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Design and implementation of a Quarter Mode Substrate Integrated Waveguide (QMSIW) cavity filter

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***Abstract*— In this paper, a novel Quarter Mode Substrate Integrated Waveguide (QMSIW) cavity filter is presented. A prototype at 5GHz for the proposed filter has been simulated using CST Microwave Studio, and fabricated using standard Printed Circuit Board (PCB) process. The fabricated filter has been measured using a Vector Network Analyzer (VNA). The measurement results are compared with the simulation results, good agreement is observed between simulation and measurement results concerning the pass band, the selectivity and the out-of-band rejection.**

***Index Terms*—** Quarter Mode Substrate Integrated Waveguide, Half Mode Substrate Integrated Waveguide, QMSIW Cavity, QMSIW Filter.

I. INTRODUCTION

Due to the increasing demand of wireless communications in the past decades, unremitting efforts have been made to bring down the size and cost of microwave circuits. Usually, the size of Substrate Integrated Waveguide (SIW) circuits is quite larger than their microstrip or Coplanar Waveguide (CPW) counterparts. This could be advantageous for millimeter-wave applications since the fabrication tolerances of Printed Circuit Board (PCB) process will be much more relaxed with respect to circuit size and processing parameters. However, a large size of SIW components also poses a problem for their applications at low frequencies. In order to reduce the inherent size of SIW circuits, novel techniques have been proposed as Half Mode Substrate Integrated Waveguide (HMSIW) [1]-[2], Half Mode Folded Substrate Integrated Waveguide HMFSIW [2]-[3]-[4].

Many efforts have been exerted to design filters using SIW, HMSIW and HMFSIW cavities [3]-[5]-[6] at difference frequencies with and without cross coupling [7]-[8]-[9]-[19] to give different responses, filters designed were with different cavities shapes, circular, triangular, square [10]-[11]-[12]-[13], loaded or not loaded, single or multi-mode and other types [14]-[15]-[16]-[26].

In the following, a new Quarter Mode Substrate Integrated Waveguide (QMSIW) cavity is presented, and a filter based on QMSIW cavities is designed and implemented. We found that the performance of the designed filter with traditional inline-coupling configuration can give the desired specifications. The filter is designed using coupling cavity filter design method [10]-[12], [17], [19] and fabricated with standard PCB process. Excellent stopband rejection, insertion loss and selectivity are achieved. Measurement results agree well with the simulation.

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II. QUARTER MODE SUBSTRATE INTEGRATED WAVEGUIDE (QMSIW) CAVITY

Half Mode Substrate Integrated Waveguide (HMSIW) cavity can be obtained from SIW cavity by bisecting it into two sections and each half of the SIW cavity becomes an HMSIW cavity, each of the new structures can almost preserve half of original fields distribution [1]-[18]. We propose a new Quarter Mode Substrate Integrated Waveguide QMSIW cavity by bisecting the HMSIW cavity into two sections, each of them constructs a QMSIW Cavity. The QMSIW Cavity almost preserves a quarter of original fields distribution of SIW cavity.

SIW cavity is obtained by holding a part of a substrate using four ranges of metallic vias, these ranges react as equivalent electrical walls (E = 0) [2]-[18]. Therefore, a QMSIW Cavity can be obtained by bisecting the SIW Cavity two times with two fictitious magnetic walls to four sections and maintaining one of these sections. This part holds approximately a quarter of fields distribution of SIW Cavity fields. The overall size of a QMSIW $TE_{0.5,0,0.5}$ mode cavity is around a quarter of its original SIW Cavity counterpart. Therefore, the proposed QMSIW Cavity shows an excellent potential for low frequency (few GHz) applications. However, this cavity is opened to the environment around it. Which creates an interference between the cavity and circuits around it on the same substrate, in addition to the radiation. To avoid this interference and radiation, the cavity must be shielded by adding another two walls of vias beside opened sides of the cavity and cover it by a metallic cover. Fig. 1 shows the shielded QMSIW Cavity.

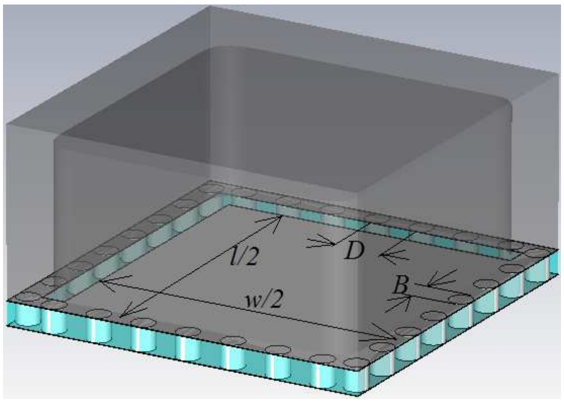
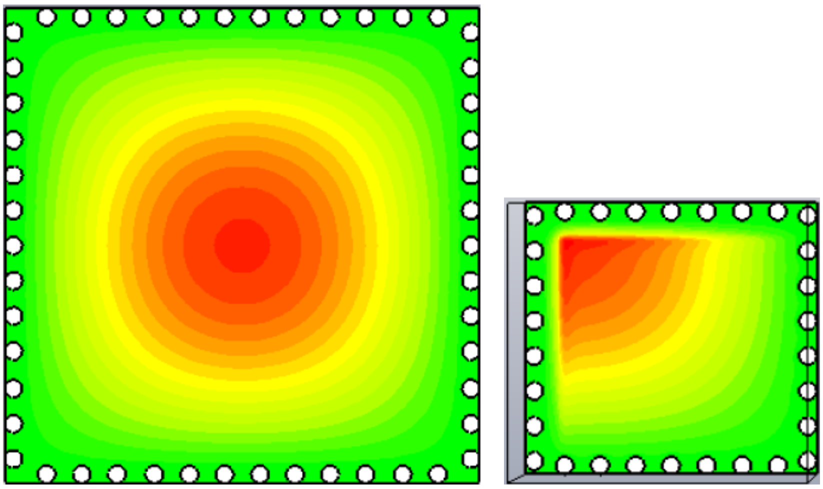


Fig. 1. shielded QMSIW Cavity

To illustrate the difference between the two fields distributions (in SIW and QMSIW cavities), Fig. 2 shows the electrical fields in the two cavities inside the substrate. It is obvious that the QMSIW Cavity holds approximately a quarter of the SIW cavity fields distribution. These results is obtained by simulating the two cavities using Eigenmode solver in CST Microwave Studio. The *Q* value of the proposed QMSIW structure is usually approximately about quarter lower than their conventional SIW since the two opened edges are not perfect magnetic walls [25] (the ***unloaded*** *Q* value of our QMSIW cavity is 196 where it is about 700 for the conventional SIW, the permittivity of the used substrate is 4.5 and the dielectric loss is not considered). It is important here to mention that we can obtain the same ***loaded*** *Q* value for the two cavities depending on feeding conditions of the cavities (see Section III. *C*.) where the ***loaded*** *Q* factor of the cavity is changeable. We must mention also that the resonance frequency of the QMSIW cavity increases a little bit because of the imperfectness of the two magnetic walls at the two open edges of the cavity (the left and top sides of the cavity), so we must increase the horizontal dimensions of the cavity to reposition the resonance frequency to the right value (the resonance frequency in these cavities is 5GHz, the height of the used substrate in the two cases is 0.8mm with permittivity 4.5, the two horizontal dimensions are 20mm for SIW Cavity and 20.66/2 = 10.33mm for QMSIW Cavity). Therefore, the area of QMSIW Cavity is approximately 27% of the SIW Cavity area.



(a) (b)

Fig. 2. Electrical field distribution in the substrate of (a) SIW Cavity (b) QMSIW Cavity

III. FILTER DESIGN

The design of microwave filter using QMSIW Cavities depends on the same design procedure of coupled resonator cavity filter, which can be found in many references in the literature [10]-[12], [17], [19], so we don’t need to illustrate the design procedure in detail. The proposed cavity is applied to our filter design.

A. *Filter specifications*

The filter is a BPF at the center frequency 5GHz, its pass band is 80MHz (1.6%) at -0.1dB (return loss is less than -16.24dB), the out-of-band rejection is 45dB at least at 200MHz from the center frequency. These specifications can be achieved by Chebyshev response, since there is no transmission zeros in the response. With Chebyshev response, (from [17]) for the desired bandwidth, the ripple in the pass band and the rejection, we found that the filter must be of the forth degree at least.

B. *Electrical parameters*

The next step is to find the electrical parameters of the filter. The parameters of the low pass prototype were found from tables in [17] as:

$$g_1 = 1.1088 \ , \ g_2 = 1.3062 \ , \ g_3 = 1.7704 \ , \ g_4 = 0.8181 \text{ and } g_5 = 1.3554$$

these values were used to obtain the coupling coefficients k_{ij} between QMSIW cavities, and the quality factor Q at the two sides of the filter (caused by connections between lateral cavities and filter

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feeding lines). Referring to [17], these values were found as:

$$Q_i = 92.19 \qquad Q_o = 92.19$$

$$k_{12} = 0.0166188 \qquad k_{23} = 0.0131521 \qquad k_{34} = 0.0166188$$

C. *Physical parameters*

The response of the designed filter is Chebyshev response, there is no transmission zeros in the response. So The designed filter belongs to inline topologies without cross coupling. The filter is of forth degree, so it consists of four resonators (QMSIW cavities). Fig. 3 shows the figure of filter's printed circuit.

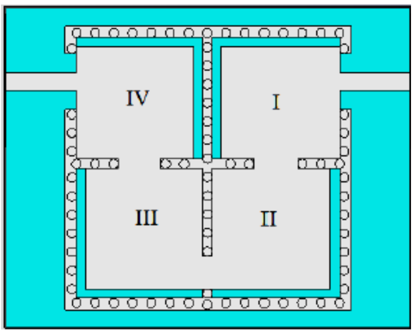

Fig. 3. top view of the filter substrate

The electrical parameters found in the last step are transformed into physical parameters (dimensions). For the filter, the chosen substrate is of permittivity 4.5 and height 0.8mm. Dimensions of the QMSIW cavities can be found using the relation: [20]

$$f_{m0n} = \frac{c_0}{2\sqrt{\varepsilon_r}}\sqrt{\left(\frac{m}{l_{eff}}\right)^2 + \left(\frac{n}{w_{eff}}\right)^2}$$

l_{eff}, w_{eff} are the effective length and width of the cavity. For TE_{101} mode ($m = n = 1$) and $l_{eff} = w_{eff}$, we can find that $l_{eff} = w_{eff} \approx 20mm$ at 5GHz where l_{eff} and w_{eff} are the effective length and width of the complete SIW Cavity calculated as: [21]

$$w_{eff} = w - \frac{D^2}{0.95B}$$

$$l_{eff} = l - \frac{D^2}{0.95B}$$

where l and w are the physical length and width of the cavity, D is the diameter of the vias and B is the distance between the axes of two neighboring vias as shown in *Fig.* 1. D and B are chosen as 0.8mm and 1.6mm respectively, these two values vitrify the following two conditions, then they inhibit the leakage of the waves between vias: [21]

$$B \prec \frac{\lambda_0 \cdot \sqrt{\varepsilon_r}}{2}$$

$$B \prec 4D$$

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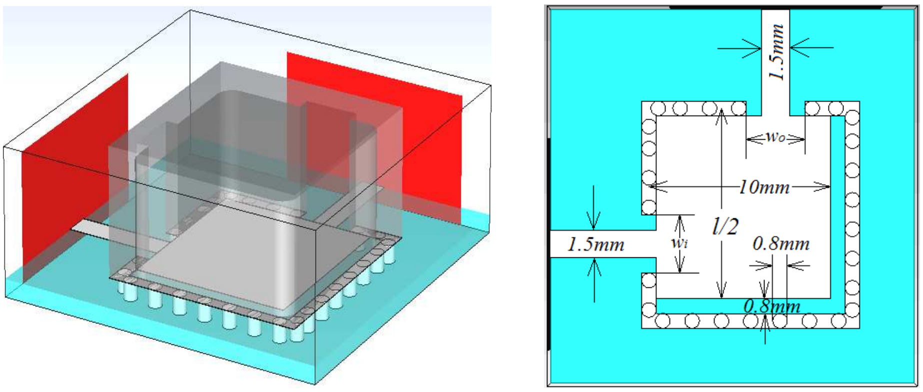
With the calculated values of l and w, the resonance frequency of the QMSIW cavity using the eigenmode solver in CST microwave studio was more than 5GHz. This increment of the resonance frequency value is ascribed to the imperfectness of the two magnetic walls at cavity open edges. Then, to reduce the resonance frequency of the cavity to 5GHz, the area of the cavity must be increased. For our filter, the width w has been fixed to 20mm (the width of the QMSIW Cavity is equal 10mm), then the length l how make the resonance frequency 5GHz is found as $l = 21.46$mm, with considering that the height of the covering box is 5mm.

The filter is connected with two 50Ω microstrip lines at the input and the output through two feeding windows in the vias ranges, as shown in Fig. 4.

Since the vias diameter, the height of the substrate and the distance between open edges of the cavities and vias ranges, are fixed, then the quality factors at the input and the output depend only on the width of these mentioned widows. We can find the dependency of the quality factor on the width of the feeding window by simulating the structure of Fig. 4 using frequency domain solver in CST Microwave Studio, changing the width of the feeding windows and calculating the value: [22]-[23]

$$Q = \frac{f_0}{BW_{-3dB}}$$

Since each of the feeding windows is opened at one of the closed edges of the cavity at the feeding point, the resonance frequency will change with changing the window width (the electrical wall at this edge changes with the changing the window width), so we had to reposition it by altering the length of the cavity to have the right resonance frequency value (5GHz). From the simulation results, we found the width of the feeding windows which gives the desired quality factor at resonance frequency 5GHz.



(a) (b)

Fig. 4. (a) shielded QMSIW Cavity connected to two microstrip lines

(b) top view of the shielded QMSIW Cavity substrate

Looking to the structure in *Fig*. 3, we can see that there are two types of coupling between QMSIW Cavities, the first type is between the cavities (I , II) and the cavities (III , IV), where there is a coupling window in the middle of the wall separating between the two cavities, and the other type is

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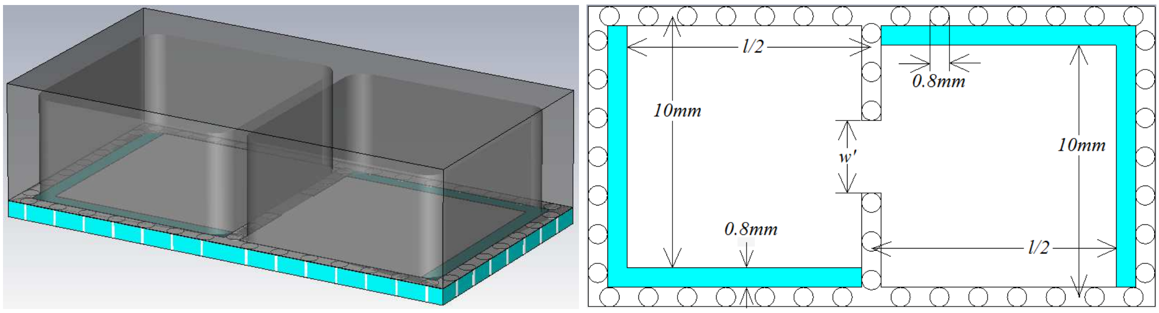
between cavities (II , III), where the coupling window is at the end of the wall separating between the two cavities at the open edges. To find the width of the coupling window, we connect normally two cavities (with coupling window between them) with two transmission lines realizing week coupling to obtain (after simulation) two resonance frequencies. These two frequencies are used to calculate the coupling coefficient from:[23]-[24]

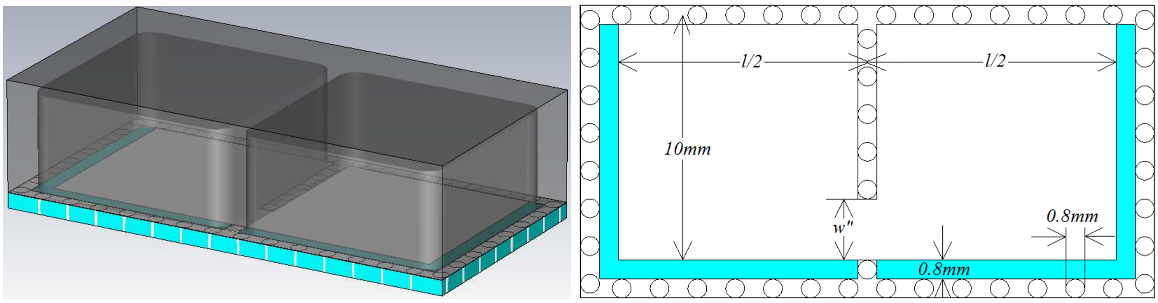
$$k = \frac{f_2^2 - f_1^2}{f_2^2 + f_1^2}$$

To effectively find the dependency of the coupling coefficient on the width of the coupling window, we have used here the Eigenmode Solver to simulate the structures of Fig. 5 and Fig. 6 for the first and second type of coupling respectively. The Eigenmode Solver gives the two mentioned resonance frequencies.



(a) (b)

Fig. 5. the first type of coupling of two coupled cavities.
(a) shielded QMSIW Cavities
(b) top view of the substrate of two shielded QMSIW Cavities



(a) (b)

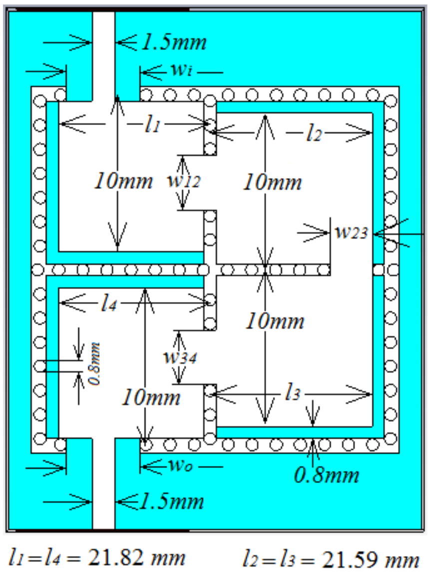
Fig. 6. the second type of coupling of two coupled cavities.
(a) shielded QMSIW Cavities
(b) top view of the substrate of two shielded QMSIW Cavities

As we can see from *Fig*. 5 and *Fig*. 6, the two cavities width is fixed at $w/2$ = 10mm. With changing the width of the coupling window between the two cavities, the two resonance frequencies change, so another coupling coefficient is obtained. Also here, with each value of the window width, the length of the two cavities is altered to reposition the center frequency between the two resonance frequencies to 5GHz (the center frequency of the filter pass band).

D. *Filter simulation*

The characteristic impedance of the microstrip lines at the filter input and output must be 50Ω. For a substrate of permittivity 4.5 and height 0.8mm, the microstrip width will be 1.5mm. Fig. 7 shows the filter circuit with the dimensions obtained. With considering that the height of the covering box is 5mm and the distance between open edges of the cavities and the vias ranges is 0.8mm.

Using the frequency domain solver in CST Microwave Studio, the filter has been simulated. Fig. 8 shows the simulated structure (the covering box is considered), where the filter's board is shown in Fig. 7 (the permittivity of the used substrate is 4.5 and the dielectric loss is not considered). Fig. 9 shows The simulation results, where these results verify the desired specifications concerning the center frequency, the bandwidth, the insertion loss in the pass band and the out-of- band rejection, in addition to the return loss in the pass band.



$w_{12} = w_{34} = w' = 4.43\ mm \qquad w_{23} = w'' = 3.63\ mm$

Fig. 7. Filter circuit with the dimensions

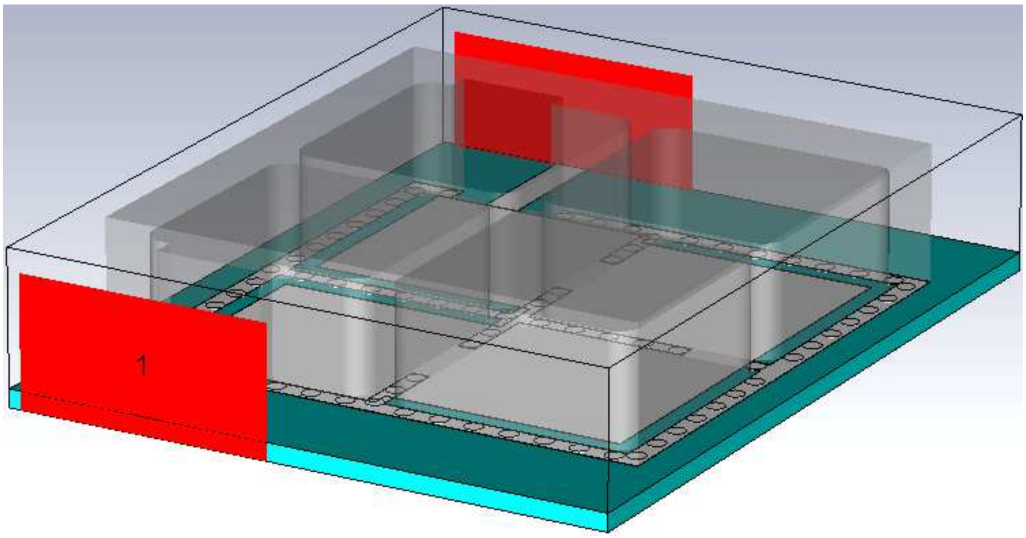


Fig. 8. the simulated structure of QMSIW cavity filter with covering box

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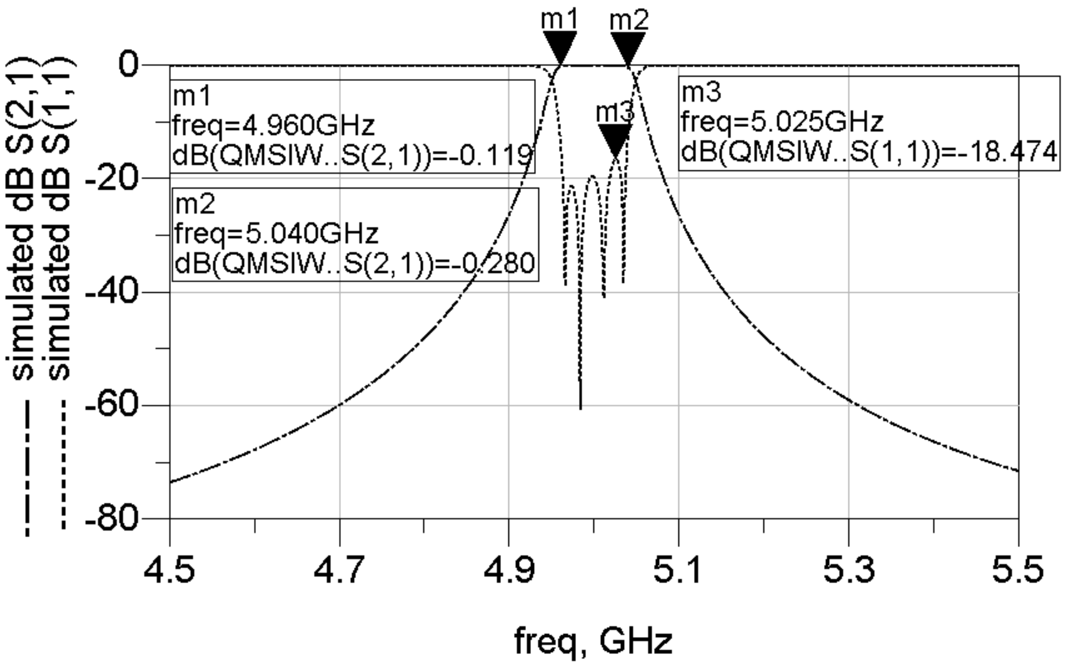

Fig. 9. simulation results of QMSIW filter

IV. FILTER IMPLEMENTATION

The filter has been implemented using a standard PCB process on a substrate whose permittivity 4.5, height 0.8mm and loss tangent angle 0.01 (from ARLON). Fig. 10 shows a photograph of the filter's printed circuit. The covering box has been fabricated of aluminum, this box is shown in Fig. 11. The covering box separates between the four QMSIW cavities and covers them, where there is four metallic cavities, the two lateral cavities should be opened over the microstrip feeding lines, as shown in Fig. 11. Fig. 12 shows the filter after assembling and connecting the input and output microstrip lines with SMA connectors.

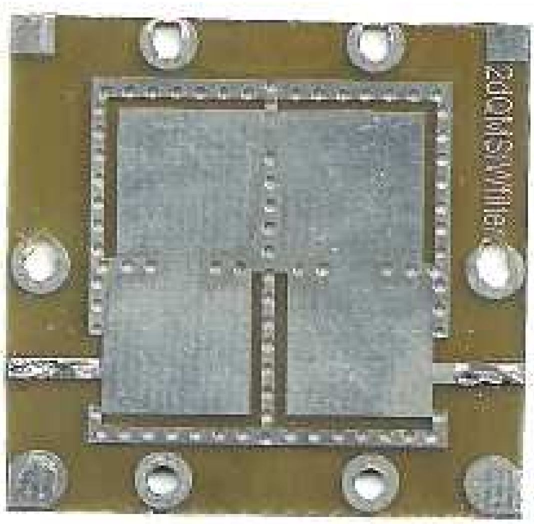

Fig. 10. the PCB of fabricated QMSIW cavity filter

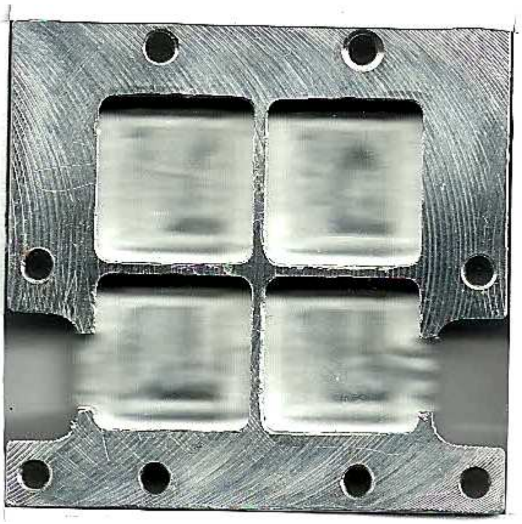

Fig. 11. the covering box of fabricated QMSIW cavity filter

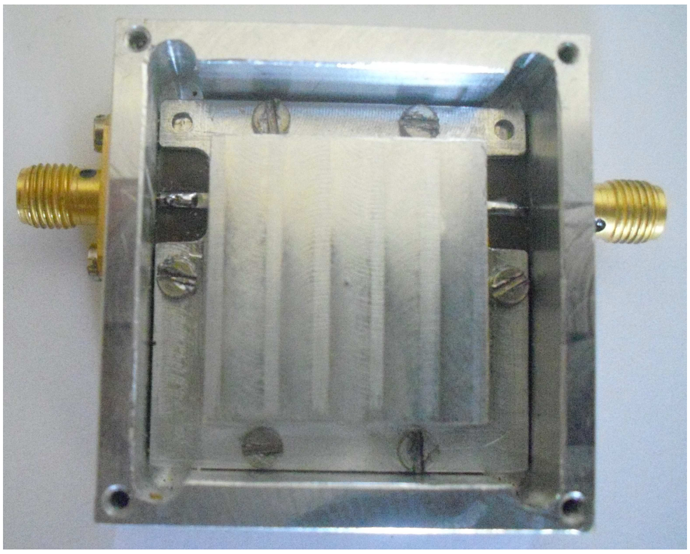

Fig. 12. the connecrorized QMSIW cavity filter

V. MEASUREMENT AND RESULTS DISCUSSION

The fabricated filter has been measured using a VNA. Fig. 13 shows a comparison between the simulation and measurement results. As we can see from Fig. 13, the center frequency of the filter is shifted from the center frequency of simulation results, this can be ascribed to the fabrication errors and the week conformity between the filter's board and the covering box, in addition to an error in the permittivity value of the used substrate. High insertion loss in the pass band also is observed in the measurement results because of the high dielectric loss of the used substrate (the loss tangent angle of the substrate is 0.01) and the imperfectness of the used materials, in addition to high ripple in the pass band. The insertion loss and the out-of-band rejection verify the desired values.

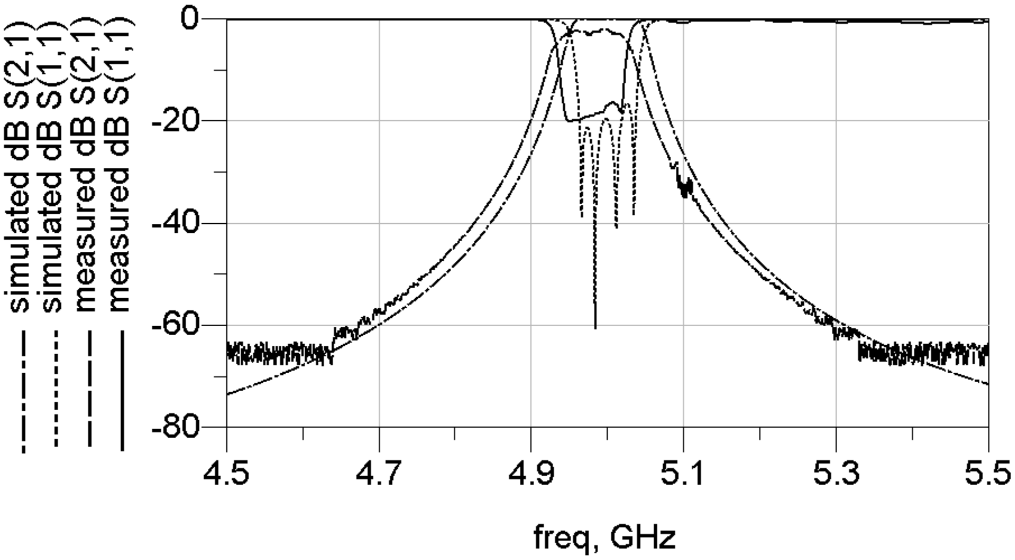

Fig. 13. comparison between simulation and measurement results

VI. CONCLUSION

This paper presents a novel quarter mode substrate integrated waveguide (QMSIW) cavity filter. A narrow pass-band prototype at C-band of the proposed filter has been designed, fabricated using shielded QMSIW cavities, and measured. Good agreement between simulation and measurement results is obtained. The measurement results show that the proposed filter has a small return loss, moderate insertion loss and good frequency selective performances in addition to good out-of-band rejection . The proposed filter has a compact size and low-cost, it is suitable for designing microwave and millimeter-wave circuits.

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