Progress In Electromagnetics Research Letters, Vol. 67, 13–18, 2017

A Compact Quarter-Mode SIW Bandpass Filter with an Extremely Wide Stopband

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Abstract—This paper presents a C-band wide stopband bandpass filter (BPF) using quarter mode substrate integrated waveguide (QMSIW) cavities. The BPF is simply constructed by combining S-shaped slot and L-shaped slot loaded quarter-mode substrate integrated waveguide. A special negative coupling scheme with symmetrical S-shaped slots on the top and bottom metal planes connected by metallic vias is developed. The proposed structure provides more design flexibility in arranging the pitch of vias owing to the extended slot length. The filter has fractional bandwidth of 25% at center frequency of 5.5 GHz with return loss better than 24 dB and insertion loss less than 1.1 dB. Moreover, its first spurious response occurs at 22.5 GHz (about four times the central frequency), exhibiting an extremely wide stopband performance. An experimental SIW filter was fabricated, and good agreement was achieved between the simulated and measured results.

1. INTRODUCTION

With the rapid development of modern communication system, compact planar filters have experienced an explosive growth [1, 2]. It is urgent to increase demand on wide stopband filter [3, 4] with compact size, high selectivity, and good stopband performance, etc. The substrate integrated waveguide (SIW) [5, 6] is an artificial waveguide structure which is a favourable technology to meet these requirements. However, SIW is still rather large for low frequency microwave components.

Research shows that quarter mode substrate integrated waveguide (QMSIW) as an alternative structure of SIW can reduce the original width by roughly 75% while preserving identical cutoff frequency and propagation characteristics. Electric field distribution in the SIW cavity resonator is symmetrical, which is beneficial for size reduction. 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. It preserves almost a quarter of original fields distribution of SIW cavity. The evolvement for the electric field distribution from the SIW cavity resonator to the QMSIW cavity resonator is shown in Fig. 1.

In this paper, a compact quarter-mode SIW bandpass filter with an extremely wide stopband is proposed. The 3-D configuration of the proposed second-order QMSIW filter is shown in Fig. 2. Two meandered L-shaped slots are etched on the upper surface of the QMSIW cavity resonator, while S-shaped slots are simultaneously etched on both sides of the QMSIW. The feed-line is directly tapped into the opened edge of the quarter SIW cavity resonator, and the tapped position can be adjusted to control external quality factor. The dominant resonant mode of the designed resonator is TE_{101}, and the designed bandpass filter is analyzed by the full-wave EM simulator sotware (Ansys HFSS 15).

Received 7 February 2017, Accepted 14 March 2017, Scheduled 24 March 2017
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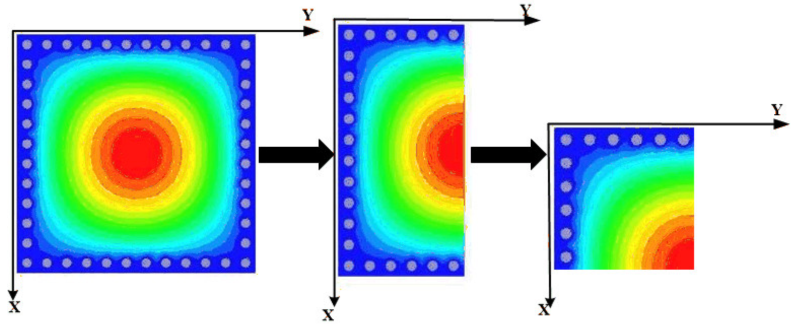


Figure 1. Electric filed distribution of full-mode SIW, HMSIW and QMSIW cavities.

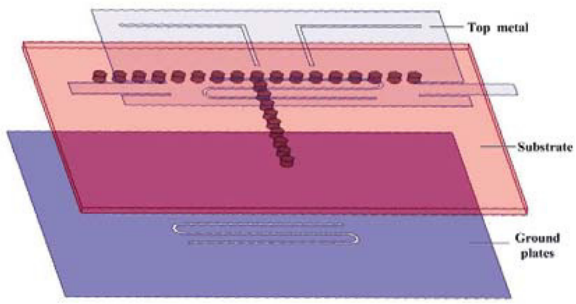


Figure 2. 3-D configuration for the proposed filter.

2. THEORETICAL ANALYSIS AND DESIGN

2.1. Quarter RW Cavity Resonator

As we know, conventional rectangular waveguide (RW) cavity is a half-wavelength resonator with short circuits at both ends. The dominant resonator mode is TE_{101} mode, and its resonance frequency is given by:

$$f_{101} = \frac{c}{2\pi\sqrt{\mu_r \varepsilon_r}} \sqrt{\left(\frac{\pi}{a}\right)^2 + \left(\frac{\pi}{b}\right)^2} \tag{1}$$

where c is the light speed in free space, ε_r the relative dielectric constant, μ_r the permeability, and a and b are the length and width of the cavity, respectively [7]. According to the analysis from Fig. 1, the electric field distribution in rectangular waveguide cavity is symmetrical. Therefore, in order to achieve more compact size, a novel quarter RW cavity is applied to the filter design, as shown in Fig. 3. This structure consists of a square patch with two short-circuited right-angle metallic walls. The dominant resonant mode is also TE_{101}, and its resonant frequency is:

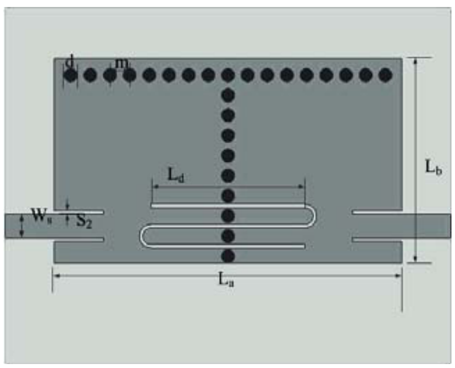
$$f_{101} = \frac{c}{2\pi\sqrt{\mu_r \varepsilon_r}} \sqrt{\left(\frac{\pi}{2L_a}\right)^2 + \left(\frac{\pi}{2L_b}\right)^2} \tag{2}$$

where L_a is the length of the square patch and L_b the width of the square patch.

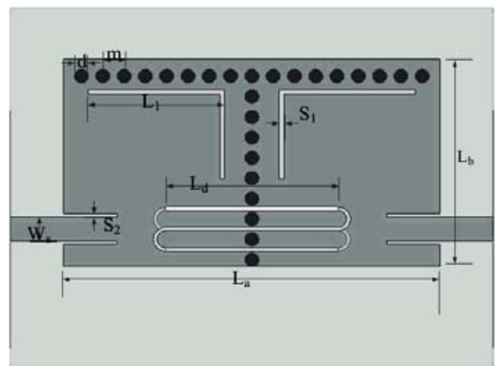
2.2. QMSIW Filter Design

Figure 3(a) shows the configuration of the S-shaped QMSIW unit cell by incorporating S-shaped slots on the QMSIW top and bottom surfaces. The structure is synthesized on a substrate of Rogers 5880 with thickness of 0.508 mm and relative permittivity of 2.2. All the metallic via holes have diameter of 0.8 mm and center-to-center spacing of 1.2 mm.

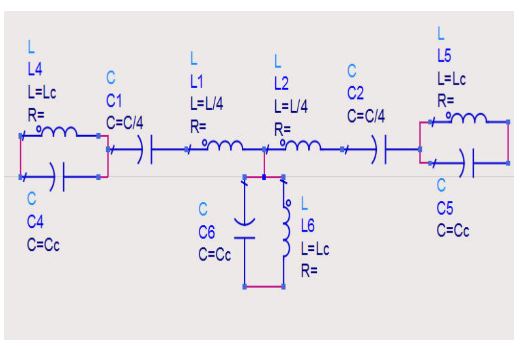
Figure 3(b) shows the geometrical configuration of the designed compact QMSIW filter loaded with L-shaped slots. This filter mainly consists of S-shaped slots, which are etched on the QMSIW top and bottom surfaces, and two L-shaped slots loaded on the QMSIW top surface. The material loss is neglected in the model. A simplified equivalent circuit for the main body of the designed filter is shown in Fig. 3(c) (The reader may refer to [5]). The QMSIW can be modeled as an ordinary two-wire transmission line (formed by the top surface and the bottom surface) loaded with some short-circuited stubs (formed by via-walls). The two L-shaped slots can be interpreted equivalently as the shunt resonant tank denoted by the capacitance C_c and inductance L_c. The inductive connection of the waveguide transmission line is represented by $L/4$ and L_c, while the capacitive coupling, which is realized by the S-shaped slot in the waveguide transmission line, is modeled by C_c and $C/4$, respectively. The corresponding simulation result based on the equivalent circuit using Agilent Advanced Design System (ADS) is shown in Fig. 3(d).



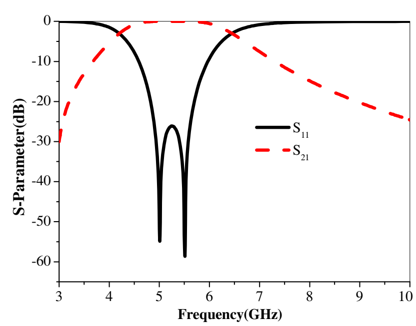
(a)



(b)



(c)



(d)

Figure 3. (a) Configuration of the S-shaped QMSIW filter unit cell. (b) Configuration of the QMSIW filter loaded with L-shaped slots. (c) Equivalent circuit model ($L_c = 3.75\,\text{nH}$, $C_c = 0.8\,\text{pF}$, $L/4 = 3.95\,\text{nH}$, $C/4 = 0.85\,\text{pF}$, respectively.). (d) Simulation result.

The filter is connected to two $50\,\Omega$ microstrip lines through a pair of coplanar waveguides with the same dimensions. Two S-shaped slots etched on the top and bottom metal planes are used to eliminate the spurious response. The central frequency of the proposed filter is $f_0 = 5.5\,\text{GHz}$. Electromagnetic analysis of the structure is performed with the commercial full-wave solver Ansys HFSS 15.0.

The passband of the QMSIW filter is formed by S-shaped slots and L-shaped slots with the center frequency controlled by their lengths. Fig. 4 shows the magnitude of the scattering parameters S_{11} and S_{21} for different values of L_d. It can be observed from Fig. 4(a), the return loss becomes lower and lower as L_d increases. From Fig. 4(b), we can see that the center frequency moves to the low frequency with increasing L_d.

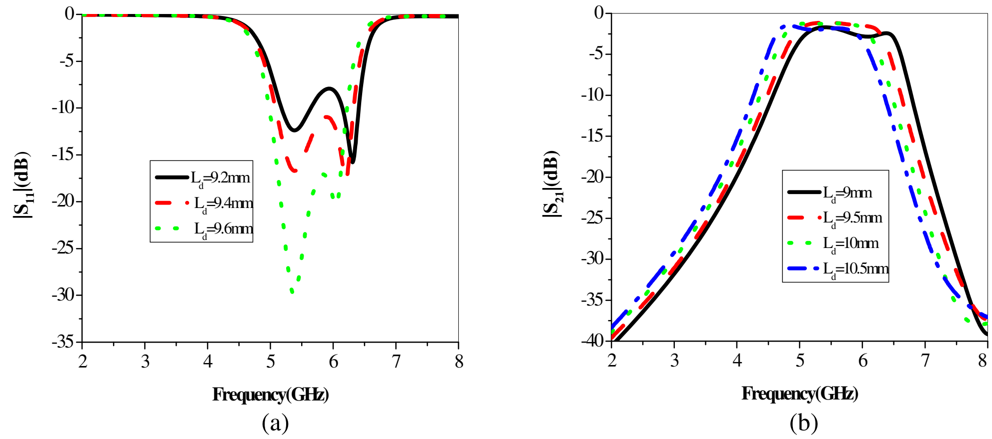


Figure 4. Simulated S-parameters for different L_d. (a) S_{11} and (b) S_{21}.

3. RESULTS AND DISCUSSION

Based on the above analysis, a two-order wide stopband bandpass filter implemented with quarter SIW cavity is simulated and analyzed. Its central frequency is 5.5 GHz with fractional bandwidth about 25%. The whole filter structure is optimized to satisfy the desired response. Its dimensions are given in Table 1. The filter was fabricated on a substrate of Rogers RT/Duroid 5880 with thickness of 0.508 mm using linear arrays of metallic via-holes with diameter of 0.8 mm and measured with an Agilent vector network analyzer. The filter has total size of $21.2 \times 12.2\,\text{mm}^2$. The simulated and measured frequency responses are shown in Fig. 5. As can be seen, they agree well with each other. The measured passband

Table 1. Dimensions of the proposed QMSIW bandpass filter.

Parameter	Value (mm)	Parameter	Value (mm)	Parameter	Value (mm)
L_a	19.2	S_1	0.25	h	0.508
L_b	10.3	d	0.8	L_3	5
L_c	8	m	1.2	L_1	7.4
W_m	2.9	m_1	3	S_2	0.2
W_s	1.4	L_2	1	L_d	9.8

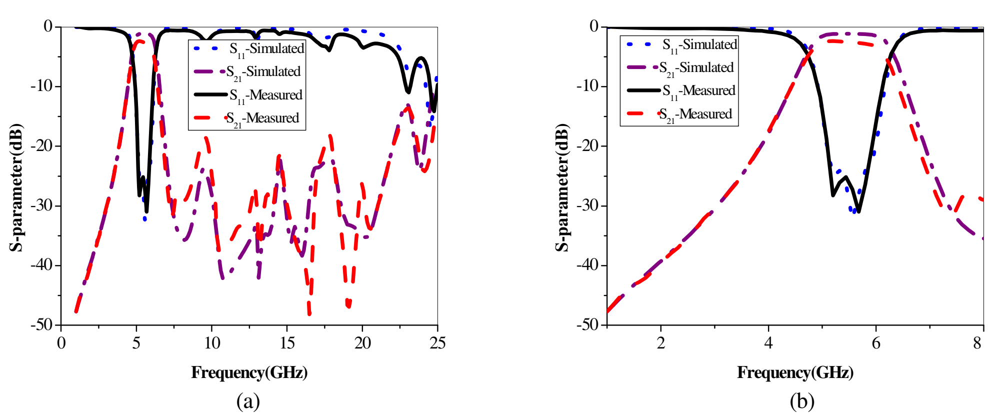


Figure 5. Simulated and measured frequency responses of the proposed QMSIW filter, (a) wide frequency response, (b) narrow frequency response.

(a) (b)

Figure 6. Photograph of the fabricated filter, (a) top view, (b) bottom view.

Table 2. Comparison with other researches.

	Freq (GHz)	FBW	IL (dB)	RL (dB)	Stopband (GHz) > 20 dB	ε_r	Size ($\lambda_g \times \lambda_g$)	Type
[7]	5.57	7.44%	2	18	$2f_0$ (10 GHz)	2.65	0.5×0.5	SIW
[8]	20	2.75%	2.78	16	$1.88f_0$ (37.7 Ghz)	2.2	1.62×1.46	SIW
[9]	6.73	101.9%	0.8	18	$3.7f_0$ (25 GHz)	2.2	0.24×0.19	ML
[10]	2.4	12.5%	2.4	15	$3.1f_0$ (7.44 Ghz)	7.6	0.058×0.0508	ML
This work	5.5	25%	1.1	24	$4f_0$ (22.5 Ghz)	2.2	0.22×0.39	SIW

is centered at 5.5 GHz with 3 dB bandwidth from 4.8 to 6.2 GHz, which is slightly narrower than the simulated one. The passband return loss is better than 24 dB, and the minimum insertion loss is approximately 1.1 dB which is the effect of loss due to dielectric substrate and finite conductivity of the top and bottom metallization layers as well as low quality of via holes metallization. In addition, it can be observed that the first spurious harmonic appears at about 22.5 GHz, which is four times of the central frequency of the filter. Broad stopband region from 6.9 to 22.5 GHz with high rejection level of 20 dB is obtained. Nevertheless, the overall filter performance is satisfactory. A photograph of the fabricated filter is shown in Fig. 6. Comparison between some other wide stopband ridge bandpass filters ([7–10]) and the proposed structure is listed in Table 2. This newly proposed structure is able to extend the bandwidth to 25% compared to [7] while maintaining a wide stopband with $4f_0$@20 dB. Also, the return loss of 24 dB is much higher than [7], which is only 18 dB. In [8], a narrow-band filter with poor performance was obtained, and the circuit size is larger than the proposed one. In [10], the filter has compact size with high selectivity and wide stopband. However, its insertion loss is not very good. The proposed filter has almost the same size as [9] but a wider stopband and better RL. It indicates that the designed filter is competitive to some degree.

4. CONCLUSION

In this paper, a compact QMSIW bandpass filter with sharp selectivity and good out-band performance is presented and analyzed. The filter is centered at $f_0 = 5.5$ GHz with fractional bandwidth of 25% and 1.1 dB insertion loss. The design strategies are implemented and performances evaluated. The effectiveness of the proposed technique was validated experimentally. The whole circuit size is about $21.2 \times 10.3 \times 0.508\ \text{mm}^3$. The measured results show that the designed filter with high selectivity has good out-of-band rejection up to 4 times of the center frequency.

ACKNOWLEDGMENT

This work is supported by the National High-tech Research Development Plan (863 Plan) (2015AA016201).

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