Analysis and Implementation of a Dual Mode Cavity Band Pass Filter

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Abstract— In this paper a compact simple structure x-band dual mode cavity band pass filter using rectangular waveguide is presented. A cavity resonator is implemented to provide a narrow band pass filter at microwave frequency. Coaxial line probes for excitation is considered. A single cavity resonator is designed to generate a degenerate resonance of two orthogonal modes (TE_{101} and TE_{011}), enabling dual-mode operation. Using dual mode cavities that support twodegenerate resonances reduces the number of physical cavities. This improvement of compact size and weight of the filter are major advantages Also, using cross coupling technique allows to produce transmission zeros near the stop band and hence improving filter selectivity In order to couple of resonators (orthogonal modes), small perturbation by small deformation of boundary is designed. This perturbation can optimize bandwidth of the pass band to desired values. By this technique the bandwidth can be enhanced to more than 6 times of single dual mode structure. Also screw is used for tuning the resonance frequency of dual mode filtering response without disturbing the coupling of the degenerate cavity modes. A prototype is designed to operate at 9050 MHz. Simulated and experimental results are provided. The insertion loss is about 0.5 dB, return loss is better than 12.5 dB and 3 dB fractional bandwidth is about 0.66%.

1. INTRODUCTION

Microwave filters play an important role in almost every RF-microwave communications system. In communication system, narrowband filters are essential components to reject the interference signals. Therefore it is necessary to utilize high Q resonant circuits to achieve a narrow bandwidth in the pass band at high frequency. Microwave band pass filters have been typically implemented using waveguide technology or cavity due to low loss, high quality factors, narrow bandwidth and high power handling capabilities [1]. On the other hand, waveguide filters are massive and heavy. A solution has been done to reduce the size and weight of filters involves using dual mode cavities that support two degenerate resonances. Therefore, to reduce the number of physical cavities, dual mode or triple mode resonators are often employed. The advantages of these filters are the fewer number of cavities and improved performance. The first working multi-mode cavity microwave filter has been introduced by Li [2]. Elliptic dual mode filters for space applications were introduced by Atia and Williams [3]. Designs in other methods were reported by many authors [4, 5]. In addition the transmission line must be coupled together. In the coaxial case, the probe excitation is carried out in the cavity resonator by introducing the probe inside the cavity. This paper presents a structure of the dual mode rectangular cavity filter using coaxial probes for excitation. By using cross coupling technique with perturbation theory, transmission zeros in the stop band are realized, so the shape factor can be improved. Also, by this technique, bandwidth of pass band can be optimized. On the one hand, cross coupled filters are difficult to tune, due to couplings affect in the filter In section II design procedure are expressed. Also geometry and prototype values are discussed. The concept of dual mode cavity resonator is explained in Section 2.1. In Section 2.2 probe excitation is designed to excite resonance modes of the cavity filter. Moreover, direct and indirect coupling dual-mode cavity resonator filters are introduced. In Section 2.3 this technique is optimized to produce coupling resonance modes of direct and cross coupling. In addition, the realization of flexible bandwidth is discussed. In Section 3.1 simulation results are presented. The procedure to control and tune the resonant frequency is shown in Section 3.2 and the feasibility of realizing the filter has been validated with the experimental data (Section 3.3). Finally conclusion is drawn in Section 4.

2. DESIGN PROCEDURE

2.1. Dual Mode Cavity Resonator

Detailed design procedures of cavity filters can be used in several texts [1, 6]. A rectangular cavity resonator is a rectangular waveguide shorted at both ends ($z = 0$, $z = L$) as shown in Fig. 1(a).

Dual-mode resonators have been widely used to realize many RF/microwave filters [7–9]. A main feature and advantage of this type of resonator is that each of dual mode resonators can used as a doubly tuned resonant circuit, and therefore the number of resonators required for a n-degree filter is reduced by half, resulting in a compact filter configuration [1]. The simplest dual mode filter is the two pole band pass filter using a single dual mode resonator. Fig. 1(b) shows the equivalent circuit of the dual mode resonator. This type of line resonator can support a pair of degenerate modes that have the same resonant frequencies.

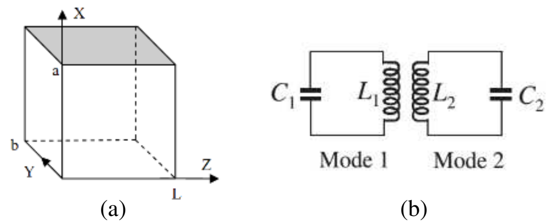


Figure 1: (a) A rectangular cavity. (b) Equivalent circuit of the dual-mode resonator.

The EM fields inside the cavity can be considered in terms of TE. Therefore, the two fundamental modes, TE_{101} and TE_{011}, are a pair of the Degenerate modes. Excitation probes position and dimensions a, b, L can be selected such that TE_{101} and TE_{011} resonate and TM_{110} does not resonate. With choosing $a = b$ (assuming the same value for two dimension of cavity) the resonance frequencies of these modes are:

$$f_{101} = f_{011} = \frac{c}{2\sqrt{\varepsilon_r}}\sqrt{\left(\frac{1}{a}\right)^2 + \left(\frac{1}{L}\right)^2} \tag{1}$$

Both the degenerate modes are excited and coupled to each other, which causes resonance frequency

2.2. Probe Excitation for TE Modes

To excite a particular mode, the cavity must be properly coupled to an external source. To obtain maximum power transfer, the resonator must be matched to the feed at the resonant frequency. Fig. 2 shows the coax to waveguide feed. Since a dual mode rectangular waveguide cavity filter operates in the TE_{101} and TE_{011} modes, the position of the probes must not to be in the symmetric line. For excitation of first resonant mode (TE_{101}), the probe should be orthogonal to "xz" plane that means the center of probe is along the electric field distribution as shown in Fig. 2(a). And for the second resonant mode (TE_{011}) it is located orthogonal to "yz" plane (Fig. 2(b)). On the one hand TE_{101} and TE_{011} modes have one half wave length variations in the x-z and y-z directions respectively. Also the positions of first and second center probes from side walls along x and y axial (L_i) can be carried out by following the technique described in [11], it is about one quarter wavelength at the resonant frequency which is the located of the shorted plane. The other position of the probe (t_i) are optimized. Therefore a direct coupling between input and output ports is created.

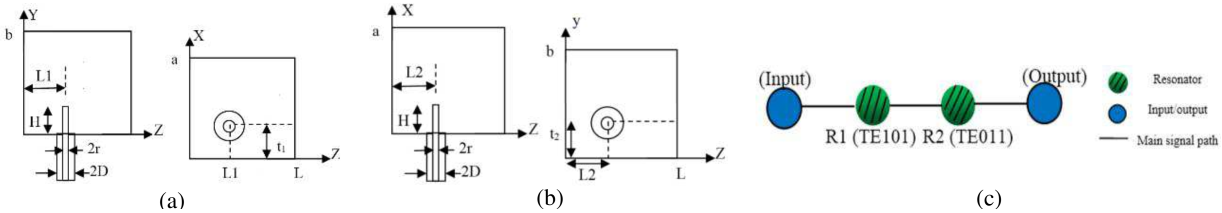


Figure 2: The geometry of the excited cavity by two probes. (a) TE_{101} mode. (b) TE_{011} mode (side view & top view). (c) Typical coupling structures of dual mode cavity filter.

Figure 2(c) shows the general coupling structure of the 2-order cavity filter, where each node represents a resonator, the full lines indicate the direct couplings. In this coupling structure, the resonators are numbered 1 to N ($N = 2$) with the input and output ports located in resonators 1 and 2, respectively. In this case the frequency response of the filter cannot be accurately predicted and cut and try process to determining the position of t_i is difficult and time consuming. Generally the disadvantage of the structure is that there is weakly coupling between two modes and the direct coupling do not create a transmission zero in the insertion loss response of the filter. Also the maximum relative bandwidth can be achieved is about 0.1%. Therefore to obtain strong coupling, transmission zeros and more bandwidth, another design is introduced. As known, dual mode cavity filter uses two orthogonal degenerate "101" and "011" thus "xz" and "yz" plane are the location of probes. As it is shown in Fig. 3 the common axis of these planes is "z" axis and probe should be place on the middle of the axis, that is, the probe is inserted from the broad dimension of the cavity and it should be kept at the place inside the cavity where electric field is maximum. Other coordinate of probes position along "x" and "y" directions of two TE_{101} and TE_{011} modes are quarter wavelength of resonant frequency. Thus only the TE_{101} and TE_{011} modes propagate in the waveguide which are matched in both directions. In this design there are direct and cross coupling between modes. Both direct and cross coupling are realized by adding perturbation that is discussed in next section. Actually without perturbation, coupling between two resonators are not provided. By this technique, in addition to realize direct and cross coupling, the bandwidth would be able increase to arbitrary values.

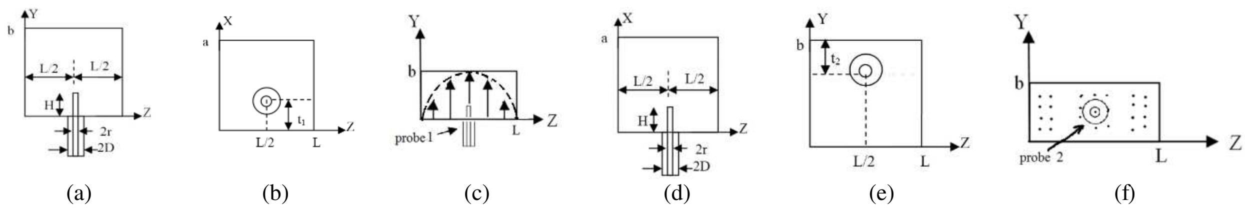


Figure 3: The geometry of the excited cavity by two probes (TE_{101} and TE_{011} modes). (a), (d) Side view. (b), (e) Top view. (c), (f) Electric standing wave patterns.

2.3. Perturbation Study

Cavity perturbation theory describes method to change the performance of a cavity resonator. These performance changes are caused by a small foreign object into the cavity or a small deformation of its boundary. When a resonant cavity is perturbed, i.e., when foreign object with distinct material properties is introduced into the cavity or when a general shape of the cavity is changed, electromagnetic fields inside the cavity change accordingly [6]. In this design cavity is perturbed by a small deformation of its boundary as shown in Fig. 4(a). This perturbation causes the electrical field, which induced by two resonator inside the cavity, is changed and direct coupling between them is occurred, also this cause cross coupling. The cross coupling can be designed in such a way that a pair of transmission zeros are introduced at the desired frequencies to improve the selectivity. The maximum number of zeros are equal the number of mode cavities. These zeroes increase the selectivity (slope) of the filter in the lower and upper stop band. Fig. 4(b) illustrates coupling scheme proposed for the filter structure where each node represents a resonator, the full lines indicate the main or direct coupling, and the dashed line denotes the cross couplings. This cross coupling that will produce a pair of transmission zeros at desired frequencies.

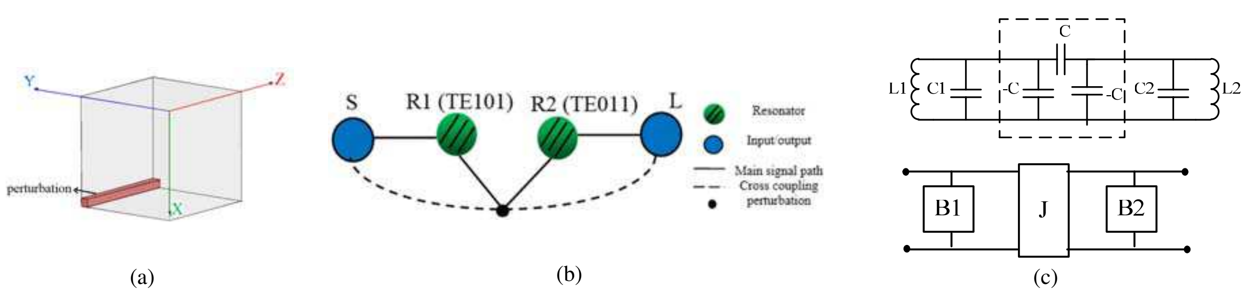


Figure 4: (a) A resonant cavity perturbed by small deformation of its boundary. (b) Coupling scheme proposed for dual mode cavity filter. (c) Equivalent circuit of the proposed second order dual-mode perturbed cavity filter along with electric coupling by an admittance inverter.

Furthermore, to indicate the effect of perturbation on the bandwidth, circuit analysis is done.

Fig. 4(c) shows the equivalent lumped element circuit of the filter. The capacitive coupling C introduced by distributed element as perturbation between two resonators. L_i and C_i ($i = 1, 2$) are inductance and capacitance of resonant loops. Actually, it can be shown that the electric coupling between the two resonant loops is represented by an admittance inverter, Fig. 4(c).

Based on admittance inverter definition [12], inductance and capacitance with an inverter J on each side looks like, a capacitance and inductance from exterior terminals. Making use of this property to analyze this technique. The resonant frequency of coupled resonators are different from uncoupled resonators. Coupling effect can reduce and increase the resonance frequencies according to:

$$f_{r\_\text{lower}} = \frac{1}{2\pi\sqrt{L_1(C_1 + C')}} \quad f_{r\_\text{upper}} = \frac{1}{\sqrt{2\pi(L_1||L')C_1}} \tag{2}$$

where C' and L' are transferred equivalent capacitance and inductance from exterior inverter terminal. Therefore, the bandwidth is increased. So, increasing the pass band or having flexible band width is another feature of the perturbation, which is shown in Section 3 Coupling capacitance between two equal shunt resonators is calculated as follows:

1. Choose an inductor value inside the given limit, the input and output coupling capacitors will become large enough that they may be eliminated from the design.

2. Compute Susceptance slope parameter by $b = \omega_0/2\ (dB/d\omega)|_{\omega=\omega_0}$ where B is the Susceptance of resonators ($B = B_1 = B_2$) that is imaginary part of input admittance of shunt resonator, ω_0 is the resonance frequency.

3. Determine coupling coefficient by: $k = J/\sqrt{b_1 b_2} = w/\sqrt{g_1 g_2}$, where$g_1$,$g_2$are prototype parameter values.

4. Compute inverting circuit to calculate of admittance inverter ($J = \omega C$) which is shown in Fig. 4(c). The negative capacitances are absorbed into adjacent elements.

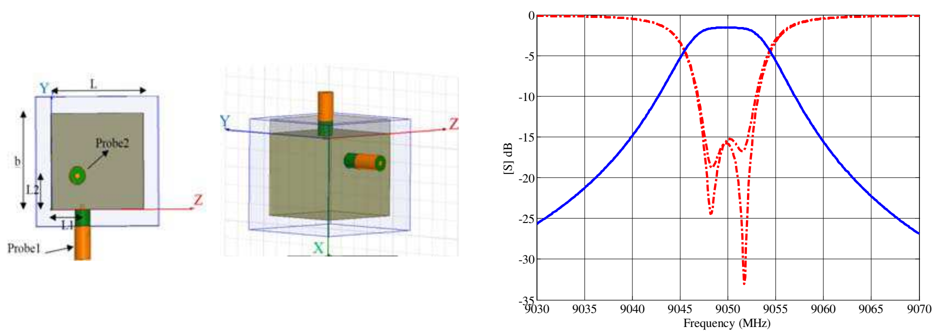
5. Thus the coupling capacitor is equals to: $C = wb_1/(\omega_0 g_1)$.

3. SIMULATION AND EXPERIMENTAL RESULTS

In this section, a second order filter based on dual mode cavities, with square cross section perturbation and without it, are designed using techniques described above.

3.1. Filter Design

The two-pole filter is designed to meet the center frequency of 9050 MHz, 3-dB bandwidth of 60 MHz, insertion loss less than 0.5 dB, and 20 dB return loss in the pass band. Fig. 5(a) illustrates a configuration of the first design of filter structure. Fig. 5(b) shows the EM simulated response of the designed filter by HFSS software. As shown there is weakly coupling between modes, the insertion loss is about 1 dB, the B.W is 10 MHz and return loss is better than 15 dB. The dimensions of the designed filter are (all in mm) indicated in Table 1. The dimensions may be slightly altered to tune the responses toward the desired ones. The center conductor of the coaxial line (SMA connector) extends a distance H into the cavity that is obtained by simulation. As a result this way of coupling does not create a transmission zero at desired frequencies and the maximum relative bandwidth can be achieved about 0.1%. Therefore to obtain strong coupling, transmission zeros and more bandwidth, other design is used. In this design the perturbed cavity as shown in Fig. 6 is excited according the way was described before. In this structure the resonant frequency is affected by the perturbation. In addition the bandwidth can be easily tuned to flexible bandwidth by varying the square cross-sectional dimension of the perturbation since the perturbation is extending along the whole length of the cavity. The final dimensions of the perturbed filter are shown in Table 2. It can be observed that, only very small adjustments are required on the achieved dimensions in the simulation. The corresponding EM simulation result can be found in Fig. 7 (dashed lines). The filter has a center frequency of 9080 MHZ, 3 dB bandwidth is about 60 MHZ, insertion loss of about 0.28 dB and return loss is better than 20 dB.



(a) (b)

Figure 5: (a) Configuration of dual mode cavity filter with two coaxial probes without perturbation. (b) Simulated response of the cavity filter.

Table 1: Dimension of the filter shown in Fig. 5(a).

	a	b	L	L1=L2	t1=t2	H
Designed	22.9	22.9	24.02	$\lambda_r/4$	-	-
Simulated	22.8	22.8	24.05	8	0.29a	1.1

Table 2: Dimension of the perturbed dual mode cavity filter shown in Fig. 6.

	a	b	L	L1=L2	t1=t2	L_Screw	H
Designed	22.9	22.9	24.02	$\lambda_r/4$	-	-	-
Simulated	22.8	22.8	24.05	8	8.3	7.3	2.4

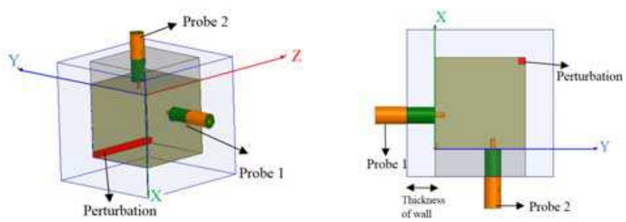


Figure 6: Configuration of dual mode cavity filter with two coaxial probes as an excitation.

3.2. Frequency Tunning

Tuning screws are screws inserted into resonant cavities which can be adjusted externally to the waveguide. But most cross coupled filters are difficult to tune since source to load couplings affect all other couplings in the filter. Whereas, this filter provide fine tuning of the resonant frequency by inserting more or less length of dielectric screw into the waveguide, thus electromagnetic fields inside the cavity change accordingly without disturbing any coupling of the degenerate cavity modes. The conventional tuning screw is used to part of the design. Fine tuning is required because of manufacturing tolerances after fabrication. Therefore, the designed frequency is considered 9080 MHz that is higher than desired frequency. Fig. 8(a) shows perturbed cavity which has a tuning dielectric screw with diameter of 4 mm on shorted wall (xy plane). Two mentioned mechanism are presented in Fig. 7 and the excellent result is obtained with screw. When the specific length of the screw has been inserted into cavity the center frequency is moved to lower frequency, from 9080 to 9050 MHz. The 3 dB bandwidth of the filter is 63 MHz centered at 9050 MHZ, insertion loss is about 0.28 dB, and return loss is better than 26.4 dB in over the pass band. The dimension of the perturbation is $1.7 \times 1.7 \times L$ and the center conductor of the coaxial line (SMA connector) extends inside the cavity about H 2.4 mm. That H is the desired length of inner conductor. Moreover the proposed filter have transmission zeros at desired frequencies. Fig. 8(b) shows two transmission zeros below and above pass band. The two transmission zeros are located at $f_1 = 8.842$ GHz and $f_2 = 9.445$ GHz. Also the first spurious resonance occurs around 11.5 GHz. Fig. 9 shows the frequency responses of the unperturbed designed filter when all transmission zeros are at infinity along with the perturbed cavity filter with two transmission zeros. Also, it is obvious that the more

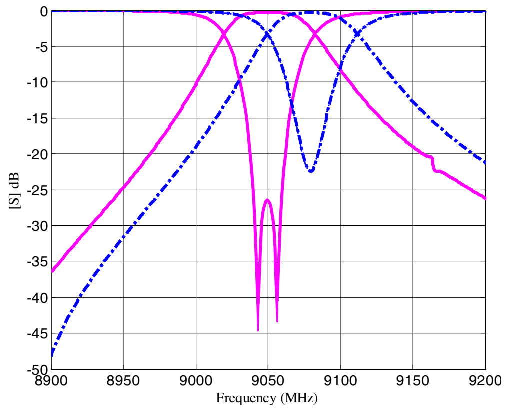
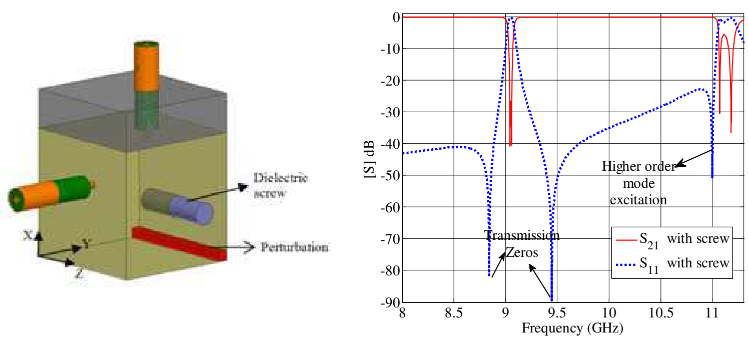


Figure 7: Simulated responses of dual mode perturbed cavity filter, dash line is without tune screw, and solid line is with tune screw.



(a) (b)

Figure 8: (a) Configuration of perturbed filter with tune screw. (b) Simulated result.

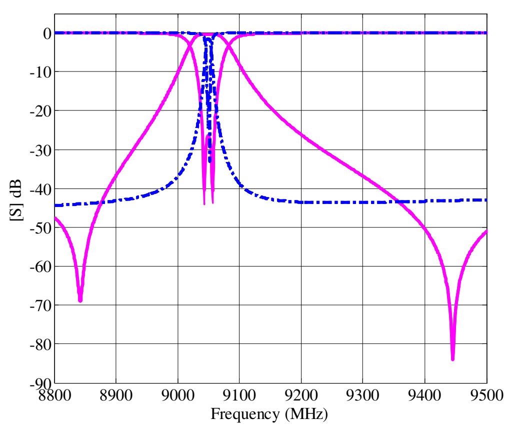
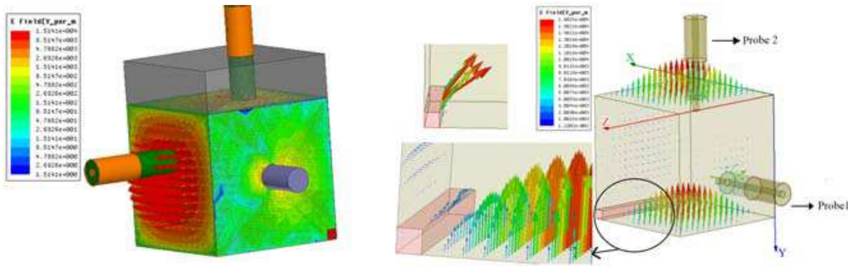


Figure 9: Comparison between unperturbed designed filter response (Dashed line) and perturbed cavity response (solid line).

bandwidth with lower insertion loss is achieved on the perturbed cavity. To analysis of electrical field inside the filter, HFSS is used as a simulator. Fig. 10(a) shows the E-field strength across the filter in 9050 MHz. Also the direction of the electrical field is important, so a vector plot uses arrows to illustrate the magnitudes of the field quantities which is shown in Fig. 10(b).

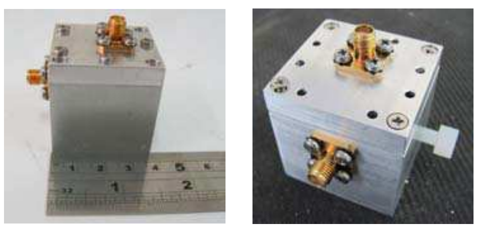
4. EXPERIMENTAL RESULTS

In order to validate the performance of the filter design, the filter was fabricated and measured. A photograph of the fabricated filter is shown in Fig. 11(a). In this work tuning screw is not part of the design, it is added only to compensate for manufacturing errors. By inserting dielectric screw on the shorted plan as shown in Fig. 11(b), the shift of resonant frequency can be completely controlled Fabricated cavity filter was measured using the Agilent 8510C Network Analyzer. Fig. 12



(a) (b)

Figure 10: (a) E-field strength across the cavity filter in frequency 9050 MHz. (b) Vector E-field strength on XZ plane of cavity filter.



(a) (b)

Figure 11: (a) Picture of the fabricated filter. (b) Insert dielectric screw.

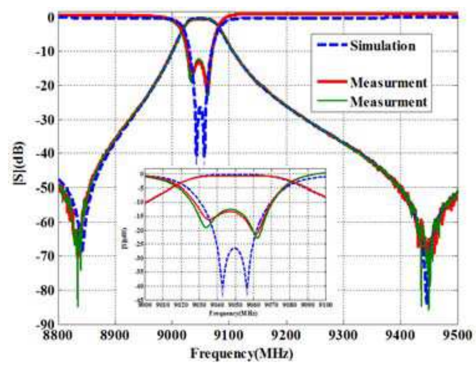


Figure 12: EM Simulated and measured results of the BPF dual mode cavity filter.

shows the comparison between the measured response as the solid curves and simulated response (dashed lines). The 3 dB bandwidth of the measured results filter is 63 MHz centered at 9050 MHZ, are the return loss of better than 12.5 dB in the pass band and the insertion loss of better than 0.5 dB.

5. CONCLUSION

In this paper a compact dual mode rectangular waveguide cavity filter was presented. This dual mode cavity design was used for the implementation of second order filters with two TE_{101} and TE_{011} mode. By using cross coupling technique with perturbation theory, transmission zeros in the stop band were realized, and the shape factor was improved. Also, by this technique, bandwidth of pass band was optimized. It was obvious that the bandwidth of the filter can be altered to desired values by changing the dimension of perturbation. Furthermore, to indicate the effect of perturbation on the bandwidth, circuit analysis was done. The proposed cavity filter is structurally compact size and requires only one tuning screw. This tuning mechanism was presented to adjust the resonant frequency without causing any coupling of the degenerate cavity modes. Finally, EM simulation was done for the filter. Full wave analysis of the filter confirms the designed filter. In order to validate the performance of the filter design, the filter was fabricated and measured. The measurement results shows close agreement with the simulation results. Although there is still a little differences between the simulated and measured results due to manufacturing tolerances.

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