Miniaturized Microstrip Bandpass Filters Using Novel Stub Loaded Resonator

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Abstract **─** In this paper, a novel structure is proposed to design two compact microstrip bandpass filters operated at 2.39 GHz and 5.73 GHz, which their sizes are 44 mm^2 and 14 mm^2, respectively. Miniaturization, resonance frequency tuning and harmonics attenuation methods are presented. Low insertion losses and wide fractional bandwidths are achieved. The obtained insertion losses and fractional bandwidths of the 2.39 GHz and 5.73 GHz filters are 0.27 dB, 0.19 dB, 46%, and 44%, respectively. Also for both filters, the second and third harmonics are attenuated. The proposed filters are fabricated and measured and there is a good agreement between the simulation and measurement results.

Index Terms **─** Harmonics attenuation, microstrip filter, miniaturization, novel structure.

I. INTRODUCTION

There have been increasing demands for the compact microstrip filters with low insertion loss due to their important role in the modern wireless communication systems [1-5]. But several microstrip bandpass filters with very large size, using different resonators, have been proposed in [6-16]. In [6], a branch line resonator and in [7], a stepped impedance resonator have been used to design microstrip bandpass filters. But they have large insertion losses and small fractional bandwidths. In [8-9], ultra-wide band microstrip bandpass filters have been presented. In [8], a ring resonator and a parallel coupled resonator have been utilized to obtain a wide fractional bandwidth filter, but its insertion loss is large. In [10-14], microstrip band pass filters with small fractional bandwidths and undesired insertion losses have been proposed. To design these filters, inductive-coupled stepped-impedance quarter-wavelength resonators [10], ring resonators [11], rectangular dual spiral resonator [12], and partially coupled resonators [13] have been used. In this paper, two miniaturized microstrip bandpass filters are designed using a novel compact resonator to solve the previous works problems in terms of the large sizes, small fractional bandwidths and the large insertion losses.

II. THEORY AND STRUCTURE

A. Resonator structure

Microstrip stub loaded cells can be used as the compact tuneable resonators. By tuning the widths and lengths of the stubs, the resonance frequency can be tuned without size increase. One of these compact stub loaded tuneable resonators is proposed and shown in Fig. 1. It is a novel U-shape structure, which is loaded by a shunt stub.

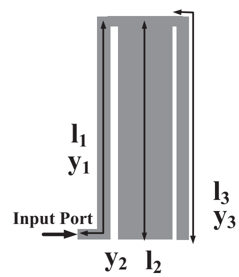

Fig. 1. Proposed resonator.

For even mode analysis, the characteristic admittance, viewed from the open end input port, is achieved as follows:

$$Ye = \frac{(y_{2e} + y_{3e})\, y_{1e}}{y_{2e} + y_{3e} + y_{1e}}. \tag{1}$$

In Equation (1), y_{1e} is the admittance of the structure connected to the input port originated from the structure with length l_1, while y_{2e} comes from the shunt stub loaded inside the U-shape structure and y_{3e} is the equivalent admittance of the open stub with the physical length l_3 (see Fig. 1). According to the transmission line theory, the input admittances of the open-circuited transmission line with the characteristic admittances y_1, y_2 and y_3 are given by [17]:

Submitted On: February 3, 2015
Accepted On: May 10, 2015

$$y_{ie} = j\, y_i \tan(k_i f_{oe})$$
$$k_i = \left(\frac{\pi}{150}\right)\sqrt{\varepsilon_{rei}}\, l_i \qquad for \;\; i=1,\,2,\, and\; 3\,, \quad (2.a)$$

where f_{oe} is the even mode resonant frequency (per GHz), ε_{rei} is the effective dielectric constant, and l_i is the physical length (per mm).

The effective dielectric constant can be calculated as follows [17]:

$$\varepsilon_{rei} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left\{\frac{1}{\sqrt{(1+12\frac{h}{W_i})}} + 0.04\left(1+\frac{W_i}{h}\right)^2\right\}. \quad (2.b)$$

In Equation (2.b), i=1, 2 and 3 and h is the thickness of the substrate with a dielectric constant ε_r. Also W_i is the width of the stub with length l_i. From Equation (2.b), the widths have significant effects on the resonator performance.

B. Resonance frequency tuning and miniaturizing method

The resonance condition for the even mode is satisfied when Y_e=0. Therefore, by substituting Equation (2) in Equation (1), the even mode resonance frequencies can be obtained as follows:

$$Y_e = j \times \frac{(y_2 \tan(k_2 f_{oe2}) + y_3 \tan(k_3 f_{oe2}))\, y_1 \tan(k_1 f_{oe1})}{y_2 \tan(k_2 f_{oe2}) + y_3 \tan(k_3 f_{oe2}) + y_1 \tan(k_1 f_{oe1})} = 0\,. \quad (3.a)$$

Therefore, if y_2=y_3, then:

$$f_{oe1} = \frac{m\pi}{k_1} \qquad for \quad m=1,2,3,\ldots, \quad (3.b)$$

$$\tan(k_2 f_{oe2}) = -\tan(k_3 f_{oe2})$$
$$so \qquad . \quad (3.c)$$
$$f_{oe2} = \frac{m\,\pi}{k_2+k_3} \qquad \& \quad m=1,2,3,\ldots$$

If the open stubs with the lengths l_2 and l_3 have the same characteristic admittances, by tuning k_1, k_2, and k_3, the resonance frequency can be adjusted simply. Under this condition (for a defined resonance frequency) if m=1 then k_1, k_2, and k_3 are minimum. Then from (2.a) and (2.b), the lengths and widths of the resonator are minimized. As a result, the resonator size is minimized. Therefore, a compact tuneable resonator is designed, which can be used in the filter structure.

C. Harmonics attenuation method

To design a single-band bandpass filter with attenuated harmonics (for a defined m) a resonance frequency is the desired resonance frequency and another one is an unwanted resonance frequency. The unwanted resonance frequency acts as a harmonic. One method to remove this harmonic is obtained when f_{oe1}=f_{oe2}. Therefore, to remove the harmonic from Equations (3.b) and (3.c):

$$k_1 = k_2 + k_3\,. \quad (4)$$

D. Odd mode analysis

By a similar analysis for odd mode, the characteristic admittance, viewed from the open end input port, Y_O, is:

$$Yo = \frac{(y_{2o}+y_{3o})\, y_{1o}}{y_{2o}+y_{3o}+y_{1o}}\,. \quad (5)$$

In Equation (5), y_{io} (i=1, 2 and 3) are the odd mode admittances of the structures which are described similar to y_{ie}. The input admittances of the open-circuited transmission line with the characteristic admittances y_1, y_2 and y_3 are given by:

$$y_{io} = -j\, y_i \cot(k_i f_{oo})$$
$$k_i = \left(\frac{\pi}{150}\right)\sqrt{\varepsilon_{rei}}\, l_i \qquad for \;\; i=1,\,2,\, and\; 3\,, \quad (6)$$

where f_{oo} is the odd mode resonant frequency (per GHz). The resonance condition for the odd mode is satisfied when Z_o=1/Y_o=0. Therefore, by substituting Equation (6) in Equation (5), the odd mode resonance frequencies can be obtained as follows:

$$Z_o = -j \times \frac{y_1 \cot(k_1 f_{oo}) + y_2 \cot(k_2 f_{oo}) + y_3 \cot(k_3 f_{oo})}{(y_2 \cot(k_2 f_{oo}) + y_3 \cot(k_3 f_{oo}))\, y_1 \cot k_1 f_{oo})} = 0\,. \quad (7.a)$$

A solution for Equation (7.a) is:

$$f_{oo} = \frac{m\pi}{2k_1} = \frac{m\pi}{2k_2} = \frac{m\pi}{2k_3} \qquad for \quad m=1,3,5,7,\ldots. \quad (7.b)$$

From (2.b) and (7.b):

$$\sqrt{\varepsilon_{re1}}\, l_1 = \sqrt{\varepsilon_{re2}}\, l_2 = \sqrt{\varepsilon_{re3}}\, l_3\,. \quad (7.c)$$

If the lengths and widths l_i and W_i be decreased so that Equation (7.c) be satisfied, then the resonance frequency is obtained and the resonator size is reduced too.

To calculate the resonator dimensions, first a substrate with ε_r=2.2 and h=0.786 mm is chosen. As a result of the presented method, the internal stub must be extensive while the resonator has a minimum size (to tune the resonance frequency with the minimum size of the resonator). Therefore, an appropriate selection of the sizes of the widths is: W_1=W_3=0.1 mm, and W_2=0.7 mm. From Equation (2.b), ε_{re1}=ε_{re3}=1.69 and ε_{re2}=1.84. Whereas the resonance frequency is a presuppose target, from Equations (2.a), (3.b) and (3.c), the length of the stubs have determinate values.

Using the proposed resonator, two compact bandpass filters with symmetric structures are designed to operate at WLANs frequencies. Figure 2 shows the proposed bandpass filter operated at 2.39 GHz. This filter is composed of four stub loaded U-shape structures. Using the coupled lines, two stub loaded U-shape structures are connected to the other two stub loaded U-shape structures. The stub loaded U-shape structures are similar to the proposed resonator, which can be analyzed in the same method.

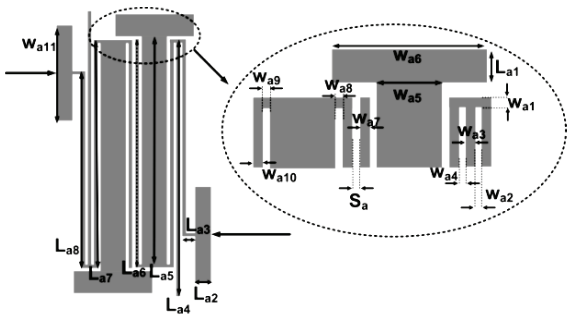

Fig. 2. Proposed 2.39 GHz filter.

As shown in Fig. 3, to design a compact bandpass filter operated at 5.73 GHz, the proposed resonator in Fig. 1 is used. This filter is composed of two resonators, similar to Fig. 1, which connected together using the coupled lines and the taped line feed structures.

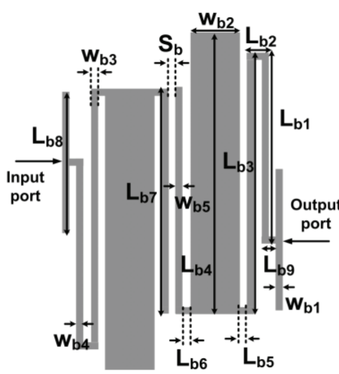

Fig. 3. Proposed 5.73 GHz filter.

The T-shape tapped lines feed structures are added to the input and output ports to improve the insertion loss without size increment. The effect of T-shape tapped line feed structure on the insertion loss (for 2.39 GHz filter) is shown in Fig. 4 (a). In Fig. 4 (a), S_{21} is shown as a function of W_{a11}. As shown in Fig. 4 (a), by increasing W_{a11}, the insertion loss is decreased. S_{21} as a function of the coupled line length is shown in Fig. 4 (b). As shown in Fig. 4 (b), by increasing L_{a6} the resonance frequency is shifted to the left. Also by decreasing L_{a6}, the coupling effect is decreased and as a result the insertion loss is increased. The T-shape cells (with the lengths L_{a5} and L_{a1}) are loaded in the inside of the U-shape structures to control the resonance frequency without size increment. By increasing the wide, the resonance frequency shifts to the left. This is shown in Fig. 4 (c). The coupled lines (in Fig. 3) play an important role to control the insertion loss and resonance frequency. The effect of this parameter is shown in Fig. 4 (d). In Fig. 4 (d), S_{21} is shown as a function of L_{b7}. As shown in Fig. 4 (d), by increasing L_{b7} the resonance frequency is shifted to the left. Also by decreasing L_{b7}, the coupling effect is decreased and as a result the insertion loss is increased. Therefore, by tuning the coupled lines lengths the insertion loss is decreased and the resonance frequency is tuned. To improve the sharpness, S_{21} is changed as a function of L_{b1}. This effect is shown in Fig. 4 (e). As shown in Fig. 4 (e), the frequency response is sharper when L_{b1} is smaller.

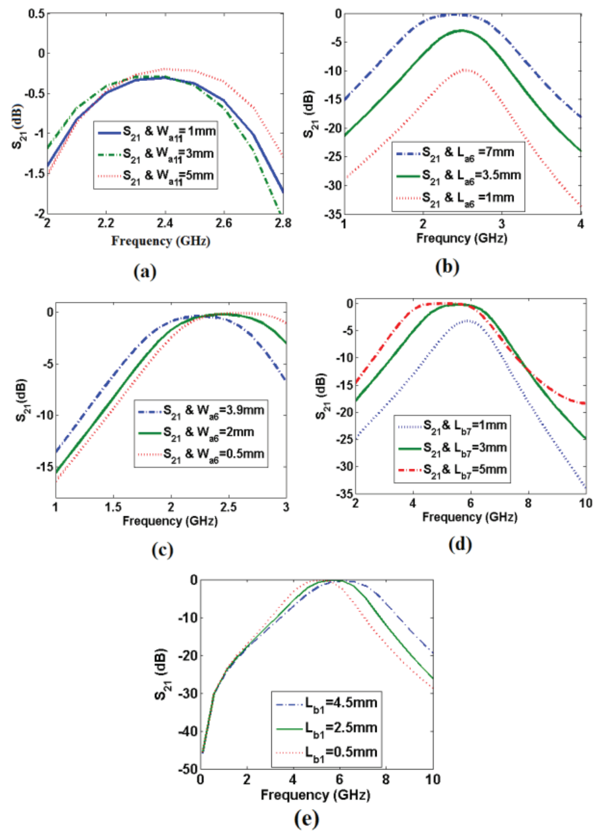

Fig. 4. (a) S_{21} as a function of W_{a11}, (b) S_{21} as a function of L_{a6}, (c) S_{21} as a function of W_{a6}, (d) S_{21} as a function of L_{b7}, and (e) S_{21} as a function of L_{b1}.

III. RESULTS

The proposed filters are simulated using ADS full wave EM simulator and fabricated on a RT Duroid 5880 substrate. They have a dielectric constant of 2.2, 31 mil-thickness and the loss tangent equal to 0.0009.

A. 2.39 GHz filter

The dimensions of the proposed 2.39 GHz filter (Fig. 2) are presented in Table 1.

The frequency response of the 2.39 GHz filter is shown in Fig. 5 (a). The wide-band frequency response of the 2.39 GHz filter is shown in Fig. 5 (b) and the photograph of the fabricated filter is shown in Fig. 5 (c). The insertion loss at 2.39 GHz is better than 0.27 dB, while the return loss is better than -12 dB.

Table 1: Dimensions of the proposed 2.39 GHz filter

L_{a1}	L_{a2}	L_{a3}	L_{a4}	L_{a5}	L_{a6}	L_{a7}
0.7 mm	0.5 mm	0.3 mm	8.1 mm	7.2 mm	7.2 mm	7.2 mm
L_{a8}	W_{a1}	W_{a2}	W_{a3}	W_{a4}	W_{a5}	W_{a6}
6.2 mm	0.1 mm	0.1 mm	0.1 mm	0.1 mm	0.8 mm	2.5 mm
W_{a7}	W_{a8}	W_{a9}	W_{a10}	W_{a11}	S_a	
0.1 mm	0.1 mm	0.1 mm	0.1 mm	3 mm	0.1 mm	

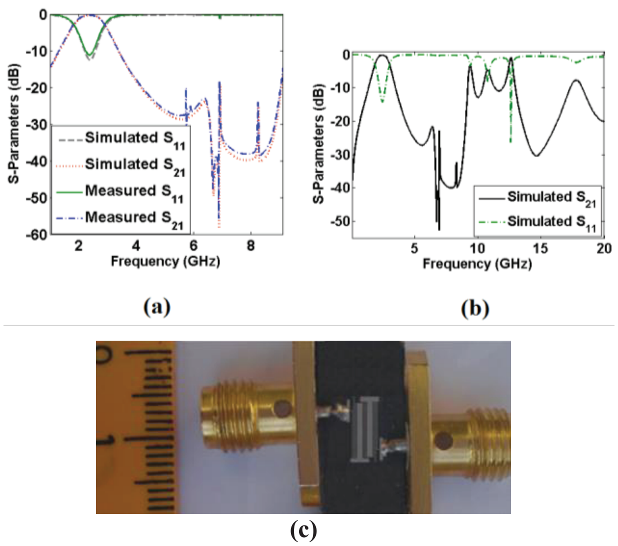

Fig. 5. (a) Frequency response of the proposed 2.39 GHz filter, (b) wide-band frequency response of the 2.39 GHz filter, and (c) photograph of the fabricated 2.39 GHz filter.

The filter size is 9×4.9 mm² (0.09 λ_g × 0.05 λ_g mm²). The obtained fractional bandwidth (FBW) is 46%. This filter has the cut-off frequencies at 1.83 GHz and 2.94 GHz. The harmonics are attenuated from 4.29 GHz up to 9 GH (3.76f_o) with a minimum attenuation above -19 dB.

B. 5.73 GHz filter

The dimensions of the proposed 5.73 GHz filter (Fig. 3) are optimized and presented in Table 2.

The frequency response of the 5.73 GHz filter is shown in Fig. 6 (a). The wide-band frequency response of the 5.73 GHz filter is shown in Fig. 6 (b). The insertion loss at 5.73 GHz is better than 0.19 dB, while the return loss is better than -13 dB. The filter size is 4.8×3.1 mm² (0.11λ_g × 0.07λ_g mm²) and its fractional bandwidth is 43%. It has the cut-off frequencies at 4.48 GHz and 6.99 GHz. The harmonics are attenuated from 9.09 GHz up to 17.28 GHz (3f_o) with a minimum attenuation above -20 dB. The photograph of the fabricated filter is shown in Fig. 6 (c).

Table 2: Dimensions of the proposed 5.73 GHz filter

L_{b1}	L_{b2}	L_{b3}	L_{b4}	L_{b5}	L_{b6}	L_{b7}
2.7 mm	0.3 mm	3.7 Mm	4 mm	0.1 Mm	0.1 mm	3.2 mm
L_{b8}	L_{b9}	W_{b1}	W_{b2}	W_{b4}	W_{b5}	S_b
2 mm	0.2 mm	0.1 mm	0.7 Mm	0.1 mm	0.1 Mm	0.1 mm

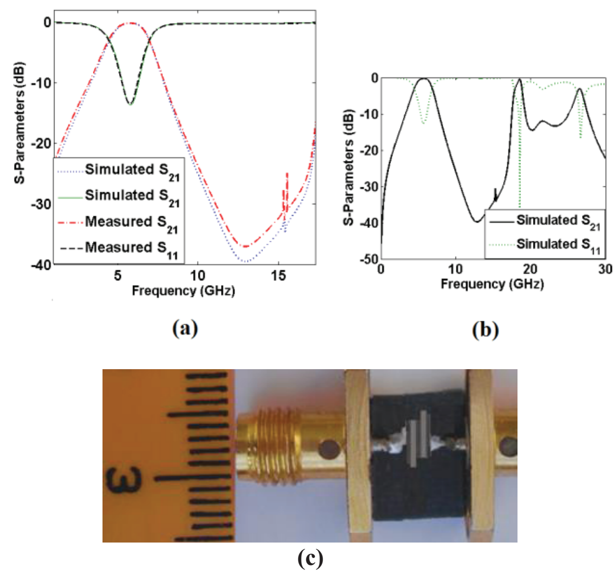

Fig. 6. (a) Frequency response of the proposed 5.73 GHz filter, (b) wide-band frequency response of 5.73 GHz filter, and (c) photograph of the fabricated 5.73 GHz filter.

In comparison with the previous works, the minimum size, good insertion losses and wide fractional bandwidths are obtained. The insertion losses, fractional bandwidths, stopband responses, and the size of the proposed filters are compared with previous works in Table 3. In Table 3, IL, F_O, FBW are the insertion loss, operation frequency and fractional bandwidth respectively. In Table 3, IL, F_O and size are per dB, GHz and mm^2 respectively.

Table 3: Comparison between the previous works and the proposed filters

References	IL	FO	Size	FBW (%)	Stopband Response	Approximated -20 dB Cut-Off Frequencies (GHz)
[6]	2.6	2	149	5.9	-27 dB up to 2.88fo	
[7]	2.5	2	2049	12	-50 dB up to 4 GHz (2fo)	1.6 and 2.4
[8]	2.5	4	177	50	-60 dB up to 7.4 GHz (1.85fo)	2.7 and 5.1
[9]	0.1	4.5	1034	66	---	2.6 and 5.2
[10]	0.85	2.35	220	11.5	---	2 and 2.6
[11]	---	2.05	126	10	---	1.3 and 1.5
[13]	3.8	1	9000	13	-30 dB up to 6.2 GHz (6.2fo)	0.9 and 1.12
[14]	1.8	1.78	488	16.5	-30 dB up to 6.8 GHz (3.8fo)	1.5 and 1.9
[15]	6.4	2.55	225	3.5	-30 dB up to 3.9 GHz (1.5fo)	2.4 and 2.6
Proposed 2.39 GHz BPF	0.27	2.39	44.1	46	-19 dB up to 9 GHz (3.76fo)	0.66 and 4.3
Proposed 5.73 GHz BPF	0.19	5.73	14	43	-20 dB up to 17.28 GHz (3fo)	1.5 and 9.1

IV. CONCLUSIONS

Two miniaturized microstrip bandpass filters (44 mm^2 BPF operated at 2.39 GHz and 14 mm^2 BPF operated at 5.73 GHz) with the good insertion losses and the wide fractional bandwidths are designed and fabricated using a novel resonator. The proposed filters are composed of U-shape structures, which are loaded by the different open stubs. For the 2.39 GHz and 5.73 GHz BPFs, the harmonics are attenuated up to 9 GHz and 17.28 GHz, respectively, where the second and third harmonics are attenuated. The obtained results show that the proposed filters have wider fractional bandwidths, lower insertion losses and minimum sizes in comparison to the previous works.

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