An Ultra-Miniature Quarter-Mode SIW Bandpass Filter Operating at First Negative Order Resonance

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***Abstract*—This paper presents an ultra-miniature bandpass filter based on quarter-mode substrate integrated waveguide (QMSIW) cavity with negative-order resonance. Ramp-shaped slots are used as interdigital capacitors (IDCs) to force the structure to operate in the negative order resonance mode. A patch with triangular slots in an additional middle metal layer along with disconnected vias is also used to increase the equivalent series capacitance of the IDC and shifting down the -1^{st} resonance for more miniaturization. The 2-pole filter has a center frequency of $\sim$690 MHz with an area of $\sim 0.05\lambda_0 \times 0.09\lambda_0$. The measured insertion loss is 2.1 dB and return loss is better than 30 dB. By employing the -1^{st} order resonance, measured out-of-band rejection of >30 dB up to $\sim$2.1 GHz is achieved. To the best of authors' knowledge, miniaturization factor of $\sim$91% compared to a conventional 2-pole SIW filter shows this is the most compact SIW 2-pole filter reported in the literature.**

***Index Terms*—Cavity filter, composite right/left handed (CRLH), miniaturization, substrate integrated waveguide (SIW).**

I. Introduction

Substrate integrated waveguide (SIW) filters are widely used over the past years because of their many advantages such as high Q, perfect isolation, planar structure, and ease of fabrication [1]. However, their use in compact wireless devices is hindered due to their large area consumption. Accordingly, miniaturization methods need to be applied to achieve more compact filters while maintaining the high performance characteristics. In [2], [3] quarter mode SIW (QMSIW) filters are introduced as a method of miniaturization. By cutting the full-mode SIW on its two fictitious magnetic walls, a QMSIW cavity resonator can be obtained which operates at a very similar mode. Hence, size reduction of approximately 75% is achieved compared to conventional SIW cavity resonators.

One other method for miniaturization of SIW filters is to use metamaterial inspired negative order resonances. In [4], a complementary split ring resonator (CSRR) is etched on the SIW cavity top metal layer in order to implement a passband cross coupled filter. Loading the SIW cavity resonator with CSRR, results in operating frequencies lower than the initial resonance frequency. However, in this case the miniaturization factor is limited by the geometrical dimensions of the designed CSRR. This issue becomes even more critical when designing QMSIW based filters. Since the size of the cavity is decreased by roughly 75%, the overall area available for CSRR structures is very small.

This paper presents an ultra-miniature 2-pole bandpass filter based on employing negative order resonance mode in an QMSIW structure. Using Ramp-shaped slots as interdigital capacitors (IDCs) on the top metal layer of the QMSIW structure, operation at negative first-order resonance becomes feasible [5]. In order to obtain more miniaturization beyond the limits defined by the size of the planar slots, two additional capacitive elements are introduced. First, a patch with triangular slots is employed in an additional middle metal layer beneath the ramp-shaped slots. Second, disconnected vias are inserted into the structure where the field distribution is maximum [6]. By doing so, a miniaturization factor of $\sim$91% is achieved for the first time compared to conventional full-mode 2-pole SIW filters with same passband frequency. The proposed filter is fabricated using common PCB process technology.

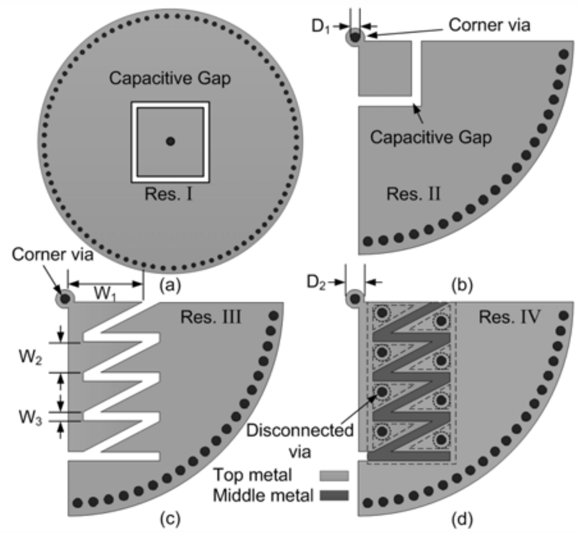

Fig. 1. (a) Gap-loaded full-mode SIW. (b) gap loaded QMSIW. (c) IDC loaded QMSIW. (d) IDC loaded QMSIW with a floating patch and disconnected vias in the center of the cavity (shown with dashed lines).

II. The Ultra-Miniature QMSIW Filter

A. Resonator Design

The initial dimensions of the SIW cavity is determined based on a resonance frequency of $\sim$2 GHz[1]. First, the SIW resonator is divided up into four sections. As a result, a QMSIW is achieved. Then by employing all the miniaturization elements, as will be explained in detail, the resonance frequency of the QMSIW cavity resonator is shifted down to $\sim$690 MHz. Fig. 1 shows the procedure used to design the final ultra-miniature QMSIW resonator. Four different resonators are shown in this figure to better demonstrate each miniaturization element employed.

1) Gap Loaded SIW Cylindrical Cavity: A full-mode SIW cylindrical cavity resonator is first loaded with a shunt via at

[1]Note that the frequency of the QMSIW resonator is almost the same.

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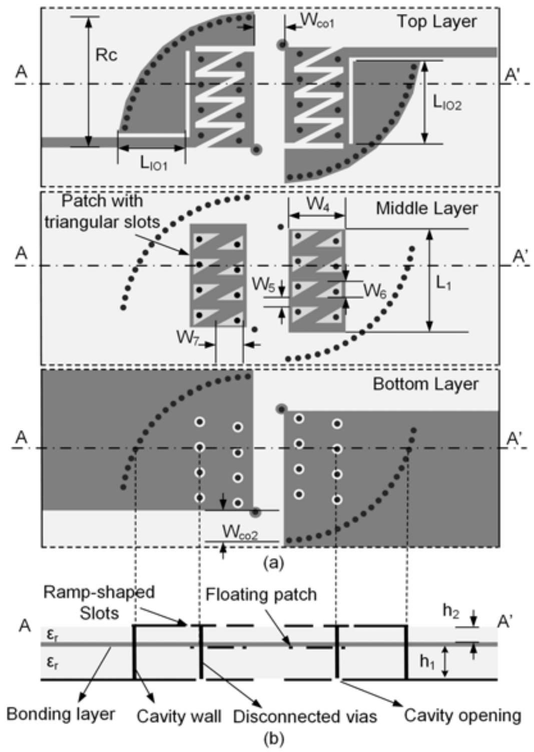

Fig. 2. (a) Top, middle, and bottom layers of the miniaturized QMSIW bandpass filter. (b) A-A' cross section view of the filter.

the center [Fig. 1(a)]. Afterwards, a capacitive ring gap disconnects the top and bottom walls and loads the cavity resonator with a small series capacitance. This series capacitance slightly shifts down the frequency of resonance.

2) The QMSIW *Resonator:* In the second step, this gap-loaded SIW resonator is divided into four identical sections as shown in Fig. 1(b), and based on the approach introduced in [2]. Since the full-mode resonator is cut on its two fictitious magnetic walls, each of the quadrants works at a frequency very close to the one of the original full-mode SIW resonator.

3) Interdigital Capacitor: In order to increase the miniaturization factor of the QMSIW resonator, the normal gap is replaced with a metamaterial inspired interdigital capacitive ramp-shaped slot [Fig. 1(c)]. The SIW wall vias including the corner via can be modeled with shunt inductors. Accordingly, by increasing the capacitance value introduced by the gap, it is possible to excite the -1^{st} order resonance mode of the QMSIW cavity resonator. By doing so, the resonance frequency shifts down and, as a result, further miniaturization is achieved. However, due to the small available area of the QMSIW, the miniaturization using the IDC gap is limited.

4) Floating Metal Patch: Since the equivalent capacitance achieved using the IDC cannot be increased more than a certain value due to size limitations, another method is used for this purpose. A floating metal patch with triangular slots is introduced [Fig. 1(d)]. As the floating patch becomes closer to the IDC structure, the series capacitance of the IDC increases. However, this dimension is also limited by the height of the substrate thickness used for the floating patch and fabrication constrains. A two-layer substrate as shown in Fig. 2(b) is used to employ an additional metal layer underneath the cavity top wall (IDC layer). This way, the height of the floating metal patch (h_2) can be controlled to some degree to maximize the series capacitance value of the IDC.

5) Disconnected Via Posts: Another capacitive element is also employed to further increase the reactive loading of the structure and push down the -1^{st} resonance of the resonator as low as possible. Disconnected vias are inserted around the IDC structure where the E-field distribution is maximum[2] [Fig. 1(d)]. By connecting the via posts to the top wall and disconnecting them from the middle floating metal patch and the cavity bottom wall, each via post acts as an equivalent capacitor in parallel with the IDC which loads the cavity more.

B. Filter Design

Fig. 2 shows the top view of the top, middle, and bottom layers of the implemented filter along with the A-A' cross section view of the filter. The substrates are both Rogers RT/Duroid 6010LM ($\epsilon_r = 10.2, tan\delta = 0.0023$) with different thicknesses of $\mathrm{h}_1 = 2.54$ mm, and $\mathrm{h}_2 = 0.635$ mm. The substrates are bonded to each other using Rogers RO4450B pre-preg material ($\epsilon_r = 3.3, h = 0.09$ mm).

A 2-pole coupled resonator bandpass filter based on the proposed ultra-miniature QMSIW cavity resonator is designed to operate at $\sim$0.7 GHz. The filter design parameters K_{12} and Q_e can be found using the low-pass Chebyshev prototype design values g_0, g_1, g_2, g_3 as [7]

$$K_{12} = \frac{FBW}{\sqrt{g_1 g_2}} \quad , \quad Q_e = \frac{g_0 g_1}{FBW} \tag{1}$$

where FBW denotes the desired filter fractional bandwidth. For a 0.01 dB ripple Chebyshev bandpass filter with a FBW of 6%, the equations in 1 result in K_{12}= 0.14 and Q_e=7.4.

While the spacing between the resonators is used to obtain the proper coupling coefficient, the L-shaped slot at the input/output is used to obtain the required external quality factor value and proper matching. First, the input/output ports of the filter are weakly coupled to the filter resonators. The vertical distance between the two resonators, $\mathrm{W}_{\mathrm{co2}}$, is set for the maximum coupling factor achievable by adjusting this parameter. Afterwards, the horizontal distance, $\mathrm{W}_{\mathrm{co1}}$, is precisely adjusted to achieve the required coupling factor using [7]

$$K_{12} = \frac{f_1^2 - f_2^2}{f_1^2 + f_2^2} \tag{2}$$

where f_1 and f_2 are the odd- and even-mode resonance frequencies, respectively.

The external quality factor (Q_e) can be found using a singly loaded QMSIW resonator. The Q_e can be computed using [7]

$$Q_e = \frac{f_0}{\Delta f_{\pm 90^\circ}} \tag{3}$$

where f_0 is the simulated resonance frequency and the $\Delta f_{\pm 90^\circ}$ is the difference of the frequencies at which a phase shift of

[2]Employing the corner via post and the IDC around it forces the maximum E-field distribution to be around the IDC slot instead of the center of the cavity resonator.

TABLE I
FINAL DIMENSIONS (mm) OF THE ULTRA-MINIATURE QMSIW FILTER

W_1	6.25	W_2	2.6	W_3	0.75
W_4	7.5	W_5	1.5	W_6	2.1
W_7	3.5	D_1	0.8	D_2	1.6
L_{IO1}	8.9	L_{IO2}	10.9	L_1	13.7
$W_{c\bullet 1}$	4	$W_{c\bullet 2}$	4.4	R_c	18

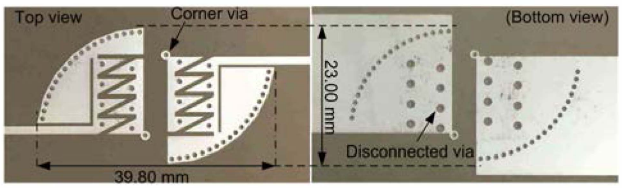

Fig. 3. Top (left) and bottom (right) views of the QMSIW filter prototype.

$\pm 90°$ occurs in the S_{11} response of the resonator. To obtain the required Q_e, the values of L_{IO1}, and L_{IO2} are adjusted. While the first one is used for coarse adjustment of the Q_e, the latter is used for fine adjustment. The final values of filter dimensions are tabulated in Table I.

III. REALIZATION AND EXPERIMENTAL RESULTS

The proposed miniature filter is fabricated and shown in Fig. 3. First, the top and bottom walls of the cavity are etched on the top-side and bottom-side metalization of the upper and lower substrates, respectively. While the middle layer is etched using the top-side metalization of the lower substrate, the bottom-side metalization of the upper substrate is completely removed. These two substrate layers are then bonded to each other using the Rogers pre-preg material. At the end, the plated via holes are drilled through both substrates.

The fabricated filter prototype is measured using a 2 port network analyzer (Agilent N5230A) after short-open-load-thru (SOLT) calibration. Fig. 4(a) shows the simulated and measured S-parameter results of the filter. The measured insertion and return loss of the filter is 2.1 dB, and >30 dB, respectively. The measured fractional bandwidth of the filter is 5.9%, which is very close to the designed value. The overall size of the QMSIW filter excluding the microstrip feed lines is 23×39.8 mm^2 which is equal to $0.05\lambda_0 \times 0.09\lambda_0$, where λ_0 is the wavelength in free space at the frequency of operation. This size translates into a miniaturization factor of $\sim$91%, considering a full-mode 2-pole SIW filter working at the same frequency.

Fig. 4(b) shows the simulated and measured response of the filter up to 2.7 GHz. Since the -1^{st} order resonance of the resonators is used in the design of the QMSIW filter, there is a transmission zero located around the 0^{th} order resonance mode. Hence, the first spurious filter passband does not occur up to $\sim$2.1 GHz while also providing a rejection level of >30 dB in the frequency range of 0.9-2.1 GHz.

IV. CONCLUSION

A novel method for further miniaturization of quarter-mode SIW filters is proposed. Metamaterial inspired ramped-shaped interdigital capacitors on the cavity top wall are employed to force the filter to work in the -1^{st} resonance mode. To increase the series capacitance value of the ramped-shaped IDCs, a metal patch with triangular slots in an additional middle metal layer and beneath the IDC slot along with disconnected vias is introduced. The proposed filter works at $\sim$690 MHz with a maximum in-band insertion loss of 2.1 dB. Using the negative order resonance mode results in an improved upper stopband rejection of >30 dB. Also, the out-of-band rejection of the filter is observed to be more than 1.2 GHz. The proposed filter is $\sim$91% smaller in area compared to a full-mode SIW 2-pole filter working at the same center frequency. To the best of authors' knowledge this is the most compact 2-pole SIW-based bandpass filter.

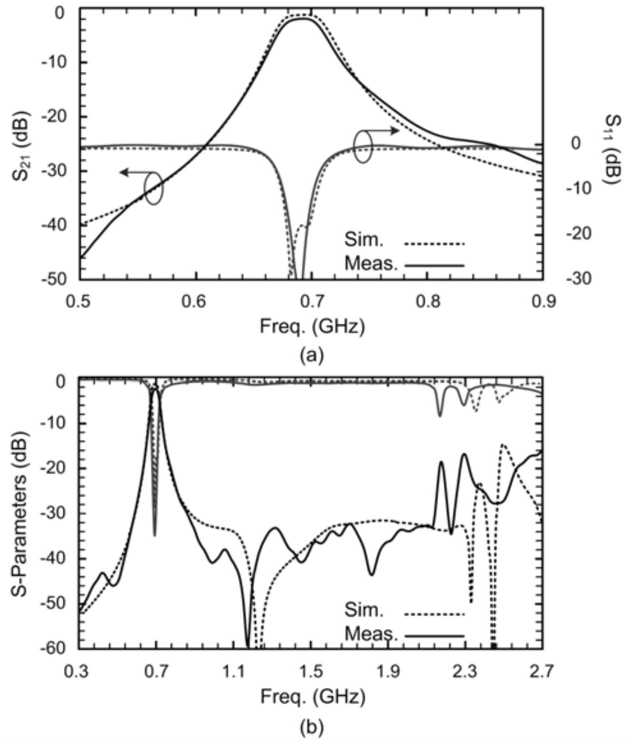

Fig. 4. (a) Measured and simulated filter response. (b) Filter response up to 2.7 GHz.

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