Compact Folded Substrate Integrated Waveguide Filter With Non-Resonating Nodes for High-Selectivity Bandpass Applications

Mehdi Salehi, Jens Bornemann
Department of Electrical and Computer Engineering
University of Victoria
Victoria, BC, Canada

Esfandiar Mehrshahi
Department of Electrical and Computer Engineering
Shahid Behehti University, G.C.
Tehran, Iran

***Abstract*—A fifth-order pseudo elliptic substrate integrated waveguide (SIW) filter based on non-resonating nodes is presented for high-selectivity bandpass applications. Three singlets and two fundamental-mode resonators are properly cascaded in a folded, thus compact topology. After optimization of the coupling apertures, the filter produces three transmission zeros for improved selectivity. An SIW filter prototype with a center frequency of 11 GHz and 600 MHz bandwidth is designed using HFSS and fabricated on RT/Duroid 5870 substrate. The measured results are in very good agreement with simulations and show excellent out-of-band rejection performance.**

Keywords—Substrate integrated waveguide (SIW); transmission zero; bandpass filter; folded filter; non-resonating node; pseudo-elliptic filter; singlets

I. INTRODUCTION

Rapid development of modern wireless communication systems has resulted in an increasing demand and interest for elliptic and quasi-elliptic filters with compact size, sharp selectivity, low insertion loss, high integration capability, and easy manufacturability. In order to improve out-of-band rejection, filters with prescribed transmission zeros are widely used.

Substrate integrated waveguide (SIW) has been proposed as a new planar structure that combines high-Q-factor and low-insertion-loss merits of traditional rectangular waveguides with simplicity of planar fabrication and low-cost integration of microstrip technology [1] - [3].

A variety of elliptic and quasi-elliptic SIW bandpass filters can be implemented by introducing transmission zeros which are generated by general cross coupling, multi-mode cavity resonators, transmission line inserted inverters, or extracted pole techniques, e.g. [4] - [9]. The use of non-resonating nodes is an efficient technique to reduce the number of cross couplings while maintaining transmission zeros. The basic building block for the modular design of these filters is the singlet, which contains one resonator and generates one transmission zero by bypass coupling. It has been introduced in E-plane waveguide circuitry [10] but is more appropriately suited in H-plane technology [11] for implementation in SIW filters.

This work was funded by the Natural Science and Engineering Research Council of Canada and the TELUS Grant in Wireless Communications.

This paper focuses on the implementation of a pseudo elliptic SIW bandpass filter by properly cascading singlets and fundamental resonators [12]. Two TE_{201} singlets and one TE_{102} singlet are used to create transmission zeros on either side of and close to the passband, thus resulting in a highly selective bandpass filter. Moreover, two fundamental-mode resonators are employed, mostly to cancel the fundamental-mode resonances of the singlets (TE_{101}, below 11 GHz) to improve the low frequency response of the filter. In this design, three independent transmission zeros are produced close to the passband of the filter by changing the position of the iris windows. The topology is folded, and the resonator arrangement is inline such that each resonator is only connected to its left and right neighbor without the need for additional inter-cavity cross coupling.

The main advantages of the proposed structure are, first, that the frequency of the resonators and position of the transmission zeros can be independently tuned and secondly, that the filter is compact due to its folded configuration such that input and output ports are accessible at a common interface. HFSS and CST simulation data are compared with experimental results and are found in good agreement.

II. DESIGN

This section describes the basis singlet topology and the design of the fifth-order SIW filter.

A. Singlet Topology

A singlet is a structure that not only acts as a resonator but also generates one transmission zero by bypassing the resonator. In an oversized H-plane SIW cavity, the resonance employed can be created by a TE_{201} or TE_{102} mode [11], [12]. Therefore, at the operating frequency, the TE_{10} mode can be exploited as a non-resonating mode that bypasses the resonator and creates a transmission zero. The position of the input and output couplings in a cavity are the main design parameters to control the transmission zero and its position with respect to the passband. If the relative position of the couplings with respect to the cavity center is offset in the same direction, the magnetic field components of the TE_{10} mode at the input and output of the cavity are out of phase and, therefore, generate a lower stopband transmission zero. In contrast, if they are offset in opposite direction, the H-field components are in phase and, therefore, generate an upper stopband transmission zero [11].

B. *Design of a Fifth-Order SIW Filter*

By extending the model of the singlet, we design a fifth-order SIW filter with three transmission zeros. The singlet structure can be used as a basic building block to design flexible higher-order inline pseudo elliptic filters in H-plane technology with the passband centered on the TE_{201}- or TE_{102}-mode resonances. The coupling scheme of the proposed structure is shown in Fig. 1 with the resonances of individual SIW cavities indicated. Note that in this folded topology, both input (S) and output (L) ports are supposed to be accessible at a common interface.

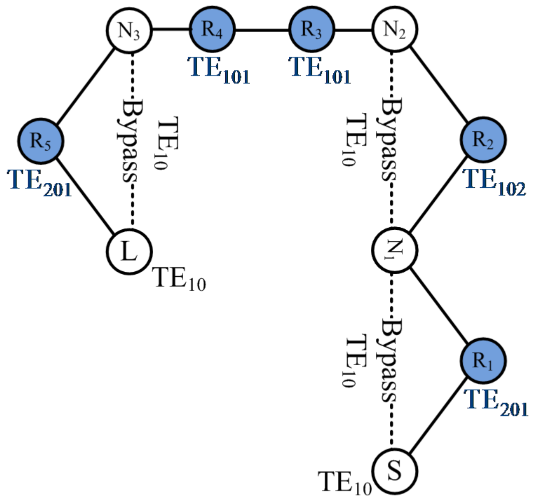

Fig. 1. Coupling scheme of the fifth-order pseudo-elliptic SIW filter and resonances of SIW cavities.

The inline topology allows for a modular design in which each transmission zero is generated and controlled by a dedicated cavity. The filter is composed of two fundamental resonators and three singlets that resonate at the center frequency. Two of the singlets (resonators 1 and 5) resonate in the TE_{201} mode and the other one (resonator 2) resonates in the TE_{102} mode. Bypass coupling of the TE_{201} and TE_{102} modes with the TE_{10} mode produces three transmission zeros, one on the left and two on the right side of the passband. To improve the spurious response in the lower stop-band, which is affected by the fundamental TE_{101} resonances of the singlets, two fundamental-mode resonators are used in the middle of the structure.

The design begins with the coupling matrix design of the individual singlets, starting with single resonator Chebyshev cavities and then introducing detuning and bypass couplings by optimizing the respective entries of the individual coupling matrices of the singlets. The filter is designed for a center frequency of 11 GHz with 5.5 percent fractional bandwidth (600 MHz), 20 dB return loss and three transmission zeros, one below (10.60 GHz) and two above the passband (11.50 GHz and 11.75 GHz). Let singlet #1 be the one between source S and non-resonating node N_1, c.f. Fig. 1, and let it create the transmission zero at 11.50 GHz, then its normalized coupling matrix is given by

$$M_1 = \begin{bmatrix} 0.0000 & 0.6595 & 0.3502 \\ 0.6595 & -0.4019 & 0.6595 \\ 0.3502 & 0.6595 & 0.0000 \end{bmatrix} \tag{1}$$

Similarly, the coupling matrix of singlet #2 between N_1 and N_2, which creates the transmission zero at 11.75 GHz, is

$$M_2 = \begin{bmatrix} 0.0000 & 0.7340 & 0.2585 \\ 0.7340 & -0.3530 & 0.7340 \\ 0.2585 & 0.7340 & 0.0000 \end{bmatrix} \tag{2}$$

Singlet #3 between N_3 and load L creates the transmission zero at 10.6 GHz. Its coupling matrix is given by

$$M_3 = \begin{bmatrix} 0.0000 & 0.6443 & -0.4379 \\ 0.6443 & 0.3952 & 0.6443 \\ -0.4379 & 0.6443 & 0.0000 \end{bmatrix} \tag{3}$$

The coupling coefficients for the other two resonators (resonators R_3 and R_4 in Fig. 1) are taken from a general five-pole Chebyshev filter design, e.g. [13], and result in M_{34}= 0.6357.

The position of the transmission zeros at either side of the passband skirts can be determined by changing the position of the coupling iris between the cavities. The length and width of the resonators is fixed by the operating frequency. Then the width and length and position of coupling apertures to control the bandwidth and transmission zeros can be determined.

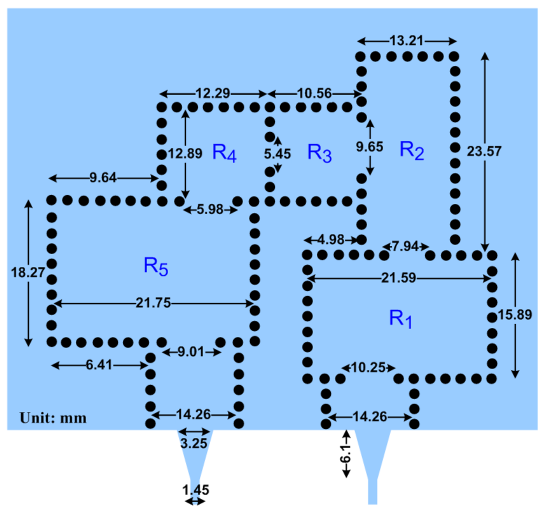

Fig. 2. Configuration and dimensional parameters of the fifth-order pseudo-elliptic SIW filter.

To speed up the process of optimization, the individual coupling matrices are first translated to all-dielectric rectangular waveguide technology. Then the entire circuit is optimized using the µWaveWizard which is based on an efficient and fast mode-matching technique. Once the filter performs to specifications, the rectangular waveguide walls and apertures, which were set to a thickness of d_{square}=0.85 mm in µWaveWizard, are replaced by circular via holes of periodic distance S=1.4 mm and circular vias of radius [14]

$$r_{circular} = d_{square} \Big/ \left(1 + \tfrac{1}{\sqrt{2}}\right) \tag{4}$$

which leads to via diameters of 1 mm.

The widths W_{eff} and lengths L_{eff} of the rectangular waveguide dimensions are transferred to equivalent SIW parameters by employing relationships in [15]. Finally, the filter is fine-tuned with HFSS and verified with CST.

Based on this approach, a fifth-order filter has been designed and simulated on 0.508 mm thickness RT/Duroid 5870 substrate with relative permittivity of 2.33, conductor thickness of 17.5 µm and loss tangent of 0.0012. The diameter of all via holes is 1 mm with center to center spacing of S=1.4 mm. Fig. 2 shows the layout of the filter and its dimensional parameters.

Finally, a linear SIW-to-microstrip taper is designed to transform the fundamental SIW mode to 50 Ω microstrip lines [16] for access with measurements equipment.

III. Measurements and Simulations

Fig. 3 shows a photograph of the fabricated prototype. For measurement purposes, the microstrip ports are equipped with coaxial connectors. Both the coax connectors and the microstrip-to-SIW transitions are deembedded from measurements using standard TRL calibration.

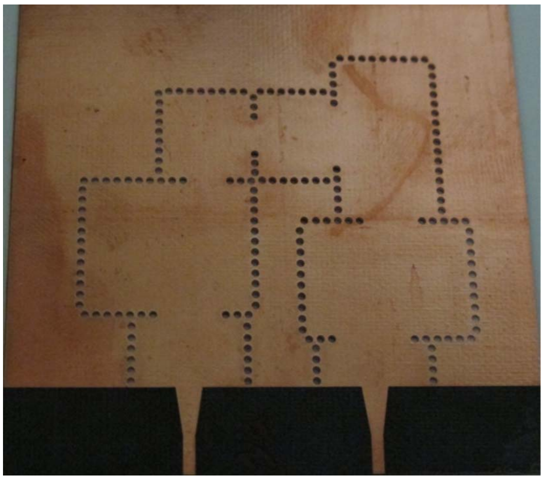

Fig. 3. Photograph of the folded fifth-order pseudo-elliptic SIW filter with non-resonating nodes.

Simulated (HFSS and CST) and measured frequency responses of the prototyped filter topology are compared in Fig. 4. The passband and the three transmission zeros are well reproduced in simulations as well as measurements. The slight difference between HFSS and CST are due to the fact that HFSS uses polygons to model the vias whereas CST models the vias as actual circles.

The measurements agree well with simulations (and better with HFSS than CST in the lower stopband) except for the slight downward shift in frequency. This shift is believed to be caused by the fact that the via holes have been drilled slightly smaller than 1 mm. Thus the cutoff frequencies of all SIW sections move slightly downwards in frequency and so does the filter response.

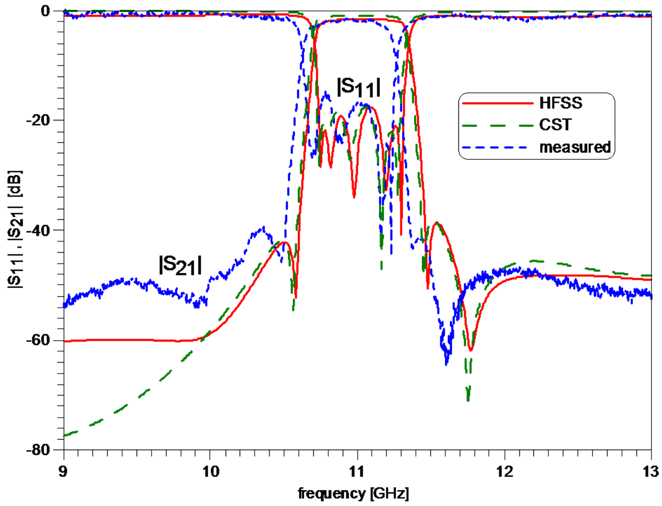

Fig. 4. Measured and simulated (comparison between HFSS and CST) performances of the fifth-order pseudo-elliptic SIW filter.

The measured insertion loss in the passband is about 2 dB, and the return loss is better than 16 dB. For comparison, the corresponding simulated values in HFSS are 1.5 dB and 17.5 dB, respectively. CST verifies the return loss as 17.5 dB but predicts a slightly lower insertion loss of 0.9 dB.

IV. Conclusions

The compact filter coupling scheme, which is new to SIW technology, presents a viable alternative for highly selective SIW bandpass filters. The folded topology of the filter allows input and output ports to be accessible at a common interface. By cascading three singlets and two fundamental-mode resonators, three transmission zeros at frequencies of 10.6 GHz, 11.5 GHz and 11.75 GHz are created to improve the selectivity of the 5.5 percent fractional bandwidth filter at 11 GHz center frequency. Simulation and measured results confirm the validity of the proposed configuration and design approach. Very good agreement between simulation and measurements is achieved, except for a slight frequency shift. Moreover, the filter has the capability of increasing the number of independently tuned transmission zeros by increasing the number of singlets. It is demonstrated that the filter topology is well suited for low-cost and sharp-skirt filters for microwave and possibly millimeter-wave planar integrated circuit operation.

Acknowledgment

The authors thank Dr. Smain Amari of Royal Military College of Canada, Kingston, ON, Canada and Mr. Uwe Rosenberg of Mician Global Engineering GbR, Bremen, Germany for providing dimensions of their waveguide filter presented in [12].

REFERENCES

[1] K.K. Samanta, D. Stephens, and I.D. Robertson, "Design and performance of a 60-GHz multi-chip module receiver employing substrate integrated waveguides," IET Microw. Antennas Propag., vol. 1, pp. 961-967, 2007.

[2] M. Bozzi, L. Perregrini, K. Wu, and P. Arcioni, "Current and future research trends in substrate integrated waveguide technology," Radioengineering, vol. 18, pp. 201-209, June 2009.

[3] M. Salehi and E. Mehrshahi, "Spurious-response suppression of substrate integrated waveguide filters using multishape resonators and slotted plane structures," Int. J. RF Microwave CAE, vol. 21, pp. 650-657, Nov. 2011.

[4] Z.C. Hao, W. Hong, X.P. Chen, J.X. Chen, K. Wu, and T.J. Cui, "Multilayered substrate integrated waveguide (MSIW) elliptic filter," IEEE Microwave Wireless Comp. Lett., vol. 15, pp. 95-97, Feb. 2005.

[5] X. Chen, W. Hong, T. Cui, Z. Hao, and K. Wu, "Symmetric dual-mode filter based on substrate integrated waveguide (SIW)," Electrical Engineeering (Springer), vol. 89, pp. 67-70, Oct. 2006.

[6] X.-P. Chen, K. Wu, and D. Drolet, "Substrate integrated waveguide filter with improved stopband performance for satellite ground terminal," IEEE Trans. Microwave Theory Tech., vol. 57, pp. 674-683, Mar. 2009.

[7] L. Wu, W. Shen, R. Qian, and X.W. Sun, "Design of substrate integrated waveguide (SIW) elliptic filter with novel coupling scheme," J. Electromagnetic Waves and Applications, vol. 26, pp. 827-835, Apr. 2012.

[8] X. Chen, W. Hong, T. Cui, Z. Hao, and K. Wu, "Substrate integrated waveguide elliptic filter with transmission line inserted inverter," Electronics Letters, vol. 41, pp. 851-852, July 2005.

[9] X. Chen, W. Hong, Z. Hao, and K. Wu, "Substrate integrated waveguide quasi-elliptic filter using extracted-pole technique," Proc. Asia-Pacific Microwave Conf., vol. 1, pp. 1-3, Suzhou, China, Dec. 2005.

[10] S. Amari, U. Rosenberg, and J. Bornemann, "Singlets, cascaded singlets and the non-resonating node model for advanced modular design of elliptic filters," IEEE Microwave Wireless Component Lett., vol. 14, pp. 237-239, May 2004.

[11] S. Bastioli, "Nonresonating mode waveguide filters," IEEE Microwave Mag., vol. 12, pp. 77-86, Oct. 2011.

[12] S. Amari and U. Rosenberg, "Characteristics of cross (bypass) coupling through higher/lower order modes and their applications in elliptic filter design," IEEE Trans. Microwave Theory Tech., vol. 53, pp. 3135-3141, Oct. 2005.

[13] I. C. Hunter, Theory and Design of Microwave Filters: London, U.K, IEE Press, 2001.

[14] Z. Kordiboroujeni, J. Bornemann, and T. Sieverding, "Mode-matching design of substrate-integrated waveguide couplers," Proc. Asia-Pacific Int. Symp. Electromagnetic Compatibility, pp. 701-704 Singapore, May 2012.

[15] M. Salehi and E. Mehrshahi, "A closed-form formula for dispersion characteristics of fundamental SIW mode," IEEE Microwave Wireless Comp. Lett., vol. 21, pp. 4-6, Jan. 2011.

[16] D. Deslandes, "Design equations for tapered microstrip-to-substrate integrated waveguide transitions," IEEE MTT-S Int. Microwave Symp. Dig., pp. 704-707, Anaheim, CA, May 2010.