A Novel Miniature Single-Layer Eighth-Mode SIW Filter With Improved Out-of-Band Rejection

Lei Li, Zengqiang Wu, Ke Yang, Xianjun Lai, and Zhenya Lei

***Abstract*— An ultraminiature two-pole bandpass filter based on the eighth-mode substrate integrated waveguide is proposed in this letter. The combination of a coplanar waveguide and circular-ring miniaturized element as a new feeding method is used to improve the out-of-band rejection by introducing two transmission zeros. The measured insertion loss and return loss of the filter operated at 690 MHz are 1.25 dB and better than 20 dB, respectively. The out-of-band rejection is better than 30 dB up to 3 GHz. The equivalent circuit, simulation, and measured results are consistent with one another. The overall size of the filter is 35 mm × 35 mm, which is equivalent to $0.08\lambda_0 \times 0.08\lambda_0$. A miniaturization factor of 98.8% is achieved.**

***Index Terms*— Circular-ring miniaturized element (CRME), eighth-mode substrate integrated waveguide (EMSIW), transmission zeros.**

I. Introduction

UNDER the high integration of wireless communication systems, the design of a low-loss bandpass filter constructed using compact resonators becomes increasingly important. The substrate integrated waveguide (SIW) has been widely used in wireless communication systems because of its good performance [1]. Much work has been done in the area of SIW filter miniaturization. In [2], a half-mode SIW and quarter-mode SIW (QMSIW) resonators, which were made by cutting the equivalent magnetic wall of SIW resonators, were used. In [3]–[5], a forward-wave passband that propagated below the characteristic cutoff frequency of the SIW structure was produced using the defected ground structure (DGS), ring gaps, and complementary split-ring resonators. In [6], the miniaturization factor was increased by using the metamaterial (composite right/left-handed transmission line) to inspire the lower order resonances (e.g., first mode). In [7], QMSIW resonator loaded ramp-shaped slots (e.g., interdigital capacitors) on the top metal layer of the cavity and an additional middle metal layer were used to reduce the size of the resonator. Among these structures, the largest miniaturization factor of QMSIW was nearly 75%. Other methods may have problems, such as a complex design of geometric dimensions and difficulties achieving a multilayer structure.

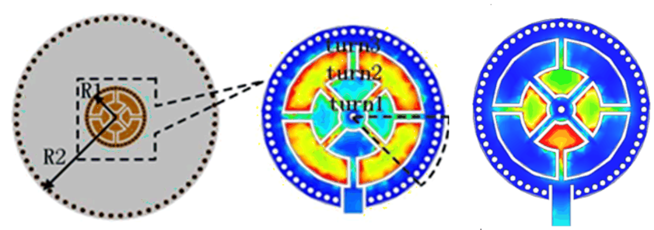
In this letter, based on previous works, the miniature eighth-mode SIW (EMSIW) resonator loaded circular-ring miniaturized-element (CRME) structure on top of a metal layer is presented. With the equivalent circuit model of the resonator and filter, this structure is used to design a two-pole bandpass filter operating at a center frequency of 690 MHz with an area of $0.08\lambda_0 \times 0.08\lambda_0$ and a fractional bandwidth of 10.2% on a single layer. Furthermore, a new feed method that combines a coplanar waveguide and CRME can improve the out-of-band rejection.

Manuscript received June 25, 2017; revised September 28, 2017 and December 29, 2017; accepted February 26, 2018. This work was supported in part by the National Natural Science Foundation of China under Grant 61101067 and in part by the Basic Scientific Research Foundation of Xidian University under Grant JB180220/20101185311. *(Corresponding author: Lei Li.)*

The authors are with the National Key Laboratory on Antenna and Microwave Techniques, School of Electronic Engineering, Xidian University, Xi'an 710071, China (e-mail: leili@mail.xidian.edu.cn).

Color versions of one or more of the figures in this letter are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/LMWC.2018.2813883



(a) (b) (c)

Fig. 1. (a) Comparison of the initial SIW and SIW with the CRME. (b) Electric field distribution of the resonator with a new feeding structure. (c) Electric field distribution of the resonator fed by the coplanar waveguide.

II. Resonator Design

A two-pole bandpass filter, which operates at 690 MHz, is implemented by combining two identical EMSIW resonators. In [7], the miniaturization factor is calculated as follows:

$$\text{Miniaturization} = \frac{A_{\text{siw},f_0} - A_c}{A_{\text{siw},f_0}} \times 100\% \qquad (1)$$

where A_{siw,f_0} is the area of the full-mode SIW resonator and A_c is the area of the resonator after reduction at an identical frequency. The EMSIW is obtained by separating the full-mode SIW from its three fictitious magnetic walls. Thus, the miniaturization factor of the EMSIW resonator is approximately 87.5%.

To reduce the effect of the grating lobes, the CRME structure is introduced in [8] and applied to the filter design in this letter because of its axis symmetric geometry feature. In this letter, the CRME on the top metal layer of the filter is described by parallel inductance and capacitance, which inspires the first-negative-order bandpass response [5]. According to formulation (1), the size of the resonator-loaded CRME is reduced by 91% compared to the initial SIW resonator that operates at the identical frequency. Application of the CRME leads to negative resonance, which significantly reduces the resonance frequency at the same size. Fig. 1(a) shows a comparison of two resonators. The resonance peaks on $|S_{21}|$ are shown in Fig. 2(a); the horizontal axis represents the resonance frequency normalized to the TM_{010} resonance frequency of the original resonator.

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

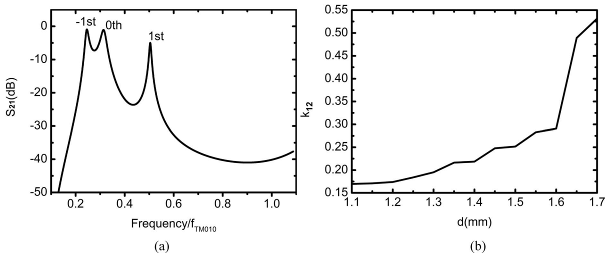


Fig. 2. (a) Resonance peaks of the resonator with the CRME. (b) Relationship between the coupling coefficient and distance d.

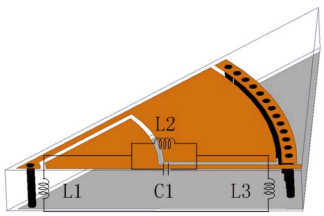


Fig. 3. Equivalent circuit of the resonator.

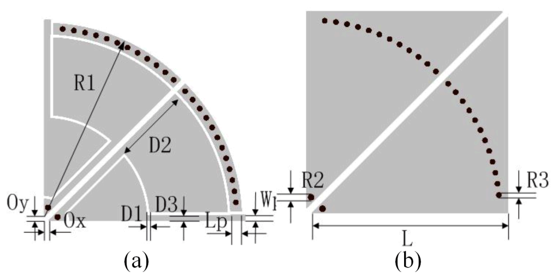


Fig. 4. (a) Top view of the filter. (b) Bottom view of the filter.

TABLE I

FINAL DIMENSIONS (mm) OF THE FILTER

R1	35	L	37	D1	0.3	d	1.4
D2	14.6	L_p	1.8	W_p	1	R2	0.3
R3	0.25	H	2				

The equivalent circuit model of the resonator is shown in Fig. 3, which is cut along the fan-shaped frame in the right side in Fig. 1(b), where L and C are the inductance and capacitance, respectively. The unloaded quality factor can be used to study the loss mechanism of the presented resonator; a Q_u value of 90 is achieved for the EMSIW resonator. Q_u degradation is caused by leakage loss from the open wall and the top CRME slot of the cavity.

III. FILTER DESIGN

This letter aims to design a filter that operates at 690 MHz, with a bandwidth of 10%, insertion loss $|S_{21}|$ of 1.5 dB, and return loss $|S_{11}|$ of better than 20 dB in the passband. Fig. 4(a) and (b) shows the top and bottom views of the filter, respectively. It is built on the substrate Rogers RT/Duroid 5880 with a relative dielectric constant of $\varepsilon_r = 2.2$, thickness of 2 mm, and dielectric loss tangent of 0.0009. The parameters are shown in Table I.

In this letter, as shown in Fig. 1(b), a new feed method that consists of a coplanar waveguide and a CRME structure

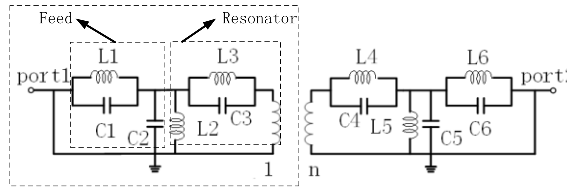


Fig. 5. Equivalent circuit of the filter. ($L1 = L6 = 4.49$ nH; $C1 = C6 = 6.53$ pF; $L2 = L5 = 1.50$ nH; $C2 = C5 = 34.61$ pF; $L3 = L4 = 11.71$ nH; $C3 = C4 = 11.41$ pF; and $n = 1.05$).

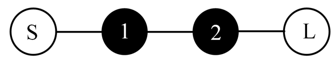


Fig. 6. Topology of the filter.

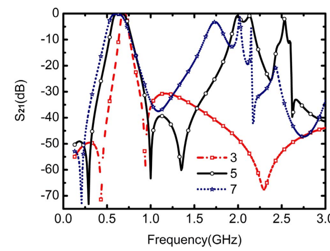


Fig. 7. Effect of the number of turns on the out-of-band rejection.

is introduced. As illustrated in Fig. 5, the new feed structure, which consists of a ground capacitance, two paralleled capacitors, and one inductor, can affect the distribution of the electric field [8]. Using the new feed structure, the miniaturization factor is increased and good impedance matching is obtained in comparison with the coplanar waveguide in Fig. 1(c).

The filter consists of two identical EMSIW resonators; the topology is shown in Fig. 6. The coupling coefficient is affected by the distance d between the two resonators, whereas the length of the feed port affects Q_e. According to formulations (2) and (3), the coupling coefficients k_{12} and Q_e of the filter synthesized by Chebyshev topology are 0.23 and 4.31, respectively, which play a key role in the design and optimization of the filter [9], where FBW is the filter bandwidth. We adjust the distance between two cavity resonators with weakly coupled input–output ports to obtain the expected k_{12} using formulation (4)

$$K_{12} = \frac{\text{FBW}}{\sqrt{g_1 g_2}} \tag{2}$$

$$Q_e = \frac{g_0 g_1}{\text{FBW}}. \tag{3}$$

Q_e can be optimized by changing the length of the coplanar waveguide L_p according to formulation (5). Fig. 2(b) shows the relationship between the coupling coefficient and distance d. We conclude that the coupling coefficient is close to the ideal value of 0.23 when d is 1.4 mm

$$k_{12} = \frac{f_1^2 - f_2^2}{f_1^2 + f_2^2} \tag{4}$$

$$Q_e = \frac{f_0}{\Delta f \pm 90} \tag{5}$$

where f_1 and f_2 are two split resonance frequencies of the resonators with the weakly coupled input–output ports [10].

The CRME is used to increase the surface inductance and capacitance of the resonator here. The out-of-band rejection performance is affected by the number of turns of the CRME.

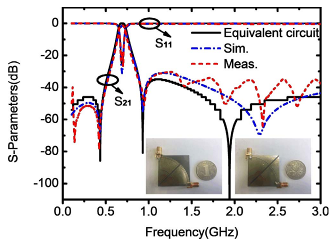


Fig. 8. Equivalent circuit, simulation, and measured wideband results of the filter.

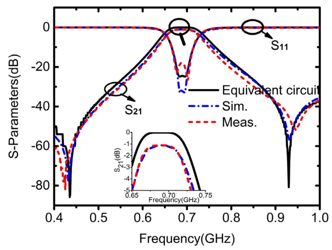


Fig. 9. Equivalent circuit, simulation, and measured results of the filter.

[The number of turns is shown in Fig. 1(b).] An excessive number of turns can degrade the out-of-band rejection, whereas too few turns cannot match the desired capacitance and inductance. The effect of the number of turns on the out-of-band rejection is shown in Fig. 7. According to the design requirements, the out-of-band rejection is good when the number of turns is 3 according to the simulation.

The equivalent circuit of the filter is shown in Fig. 5. The two-pole passband filter is completed by two EMSIW resonators with the feed structure. The two resonators are symmetrical. The inductance and capacitance values at symmetrical positions are equal. For example, for the equivalent circuit of the left resonator; the feed port is equal to surface inductance $L1$ and capacitance $C1$ when ground capacitance $C2$ is introduced. With surface inductance $L3$ and capacitance $C3$ to represent the CRME, the shunt center via of the resonator is equal to ground inductance $L2$. The two resonators are coupled through a shunt center via. The filter operates at 690 MHz, the coupling coefficient is 0.23, and the quality factor is 4.31. According to the design requirements, we adjust the resonator size and CRME parameters to change the values of $L3$ and $C3$ to ensure a single resonator operating frequency of 690 MHz. Then, we obtain suitable coupling coefficient by changing the distance between two resonators while weakly feeding them. Two controllable transmission zeros are introduced by the feed structure and CRME structure. As shown in Fig. 7, the first transmission zero at the lower frequency is controlled by the turns of the CRME. The second transmission zero at the higher frequency is controlled by parallel inductor $L1$ and capacitor $C1$ in Fig. 5. Then, the appropriate quality factor can be obtained by adjusting the length of the feeding port L_p.

IV. Simulation and Measured Results

The filter fabricated is shown in Fig. 8, which includes the top view and bottom view. The overall size of the filter, which operates at 690 MHz, is 35 mm × 35 mm, which is equal to $0.08\lambda_0 \times 0.08\lambda_0$; the bandwidth is 10.2%. The measured insertion loss and return loss are 1.25 and >20 dB, respectively. The result of the equivalent circuit, simulation, and measured results are consistent in Fig. 9. Fig. 8 shows the measured out-of-band rejection of >30 dB up to 3 GHz. Table II compares the work of this letter with the related work. Compared with other works, the filter of this letter has a small insertion loss and a better miniaturization coefficient on a single layer.

TABLE II
Comparison of Related Works in the Literature

	F(GHz)	Band (%)	Q_u	Layer	IL (dB)	Size
[5]	6.11	6.55	/	1	1.59	$\sim 0.23\lambda_0 \times 0.46\lambda_0$
[6]	0.690	5.9	186	2	2.1	$\sim 0.05\lambda_0 \times 0.09\lambda_0$
[11]	11	8	/	2	3.2	$\sim 1.004\lambda_0 \times 0.238\lambda_0$
[12]	12	8.23	/	1	1.22	$\sim 1.069\lambda_0 \times 0.468\lambda_0$
us	0.690	10.2	90	1	1.25	$\sim 0.08\lambda_0 \times 0.08\lambda_0$

V. Conclusion

A two-pole bandpass filter based on the EMSIW is presented in this letter. By applying an EMSIW resonator loaded with a CRME, the size of the resonator is reduced by 98.8%. The new feeding method and CRME structure are used to improve the out-of-band rejection by introducing two transmission zeros. Therefore, the miniature single-layer eighth-mode SIW filter satisfies the design requirements. Further research based on this theory will continue.

References

[1] D. Deslandes and K. Wu, "Integrated transition of coplanar to rectangular waveguides," in *IEEE MTT-S Int. Microw. Symp. Dig.*, May 2001, pp. 619–622.

[2] S. Moscato, L. Silvestri, N. Delmonte, M. Bozzi, L. Perregrini, and C. Tomassoni, "Compact filter solutions in substrate integrated waveguide (SIW) technology," in *Proc. IEEE Int. Workshop Electromagnetics: Appl. Student Innov. Competition*, May 2016, pp. 1–3.

[3] S. Xu, K. Ma, F. Meng, and K. S. Yeo, "Novel defected ground structure and two-side loading scheme for miniaturized dual-band SIW bandpass filter designs," *IEEE Microw. Wireless Compon. Lett.*, vol. 25, no. 4, pp. 217–219, Apr. 2015.

[4] J. D. Martinez, S. Sirci, M. Taroncher, and V. E. Boria, "Compact CPW-fed combline filter in substrate integrated waveguide technology," *IEEE Microw. Wireless Compon. Lett.*, vol. 22, no. 1, pp. 7–9, Jan. 2012.

[5] Y. D. Dong, T. Yang, and T. Itoh, "Substrate integrated waveguide loaded by complementary split-ring resonators and its applications to miniaturized waveguide filters," *IEEE Trans. Microw. Theory Techn.*, vol. 57, no. 9, pp. 2211–2223, Sep. 2009.

[6] Y. Dong and T. Itoh, "Substrate integrated waveguide negative order resonances and their applications," *IET Microw., Antennas Propag.*, vol. 4, no. 8, pp. 1081–1091, Aug. 2010.

[7] A. P. Saghati, A. P. Saghati, and K. Entesari, "Ultra-miniature SIW cavity resonators and filters," *IEEE Trans. Microw. Theory Techn.*, vol. 63, no. 12, pp. 4329–4340, Dec. 2015.

[8] F.-C. Huang, C.-N. Chiu, T.-L. Wu, and Y.-P. Chiou, "A circular-ring miniaturized-element metasurface with many good features for frequency selective shielding applications," *IEEE Trans. Electromagn. Compat.*, vol. 57, no. 3, pp. 365–374, Jun. 2015.

[9] J.-S. G. Hong and M. J. Lancaster, *Microstrip Filters for RF/Microwave Applications*. Hoboken, NJ, USA: Wiley, 2004.

[10] A. P. Saghati, A. P. Saghati, and K. Entesari, "An ultra-miniature quarter-mode SIW bandpass filter operating at first negative order resonance," in *IEEE MTT-S Int. Microw. Symp. Dig.*, May 2015, pp. 1–3.

[11] M. Bertrand, Z. Liu, E. Pistono, D. Kaddour, and P. Ferrari, "A compact slow-wave substrate integrated waveguide cavity filter," in *IEEE MTT-S Int. Microw. Symp. Dig.*, May 2015, pp. 1–3.

[12] Y.-Q. Wu and P.-P. Xu, "Cross-coupled substrate integrated waveguide filter with sharp sideband performance," in *Proc. Int. Workshop Microw. Millim. Wave Circuits Syst. Technol.*, Oct. 2013, pp. 272–274.