireless Compon. Lett.* vol. 24, pp. 230–232, 2014.
- [18] X. M. Shia, X.L. Xia, Y. C. Zhao and H. L. Yanga, "A novel compact ultra-wideband (UWB) bandpass filter with triple-notched bands," *J. Electromagn. Waves Appl.*, vol. 29, pp. 1174–1180, April 2015.
- [19] L. H. Hsieh, and K. Chang, "Compact Elliptic-Function Low-Pass Filters Using Microstrip Stepped-Impedance Hairpin Resonators," *IEEE Transactions on Microwave Theory and Techniques*, vol. 51, pp. 193–199, January 2003.
- [20] I. Bahl, *Lumped Elements for RF and Microwave Circuits*. Artech house. inc.Boston –London, 2003.
- [21] D. M. Pozar, *Microwave Engineering*, JohnWiley& Sons, Inc. USA, 2012.
- [22] C.W. Hsue, C.W. Ling, and W. Ting, "Discrete-time Notch Filter and its application to Microwave Filter," *Microwave and Optical Technology Letters.*, vol. 50, pp. 1596–1599, June 2008.
- [23] B. M. Schiffman and G. L. Matthaei, "Exact Design of Band-Stop Microwave Filters," *IEEE Transactions on Microwave Theory and Techniques*, vol. 12, pp. 6–11, 1964.
- [24] D. Packiaraj, K.J. Vinoy, M. Ramesha and A.T. Kalghatgi, "Design of compact low pass filter with wide stop band using tri-section stepped impedance resonator," *Int. J. Electron. Commun. (AEÜ)*, vol. 65, pp. 1012–1014, 2011.