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# Microwave Band Pass Filter Synthesis using Coupled Inductor for ISM Band Applications

**Brijesh Mishra[1], Vivek Singh[2], Chandrabhan Jha[3], Akhilesh Kumar Pandey[4] and Rajeev Singh[5*]**
*[1,2,4,,5*]Department of Electronics and Communication, University of Allahabad, Allahabad (U.P.)-INDIA-211002*
*[3]Shambhunath Institute of Engineering and Technology, Allahabad (U.P)-INDIA-211012*

***[5]ORCID: 0000-0001-8910-337X.***

**Abstract**
This paper describes a precise and reasonably accurate method for lumped element second order band pass filter for various wireless communication applications in ISM (Industrial, Scientific and Medical) band. A novel and simple method for synthesis by means of lumped element coupled inductors have been introduced with minimal number of elements. A pass band between 2.6 GHz to 3.2 GHz is observed for the single stage filter and between 2.3 GHz to 3.7 GHz for the two stage proposed filter design. In case of a cascaded filter more than two fold enhancement in bandwidth is observed. Optimizing the values of lumped element parameters of cascaded structure, a more flat response is obtained in the frequency range of 2.4 GHz to 3.7 GHz. The proposed circuit is realized through minimal number of lumped elements as compared to the reported structures. The pass band frequency range covers both the wireless local area network (WLAN) band (2.4-2.484 GHz) and the worldwide interoperability for microwave access (WiMAX) band (3.4-3.69 GHz) for optimized flat response.

**Keywords:** Lumped element circuit, Finite transmission zeroes, Coupled inductors, Microwave band pass filter, ISM band, Wireless LAN

## INTRODUCTION

Wireless communication system at present has gained prominence due to its application. An efficient system requires filters with high performance, good selectivity, compactness in size and ease of filter integration with MMICs. The challenge before the engineers is to design filters with good selectivity and with small dimensions. One of the suggested methods of improving selectivity of a filter is to introduce transmission zeros as compared to classical approach. The transmission zeros are achieved through various resonator configuration via coupling between inductors [1]. Lumped element design methods have been adopted to realize the microwave coupler [2] and filter circuit [3]. However, it is possible to implement lumped elements filters using passive components and one of the primary candidates is a coupled inductor [4]. Realization of such type of filters is reported using a compact low-temperature co-fired ceramic (LTCC) design. Well known second-order filters using LTCC with two transmission zeros have been reported [4-6]. In order to achieve two finite transmission zeros in the response of the filter, a two pole second order filter structure using coupled inductor [cf. Fig. 1(a) and 1(b) of Ref. 4] has been reported [4]. The authors have reported [7] a horn type antenna consisting of two different units and each unit offers one or two transmission zeros and the band-notch characteristics of the different transmission zeros have been merged into a wide rejection band to suppress the spurious response. A low pass filter utilizing the above configuration having its rejection bandwidth in the frequency range of 1.75 to 12.0 GHz is reported [7]. A dual band lumped element band-pass filter implemented in LTCC structure and designed separately as upper band and lower band structure [cf. Fig. 1(a) of Ref. 8 and table 1], exhibiting lower and upper pass-band centre frequencies at 2.4 and 5.2 GHz is reported [8]. Utilizing the concept of lumped element model, spacecraft surface charges have been investigated and modelled [9]. In the present work, the concept of single band LTCC structure [4] is utilized to convert a lumped element dual band-pass filter [cf. Fig. 1(a) of Ref. 8, table1] to a single band-pass filter. The proposed structure clearly shows an improvement in the selectivity and bandwidth at 3dB while using lesser number of components as compared to [4, 8, 12]. It is reported that the bandwidth can be extended slightly by using more sections of the proposed structure in a cascaded manner [10]. A short description of the reported filters is presented in table1. The schematic diagram shown at s.no.1 in table 1 has been modified (cf. Fig. no. 3) and after simplification a new circuit is obtained (cf. Fig. no. 4) which is equivalent to the circuit shown at s. no. 2 in table 1. The simplified circuit(cf. Fig. no. 4), which equivalent to the circuit given at s. no. 2 in table 1 is again converted to a new circuit using coupled inductors as shown at s. no. 3 in table1. In the present work, the synthesized filter has been simulated using Microwave Office and results have been mathematically verified. The simulated results suggest that the presence of the zeros do not change the pass band characteristics of the filter too much, whereas the mathematical solution clearly shows that the filter can be readily designed with the traditional filter synthesis procedure.

## THEORETICAL FORMULATIONS

The combination of lower band schematic given fig.1 and upper band schematic given by Fig.2 produces two-pole filter design as shown in Figure 3. The resonating capacitors as reported in Figure 1(a) [Ref. 8, cf. Table1] have been removed to obtain a single pass-band filter structure. The proposed single band pass filter has been obtained by combining lower and upper band schematics of Fig.1.and Fig.2 which is a second order coupled resonator band pass filter (with both capacitive and inductive couplings) in parallel with a feedback capacitor and as shown in Fig.3. The feedback capacitor $C_f$ is intended to make a pair of finite transmission zeros effective to the transmission transfer function. One zero contributes to the lower stop band and the other to the upper stop band. Capacitor ($C_{in}$) acts as an inverter as well as a dc-decoupling capacitor. It is used for matching resonators to the external impedance and also for blocking the dc signal both from the front and the back stage of the filter.

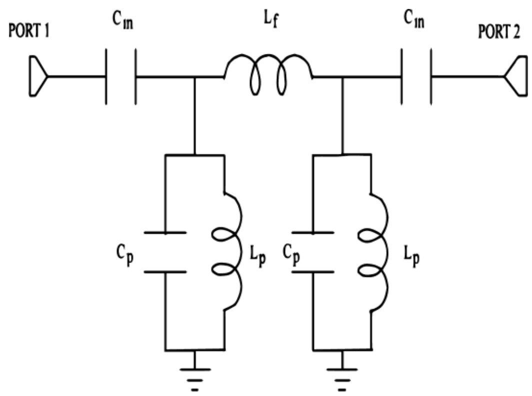



**Figure 1.** Lower band schematic (cf Fig. 2 of Ref. 8)

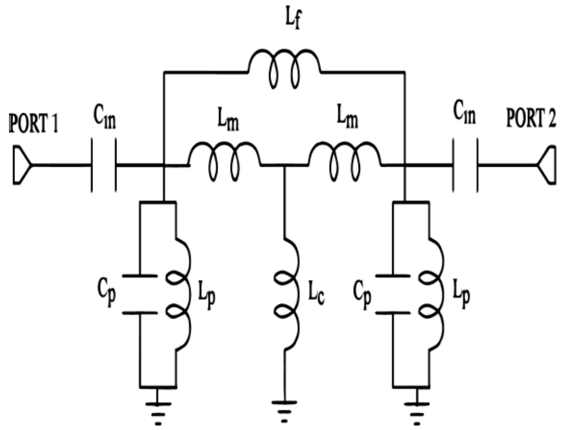



**Figure 2.** Upper band schematic (cf Fig. 3 of Ref. 8)

A T-π network conversion of the proposed single band pass filter schematic of Figure 3 is given in Figure 4 and the converted corresponding elements values are calculated accordingly. Figure 4 represents a simplified second order Chebyshev-type band pass filter which is equivalent to a two-pole second order filter as reported earlier [4].

The corresponding element values of figure 4 are synthesized after the same has been converted from figure 3 and is given as under:

$$L_2 = L_3 = \frac{(2L_cL_m + L_m{}^2)L_p}{(2L_cL_m + L_m{}^2 + L_mL_p)} \quad (1)$$

$$L_1 = \frac{(2L_cL_m + L_m{}^2)L_f}{(2L_cL_m + L_m{}^2 + L_cL_f)} \quad (2)$$

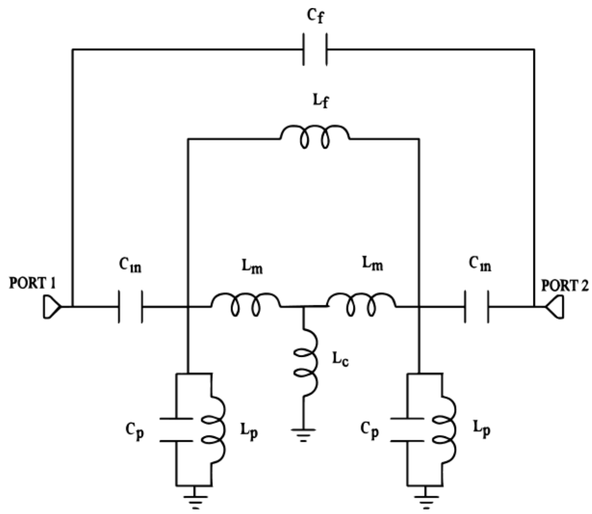



**Figure 3.** Proposed single band pass filter by combining lower and upper band schematics of Fig.1.and Fig.2

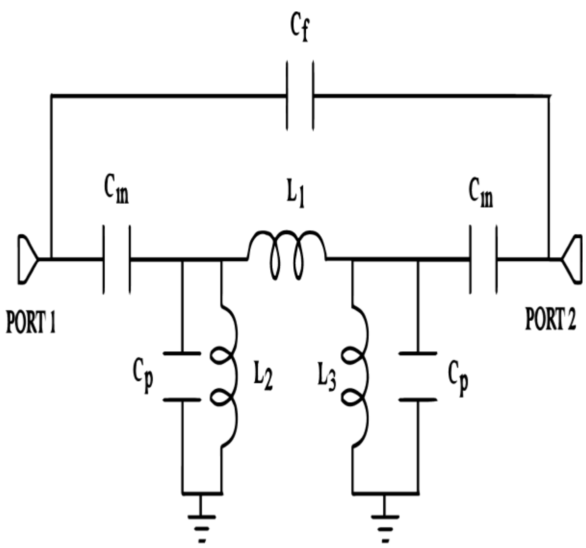
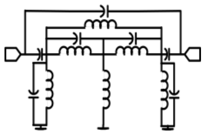
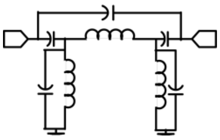
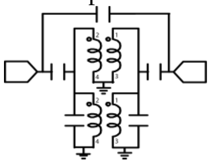
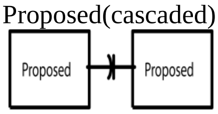
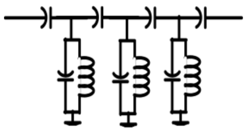



**Figure 4.** Synthesis of filter schematic of Fig.3.using lower and upper band schematics of Fig.1.and Fig.2.

**Table1:** Description of reported and proposed lumped element filter circuits, their specifications and applications

| **S. No.** | **[Reference] Schematic** | **Frequency band(GHz)** | **-3 dB BW (%)** | $S_{11}$ | **Element numbers** | **Applications** |
|---|---|---|---|---|---|---|
| 1. | [8]  | 2.26-2.56/ 5-5.64 | 12.4/12.05 | -22.4 dB | L = 6 C = 5 | WLAN |
| 2. | [4]  | 2.23-2.72 | 19.8 | -14.54 dB | L = 3 C = 5 | Mobile terminal, Bluetooth |
| 3. | Proposed  | 2.56-3.17 | 21.4 | -54.42 dB | CL = 2 C = 5 | ISM band |
| 4. | Proposed(cascaded)  | 2.26-3.70 | 49.8 | -10.72 dB | CL = 4 C= 11 | WLAN, ISM |
| 5. | [12]  | 1.47-1.57 | 6.58 | -19.4 dB | L= 3 C = 7 | GPS |

Finite transmission zeroes can be located from the following equation of admittance matrix

$$-s\,C_f + y'_{12} = 0 \qquad (3)$$

In the equation (3), $s\,C_f$ represents admittance of the feedback capacitor, $y'_{12}$ indicate the admittance matrix element of the coupled resonator filter.

Nodal analysis of the coupled resonator filter will result into the following expression

$$y'_{12} = -\frac{s\,C_{in}^{2}/L_1}{\left(s\,C_1+\frac{1}{s\,L'_1}\right)\left(s\,C_2+\frac{1}{s\,L'_2}\right)-\frac{1}{s^2 L_1^{2}}} \qquad (4)$$

$$\text{Where } C_1 = C_2 = C_{in} + C_p \;;\; \text{and} \qquad (5)$$

$$L_1' = \frac{L_2}{L_1}\;;\; L_2' = \frac{L_3}{L_1} \qquad (5A)$$

Substituting value of Equation (4) into Equation (3) and rearranging it gives as under:

$$s^4 C_1^{\,2} + s^2\left(\frac{C_1}{L'_2}+\frac{C_1}{L'_1}+\frac{C_{in}^{\,2}}{L_1 Cf}\right)+\left(\frac{1}{L'_1 L'_2}-\frac{1}{L_1^{\,2}}\right) = 0 \qquad (6)$$

Equation (6) represents a fourth order polynomial in s- domain and its two positive roots will decide the finite transmission zeroes, located at each side of the pass band. The value of $C_f$ can be found from Equation (6) with the help iterative methods. Mutual inductor of mutual inductance M between two inductors $L_1$ and $L_2$ works as two port network and its voltage equations can be written in the terms of Z-parameters. Conversion of two port networks to a coupled inductor network is possible and element values can be found by comparing equations (7) and (8).

$$\begin{bmatrix} V_1 \\ V_2 \end{bmatrix} = \begin{bmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{bmatrix}\begin{bmatrix} I_1 \\ I_2 \end{bmatrix} \qquad (7)$$

$$\begin{bmatrix} V_1 \\ V_2 \end{bmatrix} = \begin{bmatrix} j\omega L_1 & j\omega M \\ j\omega M & j\omega L_2 \end{bmatrix}\begin{bmatrix} I_1 \\ I_2 \end{bmatrix} \qquad (8)$$

The above theoretical formulation forms the basis of converting a band pass filter using schematic of Figure 4 into a band pass filter designed by using coupled inductors.

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## FILTER IMPLEMENTATION

The synthesis method outlined above can be used to design a coupled inductor band-pass filter. The theory in section 2 having been discussed, felicitates the necessity of addressing filter realization and implementation issues in detail and the filter circuit model with the desired specifications is designed. Component values in Figure 3 are computed for a second order Butterworth filter ($g_0 = 1, g_1 = 1.414, g_2 = 1.414, g_3 = 1$) using the synthesis method for a band pass filter given in [11].

Element values of Figure 4 are computed using Equations (1) and (2) and the element values are $L_1$ = 6.91nH, $L_2 = L_3$ = 1.21nH, $C_{in}$ = 0.9pF, $C_f$ = 0.08pF, $C_p$= 2.4pF.

Now using the above theoretical considerations of conversion of networks the element values of Figure 5 (proposed) in terms of elements values of Figure 3 is given as below:

$$K_u = \frac{L_c}{L_m + L_c} \tag{9}$$

$$L_u = L_m + L_c \tag{10}$$

$$K_l = \frac{L_p}{L_f + L_p} \tag{11}$$

$$L_l = \frac{L_p}{K_l + 1} \tag{12}$$

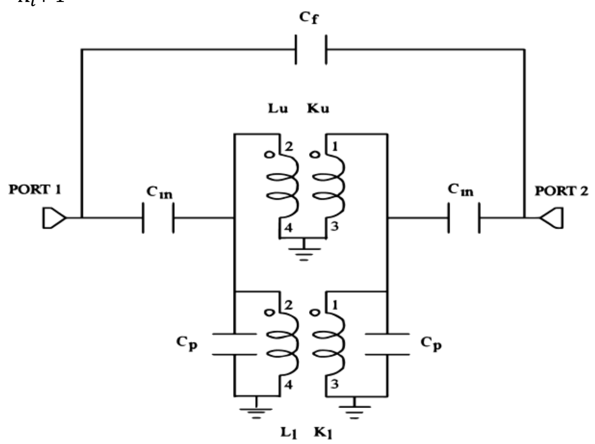


**Figure 5.** Proposed band pass filter equivalent of Fig. 4 using coupled inductors

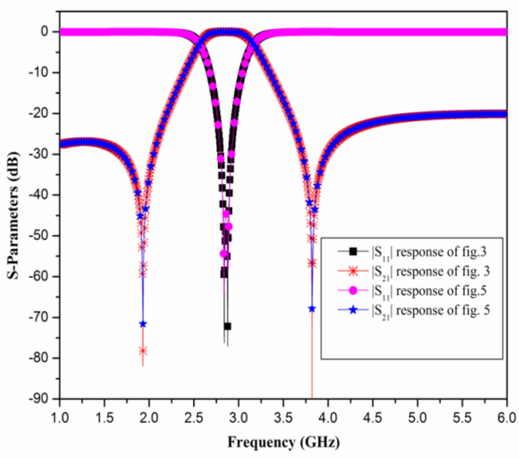


**Figure 6.** Filter response of circuits of Fig. 3 and Fig.5

The theoretical scheme presented here suggests the conversion of circuit of fig. 3 to circuit of fig. 5. The advantage of the circuit given in fig. 5 is that it uses lesser number of elements and if implement through MMICs it will require a lesser space as compared to the circuit proposed in fig. 3. However, the filter response of both the circuits (of fig. 3 and fig. 5) is same as shown in figure 6 which verifies the synthesis part of the circuit.

## BANDWIDTH IMPROVEMENT

Large bandwidth is demanded everywhere, band-pass filters being important components of wireless systems enable band selection in RF transceivers. Higher order filters with better control of the bandwidth can be designed by cascading the filters in series as shown in Figures 8 & 9. By cascading two sections the bandwidth of second order filter is fairly enhanced and controlled. We observe in Figure 2 that $L_f$ does not affect the resonant frequency of the upper pass band and the bandwidth of upper pass band is controlled by $C_K$ only. Bandwidth of cascaded filter can be improved more than two times as compared to one section band-pass filter.

## RESULT AND DISCUSSION

Table 2 provides the calculated element values for one section, two section and optimized microwave band pass filters on the basis of the synthesis proposed in above sections. The filter characteristic is simulated and verified using AWR (Applied Wave Research) Microwave Office Design. The proposed filter has pass band between 2.6 GHz to 3.2 GHz at -3dB, impedance bandwidth of 21.4% and maximum return loss of -54.52dB is observed in Figure 7. A perusal of figure 7 and table 1 reveals that the circuit given in [4] is a second order band pass filter having pass band in the frequency range of 2.23-2.72GHz, with impedance bandwidth of 19.8% at -3dB and maximum return loss is -14.54dB. The circuit given in [8] is a dual band filter structure with pass band frequencies in the range of 2.26-2.56GHz (lower) and 5-5.64GHz (upper). The impedance bandwidth is 12.4% and 12.5% respectively whereas the maximum return loss is -22.4dB. The circuit of [12] operates within the frequency range of 1.47-1.57 GHz, its impedance bandwidth is 6.58% whereas the maximum return loss is -19.4dB.

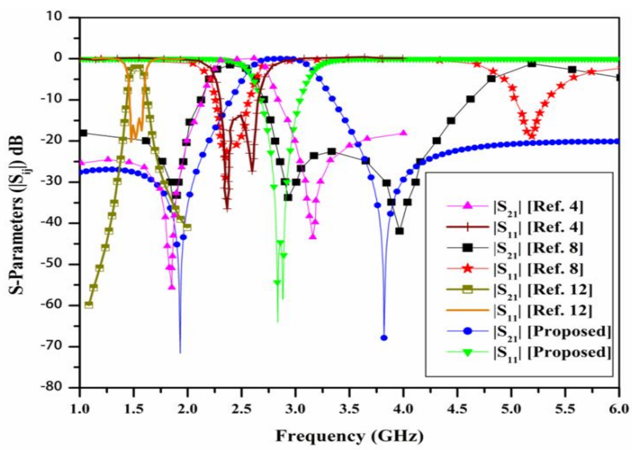


**Figure 7.** Comparative plot of filter response for the proposed circuit and reported circuits [4,8,12].

The analysis of data presented above read with data of table 1 and fig. 7 would clearly establish that the number of elements used to design the proposed filter is least (CL=2, C=5) as compared to other reported filter structures in [4, 8, 12] which are designed by using L=3, C=5 [4], L=6, C=5 [8] and L=3, C=7 [12]. We observe a maximally flat response for the proposed circuit, maximum bandwidth and better return loss as compared to the circuits reported in [4,8,12] and as observed in fig.7.

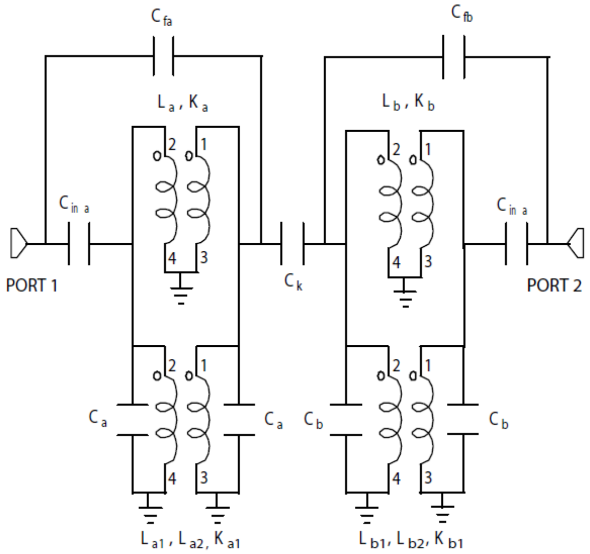


**Figure 8.** Proposed BPFs cascaded using a capacitor to demonstrate better control of bandwidth.

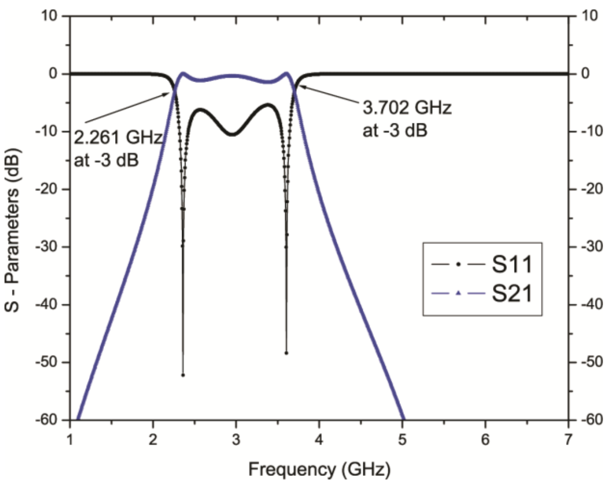


**Figure 9.**Transmission and reflection responses of two section band pass filter (Fig.8)

A pass-band between 2.3 GHz to 3.7 GHz at -3dB is observed in case of cascaded two sections as shown in Figure 9. We observe more than two folds bandwidth of 49.8% in case of cascaded filter structure as compared to a single section filter structure where we observe a bandwidth of 21.4%.

A maximally flat response is seen after optimization of element values of Figure 8. The element values of two section filter is optimized using Microwave Office and after optimization we observe a more flat response as compared to the case when the element values are not optimized. However, the better flat response as obtained in Figure 10 can be found only when the inductors are not perfectly matched.

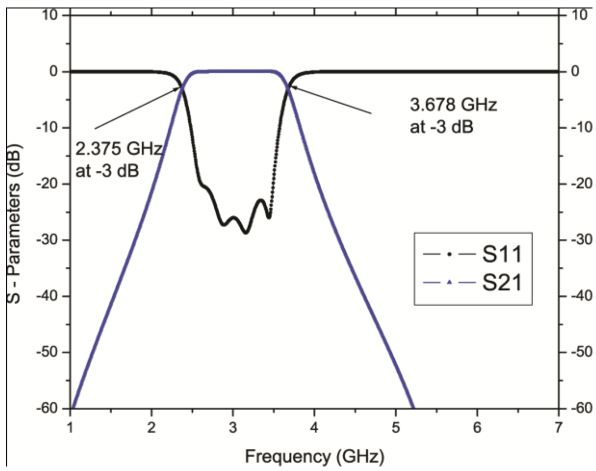


**Figure10.** Optimized transmission and reflection responses of cascaded band pass filter (Fig. 8)

## CONCLUSIONS

The present paper discusses a new alternative design to synthesize a band pass filter suitable for ISM band applications using coupled inductors. New mathematical formulation for obtaining coupled inductor filter values from lumped element values has been presented and the results have been verified by simulation using Microwave Office Suite from Applied Wave Research (AWR). The optimized filter circuit is compared with the other circuits reported in literature [4, 8,12] and clearly an enhanced bandwidth and better return loss is observed in the proposed filter structure. The number of physical elements in the proposed design is less than that of the conventional lumped element designs [4,8,12] thus reducing the overall cost of the circuit as well as making it suitable for MMIC realization if the circuit is converted to microstrip equivalent. The conversion of the filter circuit and its physical realization is left to the future scope of work.

**Table 1.** Component values of the proposed filter.

| Component values of proposed new band pass filter | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Variables | $L_f$ | $L_c$ | $L_p$ | $L_m$ | $C_{in}$ | $C_f$ | $C_P$ | $L_u$ | $K_u$ | $L_l$ | $K_l$ | - | - |
| Values | 10.3 nH | 0.6 nH | 1.7 nH | 3.0 nH | 0.9 pF | 0.08 pF | 2.4 pF | 3.6 nH | 0.167 | 1.489 nH | 0.142 | - | - |
| Component values of cascaded (two section) band pass filter | | | | | | | | | | | | | |
| Variables | $L_a = L_b$ | $K_a = K_b$ | $L_{a_1} = L_{a_2}$ | $K_{a_1}$ | $C_a$ | $C_{in\,a}$ | $C_{f\,a}$ | $L_{b_1} = L_{b_2}$ | $K_{b_1}$ | $C_b$ | $C_{in\,b}$ | $C_{f\,b}$ | $C_k$ |
| Values | 3.6 nH | 0.167 | 1.999 nH | 0.351 | 1.7 pF | 1.65 pF | 0.12 pF | 1.999 nH | 0.351 | 1.7 pF | 1.65 pF | 0.12 pF | 0.8 pF |
| Optimized component values for two section band pass filter | | | | | | | | | | | | | |
| Variables | $L_a = L_b$ | $K_a = K_b$ | $L_{a_1}$ | $L_{a_2}$ | $K_{a_1}$ | $L_{b_1}$ | $L_{b_2}$ | $K_{b_1}$ | $C_a = C_b$ | $C_{f\,a} = C_{f\,b}$ | $C_{in\,a}$ | $C_{in\,b}$ | $C_k$ |
| Values | 3.6 nH | 0.167 | 2.411 nH | 2.34 nH | 0.479 | 1.869 nH | 2.115 nH | 0.351 | 1.7 pF | 0.12 pF | 4.303 pF | 1.502 pF | 0.56 pF |

## REFERENCES


[1] L Szydlowski, N Leszczynska, "Generalized Chebyshev Bandpass Filters with Frequency Dependent Coupling Based on Stubs," IEEE Trans. on Microwave Theory & Tech., Vol. 61, pp. 3601-3612, 2013.

[2] B Mishra, V Singh, R Singh, "Design, Analysis and Simulation of Microwave Coupler", Int. Conf. on Signal Processing & Comm. (IEEE), India, pp. 370-373. 2015.

[3] A Sutono, J Laskar, WR Smith, "Development of Three Dimensional Integrated Bluetooth Image Reject Filter". IEEE MIT-S Int. Microwave Symposium Digest, pp.339-342, 2000.

[4] Yeung, L.K., Wu, Ke-Li., "A Compact Second-order LTCC Band-pass Filter with Two Finite Transmission Zeros", IEEE Trans. on Microwave Theory and Tech., Vol. 51, pp.337-341, 2003.

[5] N Kato, E Nogome, H Okamura, T Tsuru, T Taniguchi, K Tonegawa, "Composite Electronic Component and Frequency Adjustment Method of the Same". U.S. Patent 5 140 497, 1992.

[6] I Awai, A C Kundu, T Yamashita, “Equivalent Circuit Representation and Explanation of Attenuation Poles of Dual-mode Dielectric-Resonator Band-pass Filter. IEEE Trans. Microwave Theory & Tech, Vol. 46, pp. 2159-2163, 1998.

[7] C J Wang “A Low-Pass Filter Based on the Slotted-Ground-Plane Horn-Shaped Resonator”. IETE Tech. Rev., Vol. 33, pp. 199-204, 2016.

[8] H Joshi, W J Chappell, "Dual-band Lumped-element Band-pass Filter," IEEE Trans. on Microwave Theory & Tech., Vol. 54, pp. 4169-4177, 2006.

[9] V K Hariharana, S V K Shastry, A Chakrabarty, V R Katti, "Lumped Element Model for Spacecraft Surface Charging Studies," IETE Tech. Rev. Vol. 18, pp.109-121, 2001

[10] S Mass, "Designing VHF lumped-element couplers with MW Office" Copyright (C) 1999, Applied Wave Research, Inc https://awrcorp.com/download/kb.aspx?file=**VHF**_Lump_**Coupler**.pdf.

[11] G L Matthaei, L Yang, E M T Jones, "Microwave Filters, Impedance Matching Network and Coupling Structures. New York, McGraw-Hill: pp. 355-410, 1980.

[12] G Brzezina, L Roy, L Maceachern, " A Miniature LTCC Band-pass Filter Using Novel Resonators for GPS Applications" Proceedings of the 37th European Microwave Conference. pp. 536-539, 2007.