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Design and Development of Miniaturized Filters using Substrate Integrated Semicircular Cavities

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***Abstract*- A novel compact substrate-integrated semicircular cavity and miniaturized filters based on these resonators are presented. These band-pass filters are made up of two substrate integrated semicircular cavities, which couple to each other by an aperture on their common region. Detailed analysis of the filters with various topologies of the resonators is investigated. Design procedure, simulation and experimental results of the miniaturized filters are presented. The frequency characteristics in terms of the scattering parameters are taken for analysis, showing good agreement between the simulation and measured results, which validates the accuracy of numerical computation, and also show the promising performance of the proposed filters.**

***Index Terms*- Substrate Integrated Waveguides, Filters, Cavity Resonators.**

I. INTRODUCTION

Microwave filters are the subject of continuous research driven by the innovation of new communication systems. Design of high-quality filters using conventional technologies, such as rectangular waveguide or microstrip-line, is either too expensive or unable to provide required performance [1, 2]. Recently, substrate integrated waveguide (SIW) which is synthesized in a planar substrate has provided a useful technology to design integrated waveguide filters with the advantages of high *Q*-factor, low-profile and low-cost [3, 4]. SIW filters are predominantly based on rectangular cavities [5]. SIW filters with circular cavities have attracted much attention in recent years due to high quality factor values and design flexibility. Tang et al., proposed the design and implementation of compact filters and diplexers based on the SIW circular and elliptic cavities [6, 7]. Potelon et al., designed a Ku-band filter based on Substrate-Integrated Circular Cavities [8]. Wei et al., developed a novel multilayered cross coupled SIW circular cavity filter in low temperature co-fired ceramics [9]. So far no reports are mentioned on substrate integrated semicircular cavity.

In this letter, we present miniaturized substrate integrated semicircular cavity (SISCC) (which has half the dimensions compared to the SIW circular cavities and Q-factor values are approximately the same) and various topologies of filters based on this cavity. This paper is organized as follows. Section II explains the design of the SISCC resonator. Section III describes the design procedure of the filters using these cavities. Section IV presents the simulation and measured results of the filters.

II. SUBSTRATE INTEGRATED SEMICIRCULAR CAVITY RESONATOR DESIGN

An SIW semicircular cavity consists of dielectric filled waveguide which is synthesized in a planar substrate with arrays of metallic vias to realize semicircular edge walls as shown in Fig. 1. Integrated interconnects can be designed on the same substrate that are compatible with planar structures such as microstrip or coplanar waveguide. Microstrip coupling is chosen for the excitation of the resonator. The length of the microstrip interconnect is designated as ´Z´. The resonant frequency of this SIW semicircular cavity resonator depends on three geometrical parameters: radius of cavity (a), metallic via spacing (w), and the via pitch size (D). Basically, the first four eigen-modes in the circular SIW cavity are TM_{010}, TM_{110}, TM_{210}, and TM_{020} modes. The first two modes are commonly used for filter design [4, 5]. The resonant frequency of the SIW semicircular cavity resonator for TM_{110} dominant mode is given below.

$$f_r = \frac{cX_{np}}{2\pi a_{eff}\sqrt{\mu_r \varepsilon_r}} \tag{1}$$

where $a_{eff} = a - (D^2 / 0.95w)$; ´$a_{eff}$´ is the effective radius of the resonator, ´a´ is the radius of the resonator, ´D´ is the diameter of the metallic vias, ´w´ is the spacing between the metallic vias, ´c´ is the velocity of light in free space, ´ε_r´ and ´μ_r´ are the relative permittivity and permeability of the substrate, ´X_{np}´ is the pth root of the Bessel function $J_n(k_c a)=0$, ´n´ is the periodicity in the azimuthal direction and ´p´ is the number of zeros of the field in the radial direction.

A SISCC resonator is designed and fabricated on RT-Duroid 6010LM substrate with dielectric constant ε_r = 10.8, tanδ= 0.0023, thickness h=1.27 mm at a center frequency f_r=5.7GHz as shown in Fig.1. Its dimensions are given as a= 10.25 mm, d= 1.27 mm, D= 0.5mm, w= 1mm and Z= 5mm. Simulated and measured return losses of the substrate integrated semicircular cavity are 25 dB and 17 dB respectively. For comparison purposes, conventional SIW rectangular and circular cavities are designed at the same center frequency and on the same substrate. All the structures are weakly coupled to the input and output lines and then simulated using full wave simulator [8]. The metallic via spacing of 1mm and via diameter of 0.5mm are used in all cavities. Table 1 presents the dimensions, resonant frequency and unloaded Q-factor of the substrate integrated rectangular cavity, circular cavity and semicircular cavity. From table 1, it is clear that substrate integrated semicircular cavity has approximately the same Q- factor but half the dimensions compared to the conventional circular cavity.

Table 1: Substrate integrated cavity dimensions, resonant frequency and unloaded Q-factor for various topologies

Substrate Integrated Cavity type	Dimensions (mm^3)	Resonant frequency (GHz)	Unloaded Q-factor (Q_U)
Rectangular	11.5×11.5×1.27	5.66	278
Circular	10.25×1.27	5.57	313
Semicircular	10.25×1.27	5.51	303

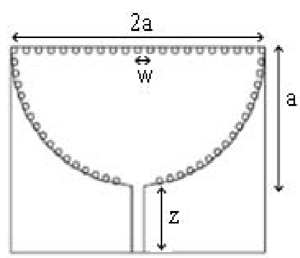


Fig.1 Schematic and Photograph of the SISCC resonator.

III. FILTER DESIGN

Figs. 2 (a), (b) & (c) depict the various configurations of the two pole filters based on the SISCC resonators. These band-pass filters consist of two substrate integrated semicircular cavities, which couple to each other by an aperture on their common region. Two SISCC resonators are arranged horizontally in various configurations as shown in Fig 2(a), (b) and (c). 50 Ω microstrips are used as input and output interconnects are coupled to both the resonators. Filters of Configuration I & Configuration II are designed to have the characteristics of two pole Chebyshev filter with FBW of 15% and ripple of 1 dB whereas Configuration III has the FBW of 6% and ripple of 1dB. The proposed filters are designed at mid band frequency (f_0) of 5.45 GHz using the SISCC resonators. As per the above specifications, the proposed filters are implemented using the coupled-resonator filter design procedures [10]. The design parameters associated with the specifications may be expressed as:

$$Q_{e1} = Q_{en} = \frac{g_0 g_1}{FBW}, K_{i,j} = \frac{FBW}{\sqrt{g_i g_{i+1}}} \qquad (2)$$

Where Q_{e1} and Q_{en} are the external quality factors of the resonators at the input and output, $k_{i,j}$ is the coupling coefficients between the adjacent resonators, and g_i $(i= 0, . . . , n+1)$ are the lowpass prototype parameters.

A single SISCC resonator is considered to determine the external Q-factor. The coupler that provides the desired coupling Q_e for the input and output cavities, can be obtained by performing a parametric analysis on a single cavity For this structure one port is weakly coupled whereas the coupling of the other port is changed by varying the lengths L1,L3 and L5 shown in Figure 3 (a). Then from the simulated responses [11] equation 2 is calculated

$$Q_e = \frac{f_0}{\Delta f_{3dB}} \qquad (3)$$

Figure 3(a) shows the respective results for the three different configurations.

To calculate the coupling between contiguous resonators for the structures in fig. 2 is simulated in a full wave simulator [11]. Therefore, the coupling coefficient of two adjacent resonators can be obtained from the simulated scattering parameters of the two resonators. The coupling coefficient is obtained by changing the width W_i between the two semicircular cavity sections. In this case, the width was varied from 4 mm to 12 mm. The metallic via inductive windows between the two cavities can be used to influence the coupling. The k value was extracted from equation given below.

$$k = \frac{f_2^{\,2} - f_1^{\,2}}{f_2^{\,2} + f_1^{\,2}} \qquad (4)$$

Where f_1 and f_2 are the corresponding resonant frequencies seen from the simulated results. Figure 3(b) shows the simulated results of different ks versus length of inset.

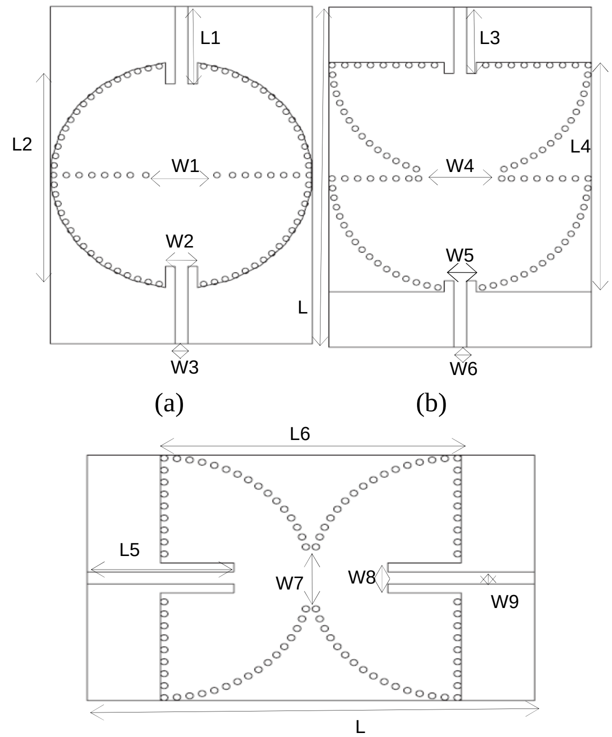
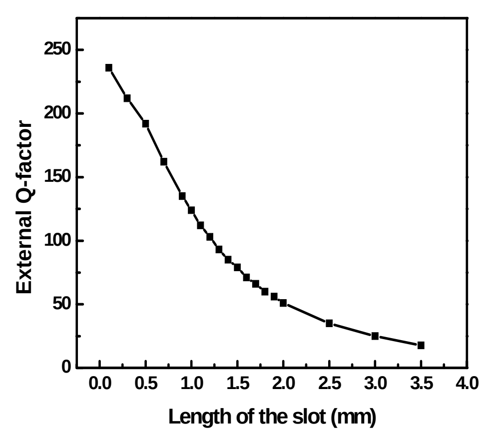
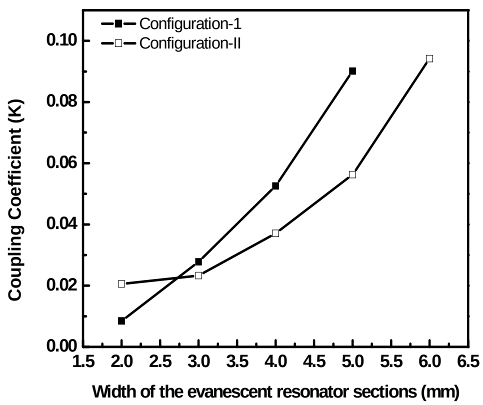


Fig.2 Various topologies of the filters based on the substrate integrated semicircular cavity resonator.
a) Configuration-I, b) Configuration–II, c) Configuration-III



(a)



(b)

Fig. 3 a) External Q-factor Vs length of the slot, b) the plot of the obtained k values vs. the width of the evanescent sections.

These filters were implemented on a full wave simulator with the dimensions calculated from the above procedure. Then they were optimized in the simulator and the final dimensions of the filters are given as: L=30.5 mm, L1=10 mm, L2=20.5mm, W1=7 mm, W2=2.5 mm, W3=1 mm, L3=10.5 mm L4=20.75 mm, W4=6 mm, W5=2.5 mm, W6=1 mm, L5=7.5mm L6=20.5mm, W7=4.7 mm, W8=2.5 mm, W9=1 mm. To validate the proposed filters, they were simulated in a full wave simulator [8]. In addition to the simulation, we have carried out the experimental studies by fabricating the printed waveguide on the microwave substrate RT-Duroid 6010 with dielectric constant ε_r = 10.8, tanδ= 0.0023, thickness h=1.27 mm. The metallic via-holes, connecting the top and bottom metal plates, were implemented by electroplating technique. The via diameter and the distance between the two adjacent via-holes is 0.5 mm.

IV. RESULTS AND DISCUSSION

Measurements are performed using Agilent PNA Series microwave Vector Network Analyzer (E8361A). Photographs of the fabricated filters are shown in Fig. 4. These filters occupy half the size compared to conventional circular cavity filters. Table 2 presents the simulated and measured filter parameters such as center frequency, return losses, insertion losses, bandwidth and FBW of all the proposed filters. The final simulated and experimental transmission and reflection coefficient responses of the filter with configuration I are shown in Fig. 5. The experimental results demonstrate that the fabricated filters have a shift in the frequency responses of about 114 MHz, 106MHz, and 144 MHz for configurations 1, 2 and 3 respectively. The variation in the theoretical and simulated FBW is due to the non symmetrical shape of the semicircular cavity resonator which in turn affected the coupling coefficient. Discrepancies in the simulated and measured results of the filters are due to the fabrication errors and material tolerances. However, very good agreement is observed between the experiment and simulation results in all filter configurations.

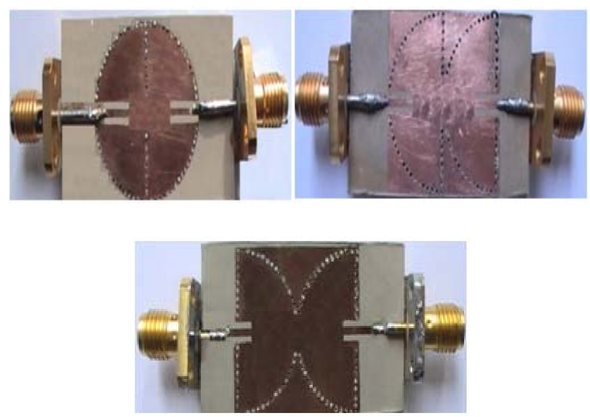


Fig.4 Photographs of the fabricated filters

Table 2: Simulated and Measured filter parameters of configuration-I, configuration-II and configuration-III f_0: Center frequency, S_{11}:Return Loss, S_{21}:Insertion Loss, BW: Bandwidth, FBW: Fractional Bandwidth, Sim: Simulated values, Mea: Measured Values.

Filter Parameters		f_0 (GHz)	S_{11} (dB)	S_{21} (dB)	BW (MHz)	FBW (%)
Type I	Sim	5.456	11.5	1.7	806	15
	Mea	5.342	10.5	2.8	969	15
Type II	Sim	5.427	14	1.28	857	16
	Mea	5.325	14	2.26	865	16
Type III	Sim	5.423	20	1.03	343	6
	Mea	5.279	15	2.41	333	6

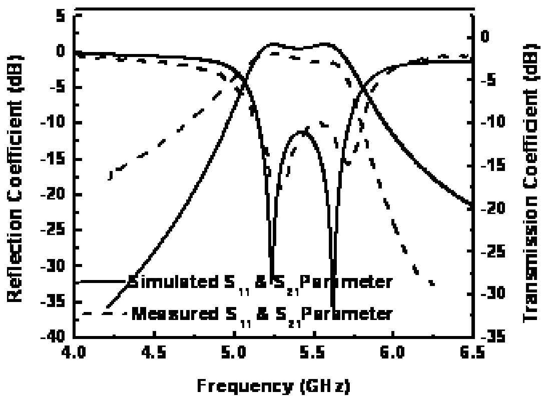


Fig.5. Simulated and Measured S- Parameters of the filter with configuration I

VI. CONCLUSION

In this article, a novel miniaturized substrate integrated semicircular cavity resonator and the filters with various topologies based on these cavities are proposed and analysed. Substrate integrated semicircular cavity resonator and filters are optimized by using a full wave simulator. Finally, these filters are fabricated and frequency responses are measured. Very good agreement between the simulations and measurements is obtained. It is verified that our proposed filters have very good selectivity and in particular they are compact in geometry. These can be directly integrated with other planar circuits at a low cost for microwave applications.

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