

Design and Development of Filtering Antenna for S-Band Applications with High out-of-band Rejection

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Abstract: In this paper, the design, simulation and fabrication of a filtering antenna is proposed. The filtering antenna structure is, therefore, framed by integrating elements, such as the feed line, parallel coupled resonators and the microstrip patch antenna array. The combined elements are designed for third order Chebyshev band pass filter with a pass band ripple of 0.1 dB and the integrated structure is more suitable for different S-band (2 GHz – 4 GHz) wireless applications. The equivalent circuit model for the proposed filtering antenna structure is analysed and the design procedure of the filter is also presented in detail. The 1x2 rectangular patch antenna array acts both as a radiating element and also as the last resonator of the band pass filter. The proposed filtering antenna structure results in high out-of-band rejection, enhanced bandwidth and a gain of about 209 MHz and 1.53 dB. The fabricated result agrees well with the simulation characteristics.

Keywords: Filter design, filtering antenna, out-of-band rejection, patch antenna array, S-band.

I. INTRODUCTION

To meet the demand of distant communication, the wireless systems operating in various frequency bands like L, S, C and X need an appropriate antenna array with good radiation characteristics. The microstrip patch antenna array is mostly preferred for different applications due to its characteristics like low profile, less cost, light weight and ease of fabrication. Due to the necessity of high gain, the antenna elements increase and hence, the feeding network gets complicated. The complexity causes unexpected resonances and results in bogus pass bands at unnecessary frequencies. Hence, the resultant fake signals can be removed by cascading a suitable bandpass filter and the patch antenna.

The combination of the filter and antenna into a solitary element helps to attain both filtering and radiating tasks concurrently. Especially, the antenna and the bandpass filter are both found to be significant components in the RF front

end to transmit or receive signals, select the required frequency band and also to suppress unwanted harmonics. In the earlier situation, antennas and filters were designed and brought together independently and linked with each other via a common reference impedance. Such imperfect matching results in additional transition loss and performance degradation. The combined elements (filter and antenna) therefore, called as filtering antenna, have been analyzed and designed in several ways [1]-[17] which is suitable for different wireless applications.

The authors [1] designed the filtering antenna by introducing four different concepts of electromagnetic structures and also analyzed their performance characteristics. In [2], the double layer stacked circular patch antenna was designed on a thin substrate and they have implemented matrix rotation techniques in the filter design to increase the return loss bandwidth. The authors [3]-[5] introduced different techniques in combining a patch element with the bandpass filter to achieve wider bandwidth and steeper response. In [6]-[7], a novel approach is followed in integrating a radiating element with the coupled line resonators. The authors [8]-[10] proposed the design of a differently shaped radiating patch and combined the structure with the conventional shaped resonator to achieve better pass band characteristics and a steeper roll off rate. The design procedure of the two pole Butterworth filter has been illustrated [11] and the prototype is therefore coupled with the fan shaped patch antenna using defected ground structure. The authors [12]-[14] proposed the novel design of a planar filtering antenna structure by considering the external quality factor. In [15], the last resonator of the filter is substituted by the radiating element which is the patch and they have used a proximity coupling feed to interconnect both the elements. The authors [16] proposed the concept of a simplified real frequency technique for better impedance matching by considering two different example structures. In [17], the authors designed an optimized microstrip structure using 3-pole hair pin resonator and a patch antenna and therefore, achieved optimal bandwidth and ideal return loss value. Even though many research works have been studied previously, however, till now more focus has not been given to the integration of the parallel coupled microstrip bandpass filter with the antenna array. In our previous work [18], we have designed the patch antenna array in series and in the

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corporate fed type and analyzed the gain, return loss plots and their radiation pattern measurements.

In this paper, the procedure of integrating a three pole parallel coupled microstrip bandpass filter with the 1x2 rectangular microstrip patch antenna array has been proposed. The radiating element which is the rectangular patch array is substituted as the last resonator. The third order ($n=3$) Chebyshev filter is designed by considering the pass band ripple of about 0.1dB, $F_{BW}=3.33\%$ and external quality factor of the filter $Q'_{e1}=30.978$ and $Q'_{e2}=35.545$. The Chebyshev approach is selected since it shows a definite ripple in the pass band region and could lead to an elevated slope in the stop band region. The proposed 3-pole filtering antenna is designed and fabricated for the centre frequency (f_0) of 2.4 GHz, using a Flame Retardant 4 dielectric substrate having a dielectric constant (ϵ_r) value of 4.4, 1.6mm substrate thickness (h) and loss tangent (δ) value of 0.02. The resultant structure is therefore designed and simulated using Ansoft High Frequency Structure Simulator Software (HFSS) which employs the finite element method to solve all 3D EM issues [19]. The proposed design not only resulted in considerable improvement in the bandwidth and gain value but also showed high out-of-band rejection. Our proposed configuration of the filtering antenna is found to be more suitable for present day S-band wireless communication system applications.

Section II clearly explains the design procedure and configuration of the filter, antenna array and filtering antenna equivalent circuit, and the simulated and fabricated results. We have also done a comparison of the proposed work with the other research works mentioned in the survey. Conclusions and future work are discussed in section III.

II. DESIGN PROCEDURE AND CONFIGURATION

A. Model of the filtering antenna

The configuration and layout of the proposed filtering antenna structure is shown in Fig. 1a and 1b. The filtering antenna contains half wavelength parallel coupled resonators, microstrip line feed and the patch element. The ground plane inserted in the centre is shared by both patch antenna and the filter. Through this configuration, the dimension of the whole structure can be considerably reduced. The elements, antenna and filter, are cascaded to match 50 Ohm impedance. The filter and antenna when united, directly result in impedance mismatch and hence, the performance of the filter gets affected, particularly near the band edges and also tends to increase the circuit's insertion loss. In order to avoid such deterioration, an additional matching network has been implemented between the filter and antenna. The matching network helps to match the quality factor value of the filter and antenna and thus, we were able to achieve a strong coupling between the two elements. We have used a sub-miniature version A (SMA) connector to feed the microwave power to the filtering antenna structure.

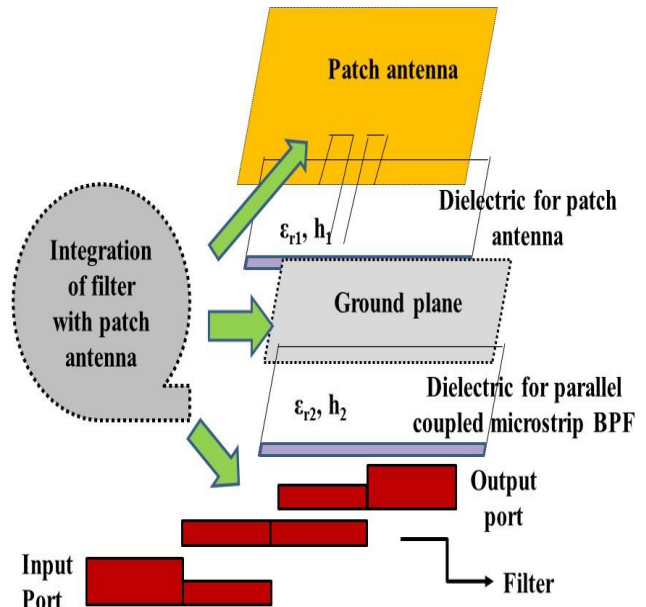


Fig. 1a. Layout of the filtering antenna structure (Top view)

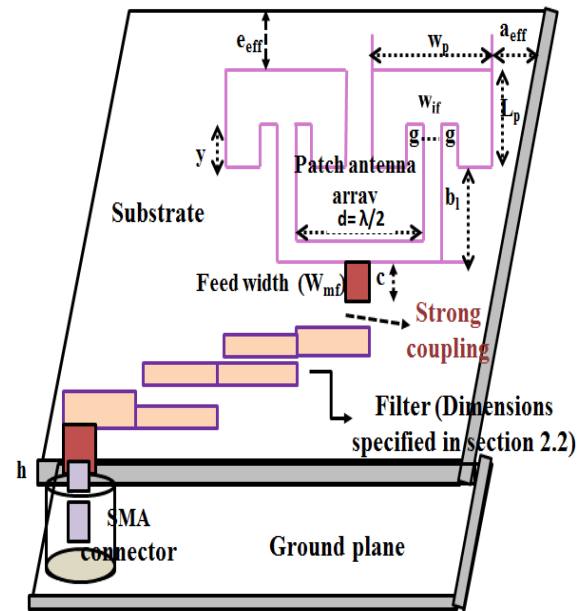


Fig. 1b. Layout of the filtering antenna structure (Front view)

From the results of our previous work [18], we identified that the corporate fed type patch structure resulted in an ideal gain of about 5.43 dB and bandwidth of 50 MHz at various distance values like λ , $\lambda/2$, $\lambda/4$ and so on. Hence, we have extended our work further by integrating the microstrip bandpass filter with the corporate fed type patch antenna array. The design specifications of the patch antenna array are listed in Table I.

Table- I: Specifications of the corporate fed patch antenna array

Symbol	Quantity	Values (mm)
Substrate Material: FR4_Epoxy		
ϵ_r	Dielectric constant	4.4
W_p	Patch antenna_ Width	38.04
L_p	Patch antenna _ Length	29.44
h	Substrate thickness	1.6
g	Feed line and patch element gap	0.3
b_l	Feed length	20.93
c	50 Ohms_ Inset depth	10.82
w_{mf}	Main feed width_ 50 Ohms	2.57
W_{if}	100 Ohms _ Feed width	0.44
y	100 Ohms_ Inset Depth	9.04
$d=\lambda/2$	Patch element distance	62.5
a_{eff}, e_{eff}	Effective length & width	5,5

B. Problem Formulation and Design of Microstrip BPF

Among various types of filters available, microstrip filters are found to be the good choice as they decrease the complexity of the microwave circuits and the passive elements used in the communication systems. Different dielectric materials like FR4, Teflon and Rogers Duroid are frequently employed as substrates in microstrip filters. The choice of those dielectric materials depends on the required frequency of operation, ease of use and allowed losses. The dielectric constant values and permittivity differ for these materials and hence, their electrical characteristics vary from one another under different operating conditions. Different types of conventional microstrip bandpass filters like hairpin type filter, half wavelength parallel coupled resonators, and stub line are commonly implemented in several RF/microwave applications [20]. Present day wireless communication systems need broadband wireless access and hence, we have used half wavelength parallel coupled microstrip band pass filters because of their simplicity, ease of fabrication and superior performance. Mathematical analysis and numerical computations are used to design the parallel coupled resonators and the design specifications vary for different applications. Regular assumptions for dielectric substrate thickness, material losses, tangent losses and conductor thickness are considered.

Standard steps are followed for designing and analysing the third order parallel coupled microstrip bandpass filter for the centre frequency (f_0) 2.4 GHz. The low pass prototype element values for the third order Chebyshev type filter with ripple 0.1 dB are obtained from the table specified [20]. The element values are $g_0=1$, $g_1=C'_1=1.0316$, $g_2=L'_2=1.1474$, $g_3=C'_3=1.0316$ and $g_4=1$. The low pass Chebyshev prototype filter element values are further transformed into the corresponding BPF L and C components using equations (1) and (2) . The filter transformation is achieved by replacing

the shunt capacitor with the parallel L and C component and the series inductor by the series LC component [20]. Here 50Ω characteristic impedance ($Z_0=1/Y_0$) is assumed for connecting the input and output resonator feed lines.

$$C_{p1} = \frac{C'_1}{Z_0 F_{BW} 2\pi f_0} \text{ and } L_{p1} = \frac{F_{BW} Z_0}{2\pi f_0 C'_1} \quad (1)$$

$$L_{s2} = \frac{Z_0 L'_2}{F_{BW} 2\pi f_0} \text{ and } C_{s2} = \frac{F_{BW}}{Z_0 2\pi f_0 L'_2} \quad (2)$$

The final obtained L and C values of the bandpass filter structure are $C_{p1}=C_{p3}=41.08\text{pF}$, $L_{p1}=L_{p3}=0.10703\text{nH}$ and $L_{s2}=114.24\text{nH}$, $C_{s2}=0.0384\text{pF}$. After obtaining the required L and C element values of the BPF prototype, the next step is to design the parallel coupled microstrip BPF structure using the equations specified below. The first step of the design is to obtain the J-inverter coefficients using equations (3), (4) and (5) and these coefficients help to obtain the characteristic impedance of the even mode and odd mode parallel coupled resonators.

$$\text{For } i=0, \frac{J'_{0,1}}{Y_0} = \left(\sqrt{\frac{\pi F_{BW}}{2 g_0 g_1}} \right) \quad (3)$$

$$\text{For } i=1 \text{ to } n-1, \frac{J'_{i,i+1}}{Y_0} = \frac{\pi F_{BW}}{2} \frac{1}{\sqrt{g_i g_{i+1}}} \quad (4)$$

$$\text{For } i=n+1, \frac{J'_{n,n+1}}{Y_0} = \sqrt{\frac{\pi F_{BW}}{2 g_n g_{n+1}}} \quad (5)$$

Where F_{BW} is the fractional bandwidth and it is given by the expression $F_{BW} = \frac{f_2-f_1}{f_0}=0.0333$. $J'_{i,i+1}$ is the characteristic admittance of the J-inverters. The external quality factors of the resonators $Q'_{e1}=30.978$ and $(Q'_{e2})=35.545$ are computed using the equation (6).

$$Q'_{e1} = \frac{g_0 g_1}{F_{BW}} \text{ and } Q'_{ei} = \frac{g_i g_{i+1}}{F_{BW}} \text{ for } i = 2 \text{ to } n-1 \quad (6)$$

The next step is to obtain the even mode Z'_{oe} and odd mode Z'_{oo} impedances using equations (7) and (8).

$$(Z'_{oe})_{i,i+1} = \frac{1}{Y_0} \left[1 + \frac{J'_{i,i+1}}{Y_0} + \left(\frac{J'_{i,i+1}}{Y_0} \right)^2 \right], \text{ for } i = 0 \text{ to } n \quad (7)$$

$$(Z'_{oo})_{i,i+1} = \frac{1}{Y_0} \left[1 - \frac{J'_{i,i+1}}{Y_0} + \left(\frac{J'_{i,i+1}}{Y_0} \right)^2 \right], \text{ for } i = 0 \text{ to } n \quad (8)$$

The calculated J inverter coefficients, and the even mode and odd mode impedance values for different values of 'i' are specified in Table II.

Table- II: Calculated coefficients of the filter

Order of the filter 'n' for different values of 'i'	J inverter coefficients $J'_{i,i+1}/Y_0$	Even mode impedance Values Z'_{oe}	Odd mode impedance Values Z'_{oo}
0	0.22517	63.794	41.277
1	0.04807	52.519	47.712
2	0.04807	52.519	47.712
3	0.22517	63.794	41.277

Using the even mode and odd mode impedance values specified above, the subsequent step is to find the dimensions of the coupled microstrip lines like width ' W_i ' and space ' G_i ' and length ' L_i '. Using equations (9) and (10), the spacing gap ' G_i ' between the resonators and width ' W_i ' can be calculated.

$$\frac{G_i}{h} = \left\{ \frac{2}{\pi} \cosh^{-1} \left[\frac{\cosh\left(\frac{\pi}{2}\right)\left(\frac{w}{h}\right)_{se} + \cosh\left(\frac{\pi}{2}\right)\left(\frac{w}{h}\right)_{so} - 2}{\cosh\left(\frac{\pi}{2}\right)\left(\frac{w}{h}\right)_{so} - \cosh\left(\frac{\pi}{2}\right)\left(\frac{w}{h}\right)_{se}} \right] \right\} \quad (9)$$

$$\frac{W_i}{h} = \left\{ \frac{1}{\pi} \left[\cosh^{-1} 0.5((p) + (q) * (r)) - \frac{\pi G_i}{2h} \right] \right\}$$

for $i = 1, 2, \dots, n$ (10)

Where $p = \cosh\left(\frac{\pi G_i}{2h}\right) - 1$, $q = \cosh\left(\frac{\pi G_i}{2h}\right) + 1$ and $r = \cosh\left(\frac{\pi}{2}\right)\left(\frac{w}{h}\right)_{se}$.

Here, $(w/h)_{se}$ and $(w/h)_{so}$ are obtained by applying the even mode and odd mode impedance values to the single microstrip lines and h is the height of the substrate. Its calculated dimensions are specified in Table III.

Table- III: Dimensions of $(w/h)_{se}$ and $(w/h)_{so}$

For different values of 'i'	$(w/h)_{se}$	$(w/h)_{so}$
0	3.8072	7.2836
1	5.0623	5.8014
2	5.0623	5.8014
3	3.8072	7.2836

Using the above values in equations (9) and (10), the final dimensions of width ' W_i ', spacing ' G_i ' are obtained and length L_i of the parallel coupled microstrip BPF are obtained using equation (11). The obtained values are specified in Table IV. The dimensions are further optimized to improve the performance of the filter and also for ease of fabrication. Hence, we have slightly adjusted the spacing gap between the resonators as $G_{1,4}=0.2$ and $G_{2,3}=1.1$.

Table- IV: Calculated and final optimized dimensions of Parallel coupled BPF in (mm)

Parameters	Calculated dimensions of the BPF	Optimized dimensions of the BPF
W_1, W_4	2.98159	2.98
L_1, L_4	17.142	17.14
G_1, G_4	0.133	0.2
W_2, W_3	3.5973	3.6
L_2, L_3	17.0096	17.01
G_2, G_3	1.28761	1.1
$L_{50\Omega}$	17.01	17.01

The length ' L_i ' of the coupled line resonator at every stage is computed using the expression,

$$L_i = \frac{\lambda}{4\sqrt{\epsilon_{re}}} \quad (11)$$

Where $\lambda=c/f_0$, c is the velocity of light in (m/sec) and

$$\epsilon_{re} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} \left(\frac{1}{\sqrt{1 + ((12 * h)/W_i)}} \right) \quad (12)$$

The dimensions obtained are rounded off and the resultant layout of the three pole parallel coupled microstrip BPF is illustrated in Fig. 2.

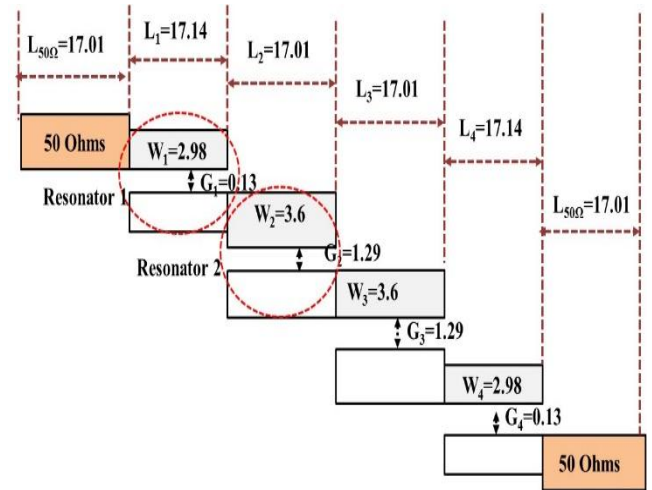


Fig. 2. Microstrip layout of the third order Parallel Coupled Microstrip BPF

The simulated return loss plot for the calculated and optimized dimensions of the filter is shown in Fig.3. The plots show a fine frequency response with their return loss value S11 for the calculated dimensions (solid line) reaching -29.27 dB at 2.27 GHz and -19.72 dB at 2.38 GHz. Insertion loss which is S21 for the calculated dimensions (solid line) is -3.2 dB and the bandwidth of

the filter is approximately found to be 280 MHz (from 2.166 to 2.446 GHz). For the optimized filter dimensions (dashed line), it is found that, the return loss S11 got reduced which is -20.65 dB at 2.28 GHz and -15.35 dB at 2.43 GHz. Insertion loss S21 is -2.86dB and the bandwidth of the filter is gradually increased to about 340 MHz (from 2.14 to 2.48 GHz). Hence, we have continued our work with the optimized filter dimensions.

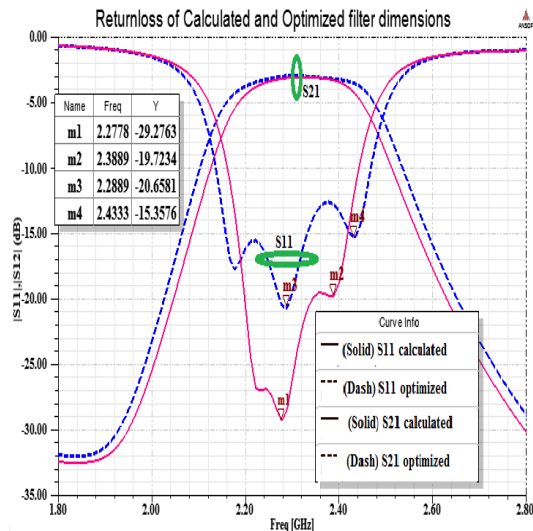


Fig. 3. Comparison of the simulated S Parameters of BPF

The next step is to design the structure of the filtering antenna, and that is obtained by integrating the parallel coupled microstrip BPF with the patch antenna.

C. Equivalent circuit model of the proposed filtering antenna structure and simulation results

The equivalent circuit of the proposed filtering antenna structure is shown in Fig. 4. A single rectangular microstrip patch antenna is represented by the parallel combination of the R_1 , L_1 and C_1 circuit [21]-[23].

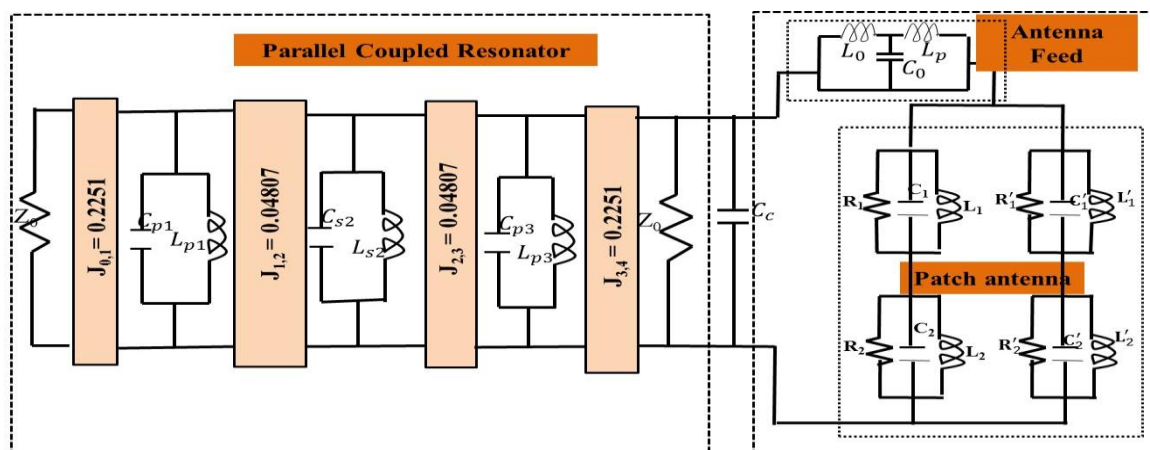


Fig. 4. Equivalent circuit of the Filtering Antenna structure

The resonant frequency of the patch is determined by the L_1 and C_1 components. The pair of slots incorporated into the rectangular patch structure of dimension $g=0.3\text{mm}$ increases the bandwidth and the second resonant frequency is determined using the L_2 and C_2 components. Similarly, the parameters of the second patch antenna are represented by R'_1 , L'_1 , C'_1 and R'_2 , L'_2 , C'_2 . The microstrip line feed is designed for the impedance 50Ω and it connects the radiating patch elements. The microstrip line feed can be represented as an equivalent T- shaped structure [24] containing capacitor C_0 , strip inductance L_0 and patch inductance L_p . Both, the half wavelength parallel coupled resonators and the antenna array are integrated using the coupling capacitor C_c . The dimensions of the filter and their parameters have already been described in section B.

Initially, we had started our work by integrating the single patch antenna with the parallel coupled microstrip BPF and the summary of our analysed results is specified in Table V.

Table- V: Single patch element and BPF

Element	Return loss	Bandwidth	Gain (dBi)
Single patch without BPF	-23 dB	70 MHz	3.29
Single patch with BPF	-25 dB	180 MHz	0.6

Through our analysis, we identified that, the integration of the filter and single patch element suppressed the unwanted frequency band apart from the required frequency which is 2.4 GHz. We also observed that the bandwidth of the filtering antenna structure is increased by about 2.5 times more when compared to the structure designed without the filter. From our simulated plot, we came to know that, the slight mismatch during interconnection resulted in the degradation on band edge selectivity and also found that, the gain value got considerably decreased which is less than 1 dB.

Hence, such problems can be surmounted by using the array of microstrip patch elements. So, we have replaced the single patch antenna with the array of patch (1x2) elements which act as the last resonator of the BPF. The dimensions of the proposed filtering antenna structure are $L_p \times W_p$ is 170mm x 93mm. The designed structure is simulated and the comparison plot is shown in Fig. 5 for the patch element array without band pass filter and the antenna array with band pass filter.

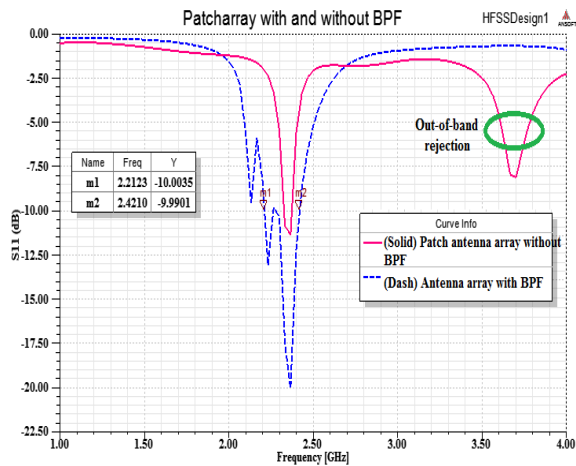


Fig. 5. Return loss plot for patch antenna array with and without BPF

For, the patch antenna array without BPF (Solid line), we were able to attain the bandwidth of about 50 MHz [18]. The value of the quality factor of the patch element array is $Q_f(\text{patch array}) = f_0/\Delta f = 48$. The integration of filter and antenna is done in such a way that, their external quality factor values are comparatively matched. Compared to the patch antenna array, the proposed filtering antenna structure (Dashed line) eliminates an unwanted frequency band which is 3.75 GHz and also resulted in the enhanced bandwidth of about 209 MHz. The combined structure shows fine characteristics with the return loss value of about -20 dB at 2.36 GHz. The impedance mismatch during interconnection results in a maximum return loss value at the passband of about -9.77 dB at 2.26 GHz and -5.89 dB at 2.16 GHz.

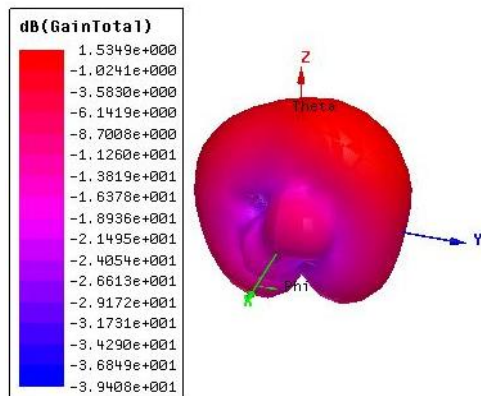


Fig. 6. Gain plot of the proposed filtering antenna

The obtained gain value and the directivity of our proposed structure is about 1.53 dB [Fig. 6] and 9.63 dB. The E-plane and H-plane far field radiation pattern of our proposed structure [Fig. 7] is simulated for different values of theta (0° to 360°) and phi (0° , 90°) for the centre frequency 2.4GHz. We have observed a unidirectional pattern in both the xz and yz planes. The HPBW for the E-plane radiation pattern is approximately about 342° .

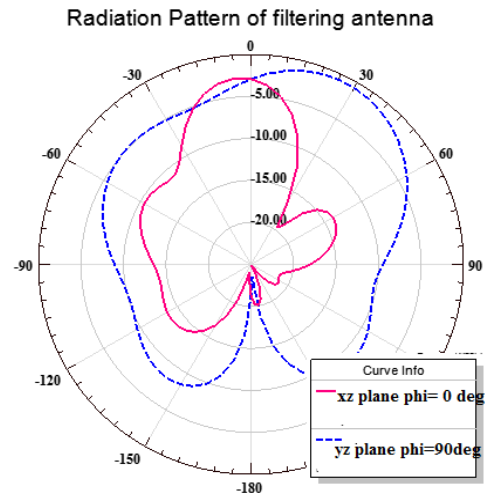


Fig. 7. Radiation Pattern

The impedance matching characteristics of the filtering antenna structure at the desired frequency points are illustrated in Fig. 8. From the plot, we inferred that, a perfect matching of 47.25 Ohms is observed at 2.398GHz. Thus, through our proposed structure, we were able to achieve a good impedance matching.

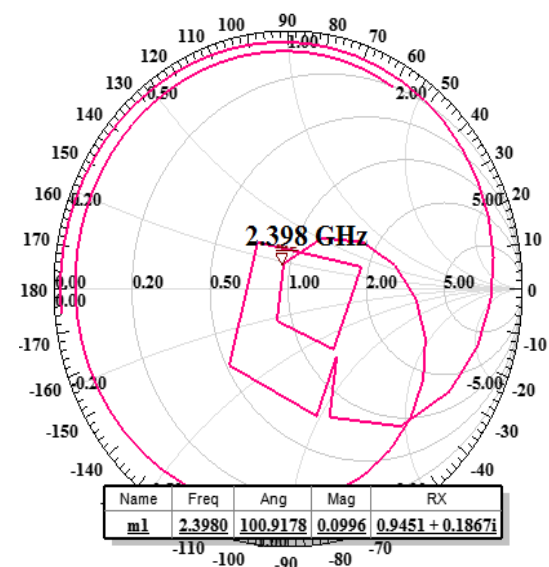


Fig. 8. Impedance matching plot

D. Measurement results of fabricated structure

The proposed filtering antenna structure is fabricated using FR4_epoxy substrate material for 1.6mm substrate thickness. The fabricated structure is then tested using a vector network analyzer which is calibrated suitably using the calibration kit that includes short, open and matched loads. The measured response is recorded for the return loss characteristics and the comparison plot is made for the simulated and fabricated responses as shown in Fig. 9. Thus, our fabricated structure also resulted in fine characteristics similar to the simulated curve achieving a bandwidth of about 200MHz [Table VI].

Table-VI: Comparison value of simulated and fabricated responses

Design	Return loss	Bandwidth
Simulated result	-20 dB	209 MHZ
Fabricated result	-26 dB	200 MHZ

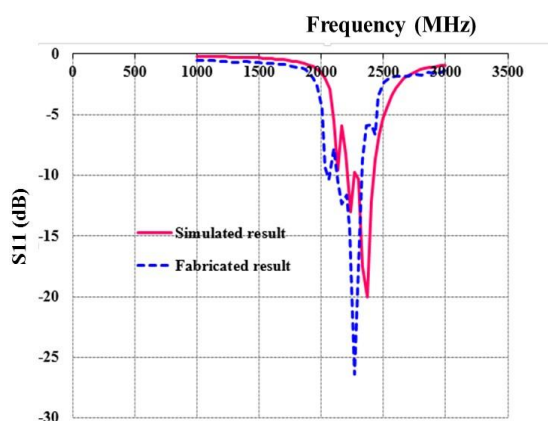


Fig. 9. Comparison of simulated and fabricated responses

The snapshot of the proposed fabricated filtering antenna structure is shown in Fig. 10.

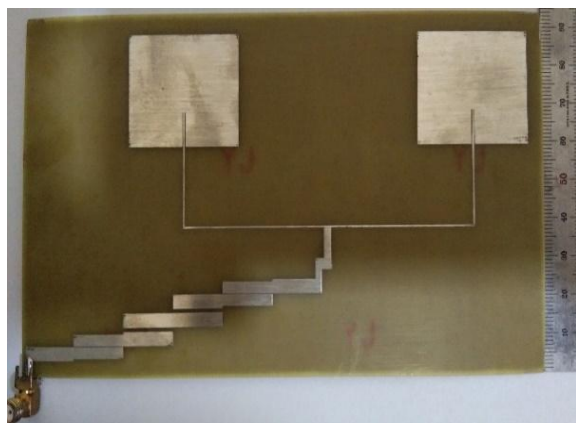


Fig. 10. Photograph of the fabricated filtering antenna structure

Finally, a comparison of the proposed filtering antenna structure is done with the other works mentioned in the literature and it is shown in Table VII. Even though different types of filtering antenna structures have been implemented, only a few papers focussed on integrating parallel coupled resonators and the patch antenna array. Our proposed structure helped to achieve significant improvement in the bandwidth (BW) of about 209 MHz, considerable return loss (RL) of about -20dB, and an optimum gain of 1.53dB, and also rejected unwanted frequency bands.

Table-VII: Comparison with other research works

Ref No .	Freq (GHz)	Antenna Type and filter	Size ($\lambda_g \times \lambda_g$)	BW (MHz)	RL (dB)	Order of the filter	Gain (dBi)
[6]	5	2x2 Microstrip patch array and hair pin resonator	1.72x1.48	200	-20	3	6.5
[8]	2.4	Inverted L and parallel coupled resonator	0.9x1.05	150	-10	2	0.65
[10]	5	U-Shaped patch and T-type resonator	0.46x0.5	200	-20	1	2.5
[12]	3	Rectangular patch and End-End coupled resonator	0.87x0.41	100	-30	5	3.5

[15]	2	Rectangular patch and Hairpin resonator	1.07x1.14	80	-35	3	4
[17]	2.45	Hairpin resonator and patch antenna	1.65x0.52	50	-15	3	--
This work	2.4	1x2 Rectangular Patch array and parallel coupled resonator	2.81x1.5	209	-20	3	1.53

III. CONCLUSION

The design, simulation and fabrication of the filtering antenna structure suitable for S-Band wireless applications is proposed in this work. The designed antenna array structure acts both as a radiating element and also as the last resonator of the band pass filter. The integration of the filter and antenna not only helps to obtain a compact structure but also decreases the cost of the communication system. Through our novel configuration, we could simultaneously observe out-of-band rejection, wider bandwidth of about 209 MHz and better frequency selectivity. The structure also shows good agreement between the simulated and fabricated responses. Our future work is to design a filtering antenna with enhanced bandwidth and gain by using a well optimized design.

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