Defected Ground Structures (DGS) and Uniplanar Compact-Photonic Band Gap (UC-PBG) Structures for Reducing the Size and Enhancing the Out-of-Band Rejection of Microstrip Bandpass Ring Resonator Filters

HEBA B. EL-SHAARAWY [1, 2], FABIO COCCETTI [1], ROBERT PLANA [1, 2], MOSTAFA EL-SAID [3] and ESSAM A. HASHISH [3]

[1] Laboratoire d'Analyse et d'Architectures des Systèmes at the Centre National de la Recherche Scientifique (LAAS-CNRS),
7 Avenue du Colonel Roche, 31077,
TOULOUSE, FRANCE.

[2] University of Toulouse,
TOULOUSE, FRANCE.

[3] Electronics and Communications Dept., Faculty of Engineering,
Cairo University,
CAIRO, EGYPT.

heba@laas.fr http://www.laas.fr/laas/

Abstract: - This paper addresses a modified bandpass ring resonator filter providing compact size, low insertion-loss, wide bandwidth, sharp rejection and suppressed higher order modes. Typically, ring resonator filters suffer from large occupation area and limited out of band rejection. These limitations are tackled in this work by means of a threefold approach. On the one hand, the use of internal folded stubs allows the exploitation of the internal ring area yielding more than 70% of overall size reduction with respect to conventional orthogonal straight stubs solution. On the other hand, the introduction of Defected Ground Structures (DGS) and Uniplanar Compact-Photonic Bandgap (UC-PBG) structures, formed by etching patterns in the ground plane of the filter, enhances by great extends the rejection of higher order modes providing a stopband that reaches 4.7 GHz beside offering a further advantage in terms of size reduction. The two approaches are first separately validated and then simultaneously combined to provide an optimized filter design. Finally, a solution employing via holes to replace the tuning stubs is explored in order to extend the lower stopband. EM simulation, equivalent circuit model, as well as measurement results validate the followed design approach and are in excellent agreement within each other.

Key-Words: - photonic bandgap, ring resonator, bandpass filter, fractional bandwidth, stopband, insertion loss.

1 Introduction

The increasing development of wireless applications introduces new requirements for transceiver architectures that feature excellent microwave performances (linearity, spurious rejection, noise figure and bandwidth) and enhanced integration density that is achieved through miniaturization of modules as well as the introduction of multi standard functionalities. All these requirements translate to the need for miniature filters with low passband insertion loss and high stopband rejection.

It has been demonstrated that ring resonator based filters feature attractive behavior [1], [2] but they suffer from two drawbacks that limit their implementation in real applications. The first one is their large size due to the two tuning stubs, while the second deals with the existence of higher order modes which limit the out-of-band rejection. Both issues degrade the whole system performance and need to be assessed to find solutions to overcome these drawbacks.

This paper aims to propose some solutions to reduce the size and increase the rejection of the upper stopband of the ring resonator filter, while keeping its overall performances with respect to its wide bandwidth, sharp rejection and low insertion-loss. In order to do so, two different design approaches are considered. The first is at the filter layout level, through a space saving redesign of the tuning stubs [3], while the second is at the wave propagation level, through the exploitation of Defected Ground Structures (DGS) and Uniplanar Compact-Photonic Bandgap (UC-PBG) Structures properties [4].

The DGS, realized by etching patterns in the ground plane, enables higher order modes suppression through the introduction of a wide stopband in the frequency response of the filter, and on the other hand introduces slow wave effect which translates into a reduction of the electrical length and hence the overall filter dimensions [5-7].

To our knowledge, the work reported to date has used the DGSs to suppress only the second order harmonic of multistage coupled ring resonator filter by etching the ground plane of the output feeding line [4]. The use of this technique yields general detrimental effects as; on the one hand it increases the filter size and the filter insertion loss while on the other it decreases the filter bandwidth due to the coupling of different stages. In the work presented here, by placing the DGSs directly under the ring resonator, the second and third harmonics are suppressed with a reduction in the filter size reaching 25.75 % of the conventional ring resonator filter.

We also investigated the use of UC-PBG structures [8] with the ring resonator filter. Despite that it is difficult to use PBG structures for the design of the microwave or millimeter-wave components due to the difficulty of their modeling and their too many design parameters that affect the bandgap property, such as the number of lattice, lattice shapes, lattice spacing, and relative volume fraction, they give wider upper stopbands suppressing the second, third and forth harmonics with a greater size reduction reaching 45.5 %.

Finally, for further enhancement of the filter response, the introduction of a transmission zero at zero frequency is eventually considered. This is done by replacing the two tuning stubs by via holes [9].

All filters are fabricated on Teflon substrate (CER 10-0250 CH/CH) of dielectric constant ε_r=9.5, dielectric thickness h=0.635mm and loss tangent 0.0035. Measurements show very good agreement with simulation results.

2 Microstrip Ring Resonator Bandpass Filter

This section presents briefly the ring resonator bandpass filter proposed by [1].The ring resonator bandpass filter consists of a ring resonator directly connected to a pair of two orthogonal tuning stubs and two orthogonal feeding lines as shown in Fig. 1. The circumference of the ring resonator ℓ_r is chosen according to the following expression:

$$\ell_r = n\lambda_g \tag{1}$$

where n is the mode number and λ_g is the guided wavelength. Each tuning stub is equal to one quarter of a wavelength designed at the center frequency and placed at the center of each side of the ring resonator. And to increase the bandwidth of the stopbands of the filter, a square stub is added at the corner of the filter [10].

A filter using the previously discussed technique is designed at 1.5 GHz. The filter behavior is investigated using the transmission line model proposed by [1], the EM simulation (Zeland IE3D) and measurement results, Fig. 2.

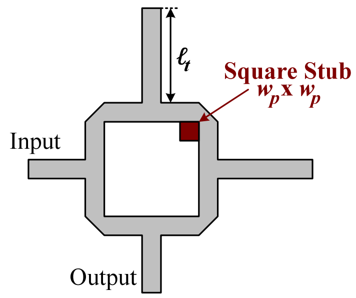


Fig. 1. Layout of the conventional ring resonator filter with two straight tuning stubs [1].

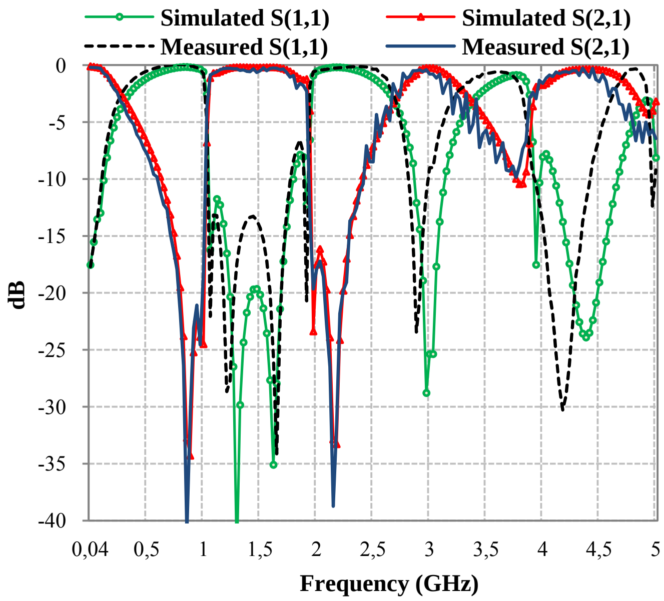


Fig. 2. Simulated and measured responses of the conventional ring resonator filter.

It was found that the filter suffers from adjacent passbands due to the higher order modes at 3 GHz and 4.45 GHz, representing the second and third harmonics of the resonant frequency, consequently the filter 10-dB upper stopband is only 0.4612 GHz. The filter also suffers from its large occupation area, due to its two tuning stubs that occupy about 72 % of the area of the filter. The following section addresses the large occupation area of the two stubs by two different techniques.

3 Miniaturization by Using Folded Stubs

In order to reduce the area occupied by the filter, a more compact design of the stubs is introduced. This has been previously considered by [2]. The disadvantage of the stub structure in [2] is its complex orientation and design parameters.

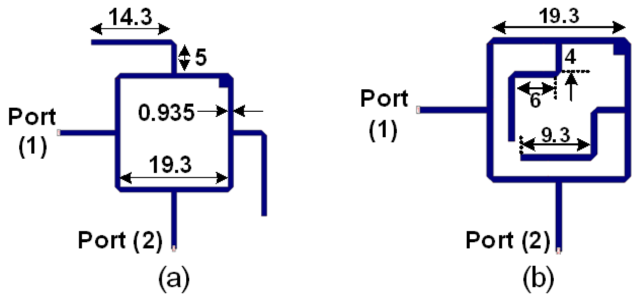


Fig. 3. Layout of the ring resonator filters with (a) external bent stubs; (b) internal folded stubs. All dimensions are in mm.

This is done here by bending the stub along the filter ring profile in a first design iteration (Fig. 3 (a)), and then reversing the stubs T-junction toward the interior of the ring in a second iteration (Fig. 3 (b)). In the latter, the stubs need to be bent twice in order to fit in the ring internal area.

In both cases, parameters such as the losses introduced by the bend, and the coupling that might take place between the ring resonator and the bent stub need to be considered.

For a 90° microstrip bend, based on the study made by [11], this bend might cause up to 2.5 dB insertion loss in the form of radiation and surface-wave losses at this frequency range. On the other hand, a mitered bend provides about 0.1 to 0.3 dB losses. Therefore, to reduce the radiation and surface-wave losses, we use mitered bends in the stub.

The second issue that should be considered is the coupling between the stub and the ring. The design presented here is based on the quasi-TEM mode properties of the coupled microstrip lines provided by [12]. Although these equations produce an error that might reach 8%, they are accurate enough to define a distance such that the coupling is below -15 dB.

The two solutions of Fig. 3 are designed on the same substrate mentioned above. The simulated and measured responses are presented in Fig. 4 (a) and (b). The filters center frequency is at 1.47 GHz and the rest of their specifications are shown in Table 1.

From the responses seen in Fig. 4, we can see a great reduction in the size of the filter reaching up to 72.6% for internal folded stubs, keeping very good overall filter performance. However, the issue of higher harmonics is not solved yet, which will be the subject of the following section.

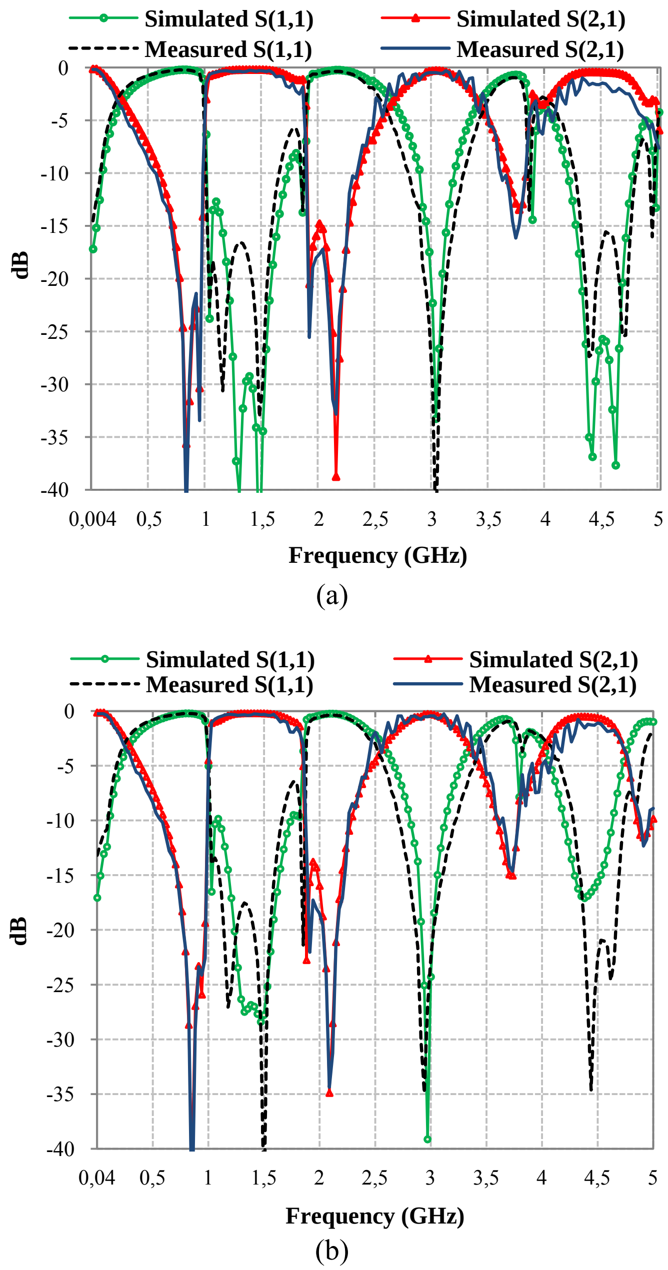


Fig. 4. Simulated and measured responses of the ring resonator filter (a) with external bent stubs and (b) with internal folded stubs.

4 Microstrip Ring Resonator Bandpass Filter with Defected Ground Structures

The use of DGSs is hereby exploited to improve the harmonic rejection of the filter. DGSs produce variations in the refractive index of the medium to introduce a certain stopband in its frequency response. Following the original interpretation and analysis made by

Table 1
Characteristics of the Filters Presented in Section 3

Filter	Insertion Loss (dB)	Return Loss (dB)	Fractional Bandwidth	Upper Stopband (GHz)	Size (mm)	Size Reduction
Conventional Ring Resonator Filter	-1.2	-8	60.6 %	0.46	40.5 x 40.5	----------
Ring Resonator Filter with External Bent Stubs	-1.12	-8.2	57.8 %	0.42	31.3 x 31.3	40.2 %
Ring Resonator Filter with Internal Folded Stubs	-0.88	-9.6	55.8 %	0.43	21.1 x 21.1	72.6 %

Yoblonovitch [13] this stopband is produced by the coupling between the forward and backward propagating waves due to periodic variations in the refractive index of the medium. This variation in the refractive index can be implemented by etching specific patterns in the ground plane.

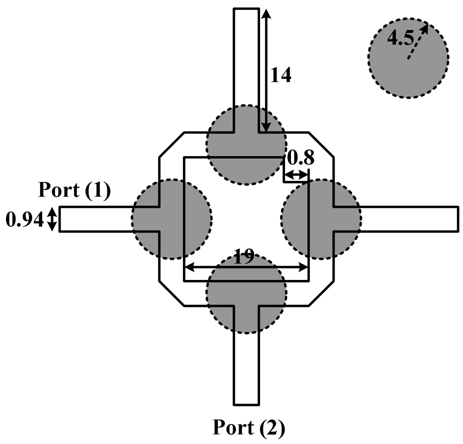


Fig. 5. Layout of the ring resonator filter with two straight stubs and circle DGSs etched in the ground plane. All dimensions are in mm.

The selected DGS is a one dimensional lattice with circles etched in the ground plane [14]. To investigate the behavior of these DGSs, simulations of a microstrip transmission line with a period between the etched circles corresponding to $\lambda_g/2$ at 3.5 GHz are performed. The simulations show a stopband starting from 2 to 4.5 GHz, which is wide enough to clear the higher order harmonics of the filter. Based on these analysis and observations, circles are etched in the ground plane of the filter. Fig. 5 shows the layout of the filter, while Fig. 6 shows the simulated and measured responses. The measured results show excellent agreement with the simulation results. All filter specifications are found in Table 2.

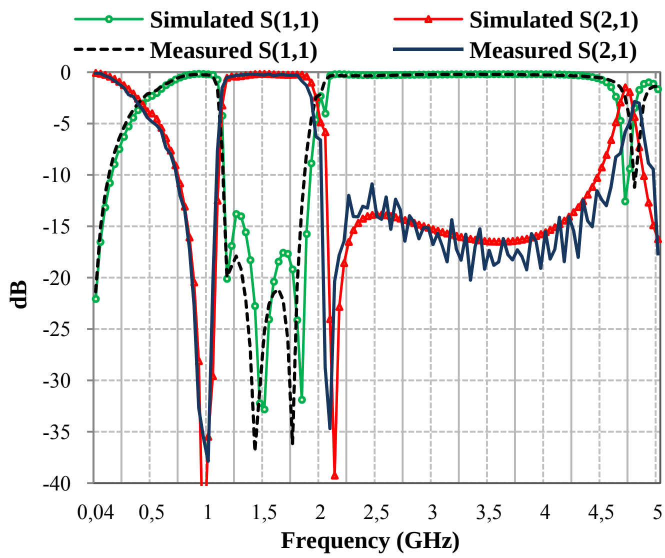


Fig. 6. Simulated and measured responses of the ring resonator filter with two unbent stubs and circle DGSs.

The etching of DGSs in the ground plane solves the two problems of the original filter simultaneously. The size of the filter is reduced by 25.75% due to the slow wave effect introduced and the stopband of the filter has increased from 0.45 GHz to 2.44 GHz suppressing the second and third harmonics introduced by the original filter design. In addition, the insertion and return loss values of the filter are enhanced due to the suppression of surface waves provided by the DGSs.

Etching periodic squares instead of etching periodic circles in the ground plane are also considered.

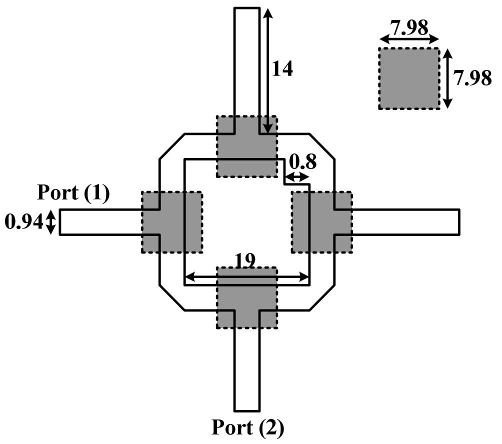


Fig. 7. Layout of the ring resonator filter with two straight stubs and square DGSs etched in the ground plane. All dimensions are in mm.

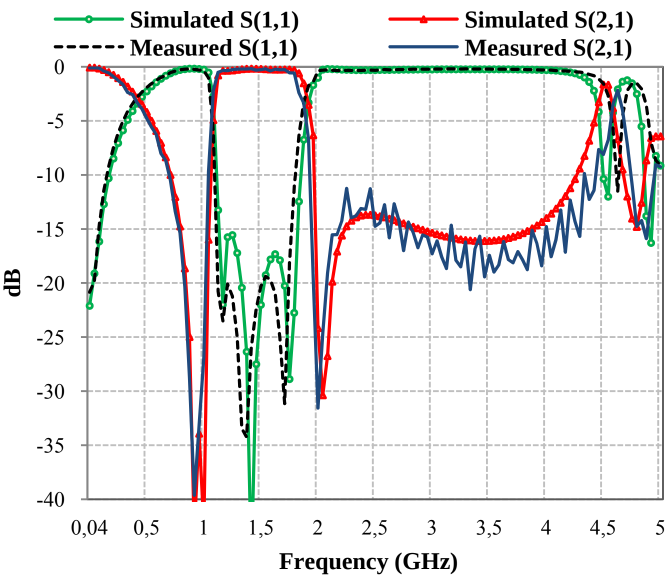


Fig. 8. Simulated and measured responses of the ring resonator filter with two straight stubs and square DGSs.

It is found that the response of the filter is the same for circles and squares under the condition that we keep the same etched area [15]. The layout of the ring resonator filter with etched squares in the ground plane is shown in Fig. 7 and the simulated and measured responses are shown in Fig. 8.

4.1 Ring resonator filter with internal bent stubs and DGSs

In this section, the two approaches described above are combined together to yield an optimized filter design endowed with maximum size reduction and enhanced selectivity.

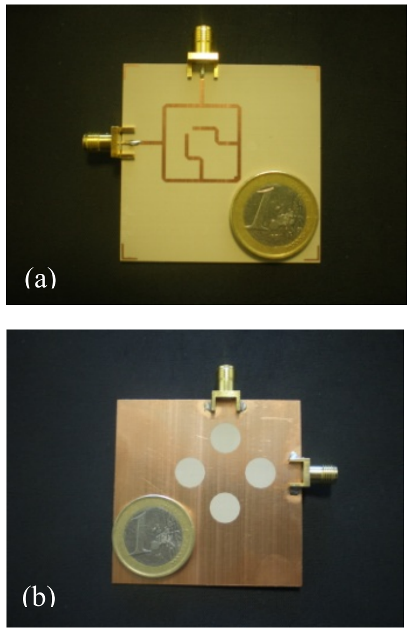


Fig. 9. Photograph of the fabricated ring resonator BPF with DGSs. (a) Top view, (b) bottom view.

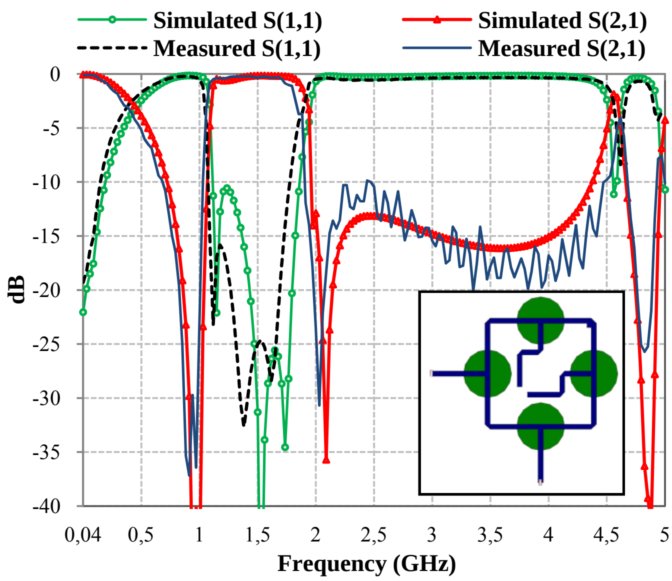


Fig. 10. Simulated and measured responses of the filter with internal folded stubs and DGSs. The inset shows the layout of the filter.

A photograph of the fabricated filter is shown in Fig. 9, while the simulated and measured responses are shown in Fig. 10. The filter size is reduced by 73.4% of its original size with a center frequency of 1.49 GHz and upper stopband of 2.4 GHz. In addition, the filter performances have been further enhanced in terms of insertion and return loss values while keeping the wide bandwidth of the original filter design.

Table 2
Characteristics of the Filters Presented in Section 4

Filter	Insertion Loss (dB)	Return Loss (dB)	Fractional Bandwidth	Upper Stopband (GHz)	Size (mm)	Size Reduction
Conventional Ring Resonator Filter	-1.2	-8	60.6 %	0.46	40.5 x 40.5	----------
Ring Resonator Filter with Straight Stubs and Circle DGSs	-0.24	-18	57 %	2.44	34.9 x 34.9	25.75 %
Ring Resonator Filter with Straight Stubs and Square DGSs	-0.23	-19	54.58 %	2.24	34.9 x 34.9	25.75 %
Ring Resonator Filter with Internal Folded Stubs and Circle DGSs	-0.28	-16	56.1 %	2.4	20.9 x 20.9	73.4 %

5 Microstrip Ring Resonator Bandpass Filter with Uniplanar Compact-Photonic Bandgap (UC-PBG) Structures

The uniplanar compact-photonic band gap (UC-PBG) structure consists of a uniformly distributed periodic metallic pattern on one side of a dielectric slab. It exhibits some interesting features such as distinctive passband and stopband, slow-wave effects, low attenuation in the passband, and suppression of surface waves when serving as the ground plane of planar microstrip circuits. Moreover, the UC-PBG structure can also be used to realize a perfectly magnetic conducting (PMC) surface, which finds applications in designing a TEM waveguide and a low profile cavity backed slot antenna [8].

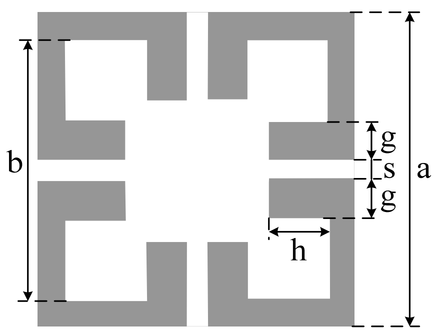


Fig. 11. One cell of the UC-PBG lattice.

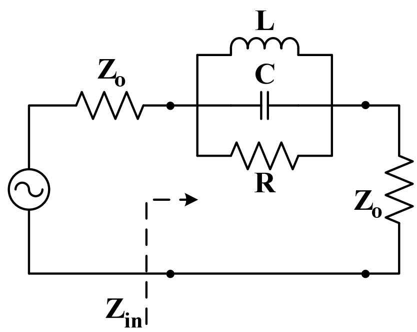


Fig. 12. Equivalent circuit of a unit cell of the UC-PBG.

The use of UC-PBG structures is hereby exploited to improve the harmonic rejection of the filter. The layout of the UC-PBG structure cell is shown in Fig. 11. This structure can be represented by the equivalent circuit given in Fig. 12, where the parallel inductor (L) and capacitor (C) accounts for the transmission zero at the resonance frequency, while the resistance (R) accounts for the different types of losses [16]. The dimensions used for the UC-PBG structures are a=12 mm, b=10.968 mm, g=1.4 mm, s=1.032 mm and h=2.926 mm. The circumference of the ring resonator ℓ_r= 60 mm, the length of each tuning stub is 13 mm and the thickness of the line is 0.94 mm corresponding to a 50Ω line.

Fig.13 shows a photograph of the fabricated ring resonator filter with UC-PBG structures etched in the ground plane and Fig.14 shows the simulated and measured responses of the ring resonator filter with PBG structures. All filter specifications are found in Table 3.

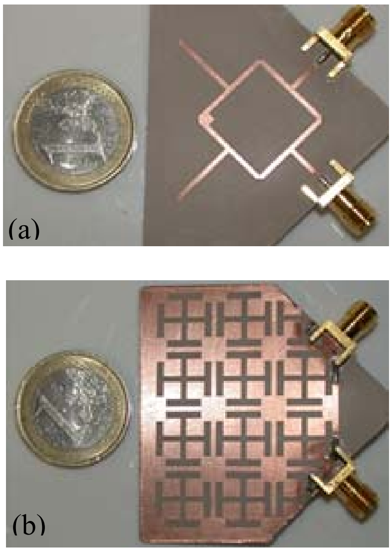


Fig. 13. Photograph of the fabricated ring resonator BPF with UC-PBG structures in the ground plane (a) Top view, (b) bottom view.

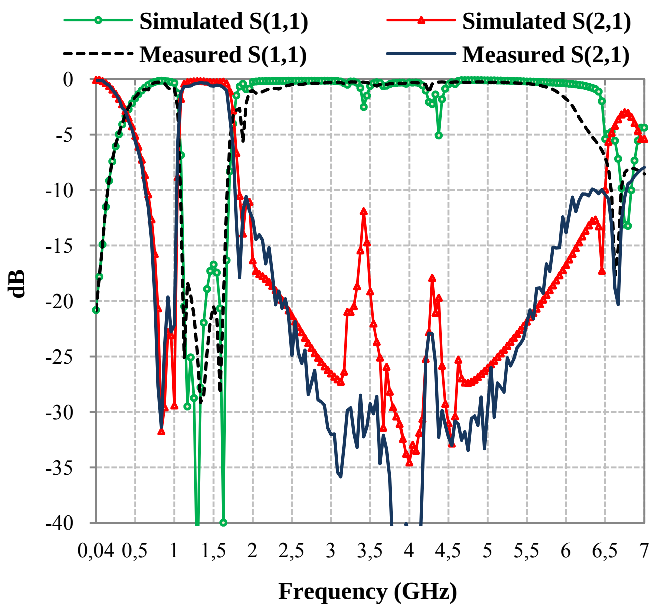


Fig. 14. Simulated and measured responses of the ring resonator filter with UC-PBG structures.

The etching of UC-PBG structures in the ground plane also solves the two problems of the original filter simultaneously. Referring to the filter dimensions given in Table 3, the size of the filter is reduced by 45.52% and the stopband of the filter has increased from 0.46 GHz to 4.7 GHz suppressing the second, third and forth harmonics introduced by the original filter design. Also, the insertion and return loss values of the filter are enhanced due to the suppression of surface waves provided by the UC-PBG structures. Compared to the results obtained by using defected ground structures presented previously on the same ring resonator filter, the DGSs introduces a size reduction of only 25.75 % and a narrower stopband of 2.44 GHz, which means that the UC-PBG structures are more efficient but suffer from the difficulty of their design.

In the following section, we will present using UC-PBG structures with the ring resonator filter with external bent stubs and internal folded stubs.

5.1 Using External Bent Stubs and Internal Folded Stubs with UC-PBG structures

In this section we are going to study the ability of using both advantages of bent stubs and UC-PBG structures.

As mentioned before, in bending the stubs, the coupling between the stubs and the ring resonator is one of the most effective parameters in the design. In our case, we used the quasi-TEM mode properties of the coupled microstrip lines provided by [12]. But for the case of UC-PBG structures etched in the ground plane, the amount of error provided by these equations increases, which makes the design more difficult, even though they still provide a reasonable initial guess. For further improvement in the design, a full electromagnetic wave simulator should be used.

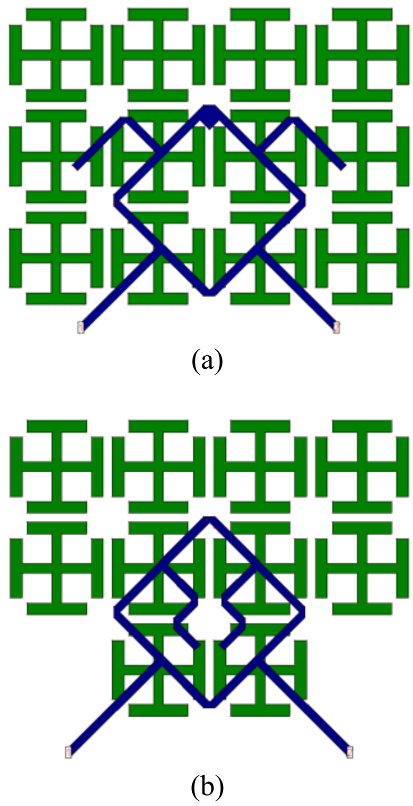
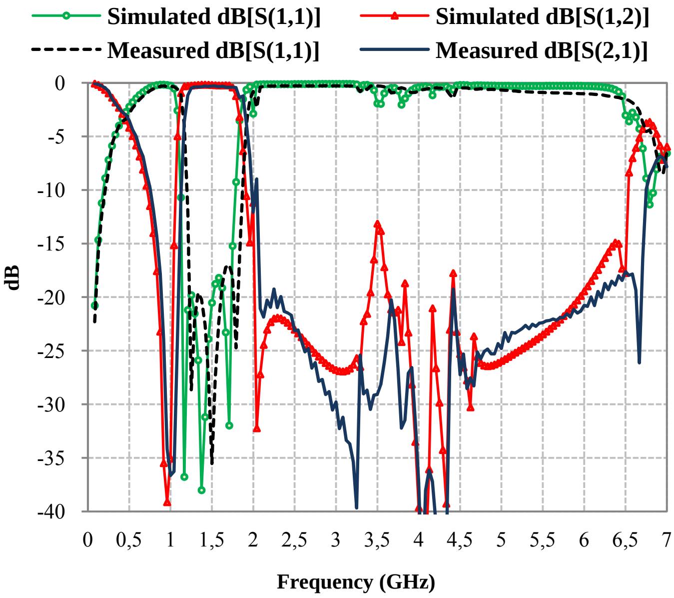
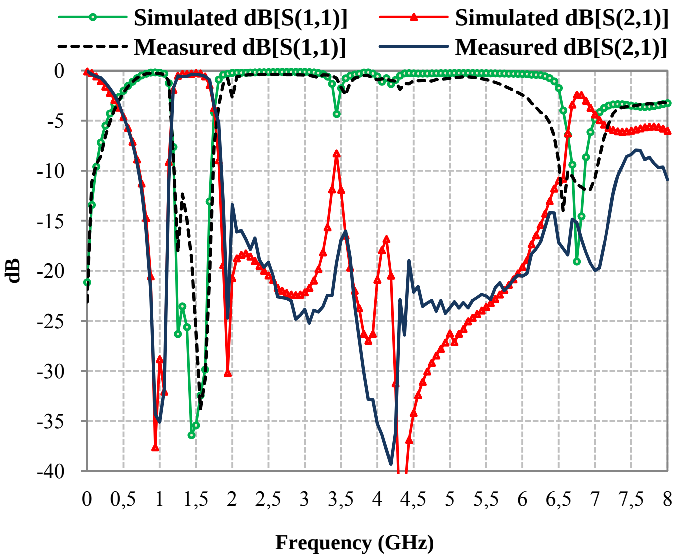


Fig. 15. Layout of the ring resonator BPF with UC-PBG structures in the ground plane with (a) external bent stubs, (b) internal folded stubs.

The two solutions of Fig. 3 with external bent stubs and internal folded stubs with UC-PBG structures are designed on the same material mentioned above. The layouts of the structures are shown in Fig.15 (a) and (b). The simulated and measured responses are presented in Fig.16 (a) and (b). All filters specifications are shown in Table 3. We can see a great reduction in the size of the filter reaching up to 84.49 % for internal folded stubs (while 68.24% is attained for the external bent stubs), accompanied by very good overall filter performance.



(a)



(b)

Fig. 16. Simulated and measured responses of the ring resonator filter with UC-PBG structures and (a) external bent stubs, (b) internal folded stubs.

This means that bending the stubs has affected neither the very good passband characteristics provided by the ring resonator filter, nor the wide stopband provided by the UC-PBG structures.

6 Suppression of the Lower Passband Using Via Holes

The use of internal folded stubs allows the exploitation of the inner ring area achieving a size reduction reaching more than 70%, while the use of DGSs and UC-PBG structures has enhanced the overall filter performance specially with respect to the suppression of the higher order mode, but still the filter suffers from a narrow lower stopband and a passband at the DC frequency range. This problem is usually solved using input/output capacitive coupling [17]. The disadvantage of this technique is its high insertion loss and the dramatic decrease in the bandwidth.

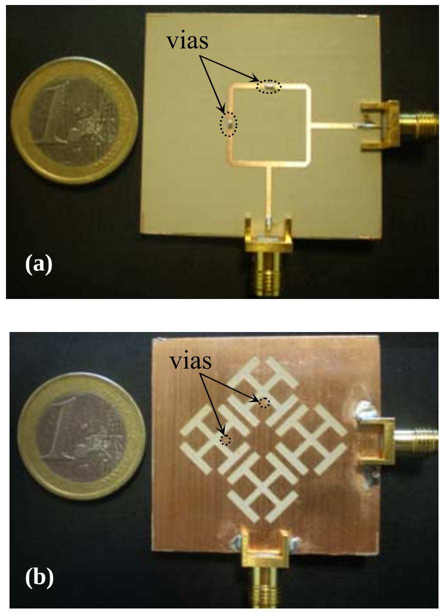


Fig. 17. Photograph of the fabricated ring resonator BPF with UC-PBG structures in the ground plane and via holes (a) Top view, (b) bottom view.

A transmission zero may be obtained by replacing the two tuning open-circuited stubs by two via holes [9]. This should not affect the response at the center frequency required. This may be explained as follows; at the resonant center frequency, the $\lambda_g/4$ open-circuited stub is equivalent to a direct short circuit at the ring-stub interface following the transmission line input impedance equation given by:

$$Z_{in} = Z_0 \frac{Z_L + Z_0 \tanh(\gamma \ell)}{Z_0 + Z_L \tanh(\gamma \ell)} \quad (2)$$

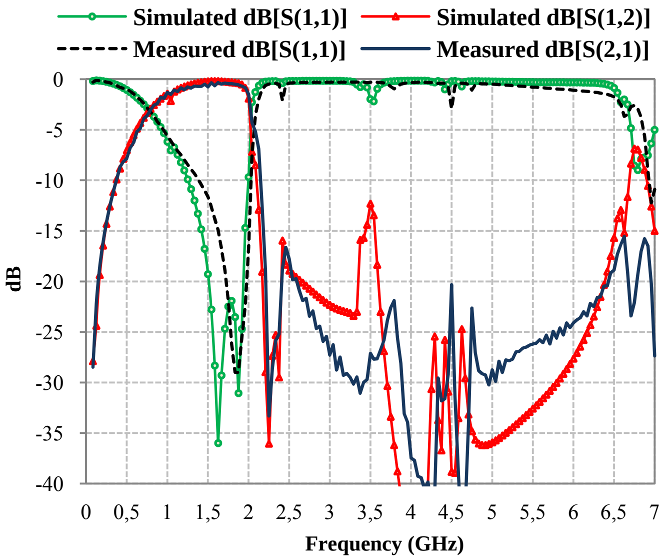


Fig. 18. Simulated and measured responses of the ring resonator filter with UC-PBG structures and via holes.

where Z_L is the load impedance (open circuit in this case), γ is the propagation constant and ℓ is the length of the stub. This short circuit is implemented using via holes. At zero frequency, the circuit acts as if there is a short circuit directly connected at the input, and therefore a transmission zero is obtained at zero frequency.

Fig. 17 shows a photograph of the ring resonator filter with via holes and UC-PBG structures. The radius of each via is equal to 0.25 mm. Fig. 18 shows the responses of the filter. All filters specifications are shown in Table 3.

The advantage of such a structure is the simplicity of the design and extremely large upper stopband that reaches more than 5 GHz. The basic disadvantage of using via holes is that the rejection in the lower stopband is not sharp enough. This is because the sharp transmission zero produced by the stub has been replaced by that at zero frequency. It should be noted that the sharp upper rejection in this case is produced by the UC-PBG structures.

7 Conclusion

This paper provides a general enhancement technique for ring resonator filters. The modifications presented here target two basic disadvantages in the ring resonator filters. The first is the large occupation area of the filter while the second is the narrow upper stopband due to its higher order passbands.

To reduce the area occupied by the filter, our first approach was to bend the tuning stubs of the filter along the ring resonator, and in a second design iteration, we tried the exploitation of the inner ring area using internal folded stubs. The advantage of this technique is that the area of the filter was reduced by a factor of 72% without affecting the good characteristics of the ring resonator filters.

To suppress the high order passbands of the filter, we investigated the use of both DGSs and UC-PBG structures. DGSs are easier in their design procedures than UC-PBG structures, but on the other hand UC-PBG structures provide a larger upper stopband. Both structures give additional advantage with respect to size

Table 3
Characteristics of the Filters Presented in Sections 5 and 6.

Filter	Insertion Loss (dB)	Return Loss (dB)	Fractional Bandwidth	Upper Stopband (GHz)	Size (mm)	Size Reduction
Conventional Ring Resonator Filter	-1.2	-8	60.6 %	0.46	40.5 x 40.5	----------
Ring Resonator Filter with Straight Stubs and UC-PBG	-0.21	-20	46.5 %	4.7	29.9 x 29.9	45.52 %
Ring Resonator Filter with External Bent Stubs and UC-PBG	-0.34	-17	50.73 %	4.66	22.9 x 22.9	68.24 %
Ring Resonator Filter with Internal Folded Stubs and UC-PBG	-0.59	-12.81	40.8 %	5.25	15.9 x 15.9	84.49 %
Ring Resonator Filter with Via Holes and UC-PBG	-0.18	-27	85 %	5.5	13.9 x 13.9	88.135 %

reduction due to the slow-wave effect introduced. The size reduction provided by UC-PBG structures is greater than that provided by DGSs.

Finally, via holes were introduced replacing the two tuning stubs to suppress the DC passband for further enhancement in the filter response.

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