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Microwave Linking the World

Dec. 8, Friday	10:10-11:50
FR-A2 (Room 201A)	**Control Circuits (Mixer, Oscillator, Switch, etc.) (II)** **Chairs:** Jia-Shiang Fu (National Central University, Taiwan), Da-Chiang Chang (Taiwan Semiconductor Research Institute, Taiwan)
	220152: A Synchronized 35 GHz Divide-by-5 TSPC Flip-Flop Clock Divider in 22 nm FDSOI Florian Probst, Andre Engelmann and Robert Weigel (Friedrich-Alexander-Universität Erlangen-Nürnberg, Germany) ***220202: A 25–50 GHz Inductor-Less Divide-by-4 with Microstrip Line Connection in 40 nm CMOS*** Sho Okii, Yohtaro Umeda and Kyoya Takano (Tokyo University of Science, Japan) Shinsuke Hara, Satoru Tanoi and Akifumi Kasamatsu (National Institute of Information and Communications Technology, Japan) ***220487: Low Phase Noise DDS-Driven PLL Frequency Synthesizer for Joint Communication and Sensing Applications*** Zhiqiang Liu (Purple Mountain Laboratories, China) Haiyang Xia and Lianming Li (Southeast University & Purple Mountain Laboratories, China) Lin Lu and Xuan Wang (Southeast University, China) Chenhui Xia (The 58th Research Institute of China Electronics Technology Group, China) ***220534: A 27-39 GHz Fractional-N PLL For 5G mm-Wave Communication With Improved Extended Range Multi-Modulus Divider*** Kai Sun, Lin Lu, Shutao Ye and Xiangning Fan (Southeast University, China) Junliang Wang (Nanjing University of Science and Technology, China) Lianming Li (Southeast University, Purple Mountain Laboratory National Mobile Communications Research Laboratory, China)
FR-B2 (Room 201B)	**Filters and Resonators** **Chairs:** Kamran Ghorbani (RMIT University, Australia), Cristiano Tomassoni (University of Perugia, Italy)
	220444: UHF Bandpass Filter Using a Combination of Semi-Lumped and Lumped Components Amir Ebrahimi and Kamran Ghorbani (RMIT University, Australia) ***220280: Compact 3-D Printed Rectangular Waveguide Diplexer With Wide Stopband Response*** Abdul Rehman and Cristiano Tomassoni (University of Perugia, Italy) ***220097: Ultra-Compact Substrate Integrated Waveguide Bandpass Filter with Unequal Termination Impedance*** Phanam Pech, Samdy Saron, Girdhari Chaudhary and Yongchae Jeong (Jeonbuk National University, Korea) ***220141: Quasi-Elliptic Bandpass Filter With Controllable Multiple Transmission Zeros Using Coupled Lines*** Girdhari Chaudhary, Phanam Pech, Samdy Saron and Yongchae Jeong (Jeonbuk National University, Korea) ***220214**: **A Compact W-band Diplexer for Integration with an Electronically Steerable Focal Plane Array Antenna System*** Sohaib Yaqoob Chaudhry, Viktor Chernikov, Artem Vilenskiy and Marianna Ivashina(Chalmers University of Technology, Sweden), Sam Agneessens and Lars Manholm(Ericsson Research,

Ultra-Compact Substrate Integrated Waveguide Bandpass Filter with Unequal Termination Impedance

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***Abstract*—This paper demonstrates the design of an ultra-compact substrate integrated waveguide (SIW) bandpass filter (BPF) with unequal termination impedances (UTI). The proposed SIW BPF is designed with quarter-mode (QM) and one-eighth-mode (OEM) SIW cavities. To validate the proposed method, a fourth-order SIW BPF with a center frequency of 5.5 GHz and UTI of 25 Ω-to-50 Ω is designed. The first and last resonators utilize OEM SIW cavities, while the second and third resonators utilize QM SIW cavities. By employing QM and OEM SIW cavities, the overall size of the proposed UTI SIW BPF is only 26.8 × 22.5 mm².**

Keywords*—Bandpass filter, one-eight-mode, quarter-mode, substrate integrated waveguide, unequal termination impedance.

I. Introduction

Bandpass filter (BPF) is a key component in wireless communication systems. In the transmitting systems, BPFs are used to minimized unwanted harmonic signal generated by amplifiers and other active devices. In the receiving systems, the BPFs are used to suppress unwanted signal and secure high quality of the desire signal. Various BPFs with different structures and realization methods were presented in literatures. The designs of BPF based on parallel couple lines with equal termination impedances of 50 Ω to 50 Ω are described in [1]–[5]. However, there are increasing demands for unequal termination impedance (UTI) BPFs. Various types of UTI BPF have been proposed in [6]–[8]. The analytical design methods are well described in the aforementioned works. However, these UTI BPFs are designed by using coupled lines, which may be difficult to implement when the center frequency (f_0) is located in higher frequency bands.

Substrate integrated waveguide (SIW) BPFs have attracted much attentions due to their merits, such as high power handling capability, high *Q*-factor, low cost, low loss, and easy fabrication in [9]–[10]. Recently, a SIW BPF with UTI of 20 Ω-to-50 Ω is presented in [11]. Similarly, the SIW BPF matching networks are presented in [12]–[14]. These SIW BPF matching networks can be designed with arbitrary real-to-real or real-to-complex UTIs. However, they have been realized using full-mode (FM) SIW cavities, which are occupied a large area on the circuit board, especially in microwave frequency range.

To reduce the size of FM SIW BPF, investigations have conducted on different mode SIW cavities such as half- mode (HM), quarter-mode (QM), and one-eight-mode (OEM). A

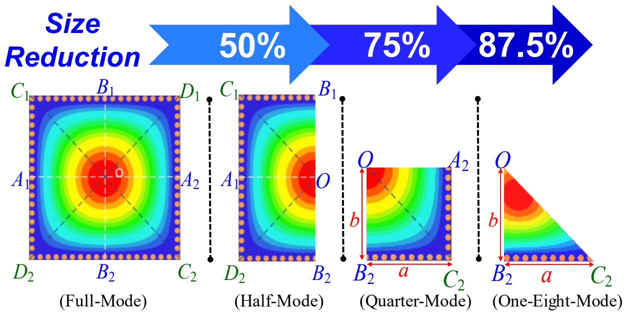

Fig. 1. Different SIW cavity types.

SIW BPF utilizing HM SIW cavities is presented in [15], where each resonator is formed by a section of HM SIW cavity between two transverse slots. Furthermore, a BPF demonstration using QM SIW cavities is presented in [16]. The BPF is composed of cascading QM SIW cavities, which are magnetically coupled with neighboring sections. In addition, a multi-layer OEM SIW BPF is investigated in [17], composed of four OEM SIW cavities with three metal layers. Moreover, the mixed-mode SIW BPF based on QM and OEM SIW cavities have been proposed for the first time in [18], presenting second- and third-order mixed-mode SIW BPFs. The circuit size can be reduced by using different mode SIW cavities, however those of them are designed with equal termination impedances of 50 Ω-to-50 Ω.

In this paper, an ultra-compact SIW BPF based on QM and OEM SIW cavities with UTI is proposed. The proposed SIW BPF is implemented on a single substrate printed circuit board (PCB). By using QM and OEM SIW cavities, the circuit size of proposed BPF is estimated to be much smaller than that of BPF realized using FM SIW cavities.

II. Design of Ultra-Compact SIW BPF with UTI

Fig. 1 shows different types of SIW cavity. The size of a HM SIW cavity is approximately 50% size of a FM SIW cavity, as it is obtained by bisecting a FM SIW cavity along its center plane. A QM SIW cavity is produced by bisecting a FM SIW cavity twice along the equivalent magnetic walls, resulting in a size reduction of around 75%. Similarly, an OEM SIW cavity is obtained by cutting the magnetic walls of a FM SIW cavity four times, resulting in a size reduction of approximately 87.5%. These SIW cavities can support the same resonant frequency of the fundamental mode. A QM

SIW cavity has two metallic walls and two open sides. Therefore, it can be located at the first, intermediate, or last stages of the BPF. Similarly, OEM SIW cavity has the same edge lengths, a and b, as QM SIW. As the OEM SIW cavity has one metallic wall and two open sides, it should be placed at the first or last stages of the BPF. The resonant frequencies (f_r) of HM, QM, and OEM SIW cavities can be estimated using the following equations [19].

$$f_r = \frac{c}{2\pi\sqrt{\mu_r \varepsilon_r}}\left[\sqrt{\left(\frac{\pi}{a_{eff}}\right)^2 + \left(\frac{\pi}{b_{eff}}\right)^2}\right], \tag{1}$$

$$a = a_{eff} + \frac{d^2}{0.95p} - \Delta w, \tag{2a}$$

$$b = b_{eff} + \frac{d^2}{0.95p} - \Delta w, \tag{2b}$$

$$\Delta w = h\begin{bmatrix} \left(0.05 + \dfrac{0.3}{\varepsilon_r}\right) \\ \times \ln\left(0.79\dfrac{a_{eff}}{h^3} + \dfrac{104(a_{eff}/2) - 261}{h^2} + \dfrac{38}{h} + 2.77\right) \end{bmatrix}, \tag{2c}$$

where c is the velocity of light in a vacuum, μ_r and ε_r are the relative permeability and permittivity of the substrate, respectively, a_{eff} and b_{eff} are the edge lengths of the equivalent resonant cavity, h represents the thickness of the substrate, d is the diameter of the metalized via, p is the pitch between adjacent via holes. Δw is the additional width that accounts for the effect of the fringing fields on the equivalent magnetic walls. f_r presented in (1) can be considered as f_0 of the UTI BPF.

Although the design of UTI BPF in this work primarily focuses on different mode SIW cavities, the design procedure remains the same as that of a general BPF. Fig. 2 shows the equivalent circuit of a typical BPF with J-inverters. The J-inverters of the coupled resonator can be defined using (3) [11].

$$J_{01} = \sqrt{\frac{\text{FBW}\, b_1}{R_S g_0 g_1}}, \quad J_{i,i+1} = \text{FBW}\sqrt{\frac{b_i b_{i+1}}{g_i g_{i+1}}},$$
$$J_{n,n+1} = \sqrt{\frac{\text{FBW}\, b_n}{R_L g_n g_{n+1}}}, \quad (i = 1, 2, 3, \ldots, n) \tag{3}$$

where R_S and R_L are the source and load resistances, respectively. FBW stands for the fractional bandwidth, while b_i represents the slope parameter. It is important to note that the first and last J-inverters are affected by R_S and R_L, respectively. The external quality factors ($Q_{eS,eL}$) and the coupling coefficient ($K_{i,i+1}$) of the resonators can be defined as the following.

$$Q_{eS} = \frac{b_1}{R_S J_{01}^2}, \quad Q_{eL} = \frac{b_n}{R_L J_{n,n+1}^2}, \quad K_{i,i+1} = \frac{J_{i,i+1}}{\sqrt{b_i b_{i+1}}} \tag{4}$$

Typically, the SIW BPF is designed by using magnetic coupling with via-hole windows. The $Q_{eS,eL}$ of SIW resonators can be extracted from electromagnetic (EM) simulation as (5).

$$Q_{eS,eL\_EM} = \frac{f_r}{\Delta f_{\pm 3dB}}, \tag{5}$$

where $\Delta f_{\pm 3\text{dB}}$ is a 3-dB BW. On the other hand, $K_{i,i+1}$ between the intermediate resonators can be determined using (6).

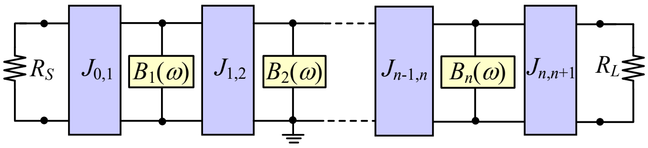

Fig. 2. Equivalent circuit of generalized BPF with J-inverters.

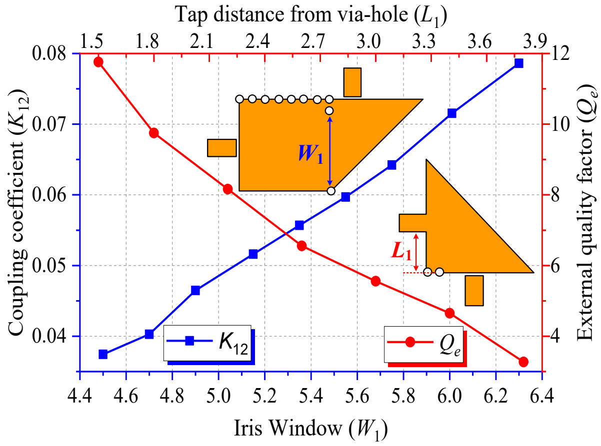

Fig. 3. Extracted $Q_{eS,eL}$ and $K_{i,i+1}$ of QM and OEM SIW cavities from EM simulation.

$$K_{i,i+1} = \pm\frac{f_{p_2}^2 - f_{p_1}^2}{f_{p_2}^2 + f_{p_1}^2}, \tag{6}$$

where f_{p1} and f_{p2} are the two split resonant frequencies.

III. Simulation and Measurement Result

In this work, a fourth-order SIW BPF with UTI of 25 Ω-to-50 Ω is designed and fabricated. The first and the last resonators are implemented using OEM SIW cavities, while the intermediate resonators are implemented using QM SIW cavities. The proposed UTI SIW BPF is designed with f_0 = 5.5 GHz, FBW = 15 %, and $|S_{11}|$ = 20 dB. Using (4), Q_{eS} = 6.3513, Q_{eL} = 6.3516, K_{12} = 0.1349, K_{23} = 0.1041, and K_{34} = 0.1345 are calculated.

A Taconic TLY PCB with ε_r = 2.2 and h = 0.508 mm was used in this design. Finally, the edge lengths of the QM and OEM SIW cavities could be estimated using (1) and (2). Fig. 3 presents the $Q_{eS,eL}$ and $K_{i,i+1}$ values for different mode SIW cavities by using EM simulation. $Q_{eS,eL}$ can be controlled by adjusting the tap position from the short circuit of the via-hole. As the tap distance from the via-hole (L_1) increases, the $Q_{eS,eL}$ value of the OEM SIW cavity is decreased. The extracted $K_{i,i+1}$ values of QM/OEM SIW cavities is increased with the widening of iris windows (W_1). The BW of the SIW BPF can be controlled by adjusting W_1.

As depicted in Fig.4, the circuit size of the proposed fourth-order UTI SIW BPF is approximately equal to that of a conventional FM SIW cavity. This means that the circuit size of the proposed UTI SIW BPF is approximately three times smaller than that of a conventional fourth-order BPF realized using FM SIW cavity. The overall circuit size of the proposed UTI SIW BPF is 26.8 × 22.5 mm^2.

The measurement results are consistent with those obtained by EM simulation. Fig. 5(a) shows the matching impedance point of the proposed UTI SIW BPF on a Smith chart. The measured source impedance is well matched to the target value. Similarly, the S-parameters within the frequency range of 1 to 18 GHz are presented in Fig. 5(b). The 3-dB BW of 840 MHz was measured from 5.16 to 6 GHz.

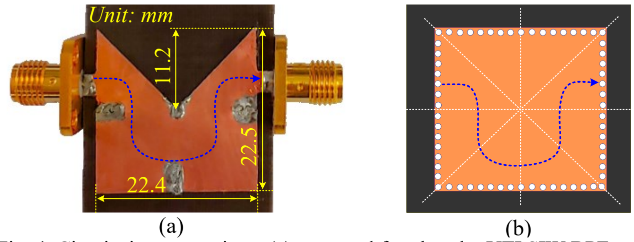

Fig. 4. Circuit size comparison: (a) proposed fourth order UTI SIW BPF and (b) a conventional FM SIW cavity.

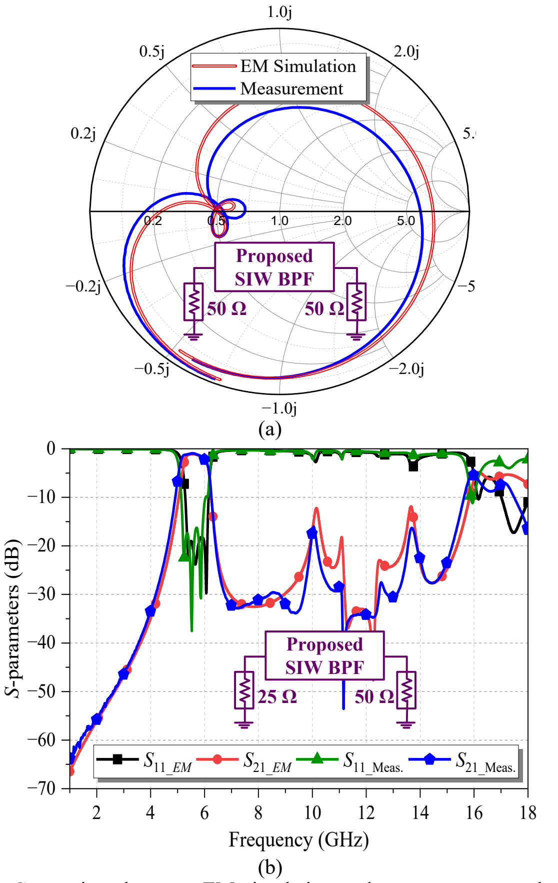

Fig. 5. Comparison between EM simulation and measurement results: (a) matching impedance point and (b) *S*-parameter responses.

The measured $|S_{11}|$ is –25.4 dB and $|S_{21}|$ is –0.98 dB at f_0. The stopband attenuation is better than 30 dB at the lower side measured from 1 to 4.2 GHz. Similarly, the attenuation level better than 30 dB was measured from 6.7 to 9.7 GHz at the higher stopband.

IV. Conclussion

This paper demonstrates the design of an UTI SIW BPF based on QM and OEM SIW cavities. By utilizing different-modes of the SIW cavity, the size of the proposed circuit is significantly compact. Since the proposed UTI SIW BPF is implemented on a single-layer PCB, it is easy to fabricate. Due to the requirement of a small PCB footprint for fabricating this UTI SIW BPF, it can be considered a cost-effective solution. The proposed method is applicable to the design of RF/microwave circuits and systems.

Acknowledgment

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References

[1] J. S. Park, J. S. Yun, and D. Ahn, “A design of the novel coupled-line bandpass filter using defected ground structure with wide stopband performance,” *IEEE Trans. Microw. Theory Tech.*, vol. 50, no. 9, pp. 2037–2043, Sep. 2002.

[2] P. Cheong, S. W. Fok, and K. W. Tam, “Miniaturized parallel couple-line bandpass filter with spurious-response suppression,” *IEEE Trans. Microw. Theory Tech.*, vol. 53, no. 5, pp. 1810–1816, May 2005.

[3] K. S. Chin, Y. C. Chiou, and J. T. Kuo, “New synthesis of parallel-couple line bandpass filter with chebyshev responses,” *IEEE Trans. Microw. Theory Tech.*, vol. 56, no. 7, pp. 1516–1523, Jul. 2008.

[4] S. Zhang and L. Zhu, “Synthesis method for even-order symmetrical Chebyshev banpass filter with alternative *J*/*K* inverters and *λ*/4 resonatoes,” *IEEE Trans. Microw. Theory Tech.*, vol. 61, no. 2, pp. 808–816, Feb. 2013.

[5] Y. Wu, L. Cui, W. Zhang, L. Jiao, Z. Zhuang, and Y. Liu, “High performance single-ended wideband and balanced bandpass filters loaded with stepped-impedance stubs,” *IEEE Access*, vol. 5, pp. 5972–5981, May 2017.

[6] P. Kim, G. Chaudhary, and Y. Jeong, “Wideband impedance transformer with out-of-band suppression characteristics,” *Microw. Opt. Techno. Lett.*, vol. 56, no. 11, pp. 2612–2616, Nov. 2014.

[7] P. Kim, G. Chaudhary, and Y. Jeong, “Enhancement impedance transorming ratios of coupled line impedance transformer with wide out-of-band suppression characteristics,” *Microw. Opt. Techno. Lett.*, vol. 57, no. 7, pp. 1600–1603, Jul. 2015.

[8] P. Kim and Y. Jeong, “A new synthesis and design approach of a complex termination impedance bandpass filter,” *IEEE Trans. Microw. Theory Tech.*, vol. 67, no. 6, pp. 2346–2354, Jun. 2019.

[9] C. J. You, Z. N. Chen, X. W. Zhu, and K. Gong, “Single-layered SIW post-loaded electric coupling-enhanced structure and its filter application,” *IEEE Trans. Microw. Theory Tech*., vol. 61, no. 1, pp. 125−130, Jan. 2013.

[10] Z. C. Hao, W. Q. Ding, and W. Hong, “Developing low-cost W-band SIW bandpass filters using the commercially available printed-circuit-board technology,” *IEEE Trans. Microw. Theory Tech*., vol. 64, no. 6, pp. 1775−1786, Jun. 2016.

[11] J. Jeong, P. Kim, P. Pech, Y. Jeong, and S. Lee, “Substrate integrated waveguide impedance matching network with bandpass filtering,” *Proc. of IEEE Radio Wireless Symp. (RWS)*, pp. 1–3, 2019.

[12] P. Pech, P. Kim, and Y. Jeong, “Microwave amplifier with substrate integrated waveguide bandpass filter matching network,” *IEEE Microw. Wireless. Compon. Lett.*, vol. 11, no. 4, pp. 401–404, Apr. 2021.

[13] P. Pech, S. Saron, G. Chaudhary, and Y. Jeong, “X-band filter-amplifier for radio frequency front-end receiver system,” *Proc. of Asia-Pacific Microw. Conf. (APMC)*, pp. 698–700, 2022.

[14] P. Pech, P. Kim, G. Chaudhary, and Y. Jeong, “Substrate integrated waveguide quasi-elliptic filter with arbitrary termination impedances,” *J. Electromagn. Eng. Sci.*, vol. 22, no. 4, pp. 472–478, Jul. 2022.

[15] Y. Wang, W. Hong, Y. Dong, B. Liu, H. J. Tang, J. Chen, X. Yin, and K. Wu, “Half mode substrate integrated waveguide (HMSIW) bandpass filter,” *IEEE Microw. Wirel. Compon. Lett.*, vol. 17, no. 4, pp. 265−267, Apr. 2007.

[16] S. Moscato, C. Tomassoni, M. Bozzi , and L. Perregirini, “Quarter-mode cavity filters in substrate integrated waveguide technology,” *IEEE Trans. Microw. Theory Techn.*, vol. 64, no. 8, pp. 2538−2547, Aug. 2016.

[17] Y. Zhu, “Design of a novel multi-layered eighth-mode substrate integrated waveguide filter by HFSS,” *IEEE 6th Int. Symp. Microw. Antenna Propag. EMC Techno.l (MAPE)*, pp. 620−622, 2015.

[18] P. Kim and Y. Jeong, “Compact and wide stopband substrate integratd waveguide bandpass filter using mixed quarter- and one-eight modesa cavities,” *IEEE Microw. Wirel. Compon. Lett.*, vol. 30, no. 1, pp. 16−19, Jan. 2020.

[19] Q. Lai, C. Fumeaux, W. Hong, and R. Vahldieck, “Characterization of the propagation properties of the half-mode substrate integrated waveguide,” *IEEE Trans. Microw. Theory Techn.*, vol. 57, no. 8, pp. 1996–2004, Aug. 2009.