Design of Miniaturized Half-Mode Substrate Integrated Waveguide Dual-Mode Dual-Band Filter for X and Ku Band Applications

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***Abstract*—With the advancement in technology, devices are required to have superior performance and be as small in size as possible, due to compactness of electronic devices. Most of these devices don't meet all criterias in one go. To enhance the criteria matching, in this work, two dual-band filters have been designed. The first one uses a SIW multi-mode resonator, two of which are magnetically coupled to form a dual-band filter. To achieve miniaturization, the full-mode multi-mode resonator is cut into two using the diagonal symmetry line. This results in a Half-Mode Substrate Integrated Waveguide (HMSIW) resonator used in the dual-band second-order filter design. Using this HMSIW, a size reduction of 50% was achieved while operating at the same frequencies as in the full mode structure. This aids to reduce the size of microwave devices and increase in selectivity. Rogers substrate with a permittivity of 2.2 has been used to design the filter. Center frequencies of operation are 9.5 GHz and 13.8 GHz for the first and second pass-bands, respectively. The insertion loss recorded was 1 dB and 3 dB for the first and second pass-band, respectively.**

***Keywords*—Multi-mode resonator, dual-band, substrate integrated waveguide, second order, half mode resonator, microelectronics**

I. Introduction

With the improvement in technology, modern and advanced communication systems are needed to handle the demands of such technological advancement. Microwave components must have high-performance capabilities and be more compact [1]. This paves the way for the development of smaller communication devices. To achieve this, multi-band filters have been developed to concentrate the hardware needed to perform specific tasks in a smaller area. In literature, several methods have been employed to develop multi-band filters. For example: Having different single-band filters and combining them into one multi-band filter. Zhang and Zhu [2] have designed a dual-band filter with a controllable in-band ripple factor and isolation between the dual pass-band. In that work, two multi-mode resonators with short-circuited stubs were connected in parallel to form the dual-band filter. Shen *et al*. [3] have designed a tri-band filter with controllable frequency and bandwidth using composite right and left-handed resonators. Three different filters operating at distinct frequencies are built and combined to create a triple band filter. Zhang and Zhu [4] have designed a tri-band band-pass filter based on λ/4 resonators. The first and third pass-band were achieved by coupling two dual-band λ/4 Stepped Impedance Resonators (SIRs). And the second pass-band was realized by two coupled λ/4 Uniform Impedance Resonators (UIRs). Zhang *et al*. [5] have realized a quad-band filter by using two resonators. The first one was an eight-mode resonator operating at the first, second, and third pass-band. The second resonator was a short-end stub-loaded resonator, forming the third pass-band. This method of designing multi-band filters had the problem of large size and also matching circuits were needed on the input and output ports.

Having a wideband filter and dividing it into different sub-bands. This can be achieved by inserting transmission zeros within the band using the coupling matrix synthesis technique. Shakib *et al*. [6] have designed a triple-band filter using Substrate Integrated Waveguide (SIW) half-mode resonators. An iterative optimization technique was used based on full-wave simulation. Transmission zeros were placed within the width of the band-pass filter, and the polynomial equations were solved. Tsai *et al*. [7] have designed a low-temperature co-fired ceramic structure which was used to design a triple-band laminated waveguide filter. Two of the three pass-bands were assigned adjacently by using split type dual-band response through the insertion of transmission zeros in the middle of a single pass-band. A four-pole elliptic response achieves the third band. Esmaeili and Bornemann [8] have presented a triple pass-band filter consisting of six cascaded singlets. Four of six transmission zeros were placed within the pass-band, thereby producing three pass-bands.

Using a multi-mode resonator, the multi-mode resonator can generate the desired modes and when proper input-output coupling is implemented, a multi-band filter can be designed as required. *Gao et al.* [9] have designed a multi-stub loaded resonator with eight resonance modes for the tri-band filter. Four modes form the highest band and the other two bands were realized by two modes. The frequencies of the three pass-bands can be controlled by

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adjusting the modes. *Li et al.* [10] have used a Ring Multi-Mode Resonator (R-MMR) and a pair of parallel coupled lines to design a tri-band band-pass filter. Since the R-MMR was symmetric, its resonant characteristics can be analyzed by using the odd and even mode analysis method. Three degenerate modes were perturbed to separate them into six resonant modes, and the tri-band filter was designed using these six modes. *Ren et al.* [11] have used four modes Stepped Impedance Square Ring Loaded Resonators (SI-SRLRs) to design multi-band filters with controllable frequency separation between the common mode and differential mode. By the addition of two more open-circuited stubs to the square ring of the SI-SRLR, a six-mode SI-SRLR was obtained. A tri-band filter was then obtained by coupling these two six-mode resonators. *Ren et al.* [12] have designed multi-band High-Temperature Superconducting (HTS) filters using multi-mode SRLRs. The SRLR had four resonant modes. Two open transmission lines were then attached to both sides of the ring of the SRLR of one wavelength. Xie *et al.* [13] have used a triple mode resonator to design a triplexer. Centered cross-shaped metalized vias holes perturb the cavity to modify the field distribution and mode frequencies.

From these literature reviews, most technologies used to design multi-band filters include R-MMR, SI-SRLRs, stub-loaded resonators [9–12], etc. However, these technologies mostly operate at lower frequencies, and they are bulky. To operate at higher frequencies, substrate integrated waveguide technology can be employed. With the properties of SIW technology, high Q factor and high power handling capability filters can be developed. This is because SIW technology has similar characteristics to the conventional rectangular waveguide [14]. The SIW consists of a substrate between copper plates on the top and bottom surface, and copper vias covering the other sides, as shown in Fig. 1.

This research work uses SIW multi-mode resonators to design a dual-band filter. The mode frequencies and field distributions have been analyzed. The design specifications of the coupling coefficients and external quality factors have been determined. The Rogers-5880 substrate has been used with a permittivity of 2.2. The first design demonstrates the filter using the full-mode SIW resonator cavity and for miniaturization, the half-mode SIW resonator has been used in the second design. This in turn, reduces the size of the filter by 50%. To the author's best knowledge, not much work on dual-band filters was reported using the triangular HMSIW resonators using the multi-mode resonance. Compared to similar devices in literature, this fares are one of the smallest filters giving a satisfactory performance.

This research paper has been organized as follows. Section II illustrates the stages that are followed in the filter design and its implementation. Section III has the results from the designed filter and an analysis of the results is also given in this section. Finally, Section IV concludes the work and recommends the future aspects.

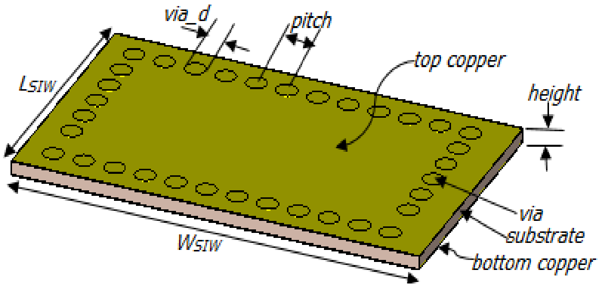

Figure 1. SIW structure and dimensions.

II. Design of Multi-Mode Dual-Band Filter

To design the filter, the following steps have been undertaken:

A. *Filter Topology*

To design a band-pass filter using resonators, an appropriate resonator that operates at the desired frequency should be constructed. Then the resonators can be utilized in different topologies to implement either single, dual, triple, quad-band filters etc. Coupled resonators, as shown in Fig. 2 can be used for a single band filter. The coupling between the resonators and external Q factors can be determined by Eq. (1) and Eq. (2), respectively [15]. These parameters can then determine the physical separation distances between the resonators and how the signals can be fed in and brought out of the filter through ports.

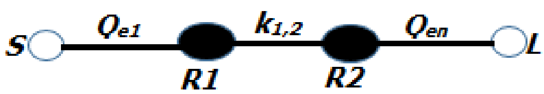

Figure 2. Second order single band filter topology

where S and L represent the source and load, respectively, $k_{1,2}$ is the coupling coefficient between resonator 1, R_1 and resonator 2, R_2 and Q_{e1} and Q_{en} are the load and source external quality factors, respectively. For a second-order filter, the coupling coefficient and external quality factor equations are given as:

$$k_{1,2} = \frac{FBW}{\sqrt{(g_1 g_2)}} \tag{1}$$

$$Q_{e1} = \frac{g_0 g_1}{FBW} \tag{2}$$

$$Q_{en} = \frac{g_2 g_3}{FBW}$$

where g is the element in the low pass filter prototype and n is the number of resonators in the filter [16]. As shown in Fig. 3, by replacing the single mode resonator in Fig. 2 with dual or / triple mode resonators, a dual or / triple band filter can be realized. One resonator is now replaced by a dual-mode resonator node. The combination of R1–R1' and R2-R2' as shown in Fig. 3 represents a dual mode resonator.

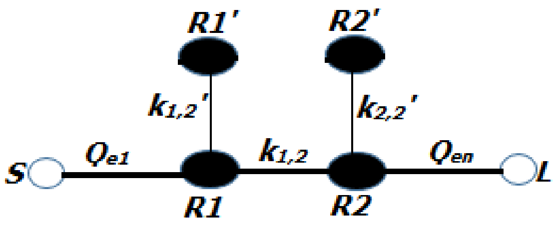

Figure 3. Second order dual-band filter topology.

B. Resonator Design

The initial size of the resonator has been determined by the procedure that follows. Since the SIW resonator has the same properties as the conventional rectangular waveguide, the modified design equations of the rectangular waveguide can be applied. The resonant frequency of the TE_{mon} in the dielectric rectangular waveguide is given by [17]:

$$f_{TE_{mon}} = \frac{c}{2\sqrt{\mu_r \varepsilon_r}} \sqrt{\left(\frac{m}{W}\right)^2 + \left(\frac{n}{L}\right)^2} \quad (3)$$

where c is the speed of light in a vacuum, m and n are the mode x- and z-directions indices, respectively. Then the sizes of the resonator length and width can be given as:

$$W_{RECT} = \frac{c}{2\sqrt{\mu_r \varepsilon_r}} \sqrt{\frac{3}{f^2{}_{TE201} - f^2{}_{TE101}}} \quad (4)$$

$$L_{RECT} = \frac{c}{2\sqrt{\mu_r \varepsilon_r}} \sqrt{\frac{3}{4f^2{}_{TE101} - f^2{}_{TE201}}} \quad (5)$$

where W_{RECT} and L_{RECT} are the width and length of the traditional rectangular waveguide, respectively. Now to get the equivalent length and width of the SIW resonator, Eq. (4) and Eq. (5) can be modified as:

$$W_{SIW} = W_{RECT} + \frac{via\_d^2}{0.95 * pitch} \quad (6)$$

$$L_{SIW} = L_{RECT} + \frac{via\_d^2}{0.95 * pitch} \quad (7)$$

where L_{SIW} and W_{SIW} denote the length and the width of the SIW cavity resonator, respectively, *via_d* is the via diameter, and pitch is the distance between two adjacent vias as shown in Fig. 1. In this work, *via_d* = 0.4 mm, *pitch* = 0.6 mm, *h* = 0.2 mm, L_{SIW} = 12.4 mm and W_{SIW} = 18 mm. The first four modes in the SIW resonator of the calculated dimensions are shown in Fig. 4. The first four modes in the resonator are TE_{101} at 9.5 GHz, TE_{201} at 13.5 GHz, TE_{102} at 17.8 GHz, and TE_{301} at 18.9 GHz. From this, by properly coupling the resonators and allowing for proper selection of the external quality factors, a dual-band filter operating at 9 GHz and 13 GHz can be realized. The input and output coupling is achieved by using a microstrip feedline with two degrees of freedom as shown in Fig. 5 where the parameters labeled insert_l and feed_l are changed one at a time and a simulation is carried out. Two sharp frequencies are observed on the S21 parameter output graph to be used to determine the implementation quality factor and compare it to the theoretical one.

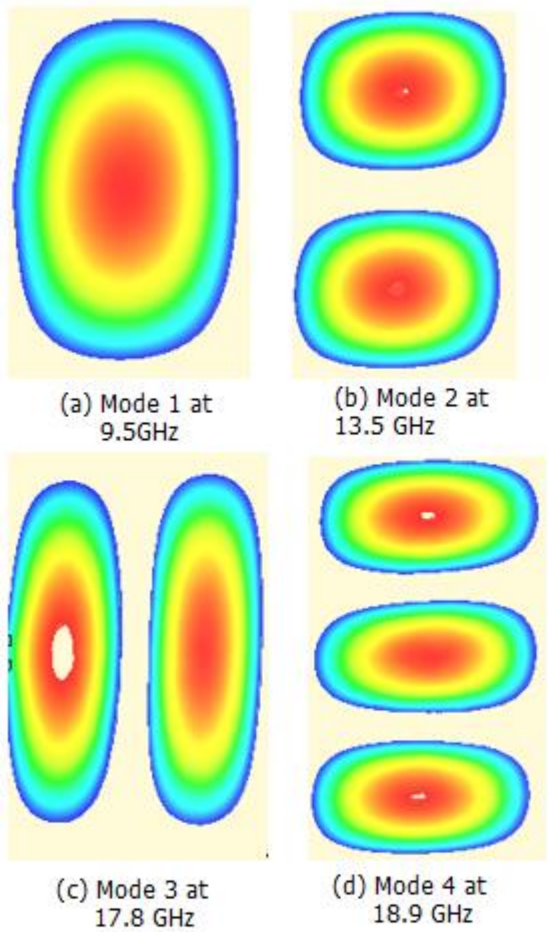

Figure 4. Resonator modes field distribution

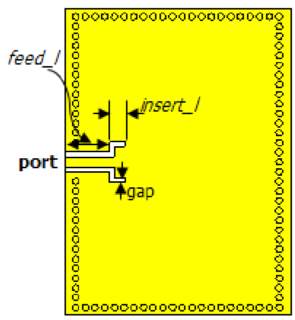

Figure 5. Determination of external quality factor.

C. Realization of the Filter

This work builds a dual-band filter based on the full- and half-mode SIW structures. Because the two pass-bands can be implemented individually, the synthesis procedure of single-band filters can be applied [18]. Eq. (1) and Eq. (2) can be used to derive the design parameters. In this work, the two center frequencies are f_1 = 9 GHz and f_2 = 13 GHz, with a fractional bandwidth of 10% and 6% for the first and second pass-band, respectively. For a maximally flat response, the g parameters as obtained from Tables in [16] are g_0 = 1, g_1 = 1.414, g_2 = 1.414, g_3 = 1, which gives $k_{1,2}{}^{I} = 0.0707$, $k_{1,2}{}^{II} = 0.0424$, $Q_e{}^{I} = Q_{en}{}^{I} = 14.14$, $Q_{e1}{}^{II}$ = $Q_{en}{}^{II}$ = 23.57, where subscripts ^{I} and ^{II} represent pass-band 1 and pass-band 2, respectively.

The filter can be implemented physically after finding the values of the coupling coefficients and the external quality factors. To get $k_{i,j}$, weakly coupled input, and output ports are employed. By simulating the structure in a full wave simulator, two split resonant frequencies can be observed [19], and the coupling coefficient is given by:

$$k_{i,j} = \frac{f_2^2 - f_1^2}{f_2^2 + f_1^2} \tag{8}$$

where f_2 and f_1 are the higher and lower frequencies, respectively. The distance l shown in Fig. 6 is varied until the desired value of k is achieved for the full mode resonator filter. The graph of variation of k and l is shown in Fig. 6, for the full mode SIW resonator. For the half-mode SIW resonator in Fig. 7, the distance indicated as $t1$ is varied and in the same graph, the variations of the coupling factor with the distance $t1$ are also shown.

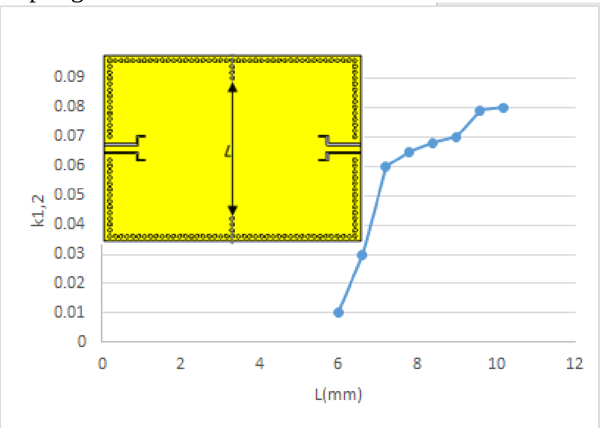

Figure 6. Determination of coupling coefficient using full mode resonator

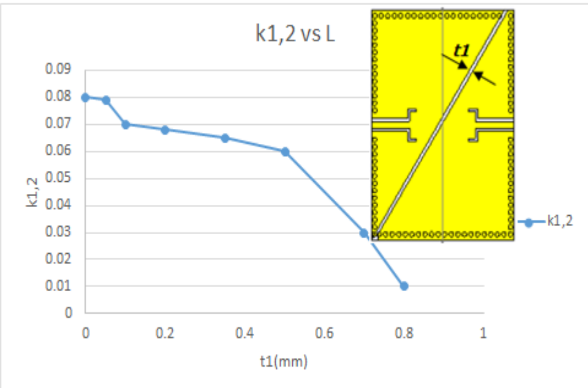

Figure 7. Determination of coupling coefficient using half-mode resonator.

The external quality factor is determined according to Ref. [20]. In continuation of the author's work [21–23], a second-order filter has been designed using Rogers-5880 substrate with permittivity 2.2. Performance analysis of a multilayer coil-based magnetic induction waveguide communication system was performed by Dandu *et al.* [24]. In this area, an analysis of metallic waveguides by using the least square-based finite difference method was done by Shu *et al*. [25]. Further to this, the characteristics of five-layered slab waveguides with double-clad metamaterials were realized by Lee and Lee [26]. Mutepfe and Srivastava [27] have analyzed an approach to high selectivity substrate integrated waveguide band-pass filter for mm-wave applications.

Fig. 5 shows the structure used to determine the external quality factor. The distances labeled ***insert_l, feed_l and gap*** are varied using a parametric sweep in the simulation software. From the S_{11} parameter output results, the 3 dB bandwidth is used in Eq. (9) together with the center frequency to derive the external quality factor:

$$Q_{e1} = \frac{2f_0}{f_{bw_{\pm 3dB}}} \tag{9}$$

where f_o is the center frequency and f_{bw} is the -3 *dB* frequency from the S_{11} output.

From these experiments, Table I shows the optimum values of the parameters, together with all the dimensions used to design the filter.

TABLE I. FILTER DIMENSIONS

Parameter	Length (mm)
W_{SIW}	18
L_{SIW}	12.4
height	0.2
pitch	0.6
via_d	0.4
insert_l	0.5
feed_l	3
gap	0.7
t1	0.2
l	9.4

III. RESULTS AND ANALYSIS

In Fig. 8, the results of the filter using full-mode resonators are shown. It can be seen that the dual-band filter operates at the first pass-band of 9.5 GHz and the second pass-band at 13.5 GHz. The return loss of the first and second pass-band is −12 dB and −22 dB, respectively. Insertion loss of the first and second pass-band being −3dB and −2.2 dB, respectively.

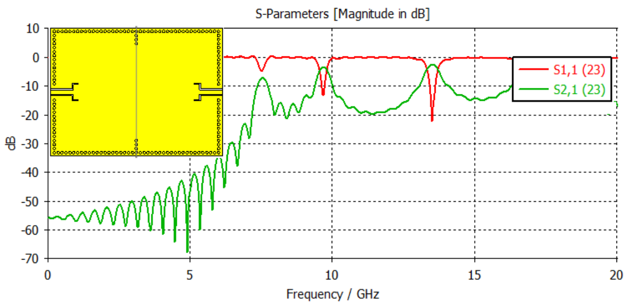

Figure 8. Results of dual-band filter utilizing full mode SIW resonators.

In Fig. 9, the filter implemented using half mode SIW resonators is simulated, and the results are as shown. It can be seen that the dual-band filter operates at a first pass-band of 9 GHz and the second pass-band at 14 GHz. The return loss of the first and second pass-band is −15 dB and −19.7 dB, respectively. Insertion loss of the first and second pass-band is −1.4 dB and −4 dB, respectively.

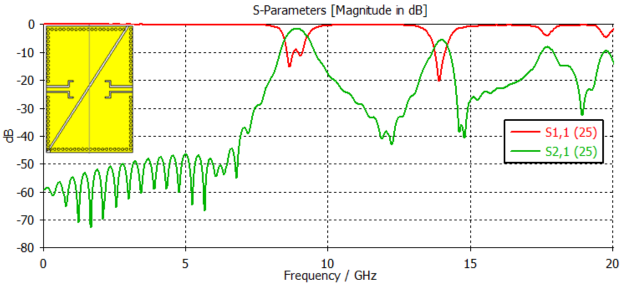

Figure 9. Results of dual-band filter utilizing half mode SIW resonators.

The results of the dual-band filter utilizing multi-mode resonators operating using full-mode SIW resonators and half-mode SIW resonators are in agreement. This shows that the size of the footprint can be reduced by 50% while maintaining satisfactory filtering performance. And this, in turn, plays a significant role in coming up with smaller miniaturized devices.

TABLE II. COMPARISON WITH EXISTING WORK

Ref.	Freq (GHz)	IL (dB)	Technology	Size (mm^2)
[28]	1/1.6	1.6/1.9	DGS*/Hairpin resonator	49×30
[29]	9/11.2	1.4/1.02	SIW	26×13.3
[30]	13.47/14.05	1/1	waveguide	40×7.89
[31]	3.6/7.1	1.3/1.8	SIW	48×24
[32]	3.64/8.06	0.8/1.2	SIR	--
[33]	5.50/8.50	2/2	CSSR*	--
[34]	4.48/5.25	1.2/1.2	SIW	28.5×57
This work	9.5/13.8	1/3	SIW	18×12.4

*Deformed Ground Structure (DGS), Complementary Slip Ring Resonator (CSPR).

From this comparison Table II, it can be seen that the filter designed from the half wave SIW resonator has the smallest size as compared to similar work. The filter also operates at a higher frequency except for the work in [30]; however, that was bulky [35, 36]. Hence for dual-band filter miniaturization, the half mode dual mode resonator can be used effectively to reduce the size of the structure by 50%.

IV. CONCLUSIONS AND RECOMMENDATIONS

In this work, two dual-band filters were designed. The first one utilizes an SIW multi-mode resonator, two combined to form a second-order dual-band filter. The filter operates at 9.5 GHz, the first pass-band and 13.8 GHz the second pass-band. Substrate Rogers-5880 was used in this design with a permittivity of 2.2 and a height of 0.2 mm. The insertion loss, as taken from the graphs was −1 dB and −3 dB, respectively. The full wave resonator was dissected into 2 on the diagonal symmetry line to achieve size reduction to form a triangular half-mode SIW structure. It was found that the same modes appear in the half-mode structure. Then two of such structures were coupled together to form a second-order half-mode dual-band filter. Satisfactory results were achieved whereby the results of the half mode structure and that of the full wave structure are in agreement. Hence for effective miniaturization of 50% size reduction, the half mode SIW structure can be adopted. Compared to other devices working in the same field, it can be found that this filter operates at higher frequency than most of the structures, and also, this filter has the smallest size in terms of square area footprint. For future work, a physical structure will be built and the bands will be increased to come up with a multi-band filter. Reconfigurability of the filter will also be implemented to change the frequency from one center frequency of the respective band to another.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Cleophas D. K. Mutepfe and Viranjay M. Srivastava conducted this research together. Cleophas has analyzed and realized the model with data and wrote the paper, Viranjay has verified the result with the designed model. Both authors have approved the final version.

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