INTERNATIONAL JOURNAL OF MICROWAVE AND OPTICAL TECHNOLOGY,
VOL.19, NO.4, JULY 2024

Design and Analysis of a Bandpass Filter Implemented in Substrate Integrated Waveguide

Omaima Talmoudi*[1], Álvaro Gómez-Gómez[2], Oscar Fernández[2], Tomás Fernández-Ibáñez[2],

Abdelwahed Tribak[1], Jaouad Terhzaz [3]

[1]Institut national des postes et télécommunications, Rabat, Morocco
[2]Departamento de Ingeniería de Comunicaciones, Universidad de Cantabria, Santander, Spain
[3]Centre Régional des Métiers de l'Education et de la Formation, Casablanca, Morocco

E-mail: omaimatalmoudi@gmail.com

***Abstract*- This paper presents a bandpass filter design based on a Substrate Integrated Waveguide (SIW) with resonant elements on both sides of the substrate. The proposed filter achieves a unique 0.5 GHz bandwidth centered at 6.54 GHz as well as demonstrates exceptional performance with a Voltage Standing Wave Ratio (VSWR) below 2, ensuring efficient power transmission. Additionally, the filter showcases a rejection level of more than 20 dB for out-of-band frequencies, highlighting its superior selectivity. The novelty of this work lies in the innovative combination of compact size, high-frequency selectivity, and excellent VSWR performance, making it a standout solution for microwave and RF applications. By presenting comprehensive numerical and experimental results, including a detailed comparison with existing designs, this study underscores the significant advancements and advantages offered by the proposed filter in terms of size, frequency response, rejection level, and VSWR optimization.**

***Index Terms*- Microstrip transition, resonant structure, substrate integrated waveguide (SIW), taper, vias.**

I. INTRODUCTION

The Substrate Integrated Waveguide (SIW) is a revolutionary approach to microwave and millimeter wave circuits, offering a compact and efficient alternative to traditional waveguide structures [1-2]. SIW is a transmission line technology that combines the benefits of planar circuits with the performance characteristics of traditional rectangular waveguides. Designed to overcome the limitations of conventional microstrip [3] and stripline technologies [4], SIW provides a low losses, high Q and compact solution for different types of applications, especially in the microwave and millimeter wave frequency range [5-6]. At its core, SIW consists of a dielectric substrate with metallic sheets in both sides and metalized vias forming a rectangular waveguide structure. This configuration allows guided propagation of electromagnetic waves while the dielectric material provides structural support [7-8].

SIW structures offer several advantages, including reduced radiation losses, increased power handling capabilities, and improved isolation between components [9-10]. The inherent integration with planar technologies facilitates active and passive component integration, increasing the versatility of SIW based circuits [7]. SIW has found applications in diverse areas such as communication systems, radar systems, and sensing devices due to its ability to support high-frequency signals with minimal attenuation degradation [11-12]. SIW is an attractive choice for modern microwave engineering due to its ease of fabrication, suitability for standard printed circuit board (PCB) processes, and potential for three-dimensional integration [13-14].

Substrate Integrated Waveguide (SIW) filters have become a central focus of microwave and millimeter-wave research, providing innovative solutions to meet the growing demands of modern communication systems. Researchers have diligently investigated various facets of SIW filter design, contributing to a substantial body of literature that highlights the flexibility and progress within this technology [5-15]

Studies have focused on optimizing SIW bandpass filters, demonstrating improved insertion loss and selectivity through novel resonator configurations [16-17-10]. Additionally, they have extended the application scope of SIW filters by proposing designs with tunable characteristics to accommodate dynamic requirements in wireless communication systems [17].

The objective of our work is to present a comprehensive analysis of a bandpass filter implemented in Substrate Integrated Waveguide (SIW), incorporating rosette-type resonant structures in both layers of the design. The inclusion of rosettes as resonant elements represents a key innovation, aimed to understand their adaptability and impact on the performance characteristics of the filter. This novel configuration is designed to enhance filter performance. Our research focuses on exploring the adaptability of rosette resonators and their potential to improve SIW bandpass filters, contributing to the development of high performance SIW filters for wireless communications and microwave circuits.

II. DESIGN DESCRIPTION

The design process focuses on creating a Substrate Integrated Waveguide (SIW) with rosettes in the upper and lower layers, including a microstrip transition line. First step is to design a rectangular SIW as a starting simple structure, as shown in Fig.1, and then place a taper and a microstrip line on both sides of the SIW, as shown in Fig.2. As we progress through these iterative steps and include the selected resonant structure, the resulting structure is the microstrip transition SIW with rosettes presented in Fig.3.

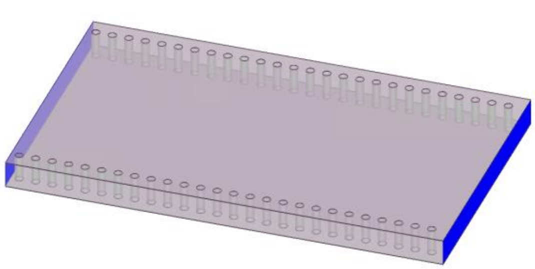


Fig.1. View of rectangular empty substrate integrated waveguide proposed design

A. Design of Transition

The empty SIW structure consists of a Taper section connecting the microstrip line to the integrated waveguide, as shown in Fig.2. The tapered section is configured to relate the line width of the microstrip to the width of the integrated waveguide as an impedance transformer [7]. After several parametric simulations, we have chosen the following values for the parameters, and Table I shows the corresponding dimensions and transition details of the SIW structure, including the transition to microstrip.

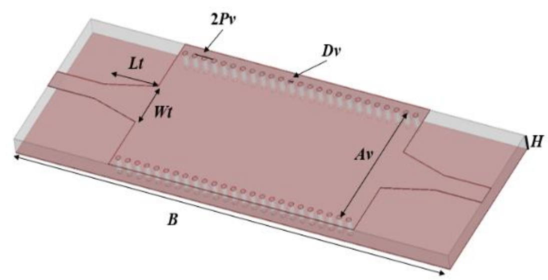


Fig.2. Empty SIW structure view including microstrip line transition

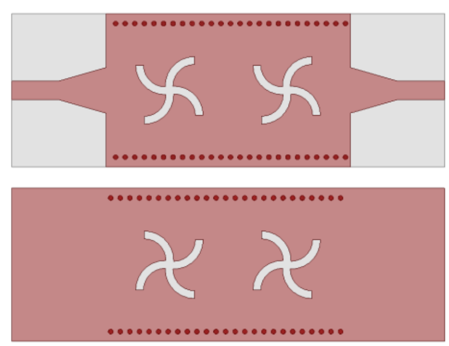


Fig.3. Top and bottom views of the substrate integrated waveguide structure including the microstrip transition line and two rosettes in each layer designed with HFSS

Table 1: Dimension of the geometrical parameter of the substrate integrated waveguide

Parameter	value *(mm)*
Substrate length including microstrip and taper *B*	44.300
Diameter of vias Dv	0.500
Substrate thickness *H*	1.524
Pitch between vias *Pv*	0.980
Width of structure *Av*	13.660
Width of taper *Wt*	4.600
Length of taper *Lt*	4.870

INTERNATIONAL JOURNAL OF MICROWAVE AND OPTICAL TECHNOLOGY,
VOL.19, NO.4, JULY 2024

It is commonly considered that the mode propagation constant TEn0 is mainly influenced by the width *Av*. Consequently, it is possible to reduce the height of the waveguide without significantly impacting the propagation of the TEn0 mode. This allows integration into a thin substrate, potentially minimizing radiation loss from the microstrip line. The dimensions, in particular, the length *Lt* and width *Wt* of the taper shown in Fig.2, must be obtained over the desired frequency bandwidth.

B. *SIW Filter Design*

The novelty of the proposed filter is the insertion of resonance elements, consisting of two rosettes on the upper plane and two complementary rosettes on the lower plane, as shown in Fig.3. Each rosette is constituted by four arms, each designed by arcs, where R represents the radius, L length, and $\alpha = L/R$ the angle of the arc, respectively. Additionally, the width W of the rosette is also depicted in Fig.4.

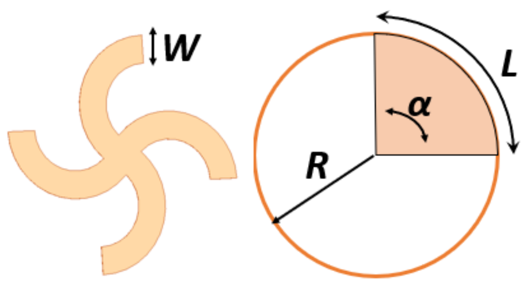


Fig.4. Schematic of the definition of the arcs that constitute the arms of the rosette

The rosettes have been chosen for their adaptability, allowing easy adjustment to the band dimensions [18]. In particular, the radius of these rosettes plays a pivotal role in determining the operating frequency band of the filter. This dynamic behavior underscores the importance of the rosettes in tailoring the performance of the filter, providing a versatile means of tuning its frequency response for a diverse range of applications in microwave and RF systems.

To obtain a bandpass filter around 6.5 GHz, both the size of the rosette arcs and the relative orientation between the upper and ground plane rosettes must be optimized to achieve the desired out-of-band rejection levels as well as the bandwidth of interest.

The proposed SIW filter is designed in the C-band using the Rogers RT/Duroid 4003 substrate, which has a 3.55 dielectric constant, a 0.0027 dielectric loss tangent, a 1.524 height mm and a metal (copper) thickness of 0.035 mm. This Rogers substrate is often used in high-frequency and high-speed applications where signal integrity, thermal management, and reliability are critical. It is well known that SIW technology provides the same performance as a high pass filter.

III. SIMULATED AND MEASURED RESULTS

A. *Simulation Results*

The simulation results were obtained with the aid of Ansys HFSS software for two different structures: (i) a rectangular SIW, as shown in Fig.1, and (ii) a modified version of the SIW featuring a taper to microstrip on both sides of the SIW, as depicted in Fig.2. At this stage, the rosettes that provide the frequency-selectivity behavior have not been included.

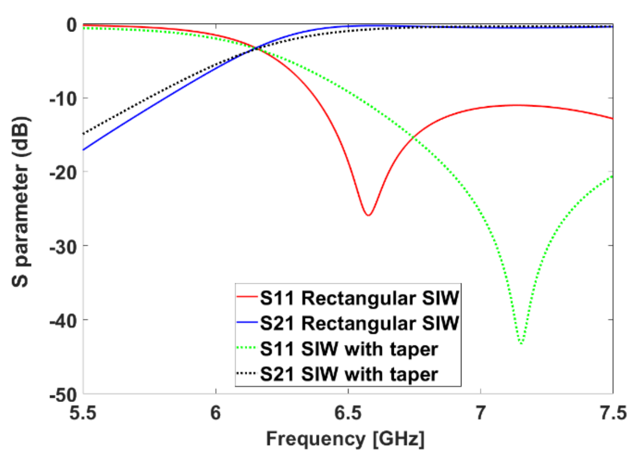


Fig.5. Variation of the S parameters vs frequency obtained with the aid of HFSS for the waveguide

Fig.5 illustrates a comparison between the S parameters acquired for a rectangular Substrate Integrated Waveguide (SIW) and an SIW including microstrip and taper elements. The simulation outcomes reveal a return loss exceeding 10 dB across nearly the entire designated bandwidth. The results obtained indicate that the SIW with taper exhibits superior return losses when compared to the rectangular configuration.

INTERNATIONAL JOURNAL OF MICROWAVE AND OPTICAL TECHNOLOGY,
VOL.19, NO.4, JULY 2024

After placing the rosettes in the SIW, we carried out a study of the geometrical parameters that define the rosette, such as radius *R*, width *W*, and angle of rosette α, to understand their effects. The aim of this analysis was to accurately determine the optimal values for these parameters and to improve our understanding of their impact on overall performance.

Firstly, the radius *R* is studied by iteratively adjusting it from 2 to 3 mm. The obtained results are shown in Fig.6. This parametric study allows a comprehensive analysis of the resonant behavior of the filter.

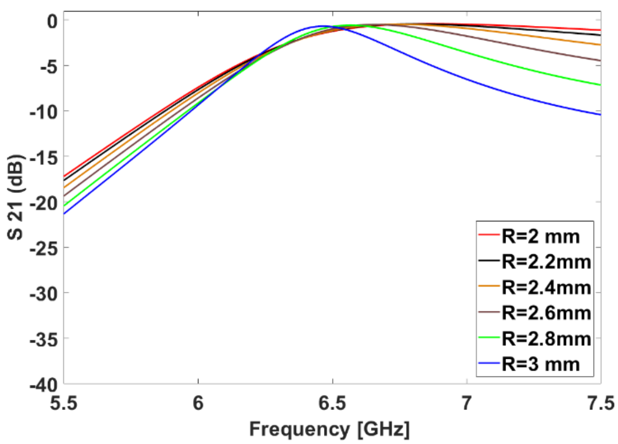


Fig.6. Effect of radius (*R*) of rosettes on S21 transmission coefficient of proposed SIW filter with rosette

Similarly, variations in the width *W* are studied to determine their effect on the bandwidth and center frequency as shown in Fig.7.

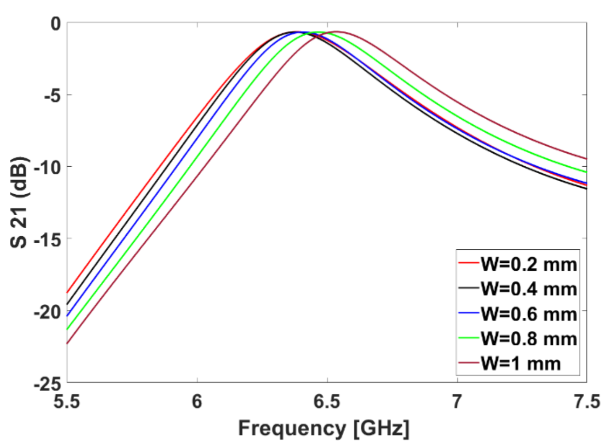


Fig.7. Effect of width of rosettes (*W*) on the transmission coefficient S21 of the proposed filter SIW with rosette

The rosette angle α was identified as a critical factor that significantly influences the coupling dynamics within the filter structure as it is directly related to the electrical length of the rosette. Consequently, a parametric study of α in both layers was carried out, as shown in Fig.8. The obtained results clearly indicate that variations in the rosette angle play a crucial role in shaping the filter characteristics, affecting aspects such as signal transmission efficiency and selectivity.

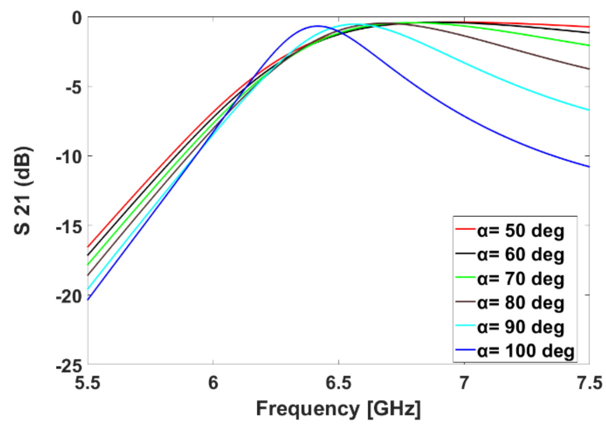


Fig.8. Effect of the angle (α) of the rosettes on the S21 transmission coefficient of the proposed filter of SIW with rosettes

These HFSS parametric studies provide valuable knowledge on how adjustments to these parameters can be used to regulate the response of the filter, ultimately improving its functionality in the frequency band. The optimal rosette dimensions are summarized as *R* = 3 mm, *W* = 0.8 mm, and α = 100º, Table I provides the rest of the parameters, including the SIW structure dimensions and the transition to microstrip.

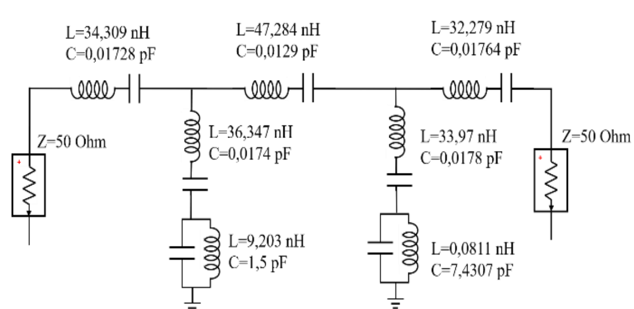


Fig.9. Equivalent circuit model of the proposed design

INTERNATIONAL JOURNAL OF MICROWAVE AND OPTICAL TECHNOLOGY,
VOL.19, NO.4, JULY 2024

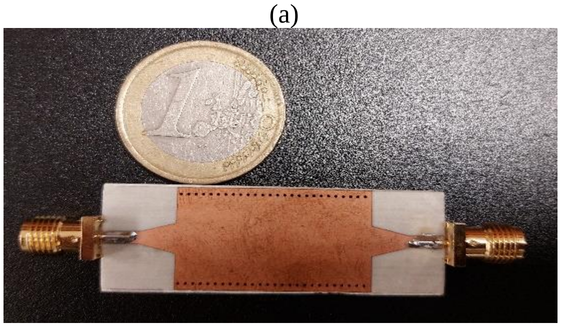
Fig.9 shows the equivalent circuit model of the described filter. It includes capacitive and inductive elements representing the transitions between microstrip and SIW sections, as well as resonators within the SIW section. Each resonator can be modeled as a parallel LC circuit. These elements play a crucial role in determining the impedance matching, insertion loss, bandwidth, and rejection characteristics of the filter. Inductances in the transitions affect the bandwidth and selectivity of the filter; higher inductance can narrow the bandwidth and improve selectivity. Capacitances primarily affect the impedance matching and coupling between different filter sections. The values of the resonance frequencies of the different series and parallel resonators have been calculated using an optimization process that allows the poles and zeros of the filter to be adjusted. For this purpose, Keysight ADS software has been used to carry out this process.

B. Fabrication and Experimental Results

a. Empty Substrate Integrated Waveguide

As a demonstration of the analysis, the empty SIW with microstrip and taper was implemented, fabricated, and measured. The cut-off frequency of the proposed SIW high pass filter is 6.54 GHz. Fig.10 illustrates a view of the fabricated prototype.

(a)



(b)

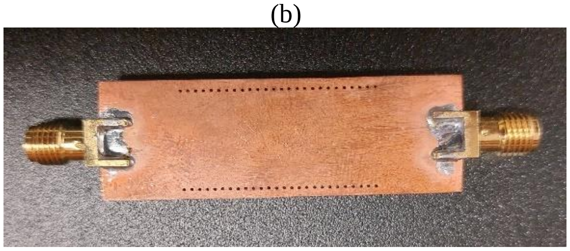


Fig.10. (a) Top view and (b) bottom view, of the manufactured empty SIW including the tapers and microstrips with a total volume of 44.3 mm × 15.66 mm × 1.594 mm

Experimental validation was carried out with a Keysight P5006A vector network analyzer (VNA). The total volume used for the proposed resonant filter, including the tapers and microstrips, is 44.3 mm × 15.66 mm × 1.594 mm.

Measured results of the empty SIW are presented in Fig.11, with a comparison to the simulated results obtained using HFSS simulator.

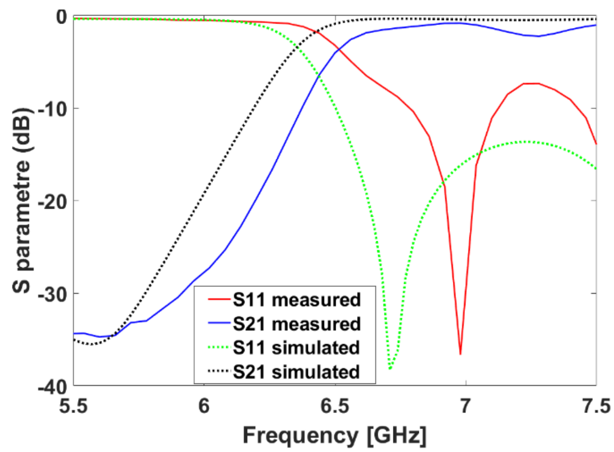


Fig.11. Simulated and measured *S* parameters of the proposed empty SIW structure with taper and microstrip

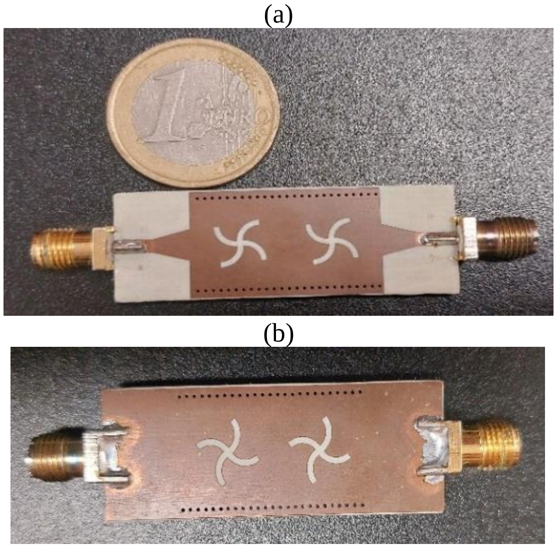
Fig.11 shows the reflection and transmission responses of the proposed empty SIW structure with taper and microstrip. The simulation results show adaptation levels better than 7.5 dB across the whole operating bandwidth. The experimental results show return losses better than 10 dB. However, the experimental results also presented some degradation compared to the simulated ones.

b. Substrate Integrated Waveguide with Rosettes

Finally, we present a numerical and experimental analysis of the SIW filter with resonant elements. Fig.12 shows a view of the fabricated SIW filter with rosettes in the upper and lower layers. Following fabrication, a Keysight P5006A vector network analyzer (VNA) was used to measure the SIW filter.

IJMOT
INTERNATIONAL JOURNAL OF MICROWAVE AND OPTICAL TECHNOLOGY,
VOL.19, NO.4, JULY 2024

(a)



(b)

Fig.12. (a) Top view of SIW filter with two rosettes, (b) bottom view of SIW filter with two rosettes

Considering that our objective is to have a bandpass filter with a center frequency of around 6.5 GHz, the SIW filter results are measured and compared to the numerical results obtained with HFSS, as shown in Fig. 13.

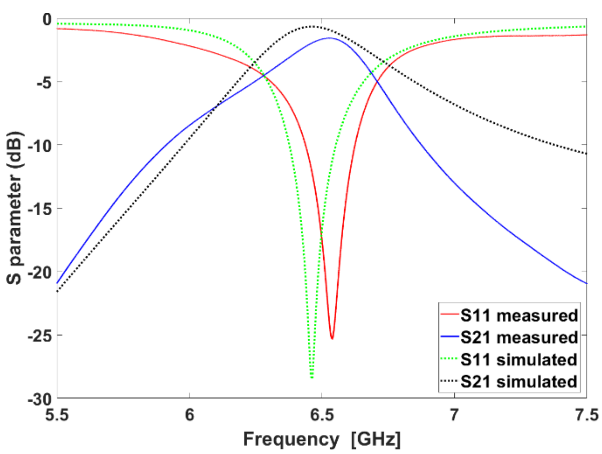


Fig.13. Simulated and measured *S* parameters of the proposed SIW filter with two rosettes in the top and bottom layers

The simulations carried out show that the measured and simulated results are in good agreement, with the apparent differences in response shown in the figures mainly due to the inherent tolerances in the manufacture of the filter. The results in Fig.13 show that the experimental center frequency has shifted slightly above 6.54 GHz. At this frequency, the return loss is better than 20 dB and the simulated insertion loss is 0.5 dB, while the measured insertion loss is 1.6 dB.

In particular, the transmission coefficient S21 in the filter response shows superior performance compared to the results obtained from the HFSS simulations, and the measured rejection frequencies are well obtained in comparison with the simulated results. This improvement confirms the efficiency of the designed filter, demonstrating its robust ability to transmit signals with minimal attenuation.

Additionally, the filter exhibits commendable selectivity, confirming its ability to discriminate unwanted frequencies and effectively isolate the desired signal. These results not only confirm the simulation results but also underline the potential of the filter for high performance applications by demonstrating its precision and selectivity in signal transmission.

Fig.14 shows the simulated and measured VSWR of the proposed bandpass filter. The VSWR is an important parameter for any microwave element, and it should ideally be less than 2 for efficient power transmission.

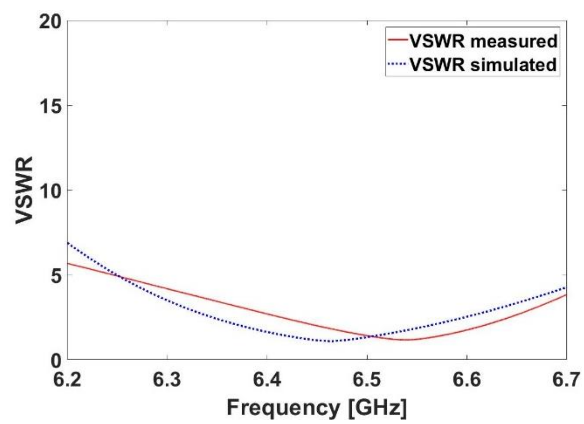


Fig.14. Simulated and measured VSWR of the proposed bandpass filter

The results show that the proposed bandpass filter exhibits a VSWR that meets this requirement. However, a slight difference can be observed between the simulated and measured VSWR values. This difference can be attributed to the presence of connector losses and cable losses in the measurement setup, which are not accounted for in the simulations.

Despite this minor discrepancy, the measured VSWR remains well within the acceptable range, demonstrating the robust performance of the proposed bandpass filter design. The close agreement between the simulated and measured VSWR values

INTERNATIONAL JOURNAL OF MICROWAVE AND OPTICAL TECHNOLOGY,
VOL.19, NO.4, JULY 2024

IJMOT

further validates the accuracy of the design and analysis techniques employed in developing this microwave component.

Table 2: Comparative analysis of the SIW filter in this paper with existing design

References	S11 (dB)	VSWR	Fc(GHz)	BW (GHz)
[19]	<-10	1.7	3.4	0.85
[20]	<-20	1.2	8.75	3.57
[21]	<-10	1.6	3	0.6
[22]	<-15	1.4	4.67	1.38
[23]	<-15	1.4	11.8/13.2	2.54/ 1.51
This work	<-20	1.2	6.54	0.5

In order to verify the characteristics of the proposed filter, a comparative analysis of the results obtained from the proposed SIW filters presented in this paper, using rosettes (as shown in Figure 11), and several other bandpass filters in SIW technology is presented in Table 2.

The analysis shows remarkable results: the filter that we proposed shows a significant improvement in both bandwidth (-3 dB) and VSWR at the center frequency, as well as return loss (S11), compared to similar bandpass SIW filter topologies documented in the technical literature. Overall, the results underscore the capability of the proposed filter design to achieve superior performance metrics compared to existing filter configurations, thus establishing its potential as a promising solution in microwave and RF applications.

IV. CONCLUSION

In summary, this paper presents a novel bandpass filter from 6.2 to 6.7 GHz using SIW technology in combination with two rosettes. Successfully simulated, fabricated, and measured, our SIW filter shows significant performance. At a center frequency of 6.54 GHz, it achieves an insertion loss of approximately 1.6 dB, showing remarkable efficiency. In addition, the Voltage Standing Wave Ratio (VSWR) of the filter remains below 2 with a return loss of more than 20 dB at the center frequency, further confirming its quality. These results not only validate our fabrication process but also underscore the practical viability of the filter, suggesting its potential in RF and communication systems requiring precise frequency control and superior rejection band performance.

ACKNOWLEDGMENT

This work was supported in part by the R+D+i Projects PGC2018-098350-B-C22 and PID2022-137619NB-I00 funded by MCIN/AEI/10.13039/ 501100011033/ERDF, EU “A way to make Europe”.

We are very grateful to Professor Jésus R. Pérez (Universidad de Cantabria) for his help with the measurements. We also thank, Paul García Cadelo and Eva Mª Cuerno García, the technicians of the laboratory in Departamento de Ingeniería de Comunicaciones (Universidad de Cantabria) for their help in manufacturing the structures.

REFERENCES

[1] M. Bozzi, A. Georgiadis and K. Wu, “Review of substrate integrated waveguide (SIW) circuits and antennas", *IET Microw. Antennas Propag.,* Vol. 5, pp. 909-920, Jun. 2011.

[2] X. P. Chen and K. Wu, “Substrate integrated waveguide filter: Basic design rules and fundamental structure features", *IEEE Microw. Mag.,* Vol. 15, pp. 108-116, Jul. 2014.

[3] C. F. Chen, S. F. Chang, and B. H. Tseng, “Design of compact microstrip sept-band bandpass filter with flexible passband allocation", *IEEE Microw. Wireless Compon. Lett.,* Vol. 26, pp. 346-348, May. 2016.

[4] L. G. Maloratsky and M. Lines, “Reviewing the basics of microstrip", *Microwaves RF,* Vol. 39, pp. 79-88, Mar. 2000.

[5] Z. Kordiboroujeni and J. Bornemann, “New wideband transition from microstrip line to substrate integrated waveguide", *IEEE Trans. Microw. Theory Techn.,* Vol. 62, pp. 2983-2989, Dec. 2014.

[6] F. Xu and K. Wu, “Guided-wave and leakage characteristics of substrate integrated waveguide", *IEEE Trans. Microw. Theory Techn.,* Vol. 53, pp. 66-73, Jan. 2005.

[7] Deslandes and K. Wu, “Integrated microstrip and rectangular waveguide in planar form", *IEEE Microw. Wireless Compon. Lett*., Vol. 11, pp. 68-70, Feb. 2001.

[8] X. P. Chen and K. Wu, “Substrate integrated waveguide filters: Design techniques and structure innovations", *IEEE Microw. Mag.,* Vol. 15, pp. 121-133, Sep. 2014.

[9] A. Sahu, V. K. Devabhaktuni, R. K. Mishra, and P. H. Aaen, “Recent advances in theory and applications of substrate-integrated waveguides: a review", *Int. J. RF Microw. Comput. Aid. Eng.,* Vol. 26, pp. 129-145, Oct. 2015.

[10] A. Rhbanou, M. Sabbane, and S. Bri, “Design of K-band substrate integrated waveguide band-pass filter with high rejection", *J. Microwaves, Optoelectron. Electromagn. Appl*., Vol. 14, pp. 155-169, Dec. 2015.

[11] Y. Cao, Y. Cai, L. Wang, Z. Qian, and L. Zhu, “A review of substrate integrated waveguide end-fire antennas", *IEEE Access,* Vol. 6, pp. 66243-66253, Nov. 2018.

[12] H. HoandK, H. Tang, "Miniaturized SIW cavity tri−band filter design", *IEEE Microw. Wirel. Compon. Lett*., Vol. 30, pp. 589−592, Jun. 2020.

INTERNATIONAL JOURNAL OF MICROWAVE AND OPTICAL TECHNOLOGY,
VOL.19, NO.4, JULY 2024

[13] K. E. Wu, M. Bozzi, and N. J. Fonseca, “Substrate integrated transmission lines: Review and applications", *IEEE J. Microw.*, Vol. 1, pp. 345-363, Jan. 2021.

[14] T. Djerafi and K. Wu, “Substrate integrated waveguide (SIW) techniques: The state-of-the-art developments and future trends", *J. Electron. Sci. Technol.*, Vol. 42, pp. 171-192, Mar. 2013.

[15] J. Muñoz-Enano, P. Vélez, M. Gil, & F. Martín, "Planar microwave resonant sensors: A review and recent developments" *Appl. Sci*, Vol. 10, pp. 2615, Apr. 2020.

[16] O. I. Hussein, K. A. Al Shamaileh, N. I. Dib, A. Nosrati, S. Abushamleh, D.G. Georgiev, & V. K. Devabhaktuni, "Substrate integrated waveguide bandpass filtering with Fourier-varying via-hole walling", *IEEE Access*, Vol. 8, pp. 139706-139714, Aug. 2020

[17] A. Iqbal, J. J. Tiang, S. K. Wong, M. Alibakhshikenari, F. Falcone, and E. Limiti, "Miniaturization trends in substrate integrated waveguide (SIW) filters: A review", *IEEE Access*, Vol. 8, pp. 223287-223305, Dec. 2020.

[18] E. Plum, J. Zhou, J. Dong, V. A. Fedotov, T. Koschny, C. M .Soukoulis, & N. I Zheludev," Metamaterial with negative index due to chirality", *Phys. Rev. B*, Vol. 79, pp. 035407, Jan. 2009.

[19] J. D. D. Ruiz Martínez, F. L.Martínez Viviente, A .Álvarez Melcón, & J. Hinojosa Jiménez, “Substrate integrated waveguide (SIW) with koch fractal electromagnetic bandgap structures (KFEBG) for bandpass filter design” , *IEEE Microw. Wireless Compon. Lett.*, Vol. 25, pp. 160-162. Mar. 2015

[20] K. Becharef, “Design of Miniaturized SIW and CSIW (Corrugated SIW) Bandpass Filter Using Form E Interdigital”, Jan. 2022

[21] A.Coves, & M. Bozzi, “ Novel Filtering Applications in Substrate-Integrated Waveguide Technology”, *Hybrid Planar-3D Waveguiding Technologies. IntechOpen.*, Jul. 2022.

[22] L. Huang, & N. Yuan, “A compact wideband SIW bandpass filter with wide stopband and high selectivity”, *Electronics.*, Vol. 8, pp. 440, Apr. 2019.

[23] Y. B. Patel, & A. Patel, “HMSIW Based Highly Selective Dual-Band Band-Pass Filter”, *IJMOT*, Vol. 18, pp.601-606 Nov. 2023.