Scattering matrix simulation of the volumetric strip-slot transition and estimation of its frequency properties

D G Fomin, N V Dudarev and S N Darovskikh

School of Electronic Engineering and Computer Science, South Ural State University (National Research University), 76, Lenin avenue, Chelyabinsk, Russia, 454080

E-mail: Fomin95@ya.ru

Abstract. The main lines in the development of wireless communication technologies are their microminiaturization, expanding the functionality of their built-in devices, and fastening the data exchange between the components of radio engineering complexes. In this case, one of the relevant issues is the development of frequency-selective devices operating in the microwave frequency range. A promising line for the creation of such devices is their integrated design based on a volumetric strip-slot transition. This article presents theoretical and experimental research of the s-parameters of the volumetric strip-slot transition. The frequency-selective properties of the volumetric strip-slot transition were estimated based on the obtained dependences of the s-parameters. The theoretical results were obtained by creating a matrix mathematical model, by designing an equivalent circuit in a circuit-simulation program, and by the numerical simulation based on solving a boundary value problem in a strict diffraction statement, using direct numerical methods. The experimental results were obtained using a sample of the volumetric strip-slot transition. The presented results of the three types of simulation and the experimental results are in good numerical relation to each other.

1. Introduction

The main lines in the development of wireless communication technologies are their microminiaturization, expanding the functionality of their built-in devices, and fastening the data exchange between the components of radio engineering complexes. In this case, one of the relevant issues in microwave technologies is the development of frequency-selective devices operating in the microwave frequency range. Nowadays several types of filters are widely used for providing the required frequency selective characteristics. The most widespread types of filters are: filters based on boards with distributed parameters (strip and microstrip technologies), filters based on waveguide structures, filters based on microcircuits, filters based on lumped LC elements, and ceramic filters based on volumetric coaxial resonators. Filters based on boards with distributed parameters have relatively high bandwidth losses. Waveguides-based filters have significant dimensions and weight indices. Ceramic filters based on volumetric coaxial resonators have the following disadvantages: a limited operating frequency range; losses due to an external linkage between resonators; manufacturing complexity. Microcircuit filters do not always meet the power requirements. Filters based on lumped LC elements have a limited range of nominal values, which is their disadvantage [1].

A promising line for solving these issues when designing frequency-selective devices is their volume-modular construction based on the use of volumetric strip-slot transitions. The purpose of this
The article is to present the theoretical and experimental research of the s-parameters of the volumetric strip-slot transition.

2. The design of the volumetric strip-slot transition

The volumetric strip-slot transition is a device designed for contactless transmission of a microwave signal between the parts of volumetric-modular integrated circuits. The volumetric strip-slot transition consists (figure 1) of two or more strip transmission lines 1, 2 located on different sides 3-6 of a multilayer foil dielectric structure; a slot resonator 7 cut in a metal plane located between the layers with strip lines. The strip lines intersect with the slot line and end with idle mode at a distance of a quarter wavelength ($\lambda/4$) at the center frequency from the intersection point [2-4].

![Figure 1. The design of the volumetric strip-slot transition.](image)

The described design of the volumetric strip-slot transition allows to carry out the frequency-selective transmission of the microwave signal from one strip line to another one by the excitation of the slot resonator.

3. Theoretical research methods

3.1. Mathematical simulation

The equivalent circuit of the volumetric strip-slot transition was designed for the mathematical simulation [5-9]. The equivalent circuit presented in the form of a cascade connection of two-port networks and described using matrices of the ABCD-parameters and elements of the scattering matrix – the transmission and reflection coefficients in the frequency range. In the process of the equivalent circuit design the following simplifications were used:

- Strip transmission lines are considered as a two-wire line segment with the electrical length equal to $\theta_1$ and characteristic impedance equal to $Z_{\text{STRIP LINE}}$.
- Strip resonators with idle mode at the end are presented as series resistance defined as the input resistance of the transmission line with idle mode at the end. The characteristic impedance of the strip resonators with idle mode at the end is equal to $Z_{\text{STRIP LINE}}$ and the electrical length is equal to $\theta_2$.
- The slot resonator is located in the antinodes of the magnetic fields of the strip lines. Thus, the strip lines transmit microwave signal to the slot resonator by the magnetic fields directed along the slot resonator. The transformer is an element that used for the contactless transmission of microwave energy due to magnetic fields.
- The slot resonator can be presented as a parallel connection of two segments with a short-circuit mode at their ends. The length of the segments with a short-circuit mode at their ends is equal to half the length of the slot resonator $\theta_3$, the characteristic impedance is determined by the characteristic impedance of the slot transmission line and is equal to $Z_{\text{SLOT LINE}}$. 

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The equivalent circuit of the volumetric strip-slot transition is a combination of strip lines, strip resonators with idle mode at the end, transformers, and the slot resonator. The equivalent circuit of the volumetric strip-slot transition is presented in figure 2.

![Equivalent circuit of the volumetric strip-slot transition](image)

**Figure 2.** The equivalent circuit of the volumetric strip-slot transition.

The resulting matrix of the ABCD parameters of the volumetric strip-slot transition is determined by equation (1).

\[
\begin{bmatrix}
A & B \\
C & D
\end{bmatrix} = \begin{bmatrix}
\cos(\theta_1) & i\sin(\theta_1)(Z_{\text{STRIP LINE}})^{-1} \\
i\sin(\theta_1)\cos(\theta_1) & \frac{iZ_{\text{STRIP LINE}}}{\cos(\theta_1)}
\end{bmatrix} \times ... \\
\begin{bmatrix}
1 & -iZ_{\text{STRIP LINE}}\cot(\theta_1) \\
1 & 1
\end{bmatrix} \times ... \\
\begin{bmatrix}
1 & 0 \\
-iZ_{\text{SLOT LINE}}\tan(\theta_1) & 1
\end{bmatrix} \times ... \\
\begin{bmatrix}
N^{-1} & 0 \\
0 & N
\end{bmatrix} \times ...
\]

Equations (2), (3) are used to recalculate the coefficients of the resulting matrix of the ABCD parameters into the reflection (\(S_{11}\)) and transmission (\(S_{21}\)) coefficients.

\[
S_{11} = \frac{(A + B(Z_{\text{STRIP LINE}})^{-1} - CZ_{\text{STRIP LINE}} - D)}{A + B(Z_{\text{STRIP LINE}})^{-1} + CZ_{\text{STRIP LINE}} + D}
\]

\[
S_{21} = \frac{2}{A + B(Z_{\text{STRIP LINE}})^{-1} + CZ_{\text{STRIP LINE}} + D}
\]

3.2. Circuit simulation

The developed equivalent circuit of the volumetric strip-slot transition was simulated in the circuit simulation program to confirm its correctness (figure 3).

![Circuit simulation](image)

**Figure 3.** The equivalent circuit of the volumetric strip-slot transition.
3.3. Numerical simulation

The next step of the theoretical research of the volumetric strip-slot transition dealt with the numerical simulation based on solving the boundary value problem in a strict diffraction statement, using direct numerical methods. The obtained results are presented in the form of the elements of the scattering matrix - transmission and reflection coefficients.

In the numerical simulation, the volumetric strip-slot transition was implemented on a 2 mm-thick Arlon AD350 foil-clad dielectric.

The following simulation parameters were set for the above presented methods of the theoretical research of the s-parameters of the volumetric strip-slot transition:

- the central frequency is equal to 900 MHz,
- the input impedance of the strip line is equal to 50 Ohm,
- the length of the slot resonator is equal to \( \lambda/2 \) at the center frequency,
- the length of the strip resonators with idle mode at the end is equal to \( \lambda/4 \) at the center frequency.

4. Theoretical research results

The above presented theoretical simulations resulted in the following dependences of the reflection (\( S_{11} \)) and transmission (\( S_{21} \)) coefficients in the frequency range (figures 4, 5)

![Graph 1](image1.png)  
**Figure 4.** The dependences of the reflection coefficient (\( S_{11} \)) in the frequency range obtained by the theoretical research.

![Graph 2](image2.png)  
**Figure 5.** The dependences of the transmission coefficient (\( S_{21} \)) in the frequency range obtained by the theoretical research.

Thus, the mathematical, circuit, and numerical simulations proved the presence of the frequency-selective properties of the volumetric strip-slot transition. It can be concluded from figures 4, 5 that the results of the performed simulations are in good numerical relation to each other.

5. Experimental research

To provide the experimental research the sample of the volumetric strip-slot transition was developed. The sample design is presented in chapter 2 of this article. 2 mm-thick Arlon AD350 was used as a dielectric material. The photo of the sample of the volumetric strip-slot transition is presented in figure 6.

The s-parameters of the presented volumetric strip-slot transition sample were obtained using the vector network analyzer Obzor TR1300/1 (figure 7).
Figure 6. The experimental sample of the volumetric strip-slot transition.

Figure 7. The dependences of the reflection ($S_{11}$) and transmission ($S_{21}$) coefficients in the frequency range obtained by the experimental research.

6. The results discussion

The theoretical and experimental results are combined and presented in figures 8, 9.

Figure 8. The results of the theoretical and experimental research of the reflection coefficient $S_{11}$ in the frequency range.

Figure 9. The results of the theoretical and experimental research of the transmission coefficient $S_{21}$ in the frequency range.

It follows from the graphs presented in figures 8 and 9 that the theoretical and experimental results are in good numerical relation to each other. An insertion loss of about 1 dB at the center frequency can be explained by the use of poor quality RF connectors.

Table 1. Frequency-selective properties based on simulation and experiment results.

| Type of simulation       | Relative bandwidth at the level of -3 dB relative to the maximum transmission coefficient $S_{21}$, % | Quality factor $Q$ | Relative bandwidth at the level of the reflection coefficient $S_{11}$ below -20 dB, % |
|-------------------------|-------------------------------------------------------------------------------------------------|-------------------|-------------------------------------------------------------------------------------|
| Mathematic simulation   | 16.66                                                                                           | 6                 | 2.5                                                                                 |
| Circuit simulation      | 14.28                                                                                           | 7                 | 1.5                                                                                 |
| Numerical simulation    | 13.57                                                                                           | 7.36              | 1.4                                                                                 |
| Experimental results    | 11                                                                                              | 9                 | 0.85                                                                                |

7. Conclusion

In this article the theoretical and experimental researches of the s-parameters of the volumetric strip-slot transition are presented. The frequency-selective properties of the volumetric strip-slot transition are presented. The matrix mathematical model of the volumetric strip-slot transition and its equivalent
circuit are used for the theoretical research. Numerical simulation is based on the solution of a boundary value problem in a strict diffraction statement, using direct numerical methods.

The experimental research of the s-parameters of the volumetric strip-slot transition sample using the vector network analyzer is carried out. The presented results of the three types of simulations and the experimental results are in good numerical relation to each other. In particular, based on the experimental results, it is established that the relative bandwidth of the volumetric strip-slot transition at the level of the reflection coefficient $S_{11}$ below -20 dB is equal to 0.85 % relative to the center frequency; the relative bandwidth at the level of -3 dB relative to the maximum transmission coefficient $S_{21}$ is equal to 11% and the quality factor Q is equal to 9.

The results of this research indicate that the volumetric strip-slot transition has specific frequency-selective properties and can be used in a wide range of microwave devices in radio engineering systems. The main advantage of the volumetric strip-slot transition is its design simplicity while maintaining its functional purpose.

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