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LOW-COST C-BAND SIW BANDPASS FILTER USING FR4-EPOXY SUBSTRATE

Abed Ahcéne[1], Bouchekhlal Ahmed[2], Amrouche Aissa[3] and Bendoumia Rédha[1]

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ABSTRACT

This paper describes a substrate-integrated waveguide (SIW) filter built on an Fr4-Epoxy substrate with a dielectric constant εr = 4.4 and a height of h = 1.6mm. SIW-based devices have piqued the interest of researchers in recent years due to their low loss, small size and low cost. The goal is to simulate and realize an SIW filter for C-band applications. The designed filter is analyzed using the reflection coefficient S11 and electric field distributions. We used the HFSS simulator. According to the findings, there is a high degree of agreement between the simulated and realized filters. The results also show that the filter has a very good response. It also displays bandwidth around C-band frequencies (6.3GHz). This filter's pass-band ranges from 5.39 to 6.83GHz, with an insertion loss of 4.2dB and a return loss of 45.49dB.

KEYWORDS

SIW, Bandpass filter, C-band, Fr4-Epoxy.

1. INTRODUCTION

High-performance RF/microwave filters with critical properties such as weight, cost, insertion loss, quality factor and power handling capacity, are required for modern communication systems for satellite and mobile applications and meeting all of these requirements can be difficult. Rectangular Waveguides (RWs) are common microwave components, but they are difficult to manufacture and incorporate into low-cost planar structures [1]. Scientists have chosen to create a planar structure to solve this problem.

Over the past decade, substrate-integrated waveguides (SIWs) have grown in popularity, being a new technology representing a very promising solution technology which has been the focus of intense and ever-increasing research efforts [2]. Complete shielding, comparatively low losses and straightforward, affordable manufacturing are all combined by SIW technology, making it the ideal platform for developing the next generation of wireless systems. This technology has been integrated into several applications as a result of its numerous advantages, including low production costs, high-quality factor and ease of integration into telecommunication circuits.

Filters and feeder-to-filter transitions are just a few examples of the many projects that have utilized SIW technology, which can make converting nonplanar circuits into planar circuits easier for simple integration with other planar circuits and systems. To address this issue, researchers decided to construct a planar structure and the SIW, which is a very encouraging arrangement.

In addition to the conventional SIW, several new structures have been proposed to decrease size, boost single-mode bandwidth and lower losses. A waveguide width a reduction of 50% is possible with the folded SIW [3]. The ridge [4] and the empty [5] SIW increase the bandwidth while decreasing the size and the half-mode SIW decreases the width while increasing the single-mode bandwidth by a factor of two.

Similar to this, several brand-new SIW filter setups have been proposed to enhance filter performance, minimize footprint and lower losses [6]. SIW cavities in the half mode [7] and the quarter mode [8] have all been used to reduce the size of the filter. A small size and a wide stopband have also been achieved using a substrate-integrated coaxial line. Tiny SIW cavities utilizing interdigital capacitors have been proposed as a way to reduce filter dimensions.

A preliminary analysis of a bandpass filter based on a regularly drilled SIW structure was recently

1. A. Abed and R. Bendoumia are with DIC Laboratory, Department of Electronics, University of Blida 1, Algeria. Emails: abedahcene@gmail.com and r.bendoumia@yahoo.fr
2. A. Bouchekhlal is with Higher School of Signals (HSS), Koléa, Tipaza, Algeria. Email: bouchekhlalahmed@umc.edu.dz
3. A. Amrouche is with Computational Linguistics Department, CRSTDLA, Algeria. Email: amrouche-a.dz@ieee.org

presented. In this structure [9], perforations in the dielectric substrate allow for a local effective permittivity reduction in this structure, resulting in waveguide sections below cut-off.

[10] described a new SIW filter class based on dielectric substrate perforations. The air-hole perforations enable the SIW's characteristic impedance and cut-off frequency to be modified locally, allowing for filtering structures' straightforward design. The design of four-pole filters operating at 3.6GHz is tested and discussed. The filter in [11] changes the effective dielectric permittivity and, as a result, the waveguide's characteristic impedance locally. Perforations in particular are used to form a waveguide section below the cut-off of the filter band. Impedance inverters that connect half-wave SIW resonators are realized using the waveguide sections below cut-off.

[12] described a novel SIW filter with periodic dielectric layer perforations. Waveguide sections are below cut-off, because perforations reduce local effective dielectric permittivity. This effect is used in the implementation of immittance inverters *via* analytical formulae that provide simple design rules for direct filter synthesis.

Costa et al. [13] proposed the X-band wireless bandpass filter based on an E-plane SIW (SIEW) structure. The prototype has a bandwidth of 1.2GHz and a resonance frequency of 10.54GHz, which is defined as the −3dB transmission coefficient reference level. Rhbanou et al. [14] used an iris and a SIW resonator topology to demonstrate a high-rejection K-band SIW bandpass filter design.

Nwajana et al. [15] proposed a transition structure from CPW-to-SIW, where the input/output couplings of the filter were controlled by the CPW-to-SIW transition structures, which took advantage of the step impedance between the 50ω input/output feedline and the transition, while the SIW filter has a very low milling or etching requirement, which reduces fabrication error. Nawaz et al. [16] developed a technique for switching from SIW to microstrip. The transition is wide-bandwidth, spanning the frequency range from 8 to 12GHz [17]. The measured return loss is less than 10dB and the in-band insertion loss is less than 0.6dB.

Caleffo et al. [18] proposed a new method for determining the physical size of the tapered transition, which achieves impedance matching without the need for any computational optimization between the feeder with built-in microstrip technology and SIW. Fellah et al. [19] proposed using a brand-new half-mode SIW (HMSIW) bandpass filter based on defective ground structure cells (DGSs). To meet design specifications for small size, low insertion loss and high rejection, using the periodic square Complementary Split Ring Resonator (CSRR) resonant characteristics of DGS, an X-band bandpass filter is made and examined. This study investigates a new type of filter topology based on SIW technology that can meet all of these band- pass filter structure design specifications. Filters are required in every field that uses telecommunications, including space telecommunications, because of their increasing importance in transmission systems.

The desire to develop a low-cost filter with adequate performance drives our work. Furthermore, the proposed structure allows for the control of the filter's bandwidth. To address this issue, we proposed a new type of filter by dividing the waveguide into two cavities and connecting them with metallic *vias*; this structure allows us to vary the distance, allowing us to pass the frequency of interest. The lower cost of the substrate in comparison to the others demonstrates the choice. This structure is suitable for systems that do not require a high level of performance.

To accomplish our goals, we have divided this article into three sections, which are organized as follows: The first section describes the C-band and the filtering function which relies on the substrate-integrated waveguides; the second section focuses on the C-band filter design. Section three will present the simulation results of the running SIW filter.

2. C-BAND SIW BANDPASS FILTER

C-band is the part of the electromagnetic spectrum characterized and sits between the two Wi-Fi bands, which are 2.4GHz and 5GHz. Likewise, for the 2.6GHz band that Clearwire and later Sprint used for 4G starting in 2007 and any T-Mobile in their current mid-band 5G uses. Owing to its extensive geographic coverage area and strength in a variety of propagation conditions, the C-band is widely used for satellite communications.

While the C-band spectrum has traditionally been reserved exclusively for satellite use, there is a trend toward allocating some C-band spectrum to terrestrial broadband operators in preparation for the up-coming deployment of 5G. Its transmission attributions are truly outstanding and its security is well established.

2.1 Analog Bandpass Filter

Originally, analog filters were constructed using resistance, capacitance and inductance. Their primary application was for frequency division multiplexing systems in the telephone industry. In integrated circuits that combine analog and digital signal processing tasks, analog filters are becoming more and more significant. Mixed-signal design is the process of making such circuits. The amplitude and phase spectra of an analog filter are used to determine its properties. Frequently, the amplitude spectrum as a function of ω (or f) is used. The magnitude is usually expressed in logarithmic units of dB (decibels). The ordinate units for the phase spectrum are degrees or radians *versus* ω (or f).

Analog filters can be classified into four categories: Low-Pass, High-Pass, Band-Reject and Bandpass. The Bandpass filter for C-band applications is the main topic of this work.

A bandpass channel is utilized when you need to communicate signals in a specific recurrence band and block signals at higher and lower frequencies, ω_1 and ω_2, respectively. This is finished by "tuning" an ideal recurrence, for example, a radio or TV signal. The ideal recurrence band is based on a recurrence ω_0 called the middle recurrence.

The recurrence groups underneath or more than the pass-band are called stop groups. The band edge frequencies are those frequencies where the pass-band and stop-band intersect.

2.2 Classical Waveguide

A waveguide is a physical system that guides electromagnetics beyond a certain distance to confine them in a specific medium. Waveguides are used in microwave transmission technology, obstacle detection, high-power and ultra-short-wave broadcasting technology, among other applications. Waveguides have recently adopted nano-level planar geometric shapes and materials to perform functions, such as coupling, modulation, multiplexing and amplification [20]. In terms of wave propagation, there are three modes to consider: TE, TM and TEM stand for transverse electric, magnetic and electromagnetic modes, respectively.

Only the dominant mode is propagated, which is distinguished by the lowest cut-off frequency f_c. We can really see this by using the following equation:

$$f_c = \frac{C}{2}\sqrt{\left(\frac{n}{a}\right)^2 + \left(\frac{m}{b}\right)^2} \quad (1)$$

where: a is the waveguide length; b is the waveguide width, C = 2.99 108m/s is the velocity, m and n are mode indices. Equation 1 calculates the cut-off frequency for any arbitrary mode in an RW. Furthermore, the cut-off frequency for the mode TE_{10} is given by.

$$f_c = \frac{C}{2a} \quad (2)$$

2.3 Substrate-integrated Waveguide (SIW)

Vertical metal walls are formed by two rows of metallic *via*-holes in contact with metal layers above and below the substrate (Figure 1). The latter is sandwiched between the two plates to allow the fundamental mode (TE_{10}) to propagate [21].

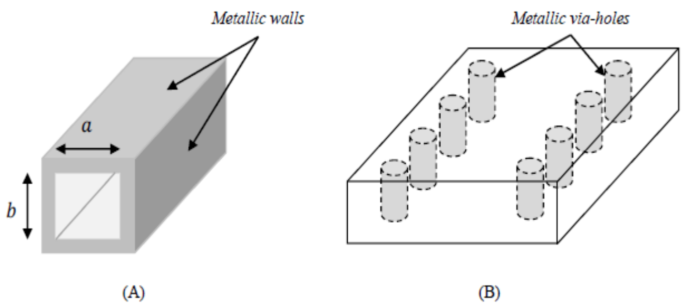


Figure 1. (A) Rectangular waveguide (B) Waveguide in SIW technology.

$$D_v \leq \frac{\lambda_g}{5} \tag{3}$$

$$P \leq 2D_v \tag{4}$$

a_d is given by the equation with the same cut-off frequency:

$$a_d = \frac{a}{\sqrt{\varepsilon_r}} \tag{5}$$

The following formula calculates the distance a_{SIW} between the two metallic *via*-hole cylinder rows.

$$a_{SIW} = a_d + \frac{D_v^2}{0.95P} \tag{6}$$

where: λ_g is the wave length of the waveguide, D_v is the *via* diameter and P is the spacing between two adjacent *vias*.

The dimension "b" is unimportant in the SIW filter for the TE_{10} mode, because it has no effect on the waveguide's cut-off frequency. As a result, the thickness of the substrate has no effect on the dielectric loss. The design and analysis of microwave bandpass filters using SIW technology are proposed and demonstrated in this article. Figure 1 (a) depicts a rectangular waveguide structure with dimension "b" representing the side walls of the rectangular waveguide and dimension "a" representing the top and bottom planes of RW.

3. Methods and Materials

Based on SIW technology, we created a bandpass filter. The suggested filter works in the frequency band [4 − 8GHz]. This filter is obtained by dividing the waveguide into two cavities. Figure 2 depicts the SIW C-bandpass filter structure.

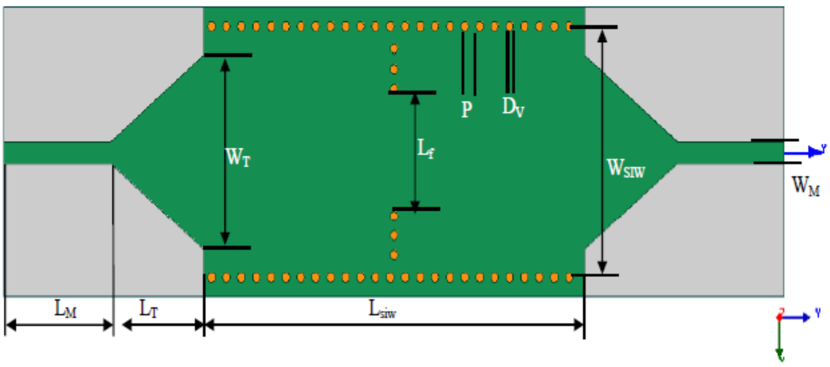


Figure 2. SIW bandpass filter structure.

where: W_{SIW} is the integrated waveguide width, L_{SIW} is the integrated waveguide length, W_T is the tapered line width, L_T is the tapered line length, W_M is the micro-strip line width, L_M is the micro-strip line length, L_f is the aperture length and h is the substrate thickness.

The standard RW of the C-band is WR-137. Table 1 summarizes its characteristics.

Table 1. Standard rectangular waveguides of the C-band.

Recommended Frequency Band	$5.8 - -8.20GHz$
Cut-off Frequency of Lower Mode	$4.301GHz$
Cut-off Frequency of Upper Mode	$8.603GHz$
Dimension $(m \times m)$	34.8488×15.7988

3.1 Microstrip Part Design

A quarter-wave tapered transformer and a 50Ω track are connected in series to form the micro-strip component. In this section, the design parameters are the transition-line length LT and width WT.

The width W_T of the tapered line can be found by solving Equation 7:

$$\frac{\frac{1}{4.38H}}{\left[\frac{W_T}{H}+1.393+0667\ln\left(\frac{W_T}{H}+1.444\right)\right]} = \frac{e^{\frac{-0.627\varepsilon_r}{\frac{\varepsilon_r+1}{2}+\frac{\varepsilon_r-1}{2\sqrt{1+\frac{12H}{W_T}}}}}}{a_d} \tag{7}$$

The taper length L_T is given by Equation 8:

$$L_T = \frac{\lambda_g}{4} \tag{8}$$

and

$$\lambda_g = \frac{C}{f\sqrt{\varepsilon_r}} \tag{9}$$

4. RESULTS AND DISCUSSION

The fundamental SIW mode has an electric field distribution similar to the TE_{10} mode of an RW. The filter is created by combining generalized bandpass filters. In order to use the designed filter for SIW C-band applications, the waveguide and hole dimensions are calculated and shown in Table 2. The hole dimensions are calculated using the C-band lowest mode's cut-off frequency f_c = 4.301 GHz. The multi-layer structure is built on an FR-4 substrate with a dielectric constant of 4.4 and a thickness of 1.6*mm*.

Table 2. Parameters of the proposed C-band bandpass filter.

Parameter	Description	Dimension
f_C	Cutoff frequency of lowest mode	4.301*GHz*
λ_g	Dielectric material wavelength	33.25 *mm*
W_{SIW}	SIW width	16.96 *mm*
D_V	Metal *via* diameter	0.66 *mm*
P	Space length between adjacent *vias*	1.33 *mm*
L_a	Aperture length	$0.24\lambda_g$
L_{SIW}	SIW length	33.92 *mm*
W_M	Tapered micro-strip width	1.53 *mm*
L_M	Tapered micro-strip length	9.55 *mm*
W_T	Transition width	13.22 *mm*
L_T	Transition length	8.31 *mm*

To realize the SIW filter and achieve our objectives, we first simulated it with the HFSS software, a powerful electromagnetic simulator for 3D problems. Then, we implemented the filter and tested it, and finally we compared the results to those of others in the field. The outcomes are denoted as the reflection coefficient S_{11} and the transmission coefficient S_{21}. The passband insertion loss of a perfect SIW filter must be 0 and the stopband attenuation must be infinite. The SIW filter in this work operates at frequencies ranging from 5.39GHz to 6.83GHz. The numerical analysis is used to determine the dimensions of the waveguide and *via* holes.

4.1 C-band SIW Bandpass Filter Simulation

Figure 3 depicts the distribution of the electric field. This distribution expresses the filtering function of the proposed structure. This is provided by the additional *vias* at the end of each cavity.

The proposed filter is designed and analyzed with HFSS software in the frequency band [5 − 8GHz]. We consider three values of L_f : $0.22\lambda_g$; $0.24\lambda_g$ and $0.26\lambda_g$.

Figure 4 depicts the proposed filter's reflection and transmission coefficients. The results show that this filter is bandpass. The frequency ranges of this filter are [5.6530 − 6.4600GHz] with $0.22\lambda_g$, [5.5450 − 6.5890GHz] with $0.24\lambda_g$ and [5.4400 − 6.8200GHz] with $0.26\lambda_g$. We notice that the chosen filter has $L_f = 0.24\lambda_g$ and performs well in terms of bandwidth [5.43 − 6.45GHz], its insertion loss −4.77dB and its return loss −11.48dB.

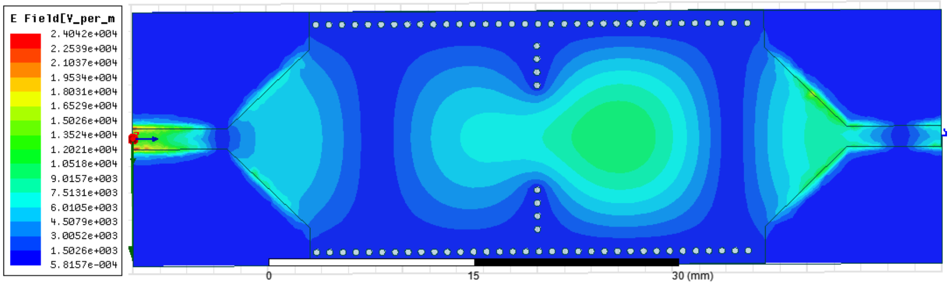
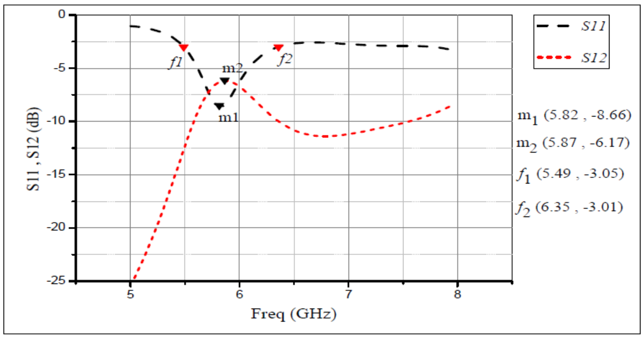
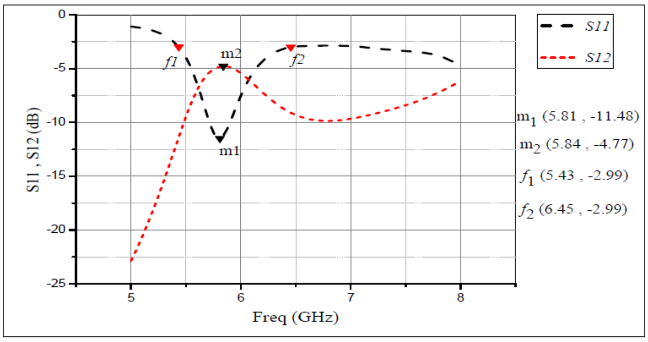


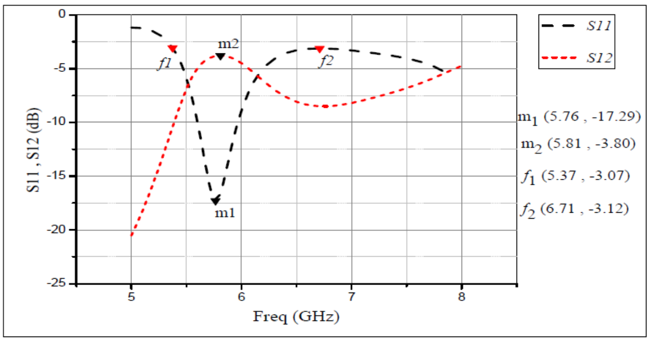
Figure 3. Electric field distribution of C-band bandpass filter.



(A)



(B)



(C)

Figure 4. S-parameters of C-band bandpass filter (A) 0.22λ_g (B) 0.24λ_g (C) 0.26λ_g.

4.2 C-band SIW Bandpass Filter Realization

After the simulation phase, we moved on to the practical realization of the simulated filter. The prototype is realized under a substrate of type Fr4-Epoxy with a dielectric constant of ε_r = 4.4 and a thickness of h = 1.6*mm*. Figure 5 shows the prototype of the SIW C-band filter:

(A)

(B)

Figure 5. C-band bandpass filter (A) top view (B) bottom view.

To characterize this filter, the prototype is equipped with two ports for the SMA connectors. The dimensions of the SIW C-bandpass filter are grouped in Table 2.

Pressure contact is used in industrial applications, which is a sophisticated and expensive method of soldering, whereas solder paste is simple to use and less expensive. However, in some cases, it has an impact on the performance of the system that uses it. In our case, we used solder paste to connect SMAs (connectors). Furthermore, because the voltage used is insufficient and the solder point does not heat up, there is no discernible effect on the filter performance.

The characteristics of the realized filter are measured with an Agilent PNA-L N5230 C network analyzer. Figure 6 represents the evolution of the parameter S11 measured with a network analyzer in the frequency range from 5 to 8GHz. For ease of comparison, the measurement and simulation results are shown together.

The results of the initial measurement and the simulation are clearly in excellent agreement in terms of insertion loss, as shown in Figure 6. The realized filter shows very high performances with a fractional bandwidth of 23.56%, a return loss of −45.49dB and an insertion loss of −4.2dB.

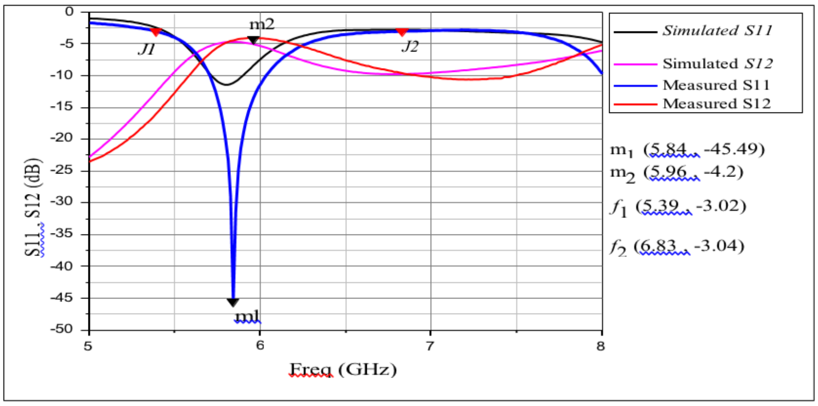


Figure 6. S-parameters of the realized filter.

4.3 Comparative Study

Table 3 compares the effectiveness of the proposed C-band SIW bandpass filter to some previously reported filters.

Table 3. A comparative study of our work and previously reported SIW bandpass filters. (ε_r: relative permittivity, Thick: thickness, f_c: center frequency, FBW: -3dB fractional bandwidth, RL: return loss (dB), IL: insertion loss (dB), λ_g: guided wavelength).

Ref.	Substrate $\varepsilon_r/Thick$	fc GHz	FBW (%)	RL (dB)	IL (dB)	Size (λ_g^2)
[20] (I)	6.5/0.762	2.73	14.65	21	0.75	0.043
[20] (II)	6.5/0.762	1.72	5.7	17.75	1	0.017
[21] (SM)	2.2/0.508	2.45	24.1	26	0.38	0.048
[21] (TM)	2.2/0.508	2.45	36.7	18	0.25	0.048
[22]	2.33/0.787	1.84	14.67	23.9	0.51	0.0147
[23]	2.33/0.78	14.74	76	17.6	1.5	0.7035
This work	4.4/1.6	5.84	23.56	45.49	4.2	0.52

In the comparison process to some references in the field, the fractional bandwidth, return loss and insertion loss were used. According to the results, with f_c = 5.84GHz, the proposed filter performed well in terms of compact size and high in-band return. Measured return loss was improved to 45.49dB.

When compared to other works, insertion loss is high and this is due to two factors. The first is the dielectric constant of the Fr4-Epoxy substrate, which is fixed at εr = 4.4 and has a significant impact on it. We used various dielectric constant values (simulation) and the results show that as the dielectric constant value decreases, the insertion loss decreases to less than −0.9dB. The second factor is provided by the use of solder paste, but it has little effect on the performance of the realized filter.

5. CONCLUSION

This paper presented an SIW C-bandpass filter, which is a cavity-resonator SIW design. The methods for designing filter parts and microstrip parts are discussed. The pass-band of this filter is from 5.39 to 6.83GHz with an insertion loss of 4.2dB and a return loss of 45.49dB. When compared to traditional waveguide filters, this filter is less expensive and easier to integrate into various planar circuits. The presented results show that the simulated and measured filter responses are in good agreement in terms of insertion loss. Our findings are consistent with earlier studies on this subject.

The suggested filter has a number of benefits, such as easier integration, fractional bandwidth, lower insertion loss and high return loss when compared to other SIW bandpass filters. This SIW bandpass filter is appropriate for real-world use. As a perspective, we are working to optimize the parameters of the proposed filter to control its frequency band and integrate it into a real system

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ملخص البحث:

تصف هذه الورقة مرشِّح تمرير نطاقٍ تردّدي مُدْمَج في طبقة أساسٍ من نوع إيبوكسي FR4، علماً بأنّ هذه التّقنية قد جذبت انتباه الباحثين في مجال المرشِّحات الإلكترونية في الآونة الأخيرة بالنّظر الى ما تتميز به من انخفاض الفقْد وصغر الحجم وانخفاض التكلفة للمرشِّحات النّاتجة عنها.

ويتمثل الهدف في محاكاة وتحقيق مرشِّح تمرير نطاق تردّدي مُدْمَج في طبقة أساس يصلح لتطبيقات نطاق (سِي). وقد جرى تحليل المرشِّح المقترح باستخدام مُعامِل الانعكاس وتوزيعات المجال الكهربائي، علماً بأنّه تمّ استخدام مُحاكي HFSS لإجراء عملية المحاكاة. وأشارت النتائج التي تمّ الحصول عليها الى درجة عالية من الاتّفاق بين المحاكاة والتّجارب العملية. كذلك بيّنت النّتائج أنّ المرشِّح المقترح كانت له استجابة عالية جداً. أمّا نطاقهُ التردّدي لتمرير المرشِّح فتراوح من (5.39) جيجاهيرتز الى (6.83) جيجاهيرتز، وبلغ فَقْد الإدخال للمرشِّح (4.2) ديسيبل، وفقْد الإرجاع (45.49) ديسيبل.