Gap-Coupled Resonator Loaded Ultra-Wideband Filtenna for Frequency-Notching Applications

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***Abstract*— A fifth order gap-coupled resonator loaded ultra-wide band (UWB) filtenna is proposed in this research article. The band-stop butterworth filter is designed at the ISM frequency of 5.8 GHz and an ultra-wideband circular shaped microstrip patch is integrated with the extended end of the filter. The filter is designed using the concept of the gap coupled microstrip stub sections with a metallic via connected at the end producing all the necessary capacitive and inductive effects to show its band-stop property at the ISM band. It produces a sharp narrow--band notch at 5.8 GHz and helps the antenna to utilize all the available frequency bands by eliminating the possibility for the antenna to interfere with only 5.8 GHz ISM band.**

***Keywords*— filtenna, ultra-wide band antenna, frequency notching, band-stop filter, ISM band.**

I. INTRODUCTION

In our world of modern wireless communication, planer ultra-wideband microstrip antennas have become very popular candidate and they are gaining more interest with time from the antenna and electromagnetics community because of few of their unique qualities. Firstly, Ultra-wide band planer antenna supports high data rate, less power consumption, low cost, and ease of fabrication etc. And the second major factor is that the wireless portable device needs antennas operating at different frequencies for various wireless transmission functions, and operation bands and functions are increasing more and more, which may result in many challenges in antenna design. So, it effectively reduces the number of antennas in the devices. In [1]-[4] references, the concepts and the different interesting applications of the ultra-wide band antennas are discussed in a detailed fashion.

Among all the different existing filter families, butterworth and chebyshev filters are the two popular categories. Butterworth filters are well known as maximally flat filters. Though it has the filter edge approximation error around the transition between the passband and stopband, the passband envelop of the overall response remains almost flat where the chebyshev filters have relatively accurate and sharp edge approximation but the response includes some ripples in its passband [5-8]. Here in order to make reduce the ripples from the passband, a fifth order maximally flat band-stop filter is designed using the concept of gap-coupled microstrip resonators [9-10].

A novel structure of an ultra-wideband filtenna is proposed for notching the ISM band of 5.8 GHz. One of the ends of the fifth order gap-coupled butterworth band-stop filter is extended and connected to a circular planar ultra-wide band patch antenna. In case of gap-coupled resonators, controlling the strength of the frequency-notch characteristics is very easy by only varying the gaps of the stubs with the feeding microstrip transmission line. For all the other frequencies except the stop band frequency of the filter, the band pass filter remains almost transparent. At the resonance of the band-stop filter 5.8 GHz, the stop band characteristics of the filter produces a narrow band notch to eliminate the interference of the antenna with the 5.8 GHz ISM band.

In this research manuscript, Section II reveals the design parameters and details of the proposed ultra-wide band filtenna structure. And the following sections, Section III, IV, V and VI include the discussion on the important results and the observations, the empirical relation development for the strength of the frequency notching characteristics, conclusion and the conclusion respectively.

II. DESIGN OF PROPOSED FILTENNA

Figure 1 (a) and (c) shows the equivalent lumped circuit model and the microstrip layout of the proposed 5^{th} order gap-coupled resonator loaded band-stop butterworth filter having the stop band centre frequency at 5.8 GHz. The filter structure is designed on the top of Rogers 5880 substrate material (ϵ_r=2.2, tanδ=0.0009) having the dielectric height h_t = 1.575 mm and the planar dimension of $L_{sub}\times W_g$ where L_{sub} = 96 mm and W_g = 50 mm are the length and width of the substrate respectively. As shown in Fig. 1(c), proposed band-stop filter comprises five gap-coupled microstrip stub sections where each of them having length, L_1 = 12.19 mm and width, W_1 = 4.64 mm. Each stub is attached with one metallic via of radius R_1 at the end to provide the proper arrangement of the capacitances and inductances to produce the appropriate band stop property. The two different gaps kept between the stubs and the 50 ohm microstrip feeding line are g_p = 0.2 mm and g_x = 0.6 mm where the width of the feeding line is denoted by W_3 = 4.89 mm. Figure 1(d)-(f) presents the distribution of current

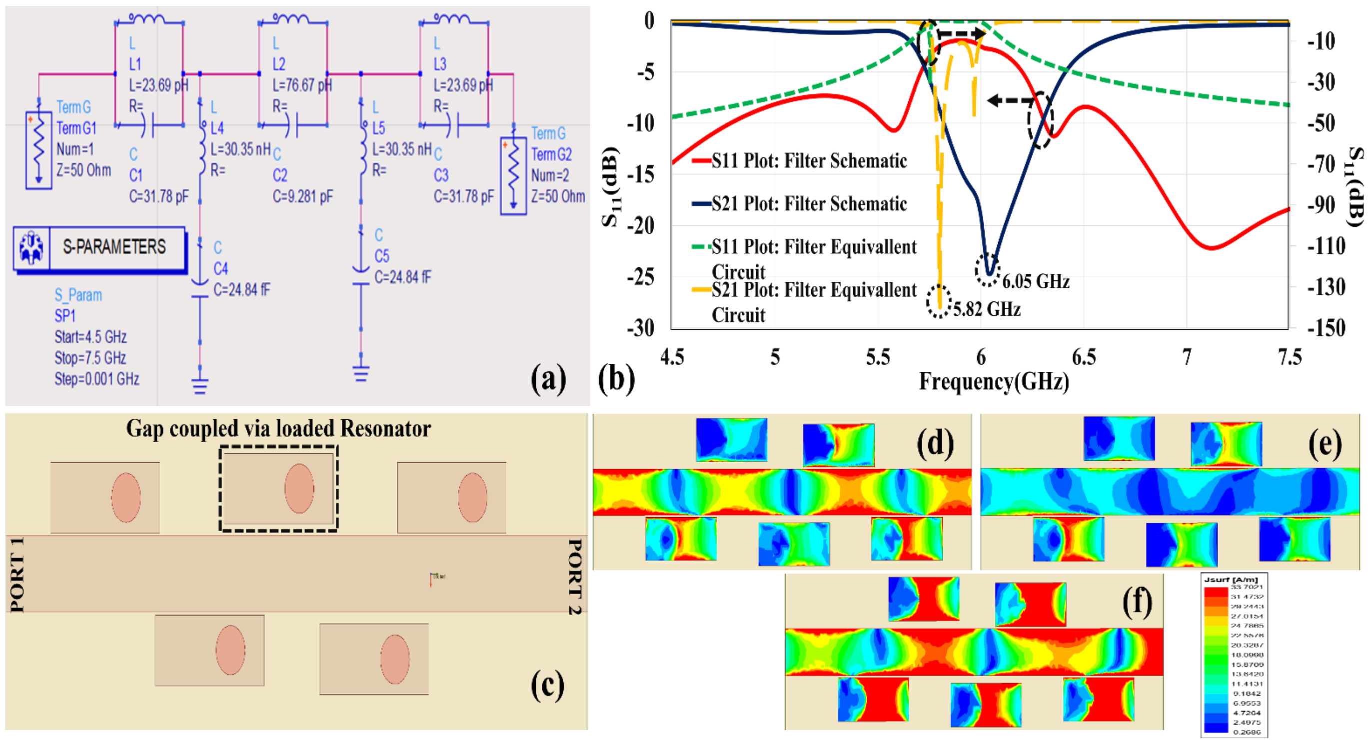

Fig.1: (a) Circuit Design of proposed Gap coupled BRF (b) S parameter of the Equivalent and Circuit model (c) Top View of Gap coupled BRF, Surface Current Distribution for (d) 5 GHz (e) 5.8 GHz & (f) 6.5 GHz.

density on the filter at 4.5 GHz, 5.8 GHz and 6.5 GHz respectively.

Figure 2 (a)-(c) reveal the schematic diagram, top view and back view of the ultra-wideband filtenna where the planar ultra-wide band patch antenna is integrated with the extended hand of the band-stop filter. The circular patch antenna has the radius *R2* = 14 mm. The design parameters of the proposed filter and filtenna are shown in the Table-I below in detail.

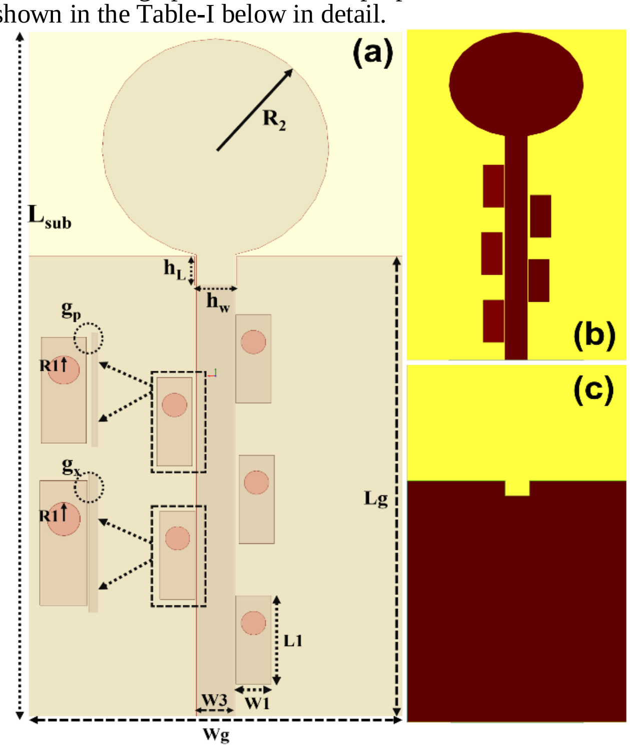

Fig.2: (a) Schematic diagram, (b) Top view and (c) Bottom view of the Proposed UWB Filtenna structure.

Table-I
Design parameters of the band-stop filter

parameters	values(mm)
L_{sub}	96
W_g	50
L_g	64.5
ht	4
h_W	5.5
g_P	0.2
g_x	0.6
L_1	12.19
W_1	4.64
W_3	4.89
R_1	1.66
R_2	14

III. RESULT AND DISCUSSION

Figure 1(d)-(f) shows the current density on the filter at 5 GHz, 5.8 GHz and 6.5 GHz respectively. This is the evidence of the band stop characteristics of the proposed gap coupled resonator loaded BRF. As shown in Figure 1(e), at resonance frequency, f_0=5.8 GHz the current reaching at Port 2 from Port 1 is very less as the result of the strong band notching characteristics of filter whereas, being loosely coupled at 5 GHz and 6.5 GHz, the gap-coupled resonators don't harm the transmission.

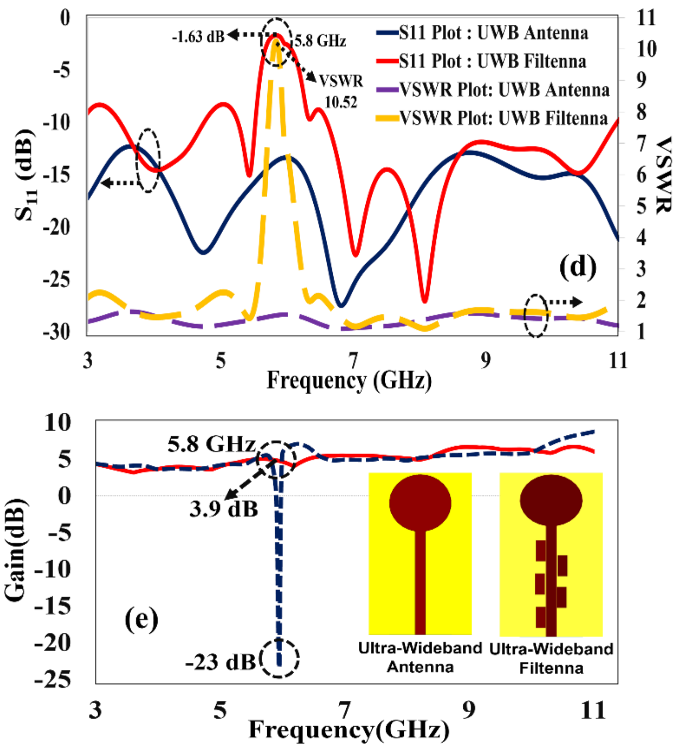

Fig.3: (a) S_{11} and VSWR plots and (b) Gain stability over frequency of both the UWB antenna and proposed UWB Filtenna structure.

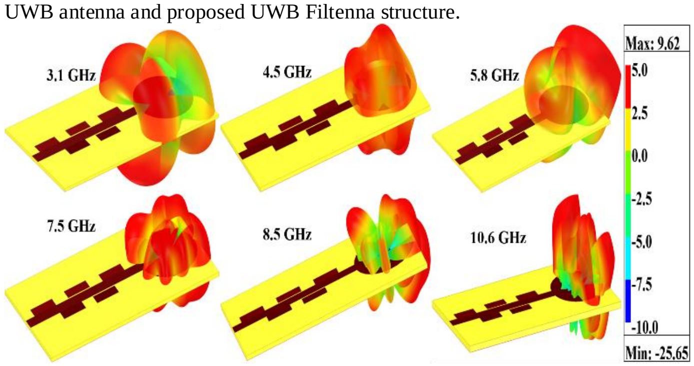

Figure 4: 3D radiation pattern for different intermediate frequencies between 3-10 GHz including the bandstop frequency f_0=5.8 GHz

Figure 3(a) reveals the S_{11} and VSWR plots for both the ultra-wideband antenna and the proposed gap-coupled resonator loaded proposed filtenna. Here the S_{11} response of the filtenna reaches up to -1.63 dB & VSWR response touches the value of 10.52. The same way, in figure 3(b) a huge depression in gain stability curve can be observed. The gain of the ultra-wideband antenna drops down up to -23 dBi at the notching frequency of 5.8 GHz ISM band. From Figure 4, 3D radiation pattern for different frequencies between the ultra-wideband range (3-10 GHz) has been noted.

To ensure that the proposed ultra-wideband antenna doesn't radiate the ISM 5.8 GHz band, the notching characteristics of the integrated filter should be very strong. The strength of the notch directly depends on the magnetic coupling between the 50 Ohm microstrip feeding line and gap-coupler stubs. Figure 4 clearly shows variation of the strength of the notch at 5.8 GHz with the variation of gap between the 50 Ohm microstrip feeding line and gap-coupled resonating stubs. The coupling and the gaps are distributed in a non-linear regression. A customized empirical relation has been designed to characterize the effect of coupling w.r.t. The variation of gap.

A reconfigurable filtenna can enable channel-aware low-noise amplifier (CA-LNA) – [13] and [14]. A CA-LNA has single-input and single-output reconfigurable impedance matching networks (IMNs) [13]. These IMNs are varactor-based control bit settings for each multi-radio frequency band of interest. Each bit is set to configure all IMNs for band-specific optimum performance metrics. This enables the LNA to deliver the best system-level performance metrics possible in a compact monolithic microwave integrated circuits (MMICs) package. This results in the lowest cost, size, weight and power (C-SWaP) adaptive and dynamic receiver frontend architecture possible. This novel reconfigurable LNA design approach obviates multiple shortcomings of conventional multiband receiver frontend designs. The prominent benefit is the removal of a band-select switch at the LNA output. This sets the receiver temperature margin at 6 K [14-15] and reduces the transceiver's output loss by 0.8–1.0 dB, yielding a better performance over the conventional design techniques. The reconfigurable LNA closely approximates the performance metrics achieved by independently tuned band-specific receivers with an optimum load impedances and smart switch placement. This would benefit regenerative transponders [16].

IV. EMPIRICAL RELATION DEVELOPMENT

In this article, an Empirical relation has been proposed for the gap coupled resonator loaded UWB filtenna. Depending upon the spacing between the microstrip line and the magnetically coupled stub resonators, the effect on the S parameter plot at the notched frequency (f_0 =5.8 GHz) has been modelled as a customized empirical nonlinear relationship. Due to the non-linear variation on magnetic coupling between the microstrip line and the gap coupled resonators, different current basis vectors has been correlated and returns to nonlinear S parameter relationship. From the parametric data taken from the simulation environment, due to the nonconvex nature and some non-linear dependency of column basis vectors, linear regression become inefficient to correlate different basis values. Therefore, Gaussian curve fitting tool is used to achieve the estimation of the optimum correlation between basis data and final empirical equation using MATLAB computational platform. The formulated empirical relation and achieved different regression coefficients (with 95% confidence bounds) are given below.

$$S_{11}^{(1)}(\text{dB}) \;=\; \sum_{n=1}^{8} a_n \exp\left(-\left(\frac{x-bn}{cn}\right)^2\right) \qquad (1)$$

Here, S_{11} is the estimation of reflection coefficient in dB, where the Gap(g_p & g_x) is the input basis vectors for the notching frequency of 5.8 GHz with a_1 = -22.52 , a_2= -258.6, a_3 = 47.22, a_4 = 51.54, a_5 = 1.954, a_6 = 70.83, a_7 = 135.6, a_8 = -414, b_1 = 0.0925, b_2 = -258.6, b_3 = 0.00667, b_4=2.087, b_5 = 1.215, b_6 = 0.2063, b_7 = 3.431, b_8 = -868, c_1 = 0.306, c_2 = 1.511, c_3 = 0.3653, c_4 = 1.47, c_5 = 0.3856, c_6 = 1.04, c_7 = 0.9678 and c_8 = 7.404 with Goodness of Fit where SSE: 7.05, adjusted R-Square: 0.9774 & RMSE : 1.084 which are not sufficiently good to estimate the predicted regression fit.

Next, nonlinear polynomial curve fitting tool is also used to approximate the optimum correlation for the basis data in the same way, The final empirical equation achieved here with the different regression coefficients (with 95% confidence bounds) are given below.

$$S_{11}^{(2)}(\mathrm{dB}) = \sum_{n=0}^{9} p_n x^n \qquad (2)$$

In this case, S_{11} is the estimation of reflection coefficient in dB, where the Gap(g_p & g_x) is the input basis vectors for the notching frequency of 5.8 GHz with p_0 = -1.43, p_1 = 6.36, p_2 = -53.12, p_3 = 57.2 , p_4 = -54.96, p_5 = -164.5, p_6=142 -1.43, p_7 = -59.6, p_8 = 12.46 and p_9 = -1.041 with Goodness of Fit where SSE: 5.99, adjusted R-square: 0.996 and RMSE: 0.547, which are sufficiently estimate the predicted regression fit.

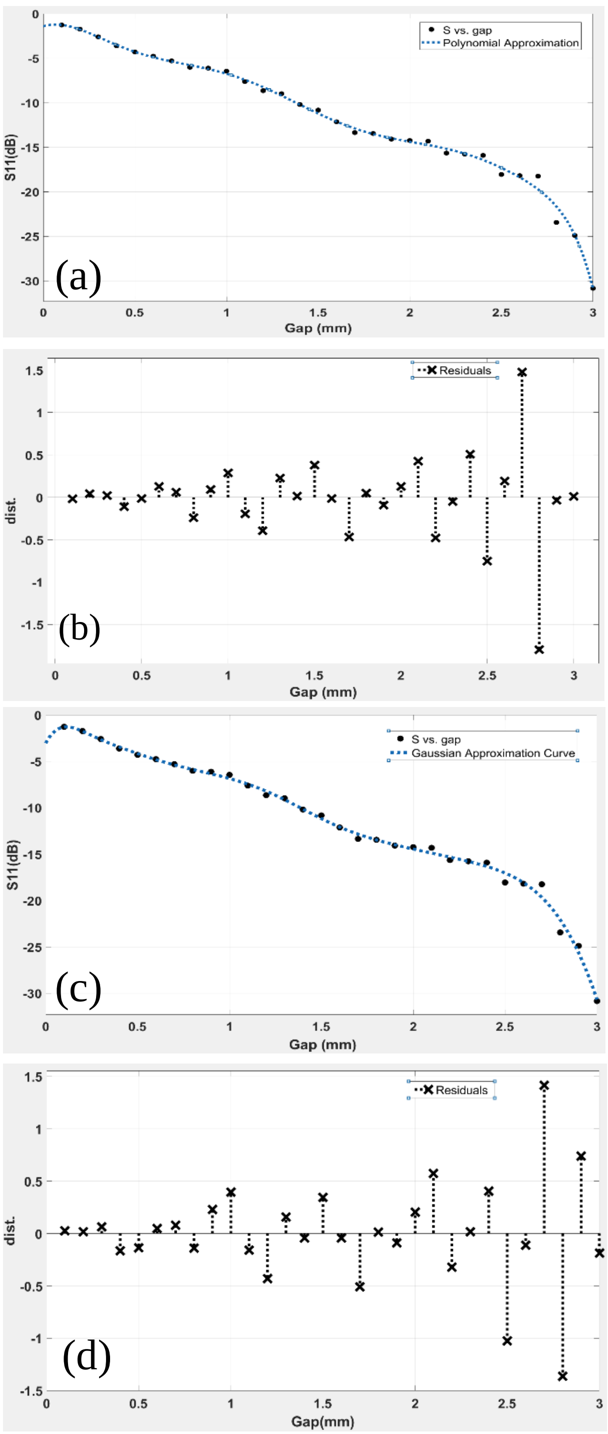

Fig.5: (a) Gap vs Frequency Plot for Non-linear polynomial regression analysis. (b) Residual plot between Gap vs dist. (distance between each consecutive point mentioned in Fig 4(a)).

To characterize the effect of Gap-coupled resonator on the basis of gap between the microstrip feedline and the gap coupled resonating sections, a mathematical modelling has been modelled (considering the Adjusted R Square=0.9675). By taking the input basis vectors as the gap between the microstrip feedline and gap coupled resonator elements, the equivalent effect on the S_{11}(dB) for the f_0=5.8 GHz has been modelled through equation 1. Equivalent Contour and Residual plot is given for the support on the surface equivalence non-linear modelling of the given relation. As mentioned in equation 1; the polynomial relation has been modelled through Goodness of Fit optimization process to characterize the RMSE value. To achieve maximum matched gap-coupled condition, the contour plot can and the residual plot has been given into Figure 6. All polynomial co-efficient bounds have been given in Table II.

$$S_{11}^{(3)}(dB) = \sum_{m=0}^{N} \sum_{n=0}^{N} P_{mn} x^n y^m \qquad (3)$$

The respective co-efficient of the polynomials are mentioned below:

TABLE II
POLYNOMIAL CO-EFFICIENT FOR REFLECTION CO-EFFICIENT (DB)

n \ m	0	1	2	3	4	5
0	-1.275	5.226	-212.8	650.5	-717	268.2
1	3.565	37.2	-143.3	122.2	-24.25	0
2	-11.67	10.96	56.03	-45.16	0	0
3	3.241	-28.09	4.546	0	0	0
4	6.294	6.412	0	0	0	0
5	-2.907	0	0	0	0	0

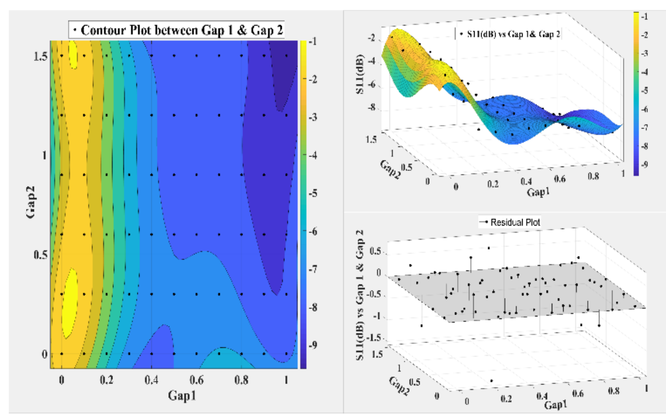

Figure 6 : 3D & 2D imaging of Contour & Residual plot between S11 (dB) with gap coupling parameters (g_p & g_r)

To analyse the effect of variation on the effective width of the gap coupled resonator section (W1) with respect to the gap between microstrip feedline and gap coupled section (Gap1) , a mathematical relationship has been modelled (mentioned in equation 2) using Goodness of fit approximation technique (considering the Adjusted R Square=0.9975). On the basis of clustered distribution of S11 (dB), non-linear relationship between the input basis vectors has been observed by the contour plot (mentioned in figure 7). All the polynomial co-efficient bounds have been given in Table III.

$$S_{11}^{(4)}(dB) = \sum_{m=0}^{N} \sum_{n=0}^{N} P_{mn} x^n y^m \qquad (4)$$

The respective co-efficient of the polynomials are mentioned below:

TABLE III
POLYNOMIAL CO-EFFICIENT FOR REFLECTION CO-EFFICIENT (DB)

n \ m	0	1	2	3	4	5
0	9.09e4	-5438	-529	1916	-919.7	112
1	-1.1e5	4906	-198.8	-475.3	155.7	0
2	5.4e4	-1611	114.5	17.88	0	0
3	-1.3e4	229.2	-10.3	0	0	0
4	1598	-11.97	0	0	0	0
5	-77.49	0	0	0	0	0

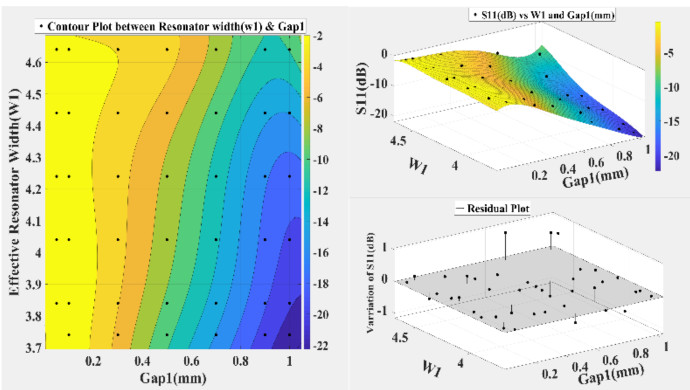

Figure 7 : 3D & 2D imaging of Contour & Residual plot between S11 (dB) with gap coupling parameter(g_p) and Effective resonator width (W1)

A study on different kind of band-stop filters and a comparative study between their scattering parameter responses of the equivalent circuit models and microstrip layouts. A fifth order gap-coupled resonator band-stop filter loaded ultra-wide band filtenna structure is proposed. The filter shows its resonance at 5.8 GHz and produces the sharp frequency-notch and creates a significant suppression in gain stability plot within the ultra-wideband response of the attached antenna. The proposed idea is actually very simple to implement and it can be easily scaled to any other futuristic frequency notching and different filter applications.

V. CONCLUSION

A fifth order gap-coupled resonator band-stop filter loaded ultra-wide band filtenna structure is proposed in this research article. The filter touches its resonance at 5.85 GHz and produces the sharp frequency-notch and creates a significant amount of depression in gain within the ultra-wideband response of the attached antenna. The proposed idea is very simple and can be easily scaled to any other futuristic frequency notching and different filter applications.

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