# 7th order harmonic suppression and wide rejection band using CSRR backed BSF

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To obtain the high rejection level for undesired band from a microstrip band pass filter, a complimentary split ring resonator (CSRR) backed bandstop filter (BSF) has been used at the input of bandpass filter. This arrangement gives harmonic suppression for symmetric passband response with a minimum area of filter. In this paper, we have investigated role of CSRR backed BSF for suppression of higher order harmonics along with wider rejection bandwidth. Through better optimization, we report a filter of area $154.242 \times 30$ mm$^2$, which consists of BSF/CSRR at both input and output ports. Simulation results demonstrate the rejection level of 18.94 dB for the fifth order harmonic with maximum rejection of 115 dB in stop band. Better rejection upto the seventh order and wide rejection bandwidth of 4.6 GHz (1.7 – 6.3 GHz) have been obtained experimentally.

## 1 Introduction

In wireless broadband, mobile, satellite communications, radar, navigation and sensing systems, where the sensitivity is generally higher, a presence of nearby frequency signals makes the system virtually non-functional by transmitting or detecting the wrong information. Microstrip or coplanar waveguide based filters are preferred as these allow propagation of undesired passband or fractional frequency, owing to dispersive and resonating nature of phase velocities. Therefore, other frequency signals than the fundamental or desired frequency are also transmitted (or received) from the communication (or by radar) system, which are multiple of this frequency. Such spurious or harmonic signals are required to be removed or suppressed for the smooth functioning of the system. To accomplish this task, various approaches are proposed and verified with parallel coupled microstrip line (PCML) filter experimentally. By utilizing periodic photonic bandgap (PBG) structures[1], continuous perturbation of the coupled line width[2], corrugated PCML[3] and periodic grooves[4], a second harmonic has been successfully removed. A microstrip line loaded with split ring resonator (SRR) generates magnetic field lines and gives rise to a negative permeability medium over a narrow band[5], such band serves as a stop band for a notch filter. When loaded with complementary SRR (CSRR), microstrip line induces electric field lines and gives rise to a negative permittivity medium over a wider stop band. In this way, loaded with either SRR or CSRR, microstrip line forms a high Q and very compact BSF. So in further advances, split ring resonator (SRR) and complementary SRR (CSRR) are also implemented[6,7] and along with conventional band stop filters (BSF), these have demonstrated the removal of harmonics from BPF response[8]. Such approaches have advantages of improved rejection without increasing the effective area of the whole filter. However, these designs lack the fabrication simplicity and smoother response in the undesired band or frequency range. In another approach, area of waveguide BPFs is reduced by 66% using rectangular CSRR elements placed inside[9]. A narrow bandpass filter in a rectangular waveguide by etching a CSRR in the center of a metallic sheet is demonstrated in S-band, which has reduced the dimensions of the irises coupled resonant-cavity waveguide filters[10].

In a novel proposal[11,12], an open stub-spurline band stop filter (BSF) of center frequency of 4 GHz was used with BPF of center frequency of 0.9 GHz. It was

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demonstrated that a CSRR with resonant frequency of 2 GHz under the 50 Ω microstrip line of this BSF effectively enhanced the rejection bandwidth and the harmonic suppression upto 5th order has been achieved as more than 20 dB rejection level in simulation and measurement results. However, the area of this filter is still large which may also increase the loss of the whole communication (or radar) system, and so it is important to reduce the area of overall filter keeping the same or better rejection performance. Thus, in this paper, we intend to investigate the effect on harmonic suppression by further reducing the area of this kind of filter and the deciding role played by BSF and CSRR specifications. For comparison study, the same filter parameters are chosen as reported in literature[11] and optimization with single BSF/CSRR and dual BSF/CSRR is performed using computer simulation technology (CST) software. Improvements in results on placing BSF/CSRR are discussed in detail in the frequency band 1 – 6.5 GHz, which has been verified by the measurements.

## 2 Design of Modified Harmonic Suppressed Bandpass Filter

To fabricate the BPF design with two BSF/CSRR, we have taken FR4 substrate having $\varepsilon_r$ = 4.5 and height 1.5 mm, loss tangent (tanδ) = 0.004 and thickness of copper = 0.018 mm. The resonance frequency of CSRR[11] can be tuned by changing its physical dimensions as shown in Fig. 1 (a). We have optimized the dimensions of CSRR and taken $L_1$ = 9.3 mm as the length of outer loop, $L_2$ = 7.3 mm as the length of inner loop, $c$ = 0.5 mm as the width of loop, $d$ = 0.5 mm as gap between two loops and $g$ = 0.5 mm as gap in loop. The resonance frequency of CSRR is verified as 2 GHz by estimating the mutual inductance of $4.17 \times 10^{-5}$ H and mutual capacitance of $1.52 \times 10^{-16}$ F.

As shown in Fig. 1(b), the dimensions of the open stub-spurline band stop filter are obtained by the procedure discussed in earlier reports[8,11,12]. This filter is optimized at the center frequency of 4 GHz to meet the rejection requirement. The physical dimensions of 50 Ω microstrip line at 4 GHz are obtained as width

($W$) = 2.818 mm and length ($L$) = 10.05 mm. So for BSF, dimensions found are, $L_3 = L_4 = L_5$ = 10.049 mm, $W_1$ = 2.818 mm. After optimization, $L_3$ becomes 9.8 mm and $W_2$ is taken as 30% of $W_1$, i.e., 0.845 mm. In order to make comparison with BPF reported in earlier study[11], a first order Chebyshev conventional BPF is designed with center frequency of $f_c$ = 0.9 GHz with 10% fractional bandwidth (FBW) and 0.5 dB ripple in the passband[13]. The optimized dimensions of coupled line are given in Table 1, which are obtained same for both sections of the schematic as shown in Fig. 1(c). By embedding the spurline based BSF backed with CSRR at the input port, simulation was performed for minimum area of complete filter. In the next simulation, second BSF backed with CSRR was placed at output port of the PCML BPF.

## 3 Simulation using CST Microwave Studio

The complete dimensions of the final BPF with two BSF/CSRR are given in Fig. 2 where shaded (blue) area is representing copper (Cu) and white area is representing substrate (with etched Cu).

The simulated S-parameters of all three filters are shown in Fig. 3. In conventional BPF, harmonics appeared at near 1.5 GHz, 2.65 GHz, 3.61 GHz, 4.38
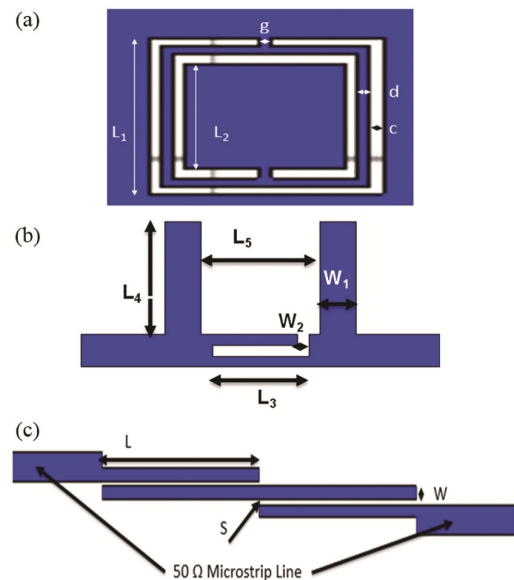


Fig. 1 — (a) Representation of CSRR, (b) geometry of spurline BSF and (c) schematic of conventional PCML BPF.

Table 1 — Optimized values of physical parameters of the first order Chebyshev BPF.

| Immittance values $g_n$ | $Z_o J_n$ | Even mode impedance $Z_{0e}$ (Ω) | Odd mode impedance $Z_{0o}$ (Ω) | Width $W$(mm) | Spacing $S$ (mm) | Length of section $L$ (mm) |
|---|---|---|---|---|---|---|
| 1 | 0.474 | 84.95 | 37.53 | 1.22 | 0.5 | 46.972 |
| 2 | 0.474 | 84.95 | 37.53 | 1.22 | 0.5 | 46.972 |

GHz, 5.38 GHz and 6.06 GHz are passed owing to less reflection as can be seen in Fig. 3(a), whereas in BPF with one BSF/CSRR, peak near 1.5 GHz becomes small as well as other peaks are greatly reduced (red). This indicates that signals at these frequencies are reflected or not being transmitted due to absorption as open stub-spur line based BSF offers a wide bandwidth and rejection level is further enhanced by using CSRR on the back[11]. Few fractional frequencies are observed in the $S_{11}$ response (blue) of BPF with two BSF/CSRR for frequencies above 3.8 GHz. Beyond this frequency, little variations in the responses are observed for last two filters with BSF/CSRR, otherwise the responses are found to be same for in the lower frequency range below 3.8 GHz.

In Fig. 3(b), $S_{21}$ responses show nearly same passband (0.76 - 1.03 GHz) response as BPF is designed to pass 0.9 GHz, however 0.89 GHz is found as center frequency for three filters. In BPF with BSF/CSRR, a signal of 2 GHz is absorbed by CSRR as its resonant frequency due to formation of negative permittivity medium, whereas BSF reflected back signal of 4 GHz effectively. These effects resulted $S_{21}$ of -91.99 dB at 2 GHz and -11.97 dB at 4.45 GHz (i.e., $5f_0$). Indeed, some peaks of near 0 dB in $S_{21}$ response are observed for conventional BPF at 2.4 GHz, 3.4 GHz and 4.4 GHz after the passband, these harmonic peaks are greatly removed by incorporation of BSF/CSRR. As frequencies above 2 GHz are suppressed by one BSF/CSRR, the rejection level as well as bandwidth of rejection increased significantly on placing the second BSF/CSRR at the output of BPF. The numerical performances of three BPFs are compared in Table 2.

In BPF with two BSF/CSRRs, the range of stop band is found from DC to 0.76 GHz before passband and 1.03 GHz to 4.49 GHz after pass band. Thus with
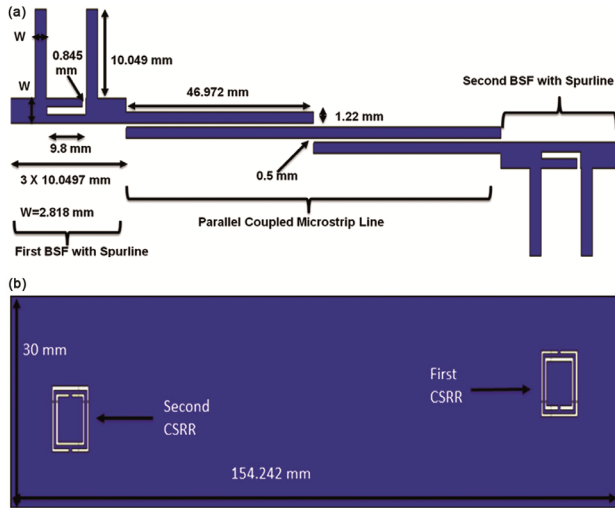


Fig. 2 — Final modified filter (a) top layer dimensions and (b) bottom layer dimensions.

Table 2 — Comparison between conventional BPF with one BSF/CSRR and with two BSF/CSRR.

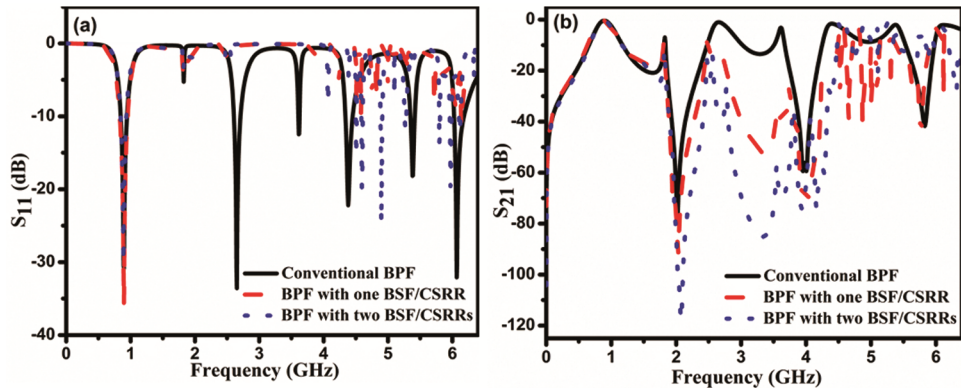| Parameters | Conventional BPF | BPF with one CSRR | BPF with two CSRR |
|---|---|---|---|
| $S_{11}$(dB) @ $f_0$ | -30.84 | -35.37 | -29.85 |
| $S_{21}$(dB) @ $f_0$ | -0.40 | -0.41 | -0.44 |
| Center frequency $f_0$ (GHz) | 0.89 | 0.89 | 0.89 |
| Pass band bandwidth (MHz) | 263 | 301 | 271 |
| Fractional bandwidth $\Delta$(%) | 8.96 | 8.97 | 8.90 |
| Maximum rejection near 5th harmonic (dB) @ 4.45 GHz | - | -11.87 | -18.94 |
| Maximum rejection level in stop band (dB) @ 2 GHz | - | -91.99 | -115.68 |
| Area: width (mm)×height (mm) | 184.32× 20 | 169.28×30 | 154.24×30 |



Fig. 3 — Comparison of conventional BPF, BPF with one BSF/CSRR and BPF with two BSF/CSRRs, (a) $S_{11}$ response and (b) $S_{21}$ response.

better optimization, we achieved a negligible insertion loss, i.e., $S_{21}$ (- 0.41 dB) at 0.89 GHz even on placing one BSF/CSRR and two BSF/CSRR as well as better $S_{11}$ (-35.37 dB) is obtained than the earlier reported values[11] of $S_{21}$ (-1.43 dB) and $S_{11}$ (-20 dB) at 0.9 GHz, respectively. The rejection level is found better than −18.94 dB from 1.7 GHz to 4.45 GHz in BPF with two BSF/CSRRs, which confirms that harmonic suppression up to $5f_0$. Also the maximum rejection level of -115.68 dB in the stop band (∼ 2 GHz) is achieved using two BSF/CSRR compared to -91.99 dB obtained for one, whereas previously this value is reported to be -75 dB at the fifth harmonic (∼ 4 GHz)[11]. This high value of rejection is offered by the second CSRR under BSF due to elecric field coupling near its resonance (i.e., 2 GHz). Such high rejection for undesired band in BPF response is really useful in the radar applications, where the sensitivity is upto - 120 dB. The high rejection level obtained in our simulated filter is sufficient to successfully suppress the undesired signals upto the fifth order harmonic. Also, the area of this BPF is decreased by 8.88% with respect to BPF with one BSF/CSRR with optimization in order to design a compact system.

## 4 Measurement Results

To validate the simulation results, we fabricated BPF with two BSF/CSRR on FR4 substrate ($\varepsilon_r$=4.5, height $h$ =1.5 mm and Cu thickness 18 μm) with the physical dimensions discussed in the section 2 (Fig. 4). The measured S-parameters of this filter are obtained from a vector network analyzer model N5227A of Keysight Technologies, USA and their comparison with the simulated results are shown in Fig. 5. The little differences in the simulated and experimental results are observed due to the tolerances in the fabrication process and slight change in substrate specifications.

In Fig. 5(a), smooth rejection in the stop band is found in the measured $S_{11}$ response even after 4 GHz to 5 GHz compared to the simulated response. Due to the open stub-spur line BSF proximity to CSRR, a large amount of electric field coupling occurs[9]. This coupling affects the resonance frequency and stop bandwidth of these filter components. In simulation, this coupling was not compensated and it has enabled the transmission of signal with small variation after 4.45 GHz. So compared to the simulated results, measured $S_{21}$ response is showing exact designed center frequency of 0.9 GHz for BPF and the better rejection level of - 49.78 dB is obtained at 4.5 GHz ($5f_0$) by two BSF/CSRR (Fig. 5(b)). In the stop band,
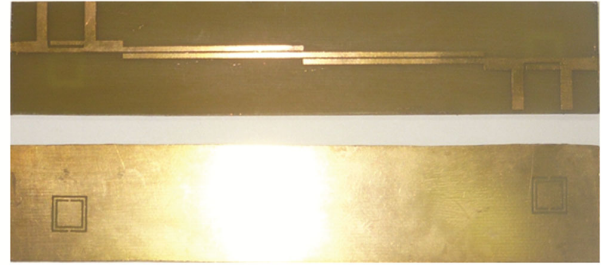


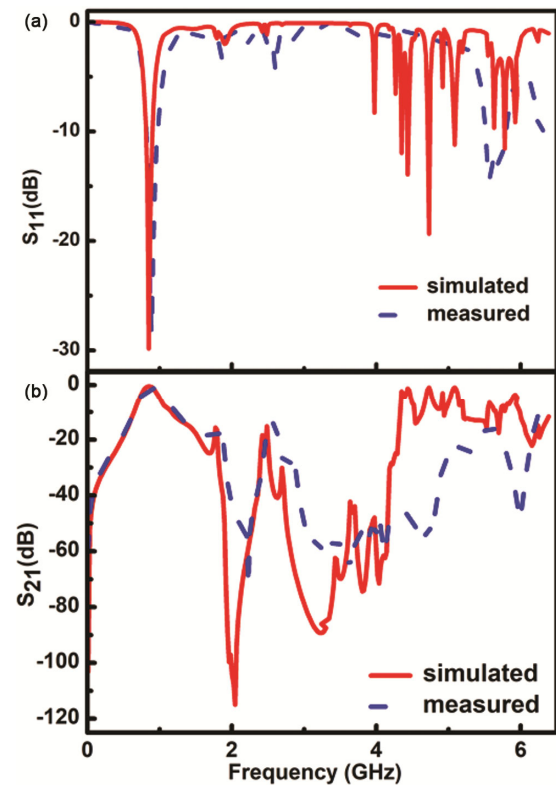Fig. 4 — Fabricated structure of BPF alongwith BSF (top) with two CSRRs (bottom).



Fig. 5 — Comparison of simulation and measured responses for BPF with two BSF/CSRR (a) $S_{11}$(dB) response and (b) $S_{21}$(dB) response.

however a maximum rejection level (-72.40 dB @ 2.23 GHz) has been found by CSRR than in the simulation result. Thus the stop bandwidth (< - 10 dB) is enhanced in the measured results upto 6.3 GHz (i.e., 7th order harmonic). The overall measured results have confirmed that the proposed design of such compact filter is satisfactory to the application of harmonic rejection.

## 5 Conclusions

In this work, the effect of additional BSF/CSRR is investigated on the performance of microstrip BPF for harmonic supression through the simulation and experimental study. The spurline based BSF backed

by CSRR at both input and output ports of BPF was optimized to have minimum dimensions without compromising the rejection performance. This BPF has been found to provide better performance in terms of harmonic suppression in the frequency band after the desired passband. The placing of second BSF/CSRR improves the rejection level as well as increases the stop bandwidth beyond the fifth harmonic. In future, applications of such compact BPF filters with effective suppression will be explored in a low-weight system design.

## Acknowledgment

## References

1   Yang F R, Ma K P, Qian Y & Itoh T, *IEEE Tran Microw Theory Tech*, 47 (1999) 1509.

2   Lopetegi T M, Laso A G, Hernandez J, Bacaicoa M, Benito D, Garde M J, Sorolla M & Guglielmi M, *IEEE Trans Microw Theory Technol*, 49 (2001) 1593.

3   Kuo J T, Hsu W H & Huang W T, *IEEE Microw Wirel Compon Lett*, 12 (2002) 383.

4   Kim B S, Lee J W & Song M S, *IEEE Microw Wirel Compon Lett*, 14 (2004) 413.

5   Öznazlı V & Ertürk V B, *www.emo.org.tr/ekler/0a7476842882400_ek.pdf,* (2006) 1.

6   Garcia-Garcia J, Martin F, Falcone F, Bonache J, Gil I, Lopetegi T, Laso M A G, Sorolla M & Marques R, *IEEE Microw Wirel Compon Lett*, 14 (2004) 416.

7   Garcia-Garcia J, Martin F, Falcone F, Bonache J, Baena J D, Gil I, Amat E, Lopetegi T, Laso M A G, Iturmendi J A M, Sorolla M & Marques R, *IEEE Trans Microw Theory Technol*, 53 (2005) 1997.

8   Tu W H & Chang K, *IEEE Microw Wirel Compon Lett*, 15 (2005) 268.

9   Bahrami H, Hakkak M & Pirhadi A, *Prog Electromagn Res*, 80 (2008) 107.

10  Ortiz N, Baena J D, Beruete M, Falcone F, Laso M A G, Lopetegi T, Marques R, Martin F, Garcia-Garcia J & Sorolla M, *Microw Opt Technol Lett*, 46 (2005) 88.

11  Karthikeyan S S & Kshetrimayum R S, *Prog Electromagn Res Lett*, 7 (2009) 193.

12  Yang S, *Int J Electromagn Appl*, 5 (2015) 108.

13  Pozar D M, *Microwave engineering*, 4th Edn, (John Wiley & Sons, Inc: New Jersey), 2012.