Multi passband filter with one-twelfth mode miniaturized based on substrate integrated waveguide

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Abstract In this letter, the one-twelfth mode of equilateral hexagonal substrate integrated waveguide (TMSIW) is proposed for the first time. Comparing with traditional substrate integrated waveguide (SIW), the size of TWSIW is only 1/12 which is reduced 11/12 while the resonant frequency of TWSIW is almost unchanged. Loading a complementary split-ring resonator (CSRR) structure, the miniaturization is further improved and the filter selectivity is improved. The filter design uses two of TWSIW which is connected with a microstrip line. The structure is not complex, easy to process, low loss, and the passband has a certain bandwidth. After processing and testing, it shows that the measurement results of filter give good agreement with the simulation results. This filter has advantages in all indexes by comparing with other works.

key words: Bandpass filter, three-band, twsiw, csrr, miniaturization
Classification: Microwave and millimeter wave devices, circuits, and hardware

1. Introduction

In recent years, the substrate integrated waveguide (SIW) has attracted people's attention due to its high-quality factor, high-power, low-loss, low-cost, easy fabrication and easy integration with planar integrated circuit \[1\]-\[16,19,21,23,24\]. The miniaturization and multi-passband SIW filters have gradually become research hot-spot \[17,22,25,26,27,30\]. Many improvement methods of the SIW structure have been performed at present. A SIW filter loaded square CSRR has been proposed in \[2,18,20,29\]. CSRR influence cavity mode changes seriously because of its large size. Only a stable passband can be generated. A defected microstrip structure (DMS) is proposed to improve the selectivity of half mode substrate integrated waveguide (HMSIW) filter \[6\]. The 1/4 mode substrate integrated waveguide cavity (QMSIW) is proposed \[8\]. The metallized via array and the multiple resonant modes is used in the design of filter, which can effectively control passband bandwidth. \[9\] uses QMSIW and 1/8 mode substrate integrated waveguide (EMSIW) cavities to reduce the electrical size of the filter. An EMSIW resonator is proposed in \[10\]. By means of multi-layer and cross coupling, it can not only reduce the circuit size, but also improve the selectivity of the filter, however the structure is too complicated. A Triple passband filter has been proposed in \[13\] Fig.10 and a multiband SIW filter has been designed in \[14\] and \[15\]. Although all of them has transmission zeros, the size is too large by using the third order or more resonant cavities, where the filter in \[14\] and \[15\] use multilayer boards and the structure is too complex. A SIW filter is proposed in \[16\], which use the tech LTCC. Although the size become very small. However, the manufacturing process is more difficult, the structure is complicated and the loss is large. Given the problem in \[2,18,20,29\]. Therefore, the problem is that we need to generate three stable passbands, so we must change the CSRR structure and adjust its loading position to meet the requirements of multi passband. In this letter, the filter uses the three mode coupling effects of two TWSIW cavities to generate three passbands. This structure can realize miniaturization, not complex and low insertion loss. Furthermore, the passband bandwidth can be adjusted by the coupling of microstrip lines easily.

2. Design of the TMSIW cavity.

2.1 The proposed TMSIW Cavity

The SIW structure is formed by periodic arrangement of metallized through holes on dielectric substrate. The diameter of metal hole (D) and the spacing of them (P) are the main parameters in the SIW structure. D/P > 0.5 and D/\lambda < 0.1, the magnetic wall of TMSIW composed of metal through holes has almost no electromagnetic leakage. D=0.6mm, P=1mm has been selected.

\begin{figure}[h]
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\includegraphics[width=0.5\textwidth]{figure.png}
\caption{The structure of TMSIW}
\end{figure}

\begin{figure}[h]
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\includegraphics[width=0.5\textwidth]{figure.png}
\caption{The simulated field distribution}
\end{figure}

\begin{figure}[h]
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\includegraphics[width=0.5\textwidth]{figure.png}
\caption{The fabricated filter}
\end{figure}

\begin{figure}[h]
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\includegraphics[width=0.5\textwidth]{figure.png}
\caption{The measurement results}
\end{figure}

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DOI: 10.1587/elex.19.20220011
Received January 07, 2022
Accepted January 24, 2022
Publicized February 03, 2022

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In the beginning of designing, hexagonal SIW cavity has been selected as the prototype, which electric field distribution of three modes has been obtained in Fig.1. It includes the fundamental mode and two high-order modes of the resonator. The reason why those three resonant modes are selected is that the electric fields of these three resonant modes are symmetrically distributed. The 1/6 mode substrate integrated waveguide (SMISIW) and TMSIW cavity can be generated by cutting the common magnetic wall. Fig.3 show the electric field distribution of three modes of hexagonal TMSIW. The shape of TMSIW is a right triangle with an acute angle of 60° and a metal through-hole array only on the short right side. The size of TMSIW is 1/12 of that of regular hexagon SIW, reducing by 91.7%. It can be seen that the electric field distribution of the three same modes in TMSIW cavity is similar to that of hexagonal SIW and SMISIW. The same resonant frequency as SIW is obtained by HFSS eigenmode solver.

2.2 TWSIW Cavity
The TMSIW cavity will be studied when the prototype cavity has been ensured. The basic model has been shown in Fig.4. L is the side length of cavity, which dimension is mm. The metal hole has been replaced by PEC in HFSS for simplifying the calculation process.

The relationship between resonator length L and resonant frequency and resonator unloaded quality factor Qo has been proposed in Fig.4. Three selected resonant frequencies and unloaded quality factor Qo has be determined by adjusting the value of L.

3. Filter Design

3.1 Multi BPF design theory
There are many ways to design BPF. In this letter, the high-order mode of TMSIW resonator is adopted in chapter 2.2, including fundamental mode and two high-order modes. By coupling two resonator cavities and optimizing the appropriate structural parameters, the passband has a certain bandwidth and a certain center frequency. The following steps should be completed to design the Multi passbands filter.
1. Selecting a suitable resonator cavity by analyzing the electric field distribution according to the design requirements.
2. The three passbands center frequency $f_i, i = 1, 2, 3$ will be determined by selecting a proper value of L in Fig.4.
3. The cavity tap position will be decided by selecting the appropriate $Q_{ei}$ in Fig.6, which can also determine the bandwidth of three passbands roughly.
4. To determine the accurate model of BPF model, the coupling coefficient can be adjusted by controlling the width, length, and position of middle microwave stripe.

3.2 External Q value extraction
The feed position of the cavity is considered first when a filter will be designed with TMSIW cavity. The tap position is very important to adjust the external $Q_{ei}$ value of the filter and S11. Sketch map of resonant cavity with feed tap has been shown in Fig.5.

$$Q_{ei}, Q_{e2}, Q_{e3},$$ respectively, representing the $Q_{ei}$ in the first, second and third passbands, can then be extracted from the phase and group delay responses of S11 using the formula [31].

$$Q_{ei} = \frac{f_i}{\Delta f \pm 90°}, \quad i = 1, 2, 3$$  \hspace{1cm} (1)

Where $f_i$ denotes the frequency at which the group delay of S11 reaches the maximum and $\Delta f \pm 90°$ represents the absolute bandwidth (ABW) between $\pm 90°$ points with respect to the absolute phase at $f_i$, as illustrated in Fig.5.
The variable \( lp \) is a very vital parameter, which is closed to \( Qe_1 \) and has been marked in Fig.8. Fig.6 shows the extracted curves of \( Qe_1 \) versus the \( lp \) as a variable.

![Fig. 6 Relationship between tap position and external Q-value](image)

As can be seen, with the increase of \( lp \), \( Qe_1 \) increases monotonically while \( Qe_2 \) and \( Qe_3 \) decreases first then increases. The required \( Qe_1 \) value can be obtained by adjusting \( lp \).

In addition, \( \Delta_2 / \Delta_1 = Qe_1 / Qe_2 \), \( \Delta_2 / \Delta_3 = Qe_3 / Qe_2 \) could be obtained in this kind of design method roughly (\( \Delta_1, \Delta_2 \) and \( \Delta_3 \) are the \( nth \) passband bandwidth). The detailed reason has been described in reference [32].

3.3 Loading CSRR

In order to further realize miniaturization of filter, we etch the CSRR structure on the top surface of TMSIW cavity. According to the resonant cavity model, the electric field distribution of cavity is calculated by HFSS. The initial position of the CSRR is determined by the electric field distribution of each mode of the resonator. Avoiding placing it in the position with the strongest field strength, but also need to affect mode coupling. The placing position will be analyzed according to the three modes of electric field graph, and then use HFSS software to optimize parameters. The optimization parameters of the structure are as follows.

![Fig.7 top view of cavity (a1=1.6mm, a2=1.45mm, g_a=1mm, b1=1mm, b2=0.85mm, g_b=0.8mm, lcx=4.2mm, lcy=15.8mm)](image)

3.4 Design of filter

The top view of TMSIW compact filter loaded with CSRR is shown in Fig.8. The structure of the filter is symmetrical and consists of two TMSIW cavities, coupling line and input-output line. The characteristic impedance of the input and output microstrip line of the filter is 50 \( \Omega \), which is directly connected with the TMSIW cavity. The coupling strength between TMSIW walls can be realized to adjust the insertion loss and bandwidth of the filter by adjusting the position and size of the coupling line. Its essence is to adjust the coupling coefficients of three modes between two resonant cavities.

The coupling coefficient \( K \) of two TMSIW resonant cavity has been studied for designing a proper performance filter. \( K \) will be obtained through using the formula (2) usually.

\[
K = \frac{f_1^2 - f_2^2}{f_1^2 + f_2^2}
\]

where \( f_1 \) and \( f_2 \) are the lower and higher resonant frequencies, respectively. Taking the variable \( lmx \) as an example, the result of relationship between \( K \) and \( lmx \) has been proposed in Fig.9.

![Fig. 8 Top view of filter (w=2.4mm, l1=5mm, lp=12.6mm, wm=1.8mm, lmx=3mm, lmy=12.2mm.)(image)]

![Fig. 9 Schematic diagram of relationship between K and lmx.](image)

As can be seen that \( Kmode1 \), \( Kmode2 \) and \( Kmode3 \) are the \( nth \) passband coupling coefficient of filter. \( Kmode1 \) will decrease slightly, then \( Kmode2 \) will decrease more along with the increase of \( lmx \). However, \( Kmode3 \) remain unchanged, which has also been verified by the
The corresponding results for S21 are shown in Fig.10, which represent the three passbands bandwidth and insert loss can be controlled by adjusting the variable lmx. The first and second passband bandwidth will decrease when lmx increases. In essence, because the coupling coefficient Kmode1 and Kmode2 are reduced. The third passband remains unchanged because the value of Kmode3 is stable. K has the ability to performance the passband condition of filter. Meanwhile, the length (wm) and position (lmy) of couple stripe can be used to optimize the filter exactly.

3.5 Filter Processing Test

The dielectric substrate RT/Duroid 5880 with dielectric loss tangent of 0.0009, thickness of 0.787mm, and dielectric constant of 2.22 is adopted, and the cavity side length is 26.5mm. Circuit physical map as shown in Fig.11, which size is 26.5mm×25mm.

To verify proposed TMSIW cavity can be used in miniaturized filter design and demonstrated the feasibility of the proposed design method of multiband filters, we processed the circuit layout, and tested it with E8363B PNA Network Analyzer. The simulation and test curve are shown in Fig.12 which shows that the three passbands center frequency are 3.5GHz, 8GHz and 12.6GHz; The bandwidths are 40%, 15% and 10.3% respectively; The minimum insertion loss of three passbands is 1dB, 1.26dB and 1.66dB respectively; Moreover, the out of band suppression of 6.1GHz filter reaches -40dB. The return loss of the three passbands is greater than 10dB, which meets the technical requirements. In addition, by comparing the simulation and test curve results, it can be seen that the physical test results are basically the same, but there are some errors in the test results, which can be attributed to the machining accuracy deviation and the error of dielectric substrate electrical characteristic parameters, as well as the short-circuit metal through-hole deviation and welding process.

### 3.6 Comparison with references

| Ref. | CFs (GHz) | No.Pb | IL, dB | BW, % | Size(λg) |
|------|-----------|-------|--------|-------|-----------|
| [13] | 13/14/15  | 3     | 1.7/1.8/2.2 | 4.12/3.52/2 | 3.38×1.19 |
| [14] | 11.98/14.54/15.95 | 3 | 2.54/2.57/2 | 30/19.2/18 | 1.53×1.7 |
| [15] | 11.53/12.51/14.7/15.22 | 4 | 1.33/1.22/1.43/1.42/1 | 41/1 | 2.15×1.27 |
| [16] | 29/34/8/36.8 | 3 | 1.65/1.68/1.79 | 34/4/14.3/0.79 | 1.35×1.13 |

This work: 3.5/8/12.6 3 1/1.26/1.66 40/15/10.3 0.39/0.37

Tt: passband center frequency (CFs), number of passbands (No.Pb), insert loss(IL), 3dB-bandwidth(BW) and physics size. (λg is the wavelength in the dielectric substrate at the center frequency of the first passband)

### 4. Conclusion

This letter proposes the TMSIW for the first time and presents a design method of TMSIW multi passband filter loaded with circular CSRR. This method can not only greatly reduce the size of the filter, but also be applied to the design of multi-pass band. Through processing validation and comparing with other published multiband filters, the results show that the multi passband compact filter circuit designed by this method has the advantages of small physical size, simple structure, low loss and certain relatively broad bandwidth, and can be widely used in microwave circuit design.

### References

[1] H. Jing, et al, "A Novel Strip-Line Hybrid Triple-Mode SIW Filter," 2019 IEEE MTT-S International Wireless Symposium (IWS), Guangzhou, China, 2019, pp. 1-3, doi: 10.1109/IEEE-IWS.2019.8803871.

[2] X. Zhang, et al, "A SIW filter with square complementary split-
ring resonators (CSRRs).” 2017 USNC-URSI Radio Science Meeting (Joint with AP-S Symposium), San Diego, CA, 2017, pp. 45-46, doi: 10.1109/USNC-URSI.2017.8074889.

[3] M. P. dos Santos et al., “Design of a SIW Chebyshev Bandpass Filter with Inductive Coupling.” 2018 IEEE MTT-S Latin America Microwave Conference (LAMC 2018), Arrecife, Peru, 2018, pp. 1-3, doi: 10.1109/LAMC.2018.8699015.

[4] Souri, N. et al., “A Dual Stopband SIW Ka-V Band Filter,” 2019 27th Iranian Conference on Electrical Engineering (ICCEE), Yazd, Iran, 2019, pp. 437-441, doi: 10.1109/IranianICCEE.2019.8768469.

[5] Y. Yu, et al., “Miniaturized Bandpass Filter Based on Capacitor-Loaded Half-Mode Substrate Integrated Waveguide (HMSIW) and Open-Circuit Stubs,” 2018 International Conference on Microwave and Millimeter Wave Technology (ICMMT), Chengdu, 2018, pp. 1-3, doi: 10.1109/ICMMT.2018.8563330.

[6] N. Layal et al., “Design of Half Mode Substrate Integrated Waveguide (HMSIW) filter with series Defective Microstrip Structure (DMS) for Ku band operation,” 2017 1st International Conference on Electronics, Materials Engineering and Nano-Technology (IEMENTech), Kolkata, 2017, pp. 1-4, doi: 10.1109/IEMENTech.2017.8076922.

[7] W. J. et al, “Compact dual-mode dual-band HMSIW bandpass filters using source–load coupling with multiple transmission zeros,” in Electronics Letters, vol. 55, no. 4, pp. 210-222, 21 2 2019, doi: 10.1049/el.2018.7694.

[8] M. Li, Q. Ji., C. Chen, W. Chen and H. Zhang, "A Triple-Mode Bandpass Filter With Controllable Bandwidth Using QMSIW Cavity," in IEEE Microwave and Wireless Components Letters, vol. 28, no. 8, pp. 654-656, Aug. 2018, doi: 10.1109/LMWC.2018.2842678.

[9] Z. Xiangjun, et al. "Minimization of wideband LTCC bandpass filter using QMSIW and EMSIW cavities," 2015 IEEE MTT-S International Microwave Workshop Series on Advanced Materials and Processes for RF and THz Applications (IMWS-AMP), Suzhou, 2015, pp. 1-2, doi: 10.1109/IMWS-AMP.2015.7325056.

[10] P. Li, et al., “Design of compact bandpass filter based on ESMIW cavities,” 2017 International Applied Computational electromagnetics Society Symposium (ACES), Suzhou, 2017, pp. 1-2.

[11] Xian-long Yang et al., “ Q/V Dual-Band Filter with Perturbation in Single Substrate Integrated Waveguide Circular Cavity,” 2021 IEEE MTT-S International Wireless Symposium (IWS), Nanjing, 2021, doi:10.1109/IWS52775.2021.9490625.

[12] Taijun Liu, “Isosceles Triangular Cavity Based Dual-Band SIW Filters for 5G Millimeter-wave Systems,” 2021 International Conference on Microwave and Millimeter Wave Technology (ICMMT), Nanjing, 2021, doi:10.1109/ICMMT52847.2021.9618443

[13] H.-W. Xie, et al., “Substrate-integrated waveguide triple-band bandpass filters using triple-mode cavities,” IEEE Trans. Microw. Theory Techn., vol. 66, no. 6, pp. 2967–2977, Jun. 2018.

[14] X. Guo, et al., “Design method for multiband filters with compact configuration in substrate integrated waveguide,” IEEE Trans. Microw. Theory Techn., vol. 66, no. 6, pp. 3011–3018, Jun. 2018.

[15] Kang Zhou, et al., “Synthesis Design of SIW Multiband Bandpass Filters Based on Dual-Mode Resonances and Split-Type Dual- and Triple-Band Responses,” IEEE Trans. Microw. Theory Techn., vol. 67, NO.1, January 2019

[16] W.-L. Tsai, T.-M. Shen, B.-J. Chen, J.-Y. Huang, and R.-B. Wu, “Triband filter design using laminated waveguide cavity in LTCC,” IEEE Trans. Compon., Packag., Manuf. Technol., vol. 4, no. 6, pp. 957–966, Jun. 2014.

[17] Deepthi Gupta, et al., “CSRR Based Low Pass Microstrip Filter Using Stepped Impedance,” 2014 International Conference on Medical Imaging, m-Health and Emerging Communication Systems (MedCom) Greater Noida, India . doi: 10.1109/MedCom.2014.7005571

[18] S. Moitra, et al., “Circular Complementary Split Ring Resonators (CSRR) based SIW BPF,” 2019 Second International Conference on Advanced Computational and Communication Paradigms (ICACCP),Gangtok, India, 2019, pp. 25-28, doi: 10.1109/ICACCP.2019.8885003

[19] Xiaobang Ji, et al., “A quasi-elliptic response triple-mode SIW bandpass filter with controllable transmission zeros,” IEICE Electronics Express, Vol.16, No.19, 1–4 doi:https://doi.org/10.1587/ex.16.20190541

[20] Runlian Qin, et al., “Dual-band filter with high out-of-band rejection using ACSR-SIW technology,” IEICE Electronics Express, Vol.17, No.12, 1–6, doi:https://doi.org/10.1587/ex.17.20190743

[21] Hailu Jin, et al., “Slow-wave substrate integrated waveguide with rotary tensor unit cells for filters application,” IEICE Electronics Express, Vol.18, No.20, 1–6, doi: 10.1109/ex.2018.20210334

[22] Ji Ding, et al., “Compact in-line triplet SIW bandpass filter using etched GCPW line resonator,” IEICE Electronics Express, Vol.13, No.4, 1–8, doi:https://doi.org/10.1587/ex.13.20151120.

[23] Yao Yi, et al,” A Bandpass Filter With Switchable Frequency and Bandwidth on Substrate Integrated Waveguide,” ICMNT, Nanjing, China. doi: 10.1109/CM21547.2021.9618405.

[24] Xian-Long Yang, et al. "Dual-Band Substrate Integrated Waveguide Filters With Perturbed Circular Cavity," IEEE Microwave and Wireless Components Letters, doi: 10.1109/LMWC.2021.3125098.

[25] Baichuan Chen, et al., "A W-band Compact Substrate Integrated Waveguide Bandpass Filter With Defected Ground Structure CMOS Technology," IEEE Transactions on Circuits and Systems II: Express Briefs , doi: 10.1109/TCSII.2021.3123655

[26] Yan Zheng, et al., "Dual-Band, Dual-Mode, Microstrip Resonator Loaded, Compact Hybrid SIW Bandpass Filter," 2021 IEEE MTT-S International Microwave Symposium (IMS), Atlanta, GA, USA, 2021, doi: 10.1109/IMS19712.2021.9574892.

[27] B. C. Pan, P. Yu, Z. Liao, F. Zhu and G. Q. Luo, "A Compact Filtering Power Divider Based on Spoo Surface Plasmon Polaritons and Substrate Integrated Waveguide,” in IEEE Microwave and Wireless Components Letters, doi: 10.1109/LMWC.2021.3161669.

[28] J. Qiang, F. Xu, L. Yang and J. Zhan, "Enhanced Performance of Multilayer Bandpass Filter Using Slow-Wave Empty Substrate-Integrated Waveguide (SW-ESIW),” in IEEE Microwave and Wireless Components Letters, vol. 31, no. 12, pp. 1279-1282, Dec. 2021, doi:10.1109/LMWC.2021.3110107.

[29] B. Jin, P. Zhang, J. Mu, M. Zhang and M. Li, "A Miniaturized Bandpass Filter Basing on HMSIW Loaded Dual-mode CSRR," 2021 IEEE MTT-S International Wireless Symposium (IWS), (2021), pp. 1-3, doi:10.1109/IWS52775.2021.9499651.

[30] K. F. Chen, X. Yang, L. Zhou and J. F.-M. Mao, "Miniaturized Half-Mode T-Septum SIW Bandpass Filter With an Ultrawide Stopband,” in IEEE Microwave and Wireless Components Letters, vol. 31, no. 7, pp. 853-856, July 2021, doi: 10.1109/LMWC.2021.3076456.

[31] J.-S. Hong and M. J. Lancaster, Microstrip Filters for RF/Microwave Applications. New York, NY, USA: Wiley, 2001, pp. 257–258.

[32] K. Zhou, C.-X. Zhou and W. Wu, "Resonance Characteristics of Substrate-Integrated Rectangular Cavity and Their Applications to Dual-Band and Wide-Stopband Bandpass Filters Design," in IEEE Transactions on Microwave Theory and Techniques, vol. 65, no. 5, pp. 1511-1524, May 2017, doi: 10.1109/TMTT.2016.2645156.