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Novel Transformation to Design Tri-Band Filters

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Abstract—This paper introduces novel derived transformation equations to design Tri-band filters. The design utilizes the approach adopted for tri-band bandpass filter design based on asymmetric half-wavelength resonator. The obtained optimized filter by this approach is used as a reference, and the proposed transformation is applied to calculate the new filter design hardware parameters that satisfy its given specifications. The reference tri-band filter is designed to have: insertion better than 1.3 dB and return loss less than −10 dB at the resonance frequencies 1.4 GHz, 4 GHz and 5.6 GHz for L-Band DAB, Radar (G-band) and Radar (C-band) applications, respectively. To verify the transformation technique two tri-band filters are designed. The first tri-band filter is for WVL, WiMAX and WiLAN while the second tri-band filter is for UMTS, WiLAN and X-band Satellite applications. The momentum simulations for these filters show that the resulting filters specifications are: the insertion loss is better than 1.3 dB and the return loss is less than −10 dB at the resonance frequencies 1.3 GHz, 3.6 and 5.7 GHz for the first one. While the insertion loss is better than 1.4 dB and the return loss is less than −10 dB at the resonance frequencies 1.9 GHz, 5.35 GHz and 8.25 GHz for the second filter, respectively. A set of prototype of the final design of the proposed filters with optimal parameters was fabricated for experimental verification. The RT 5880 substrate is utilized in this design All the results are obtained using circuit and momentum simulation of the Agilent Design Simulator (ADS) package and the performance characteristics have been measured using the Rohde & Schwarz ZVB20 vector 4 port network analyzer. Analysis and comparison of the obtained results show that all the simulated and the measured results agree well.

1. INTRODUCTION

A novel generic transformation technique is proposed, and the design equations are derived using theoretical analysis to design dual-band filters [1]. In this work, similar transformation and design equations are also derived to design tri-band filters. Based on this transformation and these design equations, tri-band filters can be designed to meet any desired filter specifications. The reference filter design is based on the asymmetric half-wavelength resonator where the equations of transmission zeros are derived [2, 3].

This paper is organized as follows: the analysis and design steps of tri-band filter using asymmetric half-wavelength resonators structure with shunt open stubs are given in Section 2. Tri-band filter design which is considered as a reference design is introduced in Section 3. The filter design equations and the novel transformation technique are explained in Section 4. The proposed systematic tri-band filter design procedure is applied to implement two filters that meet desired specifications. The design and the obtained results are analyzed in Section 5. Furthermore, in order to verify the method, a tri-band filter is fabricated and the expected responses are discussed and compared in Section 6. The conclusions are given in Section 7.

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2. FILTER DESIGN BASED ON ASYMMETRIC HALF-WAVELENGTH RESONATORS STRUCTURE

The structure of multi-band filter using asymmetric half-wavelength resonators with eight shunt open stubs is shown in Figure 1 [3]. It consists of upper section and lower section, where each section consists of microstrip lines L_1, L_2, L_3, L_4, L_5, L_6 and L_c in addition to a coupling capacitor S where L_3 is the summation of L_{3a} and L_{3b}. The length L_4 is the shunt open stub, which is connected to the resonator directly as illustrated in Figure 2. The coupling between the two open ends of the resonators is simply expressed by the gap capacitance S.

The total length of one resonator is given by [3]:

$$L_1 + L_2 + 2L_3 = \lambda_g/2 \tag{1}$$

where λ_g is the guided wavelength at fundamental resonance frequency, f_r. For a tri-band filter with resonance frequencies: first resonance frequency, f_{r1}, second resonance frequency, f_{r2} and third resonance frequency, f_{r3}. f_r is calculated as [4–6]:

$$f_r = \frac{f_{r1} + f_{r2} + f_{r3}}{3} \tag{2}$$

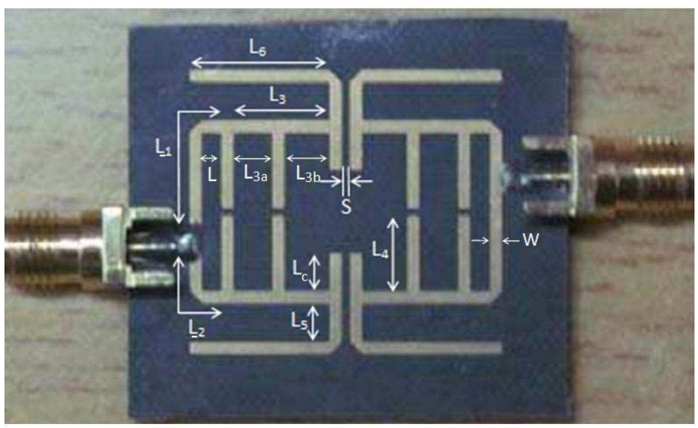


Figure 1. The tri-band filter using asymmetric half-wavelength structure with eight shunt open stubs [3].

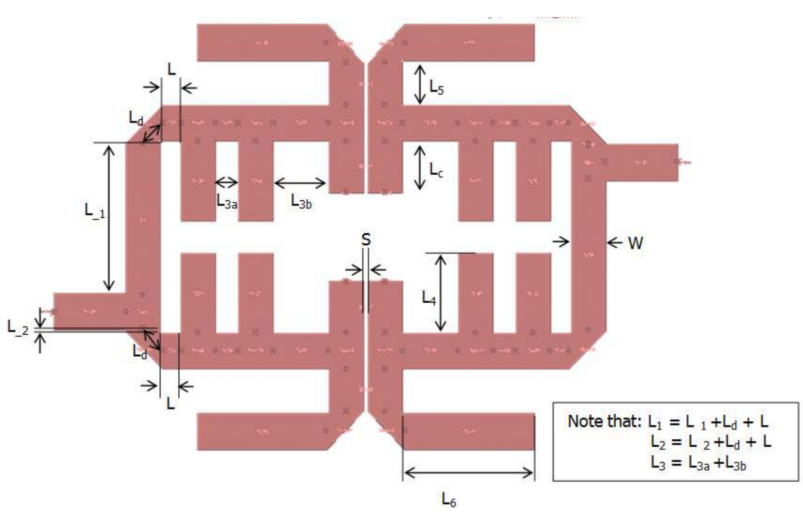


Figure 2. Layout of tri-band filter using asymmetric half-wavelength structure with eight shunt open stubs.

The guided wavelength, λ_g is calculated as:

$$\lambda_g = \frac{\nu_p}{f_r} \tag{3}$$

where, v_p is the phase velocity given by:

$$\nu_p = \frac{c}{\sqrt{\varepsilon_{eff}}} \tag{4}$$

where, c is the speed of light, and the effective relative dielectric constant, ε_{eff} is given by:

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} * \frac{1}{\sqrt{1 + 12\frac{h}{W}}} \tag{5}$$

3. TRI-BAND FILTER DESIGN USING ASYMMETRIC HALF-WAVELENGTH STRUCTURE

3.1. Filter Specifications

It is desired to design a tri-band filter for Digital Audio Broadcasting (L-Band DAB) in Europe, Radar (G-band) and Radar (C-band) applications with desired resonance frequencies: $f_{r1} = 1.4\,\text{GHz}$, $f_{r2} = 4\,\text{GHz}$ and $f_{r3} = 6.3\,\text{GHz}$ [7, 8]. It is also desired that this filter has the return loss, S_{11} is better than 10 dB and the insertion loss, S_{21} is better than 1.3 dB. In addition that the rejected frequencies take place when the insertion loss (S_{21}) is less than -3 dB and the return loss (S_{11}) is greater than -10 dB.

3.2. Design Procedure

The AN RT 5880 substrate is utilized in this design. The substrate parameters are: height, $h = 0.78\,\text{mm}$, relative dielectric constant, $\varepsilon_r = 2.2$ and loss tangent, $\tan\delta = 0.001$.

Using the filter specification, the first step is to calculate the fundamental resonance frequency, f_r using Equation (2) and λ_g using Equation (3). Start the simulation with initial guess for L_1, L_2 and L_3 that satisfy Equation (1) and the lengths L, L_4, L_5, L_6 and S are also chosen. Apply the parametric analysis till obtaining the best filter performance that meets the filter specification. The optimized filter parameters are shown in Figure 3 and listed in Table 1. The results of the momentum simulation are illustrated in Figure 4 and listed in Table 2.

Table 1. The optimized parameters of tri-band filter for L-Band DAB, Radar (G-band) and Radar (C-band).

Length	L_1	L_2	L	L_{3a}	L_{3b}	L_4	L_5	L_6	L_c	S	W
Value (mm)	13.1	3.4	1.3	1.6	3.9	5	3	8.8	3.7	0.3	2.4

Table 2. The optimized performance parameters of tri-band filter for L-Band DAB, Radar (G-band) and Radar (C-band).

Parameter	At resonance frequency $f_{r1} = 1.4\,\text{GHz}$			At resonance frequency $f_{r2} = 4\,\text{GHz}$			At resonance frequency $f_{r3} = 6.3\,\text{GHz}$		
	S_{11} (dB)	S_{21} (dB)	BW (MHz)	S_{11} (dB)	S_{21} (dB)	BW (MHz)	S_{11} (dB)	S_{21} (dB)	BW (MHz)
Value	-21.494	-0.968	79	-11.68	-1.057	46	-29.28	-0.521	280

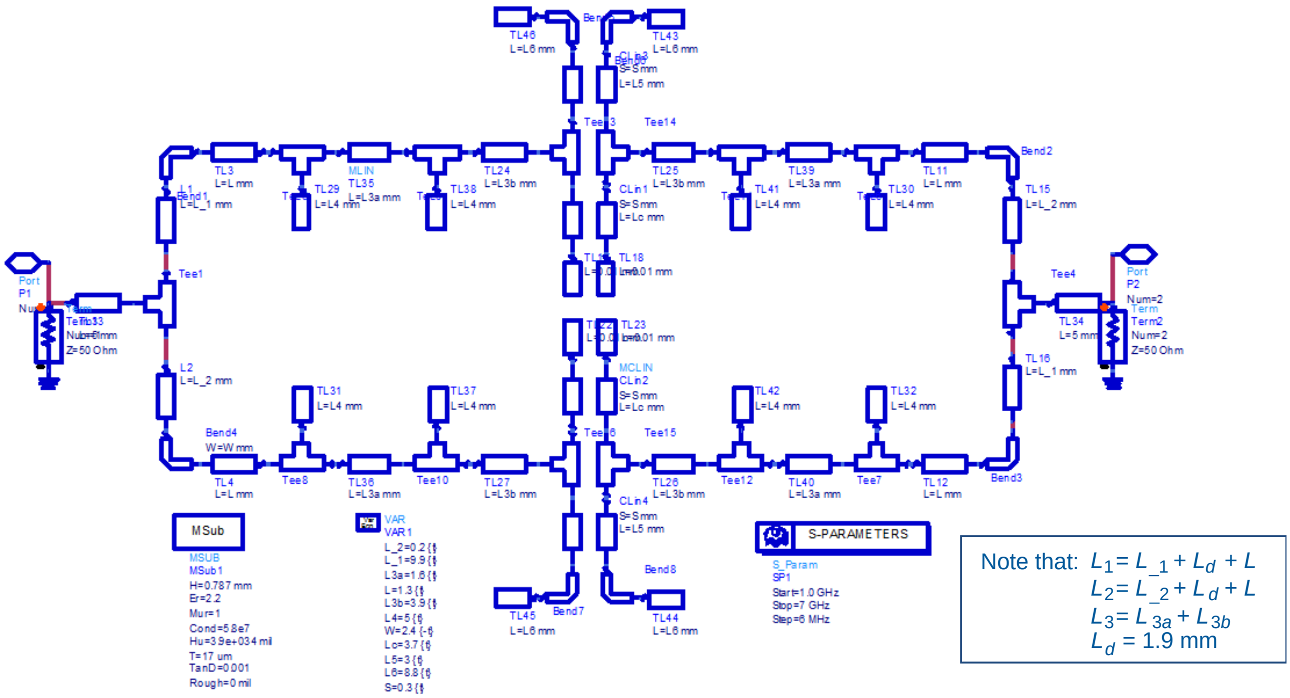


Figure 3. The optimized design of tri-band filter for L-Band DAB, Radar (G-band) and Radar (C-band).

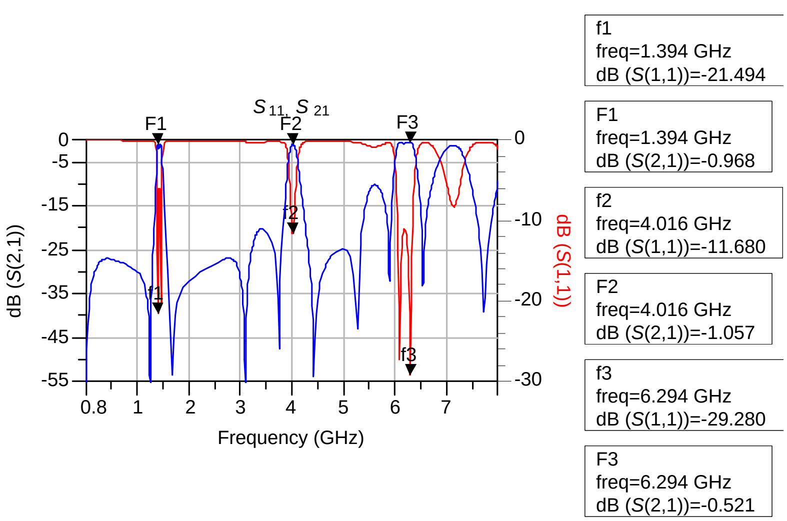


Figure 4. The momentum simulation of tri-band filter for L-Band DAB, Radar (G-band) and Radar (C-band).

4. GENERIC TRANSFORMATION FOR TRI-BAND FILTERS

Section 2 illustrated an optimized tri-band structure based on asymmetric half-wavelength resonators structure with eight shunt open stubs proposed in [2, 3]. The obtained results shown in Figure 3, Figure 4, Table 1 and Table 2 satisfy the desired filter design specification. Therefore, we will take this design as reference and then derive generic transformation equations to be utilized to design any other tri-band filter with arbitrary specifications.

From Figure 3, the filter deign parameters are: the transmission lines using of the asymmetric half-wavelength structure (L_1, L_2 and L_3), the coupling parameters (L_5, L_c and S), the length of each of the eight shunt open stubs (L_4) and the length of L_6.

Analysing the obtained results shown in Figure 1–Figure 4, Table 1 and Table 2, we can deduce that the relations of the lengths L_1, L_2 and L_3 with respect to the guided wavelength λ_g (independent to the substrate parameters) can have the form:

$$L_1/\lambda_g = 0.24 \tag{6a}$$
$$L_2/\lambda_g = 0.06 \tag{6b}$$
$$L_3/\lambda_g = 0.10 \tag{6c}$$

λ_g is the guided wavelength at fundamental resonance frequency, f_r, calculated using Equation (2) and Equation (3), respectively.

Also, the parameters, L_4, L_5, L_6, L_c and S are given by the following equations as an initial guess for their lengths then they can be tuned to obtain the desired specifications of the filter:

$$L_4/\lambda_g = 0.09 \tag{7a}$$
$$L_5/\lambda_g = 0.054 \tag{7b}$$
$$L_6/\lambda_g = 0.157 \tag{7c}$$
$$L_c/\lambda_g = 0.066 \tag{7d}$$
$$S/\lambda_g = 0.0054 \tag{7e}$$

Define a ratio; R_{ref} represents the ratio between resonance frequencies: f_{r1}, f_{r2} and f_{r3} as:

$$R_{ref} = \frac{f_{r3}}{f_{r1}} \tag{8}$$

This ratio will be considered as a reference to normalize the corresponding ratios when designing any other desired filters as will be illustrated in the following section.

This transformation technique can be used to enhance the bandwidth of the passbands where the design parameters: L_4, L_5, L_6, L_c and S are calculated using Equations (7a) to (7e) then they can be tuned to enhance the bandwidths of the passbands.

4.1. Design Procedure to Design Any Desired Tri-Band Filter

In order to design any desired Tri-band Filter with resonance frequencies: f_{r1desr}, second, f_{r2desr}, and third, f_{r3desr}, the following procedure is applied:

Calculate the desired resonance frequency f_{rdesr} from Equation (2) as:

$$f_{rdesr} = \frac{f_{r1desr} + f_{r2desr} + f_{r3desr}}{3} \tag{9}$$

Then calculate the desired wavelength λ_{gdesr} corresponding to f_{rdesr} from Equation (3) as:

$$\lambda_{gdesr} = \frac{\nu_p}{f_{rdesr}} \tag{10}$$

where, υ_p is the phase velocity which is given by:

$$\nu_p = \frac{c}{\sqrt{\varepsilon_{eff}}} \tag{11}$$

where, c is the speed of light and ε_{eff} is given by:

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} * \frac{1}{\sqrt{1 + 12\dfrac{h}{W}}} \tag{12}$$

After that the ratio between resonance frequencies: upper, f_{r3desr} and lower, f_{r1desr} is calculated from Equation (8) as:

$$R_{refdesr} = \frac{f_{r3desr}}{f_{r1desr}} \tag{13}$$

Then calculate the ratio between R_{desr} to R_{ref} which we define as design ratio R as:

$$R = \frac{R_{desr}}{R_{ref}} \tag{14}$$

And the normalized wavelength λ_{gnorm} is then calculated as:

$$\lambda_{gnorm} = \lambda_{gdesr} * R \tag{15}$$

Using the design equations: Equation (1), Equation (6) and Equation (7) to calculate the filter hardware calculated parameters as:

$$\begin{aligned} &L_1 \approx 0.24\lambda_{gnorm} \quad L_2 \approx 0.06\lambda_{gnorm} \quad L_3 \approx 0.1\lambda_{gnorm} \\ &L_4 = 0.09\lambda_{gnorm} \quad L_5 = 0.054\lambda_{gnorm} \quad L_6 = 0.157\lambda_{gnorm} \\ &L_c = 0.066\lambda_{gnorm} \quad S = 0.0054\lambda_{gnorm} \end{aligned}$$

Finally, simulate using the obtained filter design parameters and then tune using L_4 and L_c to adjust the three center frequencies to the required frequencies. Also optimize the response with slight tune in lengths and gap of coupled line (S) to have the optimum response.

5. APPLICATIONS

5.1. Tri-Band Filter Design for WVL, WiMAX and WiLAN Applications

It is required to design a tri-band filter for Wireless Video Links (WVL), WiMAX and WiLAN applications with desired resonance frequencies: $f_{r1desr} = 1.3\,\text{GHz}$, $f_{r2desr} = 3.6\,\text{GHz}$ and $f_{r3desr} = 5.7\,\text{GHz}$ respectively [7, 8], using the same substrate of the reference filter. It is also desired that this filter has the return loss, S_{11} to be better than 10 dB and the insertion loss, S_{21} to be better than -1 dB. Apply the previous design procedure, we get:

$$f_{rdesr} = \frac{f_{r1desr} + f_{r2desr} + f_{r3desr}}{3} = 3.533\,\text{GHz} \quad \varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} * \frac{1}{\sqrt{1 + 12\frac{h}{W}}} = 1.87$$

$$\nu_p = \frac{c}{\sqrt{\varepsilon_{eff}}} = \frac{3 * 10^8}{\sqrt{1.87}} = 0.219 * 10^9\,\text{m/s} \quad \lambda_{gdesr} = \frac{\nu_p}{f_{rdesr}} = 62\,\text{mm}$$

$$R_{refdesr} = \frac{f_{r3desr}}{f_{r1desr}} = 4.4 \quad R = \frac{R_{desr}}{R_{ref}} = 0.977$$

$$\lambda_{gnorm} = \lambda_{gdesr} * R \cong 60.4\,\text{mm}$$

Table 3. The optimized parameters of tri-band filter for WVL, WiMAX and WiLAN.

Length	L_1	L_2	L_3	L_4	L_5	L_6	L_c	S	W
Calculated Values (mm)	14.5	3.6	6	5.4	3.3	9.5	3.9	0.3	2.4
Optimized Values (mm)	14.1	3.9	6.1	5.6	3.7	10	3.3	0.3	2.4

Table 4. The optimized performance parameters of tri-band filter for WVL, WiMAX and WiLAN.

Parameter	At resonance frequency f_{r1}= 1.3 GHz		At resonance frequency f_{r2} =3.6 GHz		At resonance frequency f_{r3} = 5.7 GHz	
	S_{11} (dB)	S_{21} (dB)	S_{11} (dB)	S_{21} (dB)	S_{11} (dB)	S_{21} (dB)
Value	−22.367	−0.951	−14.565	−0.847	−26.058	−0.6

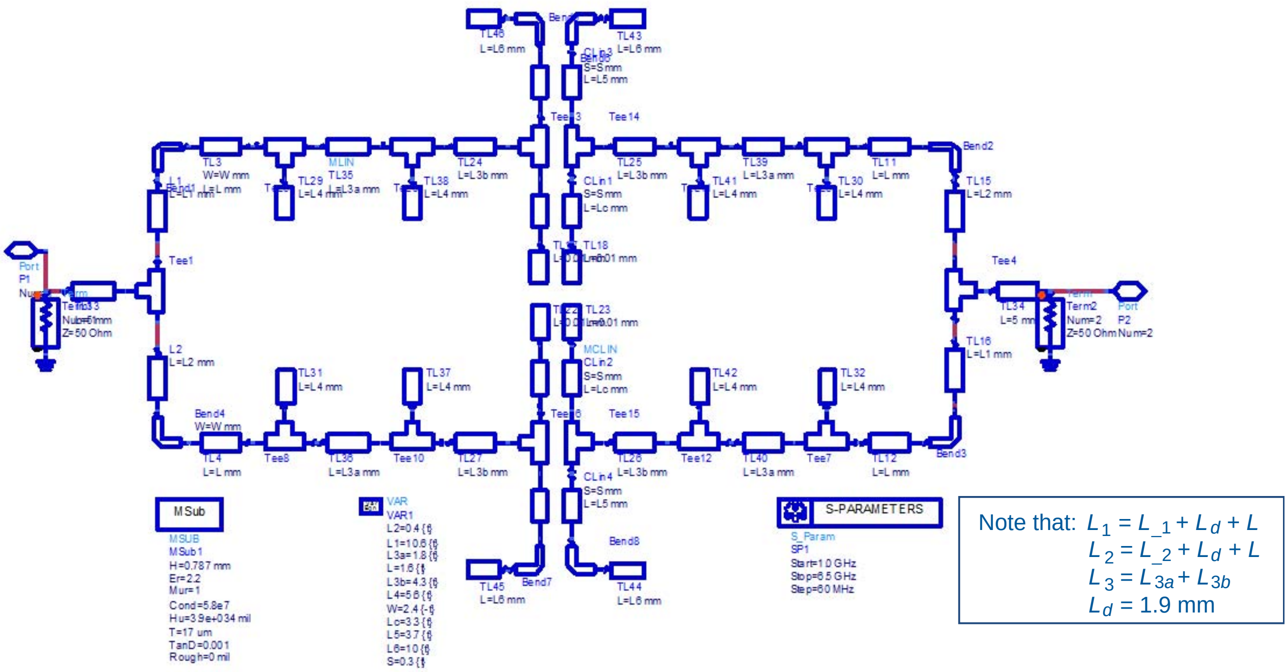


Figure 5. The optimized tri-band filter for WVL, WiMAX and Wi LAN applications.

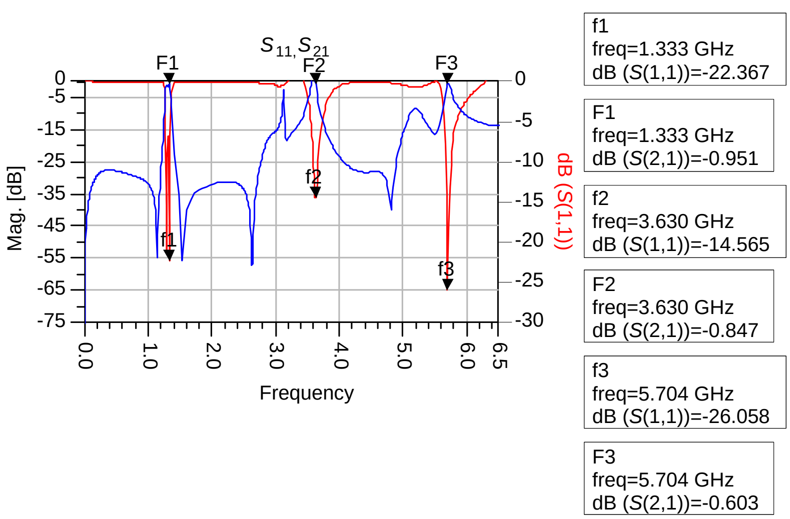


Figure 6. The momentum simulation of tri-band filter for WVL, WiMAX and Wi LAN applications.

Using the design equations: Equation (1), Equation (6) and Equation (7) calculate the filter hardware parameters as:

$$L_1 \approx 0.24\lambda_{gnorm} = 14.5\,\text{mm} \quad L_2 \approx 0.06\lambda_{gnorm} = 3.6\,\text{mm} \quad L_3 \approx 0.10\lambda_{gnorm} = 6\,\text{mm}$$
$$L_4 = 0.09\lambda_{gnorm} = 5.4\,\text{mm} \quad L_5 = 0.054\lambda_{gnorm} = 3.3\,\text{mm} \quad L_6 = 0.157\lambda_{gnorm} = 9.5\,\text{mm}$$
$$L_c = 0.066\lambda_{gnorm} = 3.9\,\text{mm} \quad S = 0.0054\lambda_{gnorm} = 0.3\,\text{mm}$$

The optimized filter parameters are shown in Figure 5 and listed in Table 3. The designed filer performance parameters as a result of the momentum simulation are illustrated in Figure 6 and listed in Table 4.

5.2. The Tri-Band Filter Design for UMTS, WiLAN and X-Band Satellite Applications

It is required to design a tri-band filter for UMTS, WiLAN and X-band Satellite applications with desired resonance frequencies: $f_{r1desr} = 1.9\,\text{GHz}$, $f_{r2desr} = 5.35\,\text{GHz}$ and $f_{r3desr} = 8.25\,\text{GHz}$ respectively [7, 8], using the same substrate of the reference filter. It is also desired that this filter has the return loss, S_{11} to be better than 10 dB and the insertion loss, S_{21} to be better than -1.5 dB. Apply the previous design procedure, we get:

$$f_{rdesr} = \frac{f_{r1desr} + f_{r2desr} + f_{r3desr}}{3} = 5.183\,\text{GHz} \quad \varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} * \frac{1}{\sqrt{1 + 12\frac{h}{W}}} = 1.87$$

$$\nu_p = \frac{c}{\sqrt{\varepsilon_{eff}}} = \frac{3 * 10^8}{\sqrt{1.87}} = 0.219 * 10^9\,\text{m/s} \quad \lambda_{gdesr} = \frac{\nu_p}{f_{rdesr}} = 42.2\,\text{mm}$$

$$R_{desr} = \frac{f_{r3desr}}{f_{r1desr}} = 4.4 \quad R = \frac{R_{desr}}{R_{ref}} = 0.97$$

$$\lambda_{gnorm} = \lambda_{gdesr} * R \cong 40.7\,\text{mm}$$

Using the design equations: Equation (1), Equation (6) and Equation (7) calculate the filter hardware parameters as:

$$L_1 \approx 0.24\lambda_{gnorm} = 9.7\,\text{mm} \quad L_2 \approx 0.06\lambda_{gnorm} = 2.5\,\text{mm} \quad L_3 \approx 0.10\lambda_{gnorm} = 4.1\,\text{mm}$$

$$L_4 = 0.09\lambda_{gnorm} = 3.7\,\text{mm} \quad L_5 = 0.054\lambda_{gnorm} = 2.2\,\text{mm} \quad L_6 = 0.157\lambda_{gnorm} = 6.4\,\text{mm}$$

$$L_c = 0.066\lambda_{gnorm} = 2.7\,\text{mm} \quad S = 0.0054\lambda_{gnorm} = 0.3\,\text{mm}$$

The optimized filter parameters are shown in Figure 7 and listed in Table 5. The designed filer performance parameters as a result of momentum simulation are shown in Figure 8 and listed in Table 6.

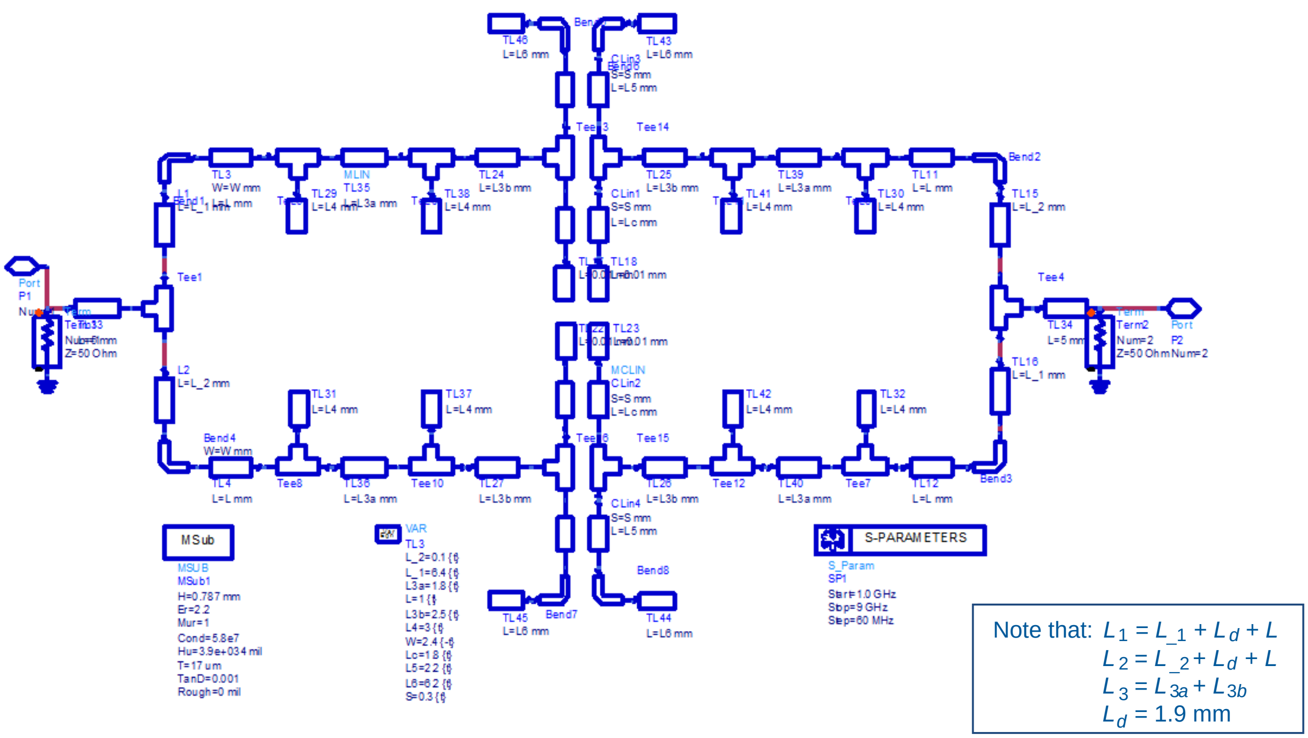


Figure 7. The optimized tri-band filter for UMTS, WiLAN and X-band Satellite applications.

Table 5. The optimized parameters of tri-band filter for UMTS, WiLAN and X-band.

Length	L_1	L_2	L_3	L_4	L_5	L_6	L_c	S	W
Calculated Values (mm)	9.7	2.5	4.1	3.7	2.2	6.4	2.7	0.3	2.4
Optimized Values (mm)	9.3	3	4.3	3	2.2	6.2	1.8	0.3	2.4

Table 6. The optimized performance parameters of tri-band filter for UMTS, WiLAN and X-band.

Parameter	At resonance frequency f_{r1}= 1.9 GHz		At resonance frequency f_{r2} = 5.35 GHz		At resonance frequency f_{r3} = 8.25 GHz	
	S_{11} (dB)	S_{21} (dB)	S_{11} (dB)	S_{21} (dB)	S_{11} (dB)	S_{21} (dB)
Value	−14.64	−1.44	−24.68	−0.75	−33.47	−0.417

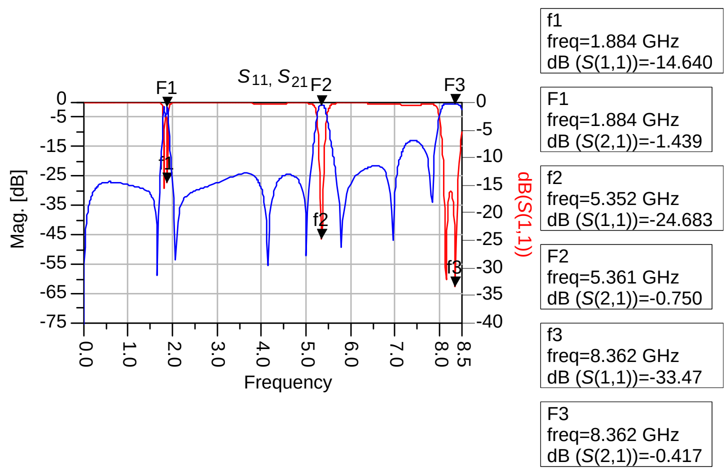


Figure 8. The momentum simulation of tri-band filter for UMTS, WiLAN and X-band satellite applications.

6. TRI-BAND FILTER FABRICATION AND PERFORMANCE MEASUREMENT

Based on the above analysis, the Tri-band filter is designed and fabricated. A commercial RT/duroid 5880 substrate of ROGERS is utilized in fabrication. The substrate parameters are: height h = 0.787 mm, dielectric constant $\varepsilon_r = 2.2$ and loss tangent $\tan\delta = 0.0009$ [9].

6.1. Tri-Band Filter Fabrication for UMTS, Wi-LAN and X-Band Satellite Applications

The Tri-band filter for UMTS, Wi-LAN and X-band Satellite applications is designed and fabricated, as shown in Figure 9.

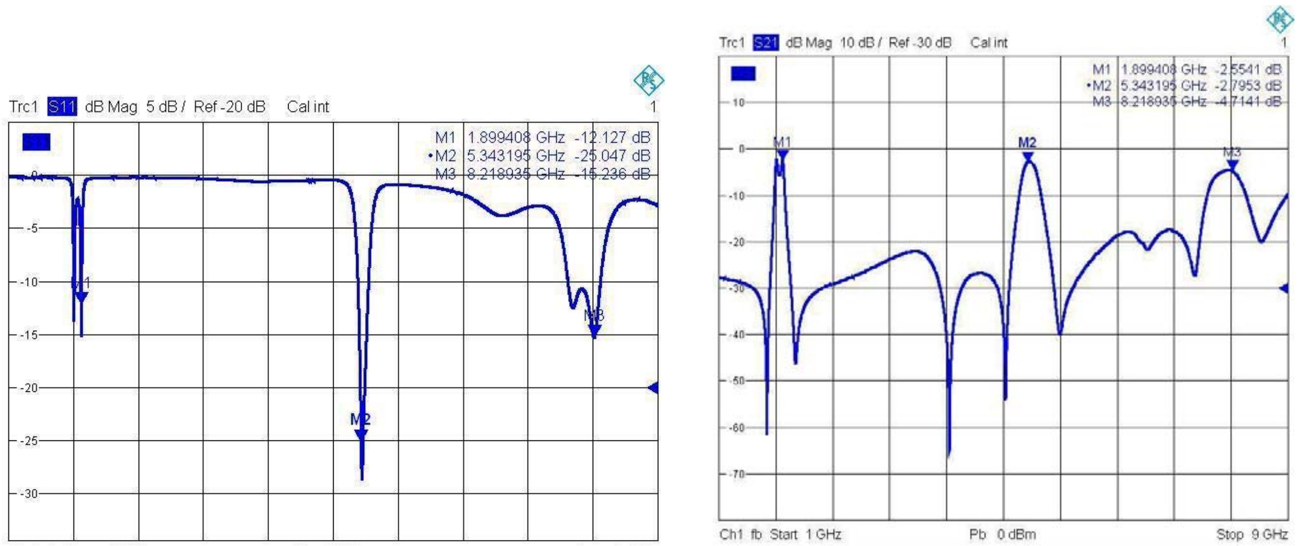
As shown in Figure 10(a) and Figure 10(b), the resonance frequencies are 1.9 GHz, 5.35 GHz and 8.25 GHz, and the insertion loss, S_{21}, is better than 2.7 dB. It noted that the insertion loss, S_{21}, at the third resonance frequency (f_{r3}) deviates in the measured response from the simulated response because of non-proficient soldering and the lossy SMA connectors used.

6.2. Comparison between Simulated Results and Measured Results

The simulated and measured performance parameters of the Tri-band filter are listed in Table 7.

From Table 7, the measured and simulated responses show good agreement, indicating that the transformation technique used to design any tri-band filter is easy, fast, generic and accurate.

Figure 9. Photograph and size of the fabricated Tri-band filter design for UMTS, Wi-LAN and X-band Satellite applications.



(a) (b)

Figure 10. The response of Tri-band filter design for UMTS, Wi-LAN and X-band Satellite applications. (a) The measured return loss (S_{11}). (b) The measured insertion loss (S_{21}).

Table 7. The optimized performance parameters of tri-band filter for UMTS, WiLAN and X-band.

Parameter	At resonance frequency $f_{r1} = 1.9$ GHz		At resonance frequency $f_{r2} = 5.35$ GHz		At resonance frequency $f_{r3} = 8.25$ GHz	
	S_{11} (dB)	S_{21} (dB)	S_{11} (dB)	S_{21}(dB)	S_{11} (dB)	S_{21} (dB)
Simulated Value	−14.64	−1.44	−24.68	−0.75	−33.47	−0.417
Measured Values	−12.13	−2.5	−25.05	−2.7	−15.24	−4

7. CONCLUSION

In this paper, a novel transformation technique and design equations are derived to design tri-band filters. The asymmetric half-wavelength structure with eight shunt open stubs is used to design a reference filter. Then the derived transformation and design equations are applied to transform other desired tri-band filter specifications to the reference one. In order to demonstrate the validity of this approach, two typical examples for tri-band filters,which are used in different wireless communications, are designed and implemented. The results obtained from hardware implementation and lab measurements agree well with that obtained from simulations. The obtained results of the designed filters indicate that this technique is easy, fast, generic and accurate.

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