Design of a highly selective bandstop filter using dual path capacitive coupled SIR structure

Jihad Younis (✉ jihadalsaqqaf@gmail.com)

Aden University, Aden, P.O.Box 6014, Yemen

Muhammad Abdul Rehman

Department of Electrical Engineering, Riphah International University, Pakistan

Sohail Khalid Khalid

Department of Electrical Engineering, Riphah International University, Pakistan

Research Article

Keywords:

Posted Date: January 27th, 2022

DOI: <https://doi.org/10.21203/rs.3.rs-1278563/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Design of a highly selective bandstop filter using dual path capacitive coupled SIR structure

Muhammad AbdulRehman^{1,+}, Sohail Khalid^{1,+}, and Jihad Younis^{2,*}

¹Department of Electrical Engineering, Riphah International University, Pakistan

²Aden University, Aden, P.O.Box 6014, Yemen

*corresponding:jihadalsaqqaf@gmail.com

⁺these authors contributed equally to this work

ABSTRACT

This article presents the design of a wideband bandstop filter (BSF) with the ultimate goal of improving selectivity. The designed filter consists of a dual-path Capacitive Coupled Step Impedance Resonator (DP-CCSIR). A theoretical analysis of the proposed DP-CCSIR structure has been presented in this paper. It has been observed that the selectivity can be improved by increasing the order of the dual coupled step impedance resonator. The proposed design produces a wideband BSF centered at 5.25 GHz with fractional bandwidth of 58.5%. The results have demonstrated that the resonant frequencies are regulated by varying the electrical length of CCSIR. Moreover, it has also been realized that dual-path CCSIR is involved in producing the finite frequency transmission poles, hence leading to better selectivity. However, the proposed design has been validated through the fabrication of three prototypes. The measurement shows good concurrence with the simulated results.

Introduction

Wireless communication systems may encounter a plethora of impurities. Non-linearities in hardware components or several carriers within the same data links are the main sources of impurities. These impurities are referred to as passive intermodulation. Many solutions have been formulated to resolve these disputes^{1,13}. One approach is to use signal interference and cross-coupling to design a wideband Band Stop Filter (BSF)¹. In another one, a wideband BSF is designed using two $\frac{\lambda}{4}$ open and circuited transmission couple lines². The proposed filter shows optimal electrical performance. However, circuit dimensions are quite compromised. To design a miniaturized BSF, parallel-coupled lines and loaded stubs are used in³. The designed filter shows good out-of-band insertion with four transmission poles. Though, only one transmission zero indicates the weak rejection of the signals. Furthermore, a wideband BSF is developed using dual-coupled resonators⁴. However, the additional capacitors may cause an undesired parasitic effect at high frequencies. In⁵, dual-section open stubs are used to design a highly selective BSF. However, the circuit size remains an issue. Additionally, a complementary split-ring resonator is used to design a wideband bandpass filter⁶. The proposed filter is compact in size. However, the electrical performance is compromised. Moreover, Band-stop filters have been designed by employing symmetrical three-layer ring structures, each with a high-impedance phase shift section, connected lines, and short-stubs⁷. The proposed filter has a relatively small circuit size, but it is pretty challenging to fabricate. In⁸, a wideband BSF is proposed using two coupled line sections with loaded stubs and an inner couple line section. The proposed filter has a very good out-of-band insertion. Whereas the filter produces only one transmission zero. Another method for designing wideband BSF is to use a step impedance couple line shunt connected with an open-circuited stub⁹. The proposed filter performs well in terms of in-band rejection, while out-of-band insertion is not good. Moreover, a wideband bandstop filter is proposed using stub loaded cross-coupling technique¹⁰. The proposed design shows good in-band isolation; however, out of band insertion is low. Two wideband bandstop filters with multiple transmission zeros are designed in¹¹ and¹², respectively. Furthermore,¹² describes the design of a triple mode microstrip bandstop filter using open-circuited stubs. However, the proposed BSF's suffers from bad electrical performance.

This paper presents a highly selective bandstop filter using a dual-path Capacitive Coupled Step Impedance Resonator (DP-CCSIR) structure. The proposed filter produces a highly selective bandstop filter with the rejection level of greater than 83dB. According to the detailed analysis, it has been observed that the selectivity is improved by increasing the order of dual coupled step impedance resonator. Moreover, the stopband is independently controlled by varying the electrical length of coupled SIR. In this configuration, the designed filter attains good electrical performance, controllable stopband frequency, and ease of fabrication.

Figure 1. Schematic model of Proposed BSF

Methodology

Figure.1 shows the schematic model of the proposed bandstop filter with two transmission paths. Path-1 entails a uniform impedance resonator with characteristics impedance " Z " and electrical length " θ " however, path-2 includes a resonator which is presented as a 1pF capacitor coupled twice with the transmission lines of impedance " Z " and electrical length " θ_1 " whereas $\theta'' = \theta_1$. Path-1 has an electrical length of 90° , while path-2 has an electrical length of 270° . The electrical length of both pathways is deliberately chosen to be out of phase, resulting in a high rejection level at higher frequencies, as illustrated in Fig. 2

Figure 2. Coordinate System Representation for Proposed BSF

An ideal transmission line model is depicted in Fig. 1. Based on this model, the filtering function is retrieved using the conversion between ABCD and Y-Parameters and vice versa. The ABCD parameters of path-2 are calculated as:-

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix}_{Path2} = T_{TL} \times T_{CP} \times T_{TL} \times T_{CP} \times T_{TL} \quad (1)$$

$$T_{TL} = \begin{bmatrix} \cos(\theta) & jZ \sin(\theta) \\ \frac{j\sin(\theta)}{Z} & \cos(\theta) \end{bmatrix} \quad (2)$$

$$T_{CP} = \begin{bmatrix} 1 & C \\ 0 & 1 \end{bmatrix} \quad (3)$$

After addressing Eq.1 and converting them to Y-Parameters, the overall Y-Parameters are found by adding the Y-Parameters of path-1 and path-2, respectively

$$Y_{Filter} = \begin{bmatrix} Y_{11} & Y_{12} \\ Y_{21} & Y_{22} \end{bmatrix} \quad (4)$$

$$\begin{aligned} Y_{11} = & \{ \frac{1}{3}(-j \sin^4(\theta)z + (-4z^2 - 1) \cos(\theta) \sin^3(\theta) + 5j \sin^2(\theta)z(-4z^2 + 1) \sin(\theta) \\ & - 2j \cos^4(\theta)z) \} \times \{ \sin(\theta)z(-\frac{1}{3}j \sin^4(\theta)z^2 - \frac{2}{3} \sin^2(\theta) \cos(\theta)z \\ & + j \cos^2(\theta)(z^2 + \frac{1}{3}) \sin(\theta) + \frac{2}{3} \sin^3(\theta)z) \}^{-1} \end{aligned} \quad (5)$$

$$\begin{aligned} Y_{12} = & \{ (I \cos^2(\theta)z + \sin(\theta)(-z^2 - \frac{1}{4}) \cos(\theta) - \frac{1}{2}Iz) \cos(\theta) \} \times \{ (z \cos^3(\theta) \\ & + I \sin(\theta)(z^2 + \frac{1}{4}) \cos^2(\theta) - \frac{1}{2}z \cos(\theta) - \frac{1}{4}Iz^2 \sin(\theta))^{-1} \} \end{aligned} \quad (6)$$

$$\begin{aligned} Y_{21} = & \{ (I \cos^2(\theta)z + \sin(\theta)(-z^2 - \frac{1}{4}) \cos(\theta) - \frac{1}{2}Iz) \cos(\theta) \} \times \{ \sin(\theta)(z \cos^3(\theta) \\ & + I \sin(\theta)(z^2 + \frac{1}{4}) \cos^2(\theta) - \frac{1}{2}z \cos(\theta) - \frac{1}{4}Iz^2 \sin(\theta))^{-1} \} \end{aligned} \quad (7)$$

$$\begin{aligned} Y_{22} = & \{ \frac{1}{4}(-8I \cos^4(\theta)z + (8z^2 + 2) \sin(\theta) \cos^3(\theta) + 7I \cos^2(\theta)z \\ & + (-4z^2 - 1) \sin(\theta) \cos(\theta) - Iz) \} \times \{ \sin(\theta)(z \cos^3(\theta)^3 \\ & + I \sin(\theta)(z^2 + \frac{1}{4}) \cos^2(\theta) - \frac{1}{2}z \cos(\theta) - \frac{1}{4}Iz^2 \sin(\theta))^{-1} \} \end{aligned} \quad (8)$$

From the Y-Parameters, the S-Parameters of the filter unit are calculated as.

$$S_{21} = \frac{-2Y_{21}Y_o}{(Y_{11} + Y_o)(Y_{22} + Y_o) - Y_{12}^2} \quad (9)$$

The magnitude of S_{21} is compared to the simulated results to validate the normalized transfer matrix, as shown in Fig 3.

Figure 3. Comparison of S_{21} with simulated and mathematical results

Next, the filtering function will be retrieved to examine the transfer function. For the Chevishev type frequency response, the form of the transfer function is given by:

$$|S_{21}(\theta)|^2 = \frac{1}{1 + \epsilon^2 F^2(\theta)} \quad (10)$$

Here $F(\theta)$ is the filtering function, and ϵ is the ripple factor, which controls the ripple-level in the passband. Eq 10 is employed to obtain the filtering function after solving Eq 9. For normalization, the capacitance is set to be 1F, and ripple level ϵ is also chosen to be 1.

$$F^2(\theta) = \left\{ \frac{1}{4} \alpha \cos^8(\theta) \beta \cos^6(\theta) \gamma \cos^4(\theta) \varphi \cos^2(\theta) - z^8 + 2z^4 - 1 \right\} \times \\ \left\{ (z^2 \cos^2(\theta) (4 \cos^2(\theta) z^2 - \cos^2(\theta) + 1) (4 \cos^2(\theta) z^2 - \cos^2(\theta) - 4z^2))^{-1} \right\}$$

$$\alpha = -16z^8 + 136z^6 + 321z^4 + 136z^2 - 16 \quad (11a)$$

$$\beta = 40z^8 - 366z^6 + 658z^4 - 246z^2 + 40 \quad (11b)$$

$$\gamma = -33z^8 + 264z^6 - 351z^4 + 144z^2 - 33 \quad (11c)$$

$$\varphi = 10z^8 - 34z^6 + 28z^4 - 34z^2 + 10 \quad (11d)$$

Eq. 11 shows a filtering function of the proposed topology shown in Fig . 1. The driven filtering function shows that four TPs are obtained across the stopband. The filtering function has been mapped to Chebyshev type 1 polynomials to extract electrical parameters. It is worth mentioning that the frequency-dependent terms, both in the nominator and denominator, have to be compensated with the help of electrical parameters. Therefore, the procedure presented in¹⁵ is opted to nullify the effect of the frequency-dependent term.

Figure 4. Simulated results of the ideal transmission line model

Fig. 4 shows the S-parameter response of the ideal design topology. The detailed analysis has demonstrated that the position of transmission zero is controlled independently by changing the electrical length of path-2. As shown in Fig. (5), for $\theta_1 = 90^\circ$, the position of transmission zero is at 5 GHz. With the increase in θ_1 value, the transmission zero moves towards a lower frequency. At the same time, the transmission zero moves towards the higher frequency by decreasing the value of θ_1 .

Figure 5. Simulated frequency response with different values of electrical length

Also, selectivity of the response can be increased by altering filter order with electrical parameters of the circuit being kept constant. It should also be noted that the fractional bandwidth is measured at 10 dB which increase Fig 6 (a) depicts the response of first-order filter, whereas Fig 6 (b) and (c) show the response of the second-order and third-order filter structures respectively. The fractional bandwidth (FBW) of first-order filter is 29.8% whereas the second and third-order filters have 51% and 58.5% fractional bandwidth respectively. Moreover, it is inferred that fractional bandwidth is independently controlled by varying the width of path-1 (W_1). Fig 7 shows that w_1 and FBW are inversely proportional to each other as increasing the value

of (W_1) will decrease the FBW and vice versa.

Figure 6. 10-dB Fractional bandwidth with different transmission modes

Figure 7. 10-dB Fractional bandwidth response with variable width W_1

Results:

For the validation of the proposed topology, three prototypes have been fabricated on Roger duroid 5880 substrate with $\epsilon_r=2.20$, $\delta=0.0009$, $h=0.787$, $T=0.0175$ mm. Using the line calculator, ideal electrical parameters are converted to physical parameters, which are $W_{in}=2.6$, $W_1 = 1.5$, $W_2 = 1.46$, $W_3 = 0.2$, $W_4 = 2.96$, $L_{in} = 10.85$, $L_1=8.68$, $L_2=9.53$, $L_3=1.21$, $L_4=0.6$, $L_5=0.9$, and $G= 1.3$ (Unit in mm). Microstrip tapered lines are used to avoid the losses due to the steps in transmission lines. In full-wave EM simulations, the effects of substrate loss are corrected by incorporating tuning and optimization. Theoretical analysis

Figure 8. Transmission line model of Proposed BSF

reveals that the destructive interference is responsible for the generation of a high rejection notch between the signals from both paths. Prototype 1 with single order BSF is shown in Fig. 8. The proposed BSF is designed and fabricated with center frequency of 5.25 GHz. Four transmission poles around the stopband are achieved with 5.6 GHz to 16 GHz out-of-band insertion as shown in Fig. 9 (b). The mismatch between measured and simulated results is due to substrate losses at high frequencies. Fig. 9 (a) shows the electrical field spectrum at various frequencies for proposed BSF. It depicts that at stopband frequency, both paths contribute as a maximum field.

Figure 9. (a)Current distribution of Single Mode BSF (b)S-Parameter response of the fabricated Single-Mode BSF

Fig.10 (a) shows the electrical field spectrum of a second-order dual-path SIR structure having the same physical parameters. By increasing the order of the proposed BSF, two transmission zeros are measured with an increased rejection level. Furthermore, six transmission poles have been measured around the stopband, located at 2.94, 3.3, 7.9, 10.1, 13.6, and 15.56GHz. It is also worth mentioning that by increasing the order of proposed BSF, the selectivity around the stopband has also been increased as shown in Fig. 10 (b).

Figure 10. (a)Current distribution of Single Mode BSF (b)S-Parameter response of the fabricated Single-Mode BSF

By increasing the order of proposed BSF to three, as shown in Fig.11 (b), the transmission zeros are increased to three and the rejection level has also been increased to 104.3 dB. Here, it should be noted that the third-order BSF provides nine transmission poles around the stopband which increases the selectivity of proposed BSF. The transmission poles are measured at 2.21, 2.97, 3.7, 7.46, 8.62, 10.93, 13.15, 15.24, and 15.82 GHz. The out of stopband Return Loss (RL) is greater than 11dB. The electrical field spectrum of Proposed third-order filter is shown in Fig.11 (a).

Figure 11. (a)Current distribution of Single Mode BSF (b)S-Parameter response of the fabricated Single-Mode BSF

Table 1 illustrates the measured results of all the fabricated prototypes. From the outset, it can be seen that increasing filter order increases number of poles and zeros which leads to increased selectivity. It can also be seen from table 1 that the maximum rejection level for prototype 3 has been increased to 104.3 dB while the fractional bandwidth at 10 dB has increased to 58.5%. Furthermore, the out-of-band harmonic suppression for prototype 3 is greater than 11.9dB. From the comparison table 2, it can be stated that the prototype 3 outperforms the other design topologies presented in literatuter in terms of selectivity, out-of-band harmonic suppression and fractional bandwidth.

Table 1. Statistics for test input.)

Fabricated Topology	Transmission Zeros (TZ's)	Transmission Poles (TP's)	Out-of Band return-loss (S_{11})	Maximum Rejection Level	10dB-Fractional bandwidth (FBW)
Prototype 1	1	4	14.8 dB	62.4 dB	29.8%
Prototype 2	2	6	12.7 dB	71.8 dB	51%
Prototype 3	3	9	11.9 dB	104.3 dB	58.5%

Table 2. Statistics for test input.)

Ref	Center-Frequency	TZ's	TP's	Minimum Out of Band-RL (S_{11})	Minimum Rejection Level (S_{12})	10db-FBW
2	1	5	4	24 dB	17 dB	64%
5	1.5	4	3	≥ 20 dB	≥ 10 dB	122.5 %
7	1.5	5	4	10 dB	≥ 50 dB	122.5%
8	1.05	1	4	20dB	26 dB	55.24%
9	1.5	5	3	≥ 20 dB	≥ 35 dB	113.4%
This Work	5.25	3	9	11.9 dB	104.3 dB	58.5%

Conclusion

This paper presents a highly selective wideband bandstop filter based upon dual-path (CCSIR) structure. The designed filter operates at 5.25 GHz with a fractional bandwidth of upto 58.5%. It has been observed that the selectivity can be improved by increasing order of the dual coupled step impedance resonator. Three prototypes were fabricated to validate the theoretical concepts and analysis. The proposed wideband BSF is a viable choice for modern wireless communication systems due to its flexible design and high out-of-band insertion.

References

1. Yang, Chaoyue, and Chengfang Fu. "Analysis and Design of a New Ring Bandstop Filter Using Lumped Equivalent Circuit." *Progress In Electromagnetics Research Letters* 93 (2020): 81-87.
2. Kong, Mengdan, et al. "Wideband bandstop filter with extreme sharp skirt selectivity." *IEEE Microwave and Wireless Components Letters* 28.12 (2018): 1104-1106.
3. Cai, Yijun, et al. "Compact bandstop filters using coupled lines and open/short stubs with multiple transmission poles." *IET Microwaves, Antennas & Propagation* 13.9 (2019): 1368-1372.
4. A. C. Guyette and E. J. Naglich, "Short-through-line bandstop filters using dual-coupled resonators," *IEEE Trans. Microw. Theory Techn.*, vol. 64, no. 2, pp. 459–466, Feb. 2016.
5. Velidi, Vamsi Krishna, Ajay Babu Guntupalli, and Subrata Sanyal. "Sharp-rejection ultra-wide bandstop filters." *IEEE Microwave and Wireless Components Letters* 19.8 (2009): 503-505.
6. Munirathinam, Sathish, and Amruth Balachandran. "Compact wideband band-stop filter using stepped complementary split ring resonators." *Analog Integrated Circuits and Signal Processing* 102.2 (2020): 363-367..
7. Liu, Liang, et al. "Compact wideband bandstop filter with directly controlled rejection." *IEEE Transactions on Circuits and Systems II: Express Briefs* (2021).
8. Zuo, Xiaoying, and Lei Qin. "A novel approach to design wideband bandstop filter with wide upper bandpass bandwidth." *AEU-International Journal of Electronics and Communications* 138 (2021): 153897.
9. Ren, Si-Wei, et al. "Quasi-elliptic wideband bandstop filter using stepped-impedance coupled line." *IEEE microwave and wireless components letters* 25.6 (2015): 364-366.
10. Li, et al. "Sharp-rejection and ultra-wide bandstop filter with five transmission zero frequencies." *IET Microwaves, Antennas & Propagation* 8.2 (2014): 80-85.

11. M. Á. Sanchez-Soriano, G. Torregrosa-Penalva and E. Bronchalo, "Compact Wideband Bandstop Filter With Four Transmission Zeros," in *IEEE Microwave and Wireless Components Letters*, vol. 20, no. 6, pp. 313-315, June 2010, doi: 10.1109/LMWC.2010.2047468.
12. J. A. G. Malherbe, "Wideband bandstop filter with sub-harmonic stubs," *Electron. Lett.*, vol. 47, no. 10, pp. 604-605, May 2011.
13. Gorur, Ali Kursad, et al. "A novel compact triple-mode microstrip bandstop filter with adjustable reflection zeros." 2013 Asia-Pacific Microwave Conference Proceedings (APMC). IEEE, 2013.
14. Hunter, Ian. Theory and design of microwave filters. No. 48. Iet, 2001.
15. Khalid, Sohail, and Muhammad Farhan Shafique. "Exact synthesis design theory of analogue broadband bandpass filter." *Microelectronics Journal* 64 (2017): 53-59.
16. Pozar, David M. Microwave engineering. John wiley & sons, 2011.
17. Hunter, Ian. Theory and design of microwave filters. No. 48. Iet, 2001.