15 GHz Cavity Filter with Slot Coupling

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Received 17 August 2015, received in revised form 26 August 2015, accepted 29 August 2015

Abstract: **This paper presents investigations of high Q cavity resonator and filter at microwave frequencies. A cavity filter must be able to pass the desired signal with minimum loss, as well as eliminate undesirable signals with maximum efficiency. A bandpass filter operating at 15 GHz has been used as an example. Slot excitation with shorting vias has been applied and its performance has been evaluated by simulation. This filter exhibits an insertion loss of 1 dB at the center frequency of 14.95 GHz and a 3 dB bandwidth of 2.30 GHz with ROLL-OFF of 8.3 dB/GHz with quality factor of 5435 and return loss of 27.36 dB. By changing physical dimensions like cavity width of the filter, effects on filter's parameters have been observed through simulation. In this paper methodology to achieve the desired bandwidth, -3 dB lower edge frequency and higher edge frequency has been discussed. Three formulae have been proposed for estimating -3 dB lower edge frequency, -3 dB upper edge frequency and the bandwidth as a function of the cavity width. These formulae have been validated. The design and fabrication is fully compatible with modern microwave integrated circuit (MIC) technology. These considerations have led to the choice of silicon as substrate material, micromachining for cavity formation and metal layers for ground and microstrip lines. The characteristics of resonant cavity based bandpass filter depend on many parameters such as length, width and depth of the cavity, location and size of the coupling slots, feed line parameters, gap between the two microstrip lines. This paper has only considered the effects of varying cavity width. With these limitations in mind, the agreement between theory and simulations is very good. Further investigations need to be carried out to obtain more accurate predictions.**

Keywords: **Microstrip, cavity filter, bandwidth, cut off frequencies, Roll-Off.**

1. INTRODUCTION

Filters are essential in separating and sorting signals in communication systems. The electromagnetic spectrum is limited and has to be shared; filters are used to select the RF/microwave signals within assigned spectral limits. They are used in a variety of communication systems which typically transmit and receive amplitude and/or phase modulated signals across a communication channel. Microstrip bandpass filters using distributed components are quite popular in modern communication systems. The design approach with coupled resonator microstrip filters makes the filter simulation procedure simple [1].

1.1 Rectangular resonant cavity

A resonant structure can be constructed by terminating a section of rectangular waveguide in short circuits at its two ends, $z = 0$ and $z = d$, thus forming a closed box or cavity as shown in Figure (1.1). Electric and magnetic energy is stored within the cavity, and power can be dissipated in the metallic wall of the cavity as well as in the dielectric material filling the cavity. The energy stored by the resonator is associated with the electromagnetic field within the volume of the cavity. Coupling to the resonator can be done by a small aperture or a small probe or loop. The incident and reflected travelling waves superimpose on one another to produce standing waves in the rectangular cavity. The length of the cavity is required to be a multiple of half guide wavelength at the resonant frequency in order to satisfy the boundary conditions of $Ex = Ey = 0$ on the end walls at $z = 0$ and z = d where Ex & Ey are the electric fields in x and y directions. The cavity is resonant at frequencies where d is a multiple of λ_g /2, λ_g being the guide wavelength for propagation along the z axis. A signal entering at z = 0 produces a standing wave pattern. Because of the short, the transverse electric field (E_x and E_y) is zero at z = d and at multiples of half guided wavelength along the z axis. At certain frequencies an electric field null occurs at z = 0. Since the transverse electric field is zero at the z = 0 plane, the introduction of a shorting plate at that point does not disturb the standing wave pattern. Thus at the selected frequencies, the electromagnetic field within the cavity can be sustained even in the absence of a signal source. The resonant condition is therefore given by

$$d = p (\lambda_g/2)$$

where d is the length of the cavity and p = 1, 2, 3 ..., p being any positive integer. The cavity has an infinite number of resonances.

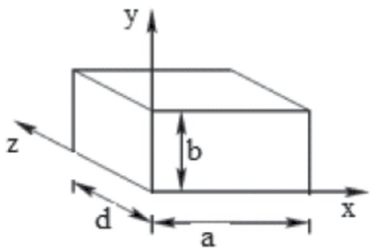

Figure (1.1): A rectangular resonant cavity [1]

The resonant frequency of TE_{mnl} or TM_{mnl} mode for the rectangular cavity shown in figure 1.1 is given by [1].

$$f_{mnl} = \frac{c_0}{2\pi\sqrt{\mu_r \varepsilon_r}}\sqrt{\left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2 + \left(\frac{l\pi}{d}\right)^2}, \qquad (1)$$

where μ_r and ε_r are the relative permeability and permittivity of the material filling in the volume of the cavity; c_0 is the velocity of light in free-space. Here ($m; n = 0, 1, 2....; l = 1, 2, 3......$), the subscripts m, n, and l represent the number of half-sine periods in the standing wave pattern along x, y and z axes respectively. a and d represent width and length respectively and b represents the height of the cavity. For $b < a < d$, the dominant resonant mode with lowest resonant frequency is TE_{101} mode.

The unloaded quality factor Q_u for the resonant cavity can be given by [1].

$$Q_u = \pi\eta \, \{1 + (pa/d)^2\}^{3/2} / 4 R_s \, [\{1 + (a/d)(pa/d)^2\} + (a/b)\{1 + (pa/d)^2\}], \qquad (2)$$

Where η is wave impedance and R_s is surface resistivity.

1.2 Slot with a shorting via: Figure (1.2), shows the slot with shorting via. Microstrip lines are utilized to excite the resonator through coupling slots etched in the top metal layer of the cavity. In order to maximize the magnetic coupling by maximizing magnetic currents, the microstrip lines are terminated with a physical short circuit realized by a metallic via. Shorted vias provide the necessary impedance matching. The coupling slots are initially located at a quarter of the cavity length from the edge of the cavity to maximize the coupling. The slot width is varied while keeping the slot length constant (λg/4 at the frequency of interest). Present investigations indicate that the optimized slot width is λg/8. The position of the slots (cavity length/4) is adjusted to obtain the desired insertion loss, resonant frequency, and input impedance.

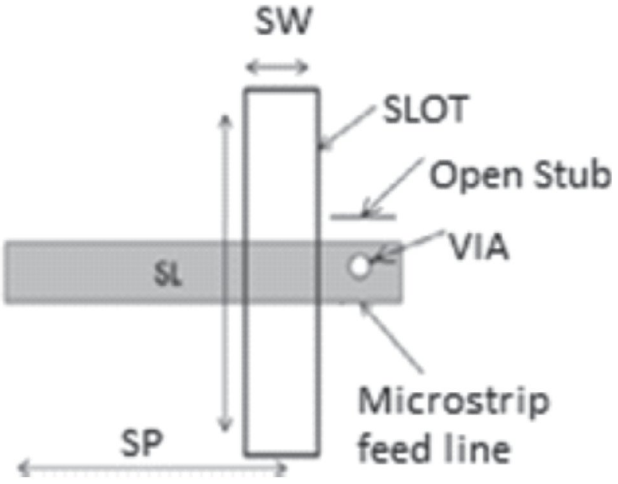

Figure (1.2): Slot with a shorting via [2]

2. FILTER STRUCTURE

Fig (2.1) shows cavity filter in silicon wafer. The cavity was provided input and output by two microstrip lines via slots in the ground plane of the microstrip lines. This provides an easy way to integrate microwave integrated circuit and monolithic microwave integrated circuit structures, if required [3]. In Microwave Integrated Circuit (MIC) technology, signal processing circuitry is also embedded in the MIC chip. The circuit components should be compatible with this technology. Due to these considerations silicon became the choice for the substrate material. Micromachining is a standard process in MIC technology. Therefore cavity resonator has been selected as the filtering element. Dimensions of the cavity filter are determined by using formulae and concepts discussed above

TABLE 2.1: Design Parameters of Cavity Filter Using Shorting Via

Design Parameters	Dimensions in mm
Cavity length	5
Cavity width	1
Cavity height	0.65
Slot position (SP)	1.25
Slot length (SL)	0.8
Slot width (SW)	0.8

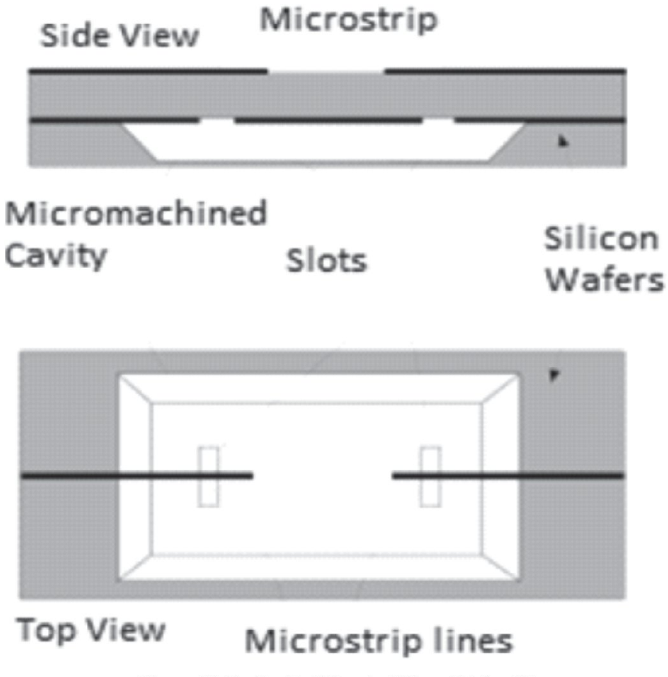

Figure (2.1): Cavity Filter in Silicon Wafer [3]

3. RESULTS

We have designed and simulated silicon based single cavity filter. With the slot length and cavity size determined, the complete filter is modeled and simulated in HFSS as shown in figure (3.1).

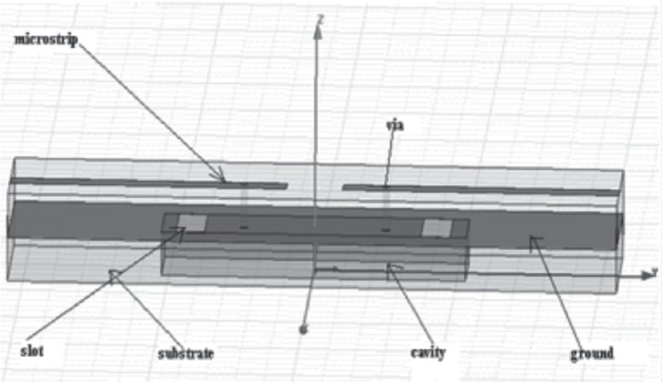

Figure (3.1): HFSS Modal of silicon cavity filter with shorting via

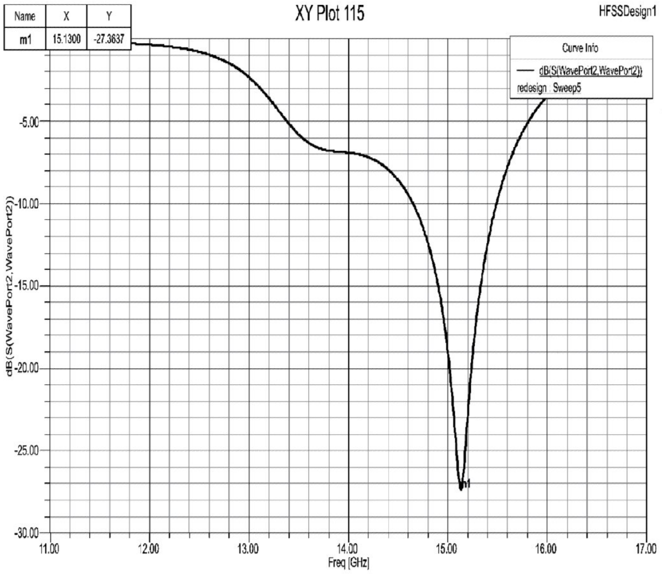

Figure (3.2): Simulated S_{11} of Single cavity filter with shorting via

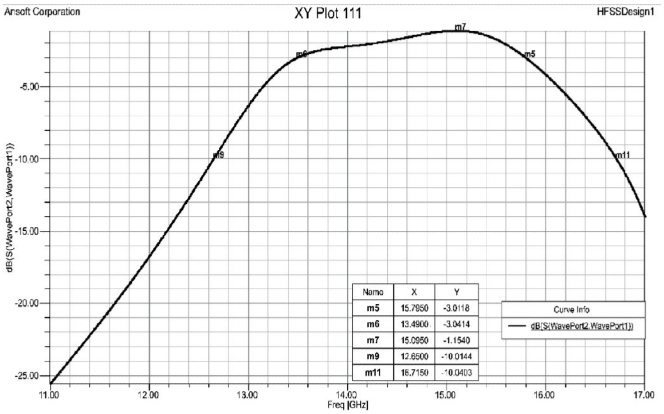

Figure (3.3): Simulation curve S_{21} or Insertion loss of single cavity filter with shorting via

Figures (3.2) and (3.3) are simulated curves. Parameters are obtained which help to calculate the following data:

3dB Bandwidth : $\Delta f = f_u - f_l = 2.30$ GHz, (3)

center frequency : $f_r = \sqrt{(f_u * f_l)} = 14.59$ GHz, (4)

(f_u and f_l represent the upper edge and lower edge -3 dB frequency points of a band-pass filter).

Insertion Loss = -1.15 dB at 15.09 GHz

Roll Off: In a bandpass filter, the amplitude of the signal should be reduced sharply in the stop bands. Roll off is a measure of the sharpness of this reduction. It is the slope of the amplitude–frequency curve. If the amplitude is in dB and the frequency range is 10 times the given frequency then the unit of Roll Off is dB/decade. If the frequency range is double the given frequency then the unit is dB/octave. Both these ranges are rather large. It is common to talk about –3 dB and –10 dB points. Therefore, the slope of the amplitude vs frequency curve has been determined between these two points. For the present investigations this gives:

Roll-Off at lower frequency side = 8.3 dB/GHz, and

Roll-Off at higher frequency side = 7.6 dB/GHz

Quality factor:

$$Q_u = \pi\eta \{1 + (pa/ d)^2\}^{3/2} / 4 R_s \{1+ (a/d) (pa/d)^2\} + (a/b) \{1 + (pa/d)^2\}$$
$$= 5435.89$$

Where η is wave impedance 377 ohm and R_s is surface resistivity of copper i.e. $5.7 * 10^7$ S/m.

TABLE 3.1 Results Obtained for the Bandpass Filter

Return loss(S11)	-27.36 dB
Resonant frequency	15.13 GHz
3 dB bandwidth	2.30 GHz
Insertion loss(S21)	-1.15 dB
Roll Off	8.3 dB/GHz and 7.6 dB/GHz at lower end and higher end respectively
Quality factor	5435.89

Effects of cavity dimensions on the filter properties were investigated. Cavity width was chosen as the physical dimension. Bandwidth, upper edge frequency and lower edge frequency were selected as filter parameters. Cavity width was systematically decreased up to 50% in steps of 10%. Analysis of results was done to optimize cavity width. The results are shown in fig (3.4).

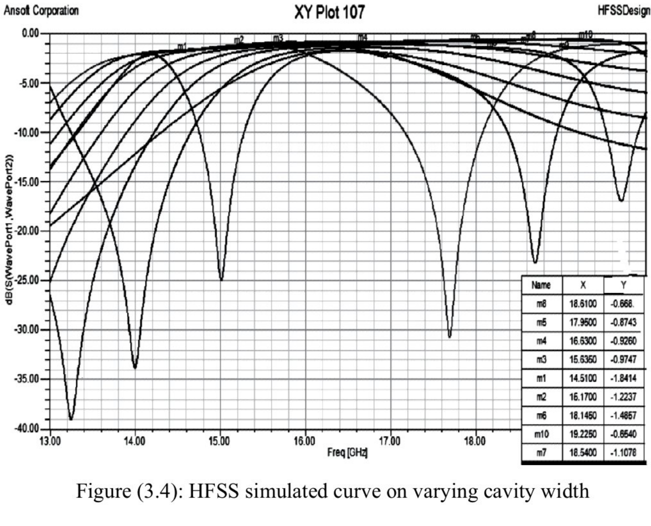

Figure (3.4): HFSS simulated curve on varying cavity width

Table 3.2 Result obtained on varying cavity width

% decrement	w (mm)	f_u (GHz)	f_l (GHz)	Band-width (GHz)
0	1	15.79	13.28	2.51
10	0.9	17.1	13.6	3.5
20	0.8	18.14	13.75	4.39
30	0.7	19	13.95	5.05
40	0.6	19.57	14.45	5.12
50	0.5	21.9	14.8	7.1

Table 3.2 shows that bandwidth decreases as cavity width increases. The dependence is linear. This is graphically represented in fig (3.5).

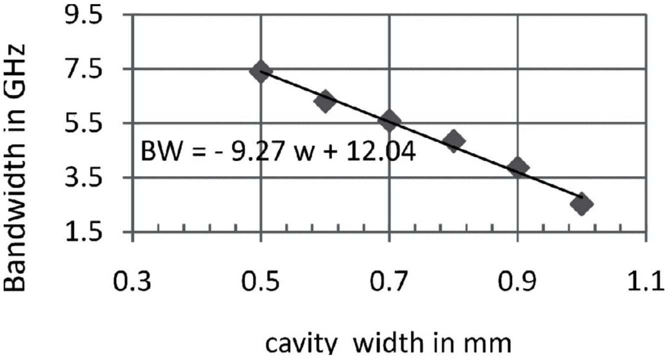

Figure (3.5): Bandwidth with respect to variation in cavity width

The cavity width is very important physical parameter of the filter. The cavity width was normalized with respect to guided wavelength as the latter includes wavelength and dielectric constant of the material in the cavity. This led us in a new direction. We plotted the curve between upper edge frequency, lower edge frequency and bandwidth (one by one) to the ratio of resonant frequency.

Table 3.3: Variation in physical parameters

Cavity width (w/ λg)	f_u / f_r	f_l / f_r	Bandwidth in GHz
0.05	1.05	0.885	2.51
0.045	1.14	0.9	3.86
0.04	1.2	0.91	4.39
0.035	1.26	0.93	5.58
0.03	1.3	0.96	6.55
0.025	1.46	0.98	7.1

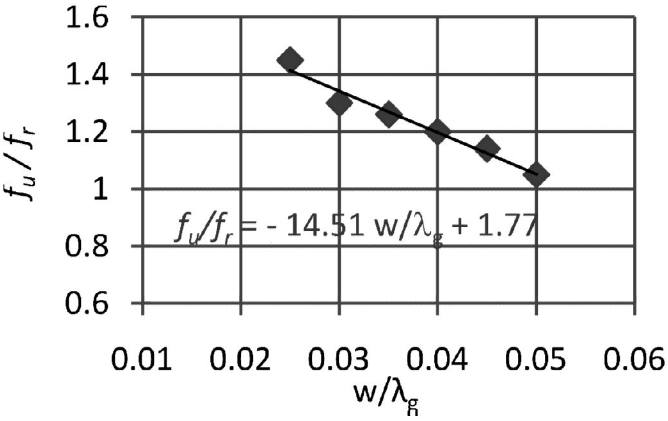

Figure (3.6): Dependence of f_u/f_r on w/λ_g

The plot shows that the fractional upper edge frequency has linear dependence on normalized cavity width. This can be mathematically expressed as.

$$\frac{f_u}{f_r} = -14.51\,\frac{w}{\lambda_g} + 1.77 \qquad (5)$$

This is an important result. While designing a cavity filter value of w can be chosen to get a particular value of f_u .

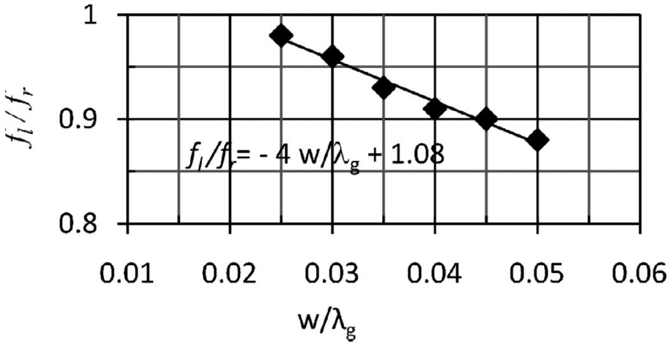

Figure (3.7) Dependence of f_l/f_r on w/λ_g

The plot shows that the fractional lower edge frequency has linear dependence on normalized cavity width. This can be mathematically expressed as

$$\frac{f_l}{f_r} = -\,4\,\frac{w}{\lambda_g} + 1.08 \qquad (6)$$

This is an important result. While designing a cavity filter value of w can be chosen to get a particular value of f_l .

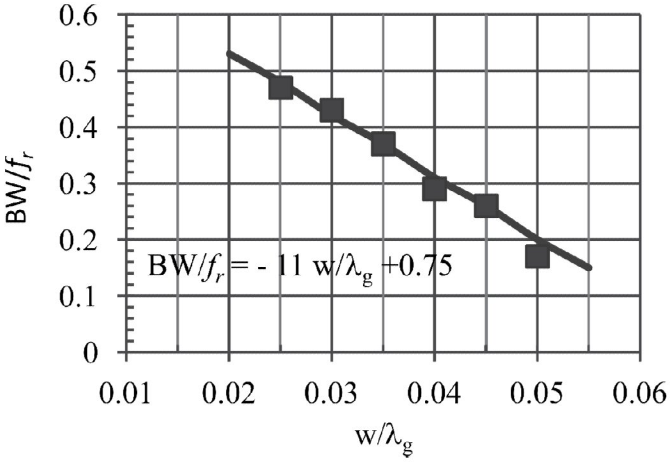

Figure (3.8): Dependence of (BW/f_r) on w/ $_g$

The plot shows that the Bandwidth has linear dependence on normalized cavity width. This can be mathematically expressed as

$$\frac{BW}{f_r} = -11\,\frac{w}{\lambda_g} + 0.75 \qquad (7)$$

This is an important result. While designing a cavity filter value of w can be chosen to get a particular value of BW

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4. VALIDATION OF MATHEMATICAL FORMULAE

It may be noted from figures (3.6), (3.7) and (3.8) that f_u, f_l and BW all decrease as w is increased for a given f_r. For validating formulae (5), (6) and (7) three different values of $w/_g$ (0.048, 0.038 and 0.028) were selected. For each value of this parameter, cavity filter was designed, modeled and simulated in HFSS. The results of these investigations are shown in figures (3.9), (3.10) and (3.11).

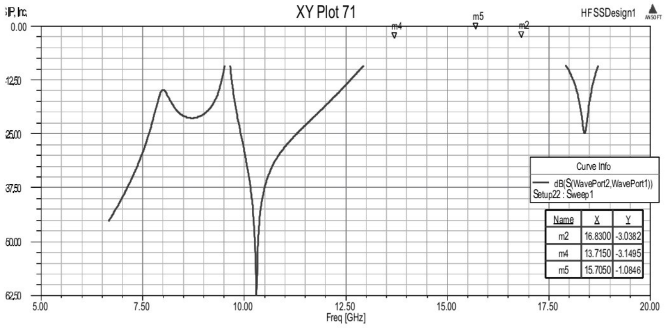

Fig.(3.9) Simulated response of cavity filter for $w/\lambda_g = 0.048$

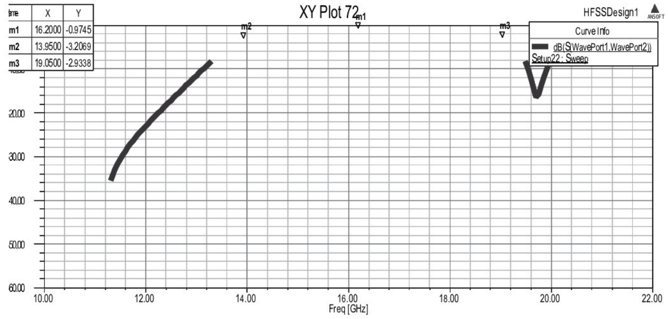

Figure (3.10) Simulated response of cavity filter for $w/\lambda_g = 0.038$

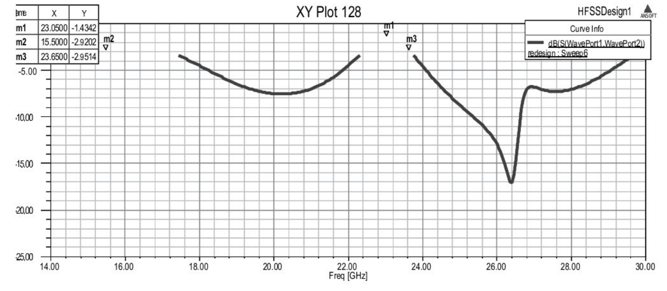

Figure (3.11) Simulated response of cavity filter for $w/\lambda_g = 0.028$

From above figures values of f_u, f_l and BW have been obtained in each case. These are shown in the Table under the headings "Simulated". Same parameters have been estimated using new formulae (5), (6) and (7) for three different values of $w/\lambda_g \rightarrow$ 0.048, 0.038 and 0.028.

Table 3.4: Validation of new formulae

w/λ_g	f_u (GHz)		f_l (GHz)		BW (GHz)	
	From New Formula	Simu-lated	From New Formula	Simu-lated	From New Formula	Simu-lated
0.05	16.33	16.83	13.5	13.715	3.37	3.12
0.04	19.87	19.05	15.13	13.95	5.4	5.1
0.03	26.12	23.65	18.53	15.5	8.46	8.2

The agreement is quite good as 1st order dependence of the frequencies on cavity width has been considered only. This is discussed in the next section.

5. DISCUSSIONS AND CONCLUSIONS

This paper has reported work on 3-D single, microstrip-fed, slot coupled micro machined resonant cavity band pass filter. Parameters of filters have been evaluated in terms of S-parameters, bandwidth and quality factor. The characteristics of resonant cavity based bandpass filter depend on many parameters such as length, width and depth of the cavity, location and size of the coupling slots, feed line parameters, gap between the two microstrip lines. This paper has only considered the effects of varying cavity width. With these limitations in mind, the agreement between theory and simulations is very good. Further investigations need to be carried out to obtain more accurate predictions.

In this paper, band pass cavity filter has been simulated for resonant frequency of 15 GHz having 2.30 GHz bandwidth with 1.15 dB insertion loss. The return loss is better than 10 dB over the whole band, and this shows it is possible to achieve a better return loss, especially at lower frequencies. Three new mathematical formulae have been proposed and validated. This paper will be helpful for the basic design of single cavity band pass filter as well to understand the effect of bandwidth and coupling in microwave devices.

6. ACKNOWLEDGEMENT

The authors are thankful to Director (Academics) and the Management of SKIT, Jaipur for giving permission to carry out this work at SKIT, Jaipur and for publishing it.

REFERENCES

[1] D.M. Pozar, *"Microwave Engineering"*, ISBN 978-81-265-1049-8, pp. - 86-88, John Wiley & Sons, Inc., New York, NY, 1998.

[2] Zhen Ma, *"LIGA Cavity Resonators and Filters for Microwave and Millimeter-Wave Applications"* International Journal of Electrical and Computer Engineering, vol. - 55, no. 8, pp.-10- 15, Nov. 2007.

[3] L. Harle And L.P.B. Katehi, *"A Vertically Integrated Micromachined Filter,"* IEEE Trans. Microwave Theory Tech., vol.-50 , No .9, pp.-2063-2068, Sept. 2002.

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