

# Stop Band Characteristics for Periodic Patterns of CSRRs in the Ground Plane and its Applications in Harmonic Suppression of Band Pass Filters

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**Abstract**-Stop band filters are designed by etching periodic patterns of complementary split ring resonators (CSRRs) in the ground plane of a microstrip line. CSRRs, being sub-wavelength resonators, their size are much smaller than the conventional microstrip resonators. As a resonator, it has been observed that a single CSRR in the ground plane has a very high Q factor and gives a high attenuation in the stop band. It has also been observed that the period of the CSRR loaded microstrip line can be made as small as  $\lambda/10$  of the operating wavelength thereby extensive size miniaturization is possible. With the increased number of CSRRs etching and decreased period of the periodic structure loaded with CSRRs in the ground plane of the microstrip line, the stop band width increases and side by side the rejection level in the mid stop band frequency increases significantly thereby further enhancing the stop band filter performance along with the extensive size miniaturization. It has been observed for the first time that combining capacitive stub loading along with CSRRs in the ground plane completely suppresses the harmonic passbands at  $2f_0$  and  $3f_0$  of parallel coupled microstrip line band pass filters and the out-of-band filter performance improves considerably (in particular, a steeper and increased out-of-band rejection has been observed), without compromising the in-band filter performance.

**Index Terms**- Stop band, Periodic Structures, Complementary Split Ring Resonators (CSRRs), Symmetric/Asymmetric Parallel Coupled Microstrip Line Band Pass Filters, Capacitive Stubs

## I. INTRODUCTION

Size miniaturization of microwave filters is of much demand in the today's rapid changing communication world. Even though end-coupled band pass filters and parallel-coupled band pass filters [1] with the half wavelength resonators are prevalent, they are much larger in size. There exist filters with quarter wavelength resonators. Even those filters size are large at the lower end of microwave frequencies. Many microstrip filter designs have been proposed for size miniaturization and performance enhancement in the past few decades but there are still some areas for improvements.

Metamaterials is one of the latest areas of research among microwave researchers [2] across the globe and they are artificial materials which produce negative- $\epsilon$  and negative- $\mu$  electromagnetic properties. Split Ring Resonators (SRRs) and Complementary Split Ring Resonators (CSRRs) also called as Sub Wavelength Resonators [3]-[4], the reason being their size are much smaller than the operational frequency wavelength, are the component particles for such exotic artificial materials. These components for metamaterials can design filter with improved filter characteristics and size miniaturization. Preliminary results of such CSRR based microstrip filters have been reported in [5]. In this paper, we will do a detailed investigation of CSRR based stop band filters: starting with a single CSRR etching in the ground plane, finding its stop band characteristics and quality factor. Then the effect of number of CSRRs etching and periodicity on the stop band

filter performance will be investigated. We will also report our new findings on the harmonic suppression of microstrip band pass filters using the open circuit stub loaded microstrip line along with CSRRs in the ground plane of the filter. Such techniques give a very good out-of-the band filter performance viz. sharp cut-off, very high rejection level and complete harmonic suppression of  $2f_0$  and  $3f_0$  harmonics of the band pass filter without compromising the in-band filter performance.

## II. SRR AND CSRR

SRR and its complementary structure, CSRR are depicted in Fig. 1(a) and (b) respectively and they are small resonant particles with high quality factor [6]. CSRR essentially behaves as an electric dipole that can be excited by an axial electric field. The CSRR has an equivalent circuit of externally driven parallel LC resonant circuit [7]. The resonant frequency of these resonant particles can be tuned by varying its physical dimensions:  $r_{ext}$ ,  $c$  and  $d$  depicted in Fig. 2. In our case, CSRR is formed by etching out the metallic portion of the ground plane of microstrip line in the shape of SRR. Both SRR and CSRR with the same dimensions resonate at the same frequency. Complementary split ring resonators (CSRRs) are used in the ground plane instead of SRRs in the same plane of the microstrip line to achieve the stop band characteristics. One of the major advantages for this is that for applications like harmonic suppression of a band pass filter, we can construct the band pass filter in upper part of the substrate and etch CSRR structures in the ground plane of the substrate hence there is more degrees of freedom for designing the filter as well harmonic suppression technique. Besides, there are no additional area requirements for harmonic suppression of filters.

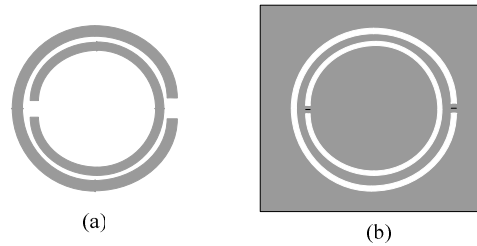


Fig.1. (a) SRR and (b) CSRR

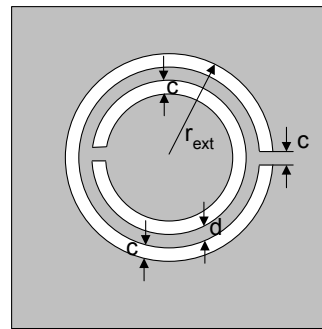


Fig.2. Structure of the CSRR showing the physical dimensions

## III. CSRR BASED STOP BAND FILTERS: RESULTS AND DISCUSSIONS

A CSRR structure is designed to resonate at 8.3 GHz of the X-band microwave frequency region. The dimensions of the CSRR structure chosen for this frequency of operation are  $r_{ext}=1.0\text{mm}$ ,  $c=0.2\text{mm}$  and  $d=0.2\text{mm}$  respectively. A parametric study on the dependence of the resonant frequency of the CSRR on various parameters has been done. The dependence on dimensions of the CSRR structure for the resonant frequency is observed as follows: with the increase of external radius ( $r_{ext}$ ), resonant frequency of the CSRR decreases and with the increase of the ring width ( $c$ ) and gap width ( $d$ ), resonant frequency of the CSRR increases. The CSRR structure is placed in the ground plane exactly below the center of a microstrip line of width 2.89mm on a FR4 dielectric substrate of  $\epsilon_r=4.4$  and height ( $h$ ) 1.6mm as shown in Fig. 3(a) and (b). Same dielectric substrate is used for all other later designs. All the designs are simulated using Zeland IE3D software [8]. The simulation results for a single CSRR etching in

the ground plane of a microstrip line are shown in Fig. 3(c).

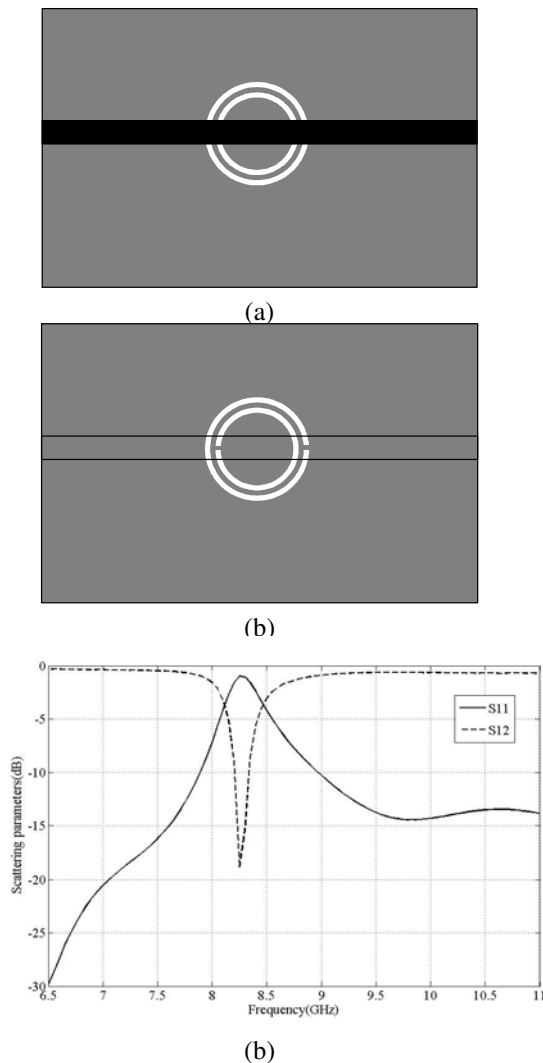


Fig.3. Single CSRR in the ground plane (a) Front view (b) Front view (Microstrip line is made transparent to make visible the opposite splits in the two concentric rings in the ground plane) (c) Scattering parameters

The results of scattering parameters versus frequency (GHz) show narrow stop band characteristics at the resonant frequency of CSRR at 8.3 GHz. By placing a single CSRR structure in the ground plane, we can obtain a narrow stop band with a very high rejection level, which is not possible with conventional microstrip resonators. It is difficult to achieve such a good narrowband stop band response with a single

element of conventional microstrip resonators. Stop band width of the above single CSRR loaded microstrip line filter is approximately 150MHz and it has a very high quality factor of 12546 at the resonant frequency of 8.3 GHz.

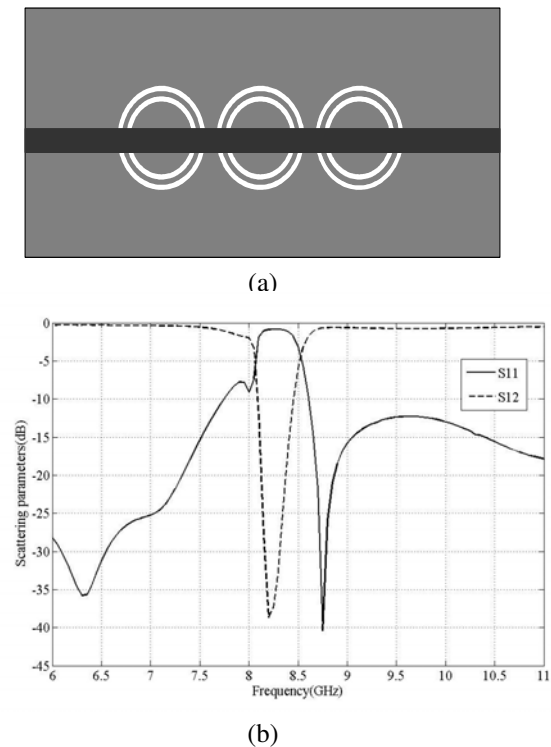


Fig.4. Stop band filter having 3 CSRRs in the ground plane (a) Front view (b) Scattering parameters

Our main concern is to enhance the stop band filter characteristics by increasing the number of CSRR structures in the ground plane. This is achieved by placing more CSRRs with the same resonant frequencies periodically. Such a stop band filter structure is shown in Fig. 4(a), which has three CSRR structures in the ground plane and all the CSRRs are resonating at the same frequency of 8.3 GHz. The distance between the centers of any two adjacent CSRRs is known as period and it is 3mm for this bandstop filter. The simulation results are shown in Fig. 4(b). The simulation results depicted in Fig. 4(b) shows a stop band at 8.3 GHz with a stop band width of approximately 400MHz.

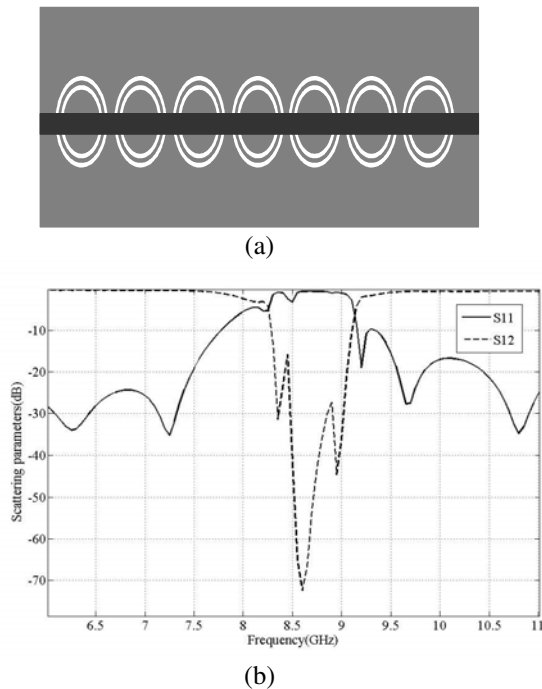


Fig.5. Stop band filter having 7 CSRRs in the ground plane (a) Front view (b) Scattering parameters

Comparing Fig. 3(b) and Fig. 4(b), we can observe an improvement in the stop band width of nearly 250MHz. We can also observe a significant increase in the rejection levels in the stop band. At the resonant frequency, the rejection level is 18dB for the stop band filter with single CSRR and it is at 38dB for the stop band filter with three CSRR structures.

The CSRR structures in the ground plane is further increased to seven as shown in Fig. 5(a) and simulated in the same frequency range of 6GHz to 11GHz. Fig. 5(b) shows the simulation results of the design shown in Fig. 5(a) with seven CSRRs in the ground plane. The results show a large stop band from 8.3 GHz to 9.15GHz with a stop band width of 850MHz, which is a significant improvement compared to the previous results of single CSRR and three CSRR structures in the ground plane.

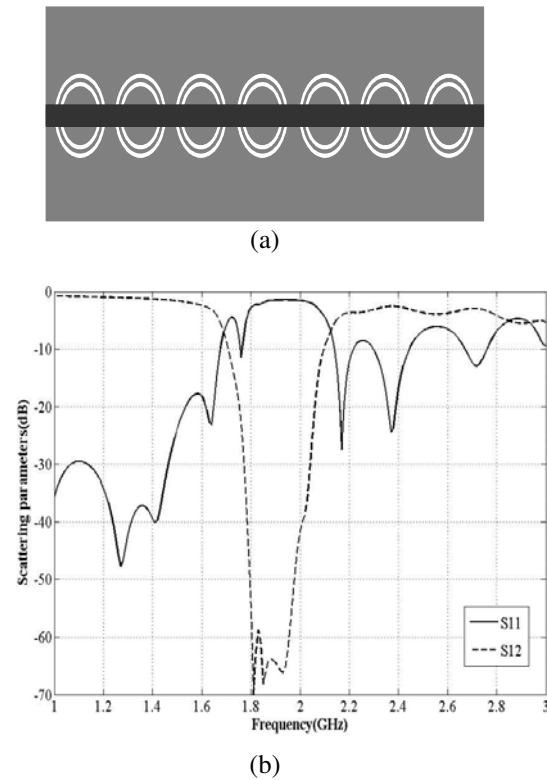


Fig.6. Stop band filter having periodicity of 20.6mm (a) Front view (b) Scattering parameters

From all these three stop band filters, we have observed a significant increase in the stop band width with the increased number of CSRR structures in the ground plane and increased rejection level in the stop band.

Periodicity of the stop band structure is also an important parameter for enhancing the properties of the stop band filter characteristics. A stop band filter is designed to operate at 1.9GHz with 7 CSRR structures in the ground plane as shown in Fig. 6(a). The dimensions of the CSRR structure are chosen to have resonant frequency at 1.9GHz. They are  $r_{ext}=5.0\text{mm}$ ,  $c=0.2\text{mm}$  and  $d=0.2\text{mm}$  for an FR4 dielectric substrate having dielectric constant of  $\epsilon_r = 4.4$  and thickness of 1.6mm. Seven CSRR structures are placed in the ground plane exactly below a microstrip line of width 2.89mm having characteristic impedance ( $Z_0$ ) of  $50\Omega$ . The periodicity of etching CSRR structures in the ground plane of the microstrip line (refer to Fig. 6(a)) is maintained at 20.6mm.

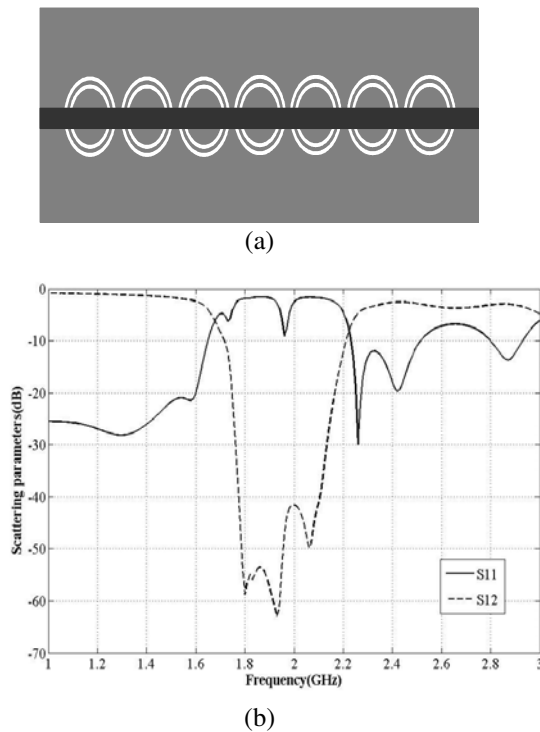


Fig.7. Stop band filter having periodicity of 15.6mm  
(a) Front view (b) Scattering parameters

Fig. 6(b) shows the simulation results of the stop band filter structure shown in Fig. 6(a). The results are plotted for the scattering parameters ( $S_{11}$  and  $S_{12}$ ) against frequency from 1GHz to 3GHz. These results show a mid stop band frequency of 1.9GHz, stop band width ranges from 1.7GHz to 2.1 GHz approximately 400MHz. The period of the CSRRs based stop band filter is changed to 15.6mm. The number of CSRRs in the ground plane is same as in the previous case. The CSRR dimensions and dielectric substrate properties are also kept the same. The simulated results of the stop band filter design of Fig. 7(a) are shown in Fig. 7(b). Results of scattering parameters ( $S_{11}$  and  $S_{12}$ ) are plotted against frequency from 1GHz to 3GHz, which show a stop band from 1.7GHz to 2.2GHz (approximate band width 500MHz). Decreasing the period of the filter by 5.0mm increases the stop band width of the filter by 100MHz. The rejection or attenuation level at the mid stop

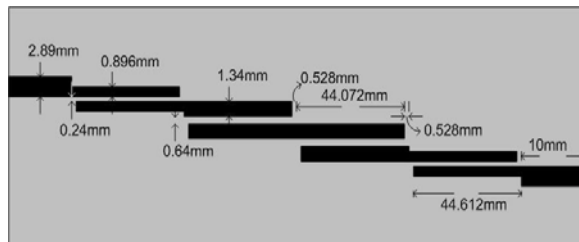
band frequency is increased by 10dB and it is at a deep rejection level of 60dB now.

All the above designs and their simulation results show that with the increase of number of CSRR structures in the ground plane and smaller periodicity, more stop band width and deeper rejection levels in the stop band is achieved. Using these two advantages of CSRR based stop band filter, spurious pass bands in microstrip line filters can be eliminated. Since all the CSRR structures are in the ground plane of the dielectric substrate, we do not need extra device area for the design of stop band filter to remove unwanted spurious pass bands of the band pass/ low pass filters unlike other conventional microstrip line stop band filters which require extra device area. The size of these resonant particles is very small with a very high quality factor and the periodicity of these structures can be maintained at a very low fraction of operating wavelength compared to the conventional filters.

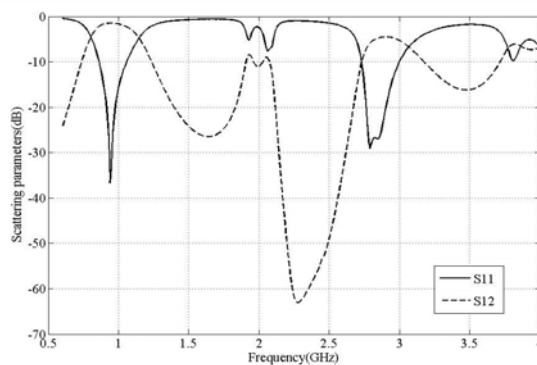
#### IV. HARMONIC SUPPRESSION OF BAND PASS FILTERS

A parallel coupled band pass filter is designed and simulated in the GSM frequency band (890MHz to 960MHz). A 3<sup>rd</sup> order 0.1dB ripple Chebyshev filter of 10% fractional bandwidth has been chosen and it has been designed to attain 23dB attenuation level at 870MHz. Fig. 8(a) shows the structure of the 3<sup>rd</sup> order parallel coupled microstrip line band pass filter. The design of this band pass filter is done following the standard design procedure given in [9]. The parallel-coupled microstrip line band pass filter is designed on a FR4 substrate of relative permittivity 4.4 and thickness of 1.6mm. The dimensions of filter are depicted in Fig. 8(a). The microstrip feed lines at the input and output ports are 50 $\Omega$  lines and their lengths are 10.0mm. Fig. 8(b) shows the simulation results of the parallel-coupled microstrip line band pass filter of Fig. 8(a). The simulation results show a passband at 940MHz and the passband ranging from 860MHz to 1060MHz. Fig. 8(c) shows the experimental results of the same filter that has fabricated and tested using Network Analyzer

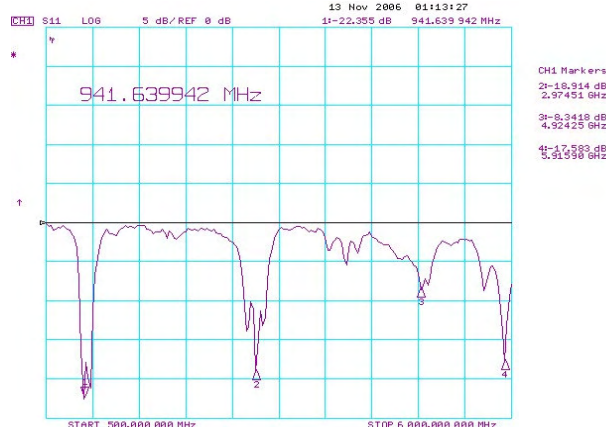
and it is in close agreement with the simulation results. Hence we believe that all our simulation results using Zeland IE3D software are accurate and reliable.



(a)



(b)

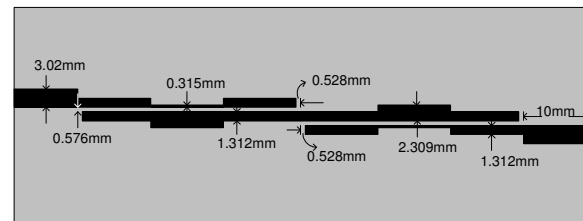


(c)

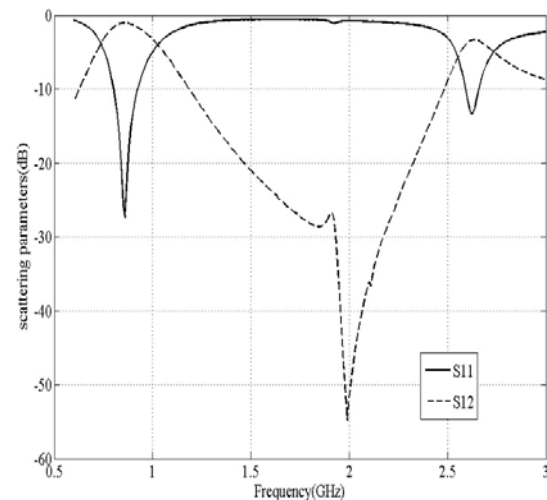
Fig.8. Parallel coupled microstrip line band pass filter (a) Filter layout (b) Simulated results (c) Experimental results

The spurious passband around 2GHz in the pass band response of the parallel coupled band pass filter can be eliminated to some extent by using asymmetric parallel coupled lines in the filter structure [10] as shown in Fig. 9(a). A first order asymmetric parallel-coupled band pass filter has

been designed to operate at GSM frequency band and the simulation results are shown in Fig. 9(b). Asymmetric parallel-coupled microstrip line was introduced in the symmetric parallel-coupled microstrip lines by changing the  $1/3^{\text{rd}}$  portion of the resonator width to 76% of its original width as shown in Fig. 9(a). Figure 9(b) shows the simulation results of the asymmetric band pass filter designed, which shows that the spurious passband at 2GHz is completely suppressed.



(a)

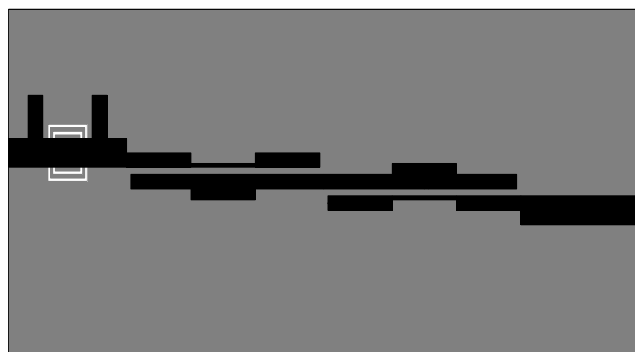


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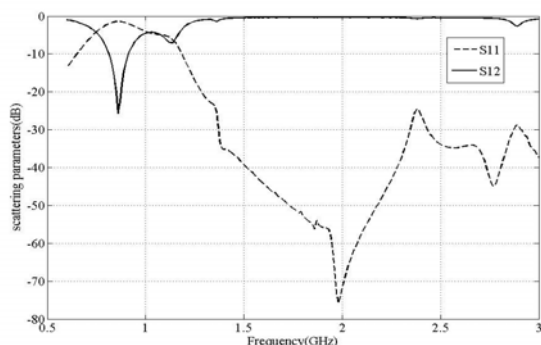
Fig.9. (a) Asymmetric parallel coupled band pass filter layout with dimensions (b) Simulation results of the asymmetric parallel-coupled coupled filter

But there is another spurious passband visible around 2.7 GHz and we want to further suppress this harmonic. Henceforth a stub loaded CSRR based structure is implemented to completely eliminate the spurious pass bands appearing at  $3f_0$  of the asymmetric parallel-coupled band pass filter. Such structures have been used for designing low pass filters with the enhanced performance in [11]. The stub loaded CSRR based structure consists of open circuited stubs at

the input port, which acts as a capacitive load as shown in Fig. 10(a). The capacitance ( $C$ ) of the stubs related to their characteristic impedance  $Z_0$  as  $Z_0\omega C = 1$  and their length is equal to  $\lambda_g/8$  for a  $50\Omega$  transmission line. The CSRR structure is placed exactly below the center of  $50\Omega$  transmission line and symmetrical to the stubs. The above described structure gives a very large band stop and the layout of the structure is shown in Fig. 10(a). The stop band structure is designed at the input feeding lines of the band pass filter with the CSRR dimensions  $L = 13\text{mm}$ ,  $c = d = 0.5\text{mm}$  where  $L$  is the outer length of the square shaped CSRR. Fig. 10(b) shows the simulation results of the band pass filter, which shows the suppression of all the nearby spurious passbands above the fundamental frequency of operation. Note that the rejection level at  $2\text{GHz}$  is about  $75\text{dB}$  and  $45\text{dB}$  at  $2.7\text{GHz}$  where the first and second harmonic passbands were present for the parallel-coupled microstrip line band pass filter.



(a)



(b)

Fig. 10. (a) Top view of the design of asymmetric parallel coupled band pass filter with open circuited stub loaded CSRR based band stop filter at the input port (b) Simulated results.

## V. CONCLUSION

Using the sub-wavelength resonator components of left handed metamaterials namely CSRR, more compact planar microstrip stop band filters have been designed. The dimensions of these resonators and the dielectric substrate parameters decide their resonant frequency. These types of resonators provide an attractive means for developing very compact filters with fully planar fabrication techniques. This is especially of benefit for the growing numbers of microwave circuits required for the compact integrated circuits (ICs) for wireless communications. Single CSRR in the ground plane gives a very narrow stop band at its resonant frequency with an extremely high  $Q$  factor but periodically placing these CSRR structures gives wide stop band. As the number of etching of these structures increases in the ground plane of the dielectric substrate, the width of the stop band increases. Stop band width also depends on the periodicity of etching of such structures in the ground plane. It has been observed that as the periodicity decreases, the stop band width increases. One of the main advantages of these particles is unlike the other conventional filter components/structures, which require large separation between them they can be placed very close (periodicity can be smaller than one tenth of the operating frequency wavelength) and side by side the filter performances are also getting enhanced/improved. Because of this property of such resonators the device areas are reduced. Since they are placed in the ground plane they will not occupy extra device area in the design of unwanted harmonic suppression of microwave devices. A 3<sup>rd</sup> order symmetric parallel coupled microstrip line filter is designed, fabricated and tested for GSM applications which show that there is good agreement between the simulation and experimental results. But there are harmonics visible at  $2f_0$  and  $3f_0$  of the fundamental frequency. Using asymmetric parallel coupled microstrip line filter, we can eliminate the first harmonic at  $2f_0$  only. This asymmetric filter is much more compact than symmetric case since the asymmetric filter is a 1<sup>st</sup> order filter unlike the

symmetric case which is a 3<sup>rd</sup> order filter. Whereas, it has been observed for the first time that capacitive stub loaded CSRR based asymmetric parallel coupled filter has no harmonic at  $2f_0$  and  $3f_0$  with a very good in-band and out-of-the-band filter performance.

### ACKNOWLEDGMENT

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