RF MEMS based tunable bandpass filter using QMSIW resonator

MUHAMMAD Z. UR REHMAN[a,b], ZUHAIRI BAHARUDIN[a,*], MOHD. A. ZAKARIYA[a], MOHD. H. MD. KHIR[a], MUHAMMAD T. JILANI[a]

[a]*Department of Electrical and Electronic Engineering, University Technology PETRONAS, Tronoh, Perak Malaysia*

[b]*Department of Physics, COMSATS Institute of Information Technology, Park road, Islamabad, Pakistan*

A tunable bandpass filter based on a technique that utilizes quarter mode substrate integrated waveguide (SIW) is presented. This concept reduces the circuit foot print of SIW to a quarter of its size, along with miniaturization good performance and high quality factor is maintained by the structure. The design concept for single-pole resonator structure is presented; and by coupling the resonators a two-pole substrate integrated waveguide bandpass filter is achieved for the centre frequency of 5.9 GHz. Packaged RF MEMS switches are utilized to achieve tuning of 0.45 GHz for two frequency states of 6.0 and 6.45 GHz. The total size of the circuit is 32.4mm x 9.7mm x 0.787mm (LxWxH).

(Received September 5, 2015; accepted October 28, 2015)

Keywords Tunable, QMSIW, Bandpass filter, RF MEMS, SIW, Miniaturization

1. Introduction

Filters have received a particular attention with the advent of various wireless systems, this interest has dramatically increased with the introduction and development of new millimeter waves applications over the past years. Efficient filters demand has also increased with the development of chip-sets operating at 60 GHz or even higher frequencies by a number of semiconductor industries [1]. A promising candidate for filters is the Substrate Integrated Waveguide (SIW) structure, which is achieved through incorporating the rectangular waveguide structure into the microstrip substrate [2].

Technical literature review reveals that waveguide components such as antennas and filters have been implemented in SIW structure. However, most of these SIWs based filters have been operative in the microwave frequency range, with a few exceptions at higher frequency. These filters are relatively large in contrast to microstrip planar filters and this is more evident in the lower microwave frequency band. In order to reduce the size of the SIW devices, some novel structures based on SIW technology have emerged; these include Half-mode SIW (HMSIW), Folded SIW (FSIW), Folded half-mode SIW (FHMSIW) and Quarter-mode SIW (QMSIW) structures [3].

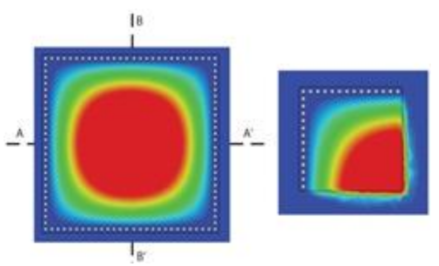

Fig. 1. Electric field distributions of SIW and QMSIW

The QMSIW concept was proposed to further reduce the size of SIW components, its size is only a quarter of SIW resonator cavity. Fig. 1 represents the electric field of a QMSIW's resonant mode and its comparison with SIW electric field distribution. A QMSIW is obtained through placement of an open circuit along the symmetric plane in the transmission direction; whereas the remaining quarter keeps the remaining distribution fields intact if the cutting planes are magnetic walls. The open sides aperture of the QMSIW are nearly equivalent to a perfect MW due to the high ratio of width to height, and it has been shown that QMSIW retains low loss characteristics obtained through SIW structures. The QMSIW based bandpass filters have been reported in [4].

In this paper a QMSIW resonator based tunable bandpass filter is presented. This resonator structure is a miniaturized form of SIW cavity, and exhibits similar low-loss and high quality characteristics as found in its other counterparts. The proposed tunable bandpass filter configuration is suitable for integration with planar devices and its small footprint area allows other devices to be easily integrated on a single board.

2. Substrate integrated waveguide

SIWs are formed through embedding conducting rows of vias in a dielectric filled substrate; the vias connect the top metal to the bottom metal of the dielectric substrate as shown in Fig. 2. The SIW as being employed in its various variations has provided with further miniaturization of circuit footprint area. The bisecting of the SIW cavity shown in Fig. 1 at points *A* and *A'*, would yield Half mode SIW (HMSIW). Further bisection of the formed HMSIW at plane *B* and *B'* would result in the QMSIW. In the formation of these variants the cutting planes are considered perfect magnetic walls.

The design of the QMSIW follows the same design rules as that of SIW. Dealandes and Wu [5] study reveals two primary design rules for SIW structures as given in Equation 1. The two primary rules are followed in order to ensure same design and modeling methodology adopted for rectangular waveguides. These rules pertain to the diameter *d* of the via posts and the via post spacing *s*:

$$d < \frac{\lambda_g}{5}, s \leq 4d \tag{1}$$

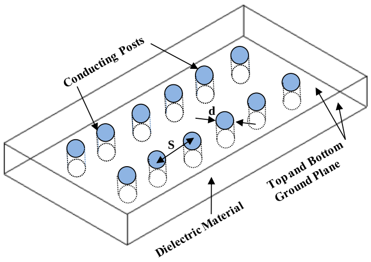

Fig. 2. SIW structure geometry

The choice of diameter and separation between the two vias forms the basis of the QMSIW filter. These two parameters should be selected in a manner that minimum radiation loss is exhibited. In our design *d* and *s* are chosen to be 0.5 mm and 1 mm respectively, these values ensure less radiation losses and the SIW cavity acts closely to a rectangular waveguide. For the dominant TE_{101} mode, the dimensions of the SIW resonator structure are determined by using the relation in Equation 2 [5].

$$f_{TE_{101}} = \frac{c}{2\sqrt{\mu_r \varepsilon_r}} \sqrt{\left(\frac{1}{W_{eff}}\right)^2 + \left(\frac{1}{L_{eff}}\right)^2} \tag{2}$$

W_{eff} and L_{eff} are the effective width and length of the SIW cavity, respectively, and are given by:

$$W_{eff} = W - \frac{d^2}{0.95s}; L_{eff} = L - \frac{d^2}{0.95s} \tag{3}$$

Where; *W* and *L* are the real width and length of the SIW cavity, *c* is the velocity of light in free space. The width and length of the single-pole resonator structure is chosen to be half of the computed width and length using Equations 2 and 3 as shown in Fig. 3, as only a quarter of footprint is to be utilized.

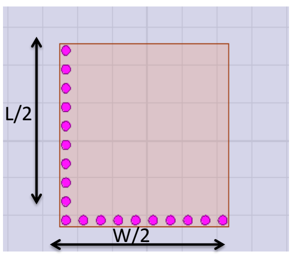

Fig. 3. Dimensions of the QMSIW resonator

The QMSIW bandpass filter is designed using Roger RT/Duriod 5880 material substrate with a dielectric constant of 2.2 and substrate thickness of 787µm. Theoretically, the resonance frequency does not depend on the thickness of the substrate. However, it has been observed in literature that it does play a role on the loss (mainly on radiation loss). The thicker the substrate the lower is the loss or higher Q.

The conventional simulation based design methodology is followed to design and couple the single QMSIW resonators; hence forming the two-pole bandpass filter. The two single QMSIW resonators are coupled together through capacitive coupling along the RF input and output microstrip-to-SIW transition areas and a capacitive coupling is located for inter-resonator coupling of the QMSIW cavities as can be seen in Figure 4.

The inter-resonator coupling and input-output coupling dimensions are computed based on the coupling coefficients and external quality factors derived expressions based on lowpass prototype parameters [6].

$$K_{1,2} = \frac{FBW}{\sqrt{g_1 g_2}}, Q_{e1} = \frac{g_0 g_1}{FBW}, Q_{e2} = \frac{g_2 g_3}{FBW} \tag{4}$$

These values are then compared to the simulated extracted coupling coefficients and external quality factors for a particular cavity geometry, as depicted in Fig. 5 for inter-resonator coupling dimensions and in Fig. 6 for input/output coupling dimensions.

$$Q_{ext} = \frac{f_0}{\Delta f_{-3dB}} \tag{5}$$

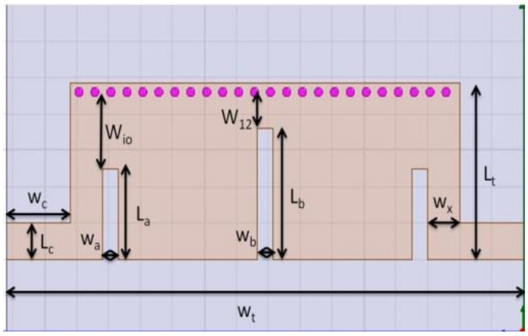

Fig. 4. Two pole bandpass filter structure

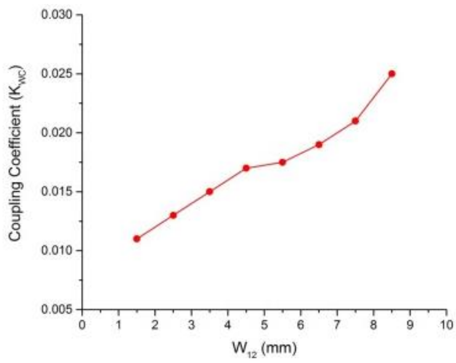

Fig. 5. Coupling Coefficient for Inter-resonator coupling

Iterations and adjustments to the dimensions of the coupling areas of the filter are performed until the calculated values match the extracted values from full-wave simulation, providing the desired filter response. The dimensions of the two-pole bandpass filter are listed in Table 1.

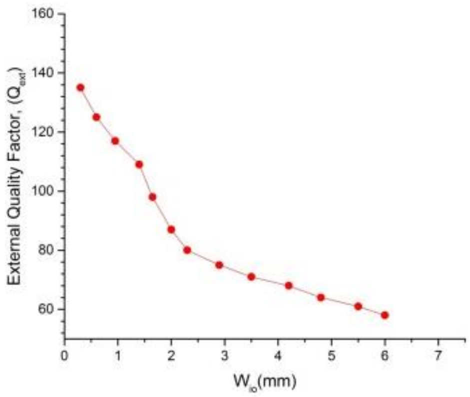

Fig. 6. External Q-factor for Input/output couplings

QMSIW is tuned through connecting/disconnecting inductive via posts using RF MEMS switches. The tuning network is composed of two via posts, and each via is connected through a section of transmission line to each QMSIW resonator. Whereas a Single Pole Single Throw (SPST) RADANT RMSW201 RF MEMS switch is attached to two transmission lines connecting each resonator. The two switches (S1, S2) configurations are used to yield two distinctive frequency states.

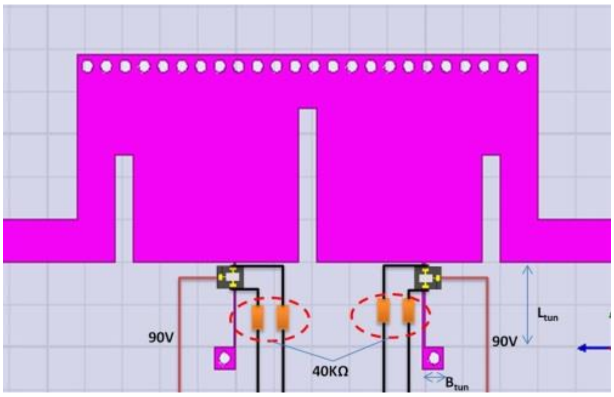

Fig. 7. Functionality of the RF MEMS Tunable filter

The implementation of the tunable QMSIW resonator based bandpass filter along with the operational diagram of the RF MEMS switches and the onboard bias circuitry is shown in Fig. 7. As depicted in Fig. 7 both the SPST switches are composed of two separate gates and drains, whereas a source is used to connect/disconnect transmission line with the inductive via post. An on state of the switch refers to connecting the transmission line to the via; whereas the off state refers to disconnecting the via post from the resonator. The states are selected in a way that the highest frequency is achieved when both the vias are connected, and the lowest frequency is when all are in the off state. The two distinctive frequency states were achieved through full-wave simulations in HFSS.

The filters are actuated with a voltage of 90 V, and an onboard bias circuitry is built to place the switches. The bias lines of 0.5 mm thickness with length of 5.0 mm are placed on the board to actuate the RF MEMS switches. The voltage of 90V is applied at the gate of the switch, while GND is connected through 40 Kohm resistors to the drain and source of the switch.

Table 1. Two pole Bandpass filter dimensions

Notation	Value (mm)	Notation	Value (mm)
L_a	5	W_b	1
L_b	7.2	W_c	4
L_c, W_x	2, 2	W_t	32.4
L_t	9.7	W_{12}	2.0
W_{io}	5.2	B_{tun}	1.0
W_a	1	L_{tun}	5.0

3. Results and discussions

The desired static filter's design structure shown in Fig. 3 and Fig. 4 are realized with the responses shown in Fig. 8 and Fig. 9 respectively. The simulations are carried out using High Frequency Structure Simulator (HFSS) full-wave simulations.

Fig. 8 shows the response of the single pole filter designed for 6 GHz, the response of the filter is obtained using the resonator structure shown in Fig. 3, the resonator designed based on the requirements using the equations presented in Section 2. The simulated S_{21} and S_{11} response of the QMSIW bandpass filter for the single pole reveals that the S_{11} value at the center frequency of 5.85 GHz is less than -25 dB, whereas the S_{21} response is greater than -3 dB and the passband bandwidth at -10 dB is greater than 800 MHz.

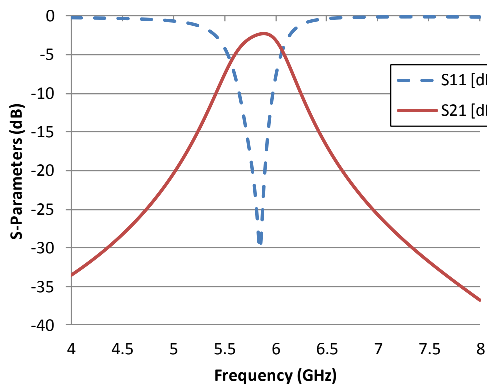

Fig. 8. Single pole response of the QMSIW filter

The measured and simulated S_{21} and S_{11} responses of the two pole static bandpass filter are shown in Figure 9.

The S_{21} response at the centre frequency of 5.9 GHz is better than -2 dB and its corresponding S_{11} response at the centre frequency is less than -15 dB. The passband bandwidth at -10 dB is greater than 900 MHz, whereas the lower and upper stopband rejections are better than -25 dB. These responses are summarized in Table 2. The simulated and measured responses are in close agreement.

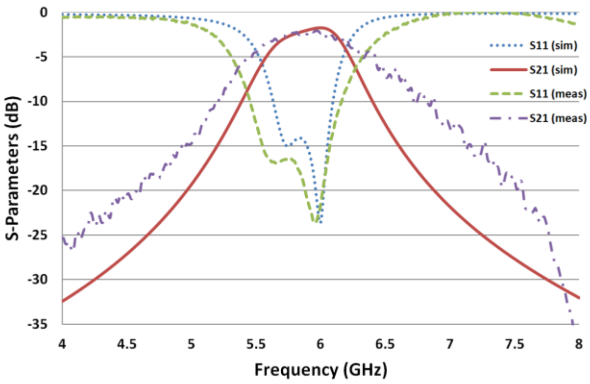

Fig. 9. Measured and Simulated response of the two pole static bandpass filter

The S_{21} and S_{11} responses of the QMSIW tunable bandpass filter depicted in Fig. 10 reveals that when the switch is disconnected (off state) a two pole bandpass response is achieved at 6.0 GHz, whereas when the RF MEMS switch connects the via posts through microstrip strips the two pole response of 6.45 GHz is achieved. The passband bandwidth at -3 dB for both the resonant frequencies is observed to be greater than 500 MHz. The upper passband produced due to cancellation of the TE_{101} and TE_{201} modes is distanced enough from the filter passband, hence a pure Chebyshev response is observed.

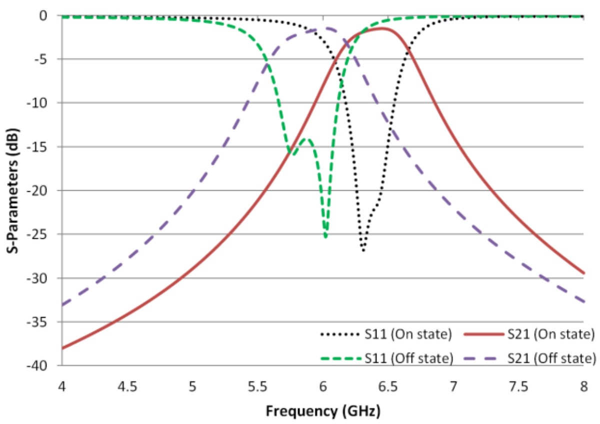

Fig. 10. Response of the Tunable RF MEMS based two pole QMSIW filter

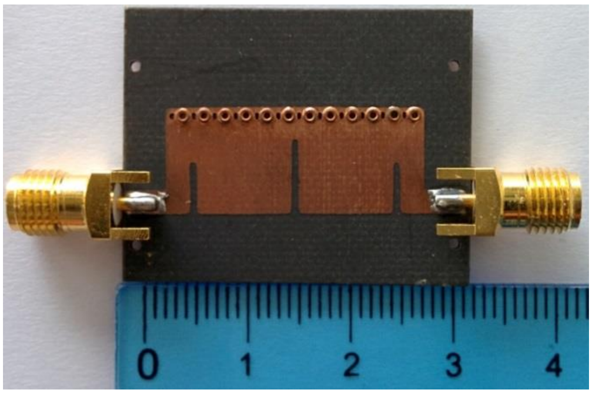

Fig. 11. Fabricated two pole QMSIW bandpass filter

Table 2. Response of the Tunable Two pole QMSIW filter

Key Parameters	Simulated	Measured	Tunable On State	Tunable Off State
Passband Centre Frequency (GHz)	5.9	5.86	6.45	6.00
Passband Return Loss, S_{11} (dB)	< 20	< 20	< 20	< 20
Passband Insertion Loss S_{21} (dB)	> -2	> -2.2	> -1.50	> -1.49
Stopband rejection (dB)	> 25	> 25	> 25	> 25
Passband Bandwidth at -3 dB	0.6 GHz	0.56 GHz	0.56 GHz	0.61 GHz

4. Conclusion

A tunable bandpass filter based on QMSIW structure along with RF MEMS switches is proposed in this paper. The filter has presented good performance and a miniaturized version of the SIW structure is exploited in the design process. The filter has also presented broad bandwidth at the -10 dB level. The tunable filter is unique in terms of the tuning mechanism exploiting use of additional via with resonant lengths. The RF MEMS two states switchable bandpass filter is designed and measured for performance; the filter shows two distinct frequency states at 6.0 and 6.45 GHz with a nearly constant bandwidth of 600 MHz. The simple structure of the filter allows readily integration with planar circuits and devices.

Acknowledgment

This work was supported by Fundamental Research Grant Scheme (FRGS) of Department of Higher Education, Malaysia. The authors would like to thank Universiti Teknologi PETRONAS (UTP) in particularly Centre of Graduate Studies (CGS) in providing research fund for this study.

References

[1] A. M. Niknejad, H. Hashemi, Springer (2008).
[2] J. Hirokawa, M. Ando, IEEE Trans. on Antennas and Propagation, **46**(5), 625 (1998).
[3] M. Z. Rehman, Z. Baharudin, M. Zakariya, M. Khir, M. Khan, Proc. of Business Eng. and Industrial Appl. Colliq., Malaysia, 2013, p. 109.
[4] Z. Zhang, N. Yang, K. Wu, Proc. IEEE Radio and Wireless Symposium, 2009, p. 95.
[5] D. Deslandes, K. Wu, IEEE Trans. on Microwave The. and Tech. **54**(6), 2516 (2006).
[6] H. J. Tang, W. Hong, Z. C. Hao, J. X. Chen, K. Wu, Electronics Letters, **41**(19), 1068 (2005).

*Corresponding author: zuhairb@petronas.com.my