Analysis of higher order Microstrip Filter to Reduce Out-of-Band Emissions

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ABSTRACT In this paper a fifth order wide-band Chebyshev micro-strip filter is designed at 5.2 GHz frequency, where the spectrum contains white spaces. The fifth order is extended to 7th, 9th, 11th, and 13th order and simulated using HFSS EM simulator. Simulation results show that compared to 5th order, the higher order filters provide more and more reduction in out-of-band emissions in increasing order from 5th to 13th order filter. A 13th order filter is fabricated and tested for more reduction in the OOBE by using dumbbell shaped slots as defected ground plane structure. Five such slots are made in the ground plane for better results to reduce more OOBE. This 13th order filer with slots is fabricated and tested. The substrate chosen is FR4 with height 1.6 mm. Here we have given a mathematical treatment for emission mask for OOBE according to ITU recommendations. The designed filter's transmission characteristics from port 1 to port 2 give good agreement with the recommendations.

INDEX TERMS Cognitive Radio, Emission mask, Microstrip filter, Out-of-band emission.

I. INTRODUCTION

Recently Cognitive Radio (CR) technology has drawn attention of communication engineers, researchers and entrepreneurs to solve spectrum congestion problems. If primary users (PUs) cannot use the channel bandwidth, secondary users (SUs) can use the available spectrum without any interference with the PUs. Synchronizing PUs and SUs is not feasible, since they transmit independently [1]. Therefore in order to reduce interference from SUs to either PUs or neighboring SUs, Out-of-Band-Emission (OOBE) from the SUs transmitter has to be minimized and adjacent channel interference has to be reduced [2]-[3]. The CR must have the ability to transmit or receive in any white space between few MHz to few GHz frequency bands.

The unwanted emissions are OOBEs and spurious emission. Emissions in frequency domain outside the necessary bandwidth resulted from modulation process are OOBEs. "Inter-modulation products, frequency conversion products, parasitic emissions and harmonic emissions are examples of spurious emissions"[4]. "The necessary bandwidth is the range of frequencies sufficient to transmit the information at a specified rate and required quality of service" [5]. ITU recommendations for start and end of OOB domain is such that the offset plus or minus from the necessary bandwidth, B_n's centre for the start of the OOB domain is 0.5 $*B_n$, where B_n is necessary bandwidth. For a narrow band $B_n < B_L$, wideband $B_n > B_U$, where B_L and B_U are lower and upper threshold values of necessary bandwidth. For normal band it lies between B_L and B_U. The frequency separation between the centre frequency and the spurious boundary for narrow band is 2.5 B_L and B_U + 1.5 B_n for wideband [6].

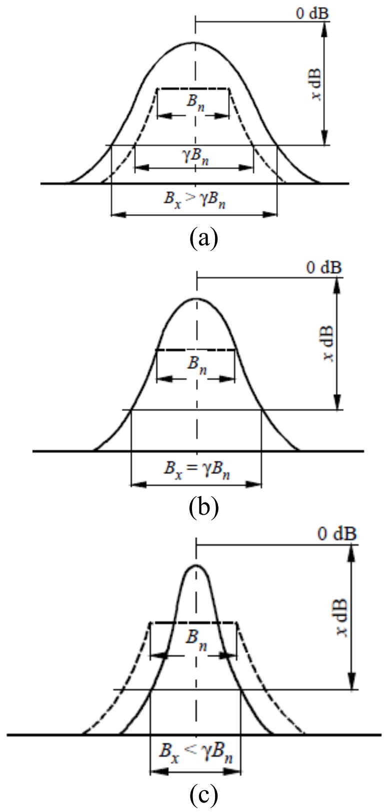


FIGURE 1. Definition of necessary bandwidth (a). Emission wider than optimum, (b). Emission corresponding to optimum, (c). Emission narrower than optimum.

In the spectra shown above, B_n is necessary bandwidth, B_x is bandwidth at x dB, x is the value of measurement level in dB, γ parameter of the limiting curve for the out-of-band spectrum and β/2 half of the permissible out-of-band power. "The power of the out of band is understood as the total power emitted by the out of band frequencies" [7]. The permitted out-of-band power is defined as a percentage 'β' of the radiated total mean power and extracted from the limiting curve. The methods to determine OOB emission energy, calculation of total power in an adjacent band and emission mask are described in ITU recommendations [7-9].

In the following section a 5th order Chebyshev filter is designed at centre frequency 5.2 GHz which falls in unlicensed Wi-Fi band. This band must coexist with LTE cellular and wireless LAN frequencies wherein it is much required to mitigate crosstalk and co-channel interference respectively. It is also useful to suppress the harmonic, parasitic and spurious emissions [10-11].

II. FILTER DESIGN

The geometrical specifications of the filter are; Substrate FR4 with height 1.6 mm, ground plane and the filter on the top of substrate is of copper and thickness 0.035 mm, centre frequency 5.2 GHz and terminal impedance is 50 Ω. The first step in design of micro-strip filters is to determine the order of the filter as per the given specifications using (1) as depicted in [11].

$$n \geq \frac{\cosh^{-1}\left(\sqrt{\frac{10^{0.1L_{As-1}}}{10^{0.1L_{Ar-1}}}}\right)}{\cosh^{-1}(\Omega_s)} \quad (1)$$

Where, L_{As} is stop band attenuation and L_{Ar} is pass-band ripples. Considering filter as a two-port network, the prototype values depending on the Chebyshev approximation are calculated from equations in (2).

$$\left.\begin{array}{l} g_0 = 1.0 \\ g_1 = \frac{2}{\gamma}\sin\left(\frac{\pi}{2n}\right) \\ g_i = \frac{1}{g_{i-1}} \frac{4\sin\left[\frac{(2i-1)\pi}{2n}\right]\sin\left[\frac{(2i-3)\pi}{2n}\right]}{\gamma^2 + \sin^2\left[\frac{(i-1)\pi}{2\pi}\right]} \\ g_{n+1} = \begin{cases} 1.0 & for\ n\ odd \\ \coth^2\left(\frac{\beta}{4}\right) & for\ n\ even \end{cases} \end{array}\right\} \quad (2)$$

Where,

$$\beta = \ln\left[\coth\left(\frac{L_{Ar}}{17.37}\right)\right]\ and\ \gamma = \sinh\left(\frac{\beta}{2n}\right) \quad (3)$$

For a pass-band ripples of 0.01 dB, with centre frequency 5.2 GHz, fractional bandwidth of 0.192 to get a bandwidth > 500 MHz at 5.2 GHz and terminal impedance of 50 Ω, the proto-type values are found as, $g_0 = 1, g_1 = 0.7563, g_2 = 1.3049, g_3 = 1.5773, g_4 = 1.3049 = g_2, g_5 = 0.7563 = g_1,\ and\ g_4 = 1 = g_1.$

For the lumped model of the filter, impedance and frequency scaling are performed using (4) through (9),

$$L'_1 = \frac{L_1 Z_0}{\omega_0 \Delta} \quad (4)$$

$$L'_2 = \frac{\Delta Z_0}{\omega_0 C_2} \quad (5)$$

$$L'_3 = \frac{L_3 Z_0}{\omega_0 \Delta}\ etc. \quad (6)$$

$$C'_1 = \frac{\Delta}{L_1 Z_0 \omega_0} \quad (7)$$

$$C'_2 = \frac{C_2}{L_1 \Delta \omega_0} \quad (8)$$

$$C'_3 = \frac{\Delta}{L_3 Z_0 \omega_0}\ etc. \quad (9)$$

Where, Δ is fractional bandwidth, FBW=0.192. For the distributed model, length of capacitance and length of inductance are calculated using,

$$Length\ of\ capacitance = \frac{Z_l}{R_0 C_k} \quad (10)$$

$$Length\ of\ inductance = \frac{L_k R_0}{Z_h} \quad (11)$$

Where, Z_l = low impedance value = 26.21Ω, Z_h = high impedance value = 82.04 Ω and R_0 = Characteristic impedance. For first element shunt, Chebyshev approximation leads to circuit prototype shown in Fig. 2.

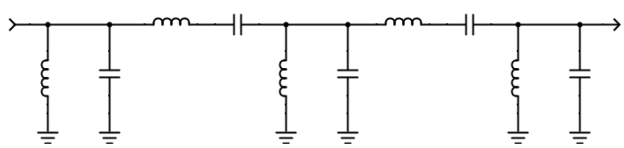


FIGURE 2. Distributed model of the Chebyshev 5th order filter.

For $L_1||C_1$ the first shunt element, the distributed parameters are inductance (in nH), L_1=0.008, L_2=519.214, L_3=0.004, L_4=L_2, and L_5=L_1, capacitance (in pF), C_1=120.376, C_2=0.002, C_3=251.038, C_4=C_2, and C_5=C_1.

The electrical lengths of the distributed parameters are calculated using (12) and (13),

$$For\ L_l||C_l,\ (parallel\ element)\beta l = 90^o \quad (12)$$

$$and\ L - C(series\ element), \beta l = 180^o \quad (13)$$

Where $\beta = 2\pi/\lambda_g$ and λ_g is guide wavelength. The dimensions of the low impedance element are found to be length, L_l = 8 mm, width, W_l = 1 mm and that for a high impedance element are L_h = 14.27 mm & W_h = 10 mm. Fig. 3 shows the dimensions of the 13th order Chebyshev filter with combination of low and high impedance elements.

The parameters used to design the filter are wide band rejection, very high attenuation in the stop band, to fit in the specifications of FCC spectral mask.

Initially a 5th order filter was designed at centre frequency of 5.2 GHz and bandwidth > 500 MHz for UWB application, to fit the attenuation mask as described by FCC [7]. Then the order of the filter is increased for high stop band rejection and ground plane defects are placed to get sharp roll off in the stop band so that spurious emissions, harmonic emissions and parasitic emissions are rejected.

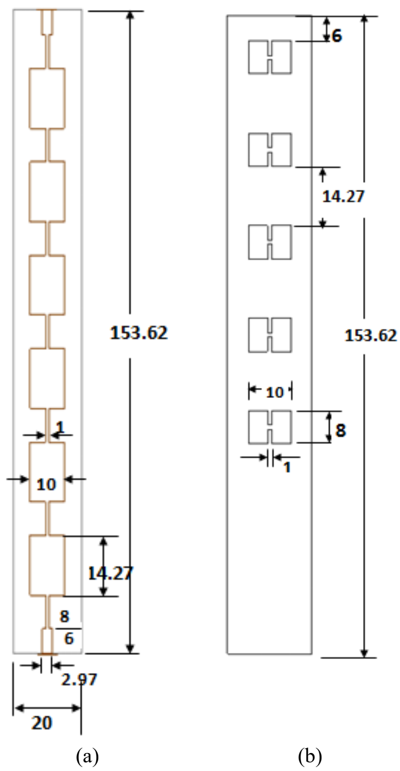


FIGURE 3. Dimensions of the 13th order Chebyshev filter (a) top view and (b) DGS array in bottom view.

III. SIMULATION

The filter is first simulated in the circuital model using Quite Universal Circuit Simulator (QUCS) open source software. Filter synthesis tool is used to design and rig up the 13th order Chebyshev band-pass filter circuit. Fig. 4 presents the circuit model of the filter from QUCS and Fig. 5 presents the return loss S_{11} & transmission characteristics of the filter from port one to port two S_{21}.

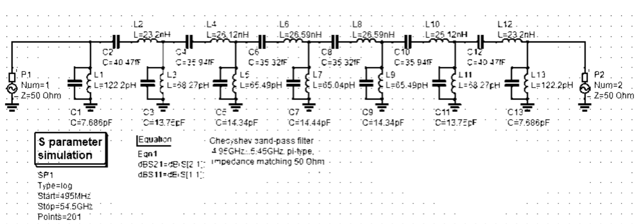


FIGURE 4. 13th order Chebyshev band pass filter circuit model in Qucs.

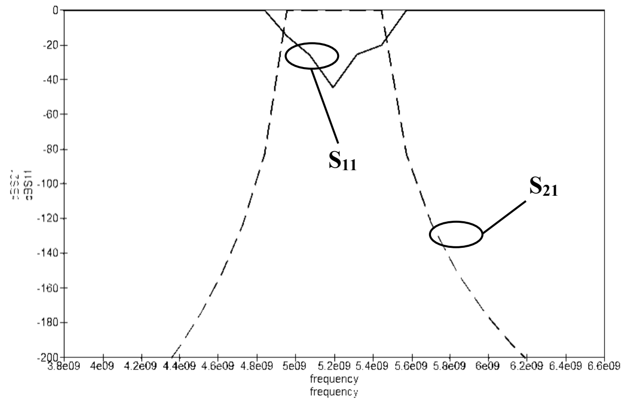


FIGURE 5. Return loss and Transmission S_{21} of the filter circuit

The circuit simulation is with ideal cases of perfect impedance matching at the two ports for 50 Ω, since it is a circuit there will be no radiation losses. The minimum return loss -44.5 dB is obtained at 5.19 GHz frequency with a bandwidth of about 540 MHz and the insertion loss is -0.1 dB.

The filter is simulated using HFSS EM tool. Fig. 6 and Fig. 7 depict the 5th order filter structure and return loss & gain respectively.

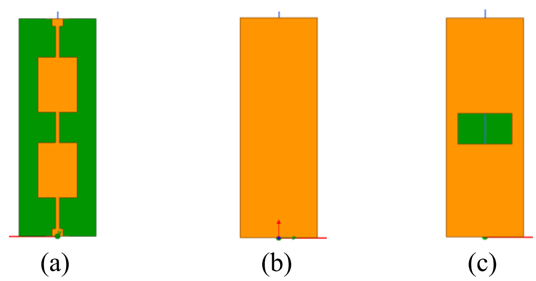


FIGURE 6. 5th order Chebyshev band pass micro-strip filter (a) Top View (b) Bottom View without slot (c) Bottom View with slot in the ground plane.

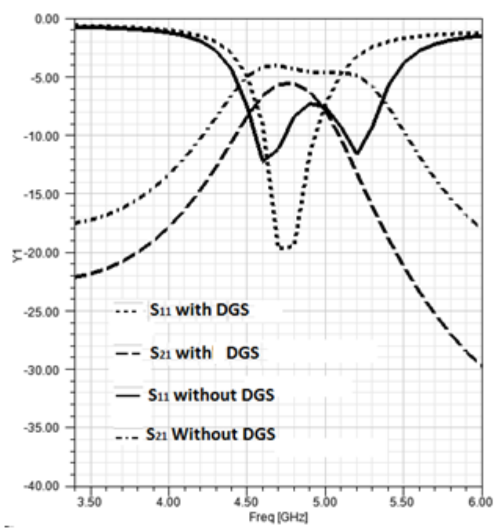


FIGURE 7. 5th order Chebyshev band pass micro-strip filter S_{11} and S_{21} with and without DGS.

It is observed that without the defected ground, the filter behaves as a wideband filter and with a ground plane containing a slot of size 14 mm X 8 mm becomes a slightly narrow band. And the S_{21} curve show that, with slot in the ground plane reduces the out of band emissions. The 5th, 7th, 9th, 11th and 13th order filters are simulated, by extending the number of low and high impedance elements. The structures of all order are shown in Fig. 8. These filters' simulation results for S_{21} are shown in Fig. 9. As the order of the filter is increased from 5th to 7th and so on to 13th order, it is observed more of the OOBE are reduced. Later an 11th order filter is made defected ground, means, with a slot in the ground that results into reduced OOBE.

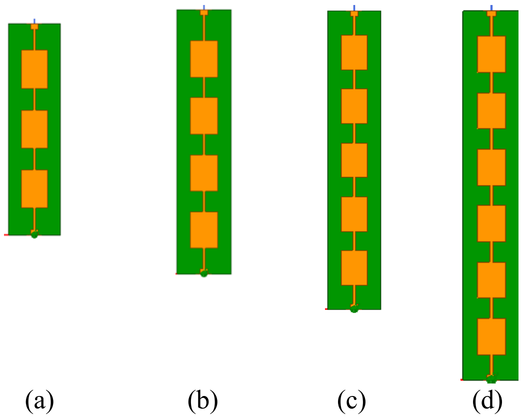


FIGURE 8. Structure of Higher order micro-strip Chebyshev filter of orders (a) 7th (b) 9th (c) 11th (d) 13th.

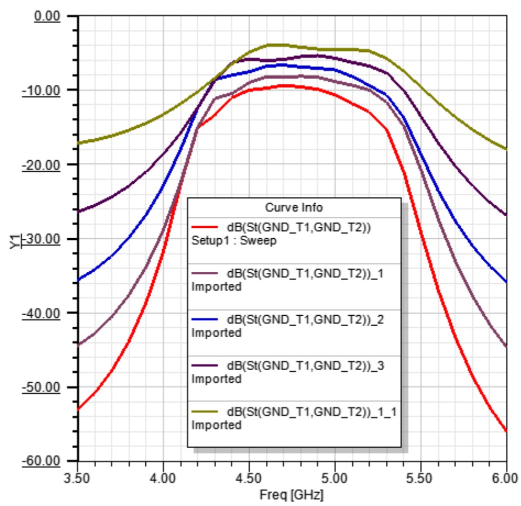


FIGURE 9. S_{21} of the higher order filters.

The current density on the top of the filter and that on the surface of the ground plane is presented in Fig. 10. The surface current variations on the filter top and on the ground plane are compared. It can be seen that on the filter top from where there is a slot on the ground plane the surface current density reduces from port 1 to port 2 near port 2. On the other case of without slot in ground, current density is observed near port 2. "The H-shaped Ground Plane Aperture (GPA) behaves as a series high impedance inductive element and low impedance shunt capacitive element. Hence the GPA provides large impedance ratio and so a good stop band characteristics. The filter with GPA EBG structure shows sharper cut-off in the stop-band and the out of band emissions are suppressed effectively" [12]-[18].

Later the total effective inductance is increased by making dumbbell shaped slots EBG structure in the ground plane as shown in Fig. 11. Here we have selected the 13th order Chebyshev filter and simulated in HFSS. For the designed and fabricated 13th order Chebyshev band-pass micro-strip filter, the simulated return loss and the gain with respect to frequency is shown in Fig. 12. Two peaks are observed, one at 4.5 GHz with return loss of -11 dB and other at 5.2 GHz with return loss of -27 dB. S_{21} is not evident at the first peak in simulation so the return loss at 4.5 GHz is ignored. The use of H-shaped EBG structure in the ground plane is very useful for improving the stop-band attenuation. Deep attenuation in the stop-band has degraded the selectivity and has increased the insertion loss in the pass band. The insertion loss obtained is -18 dB in simulation. The comparison of S_{21} for the cases of 5th, 7th, 9th, 11th, 13th, and 13th order with dumbbell shaped slot creating a DGS is shown in Fig. 13.

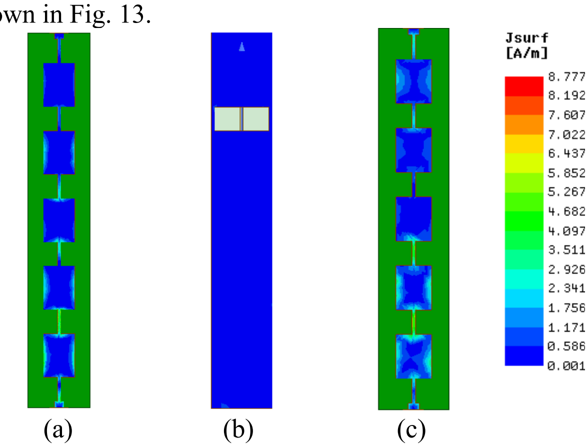


FIGURE 10. Surface current density (J) variation on the (a) filter top (b) ground plane (c) filter top without slot in ground.

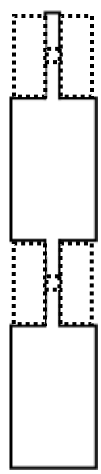


FIGURE 11. Dotted line structure is slot in the ground plane.

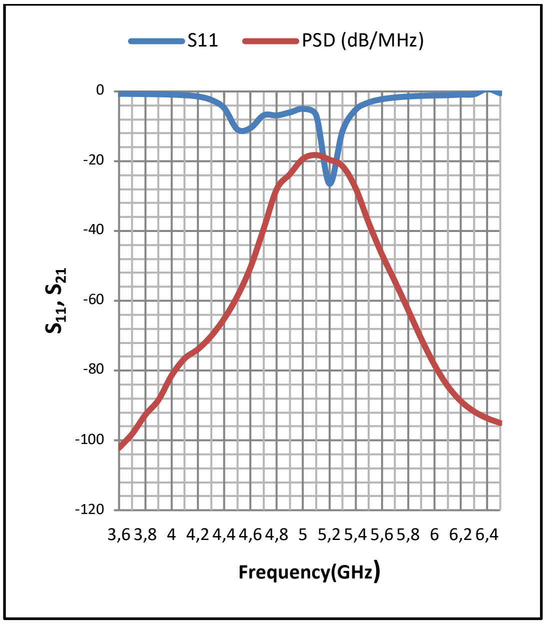


FIGURE 12. S_{11} and S_{21} variation with frequency of the 13th order filter.

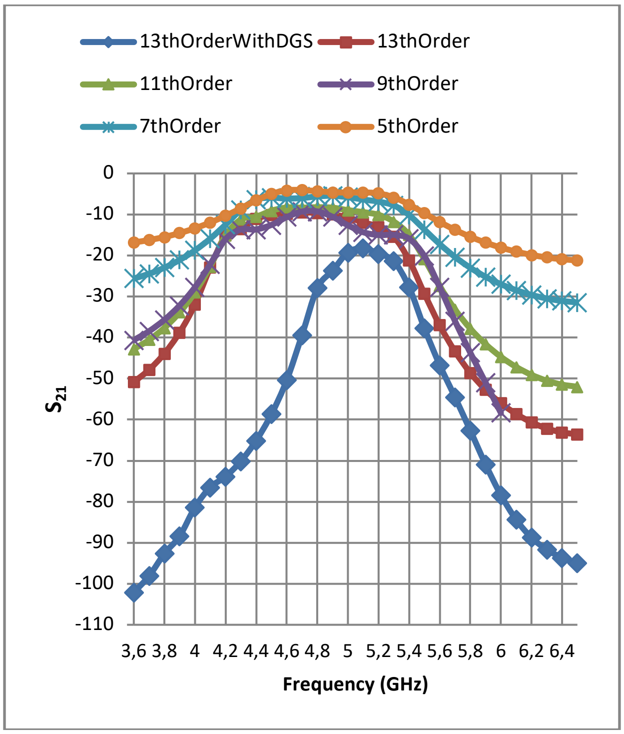


FIGURE 13. S_{21} comparison of the higher order filters with that of the 13th order with DGS.

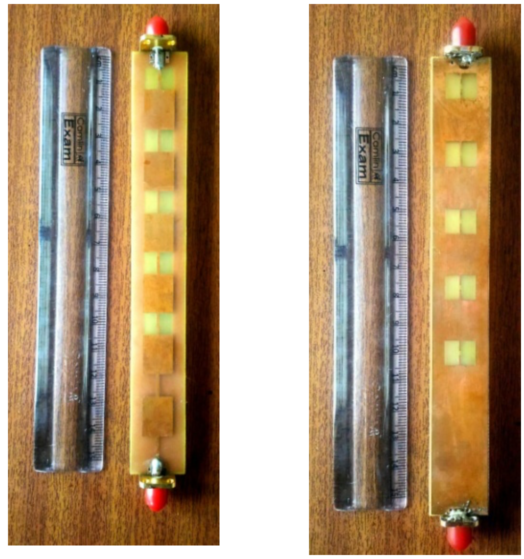
Fig. 14 presents the front and back view of 13th order Chebyshev filter which has been fabricated and tested. Fig. 15 shows the comparison of gain of the simulated and fabricated filter. The measured insertion loss is -10.2 dB, which is higher. This is due to the following reasons;

i). Impedance mismatch at the two ports

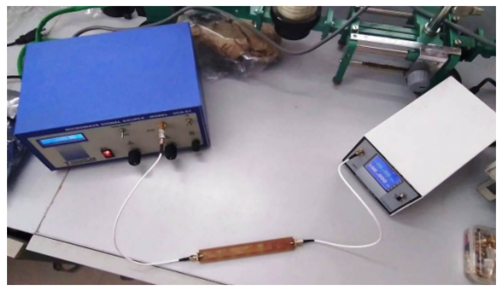
ii). Radiation losses at higher frequencies

iii). Excessive length of the filter

It is observed that this higher order filter with DGS will give more reduction in OOB around 5.2 GHz frequency with very wide bandwidth.



(a) (b)



(c)

FIGURE 14. Photograph of the 13th order with DGS (a) front view (b) back view, (c) testing using power meter.

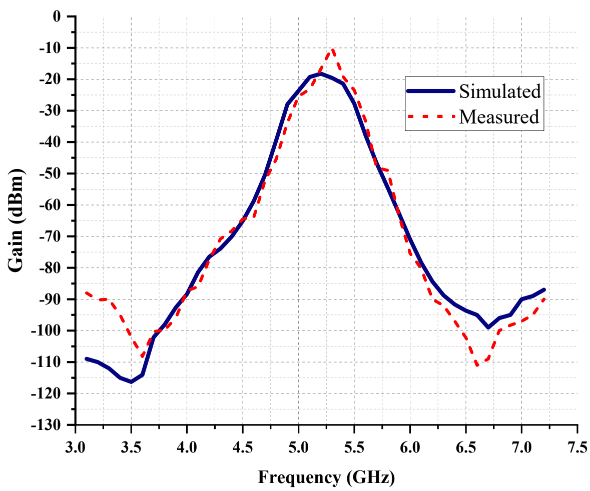


FIGURE 15. Comparison of simulated and measured gain (S_{21}) of 13th order Chebyshev microstrip filter with dumbbell shaped DGS.

TABLE I. Comparison of the proposed filter with others in references

Ref.	Size of the filter (mm × mm)	Centre Frequency (GHz)	Bandwidth (MHz)	IL (dB)	No. of Bands
[16]	11.6 × 14.5	4.90	600	-0.30	1
[17]	15.0 × 05.7	1.62	400	-2.56	1
[18]	20.0 × 19.5	4.20, 7.7	400, 500	-1.00	2
[19]	20.0 × 20.0	6.10	200	-1.5	1
[20]	0.84 × 1.60	10, 13.5	> 500	-3.1	2
[21]	10.0 × 14.0	3.55	440	-2	1
This Filter	20 × 153.62	5.20	600	-10.00	1

IV. CONCLUSION

The DGS prepared in the ground plane is little tricky, where only five units of array of dumbbell shaped etching is completed as slots. Two more slots are removed at the bottom part to increase total effective inductance to improve the stop band and hence to extend more reduction in OOBE. The measured results obtained are compared with that of simulation results. This filter can be used in an antenna feed, so that, the antenna does not radiate out of band. This filter is designed for cognitive radio applications.

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