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Sharp Rejection and Wide Stopband Microstrip Lowpass Filters using Complementary Split Ring Resonators

I. F. da Costa
Federal Institute of Rio Grande do Norte (IFRN)- BR 406, Km 145, CEP: 59000-000, Ceará-Mirim/RN - Brazil, iradilson@gmail.com
A. L. P. S. Campos
Federal University of Rio Grande do Norte (UFRN) - Av. Sen. Salgado Filho, 3000, CEP: 59072-970, Natal/RN - Brazil, antonio.luiz@pq.cnpq.br
A. Gomes Neto
Federal Institute of Paraíba (IFPB) - Av. Primeiro de Maio, 720, CEP: 58015-430, João Pessoa/PB - Brazil, alfredogomesjpa@gmail.com

Abstract*— Chebyshev microstrip lowpass filters with improved performance, achieved by means of circular complementary split ring resonators (CSRR), are presented. CSRR particles exhibit frequency rejection bandwidths in the vicinity of their resonant frequencies that can be used to meliorate both selectivity and stopband in microstrip lowpass filters. Two configurations have been used: a stepped-impedance model and a configuration using open-circuited stubs. Microstrip filters having 5, 7 and 9 poles were designed and fabricated. Selectivity values up to 86 dB/GHz and suppression levels reaching 60 dB in the stopband were obtained. The filters have cutoff frequency around 2 GHz and rejection band up to 10 GHz. The insertion of the designed CSRR resonators in the ground plane of the filters removes all the transmission spurious observed in the analyzed frequency band. No considerable variation in the passband group delay is observed in the CSRR-based lowpass filters. A comparison is made among the filters designed in this and other referenced works, considering their number of poles and size. The measured results are in good agreement with the simulated ones. The presented filters can be candidates for applications using the VHF, UHF and L bands, being also very effective in the rejection of the S and C bands. Applications that demand the rejection of the first half of the X band can also use the filters detailed in this paper.

***Index Terms*—** Complementary split ring resonators, Microstrip filters, Microwave, Selectivity.

I. INTRODUCTION

Filters are important elements in many radiofrequency/microwave applications. Wireless Communications, for instance, continue to impose strict filter design requirements, demanding lightweight structures having high performance and reduced dimensions and cost [1]. An alternative to planar structures is fabricating them using microstrip technology. Improvements in performance for microstrip lowpass filters can be obtained using higher degree structures [2].

The use of complementary split ring resonators (CSRR), first presented by Falcone *et al*. [3], is an

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option to meliorate the selectivity of microstrip filters, as well as to eliminate undesired transmission spurious. As a consequence, this method can wide the stopband of microstrip filters [4], [5].

The CSRR resonator is a negative image of the split ring resonator (SRR), proposed by Pendry *et al*. [6]. SRRs and CSRRs have a dual relation. CSRRs behave as particles able to produce negative values of permittivity ε in the vicinity of their resonance [3].

This work presents Chebyshev microstrip lowpass filter designs which have their responses improved by means of CSRRs. The resonators were entailed on the ground plane of the filters. These particles were properly polarized by the microstrip sections of the filters. In order to verify these results, traditional microstrip lowpass filter having n = 5, 7 and 9 poles have been designed and fabricated. Stepped-impedance and open-circuited stubs lowpass filters were used as microstrip configurations.

II. Microstrip Lowpass Filters: Design and Analysis

In *Fig*. 1, the lowpass filter configurations used in this paper are shown. Two configurations have been chosen. The first one, known as stepped-impedance, uses high-impedance microstrip lines to approximate the inductors (L), whereas the capacitors (C) are built using low-impedance microstrip lines. The second configuration uses open-circuited stubs to fabricate the capacitors, maintaining the high-impedance lines to approximate the inductors [1], [2].

The formulations in [1] have been used to design the dimensions of the microstrip sections for each filter. The specifications for the structures are: cutoff frequency (f_c = 2 GHz), filter order n (n = 5, 7 and 9), frequency response (*Chebyshev*, with passband ripple = 0.01 dB), and source/load impedance Z_0 (= 50 Ω).

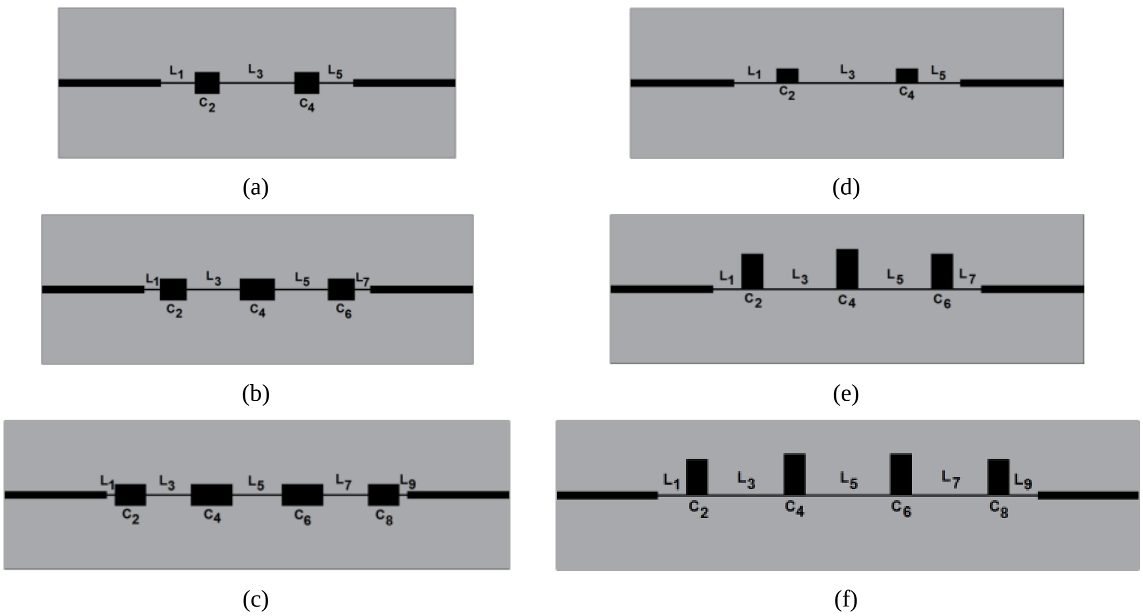

Fig. 1. Microstrip lowpass filters. Stepped-impedance configuration: (a) *F1*, order n = 5; (b) *F3*, order n = 7 and (c) *F5*, order n = 9. Configuration using open-circuited stubs: (d) *F2*, order n = 5; (e) *F4*, order n = 7 and (f) *F6*, order n = 9.

Filters *F1*, *F3* and *F5* (see *Fig*. 1) are the stepped-impedance microstrip filters. The remaining (*F2*,

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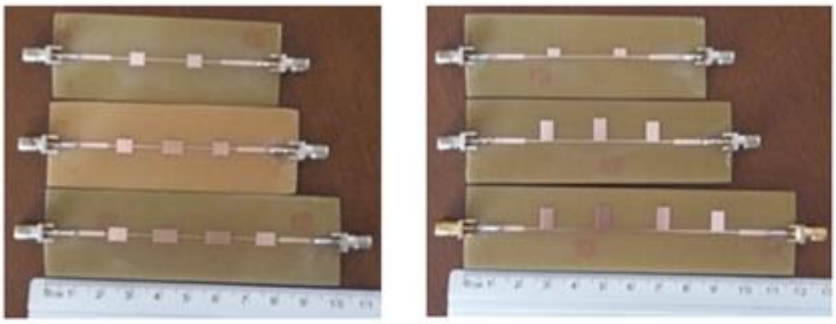
F4 and *F6*) are the ones using open-circuited stubs. The low-impedance and high-impedance lines have, respectively, characteristic impedances of 24 Ω and 100 Ω. Access lines ($\lambda_g/4$ long) of 50 Ω have been used [1]. The filters have been designed and fabricated on a FR-4 (ε_r = 4.4; thickness = 0.8 mm) laminate. A standard photo etching technique was used to fabricate the structures. Table I comprises the width (*W*) and length (*l*) of the microstrip sections for each filter, shown in *Fig.* 1. The fabricated filters are shown in *Fig.* 2.

TABLE I. DIMENSIONS (IN MM) OF THE MICROSTRIP SECTIONS OF THE FILTERS

Filter	Dim.	L_1	C_2	L_3	C_4	L_5	C_6	L_7	C_8	L_9
***F1* (5-pole)**	Width (*W*)	0.35	4.41	0.35	4.41	0.35				
Fig. 1(a)	Length (*l*)	6.79	5.00	15.02	5.00	6.79	-	-	-	-
***F2* (5-pole)**	Width (*W*)	0.35	4.41	0.35	4.41	0.35				
Fig. 1(d)	Length (*l*)	8.36	3.11	19.33	3.11	8.36	-	-	-	-
***F3* (7-pole)**	Width (*W*)	0.35	4.41	0.35	4.41	0.35	4.41	0.35		
Fig. 1(b)	Length (*l*)	3.09	5.39	10.60	7.03	10.60	5.39	3.09	-	-
***F4* (7-pole)**	Width (*W*)	0.35	4.41	0.35	4.41	0.35	4.41	0.35		
Fig. 1(e)	Length (*l*)	5.61	7.36	14.56	8.30	14.56	7.36	5.61	-	-
***F5* (9-pole)**	Width (W)	0.35	4.41	0.35	4.41	0.35	4.41	0.35	4.41	0.35
Fig. 1(c)	Length (*l*)	1.59	6.32	8.99	8.38	9.89	8.38	8.99	6.32	1.59
***F6* (9-pole)**	Width (*W*)	0.35	4.41	0.35	4.41	0.35	4.41	0.35	4.41	0.35
Fig. 1(f)	Length (*l*)	5.74	7.50	15.40	8.59	17.28	8.59	15.40	7.50	5.74



(a) (b)

Fig. 2. Photographs of the fabricated microstrip lowpass filters: (a) Stepped-impedance configuration; (b) configuration using open-circuited stubs to realize the capacitors.

The filters were measured using an Agilent EN5071C vector network analyzer. Simulated and measured results of the S_{11} and S_{21} parameters of the lowpass filters are shown in *Fig.* 3. The simulated results were performed using an *Ansoft HFSS v13* computational tool. As it can be seen in *Fig.* 3, the measured and simulated results are overall in good agreement. The filters present values of insertion loss in the passband around 1 dB. A reason for this can be attributed to the lossy FR-4 substrate used, along with the losses due to welding and the insertion of connectors and cables in the measurement setup.

According to *Fig.* 3, the roll-off (rate of transition between the cutoff and rejection frequencies) of

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these conventional filters has been improved in consonance with the increase in the degree *n* of the filters. Nevertheless, they have a slow transition between the 3 dB cutoff frequency, f_c, and the 20 dB stopband frequency, f_s. The width of this transition is frequently referred as transition bandwidth (BW_t). Besides this limitation, it can be seen that the filters have undesired transmission spurious within the frequency band under consideration (up to 10 GHz). The next section presents the CSRR insertion procedure in order to improve the performance of these filters.

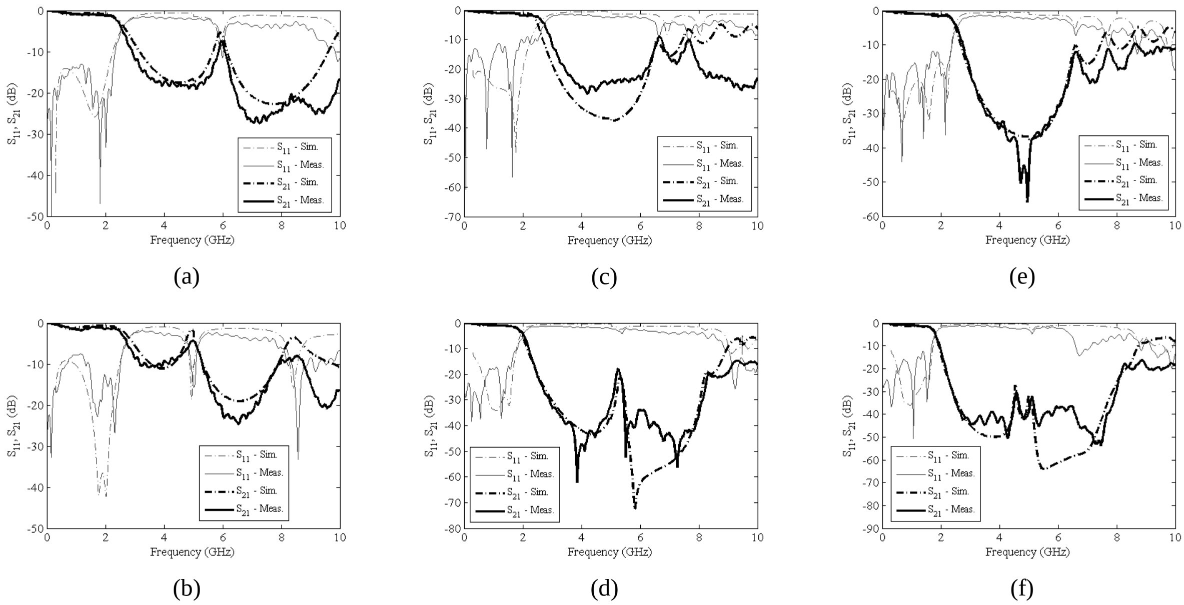

Fig. 3. Simulated and measured S parameters of the traditional filters: *F1* (a), *F2* (b), *F3* (c), *F4* (d), *F5* (e) and *F6* (f). Fig. 1 and Table I detail, respectively, the layout and the dimensions of each filter.

III. CSRR-BASED MICROSTRIP LOWPASS FILTERS

The lowpass filters described in the previous section had their ground planes modified by the insertion of circular CSRR resonators. The configuration of a circular CSRR and its relevant dimensions are shown in *Fig.* 4. The modified lowpass filters are depicted in *Fig.* 5.

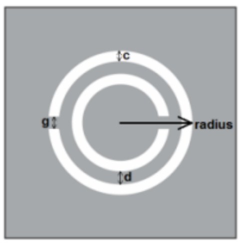

Fig. 4. Configuration and relevant dimensions of a circular CSRR. The metal parts are depicted in grey.

The relevant dimensions of the CSRRs used in this paper are organized in Table II, as well as their resonant frequencies. These values have been calculated using the model in [7]. The fabricated modified ground planes are shown in *Fig.* 6. The CSRR resonators on the ground planes are aligned with the center of their respective microstrip lines, except for those in the extremities, which are 7 mm away from the input and output of the structures.

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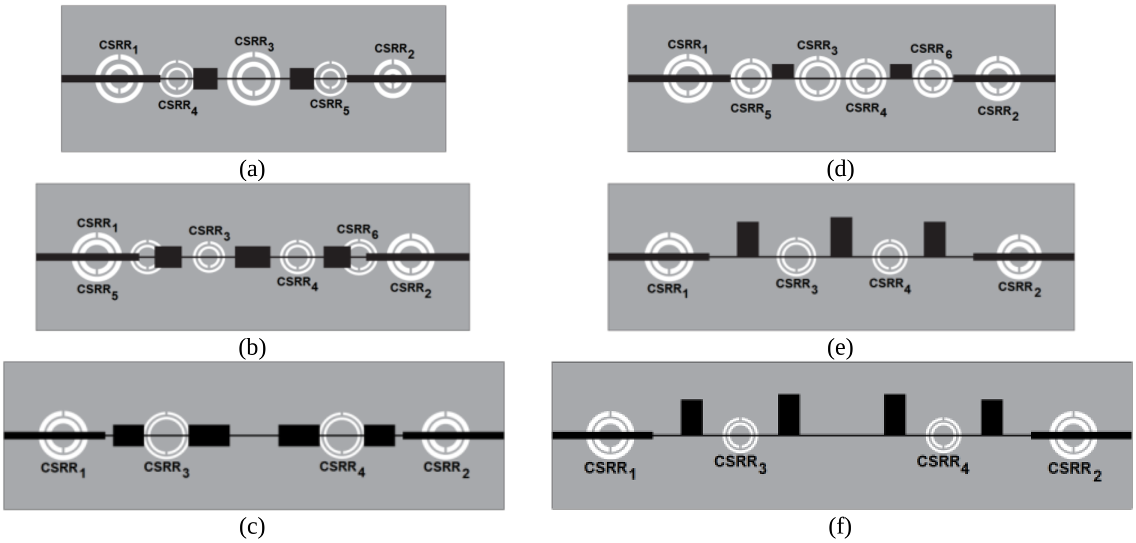
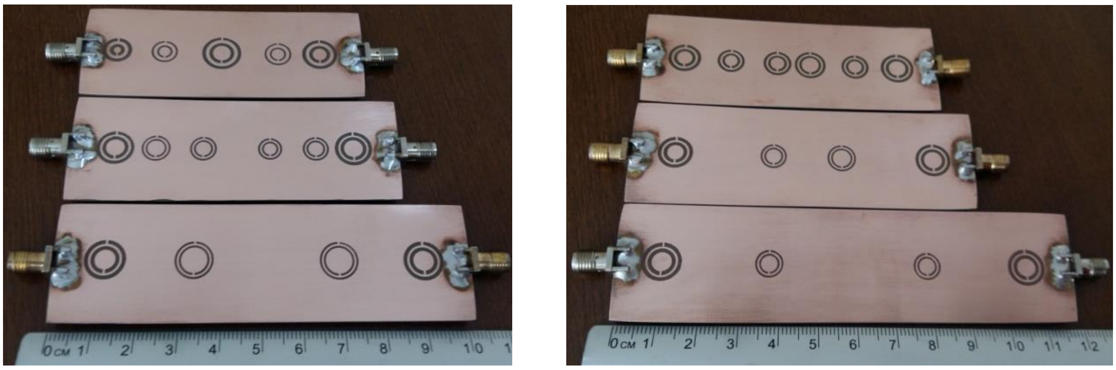


Fig. 5. CSRR-based microstrip lowpass filters. The microstrip sections of the filters are depicted in black and the metallization of the ground plane is depicted in grey.

TABLE II. CSRR DIMENSIONS FOR THE FILTERS DEPICTED IN *FIG*. 5.

Filter	**CSRR**	**radius (mm)**	***c*** **(mm)**	***d*** **(mm)**	f_0 **(GHz)**
F7	1/2/3	5.0/4.0/5.5	1.0	1.0	3.2/4.5/2.8
(*Fig.* 5a)	4/5	3.8/3.6	0.5	1.0	4.0/4.4
F8	1/2	5.0/4.6	1.0	0.5	2.7/3.1
(*Fig.* 5d)	3/4/5/6	4.6/4.1/4.1/3.9	0.8	0.5	2.9/3.4/3.4/3.6
F9	1/2	5.0/4.8	1.0	0.5	2.7/2.9
(*Fig.* 5b)	3/4/5/6	3.2/3.5/3.5/3.7	0.5	0.5	4.3/3.8/3.8/3.5
F10	1/2	5.0/4.6	1.0	0.5	2.7/3.0
(*Fig.* 5e)	3/4	4.0/3.6	0.5	0.5	3.2/3.7
F11	1/2	5.0/4.9	1.0	0.5	2.7/2.8
(*Fig.* 5c)	3/4	4.8/4.7	0.5	0.5	2.5/2.6
F12	1/2	4.9/4.9	1.0	0.5	2.8/2.8
(*Fig.* 5f)	3/4	3.6/3.6	0.5	0.5	3.7/3.7



(a) (b)

Fig. 6. Photographs of the fabricated CSRR-based microstrip lowpass filter ground planes: (a) stepped-impedance configuration; (b) configuration using open-circuited stubs.

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A flowchart depicting the design procedure used to obtain the CSRR-based microstrip lowpass filters is shown in *Fig*. 7. As it can be seen, after the simulation of the initial lowpass filter, the process of insertion the CSRR resonators repeats until the intended performance parameters are reached. The performance parameters mentioned in *Fig*. 7 will be clarified in the next section.

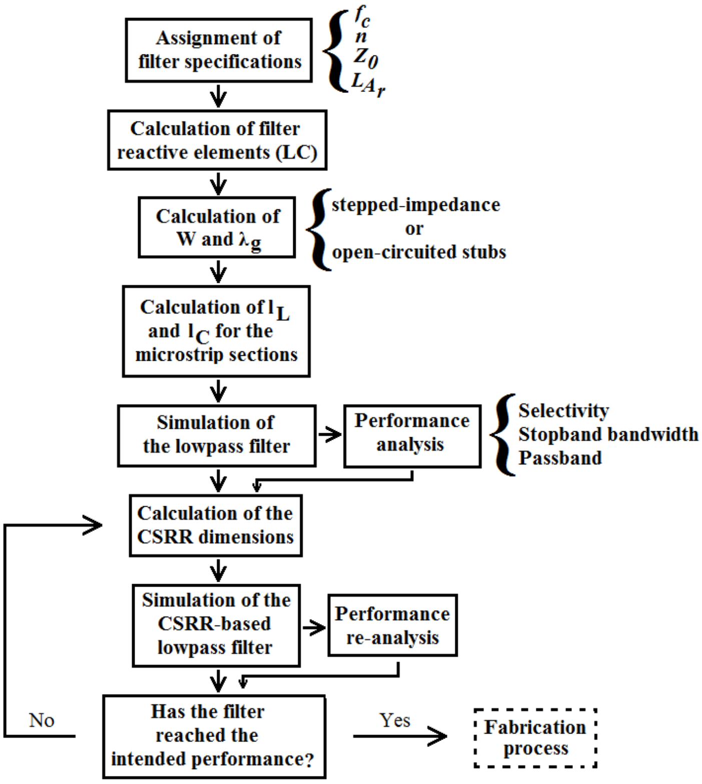

Fig. 7. Design procedure used to obtain the CSRR-based microstrip lowpass filters.

IV. RESULTS

Simulated and measured S_{11} and S_{21} results (in dB) of the designed CSRR-based lowpass filters are shown in *Fig*. 8, *Fig*. 9 and *Fig*. 10. A good agreement is observed between the simulated and experimental responses. The results were analyzed considering the experimental values. A comparison between the CSRR-based 5-pole microstrip lowpass filter results is shown in *Fig*. 8.

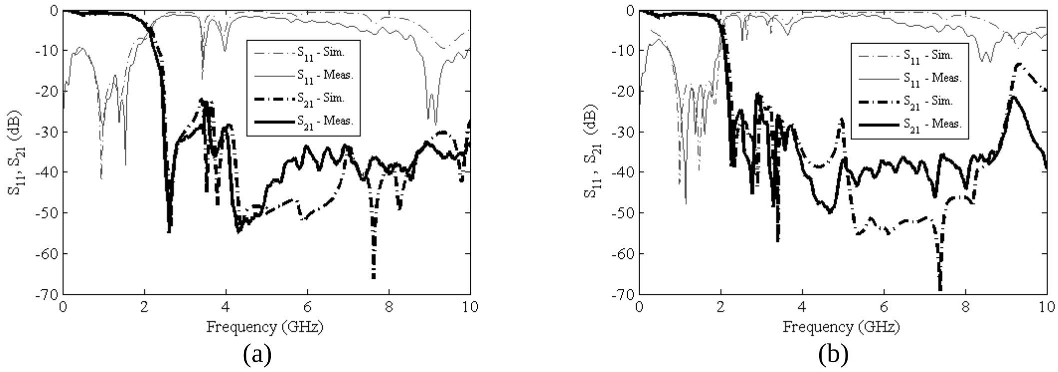

Fig. 8. CSRR-based 5-pole microstrip filter *S* parameters, simulated and measured: (a) *F7*: stepped-impedance configuration and (b) *F8*: open-circuited stubs configuration.

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According to *Fig.* 8(a), filter *F7* has a 3 dB cutoff frequency of 1.95 GHz. The attenuation of this filter drops to 20 dB at 2.44 GHz. The 3dB cutoff frequency of filter *F8*, whose response is shown in *Fig.* 8(b), is 1.97 GHz. The rejection of this filter occurs at 2.17 GHz. Consequently, *F8* is a more selective filter than *F7*. Both filters have values of insertion loss in the passband around 1.1 dB. Table III contains the values of the 3 dB cutoff frequency (f_c), stopband frequency (f_s) and selectivity (ξ) of the filters. The calculation of ξ follows the expression (1), defined in [8]:

$$\xi = \frac{\alpha_2 - \alpha_1}{f_s - f_c} \quad (1)$$

where α_2 and α_1 represent, respectively, the 20 dB and 3 dB attenuation points.

TABLE III. CUTOFF FREQUENCY, STOPBAND FREQUENCY AND SELECTIVITY OF THE LOWPASS FILTERS.

Filter	f_c (GHz)		f_s (GHz)		ξ (dB/GHz)	
	Sim.	Meas.	Sim.	Meas.	Sim.	Meas.
F1	2.54	2.44	-	-	-	-
F2	2.74	2.57	-	-	-	-
F3	2.39	2.58	3.05	3.42	25.84	20.19
F4	1.88	1.88	2.49	2.49	27.54	27.54
F5	2.42	2.42	3.03	3.03	27.69	27.69
F6	1.73	1.73	2.10	2.17	45.90	38.25
F7	2.02	1.95	2.49	2.44	36.24	34.43
F8	2.02	1.97	2.25	2.17	76.51	86.07
F9	2.05	1.85	2.32	2.12	61.82	61.82
F10	1.63	1.63	2.12	2.05	34.43	40.49
F11	2.00	1.92	2.27	2.15	62.59	76.54
F12	1.68	1.58	2.00	1.87	52.96	57.37

The responses for the 7-pole CSRR-based filters are shown in *Fig.* 9. Filters *F9* and *F10* have cutoff frequencies of, respectively, 1.85 and 1.63 GHz. The rejection for these filters starts at 2.12 and 2.05 GHz, respectively. The values of insertion loss in the passband for *F9* and *F10* are around 1.2 dB. The selectivity values of these filters are presented in Table III.

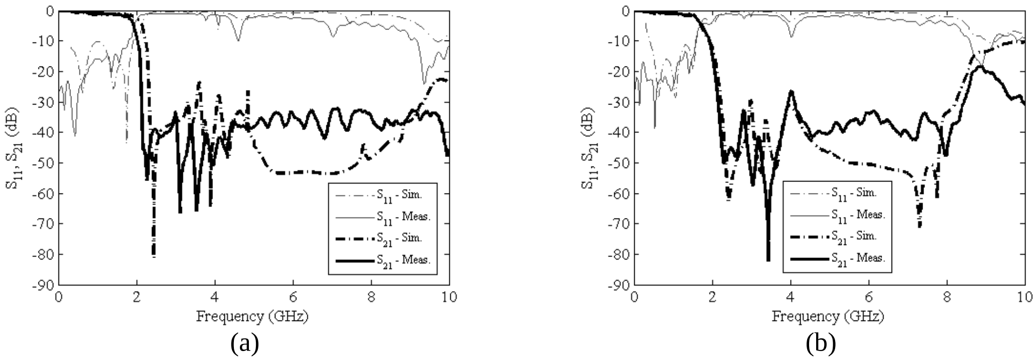

Fig. 9. CSRR-based 7-pole microstrip filter *S* Parameters, simulated and measured: (a) *F9*: stepped-impedance configuration and (b) *F10*: open-circuited stubs configuration.

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The responses for the 9-pole CSRR-based filters are depicted in *Fig.* 10. *F11* and *F12* have 3 dB cutoff frequencies equal to 1.92 and 1.58 GHz, respectively. The corresponding frequency values for the 20 dB attenuation points are 2.15 and 1.87 GHz. It is worth noticing that filter *F11* presents an excellent rejection band between 2.42 and 5.23 GHz, with a very high rejection level (> 50 dB). It can be observed that the insertion loss in *F11* and *F12* is around 1.3 dB, considering the passband. Different from the previous filters, these 9-pole CSRR-based filters present higher levels of ripple in the passband, which can be a drawback.

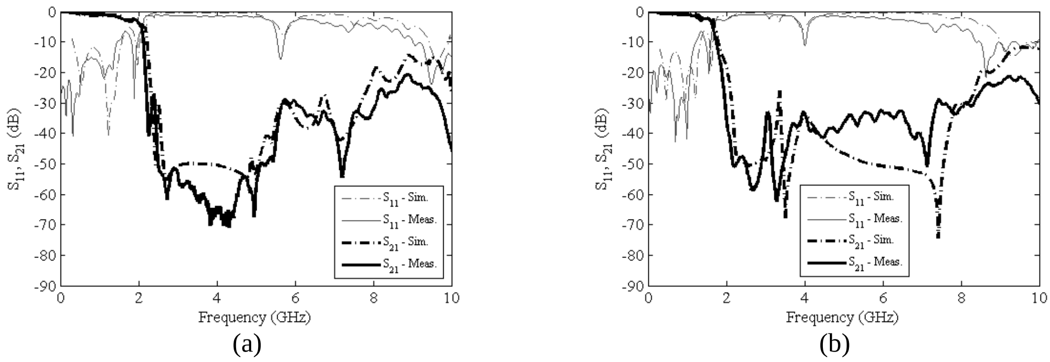

Fig. 10. CSRR-based 9-pole microstrip filter S parameters, simulated and measured: (a) *F11*: stepped-impedance configuration and (b) *F12*: open-circuited stubs configuration.

Comparing the results of the CSRR-based microstrip lowpass filters with the traditional ones (see Table III and *Figs*. 8-10), it can be affirmed that the CSRR-based filters having 5 poles presents a performance comparable (*F7*) or much more superior (*F8*) to the best result obtained by the traditional filters (*F5* and *F6*), which are 9-pole structures. This leads to a filter with an area reduction of approximately 27%. The transmission spurious bands of the conventional microstrip lowpass filters (see *Fig*. 3) were all removed due to the insertion of the designed CSRR resonators.

Table IV presents a performance comparison among some of the designed lowpass filters and other referenced works. As it can be noticed, *F8* has an excellent transition bandwidth of 200 MHz, and a stopband bandwidth of $4f_c$. This result is quite satisfactory, considering that the procedure to design this filter is considerably easier than the approaches described, for instance, to design the filters presented in [5] and [9]-[13]. It is also shown a comparison among the sizes of the designed filters and some references. The parameter λ_g, in Table IV, is the guided wavelength of a 50 Ω microstrip line at the cutoff frequency of the filter, as stated in [5].

Finally, simulated and measured group delay results are shown in *Fig*. 11. Considering the filters *F11* and *F8*, which have the best performances (see Table IV), it can be seen that the experimental group delay in the passband (< 2GHz) for both filters has no considerable variation, maintaining its values up to 5 ns. The differences observed between the simulated and measured group delay curves can be interpreted, firstly, as an outcome of the welding losses, present only in the fabricated filters. Secondly, other losses, as those present in the use of connectors and cables, are also part only of the experimental results. Some disturbances in the group delay curves are seen around the resonance frequencies of the added CSRR resonators.

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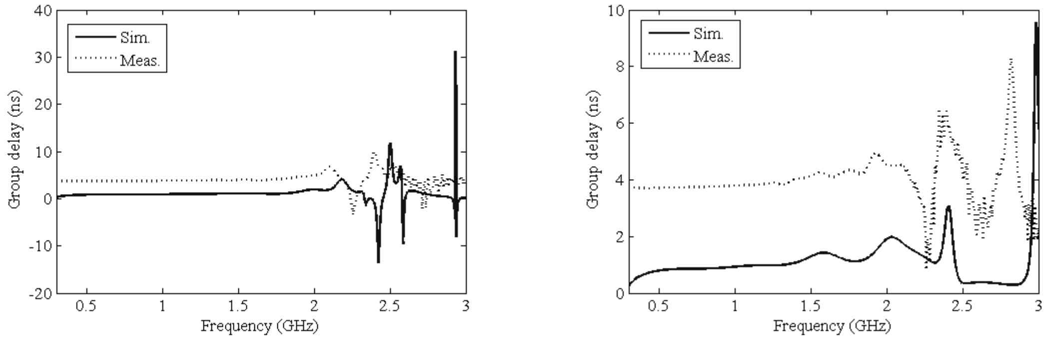

(a) (b)

Fig. 11. Simulated and measured group delay: (a) filter *F11* and (b) filter *F8*.

TABLE IV. PERFORMANCE COMPARISON AMONG SOME OF THE PROPOSED FILTERS AND REFERENCED WORKS.

Reference	**Cutoff Frequency** (GHz)	**Transition Bandwidth** (GHz)	**Stopband Bandwidth**	**Size** (width x length, in λ_g)
[5]	3.94	0.53	0.3f$_c$	---
[9]	2.95	1.05	5.4f$_c$	---
[10]	1.09	0.34	10f$_c$	0.16 x 0.08
[11]	1.08	0.37	6f$_c$	0.22 x 0.18
[12]	2.49	0.31	1.7f$_c$	---
[13]	2.07	0.47	8.6f$_c$	---
This work (F12)	1.58	0.30	5.1f$_c$	0.29 x 1.14
This work (F9)	1.85	0.27	4.2f$_c$	0.34 x 0.97
This work (F11)	1.92	0.22	4.1f$_c$	0.35 x 1.19
This work (F8)	1.97	0.20	4f$_c$	0.36 x 1.03

V. CONCLUSION

Chebyshev microstrip lowpass filters with improved selectivity and stopband are presented in this work. The advantage of this approach is the possibility of maintaining the design procedure of traditional microstrip lowpass filters, presented in many references, thus keeping the dimensions of the structures. This work compares filters having 5, 7 and 9 poles, presenting them with two configurations: stepped-impedance and open-circuited stubs. The insertion of CSRR resonators on the ground plane of the microstrip lowpass filters leads to selectivity values up to 86 dB/GHz, as well as the removal of undesired transmission spurious observed in the analyzed frequency band. It is important to highlight that rejection levels exceeding 60 dB in the stopband were obtained, considering frequencies up to 10 GHz. A size reduction can be achieved using low order microstrip lowpass filters with CSRRs entailed on the ground plane.

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The group delay observed in the filters keeps almost unaltered in the passband. Losses due to welding and use of connectors and cables are present in the experimental results. The filters in this paper can be used in applications using the VHF, UHF and L bands. For instance, applications as satellite navigation and telecommunications use carriers having frequencies within the L band (1-2 GHz). Also, if the rejection of the S and C bands is required, the filters in this paper are good alternatives. Work is ongoing on the miniaturization of the structures presented here.

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