A Compact Wide Bandpass Filter for Satellite Communications with Improved Out-of-Band Rejection

Badiaa Ait Ahmed [1], **Azzeddin Naghar**[2], **Otman Aghzout**[1], **Ana Vazquez Alejos**[3] **and Francisco Falcone**[4]

[1] Department of Computer Science Engineering, SIGL Lab. ENSA,
University of Abdelmalek Essaadi ,Tetuan, Morocco
[2] BSA-Innovation LAB Radio Frequency Systems RFS, Lannion,France
[3] Department of Signal Theory and communications,
University of Vigo, Pontevedra, Spain
[4] Department of Electrical and Electronic Engineering,
Public University of Navarra,Pamplona, Spain
*corresponding author, E-mail: oaghzout@uae.ac.ma

Abstract

This paper presents a compact C-band bandpass filter with improved out-of-band rejection. It consists of a symmetric three-pole parallel coupled line microstrip loaded with complementary split ring resonators ($CSRRs$) and slot resonators. Enhancements regarding the filter responses are obtained by etching these two parasitic shapes successively. When, $CSRRs$ are introduced in the ground plane, exactly in the back of the transmission line of $50~\Omega$, improvements on the filter selectivity level are achieved. Whereas, the slot resonator elements are implemented on the feed line to permit the suppression of the second harmonics. To reduce the second harmonics of $11.1 - 13~GHz$, the parasitic elements are both combined, widen the filter rejection of 5.81%. The surface current distribution together with the equivalent circuit are also studied in order to demonstrate the slots and the CSRRs effect parameters on the behavior of the proposed filter. A prototype of the optimal filter is fabricated and measured.Theory and experiment results prove the validity of the new design procedure.

1. Introduction

Parallel-coupled line microstrip filters are known as one of the most commonly used designs in practical wireless communication and microwave applications, due to their design simplicity, planar structure, and relatively wide bandwidth [1]. However, this type of filter suffers from spurious responses that limit their performances and their integration in RF front-end of wireless microwave systems. Hence, these filters require high selectivity [2] and spurious suppression [3-4]. These spurious appear in the out-of-band rejection at the even- and odd-mode characteristics, which produce, a poor out-of-band rejection. For this reason, various methods have been proposed to overcome the aforementioned challenges. To eliminate the spurious suppression many techniques are used. Some authors for example, proposed an open stubs with improvements in over coupled end sections and period perturbation to get multi-spurious suppression, [5]. Others integrated an open

stub of the band pass filter (BPF) over the antenna slot to suppressing the high-order spurious, [6]. On other hand, many works used the meandered quarter-wavelength resonators to suppress the unwanted harmonics [7]. To enhance the filter selectivity in out-of-band rejection, several techniques have been used to face this kind of problems. For example, [8] integrated two short-circuited stubs with one quarter-wavelength to develop quadruple-mode MMR filter. Besides, [9] proposed a quarter wavelength short-circuited stub to be added at each side of the central coupled line, with the aim to increase significantly the selectivity of both edges of the passband filter. Although, [10] adopted a defected ground structure (DGS) technologies. However, [11] proposed transmission zeros (TZs) and [12] adjusted multi-stage cascade resonators. The selectivity enhancement, and the harmonic suppression were treated in [13] by seven transmission zeros (TZs). Although, most of these approaches still need some enhancements. In this paper, we propose a design and analysis of a performed wideband bandpass filter based on complementary split ring resonators ($CSRRs$) and slot resonators. The proposed filter can be used for different technology , in particular for the satellite communication systems. The main objectives of this paper is to improve the filter selectivity, suppress the spurious response and eliminate the transmission at high frequency. To achieve this , firstly, the parallel-coupled line microstrip bandpass filter is optimized to cover the microwave C-band from $4.6 to 7.5~GHz$. Secondly, two symmetrical resonator types such as Slot and $CSRR$ elements are analyzed, regarding the second harmonics reduction. After that, these parasitic elements are added to the circuit to yield spurious suppression and selectivity improvement for the desired resonance frequencies. These elements are loaded on the fiter design in two steps. exactly in the transmission line of $50 - \Omega$ and below it respectively, see figures below.The experimental validation is done for the first case related to the spurious suppression and the selectivity enhancement. To widen the rejection between these two dips, two additional $CSRRs$ particles with close resonances are

etched to eliminate the unwanted transmission at high frequencies. An L-C equivalent circuit model is also presented and calculated for all design procedures to demonstrate the performance of the proposed filter. The optimized design structure offers a miniaturized C-band bandpass filter with better out-of-band rejection.

2. Bandpass filter design with spurious suppression

2.1. Geometry of the proposed filter

Fig. 1. shows a general layout of proposed three-pole Chebyshev parallel coupled line microstrip band-pass filter. This structure implements the Roger $RT/DuroidRO3010$ substrate with the dielectric constant of 10.2 and thickness of 1.27. The parameter dimensions of the optimized filter are fixed at the operating frequency centred at $6\ GHz$ with the equal ripple of $0.1\ dB$. These ripples were calculated by the tools developed in [10] and optimized by the CST MWs Electromagnetic Simulator. The corresponding even- and odd-mode impedance characteristics are $Z_{0e} = 94\ \Omega$, $Z_{0o} = 40\ \Omega$ for sections 1, 4 and $Z_{0e} = 72.3\ \Omega$, $Z_{0o} = 34.2\ \Omega$ for sections 2, 3. The L-C elements for serial
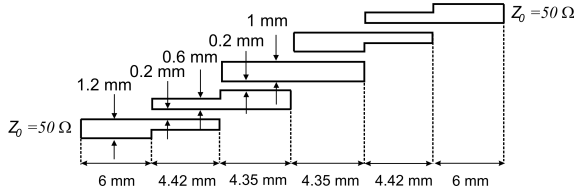

Figure 1: Configuration of the proposed C-band parallel coupled bandpass filter

and parallel coupled bandpass filter are calculated using the Chebyshev function, [1] as can be shown in the following equations:

$$L_s = \frac{FBW.\omega_0}{Z_0.g} \qquad ; \qquad C_s = \frac{FBW}{Z_0.g.\omega_0} \qquad (1)$$

$$L_p = \frac{FBW.Z_0}{\omega_0.g} \qquad ; \qquad C_p = \frac{g}{FBW.Z_0.\omega_0} \qquad (2)$$

Where g is the Chebyshev element and FBW is the fractional bandwidth, $FBW = \frac{\omega_1.\omega_2}{\omega_0}$ with $\omega_0 = (\omega_1.\omega_2)^{0.5}$
The calculated values of the L-C components for the circuit presented in Fig.3, are: $C_1 = C_3 = 0.218\ pF$, $C_2 = 1.460\ pF$, $L_1 = L_3 = 3.283\ nH$, $L_2 = 0.489\ nH$.

The frequency response of the resulting bandpass filter is plotted in Fig. 2, indicating a good agreement between simulation and the equivalent circuit model developed in Fig.3. From Fig.2, it is observed also that the filter covers the microwave C-band from $4.6 - 7.5\ GHz$ with low passband insertion loss of $0.6\ dB$. although, the results obtained are acceptable. from the figure it is clear to appreciate the presence of an unwanted harmonic step band of $11.1 - 13\ GHz$.
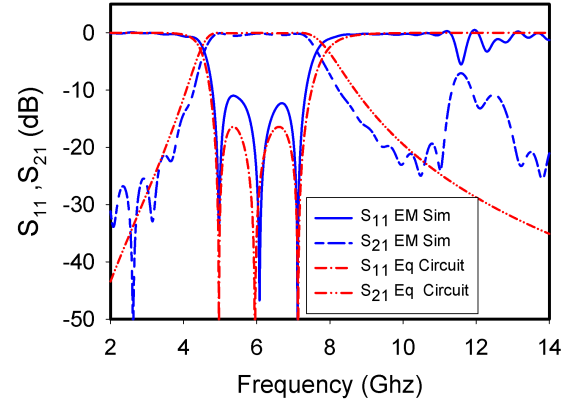

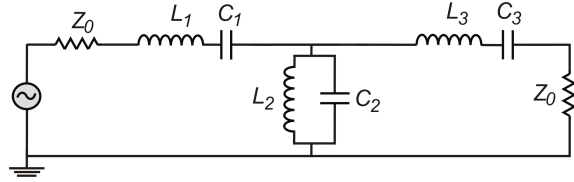Figure 2: Electrical response of the conventionnel UWB parallel coupled bandpass filter

Figure 3: Equivalent circuit model of the conventionnel UWB parallel coupled bandpass filter

2.2. Spurious Suppression using Slot/CSRR resonators

In order to enhance the filter response presented in the previous section by eliminating the second harmonics response, two different techniques are introduced. The first technique, is presented in Fig.4 it consists of embedding open stubs in the transmission feed with the aim to obtain the rejection in the desired frequency band. The frequency rejected depends on the length of the stub [11]. As can be shown from Fig.4, the second technique its based on the insertion of $CSRRs$ parasitic elements in the ground to provide negative effective permittivity and to produce a sharp rejection [12]. These techniques are introduced separately to be compared to each other. It can be noticed that, the rejection enhancement is achieved in both cases. The resonance frequency for the $CSRRs$ can be calculated by the fellow equation:

$$\omega_0 = \sqrt{\frac{2}{\pi r_0 L_0 C}} \qquad (3)$$

Where r_0 is the average radius of the two annular slots, L_0 is the inductance per unit length between the annular slots and C is the total capacitance of the SRR.
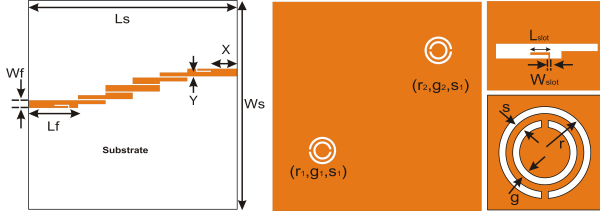
Figure 4: Configration of the filter with stubs and CSRRs ($r_1 = r_2$, $g_1 = g_2$, $s_1 = s_2$, $x = 4.2\ mm$, $y = 0.3\ mm$, $L_{slot} = 2.4\ mm$, $W_{slot} = 0.2\ mm$)

To validate the proposed designs, several filter prototypes are fabricated using Rogers $RO-3010$ substrate. The photograph of the manufactured prototypes is presented in Fig. 5.
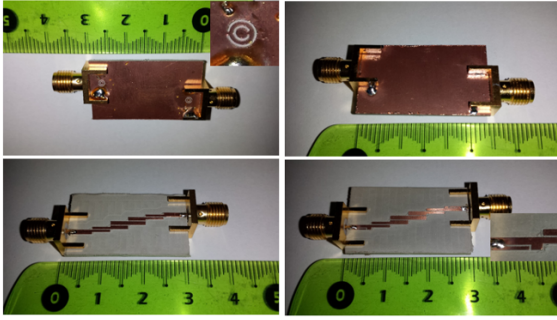

Figure 5: Photograph of the proposed filters : Top and butom layers with CSRRs (left), Top and butom layers with Slots(right)

The effect of the proposed resonators on the spurious suppression, compared to conventional filter design is presented in Fig. 6. It is clear that the open stub technique offers more than $20\ dB$ rejection level in the undesired passband of $(11 - 13)\ GHz$ with a passband insertion loss of $1\ dB$, while the CSRR method produces rejection level more than $20\ dB$ with low passband insertion loss of $0.8\ dB$. Note that the differential between simulation and measurement results is due to the fabrication tolerances, as well as the location of the $CSRR$, in the vicinity of the soldered microstrip launcher ports.
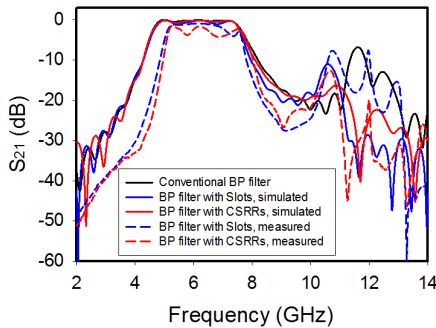

Figure 6: Simulated and measured insertion loss of the proposed C-band bandpass filter

To enhance the proposed filter presented previously, two-slots are etched on the feed line and $6 - CSRRs$ with three close resonance frequencies are collocated exactly bellow the transmission line. It should be noted that the whole structure design remain the same in terms of symmetry and size.

3. Bandpass filter with performed out-of-band rejection

3.1. Miniaturized Slot- and CSRR-loaded bandpass filter with enhanced selectivity

Based on the same filtering structure, we propose adjusting the $CSRR - grounded$ element to operate at $8.75\ GHz$ in order to improve the filter selectivity at this frequency. This configuration offers a miniaturization capability in terms of selectivity enhancement and spurious suppression. Fig. 7 illustrates the equivalent circuit model of the parallel-coupled microstrip band pass filter ($PCMBPF$) loaded with Slots and $CSRRs$ resonators. $\omega_i = \sqrt{\frac{1}{L_i(C_{ci}+C_i)}}$, (i=4,5,6,7,...) is the angular resonance frequency of transmission line loaded with single $CSRR$, [14,15]. From [16] and [17]:

$$C_c = \frac{\varepsilon}{d} \qquad (4)$$

$$C = 4\left(\frac{\varepsilon_0}{\mu_0}\right)Ls \qquad (5)$$

$$L = \frac{L_0}{4} = \frac{\pi r_0 L_{pul}}{2} \qquad (6)$$

Where C_c is the coupling capacitance between the line and the $CSRR/Slots$, C and L being the reactive elements, d is the space between the rings, r_0 is the average radius and L_{pul} is the per unit length capacitance between the rings.
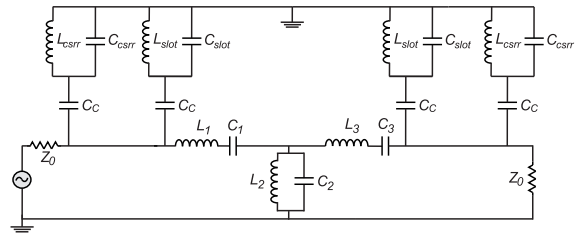

Figure 7: Equivalent circuit model with two $CSRR$ and slot-loaded in the ground and the transmission lines respectively

Fig.8. depicts the insertion loss of the model presented in Fig.4. As can be seen, good agreement between EM simulation and equivalent circuit results are achieved with high miniaturization capability in terms of selectivity and harmonics reduction for both resonance frequencies of 8.75 and $11.56\ GHz$ respectively. To widen the rejection between both S_{21} dips and eliminate the undesirable transmission at high frequencies, four $CSRR$ particles should be added with close resonance frequencies.
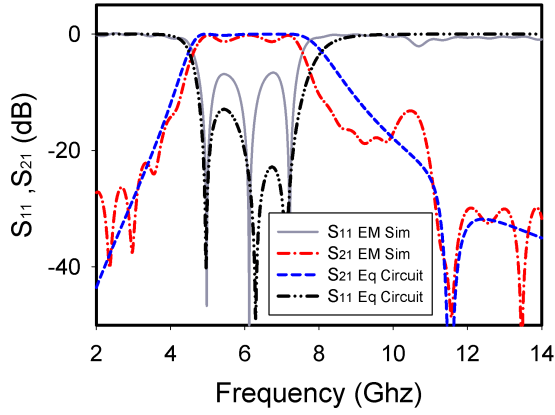
Figure 8: Insertion loss of the proposed C-band bandpass filters with Slot and $2 - CSRRs$

Figure 10: Frequency responses of the conventional and the proposed wideband bandpass filter for EM simulation and equivalent circuit model

Based on the CSRR resonance frequency expression given in [18] , the calculated components values of the equivalent circuit model depicted in Fig. 7, are: $C_{csrr} = 0.04$ pF, $C_c = 0.03$ pF, $C_{slot} = 0.15$ pF, $L_{csrr} = 4.9$ nH, $L_{slot} = 1.27$ nH.

$$\omega_{g,Slot} = \sqrt{\frac{1}{L_{s_l} + C_{s_l}}} \qquad (7)$$

Where ω_g is the angular resonance frequency of the transmission line loaded with single $Slot$.

3.2. Bandpass filter rejection performance

The optimized bandpass filter and loaded by slot resonators and $CSRR$ parasitic elements is presented in Fig. 9. These resonators are integrated with the aim to eliminate the unwanted transmission at high frequencies, in particular at 8.75 GHz, 9.34, 10.17 and 11.56 GHz.
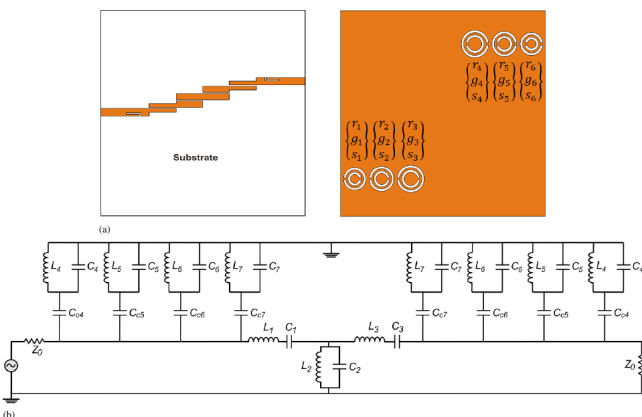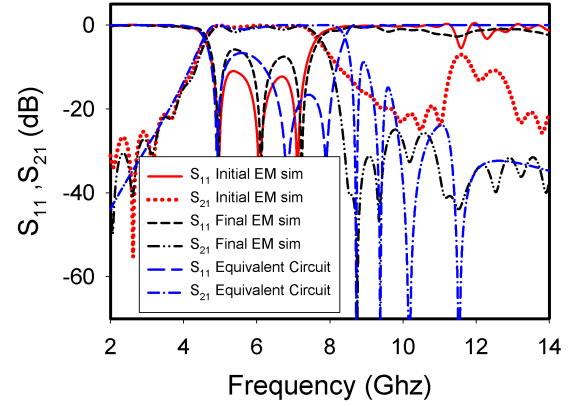

Figure 9: (a): Top and Bottom views of the optimized filter design, (b) : Correspondent equivalent circuit

The frequency response depicted in Fig.10 indicates that the filter covers the microwave C-band $(4.6 - 7.5$ $GHz)$ with a wide rejection performance within the whole frequency band from 8 to 14 GHz with $S_{21} \prec 20$ dB, compared to the filter of Fig.1. A high selectivity at 8.75 GHz is also obtained with harmonics suppression around 11.56 GHz. In addition frequency response of the calculated equivalent circuit matches very well with EM simulation, regarding both selected and rejected frequency bands.

The updated component values of equivalent circuit L and C for serial and parallel combination with three $CSRRs$ are: $C_6 = 0.1$ pF, $C_{c6} = 0.08$ pF, $C_7 = 0.035$ pF, $C_{c7} = 0.029$ pF, $L_6 = 1.36$ nH, $L_7 = 4.5$ nH.
Table 1. shows the parameter values of the three $CSRR$ elements with their corresponding radiation frequencies.

Table 1: Parameter and frequency values of $3 - CSRRs$

Coupled Rings	Frequency (GHz)	Space Gap(mm)	Diameter of Outer Ring(mm)	Diameter of Inner Ring(mm)
1	8.75	0.2	2.4	1.6
2	9.34	0.2	2.2	1.4
3	10.17	0.2	2	1.2

While Table 2. summarized L and C parameter values of the equivalent circuit related to the filter with three $CSRRs$ and $Slot$.

Table 2: Element parameters of the structures shown in Fig. 9

	1-CSRR	2-CSRR	3-CSRR	Slot
F_i(GHz)	8.75	9.34	10.17	11.56
L_i (nH)	4.9	4.5	1.36	1.27
C_i (pF)	0.04	0.035	0.1	0.15
$C_c i$ (pF)	0.03	0.029	0.08	0.03

To show the slots and parasitic elements $CSRR$ effects, a study of the current distribution of proposed design in Fig. 9 is taken into consideration.
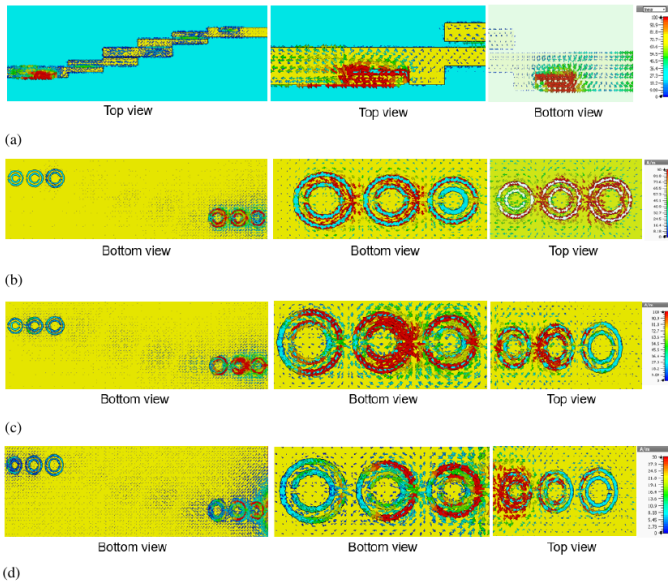

(a)

(b)

(c)

(d)

Figure 11: Current distribution of the proposed filters at : (a): 11.56 GHz, (b): 8.75 GHz , (c): 9.34 GHz and (d): 10.17 GHz

The behavior of the current is presented in Fig. 11 for the operating frequencies of $(8.75, 9.34, 10.17$ and 11.56 $GHz)$, of the rejected bands. It can be noticed that the quasi-static resonance frequencies of the $slot/CSRR$ elements are located just in these four frequencies, which proves that the transmission is then eliminated for those close frequencies resulting in a wide rejection performance.

In Table 3 we compare the performance of the proposed band pass filter with other filters published in literature. We can observe that the developed filter in this paper is more suitable and presents more advantages than other filters cited in the literature. It's clear that our filter is characterized by a small size, wide rejection bandwidth and high selectivity level. We note also that the technique used in this paper permits to eliminate the transmission at high frequency and suppress the spurious responses.

Table 3: Comparison of the proposed filter and similars published in literature

Ref.	Technique	Size (mm^2)	Wide Stopband	Frequency (GHz)	Rejection Level(dB)
[19]	U-slot DGS	508.2	Yes	2.8 10	35 28
[20]	T-shaped L- DMS	320	No	3.5 7.5	28.6 25.1
[21]	Stubs	419.9	Yes	5.2 10.85 12.42	22 ,7 25 56
[22]	Stubs	–	No	6.6	32
[23]	E-shaped	476	Yes	5.8 8.0	15
This Work	Slot CSRR	291.04	Yes	8,75 9,34 10,17 11,56	More than 70 for all frequencies

4. CONCLUSION

In this paper, a compact wideband parallel coupled line microstrip bandpass filter with improved out-of-band rejection performance is proposed for C-band satellite communications. By loading a slot and $CSRR$ parasitic elements with close resonances in both filter sides, we achieved a high miniaturization capability in term of out-of-band rejection without affecting the in-band filtering characteristics. This miniaturization concerns the spurious suppression, the selectivity improvement and the wide rejection performances. The simulation results, equivalent circuit modeling and experimental validation indicate that the proposed techniques are a good candidate to miniaturize parallel coupled line microstrip bandpass filters for the required applications. This design idea can be extended to load the $CSRR$ resonators in the ground plane bellow the coupled lines by considering the odd and even characteristics modes.

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