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# Multi-layer bandpass filter

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An innovative approach to reducing the longitudinal dimensions of a filter made using SIW (Substrate Integrated Waveguide) technology is presented. To reduce the size of the filter, a method of bending a fourth-order filter with inductive diaphragms is proposed. The frequency response of the filter has a shape close to rectangular, which significantly improves its selectivity. The developed filter has the following parameters: a bandwidth of 250 MHz, a reflection coefficient of no more than −20 dB, and a transmission coefficient in the range from −0.2 to −0.5 dB. The filter is made on a standard FR-4 substrate with a dielectric constant of 2.2 and on a paper substrate with a dielectric constant of 6. A comparison of the frequency characteristics of the computer model and the created prototypes demonstrated a good agreement between the theoretical and experimental results. Keywords: SIW filter, band-pass filter, microwave filter, multilayer structure.

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## Introduction

One of the key tasks of modern radar systems and communications is the development of small-size and efficient components capable of stable operation at high frequencies. The microstrip and coplanar transmission lines which have long been the basis for implementation of many radio systems, are gradually giving way to the new technologies such as SIW (Substrate Integrated Waveguide) [1]. This innovative technology makes it possible to create devices that combine the best qualities of traditional waveguide systems, reducing their overall characteristics.

The main advantage of SIW technology is that it provides minimal energy loss during signal transmission, while significantly reducing the size and weight of the final product, provides high level of transmitted power, minimizes signal loss and allows creating the small-size devices [2]. This improvement is critical for applications where the device weight and geometry matter, for example, in the aircrafts and satellites or in the mobile communication systems.

One of the main advantages of this technology is the ability to integrate the waveguide directly into the substrate, which significantly reduces the size and weight of the device compared to the conventional waveguide systems. This is of special relevance for the portable devices and systems where each gram of weight matters.

The SIW concept is a multi-layered structure consisting of a dielectric bounded on both sides by metal layers and rows of metallized holes. The pins pass through all structure layers playing the role of the waveguide walls. Electromagnetic waves propagate along the cavity between these elements in accordance with the principles of wave propagation in closed channels. This configuration provides high radiation directivity and minimal signal attenuation, making it ideal for applications in radio frequency and microwave devices.

However, one should bear in mind that if SIW-structure is used it is required to thoroughly analyze which substrate materials and structure geometry should be used. If the dielectric or the distance between the pins are selected incorrectly it may result in higher losses. The deployment of SIW elements in existing systems requires improvement of the matching scheme to avoid unwanted reflections and power losses. Nevertheless, if used correctly, this technology can radically change the technical parameters of the equipment, reducing its size and weight, while also lowering the production costs.

As part of this study, a two-layer bandpass filter based on SIW technology was developed. The filter addition method was applied, which made it possible to obtain an architecture with reduced geometric parameters without deterioration of the amplitude-frequency response. The use of a multilayer design made it possible to significantly reduce the length of the filter compared to its single-layer counterparts, while the height increased only slightly.

## 1. Filter analysis

This paper outlines the findings of modeling the SIW band-pass filters in CST Studio software. The initial design was a fourth-order filter on classical inductive diaphragms, shown in Fig. 1 [3]. Key parameters of the filter: $d_1 = 7.8$ mm, $d_2 = 8.8$ mm, $d_3 = 9.2$ mm, $g_1 = 9.5$ mm, $g_2 = 7.2$ mm, $r = 0.51$ mm, $p = 1.6$ mm, $b_1 = 10$ mm,

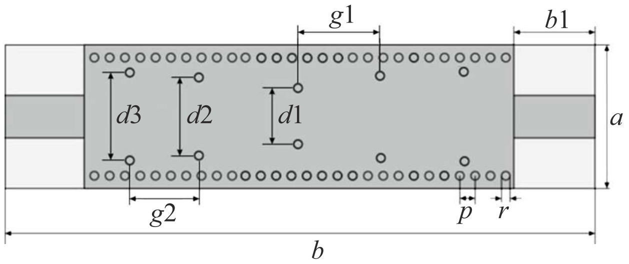


**Figure 1.** 4th order SIW-filter based on inductive diaphragms.

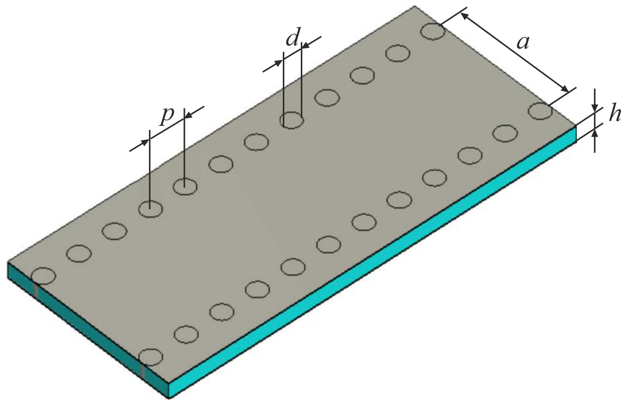


**Figure 2.** SIW-structure.

$b = 40$ mm, $a = 16.9$ mm. The transition holes between the layers are located in the resonator area, which facilitates the selection of optimal filter sizes. In contrast to model described in [4], here only two small transition holes are used. Their presence causes the resonant frequency to shift towards lower band, which requires diminished sizes of the resonant sections to compensate for this effect. Also, the introduction of two transition holes helps to increase the degree of coupling between the resonant elements, which improves the selectivity of the filter and reduces the amount of spurious resonances.

The SIW design concept is based on the same principles as the design of classical rectangular waveguides: waveguides integrated into the substrate can be represented as conventional metal rectangular waveguides with a dielectric inside. Unlike rectangular waveguides, in SIW electromagnetic waves are limited to metal layers and parallel rows of metallized holes and propagate inside the structure. Fig. 2 shows the key parameters necessary for correct design of SIW-filters; $d$ — diameter of transition holes, $p$ — inter-center distance of transition holes $a$ — width of the structure, $h$ — thickness of dielectric.

If parameters of SIW-structure were calculated correctly the energy losses in transition holes will be minimal.

The SIW structure operates similarly to a conventional rectangular waveguide filled with a dielectric, with an effective width aeff. As a result, the cutoff frequency of SIW ($f_c$) coincides with the cutoff frequency of a conventional rectangular waveguide. The cutoff frequency values are set according to generally accepted recommendations for different frequency bands [5–7]. The formula for calculating the effective width of the waveguide is as follows:

$$a_{\text{eff}} = \frac{c}{2f_c\sqrt{\varepsilon}}, \tag{1}$$

where $c$ — speed of light in vacuum, $\varepsilon$ — relative dielectric constant of material. In order to ensure physical feasibility of the filter and prevent the increase in radiation losses, the diameter of each hole must be less than the distance between adjacent holes, i.e. the condition shall be met

$$d < p. \tag{2}$$

If this rule is not observed it may lead to significant radiation losses and deterioration of the overall characteristics of the filter. If the diameter of the metallized holes is selected correctly it may reduce the amount of electromagnetic energy leakage outside the structure.

Given the production constraints, such as time costs and manufacturing complexity, feasibility of SIW structure directly depends on the number of transition holes. If there are too many transitions, it will complicate the production process and may result in lower fabrication precision, which negatively affects the performance of the filter. Therefore, it is important to observe certain restrictions on the number of transitions relative to the wavelength.

According to the data given in literature [8], the number of transition holes in SIW structure should be such that the total area of these holes does not exceed 20 % of the cross-sectional area of the waveguide. This limitation is related to the need to maintain a high level of shielding and minimize the radiation losses. An excessive number of holes can lead to compromised integrity of the structure and poorer effectiveness of the shielding properties of the waveguide, which, in turn, will negatively affect the transmission of electromagnetic energy and stability of the system in whole. Also, due to its structure, the phenomenon of bandwidth blocking in the operating frequency range may occur in the waveguide integrated into the substrate. Based on the above, the following double condition should be used to avoid the mentioned effects:

$$0.05 < \frac{p}{c} < 0.25. \tag{3}$$

In this case the structure width „a" may be defined as

$$a = a_{\text{eff}} + \frac{d^2}{0.95p}. \tag{4}$$

To perform necessary computations, the wavelength $\lambda$ shall first be determined. For $\sim 10$ GHz, at which the designed filter should operate the wavelength shall be about 30 mm.

Fig. 3, $a$ illustrates the diagram of resonators interaction. It helps to visually evaluate and adjust the coupling between the resonators, providing a good initial approximation for the

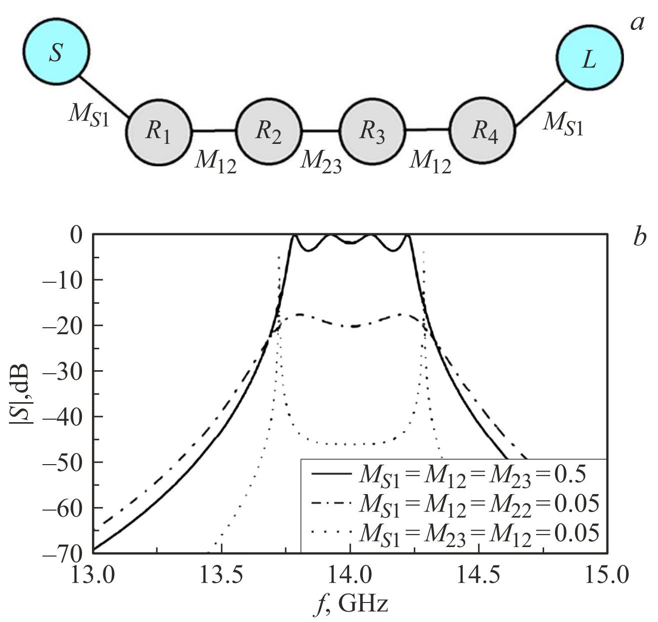


**Figure 3.** 4th order SIW-filter (*a*). MW filter resonators coupling (*b*). Frequency response at different level of coupling between resonators.

optimization function. In the diagram, the circle represents a rectangular resonator, the input *S* and the output *L* correspond to TE10 mode at the input and output, and MS1 represents connections of the resonant system with the source and load. The coupling between the resonant system and neighboring resonators is designated as M12 and M23. Each resonator is connected to the previous one and the next one through the corresponding transition elements, which ensure the transfer of electromagnetic energy between the resonant sections. This configuration allows controlling the filter bandwidth. Fig. 3, *b* shows the amplitude-frequency response at various degree of coupling between the resonators.

The amplitude-frequency response of the filter demonstrates the dependence of the output signal amplitude on the input signal frequency at different levels of coupling between the resonators. These graphs show how the shape of the bandwidth changes depending on the magnitude of the coupling coefficient between the resonant elements. With weak coupling between the resonators, the bandwidth is narrow, with steep slopes, which ensures high selectivity of the filter, however, this may be accompanied by an increase in insertion losses and a decrease in throughput. Strong coupling, on the contrary, expands the bandwidth, making the filter more versatile for processing broadband signals, but at the same time reducing its selectivity. The choice of the optimal coupling depends on the requirements of the specific task and the desired filter characteristics.

Reducing the geometry plays a key role in the design of resonant cavities and SIW filters. The size of SIW cavity is determined by the resonant frequency of the main mode, however, various solutions have been proposed to reduce the size of the cavity. The bending SIW structures make it possible to reduce the size by half, bending the structure around the metal partition and thereby creating a two-layer topology.

It was mentioned earlier that the correct choice of the diameter of through holes and periodic distance between transition holes is crucial in reducing radiation losses in SIW structure. These parameters have a direct impact on the quality of shielding and propagation of electromagnetic waves inside the waveguide. It should also be noted that the width of the structure determines the cutoff frequency for the main (lower-order) SIW operating mode. The correct setting of a allows to fine-tune the filter's operating frequency band and avoid undesirable effects associated with the excitation of higher modes.

It is also extremely important to design a junction transition when integrating SIW with other types of transmission lines, such as microstrip and coplanar lines. Effective signal transmission between these different structures is often difficult, since each of the structures is characterized by its own unique modes of electromagnetic waves propagation and electrical parameters.

The main goal of developing a high-quality transition element is to activate the appropriate transmission mode in SIW resonator, while minimizing power loss and ensuring stable operation over the widest possible frequency band [9–11].

As a result, a special transition was designed that ensures optimal placement of the input and output connectors (port *1* and port *2*), as shown in Fig. 4. Such a transition helps to convert the microstrip line into SIW, and to reduce losses in the transition, a 45-degree transect is used in a Γ-junction.

To improve transition, the frequency band, architecture, and materials used were taken into account in order to develop a correct transition element that does not distort the signal during the transition from the source to the load.

Based on SIW technology, a bandpass filter was developed in CST Studio Suite software.

To implement a method that minimizes central coupling with a higher-order mode, two diaphragms and two resonators are used in the filter, as shown in Fig. 5. This configuration makes it possible to effectively suppress higher-order modes, which leads to improved filter selectivity and

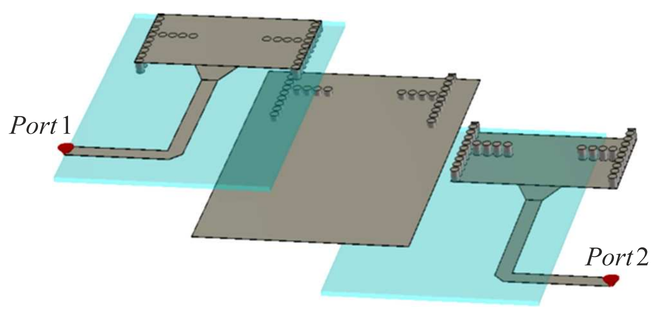


**Figure 4.** Junction between the microstrip line and SIW-structure.

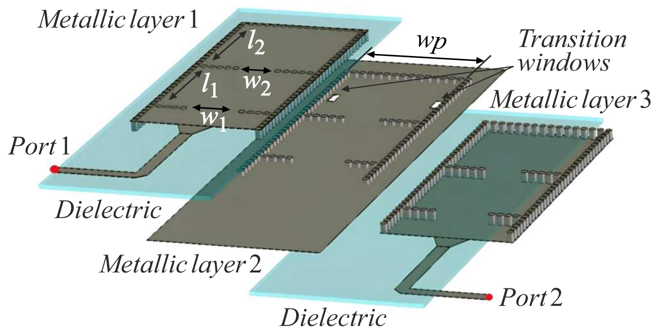


**Figure 5.** Topology of a double-layer SIW-filter.

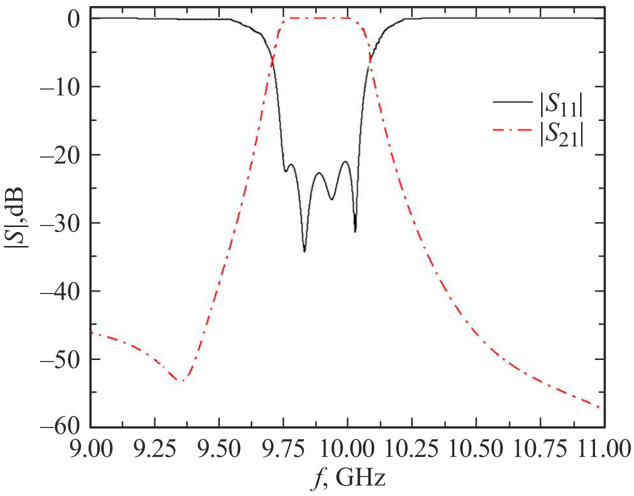


**Figure 6.** Amplitude-frequency response of the band-pass filter.

reduced spurious resonances. This means that there are only two central cavities. The cavities are arranged one on top of the other, eventually forming a two-layer structure.

Based on presented data, the device is made on a substrate with a dielectric constant of $\varepsilon = 2.2$ and a layer thickness of $h = 0.508$ mm. Metal used for grounding, — copper material 35 $\mu$m thick. The parameters of the transition windows that connect the upper and lower layers of the structure are $l_s = 2.4$ mm and $ws = 0.9$ mm. The length and width of the resonators are equal 13.58, 14.51 and 15.3 mm, respectively. Dimensions of diaphragms: $w_1 = 6.53$ mm, $w_2 = 4.98$ mm. Calculations were performed for a filter tuned to a center frequency of 10 GHz. The wavelength-dependent parameters were determined using well-known formulae: $d = 0.8$ mm, $a = 13.8$ mm, $p = 1$ mm.

For the developed bandpass filter model, electrodynamic modeling was performed using CST Studio Suite software package. The results obtained are presented in the form of frequency dependencies of the scattering matrix in Fig. 6, where S- parameters of the filter are shown: $|S_{11}|$ — reflectance coefficient and $|S_{12}|$ — transmission coefficient. The analysis of $S$-parameters allows estimating the main characteristics of the filter, such as bandwidth, attenuation level in the barrier band and selectivity. The reflectance coefficient $|S_{11}|$ shows the fraction of power that returns back to the signal source from -due to inconsistencies in the impedances at the filter input. Low values indicate good consistency, which contributes to the efficient passage of the signal through the filter. The transmission coefficient $|S_{12}|$ characterizes the ratio of the power passed through the filter to the power received at its input. High values in the bandwidth demonstrate low power loss when the signal passes through the filter. At the same time, low values outside the bandwidth confirm the effective suppression of unwanted frequencies.

The modelling results indicate that the model of SIW-waveguide reduces transmission losses to 0.5dB in the required frequency range near 10 GHz.

The curve of $S$-parameters clearly illustrates that the filter has a bandwidth of 250 MHz, whereas the reflectance coefficient doesn't exceed $-20$ dB, and the transmission coefficient lies in the range from $-0.2$ to $-0.5$ dB.

Losses in SIW structures are higher than in traditional rectangular waveguides due to the presence of a dielectric substrate. The main contribution to the total losses is made by ohmic losses due to the presence of dielectric material of the substrate and the transition holes. Nevertheless, proper design of SIW-components makes it possible to minimize these effects and ensure high efficiency of the filter in a given frequency range.

## 2. Fabrication

The filter was fabricated using metal sputtering technology on a dielectric substrate of type FR-4. This fabrication process makes it possible to obtain a uniform coating that provides reliable adhesion and good electrical properties. Figure 7 presents the general view of the fabricated prototype filter. Additionally, the metallization of through holes was carried out by the method of full metal filling. This technology contributes to the creation of a continuous metal shield, which reduces the likelihood

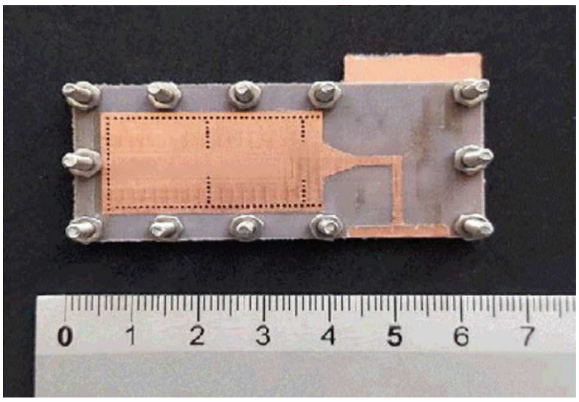


**Figure 7.** Photo of the fabricated filter on FR-4 substrate.

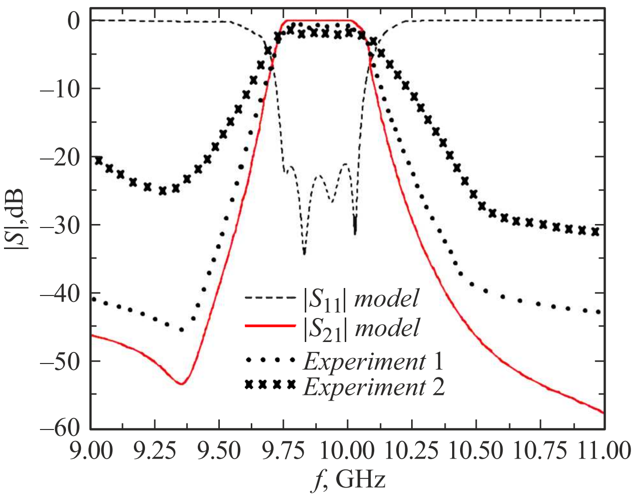


**Figure 8.** AFR of the fabricated filter prototype and its computer model compared.

of electromagnetic energy leaks and increases the overall efficiency of the filter. The methods of screw clamping and gluing between the layers were used to ensure accurate alignment and alignment of the layers.

Figure 8 shows the amplitude-frequency response of the prototype filter on the dielectric substrate FR-4 (Experiment 1) and its computer model compared. The main sources of losses in the bandwidth of this device are internal losses in the dielectric and errors that occur during production and assembly, especially during the bonding of layers.

At the next stage of research, to assess the practical applicability of the filter, it was decided to manufacture a multilayer SIW-filter on a paper substrate with a dielectric constant of 6. The dielectric layer thickness was 0.22 mm, and metallization was made using copper material 8 $\mu$m thick. For the initial synthesis of a band-pass SIW-filter on a paper substrate, the dimensions of the filter on FR-4 substrate were used, which provided a good starting approximation. It took several iterations to achieve comparable amplitude-frequency responses. Figure 8 shows the amplitude-frequency response of SIW-filter on a paper substrate (Experiment 2) in comparison with previous results. It can be seen from the graph that the bandwidth losses are approximately $-3.5$ dB, which is explained by losses caused by the paper substrate at frequencies of about 10 GHz, as well as possible inaccuracies in the filter fabrication process.

The analysis of the obtained results indicates a good agreement between theoretical calculations and experimental data. $S$-parameters of the filter prove correctness of the filter synthesis. This highlights the versatility and flexibility of the proposed design that may successfully adapt to different materials.

## Conclusion

The study of theoretical and experimental data has confirmed the possibility of developing new structures. These designs will help reduce the size and weight of the devices, while maintaining the required filters response, which opens up wide prospects for their use. Electrodynamic analysis of individual structures demonstrated rapid development of filter prototypes; the final version of the band-pass filter will require only a few iterations.

The conducted research included electrodynamic analysis and synthesis of the multilayer fourth-order bandpass filter, as well as the paper substrate filter. The difference in the amplitude-frequency response of the device depending on the dielectric substrates used was also reviewed.

As part of the study, two key issues were successfully resolved: doubling the filter length and doubling its height. The results of a comparative analysis of the amplitude-frequency response confirmed a good consistency between theoretical and experimental data, which opens up prospects for further research in this field.

As a result, SIW technology successfully integrates the advantages of both waveguide and microstrip elements. The use of SIW technologies provided and extensive potential for adapting numerous algorithms and methods originally developed for traditional all-metal rectangular waveguides to new devices.

In addition, the paper states that it is possible to fabricate devices on flexible dielectric boards, which is another way to reduce the weight and geometry that are critical for the modern systems. Thus, SIW technology continues to prove its relevance and practical importance in creating innovative solutions for the radio electronics industry.

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### Conflict of interest

The authors declare that they have no conflict of interest.

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