# THIRD ORDER EDGE-COUPLED BPF ANALYSIS FOR S AND C BANDS USING TRANSMISSION LINE THEORY

AL-TAYYAR, H. A.

*College of Engineering, University of Mosul, Mosul, Iraq.*
*e-mail: huda.aqeel[at]uomosul.edu.iq*

(Received 21st January 2023; accepted 10th March 2024)

**Abstract.** A third order band pass filter (BPF) is constructed and analyzed using transmission line theory. An RF bandpass filter has analyzed using the equations from the text microwave and RF design of wireless system. The aim of this research was to evaluate the edge-coupled filter and produce equivalent analytical solutions by applying the approach of transmission line theory. However, compared to other filters, it is smaller because it employs quarter wave resonators rather than half wave resonators. After analyzing a single BPF section, certain estimates were made and the section was used for coupled line sections. The results proof the satisfied operation of this BPF at S and C bands with a wider bandwidth and compact size even when increasing the filter order. The MATLAB program for RF filter is utilized in this paper, based on the coupling matrix concept.

**Keywords**: *band pass filter BPF, compact filter, edge coupled, transmission line theory*

## Introduction

Upgrading frequency bands into a microwave filter plays an important role in many radio frequency or microwave applications. Particularly in the increasingly congested spectrum, filters play a crucial role in the performance as well as the expense of radar and communications networks. The noticeable growth in the cellular communications in recent years helped to meet the filters' necessary performance requirements as well as the commercial demands for high volume, low cost, and rapid delivery through the investigation and subsequent application of filter theory. Due to their high resilience to environmental noise and electromagnetic interference, balanced circuits have grown in significance in modern communication systems. In the meantime, the demand for dual-band operations has increased because of the rapid growth of numerous wireless communication systems (Li et al., 2017; Yang et al., 2017; He et al., 2016).

In recent years, balanced dual-band Band-pass filter (BPF) designs have attracted a growing amount of interest. Transmission-line structures have been used to produce a variety of dual-band balanced BPfs (Guo et al., 2020; Rahman et al., 2018). Wide-band radar systems and green communications are two recent wireless communications applications where RF noise is a major concern (Al-Yasir et al., 2019; Zheng et al., 2018). Theoretically zero power reflection at its input terminal for the whole frequency range in band-pass and band-stop areas are characteristics of a family of reconfigurable microwave filters that are given. They employ complementary-transfer-function channels in a frequency-adaptive duplexer-based configuration (Mezaal and Al-Zayed, 2019; Psychogiou and Gómez-García, 2017). A dual-band band-pass filter is provided with several even-mode as well as odd-mode resonant routes. It is possible to tune the operation band separately. A stub-loaded ring resonator makes up the fundamental filter construction (Jaiswal et al., 2019; Pal et al., 2019; Psychogiou et al., 2018).

For 5G wireless communications, a small micro-strip band-pass filter (BPF) that covers the 3.4 to 3.8 GHz frequency bandwidth is provided. Three resonators have utilized in the planar filter, which everyone has 50 ohm transmission line characteristic impedances for the input terminal and output terminal and is terminated by a capacitor at position of the terminal by a via to the ground of the other terminal. Third-order band-pass Butterworth characteristics are obtained at the centre operation frequency when adjusting the coupling feature between the lines (Al-Yasir et al., 2018). The Edge-Coupled Filter or is a band-pass filter BPF which is useful for narrow bandwidth (Yoon and Kim, 2021). Actually, to achieve a wider bandwidth filters this requires very tightly coupled BPF, and this will not be easy to fabricate. Even though, the analysis in this paper shows the ability of obtaining a wider bandwidth at higher frequency. One advantage of this type over the other types of filters like capacitive coupled filter and shunt coupled stubs is the smaller model; quarter wave resonators are used in place of half wave resonators. Another issue is the property of high attenuation at the undesirable frequencies, which is not available in capacitive coupled filters. The shunt stubs filter often requires characteristic impedances that are difficult to realize in practice. So by comparing wireless filters, Edge-Coupled Filter is more preferred filter in wireless systems applications.

The purpose of this paper is to analyze the characteristic performance of RF filter designs. The theoretical analysis of each filter type and transmission line is presented firstly and after that, a presentation and discussion of the some useful filters are done. The aim of this study was on the design aspects of the bandwidth filter using different schemes. The design equation for a band-pass filter has realized of the coupled line filters. A MATLAB code was written based on the analyses. Matrix manipulations and results have been plotted with the help of MATLAB.

## Materials and Methods

Maximum A filter's pass-band signals are either ripples of equal magnitude or are flat. The signal attenuation of 3 dB is known as the cut-off point. Equal-ripple filters have a larger rate of attenuation for the same order than maximally flat filters, who in turn have a higher rate of attenuation than linear phase filters. An equal ripple in the pass band of 0.5 dB, 3rd order edge coupled configuration has designed. The substrate of filter design is FR4 of dielectric constant 4.2 with thickness of 1.6mm. With reference to the tables of filter design as in Pozar and Matther (Pozar, 2012; Mahttei et al., 1980) to find the coefficients for a third order Chebyshev filter. These coefficients are g0=1, g1=1.5963, g2 =1.0967, g3=1.5963, and g4=1. These values are for third order BPF with g1 and g3 as capacitors and g2 as an inductor. This configuration design has a unity source and load impedance. This type of filters is especially convenient for building filters with a wide bandwidth as compared to the other structure of filters. This filter can be realized by j-inverter sections, so the design formulas for this filter which illustrated in *Figure 1* can be given by (Scholl et al., 2022; Gustrau, 2012; Wyndrum, 1965):

$$\frac{J_{01}}{Y_0} = \sqrt{\frac{\pi}{2}\frac{BW}{g_0 g_1}}\,\frac{J_{01}}{Y_0} = \sqrt{\frac{\pi}{2}\frac{BW}{g_0 g_1}} \qquad \text{Eq. (1)}$$

$$\frac{J_{j,j+1}}{Y_0} = \frac{\pi BW}{2}\frac{1}{\sqrt{g_j g_{j+1}}} \quad \text{; for j=1 to n-1} \qquad \text{Eq. (2)}$$

$$\frac{J_{n,n+1}}{Y_0} = \sqrt{\frac{\pi}{2}\frac{BW}{g_n g_{n+1}}} \qquad \text{Eq. (3)}$$

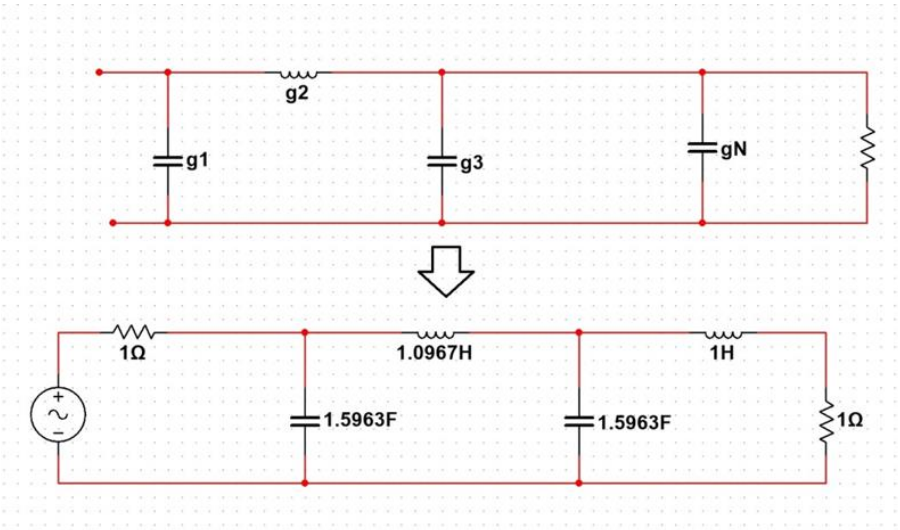

***Figure 1.*** *3rd order BPF used in coupled T.L.*

Where, g0, g1...gn are the elements of the filter when a Normalized cutoff frequency fc=1, and BW is the bandwidth of BPF; n is the order of the filter; Jj,j+1 are the characteristic admittances of each section which represented as J-inverters. The typical admittance of the BPF terminal is denoted by Y0. Even-and odd-mode characteristic impedances of the coupled transmission line resonators can be found as follows in order to realize the gathered J-inverters (Eroglu, 2022):

$$(Z_{0e})_{j,j+1} = \frac{1}{Y_0}\left[1 + \frac{J_{j,j+1}}{Y_0} + \left(\frac{J_{j,j+1}}{Y_0}\right)^2\right]; \text{ for j=0 to n} \qquad \text{Eq. (4)}$$

$$(Z_{0o})_{j,j+1} = \frac{1}{Y_0}\left[1 - \frac{J_{j,j+1}}{Y_0} + \left(\frac{J_{j,j+1}}{Y_0}\right)^2\right]; \text{ for j=0 to n} \qquad \text{Eq. (5)}$$

Where, (Z0e)j,j+1 is the characteristic impedance for even mode, and (Z0o)j,j+1 is the characteristic impedance for odd-mode. By applying the above equations in Matlab tool, the design parameters can be calculated where Y=1/Z and Z=50 ohms. The size of the BPF used in communication system transmission line is very crucial at recent improved networks. The measurements of these coupled lines demonstrate the even and odd mode impedances can be determined as below. Firstly, determination the equivalent single line ratios (w/h)s. After that, it can obtain a coupled line ratios from single line ratios. For a single line ratios determination:

$$Z_{0se} = \frac{(Z_{0e})_{j,j+1}}{2} \qquad \text{Eq. (6)}$$

$$Z_{0so} = \frac{(Z_{0o})_{j,j+1}}{2} \qquad \text{Eq. (7)}$$

Where, Z0se and Z0so are the equivalent characteristic impedances for single transmission line at even and odd-mode respectively. W/h is a metric used to evaluate the desired size for application, where W is the width of section, and h is substrate height of filter.

$$\frac{W}{h} = \frac{8\exp(A)}{\exp(2A) - 2} \qquad \text{Eq. (8)}$$

$$A = \frac{Z_c}{60}\left\{\frac{\varepsilon_r + 1}{2}\right\}^{0.5} + \frac{\varepsilon_r - 1}{\varepsilon_r + 1}\left\{0.23 + \frac{0.11}{\varepsilon_r}\right\} \qquad \text{Eq. (9)}$$

At this point, it can be able to calculate (w/h)se and (w/h)so by applying Z0se and Z0so instead of Zc in eq.9. Finally, the size metrics of the desired coupled line as W/h and S/h can be reached using formulas as follow:

$$\frac{S}{h} = \frac{2}{\pi} cosh\left[\frac{cosh\left(\left(\frac{\pi}{2}\right)\left(\frac{w}{h}\right)_{se}\right) + cosh\left(\left(\frac{\pi}{2}\right)\left(\frac{w}{h}\right)_{so}\right) - 2}{cosh\left(\left(\frac{\pi}{2}\right)\left(\frac{w}{h}\right)_{so}\right) - cosh\left(\left(\frac{\pi}{2}\right)\left(\frac{w}{h}\right)_{se}\right)}\right] \qquad \text{Eq. (10)}$$

$$\frac{W}{h} = \frac{1}{\pi}\left[\begin{matrix} \cosh(\frac{1}{2}\left(\left(cosh\left(\frac{\pi s}{2h}\right) - 1\right) + \left(cosh\left(\frac{\pi s}{2h}\right) + 1\right) * cosh\left(\left(\frac{\pi}{2}\right)\left(\frac{w}{h}\right)_{se}\right)\right) \\ -\left(\frac{\pi s}{2h}\right) \end{matrix}\right] \qquad \text{Eq (11)}$$

Where, S represents the spacing or gap between sections of BPF. The micro strip transmission line assumed to operate in TEM propagation. The relationship between the material property and size of the filter can be given by:

$$\varepsilon_{re} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\frac{1}{\sqrt{1 + \frac{12h}{W}}} \qquad \text{Eq. (12)}$$

$\varepsilon_{re}$ represents effective dielectric constant of the designed BPF, Thus the required length of section:

$$\ell = \frac{\lambda_g}{4} = \frac{c}{4f\sqrt{\varepsilon_{re}}} \qquad \text{Eq. (13)}$$

Where, $\lambda g$ is the guided wavelength, c is the speed of light. It is possible to calculate the inductances and capacitances in the filter sections as shown in the *Figure 2*. Considering a coupled line BPF composed of n+1 coupled section. Each section is numbered beginning at left terminal. At the right terminal, a load is located. As the filter is reciprocal, the direction could reverse with no alteration to the filter's operational response. *Figure 2* illustrates inductors L'ns and capacitors C'ns which scale the impedance and the frequency has transformed to BPF. For a desired BPF, a low-pass prototype series inductor Lsereies will convert into a series LC circuit, where as a shunt capacitor Cshunt will convert into a shunt LC circuit.

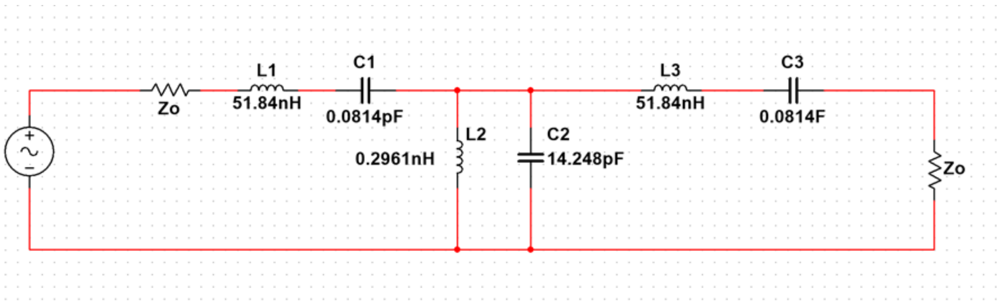

***Figure 2.*** *Equivalent circuit construction for a coupled line BPF.*

$$C_i = \begin{cases} \mathit{Shunt\ element} \\ \dfrac{g_i}{\omega_o \Delta Z_o} \\ \mathit{Series\ element} \\ \dfrac{\Delta}{\omega_o g_i Z_o} \end{cases}$$

$$L_i = \begin{cases} \mathit{Shunt\ element} \\ \dfrac{\Delta Z_o}{\omega_o g_i} \\ \mathit{Series\ element} \\ \dfrac{g_i Z_o}{\omega_o \Delta} \end{cases}$$

Where, Δ = (ω2- ω1)/ω0 is the filter fractional bandwidth.

## Results and Discussion

An edge coupled 3rd order BPF has analyzed and simulated in S (2-4 GHz) and C (4-8 GHz) bands. All the formulas were coded in MATLAB to obtain an accurate evaluation to the operation of the filter. This study concentrate on the parameters of design, the improvement of bandwidth, and finally, the importance of compact size of devices with the increasing demand on these property in recent and future communication networks.

### *Parameters of BPF*

*Table 1* illustrate the calculated impedance of every stage of the filter used in transmission line. The results obtained by Matlab coding for evaluating characteristic impedance, even and odd mode impedances. A reasonable stability in impedance values of the analyzed 3rd order BPF has indicated in the results.

***Table 1***. *Parameters of 3rd order band pass filter (3 stages).*

| K | Zo(K) | Impedance (even mode) | Impedance (odd mode) |
|---|---|---|---|
| 0 | 0.365262071928719 | 74.9339226559190 | 38.4077154630471 |
| 1 | 0.13667735104650 | 57.7679024667796 | 44.1001673621293 |
| 2 | 0.13667735104650 | 57.7679024667796 | 44.1001673621293 |
| 3 | 0.11550600901670 | 56.4423823567833 | 44.8917814551133 |

## *Bandwidth of BPF*

In this section, an effect of operation frequency upon the bandwidth of the filter has presented. The bandwidth represent the range of frequency that pass the signal through it with very low loss. The *Figure 3* shows the output response of the BPF at frequency equal to 2.45 GHz. The signal passed through this filter with minimum losses at specified frequency. This figure displays the bandwidth about 0.43 GHz at -10 dB. The *Figure 4* shows the output response of the BPF at frequency equal to 5 GHz. The signal passed through this filter with minimum losses at the specified frequency. This figure displays the bandwidth of 0.87 GHz at -10 dB. It is obvious from *Figure 3* and *Figure 4* the end coupled BPF has a narrow bandwidth at lower frequencies of millimeter wave band. At increasing frequency to the C band, the bandwidth of this type of filter will increase.

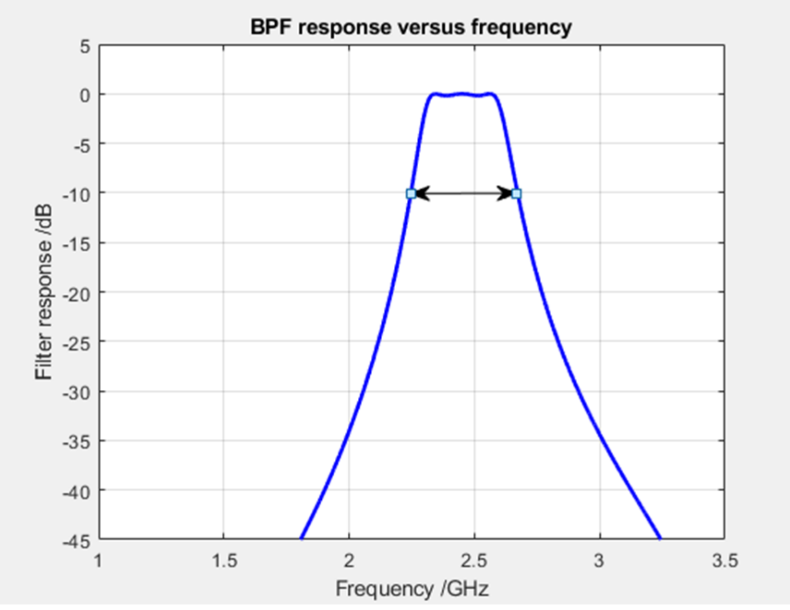

***Figure 3.*** *Plot of band pass filter response versus frequency (center frequency=2.45 GHz).*

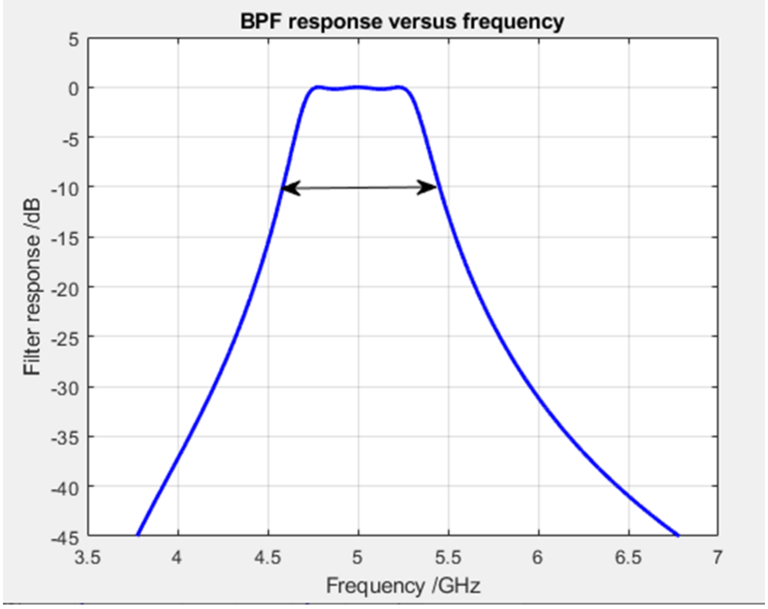

***Figure 4.*** *Plot of band pass filter response versus frequency (center frequency=5 GHz).*

### *Size of BPF*

In this section a size of filter will be discussed. The electrical length of the BPF which calculated in Eq. (13), has shown in *Figure 5*. It is obvious that the length of filter is about 16-17 mm at lower frequency (2.45GHz). The length will be decreased (8 mm approximately) with operation frequency increased (5GHz). Hence, this result insists the truth of increasing frequency needs a smaller BPF size utilized in transmission lines. Every pair of quarter-wavelength coupled sections' width and spacing distance are determined using the design formulas of the edge coupled line. *Figure 6* shows the concluded filter configuration with all of the calculated dimensions.

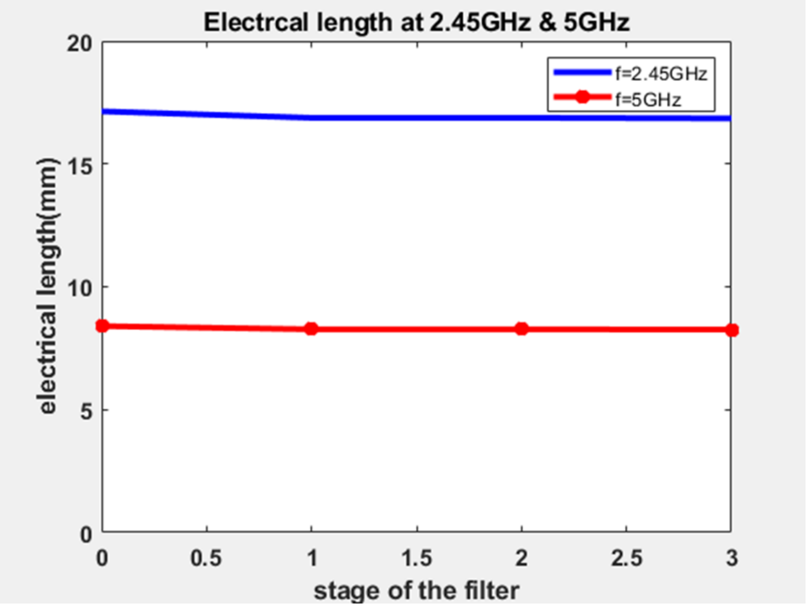

***Figure 5.*** *The electrical length of BPF at two frequencies (2.45 & 5 GHz).*

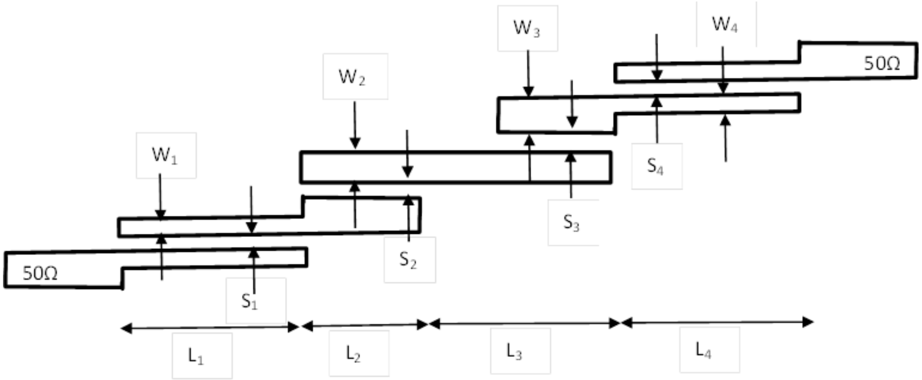

***Figure 6.*** *Layout of 3rd order edge-coupled band pass filter.*

Regarding section 1,
S/h=0.02, S=0.0321 mm and W/h=1.445, W=2.3mm.
Regarding section 2 and 3,
S/h=0.2246, S=0.36 mm and W/h=2.135, W=3.4mm.
Regarding section 4,
S/h=0.2945, S=0.47 mm and W/h=2.2085, W=3.5mm.

*Figure 7* illustrates the increasing in width of section of filter with increasing the BPF order. Hence, increasing size of the filter will be achieved at higher order. This size still has accepted values with a significant operation. *Figure 8* illustrates the increasing in spacing between sections of filter with increasing the BPF order. Hence, increasing size of the filter will be achieved at higher order. This size, also, still has accepted values with a significant operation. The *Figure 9* collects the filter size increasing with the complexity of the design. It is clear from the result that the less order gives the most compact size. The size parameters here are satisfied values even at the higher frequencies.

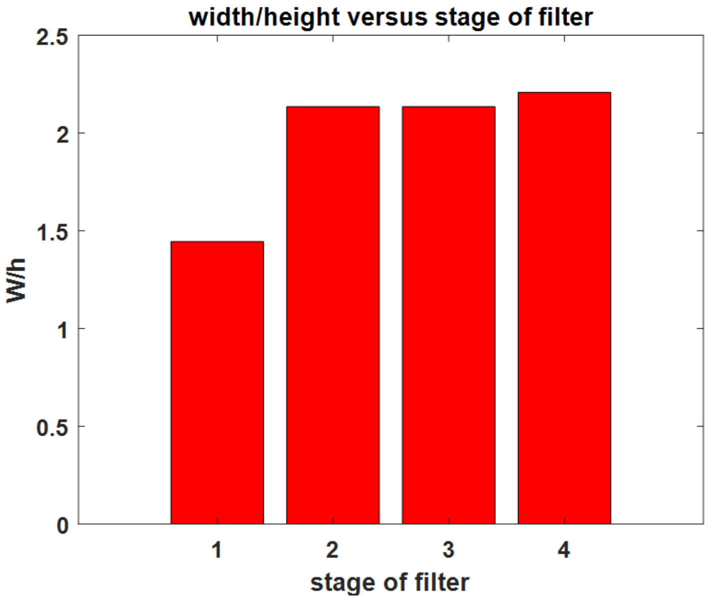

***Figure 7.*** *Width of section over height versus stage of filter.*

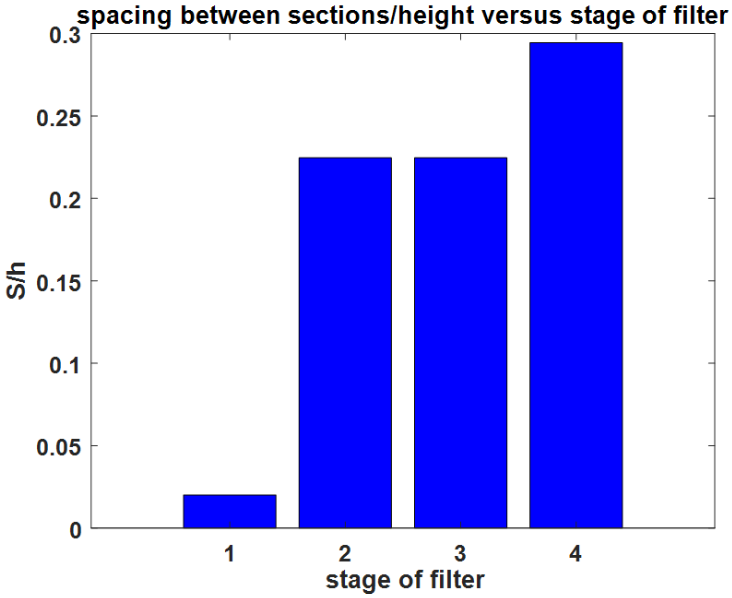

***Figure 8.*** *Spacing between sections over height versus stage of filter.*

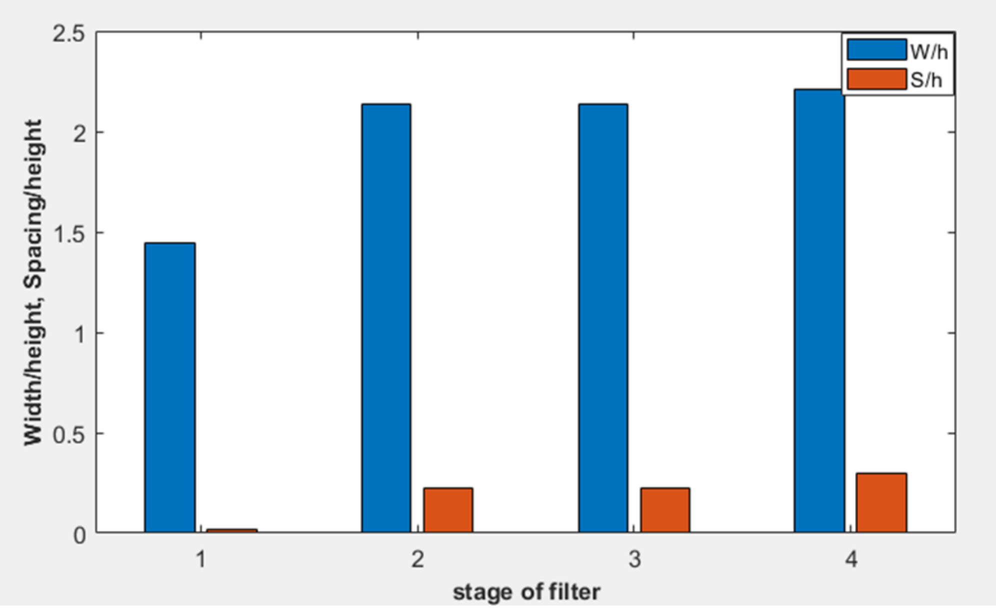

***Figure 9.*** *Width/height and Spacing/height versus increasing BPF order.*

## Conclusion

Flexibility in element value selection and more desirable element values at high frequencies are benefits of utilizing edge-coupled BPF (3rd type) over conventional band pass filters. The objective of this investigation was to analyze the edge-coupled filter as well as utilizing the transmission line approach to achieve equivalent analytic circuit. However, compared to other filters, it is smaller because it employs quarter wave resonators rather than half wave resonators. The certain estimates were made and the section was used for coupled line sections. The results proof the satisfied operation of this BPF at S and C bands with a wider bandwidth and compact size even when increasing the filter order.

## Acknowledgement

After completing this work the author presents all appreciation to who contribute for succession this work. Hope this paper assists the researchers in future with required information.

## Conflict of interest

The author declares no conflict of interest, financial or otherwise.

## REFERENCES

[1] Al-Yasir, Y.I., OjaroudiParchin, N., Abdulkhaleq, A., Hameed, K., Al-Sadoon, M., Abd-Alhameed, R. (2019): Design, simulation and implementation of very compact dual-band microstrip bandpass filter for 4G and 5G applications. – In 2019 16th international conference on synthesis, modeling, analysis and simulation methods and applications to circuit design (SMACD), IEEE 4p.

[2] Al-Yasir, Y., Abd-Alhameed, R.A., Noras, J.M., Abdulkhaleq, A.M., Parchin, N.O. (2018): Design of very compact combline band-pass filter for 5G applications. – IET Conference Publications 4p.

[3] Eroglu, A. (2022): RF/microwave Engineering and Applications in Energy Systems. – John Wiley & Sons 640p.

[4] Guo, Y.J., Xu, K.D., Deng, X., Cheng, X., Chen, Q. (2020): Millimeter-wave on-chip bandpass filter based on spoof surface plasmon polaritons. – IEEE Electron Device Letters 41(8): 1165-1168.

[5] Gustrau, F. (2012): RF and microwave engineering: fundamentals of wireless communications. – John Wiley & Sons 368p.

[6] He, X., Qiu, R.C., Ai, Q., Chu, L., Xu, X., Ling, Z. (2016): Designing for situation awareness of future power grids: An indicator system based on linear eigenvalue statistics of large random matrices. – IEEE Access 4: 3557-3568.

[7] Jaiswal, R.K., Pandit, N., Pathak, N.P. (2018): Spoof surface plasmon polaritons based reconfigurable band-pass filter. – IEEE Photonics Technology Letters 31(3): 218-221.

[8] Li, P., Chu, H., Zhao, D., Chen, R.S. (2017): Compact dual-band balanced SIW bandpass filter with improved common-mode suppression. – IEEE Microwave and Wireless Components Letters 27(4): 347-349.

[9] Mahttei, G., Young, L., Jones, E.M.T. (1980): Microwave filters, Impedance matching networks and coupling Structure. – Norwood, MA, Artech House 558p.

[10] Mezaal, Y.S., Al-Zayed, A.S. (2019): Design of microstrip bandpass filters based on stair-step patch resonator. – International Journal of Electronics 106(3): 477-490.

[11] Pal, B., Mandal, M.K., Dwari, S. (2019): Varactor tuned dual-band bandpass filter with independently tunable band positions. – IEEE Microwave and Wireless Components Letters 29(4): 255-257.

[12] Pozar, D.M. (2012): Microwave engineering. – University of Massachusetts at Amherst, John Wiley & Sons, Inc. 30p.

[13] Psychogiou, D., Gómez-García, R., Peroulis, D. (2017): RF wide-band bandpass filter with dynamic in-band multi-interference suppression capability. – IEEE Transactions on Circuits and Systems II: Express Briefs 65(7): 898-902.

[14] Psychogiou, D., Gómez-García, R. (2017): Reflectionless adaptive RF filters: Bandpass, bandstop, and cascade designs. – IEEE Transactions on Microwave Theory and Techniques 65(11): 4593-4605.

[15] Rahman, M.U., Ko, D.S., Park, J.D. (2018): A compact tri-band bandpass filter utilizing double mode resonator with 6 transmission zeros. – Microwave and Optical Technology Letters 60(7): 1767-1771.
[16] Scholl, P., Williams, H.J., Bornet, G., Wallner, F., Barredo, D., Henriet, L., Signoles, A., Hainaut, C., Franz, T., Geier, S., Tebben, A. (2022): Microwave Engineering of Programmable X X Z Hamiltonians in Arrays of Rydberg Atoms. – PRX Quantum 3(2): 10p.
[17] Wyndrum, R.W. (1965): Microwave filters, impedance-matching networks, and coupling structures. – Proceedings of the IEEE 53(7): 766-766.
[18] Yang, Y., Zhu, X., Dutkiewicz, E., Xue, Q. (2017): Design of a miniaturized on-chip bandpass filter using edge-coupled resonators for millimeter-wave applications. – IEEE Transactions on Electron Devices 64(9): 3822-3828.
[19] Yoon, K., Kim, K. (2021): Compact size of an interdigital band-pass filter with flexible bandwidth and low insertion-loss using a folded spiral and stepped impedance resonant structure. – Electronics 10(16): 12p.
[20] Zheng, S.Y., Su, Z.L., Pan, Y.M., Qamar, Z., Ho, D. (2018): New dual-/tri-band bandpass filters and diplexer with large frequency ratio. – IEEE Transactions on Microwave Theory and Techniques 66(6): 2978-2992.