Designing of Novel Eighth-Mode Forth-Order Substrate Integrated Waveguide Band-Pass Filter with High Selectivity

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Abstract—A fourth-order Substrate Integrated Waveguide (SIW) filter has been presented in this research work. The four Eighth-Mode (EM) SIW cavity resonators have been electrically coupled and source to load coupling has been achieved by a slight modification of the eighth-mode resonator cavity. Here a 87.5% size reduction has been achieved using the EMSIW, which plays a significant role in achieving miniaturized structure. The operating center frequency is *13.5 GHz* with a *3dB* bandwidth of *0.5 GHz*. The *Rogers-5880* substrate has been utilized with relative permittivity of *2.2*. The results show that the filter has three transmission zeros on either side of the pass-band, which gives high selectivity and a high out of band rejection.

Index Terms—Substrate integrated waveguide, eighth mode, resonator, selectivity, band-pass filter.

I. INTRODUCTION

With the advancement in technology, here is a scope for high-data carrying capacity from devices, which is the driving force for such devices to operate at high frequencies. With smart devices having to achieve various functions and carry various applications, the components used to accomplish these applications have to be as small as possible (micro- and nano-technology) so that the devices are not too bulky. In this line, for example, filters are such components in communication devices that have a requirement to be as small as possible while at the same time providing satisfactory and efficient results. In this regard, there is a need for devices that have the capacity to carry high-data rates, better quality factor, easy to integrate with other components, lower losses etc. The rectangular waveguide has the ability to carry high-data rates, high-quality factor, and exhibits very low losses [1], [2]. However, it also has disadvantages of its size, which is bulky and hence becomes challenging to integrate with other components.

The Substrate Integrated Waveguide (SIW) can overcome most of the conventional rectangular waveguide issues as highlighted above while maintaining its advantages to a great extent [3]. Guiding principles to the operation of the rectangular waveguide also apply to the operation of SIW, dissipation properties and field patterns are also similar [4], [5]. With the drawbacks mentioned here, various research works are ongoing in the field of SIW technology, and one such area is to do with miniaturization.

Ho and Tang [6] have used a multilayer structure to design a triple-band filter. Two miniaturized SIW cavities were stacked vertically, and the middle layer was designed with three identical patches formed by evenly trisecting a circular patch. The small size was achieved; however, since this is a multilayer topology, it becomes complicated to design. *Salim et. al.* [7] have achieved miniaturization by etching out a complimentary folded ring resonator with a meander line slot to the layer of the filter. The size of the structure was reduced. However, the selectivity was not as good on both sides of the pass-band as there were few transmission zeros. *Xie et. al.* [8] have presented a third-order miniaturized SIW filter using a half mode fan-shaped resonator operating at a center frequency of *1 GHz*. A metalized via located on the center of the circle and a semicircular ring slot etched along the circumference were used to realize the half mode resonance.

Wang and Dong [9] have presented a miniaturized mm-wave band-pass filter. This iniaturization was achieved through the use of stepped impedance slot resonators. The center frequency could also be varied by adjusting the stepped impedance size; however the selectivity was not high on the higher side of the pass-band. *Delmonte et. al.* [10] have presented a miniaturized filter based on a modified quarter mode SIW resonator. Metal vias were added to shield the open boundary of the quarter mode resonator to minimize high radiation leakage. To preserve the virtual magnetic wall, a slot was etched on the top and bottom metal surfaces, however, the losses were still high, and selectivity was not so good. *Troudi and Osman* [11] have presented a cross-coupled half mode SIW band-pass filter. The structure was loaded with an elliptical complementary split-ring resonator with an irregular impedance for miniaturization, however, the filter suffers poor selectivity.

Eighth-mode SIW resonators were used as a way of miniaturization in various existing research. *Li et. al.* [12]

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have presented a multi-layered SIW band-pass filter operating around *2.8 GHz*, utilizing four vertically stacked resonators. The cross-coupling of the load and source increased the selectivity of the filter; however, the multilayer technique complicates the design. *Li et. al.* [13] have presented a balanced and dual-band filter utilizing quarter mode and eighth mode SIW cavities. The quarter model was implemented on a single layer substrate but had lower selectivity, whilst the eighth-mode filter was a fourth-order filter and had high selectivity however being implemented on a multilayer, making the design difficult. *Guo et. al.* [14] have designed a miniaturized filter using the eighth-mode resonator loaded with a stub-capacitor which was also used for center frequency tuning. The filter had a small footprint, but the selectivity was poor, especially on the upper side of the pass-band. *Lu and Zhu* [15] have used both the quarter mode and eighth-mode resonators to achieve a third-order SIW filter operating at a center frequency of *3.66 GHz*. Metallic vias were used to shield the open boundaries of the eighth mode structure together with slots etched on the top metallic surface. The final filter had low selectivity on the higher frequency side of the pass-band. *Nie and Hong* [16] have used the eighth-mode SIW cavity for size reduction. Slots are also etched on the surface of the filter to lower the dominant frequency of the eighth mode cavity; however, the output shows poor selectivity, especially on the lower side of the pass-band.

From the above reviews, in many instances, work done so far in miniaturization using different modes of the SIW use only one or two resonators on a single substrate, this implies lower order filters which results in poor selectivity. In work that was done using more cavities for operation at higher-order for higher selectivity, multiple layers were used, which results in complicated designs [12], [13], [17].

In an effort to increase selectivity of the filter, the *Mutepfe and Srivastava* [18] have designed and analyzed a fifth-order balanced SIW filter operating at *39 GHz*. In addition, *Mutepfe and Srivastava* [19], to achieve miniaturization, have employed defective ground structures and two SIW cavity resonators to achieve a dual-band filter. In continuation of author's previous work, in this present research work, to avoid complex designs and increase selectivity while at the same time reducing the footprint, a single layer SIW band-pass filter is designed using the Eighth-Mode Substrate Integrated Waveguide (EMSIW) filter cavities. Four of these cavities were carefully placed in topology for the filter to operate as a fourth-order structure, increasing selectivity. Two EMSIW resonators were slightly modified to achieve proper coupling. The selectivity is increased by the source load coupling, which results in three transmission zeros on both sides of the pass-band. This paper has been organized as follows: Section II presents the design theory of the EMSIW resonator. Section III deals with the fourth-order filter design and implementation and its results have been analyzed and discussed in section IV. Finally, Section V concludes the work and recommends the future aspects.

II. EMSIW Cavity Design

The full SIW cavity is first designed according to the procedure and formulas described by authors' previous work *Mutepfe and Srivastava* [3]. The full SIW cavity resonator is presented together with the dimensions in Fig. 1. where l = *40 mm* and w = *15 mm*. via diameter d = *0.4 mm*, pitch p = *0.6* and height of substrate h = *3 mm*. Fig. 2 shows the electric field distribution of the full SIW structure as simulated in electronic simulator. There are four symmetric lines as indicated by W-W', X-X', Y-Y'and Z-Z', which can be regarded as virtual magnetic walls [17], [20], [21].

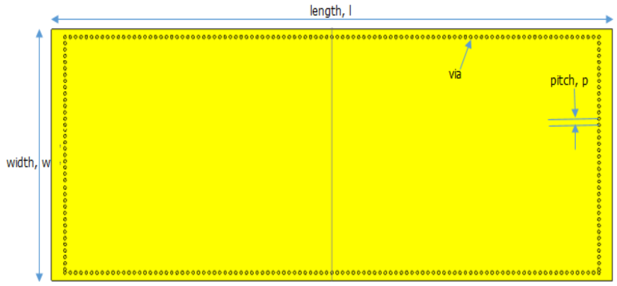


Fig. 1. SIW resonator.

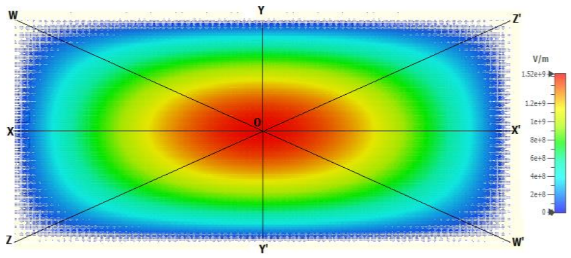
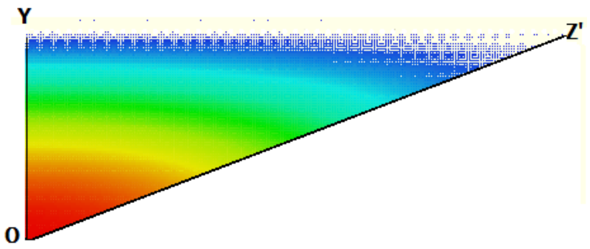


Fig. 2. Fundamental mode electric field distribution.

By bisecting this structure through the symmetry line X-X' a Half-Mode (HM) SIW resonator is achieved. If the structure is further dissected through the Y-Y' symmetry line a Quarter Mode (QM) SIW resonator is achieved. By further bisecting the quarter-wave resonator through the line O-Z' or similarly, an EMSIW resonator is obtained as shown in Fig. 3. The EMSIW is only *12.5%* the size of the original structure, which implies a smaller final design as required. It has been demonstrated that the field distribution of the HMSIW, QMSIW, and EMSIW resonators is the same as the conventional full SIW structure and they resonate at almost the same frequency [16], [22].

(a)



(b)

Fig. 3. Electric field distribution of EMSIW resonator (a) First orientation, and (b) second orientation.

Fig. 2(a) and (b) show the two orientations used in the design, with field intensity observed to be highest towards the center that is point O. Dimensions of a_{EMSIW} and b_{EMSIW} are *7.5 mm* and *20 mm*, respectively. The resonant frequency of the TE_{101} mode, f_{TE101} of the EMSIW, can be approximated by [17, 23]:

$$f_{TE101} = \frac{c}{2\pi\sqrt{\varepsilon_r \mu_r}} \sqrt{\left(\frac{\pi}{a_{eff}}\right)^2 + \left(\frac{\pi}{b_{eff}}\right)^2} \quad (1)$$

$$a_{EMSIW} = a_{eff} + \left(\frac{d}{0.95 * p}\right)^2 - \Delta w \quad (2)$$

$$b_{EMSIW} = b_{eff} + \left(\frac{d}{0.95 * p}\right)^2 - \Delta w \quad (3)$$

$$\frac{\Delta w}{h} = \left(0.05 + \frac{0.3}{\varepsilon_r}\right) * In\left(0.79\frac{(a_{eff}/2)^2}{h^3} + 104\frac{(a_{eff}/2)}{h^2} + \frac{38}{h} + 2.77\right) \quad (4)$$

where ε_r and μ_r are the relative permittivity and permeability, respectively, and c is the speed of light in vacuum. a_{EMSIW} and b_{EMSIW} are the initial sizes of the EMSIW while a_{eff} and b_{eff} are the edges of the equivalent EMSIW resonator. d and p are the via diameter and the distance between centers of two adjacent vias (also known as the pitch) and the substrate's height, respectively. Lastly, Δw is the effect of the fringing field of the equivalent magnetic walls. From Fig. 2 it can be extracted that the EMSIW cavity resonators as presented in Fig 3. However, due to the magnetic walls and fringing effects associated with the EMSIW resonator, the dimensions of a and b need to be modified according to Eq. (1) to Eq. (4) and use the values of a_{eff} and b_{eff} respectively in the fourth-order filter.

III. Proposed Fourth-Order Filter Design

Using the EMSIW resonator designed (as proposed in previous sections), a fourth-order SIW band-pass filter has been designed. *Rogers-5880* substrate with $\varepsilon_r = 2.2$ and thickness *0.3 mm* was used. Four-EMSIW resonators are placed in topology as indicated in Fig. 4, where R_1-R_4 represent the four-EMSIW cavity resonators, $c_{i,i+1}$ represent the coupling coefficient and Q_e represent the quality factor, $i = 1$ *to* 4 and $n = 1$ and 4.

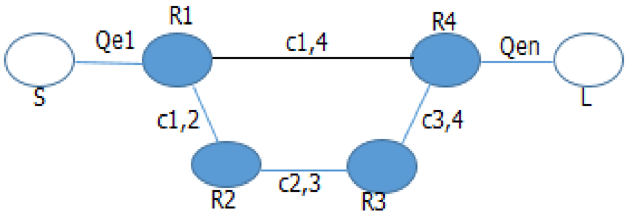


Fig. 4. EMSIW filter topology.

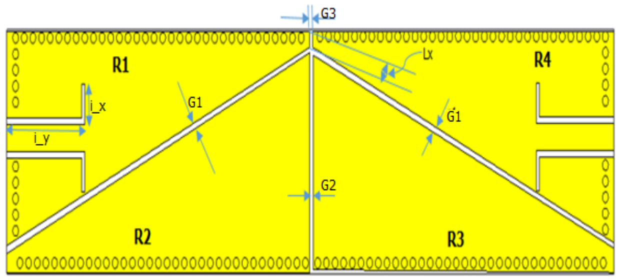


Fig. 5. Forth order EMSIW filter.

For a fourth-order Chebyshev band-pass filter with 0.*1 dB* ripple the g parameters are as follows; $g_0 = 1$, $g_1 = 1.1088$, $g_2 = 1.3062$, $g_3 = 1.7704$, $g_4 = 0.8181$, and $g_5 = 1.3554$. The coupling matrix of the filter in Fig. 4 can be determined by [24], [25]:

$$c_{i,i+1} = \frac{fbw}{\sqrt{g_i * g_{i+1}}} \quad (5)$$

$$Q_{en} = \frac{g_o g_n}{fbw} \quad (6)$$

Because of the shape of EMSIW resonator, two of such resonators can be arranged in different orientations to achieve various electrical coupling schemes, as shown in Fig. 5. The coupling between R_1 & R_2 and R_3 & R_4 is achieved by varied the distance of separation, shown as G_1. The coupling between R_2 and R_3 is achieved by varying gap G_2. Then the coupling between R_1 and R_4 is achieved by varying gap G_3. To enhance the degrees of freedom for coupling, instead of having a pointed edge of the EMSIW cavity, an edge is introduced with a distance indicated as l_x in Fig. 5. From the field pattern, the intensity is highest at the origin (O). Hence by manipulating the distance l_x and gap G_3, appropriate coupling can be achieved through simulation, which is equal to the theoretical value. Various other design parameters have been listed in Table I.

In Fig. 5, the R_1 & R_2, R_2 & R_3, and R_1 & R_4 are simulated, two split frequencies are observed on the S_{12} parameters, with peaks f_1 and f_2 being the lower and upper frequency, respectively. The structure used for the extraction of the coupling coefficient between R_1 and R_2 is shown in Fig. 6. The other resonators' coupling factors can be extracted following the same procedure [3, 23].

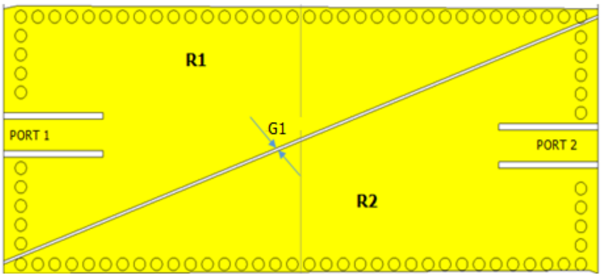


Fig. 6. Coupling factor extraction.

TABLE I. DESIGN PARAMETERS

Parameter	Dimension (mm)
G_1	0.20
G_2	0.25
G_3	0.10
i_x	1.40
i_y	5.40

The coupling coefficient can be calculated by:

$$c_{i,i+1} = \frac{f_2^{\,2} - f_1^{\,2}}{f_2^{\,2} + f_1^{\,2}} \tag{7}$$

The respective gaps are varied to adjust the electrical coupling until the simulation value derived by Eq. (7) is equal to the theoretical value determined by Eq. (5). The quality factor can be extracted by varying the distance *i_x* and *i_y* indicated in Fig. 5 and then applying:

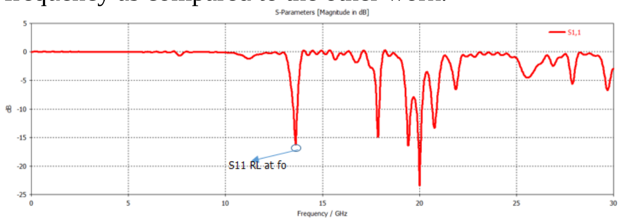
$$Q_e = \frac{2f_o}{\Delta f_{3dB}} \tag{8}$$

where f_0 is the frequency at which S_{21} gets maximum and Δf_{3dB} is the *3dB* bandwidth when S_{21} is maximum. The values for *i_x* and *i_y* are varied until the simulated *Qe* according to Eq. (8) is equal to the theoretical value given by Eq. (6).

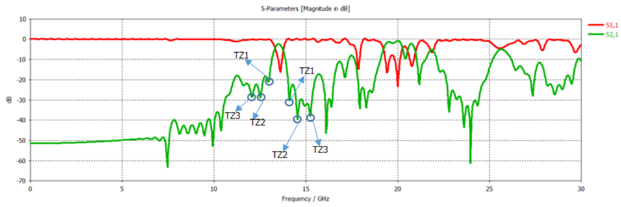
IV. RESULTS ANALYSIS AND DISCUSSIONS

The pass-band is centered at *13.5 GHz* with a *3dB* bandwidth of *0.5 GHz* as shown in Fig. 7. An insertion loss better than *-2 dBs* with a return loss of *-17 dBs* has been achieved. The source to load coupling leads to three transmission zeros on each side of the pass-band labeled in Fig. 7 as TZ_1 - TZ_3. These transmission zeros increase the filter's high selectivity on either side of the pass-band, and high out-of-band rejection is achieved.

From comparative Table II it can be concluded that this filter has higher selectivity as compared to filters of the same category and also has the highest order of operation that is fourth-order. The proposed filter has the highest number of transmission zeros on either side of the pass-band, as shown in Fig. 7. It operates at a higher frequency as compared to the other work.



(a)



(b)

Fig. 7. Output results of the proposed filter (a) S11 output, and (b) Combined S11 and S12 output.

TABLE II. COMPARISON OF THE PROPOSED DESIGN WITH EXISTING WORK

Ref.	No. of Layers	Order of filter	Frequency, fo (GHz)	TZs	Selectivity
[7]	single	--	8.5	2	low
[8]	single	3rd	1	1	high
[9]	single	3rd	28.5	2	low
[10]	single	--	4	0	low
[11]	single	--	6.8	2	low
[12]	double	4th	2.8	3	high
[26]	double	4th	3.52	4	high
this work	single	4th	13.5	6	high

With a filter operating at this frequency, applications requiring higher frequency operation can be achieved satisfactorily. With a size reduction of 87.5% as compared to the conventional SIW resonators, a device with a much smaller size can be designed and operated, which helps in the miniaturization of devices. The source to load coupling increases the number of transmission zeros, increasing selectivity, which is a requirement for efficient operation since the pass-band will have much sharper edges.

V. CONCLUSIONS AND FUTURE RECOMMENDATIONS

A fourth-order substrate integrated waveguide filter made of four eighth-mode SIW resonators was designed in this work. The center operating frequency is *13.5 GHz* and has a *3dB* bandwidth of *0.50 GHz*. It can be observed that the filter has three transmission zeros on either side of the pass-band, which increases selectivity. The TZs are due to the source load coupling that is achieved by coupling R_1 and R_4 through g_3. The proposed filter has a low insertion loss better than *2.3 dBs* and a high return loss *17 dBs*. The comparison Table II shows that the filter fares very well in selectivity and has good out-of-band rejection.

To further reduce the size of the filter, some slots in the form of complementary slip rings, stepped impedance resonators, dumbbell deformed ground structures can be etched on the surface of the filter. And as for future work, a physical structure will be fabricated, and the results will be analyzed.

Conflict of Interest

The authors declare no conflict of interest.

Authors Contributions

Cleophas D. K. Mutepfe (CDKM) and Viranjay M. Srivastava (VMS) conducted this research. CDKM have analysed and realized the model with data and wrote the paper, VMS has verified the result with the designed model. All authors had approved the final version.

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