Design Strategy for Compact Bandpass Filters Using Meander Line Resonators

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Abstract **─** The purpose of this manuscript is to present a compact design strategy for bandpass filters using Meander Line Resonators (MLR) in combination with Stub Loaded Resonators (SLR). The proposed resonator has been designed and analyzed using even-odd mode analysis. Open-ended stubs are loaded at an appropriate position in the dual-mode resonator to achieve tri, quad, and quintuple passbands. To reduce the circuit size and create transmission zeros at our desired frequencies, a symmetrical meandered shape resonator is loaded with open-ended identical stubs which are bent towards each other. A design strategy is presented step by step and the approach is validated using simulation and experiments.

Index Terms **─** Band-pass filters (BPFs), dual BPF, even and odd mode analysis, stub loaded resonators (SLR), triple BPF, quad BPF.

I. INTRODUCTION

Multiband filters are considered as one of the essential parts of multi-band transceivers. Planar filters are having a vital part in the RF front end to obtain the preferred and high-quality signals. In order to provide smooth communication by a multiband transceiver, it is necessary to have BPFs which have small circuit size and high selectivity to avoid any interference with nearby frequency bands. Multiband BPF’s have many direct and indirect advantages and can be used in different applications for various purposes. Different multiband BPF’s are developed in this regard having different functionalities and different characteristics [1-8].

Various dual bandpass filters are designed using DGS, SIRs, and SLR [6-17]. Recently, a tri-band response is achieved by means of a combination of SLR termed as SLDMRs [9]. Two SLDMRs combined with intra-resonator coupling between inner and outer rings are utilized to obtain a triple passband response. However, the size of the filter is large, and five transmission zeros are achieved. The same technique has been adopted in [12] to achieve tri-band performance with good selectivity by analyzing the loaded and unloaded quality factor. Six transmission zeros are achieved instead of five transmission zeros. The use of SIR in multiband BPFs is also exploited and several geometries are developed in [10, 11]. They utilized higher-order modes to create additional passbands. Also, such an approach generates an additional loss and greatly increases the overall size of the circuit.

Also, in [11] they presented a very compact wideband bandpass filter using a quasi-elliptic resonator in combination with DGS. The presented filter is advantageous in terms of insertion loss, 3-dB fractional bandwidth, and with two transmission zeros. The proposed filter was implemented in frequency scanning beam array antenna to increase its bandwidth. Also, in [16-18], they designed and developed a stop band filters based on slot resonators and then integrated within the antenna to achieve the corresponding notched band performance. Similarly, in [19, 20] they designed a band stop filters and then integrated within the antenna. However, this time they made the achieved stop bands tunable by utilizing active components within the filter.

Furthermore, in [21] they presented and claimed a very compact quintuple band bandpass filter utilizing multimode stub loaded resonator. A single symmetric resonator is loaded with a short-ended stub in the middle along with four pairs of open-ended stubs. The proposed bandpass filter operates at GSM-900, LTE2300, WiMAX

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(3.5 GHz), WLAN (5.4 GHz), and RFID (6.8 GHz). Likewise, in [22] quad BPF is accomplished using the technique of splitting a single wideband into multiple passbands.

This technique is complex and independent tuning of each passband is challenging. In this manuscript, we present a compact design strategy for bandpass filters using Meander Line Resonators (MLR) in combination with Stub Loaded Resonators (SLR). The presented resonator is designed and analyzed using even-odd mode analysis due to its symmetrical geometry. Open-ended stubs are loaded at an appropriate position in the dual-mode resonator to achieve tri and quad passbands. To reduce the circuit size and create transmission zeros at our desired frequencies, a symmetrical meandered shape resonator is loaded with open-ended identical stubs which are bent towards each other. A design strategy is presented step by step and the approach is validated using simulation and experiments.

This manuscript is arranged in the following manner: Section II deals with the recommended resonator analysis and to show the derivation of its corresponding even and odd mode frequencies. Section III provides the corresponding geometry of the designed filters based on the analysis in Section II along with the simulated and measured results, which is followed by the conclusion in Section IV.

II. RESONATOR ANALYSIS

A basic SLR comprising of one shorted stub and eight open stubs are provided in Fig. 1. It is further decomposed into even and odd mode circuits as shown in Figs. 1 (b) and (c), respectively. This even and odd mode can further be decomposed into five resonant circuits as shown in Fig. 1 (d) to Fig. 1 (m), respectively. Now, the resonant odd and even mode frequencies are calculated as in Table 1.

Table 1: Corresponding even and odd mode resonances

Even Mode Frequencies	**Odd Mode Frequencies**
$f_{even1} = \dfrac{(2n-1)c}{4(L_1+L_2+L_3+L_4+L_5+L_s)\sqrt{\varepsilon_{eff}}}$	$f_{odd1} = \dfrac{(2n-1)c}{4(L_1+L_2+L_3+L_4+L_5)\sqrt{\varepsilon_{eff}}}$
$f_{even2} = \dfrac{(2n-1)c}{4(L_2+L_3+L_4+L_5+L_s+L_6)\sqrt{\varepsilon_{eff}}}$	$f_{odd2} = \dfrac{(2n-1)c}{4(L_2+L_3+L_4+L_5+L_6)\sqrt{\varepsilon_{eff}}}$
$f_{even3} = \dfrac{(2n-1)c}{4(L_3+L_4+L_5+L_7+L_s)\sqrt{\varepsilon_{eff}}}$	$f_{odd3} = \dfrac{(2n-1)c}{4(L_3+L_4+L_5+L_7)\sqrt{\varepsilon_{eff}}}$
$f_{even4} = \dfrac{(2n-1)c}{4(L_4+L_5+L_8+L_s)\sqrt{\varepsilon_{eff}}}$	$f_{odd4} = \dfrac{(2n-1)c}{4(L_4+L_5+L_8)\sqrt{\varepsilon_{eff}}}$
$f_{even5} = \dfrac{(2n-1)c}{4(L_5+L_9+L_s)\sqrt{\varepsilon_{eff}}}$	$f_{odd5} = \dfrac{(2n-1)c}{4(L_5+L_9)\sqrt{\varepsilon_{eff}}}$

Table 2: Geometrical dimensions for single/dual/tri-BPF’s (all values are in mm)

Parameter	**Value**	**Parameter**	**Value**	**Parameter**	**Value**
L_m	5	L_s	2.25	W_r	2
L_f	3.25	W_s	1	W_1	0.5
W_6	1	W_7	4	L_1	14.1
L_4	4	L_5	7.02	L_6	7.07
G_1, G_2, G_3	0.5	Via	0.5	W_4	0.5
L_3	4.6	L_8	4	W_2	1.75
W3	2.17	L_2	4	L_7	5.85

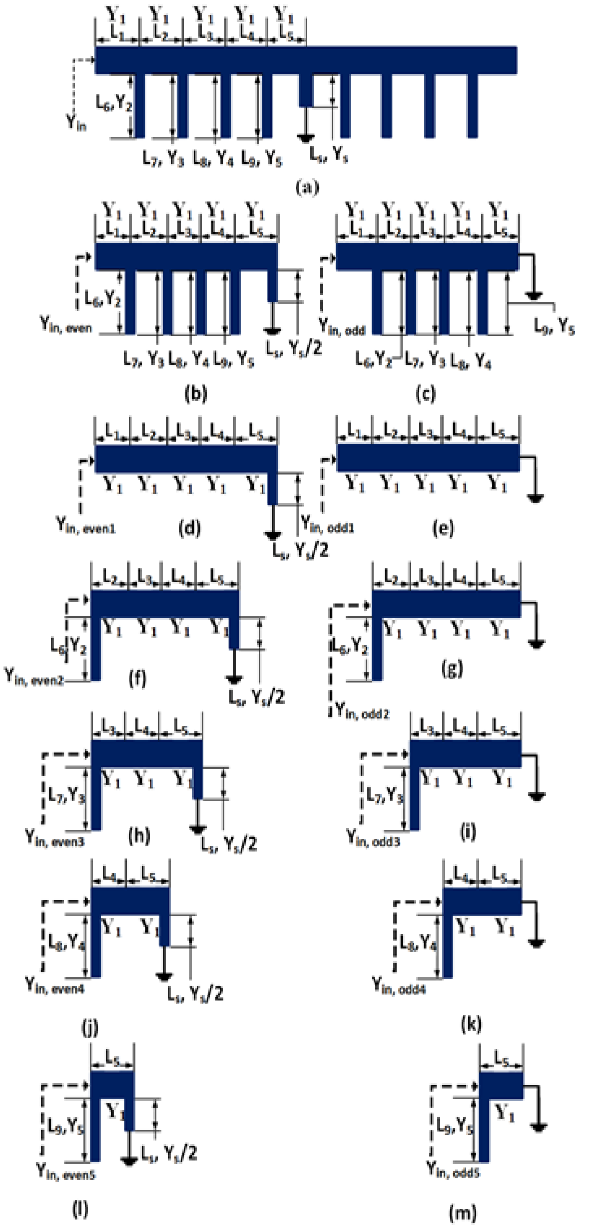

Fig. 1. Decomposition of the proposed SLR: (a) Basic SLR, (b) even mode circuit, (c) odd mode circuit (d, f, h, j, l) even mode equivalent circuits, and (e, g, i, k, m) odd mode equivalent circuits.

III. RESULTS AND DISCUSSION

Designed single, dual, triple, quad, and quintuple band bandpass filters are simulated using commercially available software ANSOFT HFSS and fabricated as well. The filters are also measured, and its frequency response is provided in each case. First, the optimization of different parameters is performed, and the final optimized parameters of the filters are provided in Table 2.

Figure 2 shows the corresponding single BPF with a simulated frequency response in Fig. 3. The proposed single BPF is designed for 1 GHz center frequency. Similarly, Fig. 4 shows the corresponding dual BPF with simulated frequency response in Fig. 5. Now the dual BPF is designed for 1 GHz and 2.5 GHz and it can be well seen from Fig. 5. Three transmission zeros are observed in this case.

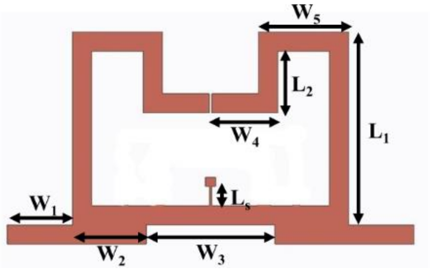

Fig. 2. Developed single BPF.

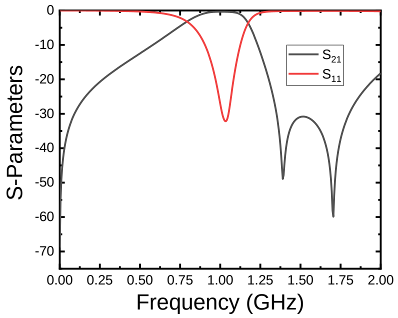

Fig. 3. Single BPF response.

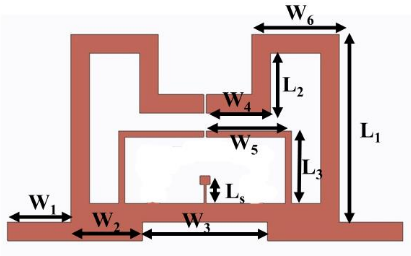

Fig. 4. Developed dual BPF.

Figure 6 shows the corresponding tri BPF aimed to operate at GSM-900, LTE-2300, and WiMAX (3.5 GHz). The measured and simulated frequency response including S_{11} and S_{21} of the developed tri-band BPF is also shown in Fig. 7. The developed tri-band BPF is aimed for useful wireless applications such as GSM-900, LTE-2300, and WiMAX (3.5 GHz). The middle frequencies of the developed tri-band BPF are 0.9550 GHz, 2.2948 GHz, and 3.5246 GHz. The corresponding 3-dB fractional bandwidth of the corresponding center frequencies is 45.25%, 20.32% and 6.09% for the 1st, 2nd, and 3rd passbands, respectively. The measured insertion loss in the three passbands is 0.32, 0.63 and 1.38 including losses from the SMA connectors. Six transmission zeros are created in the simulated frequency response at frequencies 1.43 GHz, 1.68 GHz, 3.008 GHz, 3.33 GHz, 4.0 GHz, and 5.33 GHz with more than 28 dB attenuations in order to get sharp skirt selectivity for the passbands. The geometrical dimensions of the tri-BPF are mentioned in Table 2.

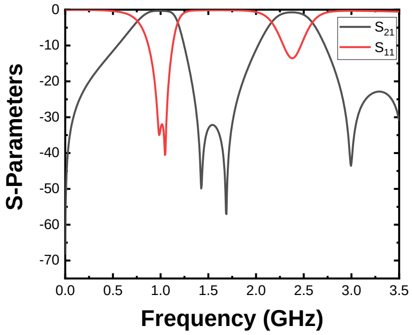

Fig. 5. Dual BPF response.

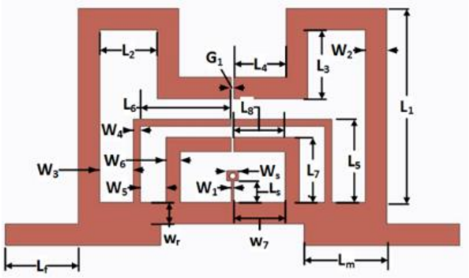

Fig. 6. Developed tri BPF.

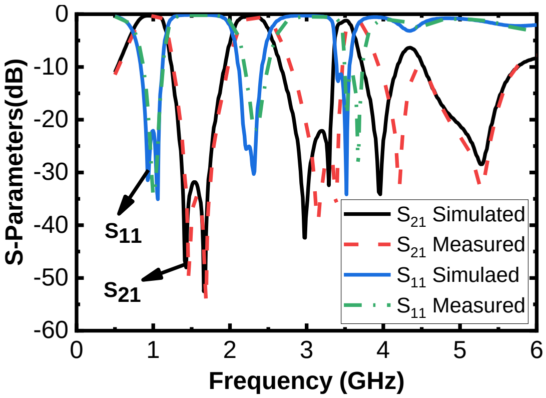

Fig. 7. Tri BPF response.

Figure 8 shows the corresponding quad BPF aimed to operate at GSM-900, LTE-2300, WiMAX (3.50 GHz) and WLAN (5.40 GHz). The frequency response of the measured and simulated results of quad-band BPF is given in Fig. 9. It is obvious that the measured and simulated frequency response agrees very well. The developed quad-band BPF is tuned for useful wireless applications which are GSM-900, LTE-2300, WiMAX (3.50 GHz) and WLAN (5.40 GHz). The operating frequencies of the quad-band BPF are 0.946 GHz, 2.2079 GHz, 3.59 GHz, and 5.4663 GHz. The percentage 3-dB fractional bandwidth all passbands are 42.64%, 21.31%, 7.074%, and 7.414%, respectively. The measured insertion loss of all the four passbands at their center frequencies including SMA connectors are 0.31 dB, 0.56 dB, 1.59 dB, and 1.63 dB respectively. Seven transmission zeros are generated with more than 28 dB attenuation at 1.39 GHz, 1.60 GHz, 2.98 GHz, 3.36 GHz, 4.11 GHz, 5.05 GHz, and 5.88 GHz in order to get high selectivity pass-band filter response. The corresponding dimensions of the quad BPF are tabulated in Table 3.

Table 3: Geometrical dimensions for quad BPF's (all values are in mm)

Parameter	**Value**	**Parameter**	**Value**	**Parameter**	**Value**
L_m	7	L_s	2	W_r	2
L_f	3.25	W_s	1	W_1	0.5
W_6	0.8	W_7	0.95	L_1	15.1
L_2=L_4	4	L_5	7.5	L_6	6.575
W_8	0.5	W_9	1	W_{10}	2.75
G_1, G_2, G_3, G_4	0.5	Via	0.5	W_4	1
W_2	1.75	W_3	2.17	L_7	5.85
L_3	4.6	L_8	4.2	L_{10}	2.75

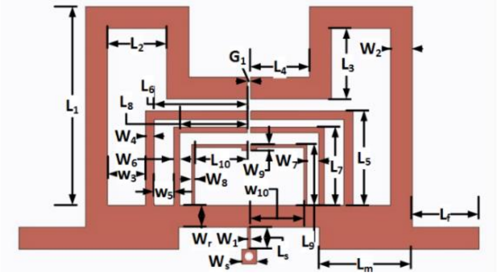

Fig. 8. Developed quad BPF.

Figure 10 shows the corresponding quintuple BPF aimed to operate at GSM-900, LTE2300, WiMAX (3.5 GHz), WLAN (5.4 GHz) and RFID (6.8 GHz). The resonance frequencies of the designed filter are calculated by using the equations mentioned in Table 1. It is seen that there is a slight difference between calculated and aimed frequencies. However, it is optimized using parametric analysis to obtain the exact resonance frequencies as desired. The designed quintuple BPF is also measured and its frequency response is provided. The simulated vs. measured S21 response are shown in Figs. 7 and 8, respectively. Good matching can be seen between the simulated and measured response of the proposed filter. Figure 11 shows that the proposed quintuple band bandpass filter is tuned to frequency bands, GSM-900, LTE2300, WiMAX (3.5 GHz), WLAN (5.4 GHz) and RFID (6.8 GHz). The operating mid frequencies of quintuple band bandpass filter are 0.96 GHz, 2.22 GHz, 3.58 GHz, 5.41 GHz, and 6.64 GHz with corresponding 3dB FBW of 36.03%, 20.95%, 7.27%, 8.57%, and 3.37%. The measured insertion loss is 0.38dB, 0.59dB, 1.47dB, 1.53dB and 2.4dB at GSM-900, LTE2300, WiMAX, WLAN and RFID frequency bands, respectively. The geometrical dimensions of the quintuple-BPF are mentioned in Table 4. The step by step fabricated prototypes of all filters are shown in Figs. 12 (a-c).

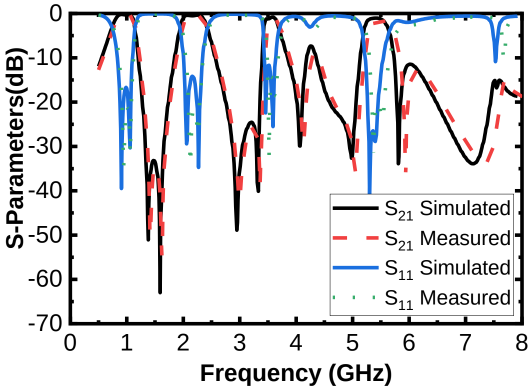

Fig. 9. Quad BPF response.

Table 4: Geometrical dimensions for quintuple BPF's (all values are in mm)

Parameter	Value	Parameter	Value	Parameter	Value
L_1	32.25	L_2	2.75	L_3	0.85
L_4	3.5	L_5	2.875	L_6	13.975
L_7	10.2	L_8	7.75	L_9	5.75
W_1	1.75	W_2	1	L_f	3.25
W_3	0.5	L_s	1.25	G_1-G_5	0.5
W_s	1	W_4	0.5	W_5	0.75
W_f	1.7	L_m	3		

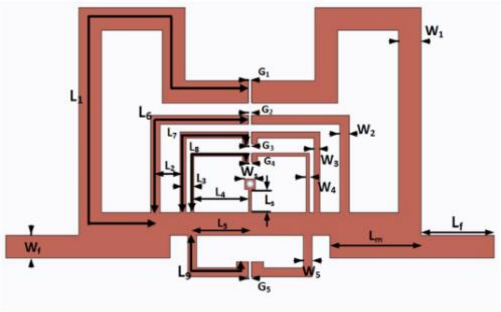

Fig. 10. Developed quintuple BPF.

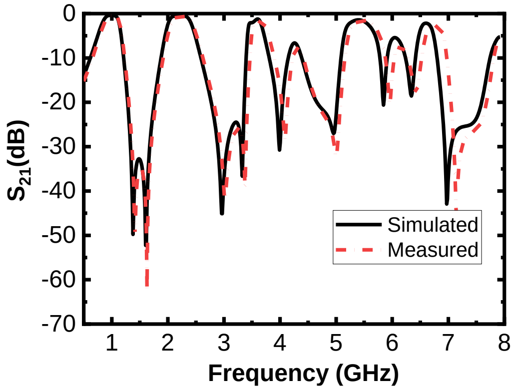

Fig. 11. Quintuple BPF response.

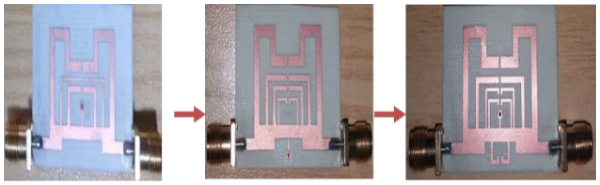
(a) (b) (c)

Fig. 12. Fabricated filters: (a) Tri BPF, (b) quad BPF, and (c) quintuple BPF.

IV. CONCLUSION

Design strategy for compact bandpass filters using Meander Line Resonators (MLR) in combination with Stub Loaded Resonators (SLR) is presented. The proposed resonator is analyzed using the even-odd mode analysis. Open-ended stubs are loaded at an appropriate position in the dual-mode resonator to achieve tri, quad, and quintuple passbands. To reduce the circuit size and create transmission zeros at our desired frequencies, a symmetrical meandered shape resonator is loaded with open-ended identical stubs which are bent towards each other. A design strategy is presented step by step and the approach is validated using simulations and experiments.

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