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2GHz Microstrip Low Pass Filter Design with Open-Circuited Stub

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Abstract: *A 3 pole 2GHz Butterworth microstrip low pass filter is designed and fabricated based on the Open-circuited stub microstrip realization technique. The filter is designed using the FR4 substrate and the performance of the design is simulated using the ADS EM simulation tool. A comparison of the fabricated Open-circuited stub filter's performance with the ADS simulation showed a marginal average deviation of less than 5%. At the cut-off frequency of 2GHz, the Open circuited stub filter produced an insertion loss of -3.009dB, while the stop-band characteristics exhibited an attenuation of -19.359dB at the stop-band frequency of 4GHz and a peak attenuation up to -35dB at 4.5GHz.*

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I. Introduction

Microwave filters are required in all RF-communication techniques[1] and they are an integral part of a large variety of wireless communication systems, including cellular phones, satellite communications and radar [2]. They represent a class of electronic filters, designed to operate on signals in the megahertz and gigahertz frequency spectrum i.e. microwaves. Microwave filters have many applications including duplexers, diplexers, combiners, signal selectors etc. Low pass filters are used in communication systems to suppress spurious modes in oscillators and leakages in mixers[3].

Depending on the requirements and specifications, Radio Frequency (RF) or microwave filters may be designed as lumped element or distributed element circuits[4]. However, the design of filters for frequencies in the microwave range above 500MHz are practically realized through the use of distributed element circuits[5]. The distributed element circuits are realized with the use of transmission line sections such as waveguide, coaxial line, and microstrip line. The analyses of these circuits are based on the transmission line theory.

Emerging wireless communication technologies continue to challenge microwave filter designers with more stringent requirements such as higher performance, smaller size, light weight and reduced cost. These requirements have made the option of microstrip filters more attractive to designers of microwave filters. Microstrip lines are low cost, compact in size and easy to integrate with other components on a single board. With the limited licensed radio frequency spectrum available and the increasing demand for the transmission of data with greater speeds, microwave engineers continue to be tasked with the development of microwave filters with higher frequency selectivity.

Open-Circuited Stub Filter

The open-circuited stub microstrip realization method is a modification of the stepped-impedance microstrip realization method. It approximates the series inductance as a high impedance transmission line while the shunt capacitance effect is simulated by an open-circuited stub using Richard's transformation.

If we consider the expression for the input impedance (Z_{in}) at any point on a lossless transmission line to be as given in equation (1).

$$Z_{in} = Z_o\left[\frac{Z_L + jZ_o tan\beta l}{Z_o + jZ_L tan\beta l}\right] \quad \text{----- (1)[6]}$$

Where Z_o is the characteristic impedance of the line; Z_L is the load impedance and β is the phase constant. If the end of the transmission line is an open-circuit i.e. $Z_L = \infty$; then the input impedance of the transmission line can be re-written as shown in equation (2):

$$Z^o_{in} = Z_o\left[\frac{1 + j\frac{Z_o}{Z_L}tan\beta l}{\frac{Z_o}{Z_L} + jtan\beta l}\right] \quad \text{----- (2)}$$

As $Z_L \longrightarrow \infty$; $\frac{Z_o}{Z_L} \longrightarrow 0$

So therefore; $Z^{o}_{in} = Z_o[\frac{1 + j(0)tan\beta l}{(0) + jtan\beta l}] = \frac{Z_o}{jtan\beta l} = -j\ Z_o \cot \beta l$ ----- (3)

Equation (3) shows that the input impedance of the open circuited stub is purely capacitive i.e. $Z_c = \frac{-j}{\omega c}$; although the impedance is not equal to the capacitive reactance but for a given capacitive element (C) and a given stub, with a particular characteristic impedance Z_o and length ι; there exists a frequency ω_c, for which the open-circuited input impedance will equal the capacitive reactance. i.e. $Z^{o}_{in} = Z_c$

Therefore at this frequency ω_c; we can write the following equations:

$X_c = \frac{-j}{\omega_c C} = -j\ Z_o \cot \beta_c l$ ----- (4)

For convenience, the length of the transmission line stub is chosen to be equal to one-eighth of the wavelength i.e$\frac{\lambda_c}{8}$[7]. So that $\beta_c l = \frac{2\pi}{\lambda_c} \times \frac{\lambda_c}{8} = \frac{\pi}{4}$.

$\frac{-j}{\omega_c C} = -j\ Z_o \cot \frac{\pi}{4} = -jZ_o$

Therefore

$Z_o = \frac{1}{\omega_c C}$ ----- (5)

From equation (V); we can conclude that the open-circuited stub will have the same impedance as a capacitor C at frequency ω_c; if the characteristic impedance Z_o is equal to $\frac{1}{\omega_c C}$

This transformation is very important in the synthesis of microwave filters; even though the transformation occurs at a single frequency; the intended results can still be achieved, for a microwave low pass filter if the filter's cut-off frequency is chosen as the reference frequency (ω_c).

Similarly, at low microwave frequency it can be assumed that the electrical length of the transmission line is short (i.e βι << 1), and as such the transmission line can be modelled as a T-circuit with impedances as shown in fig 1

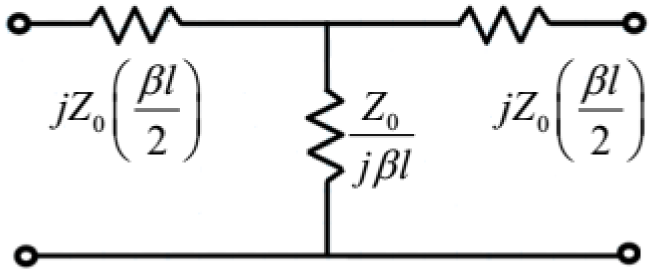

Figure 1. Transmission Line Model*[8]*

If the characteristic impedance of the transmission line is relatively large, then the shunt element will become very large and will behave like an open circuit i.e.$\frac{Z_o}{j\beta_\iota} \approx \infty$; therefore with a relatively large characteristic impedance the transmission line behaves like a series inductance of $jZ_o\beta\iota$. This realization does not give a result applicable at all frequencies, because the electrical length of the transmission line increases as the signal frequency increases, but the electrical length is required to be maintained at a small value for this approximation to produce desirable results[8].

Filter Design

The design process of the microstrip low pass begins with the design of a passive low pass prototype network (i.e LC ladder network) using the Butterworth approximation function. The obtained lumped network is then transformed to an equivalent microstrip layout using the open-circuited stub microstrip realization method. The microstrip realization methods are not exact and do not produce the best results; however they serve as a starting point from which an optimised layout can be obtained. This is achieved with the use of ADS momentum simulation software. The optimal layout design would then be fabricated on a microstrip.

Filter Specification

Cut-off Frequency (f_c) = 2 GHz
Stop-Band edge Frequency (f_s) = 4GHz
Passband Ripple = 0.5dB
Substrate Height (h) = 1.6mm
Dielectric Constant (ε_r) = 4.4
Loss Tangent (δ) = 0.02
Maximum Passband Attenuation (A_{max}) = -3dB

Minimum Stopband Attenuation (A_{min}) = -18dB
Input & Output Impedance = 50Ω

Calculation Of Filter Parameters
The normalized filter elements of a 3rd order Butterworth low pass filter is obtained from the Butterworth filter table in table 1:

Table 1 Normalized Butterworth Lpf Table Ω_c = 1 Rad/Sec Z_o = 1Ω

N	g1	g2	g3	g4	g5	g6	g7	g8	g9	g10	g11
1	2.0000	1.0000									
2	1.4142	1.4142	1.0000								
3	1.0000	2.0000	1.0000	1.0000							
4	0.7654	1.8478	1.8478	0.7654	1.0000						
5	0.6180	1.6180	2.0000	1.6180	0.6180	1.0000					
6	0.5176	1.4142	1.9318	1.9318	1.4142	0.5176	1.0000				
7	0.4450	1.2470	1.8019	2.0000	1.8019	1.2470	0.4450	1.0000			
8	0.3902	1.1111	1.6629	1.9615	1.9615	1.6629	1.1111	0.3902	1.0000		
9	0.3473	1.0000	1.5321	1.8794	2.0000	1.8794	1.5321	1.0000	0.3473	1.0000	
10	0.3129	0.9080	1.4142	1.7820	1.9754	1.9754	1.7820	1.4142	0.9080	0.3129	1.0000

g_1 = 1.0000; g_2 = 2.0000; g_3 = 1.0000

$$L_k = \left[\frac{Z_o}{g_o}\right]\left[\frac{\Omega_c}{2\pi f_c}\right] g_k \qquad \text{----- (6)}$$

$$C_k = \left[\frac{g_o}{Z_o}\right]\left[\frac{\Omega_c}{2\pi f_c}\right] g_k \qquad \text{----- (7)}$$

We obtain the de-normalized values for the inductances and capacitances using equations (6) and (7) as:
$L_1 = 3.98 \times 10^{-9}$ H; $C_2 = 3.18 \times 10^{-12}$ F; $L_3 = 3.98 \times 10^{-9}$ H
The obtained Lumped network for the Butterworth approximation function is shown in Fig 2

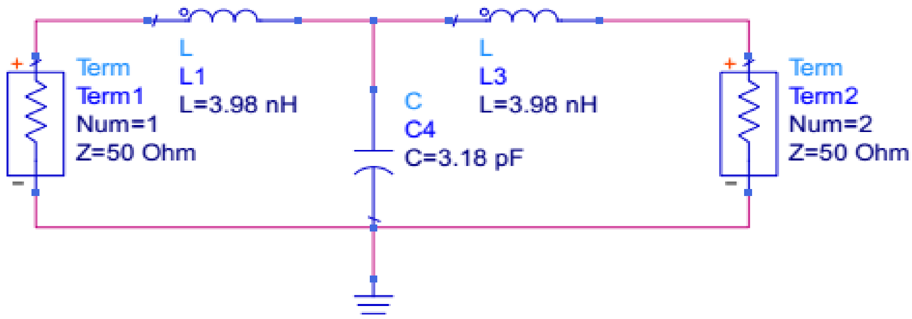

Figure 2 Butterworth 3rd Order- 2ghz Lumped Low Pass Filter

1.1 Microstrip Layout Realization Using Open-Circuited Stub Method

An Fr4 Dielectric Material With The Following Properties Was Used:
Material Properties for FR4 Substrate
Substrate Height (h) of FR4 = 1.6mm
Relative Dielectric Constant (ε_r) of FR4 = 4.4
Loss Tangent (δ) = 0.02
Copper Thickness (T) = 0.035mm

First, we select a high impedance which will simulate the series inductance, such that the short electrical length inequality in equations (8) is satisfied:

$$Z_H > \frac{4\omega_c L}{\pi} \qquad \text{----- (8) [8]}$$

$L_1 = L_3 = 3.98 \times 10^{-9}$ H
$\omega_c = 2\pi f_c = 2\pi \times 2 \times 10^9$

$$Z_H > \frac{4 \times 2\pi \times 2 \times 10^9 \times 3.98 \times 10{-9}}{\pi}$$

$Z_H > 63.68\ \Omega$
Based on the impedance calculated, the high line impedance (Z_H) was chosen as 88Ω
Source and Output Impedance (Zo) = 50Ω

The approximate expressions for the ratio of line width and substrate thickness (i.eW/h) is derived using the Wheeler and Hammerstad equations (9 – 10) to calculate the line width[9].

For W/ h ≤ 2:

$\frac{W}{h} = \frac{8 \exp (A)}{\exp (2A) - 2}$ ------------------- (9)

$A = \frac{Z_c}{60}\left\{\frac{\varepsilon_r + 1}{2}\right\}^{0.5} + \frac{\varepsilon_r - 1}{\varepsilon_r + 1}\left\{0.23 + \frac{0.11}{\varepsilon_r}\right\}$ -------------------- (10)

For the high Impedance Line (Z_H = 88Ω); we assume W/ h ≤ 2; therefore:

$$A = \frac{88}{60}\left\{\frac{4.4 + 1}{2}\right\}^{0.5} + \frac{4.4 - 1}{4.4 + 1}\left\{0.23 + \frac{0.11}{4.4}\right\}$$

$A = \frac{88}{60}\left\{\frac{5.4}{2}\right\}^{0.5} + \frac{3.4}{5.4}\{0.255\} = 2.5705$

$\frac{W_L}{h} = \frac{8 \exp (2.5705)}{\exp (5.14107) - 2} = 0.61918$

Therefore W_{oL} = 1.6 × 0.61918 = **0.99mm**

The transmission characteristics of the microstrip lines are described mainly by 2 parameters: The characteristic impedance and the effective dielectric permittivity ε_{re}. We shall obtain the effective dielectric using equations (11) & (12).

For W/h ≤ 1:

$\varepsilon_{re} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left\{\left(1 + \frac{12h}{W}\right)^{-0.5} + 0.04\left(1 - \frac{W}{h}\right)^2\right\}$----- (11)

For the high Impedance line (Z_L) = 88Ω; W/h ≤ 1; therefore:

$\frac{W_L}{h} = 0.61918$; Therefore $\frac{h}{W_L} = 1.61504$

$\varepsilon_{re} = \frac{4.4 + 1}{2} + \frac{4.4 - 1}{2}\{(1 + 12(1.61504))^{-0.5} + 0.04(1 - 0.61918)^2\}$

$\varepsilon_{re} = 2.7 + 1.7\{(0.22151) + 0.0058\}$

$\boldsymbol{\varepsilon_{(re)L} = 3.0864}$

The guided wavelength in a microstrip transmission line can be calculated using equation (12):

$\lambda_g = \frac{300}{f(GHz)\sqrt{\varepsilon_{re}}}$ mm ----- (12)

Where $\lambda_{gL} -$ Guided wavelength in the high impedance line

$\lambda_{gL} = \frac{300}{2 \times \sqrt{\mathbf{3.0864}}}$ = 85.3818mm

The physical length of the high impedance line is determined by equation (13)

$l_l = \frac{\lambda_{gL}}{2\pi} sin^{-1}\left(\frac{\omega_c L}{Z_{oL}}\right)$ ----- (13)

$l_l = \frac{85.3818}{2\pi} sin^{-1}\left(\frac{2\pi \times 2 \times 10^9 \times 3.98 \times 10^{-9}}{88}\right)$ = **8.2144mm**

For the shunt capacitor, we shall use Richard's transformation to convert the shunt capacitor to a shunt open-circuited stub. According to this transformation the length of the stub will be $\frac{\lambda}{8}$[10]. Hence the electrical length (βl) is calculated as:

$\beta l = \frac{2\pi}{\lambda} \times \frac{\lambda}{8} = \frac{\pi}{4}$ radians

From the Richard's transformation the normalized characteristic impedance of the stub is related to the normalized capacitance by equation (14)[10]

$Z_c = \frac{1}{C}$ ----- (14)

$Z_c = \frac{1}{2} = 0.5$

De-normalized $Z_c = 50 \times 0.5 = 25\Omega$
Electrical Length = $\frac{\pi}{4}$ radians

Using the ADS Line calculator the dimensions of this line is synthesized as shown in Fig 3:

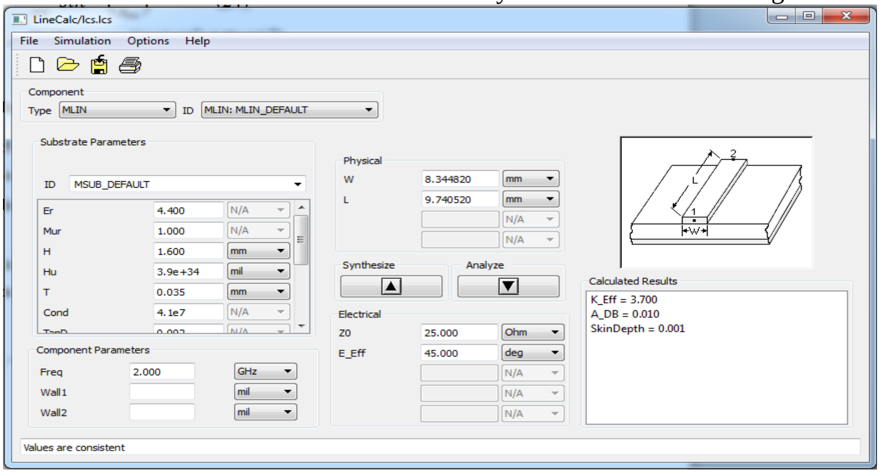

Figure 0 Ads Line Calculator For Stub Width And Length

The obtained line dimension from the line calculator is:
$W_c = 8.34$ mm; $l_c = 9.74$ mm
The open-circuited stub section presents a physically open end, which causes fringing fields to be extended beyond the physical end of the strip i.e radiation. This phenomenon can be accounted for by replacing the fringing fields by means of an equivalent shunt capacitance C_f. This capacitance is also equivalent to an extra lengthΔl.[11]
The equation for this extra length Δl is given by equation (3.26)

$$\frac{W}{h} = \frac{8.34}{1.6} = 5.2125$$

$$\Delta l = 0.412h\left(\frac{\varepsilon_{re}+0.3}{\varepsilon_{re}-0.258}\right)\left(\frac{\frac{W}{h}+0.262}{\frac{W}{h}+0.813}\right) \quad \text{------ (15) [11]}$$

$$\Delta l = 0.412(1.6)\left(\frac{3.7+0.3}{3.7-0.258}\right)\left(\frac{5.2125+0.262}{5.2125+0.813}\right) = 0.69\text{mm}$$

$l_c = 9.74 - 0.69 =$ **9.05mm**

Based on the calculations, the microstrip layout for the Butterworth open-circuited stub filter will have the following dimension:

$Z_{L1} = 88\Omega$: $W_{oL1} = 0.99$mm; $L_{oL1} = 8.2144$mm
$Z_{L3} = 88\Omega$: $W_{oL3} = 0.99$mm; $L_{oL3} = 8.2144$mm
Z_{C2} : $W_{oC2} = 8.34$mm; $L_{oC2} = 9.05$mm
$Z_o = 50\Omega$: $W_o = 3.02$mm; $L_o = 20.51$mm

1.2 Ads Optimization Of Filter Design

Fig 4 shows the ADS simulation for the filter's insertion loss based on the calculated dimensions; with -2.062db attenuation at 2.020GHz.

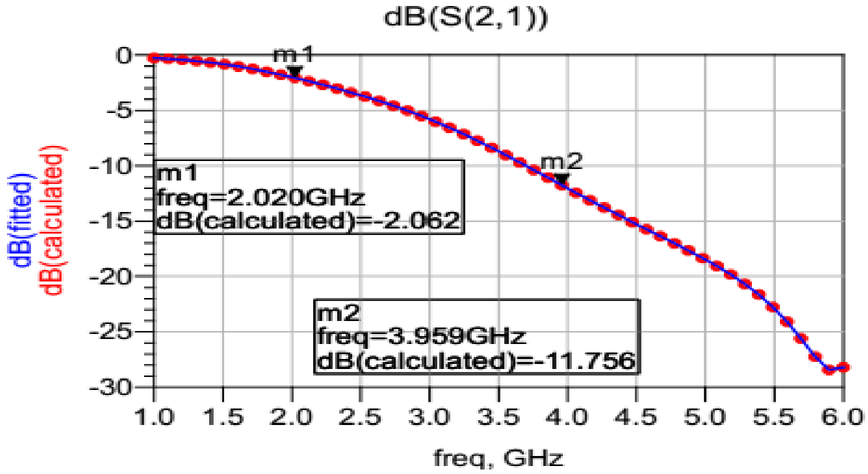

Figure 4. Filter Insertion Loss Before Optimization

After optimization the following new dimensions are obtained:
$W_{oL1} = W_{oL3} = 1mm$; $L_{oL1} = L_{oL3} = 8mm$
$W_{oC2} = 8mm$; $L_{oC2} = 11mm$; $W_o = 3mm$; $L_o = 20mm$

Fig 5 shows the ADS simulated insertion loss after optimization, the attenuation is in the neighbourhood of -3dB at the cut-off frequency and the stopband attenuation is also much improved.

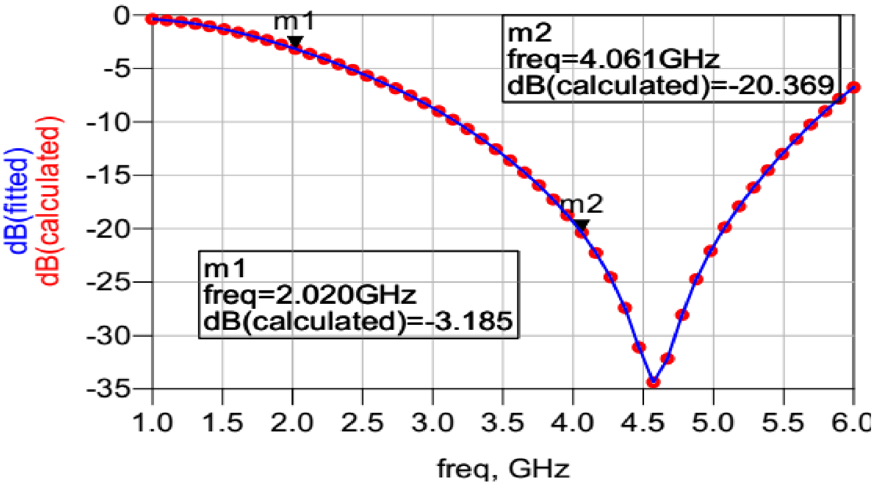

Figure 5 Filter Insertion Loss After Optimization

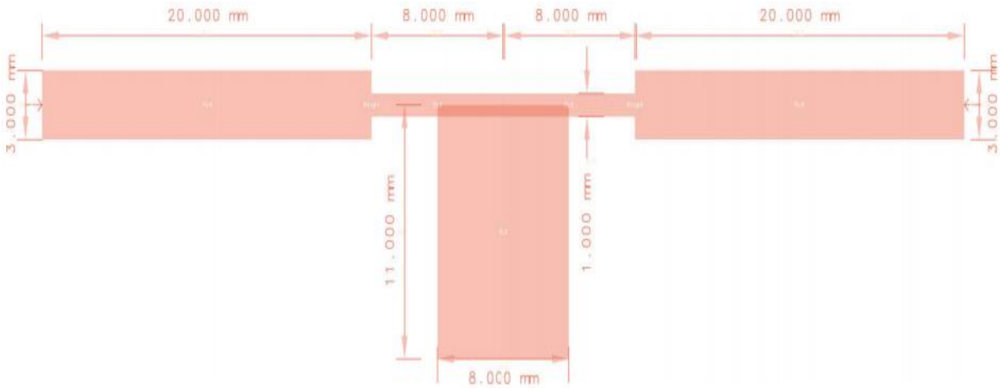

Figure 6. Open Circuited Stub 2GHz LPF Optimised Layout

II. Laboratory Test And Results

The Complete Microstrip TrainerMST532-1 kit with a Voltage Controlled Oscillator (VCO) range of 2.45GHz - 3.63GHz was used to test the fabricated filter's performance. The setup is as shown in fig 8.

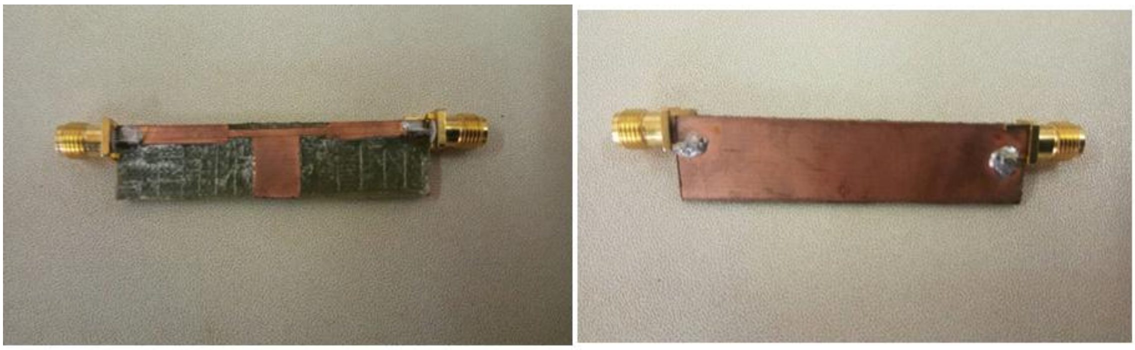

Figure 7. Fabricated Open-Circuited Stub 2GHz Low Pass Filter

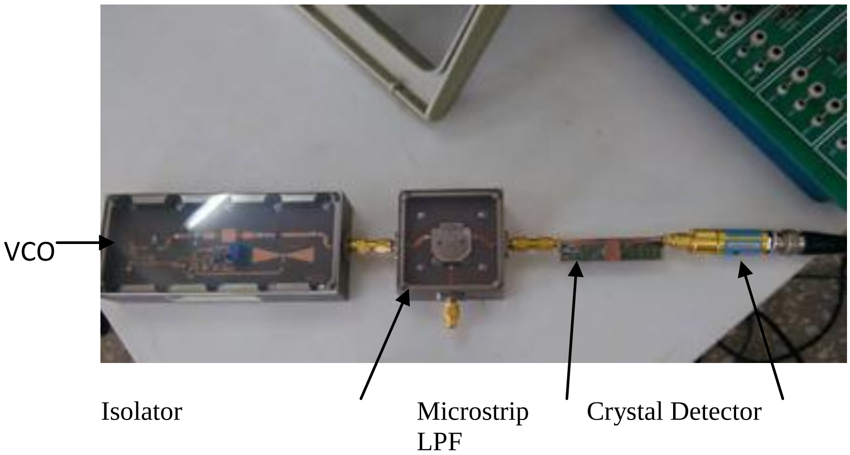

Figure 8. Microstrip Trainer Low Pass Filter Measurement Setup

Table 2 and Fig.9 shows the measurement from the tests and the plot of the Insertion Loss Ratio against frequency for the measurements obtained from the laboratory test of the 2GHz Butterworth Open-circuited stub filter.

Table 2. Measurement Results From Lpf Laboratory Test

			Direct		With LPF			
S/N	**f(GHz)**	**VCO (Volts)**	**V1(Volts)**	**P1(mW)**	**V2(Volts)**	**P2(mW)**	**P2/P1**	**10logP2/P1**
1	2.45	3.28	0.8	10.5	0.487	4.2	0.4	-3.9794
2	2.50	3.81	0.83	11.3	0.436	3.49	0.30885	-5.10253
3	2.55	4.31	0.824	11.1	0.394	2.6	0.234234	-6.3035
4	2.60	4.78	0.788	10.2	0.373	2.5	0.245098	-6.1066
5	2.65	5.5	0.76	9.6	0.347	2.3	0.239583	-6.20543
7	2.75	6.9	0.72	8.6	0.32	1.9	0.22093	-6.55745
8	2.80	7.72	0.73	8.9	0.297	1.72	0.193258	-7.13862
9	2.85	8.52	0.73	8.8	0.277	1.67	0.189773	-7.21766
10	2.90	9.48	0.676	7.6	0.257	1.39	0.182895	-7.37799
11	2.95	10.51	0.632	6.7	0.266	1.48	0.220896	-6.55813
12	3.00	11.62	0.586	5.8	0.258	1.39	0.239655	-6.20413
13	3.05	12.8	0.616	6.4	0.205	0.98	0.153125	-8.14954
14	3.10	13.95	0.574	5.6	0.16	0.6	0.107143	-9.70037
15	3.15	15.19	0.549	5.1	0.135	0.5	0.098039	-10.086
16	3.20	16.4	0.492	4.2	0.121	0.4	0.095238	-10.2119
17	3.25	17.6	0.488	4.2	0.125	0.45	0.107143	-9.70037
18	3.30	18.82	0.522	4.7	0.14	0.5	0.106383	-9.73128
19	3.35	20.09	0.636	6.9	0.169	0.7	0.101449	-9.93751
20	3.40	21.41	0.754	9.3	0.198	0.89	0.095699	-10.1909
21	3.45	22.9	0.706	8.4	0.19	0.8	0.095238	-10.2119

22	3.50	24.62	0.708	8.4	0.193	0.8	0.095238	-10.2119
23	3.55	26.38	0.784	10.05	0.2	0.89	0.088557	-10.5278
24	3.60	28.41	0.852	11.9	0.174	0.7	0.058824	-12.3045
25	3.63	30	0.592	5.9	0.175	0.74	0.125424	-12.4471

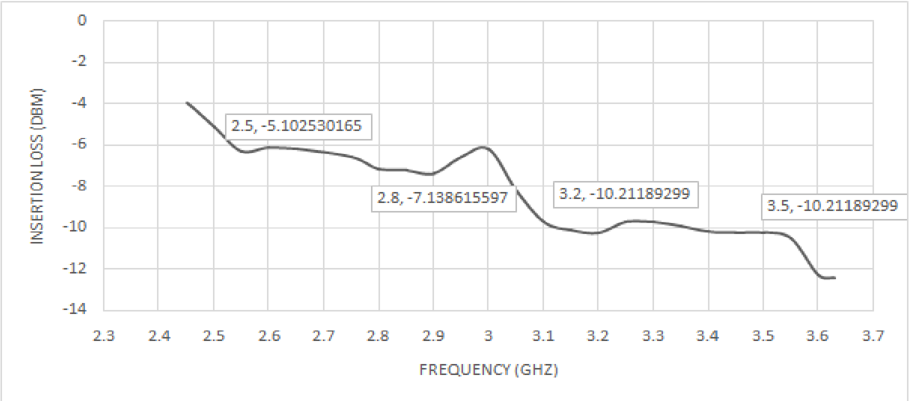

Figure 9 Insertion Loss Ratio For Butterworth Open-Circuited Stub 2ghz LPF

The ILR plot for the filter was marked at 4 points (2.5GHz, 2.8GHz, 3.2GHz, 3.5GHz) for the purpose of comparing it with the results of the EM simulation marked at the same points in Fig 10.

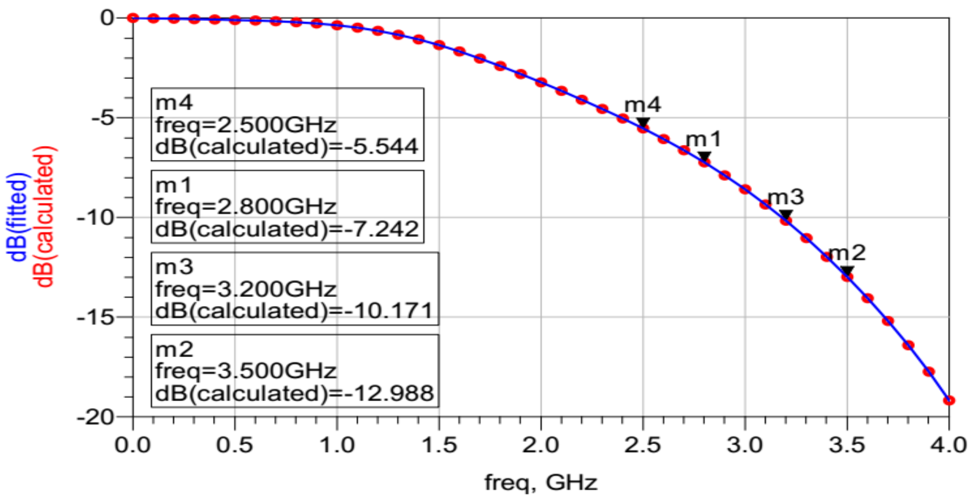

Figure 10. EM SIMULATION 2ghz Butterworth LPF

A comparison of the laboratory test and the EM simulation showed a marginal average deviation of less than 5%. However, the range of comparison was limited to the stop band performance due to the limited frequency band of the VCO (i.e 2.45GHz – 3.63GHz).

III. Conclusion

A 2GHz butterworth LPF using open-circuited stubs has been proposed and fabricated on a FR4 dielectric. The open-circuited stub filter approximates the lumped circuit model quite accurately at 2GHz, the laboratory measurement for the insertion loss were consistent with that obtained from the ADS EM simulation of the filter. The filter produced -3.009dB attenuation at the cut-off frequency and -19.359dB attenuation at 4GHz, which met the specifications for the filter. In the pass band its performance was very close to the lumped circuit model, while its stop band characteristics surpassed the design specification. The open-circuited stub filter also provides easy tuning of the stop-band performance by varying the length of the stub.

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