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Bandpass filters based on SIW and ESIW-technologies

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High-performance microwave filters manufactured using two different technologies — Substrate Integrated Waveguide (SIW) and Empty Substrate Integrated Waveguide (ESIW) — have been investigated and compared. Two filters with a center frequency of 12 GHz were designed and synthesized using SIW and ESIW-technologies, respectively, and a comparative analysis was conducted. The results of the comparison between the amplitude-frequency characteristics of the filters, obtained both through electromagnetic simulation in a computer-aided design environment and from fabricated prototypes, are presented.

Keywords: Substrate Integrated Waveguide (SIW), Empty Substrate Integrated Waveguide (ESIW), losses, Q-factor, S-parameters, bandpass filter.

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Introduction

Currently, there's a trend for development and high demand for use of high-efficiency super-high frequency (microwave — MW) filters with low insertion losses and high selectivity. This need is becoming even more urgent in view of development of space satellite communication technologies, which additionally require the miniaturization of waveguide microwave devices. Filters implemented using SIW- technology are very promising to meet such requirements.

In recent years, SIW — Substrate Integrated Waveguide [1] have gained much attention. Compared to planar circuits, these devices provide high Q factor of resonators, thus, ensuring lower operating losses, and are characterized by low cost, compactness, ease of fabrication, and the ability to integrate with other planar circuits on one substrate. Despite all these benefits, SIW-waveguides, however, have some drawbacks. Their loss and Q-factor characteristics are inferior to the conventional waveguides, mainly due to the propagation of waves through a dielectric substrate, which inserts additional losses into the frequency characteristics of the device.

To create SIW-filters, a dielectric substrate is used, enclosed between metal layers connected by an array of metal pins, which forms a specific waveguide structure. This method allows to maintain the benefits of planar technologies, while simultaneously improving the parameters of resonators.

More recently, an innovative technology — integrated waveguides with an empty substrate, known as ESIW (Empty Substrate Integrated Waveguide), has been developed [2]. This technology is aimed at mitigating the losses associated with the use of dielectric materials which is ensured by a special design where an air space is used instead of a conventional dielectric substrate. ESI waveguides consist of an empty substrate and metallized walls covered with metal caps on top and bottom, which minimizes the influence of the dielectric and thereby significantly increases the efficiency of signal transmission at high frequencies. This technology gives new possibilities for creating highly efficient microwave devices with improved frequency characteristics.

One of the key advantages of ESIW technology is a significant reduction in losses due to the absence of a dielectric in the substrate, which increases the efficiency and stability of devices. Additionally, thanks to the possibility of easy integration with other circuits on the same substrate, ESIW opens up new possibilities for creating highly efficient and compact microwave devices, becoming one of the most promising areas in this field.

Such know-how paves the way for creation of more advanced and highly efficient next-generation microwave systems, which is especially important in the context of ever-increasing requirements to performance and efficiency of electronic devices.

1. SIW-technology

Since the early 2000s, considerable attention has been paid to research and development in the field of design and modeling of devices fabricated using SIW-technology. In this period efficient methods have been developed, facilitating transition from microstrip lines to SIW-structures [3], as well as other planar transitions [4–7]; filters [8–13], couplers [14–16], diplexers [17,18], multi-ports [19], circulators [20,21] and antennas have been synthesized [22–27].

The propagation of electromagnetic waves inside SIW-structures is identical to propagation in rectangular waveguides, and the basic mode is equivalent to TE_{10} mode of the rectangular waveguide [28].

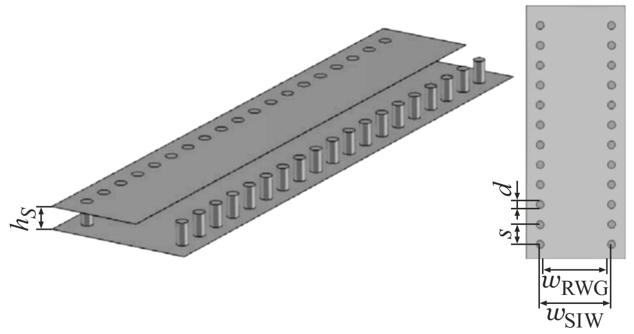

Figure 1. Classic SIW-structure.

A rectangular waveguide is generally characterized by parameters such as length a and width b, and its cutoff frequency depends on these values. In SIW structure the condition $a \gg b = h$ is met, where h — height of dielectric substrate. This ratio makes it possible to simplify the dependence of the cutoff frequency, making it determined only by the parameter IF x 5xE:

$$f_{c\_\mathrm{RWG}} = \frac{1}{2\pi\sqrt{\mu\varepsilon}}\sqrt{\left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2} \rightarrow f_{c\_\mathrm{SIW}} = \frac{1}{2a\sqrt{\mu\varepsilon}}. \quad (1)$$

The experimentally obtained formulae for the equivalent width of a classical rectangular waveguide, which has a height and dielectric constant similar to SIW-structure (Fig. 1), are represented as follows [29]:

$$W_{\mathrm{SIW}} = W_{\mathrm{RWG}} + d^2/(0.95h_S), \quad (2)$$

where W_{SIW} and W_{RWG} — width of SIW-structure and of equivalent classic rectangular waveguide, respectively d and h_S — diameter and height of metallic cylinders that form the walls of the waveguide structure:

Expression (2) has an error $\pm 5\,\%$ when the ratios $h_S < \lambda_0\sqrt{\varepsilon}/2$ and $h_S < 4d$ are provided, where λ_0 — wavelength in free space, ε — relative dielectric permittivity [29].

Experimentally, in [30], we obtained ratios with an error of $\pm 1\,\%$, which look like this:

$$W_{\mathrm{RWG}} = W_{\mathrm{SIW}}\left(\xi_1 + \xi_2/\left(\frac{s}{d} + \frac{\xi_1 + \xi_2 - \xi_3}{\xi_3 - \xi_1}\right)\right), \quad (3)$$

where

$$\xi_1 = 1.0198 + \frac{0.3465}{\frac{W_{\mathrm{SIW}}}{S} - 1.0684}, \quad (4)$$

$$\xi_2 = -0.1183 - \frac{1.2729}{\frac{W_{\mathrm{SIW}}}{S} - 1.2010}, \quad (5)$$

$$\xi_3 = 1.0082 - \frac{0.9163}{\frac{W_{\mathrm{SIW}}}{S} + 0.2052}. \quad (6)$$

In [30] a simplified empirical formula was proposed

$$W_{\mathrm{RWG}} = W_{\mathrm{SIW}} - 1.08\frac{d^2}{s} + 0.1\frac{d^2}{W_{\mathrm{SIW}}}. \quad (7)$$

Generalized rules described in [31,32] have been developed for SIW-structures with complex cross-sections. These ratios are quite general, but the need for their strict implementation requires separate consideration in each specific case.

$$d < 0.2\lambda_{WG}; \quad s \le 2d, \quad (8)$$

where λ_{WG} — wavelength in the waveguide.

Correctly selected diameter of the metallized holes and the periodic distance between them is crucial for minimizing leakage losses in SIW-structures. Optimizing these parameters helps to significantly improve the efficiency of signal transmission, reducing unwanted losses. It is important that the diameter of the holes is smaller than the gap between the transition holes, which ensures physical feasibility of the SIW structure, i.e.

$$d < s. \quad (9)$$

Since SIW is a structure with periodically controlled waves, it is important to avoid any electromagnetic interference in the operating bandwidth of the waveguide. Also, based on production constraints such as manufacturing time and implementation complexity, which directly depend on the number of transitions, it is recommended that the following condition be met [33]:

$$0.05 < \frac{s}{\lambda_c} < 0.25, \quad (10)$$

where λ_c is the wavelength of the transect.

Since SIW components are always integrated with other circuit elements within the system, it is important to discuss connections between devices. Transitions between planar signal transmission technologies such as microstrip lines and the structure of a waveguide integrated into the substrate are an important aspect of engineering the SIW devices. Several published articles describe SIW components with different types of input/output (I/O) connections. For example, a transition from a microstrip line to a SIW waveguide has been described using a simple narrowing section [4]. This narrowing segment connects a 50-ohm microstrip line to a SIW waveguide, converting the microstrip quasi-TEM mode into TE_{10} mode of SIW waveguide.

Coplanar waveguides (CPW) are also no less important than other issues in this study. Transition from CPW to SIW at 90° was described in [5]. In another paper, a transition between grounded CPW and SIW waveguide based on current probe was proposed [6]. The current passing through the probe creates a magnetic field corresponding to the magnetic field inside SIW waveguide. Transitions from a microstrip line to SIW waveguide in multilayer substrates were investigated and described in [7]. Figure 2 shows some of the well-known transition techniques used in the design of waveguide components integrated into a substrate.

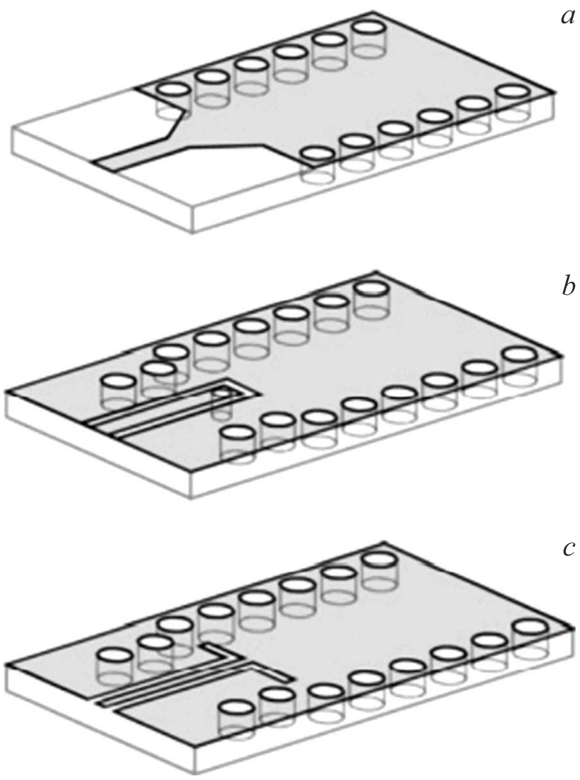

Figure 2. Well-known transitions between the microstrip line and SIW-structure: *a* — narrowing section; *b* — based on current probe; *c* — at an angle of 90°.

2. ESIW-technology

In order to combine the benefits of a rectangular waveguide with the benefits of compact and cost-effective planar circuits, a method has been developed to integrate an empty waveguide into a dielectric substrate. This method combines the high efficiency of conventional waveguides with minimal geometric size and low production costs, making it the optimal solution for the development of modern microwave devices. This method allows fabricating a simple and inexpensive structure that provides lower losses and a higher quality factor compared to similar devices made using SIW technology.

The broadband transition used in this structure makes it possible to excite a waveguide through a microstrip line, which makes it possible to connect a waveguide to conventional planar circuits. Devices manufactured using this new technique demonstrate a measured Q-factor that is four times higher than that of filters manufactured using SIW technology. This new structure was called „Empty Substrate Integrated Waveguide" (ESIW).

In ESIW technology, electromagnetic fields propagate in the air and are limited by the upper, lower and side metal walls. This structure is fabricated by cutting a rectangular hole in a planar substrate. Next, the substrate is metallized using the same technology as the metallized holes in conventional SIW-waveguides. Due to this process, the side walls of an empty waveguide are made, which effectively limit the electromagnetic fields inside the structure; an example of such a design is shown in Fig. 3.

Then thin metal plates are attached to the substrate from above and below, acting as the upper and lower covers of the waveguide. These covers not only enhance the mechanical strength of the entire structure, but also play an important role in retaining electromagnetic waves inside the waveguide, preventing their leakage and ensuring the stability of signal transmission.

Transition from the microstrip line to SIW is shown in Fig. 4, all parameters are represented in Fig. 5.

This transition may be considered as two-stage process. At the first stage, transition is performed from a microstrip line with a width of w_{ms} to a waveguide partially filled with a dielectric plate in the center along the propagation direction with a width of w_{ti}. This plate has the same dielectric constant as the microstrip line substrate. A window with a width of w_{ir} improves transition from the microstrip line to the waveguide with a dielectric plate. The

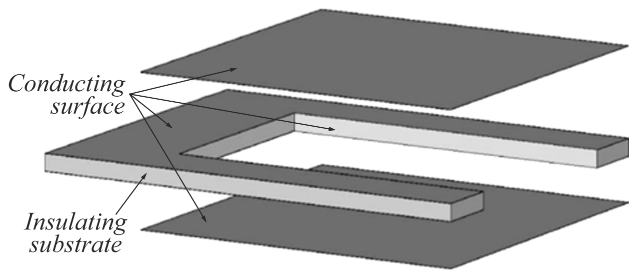

Figure 3. Principle of ESIW-structures construction.

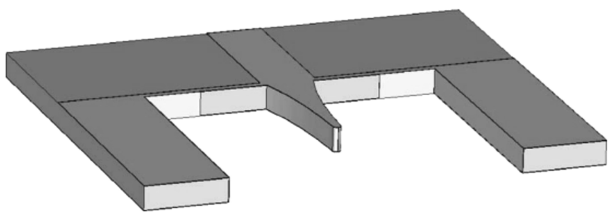

Figure 4. Transition from the microstrip line to ESIW-structure.

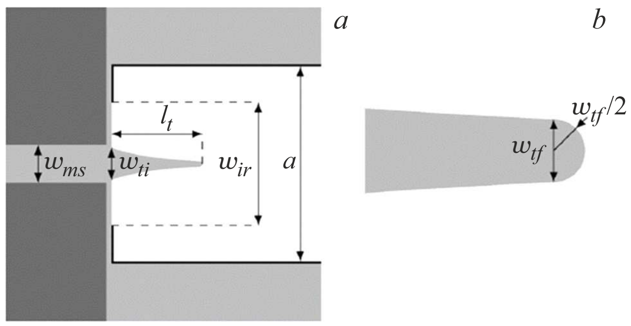

Figure 5. ESIW transition drawing: *a* — top view; *b* — rounding on the end of the structure.

window along the propagation direction is equal in size to the metallization layer width. At this stage, a small reflection occurs, since there is a significant similarity between the main modes of the microstrip line and the empty waveguide with a dielectric plate.

Immediately after the transition from the microstrip line to the dielectric plate waveguide, the plate width decreases exponentially to match the completely empty waveguide. Since the cone-shaped junction cannot have an infinite length, and also to ensure mechanical stability, its length l_t is limited, and the end is rounded. The final length after narrowing is equal w_{tf}. According to [2], the above parameters are calculated as follows:

$$l_t = \frac{\lambda_0}{4}, \quad (11)$$

$$w_{ti} = 0.8 \cdot w_{ms}, \quad (12)$$

$$w_{ir} = \frac{w_{ti} + a}{2}. \quad (13)$$

Thus, ESIW-devices are not as compact as equivalent SIW devices due to the absence of a dielectric. However, at high frequencies, the advantages of ESIW in terms of loss and quality increase. Therefore, we can conclude that ESIW is a very promising alternative to SIW, especially with a increase in frequency.

3. Modelling

Based on the described theoretical information, SIW and ESIW-filters with a center frequency of 12 GHz were synthesized from a prototype filter based on rectangular waveguides using CST Microwave Studio computer program for electromagnetic modeling. Thickness of the dielectric substrate made of Rogers 4003C was $h = 1.5$ mm with dielectric permittivity of $\varepsilon_r = 3.55$ and loss-angle tangent $\delta = 0.0027$, metallization layer thickness was $35\,\mu$m.

At the first stage of modeling, a model SIW- of a fourth-order filter was made, the drawing of which is given in Fig. 6, and Fig. 7 provides its 3D projection. The values of parameters improved using CST Microwave Studio shown in Fig. 6, are listed in Table 1. The amplitude frequency response (AFR) of SIW-filter model is shown in Fig. 8.

dx and dy parameters are individual for each specific configuration of SIW-filter and are optimized separately in order to ensure optimal matching between I/O signal lines and SIW-resonators.

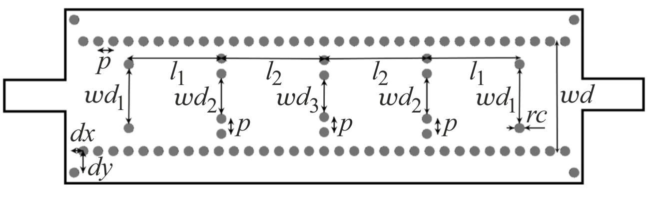

Figure 6. Drawing of SIW-filter.

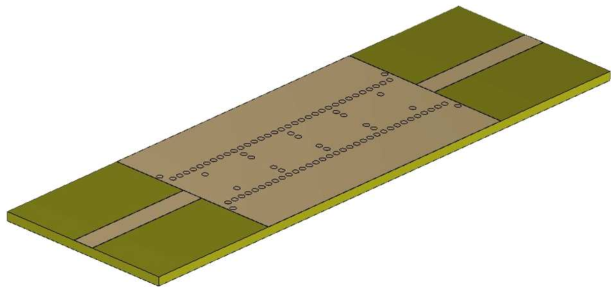

Figure 7. 3D projection of the reviewed SIW-filter.

Next, a model of ESIW-filter with a center frequency of 12GHz was made, the drawing of which is shown in Fig. 9, and in Fig. 10 — its three-dimensional projection. The improved parameters values are indicated in Table. 2. AFR of ESIW-filter model is given in Fig. 11.

For the upper and lower covers of ESIW-filter FR4 plates (Fig. 10) were used. FR4 plates were selected for reasons of simplicity and cheapness of assembly of the manufactured prototype of ESIW-filter. It is possible to achieve a lower height of ESIW-filter profile when using thin copper plates or thinner substrate plates.

4. Results

Due to the overlapping of AFR curves of synthesized filters (Fig. 12), it becomes obvious that ESIW-filter introduces lower losses, and also has a more rectangular response.

Based on modelling results, prototypes of band-pass SIW and ESIW-filters were fabricated, the photo of which is shown in Fig.13.

Fig. 14 and 15 provide comparison of modelling and experimental measurement data. The presented findings are in good agreement, but there are also differences that can be explained by radiation losses, manufacturing accuracy, and measurement errors. Also, during modelling, the connection of the input/output line to the microwave path via SMA-connectors was not taken into account.

Thus, the following conclusions can be made according to the research findings:

- ESIW-structures compared to SIW have lower insertion losses because of its structure that has no dielectric substrate in the resonance cavities area;
- SIW-structures compared to ESIW have lower sizes because of the electromagnetic wave propagation through the dielectric substrate;
- ESIW-structures emit less electromagnetic energy due to all-metal walls, unlike SIW, where there is „leakage" between metal pins.

Table 1. Values of SIW-filter parameters

Parameter	*wd*	wd_1	wd_2	wd_3	l_1	l_2	*p*	*rc*	*dx*	*dy*
Value, mm	9.97	4.88	3.18	2.29	8.46	9.38	1.50	0.50	0.83	1.66

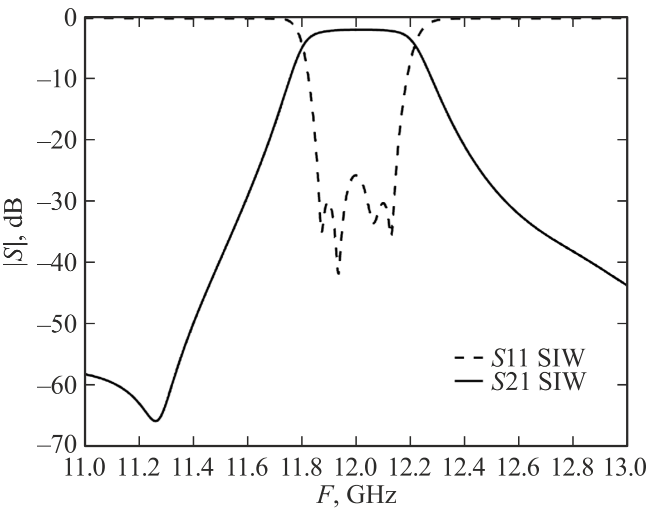

Figure 8. AFR of the studied SIW-filter.

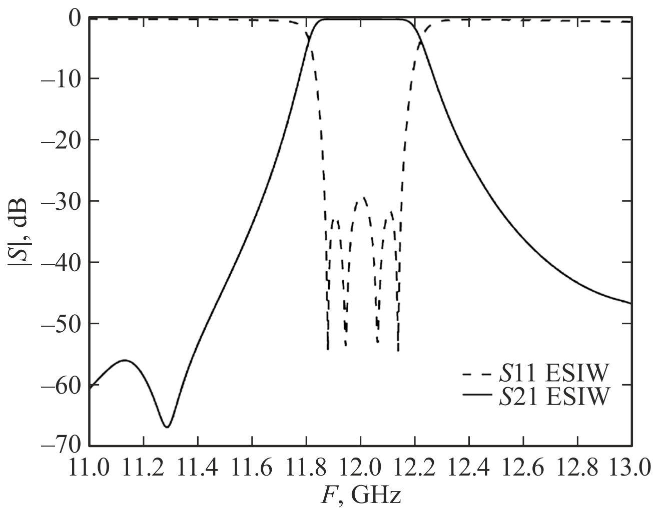

Figure 11. AFR of the studied ESIW-filter.

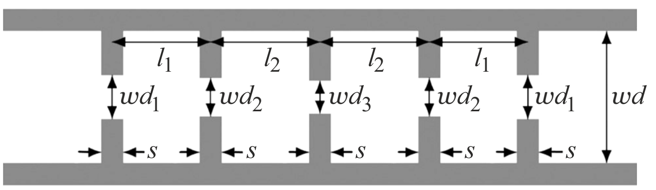

Figure 9. Drawing of the reviewed ESIW-filter.

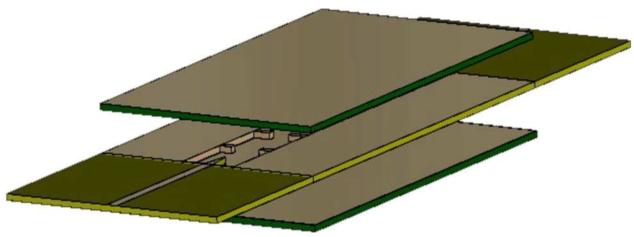

Figure 10. 3D projection of the reviewed ESIW-filter.

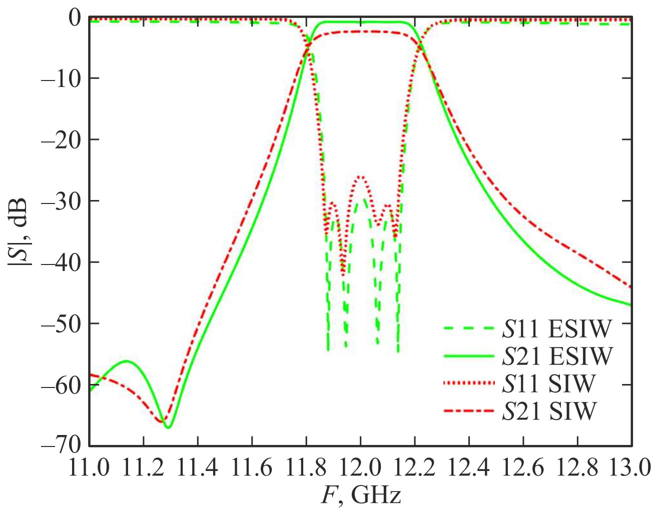

Figure 12. AFR of SIW- and ESIW-filters models compared.

Table 2. Values of ESIW-filter parameters

Parameter	*wd*	wd_1	wd_2	wd_3	l_1	l_2	*s*
Value, mm	17.46	9.64	6.51	5.98	16.12	17.94	2.03

Conclusion

In the course of the study, models of two band-pass filters with center frequencies of 12 GHz, made using SIW and ESIW-technologies were synthesized, and their prototypes were also fabricated. The compared AFR obtained during modeling and experimental measurements are in good agreement, which makes it possible for further research on this topic.

ESIW technology has both, the benefits, which are becoming more noticeable with the growth of frequency, and the drawbacks in terms of weight and size, so the use of this technology is advisable in devices that are not so weight- and size-critical, or in devices where the main criterion for selecting the technology for fabrication of waveguide filters will be minimization of the insertion loss.

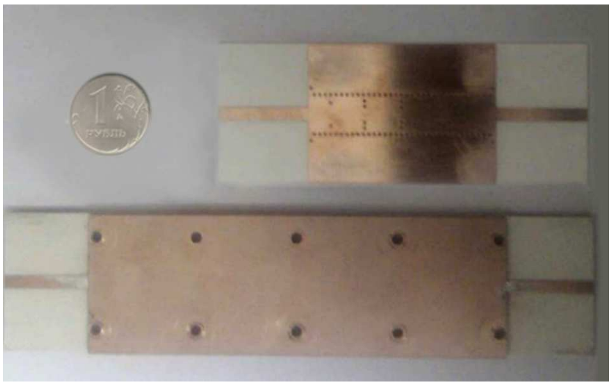

Figure 13. Photos of fabricated SIW- and ESIW-filters.

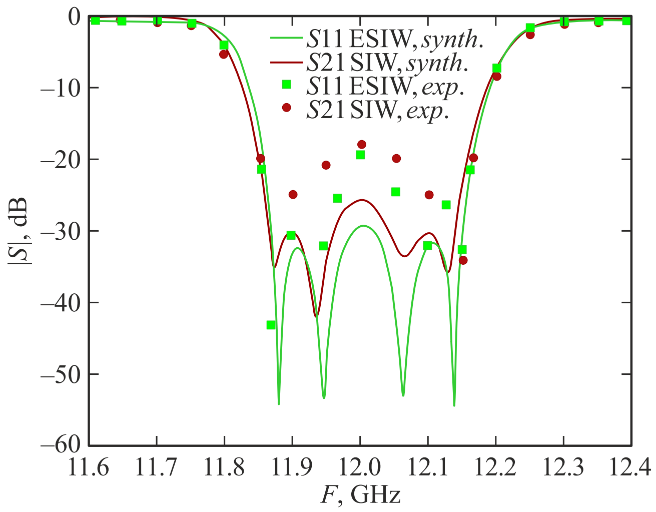

Figure 14. AFR of prototypes of SIW- and ESIW-filters compared: reflection (S11).

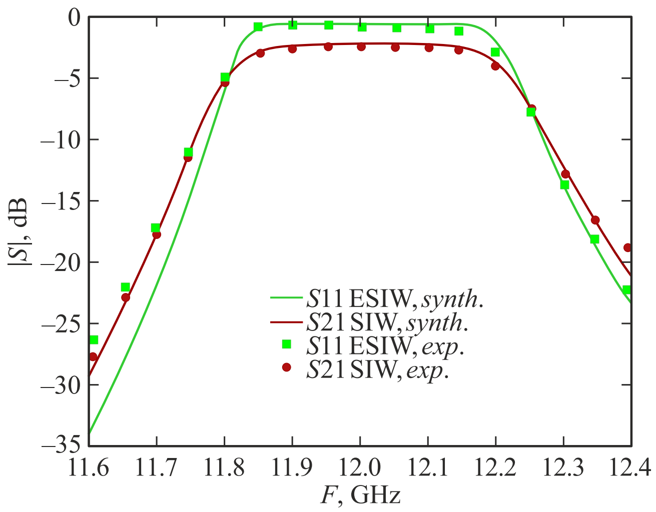

Figure 15. AFR of prototypes of SIW- and ESIW-filters compared: transmittance (S21).

In practice, based on the above, it is always necessary to seek a compromise between the benefits and drawbacks of SIW and ESIW-technologies.

Conflict of interest

The authors declare that they have no conflict of interest.

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