URSI GASS 2020, Rome, Italy, 29 August - 5 September 2020

Air-Filled Substrate Integrated Waveguide (AFSIW) Filter with Asymmetric Frequency Response

T. Martin(1),(2),(3), A. Ghiotto(2), and T-P. Vuong(3)
(1) IMS, Univ. Bordeaux, Bordeaux INP, CNRS, F-33400, Talence, France
(2) Cobham Microwave, Cobham plc, F-33170, Gradignan, France
(3) IMEP-LAHC, Univ. Grenoble-Alpes, Grenoble INP, CNRS, F-38000, Grenoble, France

Abstract

A filter with asymmetric frequency response based on air-filled substrate integrated waveguide (AFSIW) is introduced. The proposed filter is low-loss, compact, and allows the introduction of a transmission zero in the upper-side. The transmission zero is implemented using the multilayer feature of the AFSIW technological platform as the secondary path of the signal is located in the bottom substrate of the structure, while the primary path is located in the inner substrate. Furthermore, the robustness of the structure against printed circuit board (PCB) standard processes highlights the high interest of the structure. For demonstration purposes, a third-order AFSIW filter with an asymmetric frequency response operating at 21 GHz with a fractional bandwidth of 1.53% is fabricated and measured. The measured results are in good accordance with the simulation results in and out band results. The fabricated prototype exhibits measured insertion loss of 0.66 dB with an unloaded *Q*-factor of 1429, which is excellent for a planar structure.

1 Introduction

The novel development of microwave and millimeter-wave applications, such as front-end radios, new space, or fifth generation of mobile (5G) imposes stringent specifications for future generations of filters. Among the incoming challenges related to future implementations in communication systems, the efficient use of the frequency spectrum is a crucial aspect of a filter [1]. Therefore, to minimize the unused guard bands between continuous channels and to increase compactness, advanced filtering functions are highly desired [2].

In order to increase the selectivity of a filter, a common technique is to introduce out-of-band transmission zeros, allowing a sharper skirt while maintaining the same compactness. Different filter topologies exist to achieve a sharper selectivity. Among the developed techniques to implement transmission zeros, there are dual or multimode resonators [3], extracted pole [4], and cross-coupling [5]. The cross-coupling technique remains the most popular due to the ease of implementation and high reliability.

For two decades, the Substrate Integrated Waveguide (SIW) technology [6] has demonstrated its potential to be a good alternative to conventional technologies thank to the paradigm of System on Substrate (SoS) [7]. Nevertheless, for high-performance applications where insertion losses are driving most of the systems requirements, the SIW technology does not fit. Recently, the authors have proposed an alternative high *Q*-factor SIW technology, namely Air-Filled Substrate Integrated Waveguide (AFSIW) to overcome the medium insertion loss performances of SIW technology for high-performance communication systems [8]. This technological platform has already focused on filter problematic such as temperature compensation [9], power-handling capability [10], self-heating [10]. The introduction of a quasi-elliptic function has also been addressed in [11].

To further develop the technology, a three-pole AFSIW filter with a 1-3 inductive cross-coupling based on multilayer couplings, as shown in Fig. 1, is presented. First, the phase mechanisms of the filter are studied to explain the introduction of a transmission zero. Then, the multilayer aspect of the AFSIW technological platform is favourably used to implement the cross-coupling in the bottom substrate of the structure, while maintaining the electromagnetic shield and compactness. The versatility of the structure is highlighted as it is possible to achieve a lower or an upper transmission zero with the same compactness. Then, the robustness of the structure is evaluated taking into account the substrate to substrate misalignment as well as the substrate dielectric permittivity uncertainty. Finally, a third-order AFSIW filter demonstrator using an overall inductive cross-coupling is implemented in the downlink Ka-band.

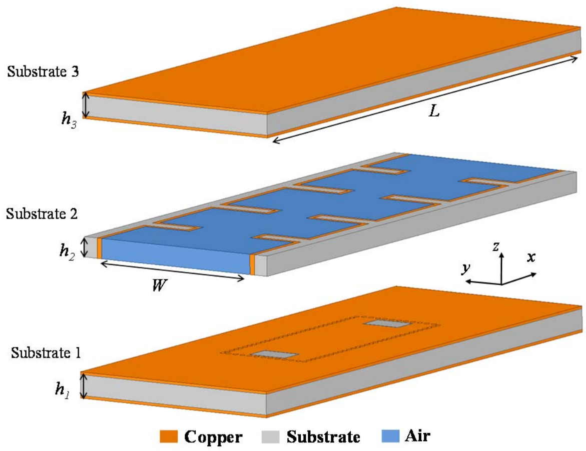


Figure 1. 3D view of the third-order in-line arrow with 1-3 cross-coupling AFSIW filter.

2 Filter Design

A suitable technique to couple non-adjacent resonators using AFSIW technology is to profitably use the multilayer aspect of the technology. Thus, another signal path is created using the bottom substrate of the structure, initially used as mechanical support, by etching the top ground of this layer. The signal is confined in the substrate using arrays of metallized via.

The proposed third-order in-line arrow filter configuration implementing a 1-3 cross-coupling diagram is shown in Fig. 2. The primary path, denoted path 1-2-3, implementing the resonators is located in substrate 2 to achieve a high *Q*-factor. The secondary path, denoted path 1-3, is implemented in substrate 1. By etching the top copper of the bottom substrate, an inductive iris is created, and the signal propagates along a SIW transmission line. To avoid signal leakage, arrays of metallized via are implemented in substrate 1.

Based on the coupling diagram, the phase relationships between the two different paths can be studied. It is commonly known that series inductors have a phase shift which tends towards -90°, and series capacitors have a phase shift which tends towards +90°. Moreover, a resonator has a phase shift approaching +90° below the resonance frequency and -90° above the resonance frequency. The proposed cross-coupling implementation introduces another phase shift due to the electrical length ϕ_{SIW} of the SIW transmission line.

By properly dimensioning the SIW transmission line, the two different paths can be out of phase below or above the resonance as it is shown in Table 1. This implies a signal cancellation causing the introduction of a transmission zero on the lower or upper skirt. It is worthy to note that based on the total phase shift presented in Table 1, the proposed structure is versatile as it is easy to control the additional electrical length ϕ_{SIW}. By controlling the dimensions of the SIW transmission line, the transmission zero can be introduced in the lower or upper skirt. For practical consideration, only the upper skirt case will be demonstrated in this paper.

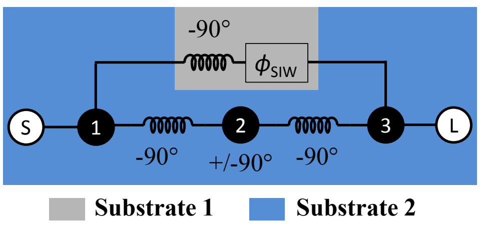


Figure 2. Coupling diagram, with source/load coupling, of the third-order AFSIW filter.

The proposed principle is implemented on a third-order AFSIW bandpass filter. The filter operates in the downlink Ka-band satellite communication frequency range (17.3 to 21.3 GHz). The proposed filter implements a 1-3 cross-coupling with an overall inductive nature, allowing the introduction of a transmission zero to the upper skirt in order to increase the selectivity of the structure. The filter, using AFSIW technology, has been designed to operate at 21 GHz with a -3 dB bandwidth of 300 MHz (i.e. a fractional bandwidth of 1.43%). First, the filter is designed without the 1-3 cross-coupling following conventional procedures described in [12]. Then, the cross-coupling is implemented with a weak coupling. The coupling is increased progressively, while maintaining the resonator frequencies in the band, to achieve the desired transmission zero.

Table. 1. Total phase shift of third-order 1-3 cross-coupled AFSIW filter for both paths using SIW transmission line

Total phase shift	Below resonance	Above resonance
Path 1-2-3	-90°+90°-90°= -90°	-90°-90°-90° = 270°
Path 1-3	$-90°+\phi_{SIW}$	$-90°+\phi_{SIW}$
Result with ϕ_{SIW} = 360°	In phase	Out of phase (creation of Tz)
Result with ϕ_{SIW} = 180°	Out of phase (creation of Tz)	In phase

The filter is based on multilayer PCB and consists of three Rogers RT/Duroid 6002 substrate with thicknesses $h_2 = 1.524$ mm and $h_1 = h_3 = 0.508$ mm. Fig. 3 represents a top view of substrate 1 and substrate 2. The different dimensions of the filter are given in Table 2.

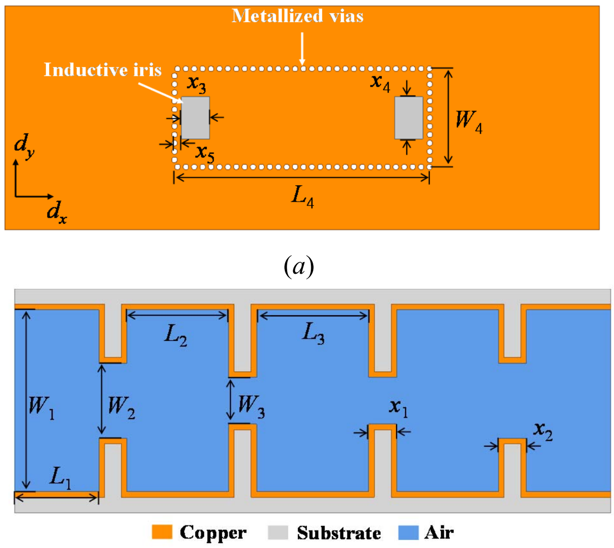


Figure 3. Top views of (*a*) substrate 1, implementing the secondary path with the 1-3 cross-coupling, and (*b*) substrate 2 implementing the primary path with the three resonators using high *Q*-factor propagation medium.

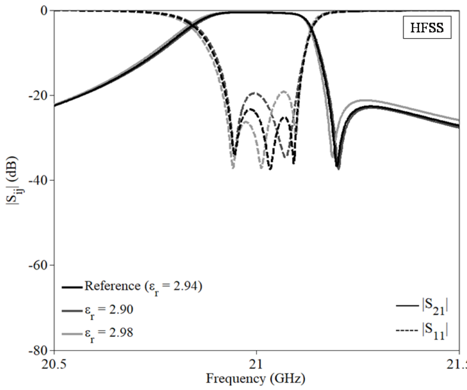
Table. 2. Dimensions of the designed 1-3 cross-coupled AFSIW filter

Dimension	$i = 1$	$i = 2$	$i = 3$	$i = 4$	$i = 5$
L_i (mm)	6	7.465	7.955	24.42	/
x_i (mm)	2	2	3.2	3	0.45
W_i (mm)	13	5.32	3.16	7	/

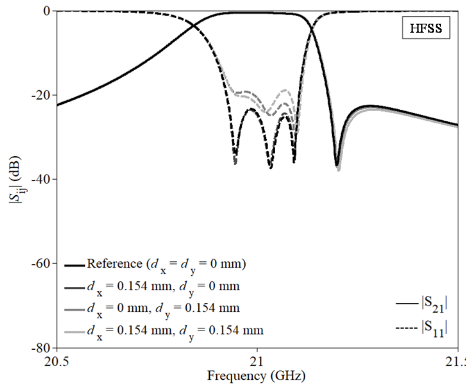
3 Robustness Against PCB Standards

As the filter is based on a multilayer PCB process, it is relevant to study the impact of a misalignment on the filter behavior. The chosen approach is to evaluate the impact of the worst case of misalignment on the filter response using a full-wave simulator. In the proposed filter configuration, only misalignment between substrate 1 and substrate 2 has an impact on the filter. With a given misalignment worst case of 0.152 mm in x and y directions, the filter behavior is studied, and the different cases are given in Fig. 4(*a*).

Additionally, the cross-coupling function is achieved using a SIW transmission line. This transmission line, based on a substrate, is subjected to the well-known substrate dielectric constant uncertainty. Thus, a study on the impact of this parameter on the filter response is also needed. The substrate dielectric constant uncertainty of Rogers RT/Duroid 6002 is +/- 0.04. Fig. 4(*b*) reports the S-parameters of the proposed filter with this given variation.



(*a*)



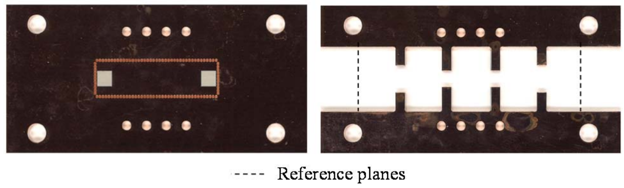
(*b*)

Figure 4. Robustness analysis against (*a*) dielectric constant variation using HFSS and (*b*) multilayer misalignment using HFSS.

From Fig. 4(*a*), the observed S-parameters of the structure show that the misalignment of substrate 1 and substrate 2 has a negligible impact on the filter behavior. Moreover, it can be observed in Fig. 4(*b*) that the substrate dielectric constant uncertainty has almost no impact on the frequency response.

4 Experimental Results

For experimental validation, a third-order with 1-3 cross-coupling AFSIW bandpass filter, using an in-line arrow configuration, has been designed and fabricated. The metallized via holes implemented in substrate 1 have a diameter d fixed to 0.8 mm and a distance between two consecutive center p of 1.2 mm. A photograph of the manufactured AFSIW filter is shown in Fig. 5.



(*a*) (*b*)

Figure 5. Photographs of (*a*) substrate 1 and (*b*) substrate 2 of the fabricated third-order with 1-3 cross-coupling AFSIW filter demonstrator. The dimensions of the fabricated filter are 61.8 x 31.15 x 2.54 mm^3.

To measure the filter demonstrator, a vector network analyzer, a test fixture [9] and a thru-reflect-line (TRL) calibration kit have been used. A comparison between simulated and measured S-parameters is shown in Fig. 6. The measured response is similar to its simulated counterpart with a 40 MHz (0.19%) frequency shift. The simulated and measured rejection frequency are in good accordance. The insertion losses are evaluated to 0.66 dB in-band, leading to an unloaded Q-factor equal to 1429. The different parameters of the demonstrator are given and compared to simulations in Table 3.

Table 4 presents a comparison with similar frequency responses to evaluate state of art. Compared to other structures, the proposed AFSIW filter benefits from a higher Q-factor, which makes it a suitable candidate for high performance applications.

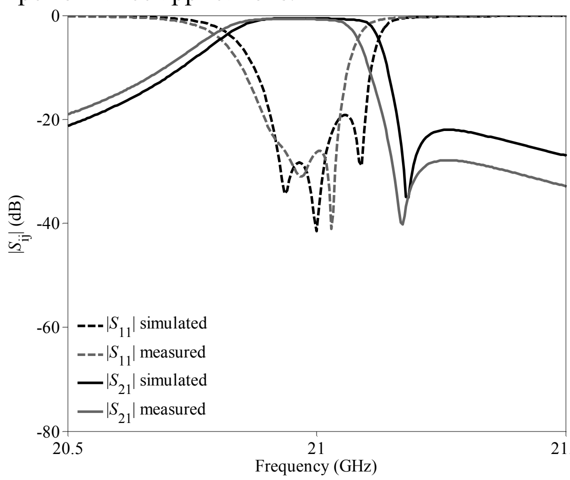


Figure 6. Simulated and measured S-parameters of the fabricated third-order 1-3 cross-coupled AFSIW filter demonstrator.

Table. 3. Comparison of simulated and measured results of third-order AFSIW cross-coupled filters.

Characteristics	Simulated (HFSS)	Measured
Return loss (dB)	> 22	> 22
Insertion loss (dB)	0.54	0.66
Center frequency (GHz)	21	20.96
Rejection frequency (GHz)	21.17	21.18
-3 dB bandwidth (MHz)	300	290
-3 dB bandwidth (%)	1.43	1.38
Unloaded *Q*-factor	1689	1429

Table. 4. Comparison of planar filters with asymmetric frequency response.

Specifications	[13]	[14]	[15]	**Proposed filter**
Process	PCB	PCB	PCB	**PCB**
Technology	Combline SIW	SIW	SIW	**AFSIW**
PCB substrate material	Rogers 4003	Rogers 5880	Rogers 6002	**Rogers 6002**
Filter order	3rd	3rd	4th	**3rd**
Total height (mm)	1.524	0.762	0.508	**2.54**
Area (mm^2)	1880	561	121	**1925**
Center frequency (GHz)	5.3	13.35	35	**20.96**
-3 dB bandwidth (%)	4.9	8.99	8	**1.38**
Insertion loss (dB)	1.8	1.25	1.2	**0.66**
Rejection frequencies (GHz)	5.68	14.2	36.2	**21.18**
Unloaded *Q*-factor	147	115	180	**1429**

5 Conclusion

The implementation and demonstration of a third-order AFSIW filter with an asymmetric frequency response is presented. The creation of the transmission zero is made using a multilayer cross-coupling by taking advantage of the AFSIW technological platform configuration. Furthermore, the structure shows a good robustness versus PCB standard processes and substrate dielectric constant permittivity uncertainty. The proposed principle is believed by the authors to be of a particular interest for diplexer applications where high rejection with narrow guard bands are required.

7 References

[1] R. V. Snyder, A. Mortazawi, I. Hunter, S. Bastioli, G. Macchiarella, and K. Wu, "Present and future trends in filters and multiplexers," *IEEE Trans. Microw. Theory Techn.*, vol. 63, no. 10, pp. 3324-3360, Oct. 2015.

[2] R. J. Cameron, "General coupling matrix synthesis methods for Chebyshev filtering functions" *IEEE Trans. Microw. Theory Techn.*, vol. 47, no. 4, pp. 433-442, April 1999.

[3] A. E. Atia and A. E. Williams, "Narrow-bandpass waveguide filters," *IEEE Trans. Microw. Theory Techn.*, vol. 20, no. 4, pp. 258-265, Apr. 1972.

[4] J. D. Rhodes and R. J. Cameron, "General extracted pole synthesis technique with applications to low-loss TE/sub011/ mode filters," *IEEE Trans. Microw. Theory Techn.*, vol. 28, no. 9, pp. 1018-1028, Sep. 1980.

[5] R. Levy, "Filters with single transmission zeros at real or imaginary frequencies," *IEEE Trans. Microw. Theory Techn.*, vol. 24, no. 4, pp. 172-181, Apr. 1976.

[6] M. Bozzi and K. Wu, "Guest editorial," *IEEE Trans. Microw. Theory Techn.*, vol. 66, no. 6, pp. 2915-2919, Jun. 2018.

[7] K. Wu, "Towards system–on–substrate approach for future millimeter–wave and photonic wireless applications," *Proc. Asia–Pacific Microwave Conference 2006*, pp. 1895–1900, Yokohama, Japan, Dec. 12–15, 2006.

[8] F. Parment, A. Ghiotto, T. P. Vuong, J. M. Duchamp, and K. Wu, "Air-filled substrate integrated waveguide for low-loss and high power-handling millimeter-wave substrate integrated circuits," *IEEE Trans. Microw. Theory Techn*., vol. 63, no. 4, pp. 1228-1238, Apr. 2015.

[9] T. Martin, A. Ghiotto, T.P. Vuong, and F. Lotz, "Self-temperature-compensated air-filled substrate integrated waveguide (AFSIW) cavities and filters," *IEEE Trans. Microw. Theory Techn*., vol. 66, no. 8, pp. 3611-3621, Aug. 2018.

[10] T. Martin, A. Ghiotto, T. Vuong, and F. Lotz, "Configurable perforated air-filled substrate integrated waveguide (AFSIW) for generic high-performance systems on substrate," *IEEE Trans. Microw. Theory Techn*., vol. 67, no. 11, pp. 4308-4321, Nov. 2019.

[11] T. Martin, A. Ghiotto, T.P. Vuong, F. Lotz, and K. Wu "Compact quasi-elliptic and highly selective AFSIW filter with multilayer cross-coupling," *IEEE MTT-S Int. Microw. Symp*., Boston, MA, USA, 2019, pp. 718-721.

[12] R. J. Cameron, C. M. Kudsia, and R. R. Mansour, *Microwave Filters for Communication Systems*, Hoboken, NJ, USA: Wiley, 2007, ch. 14, pp. 501-530.

[13] J. D. Martínez, S. Sirci and V. E. Boria, "Compact SIW filter with asymmetric frequency response for C-band wireless applications," *IEEE International Wireless Symposium (IWS)*, Beijing, 2013, pp. 1-4.

[14] S. Deng, F. Xu and L. Yang, "A compact bandpass filter with transmission zero based on SIW triangular cavities," *IEEE International Conference on Ubiquitous Wireless Broadband (ICUWB)*, Nanjing, 2016, pp. 1-3.

[15] X. Chen and K. Wu, "Self-packaged millimeter-wave substrate integrated waveguide filter with asymmetric frequency response," *IEEE Transactions on Components, Packaging and Manufacturing Technology*, vol. 2, no. 5, pp. 775-782, May 2012.