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Method of configuring channel filters of microwave multiplexers with common summing waveguide

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A method is proposed that allows independent optimization of the experimental characteristics (tuning) of channel filters included in microwave multiplexers with a common summing waveguide. It is shown that connecting an optimally selected transforming circuit to the output of a channel filter makes it possible to simulate its operation as part of a multiplexer. The method implements the software capabilities of modern vector network analyzers, which allow real-time output of the frequency characteristics of the connection of the measured filter with a virtual transforming circuit. The method was successfully tested when setting up channel filters for a prototype three-channel waveguide multiplexer/ X--band frequencies.

Keywords: waveguide, filter, multiplexer, tuning.

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Introduction

Microwave waveguide multiplexers are passive analog devices that are widely used as part of on-board relay complexes of space and ground communication systems. In particular, the waveguide output multiplexer sums frequency-spaced high-power microwave signals received at its inputs, and transmits them to the output with minimal losses and distortions. These devices are subject to strict requirements in terms of electrical parameters, operating power level, temperature stability, resistance to breakdown at low atmospheric pressure, weight and dimensions [1].

Band-pass filters (BPFs) designed for different frequency bands are the main structural elements of the multiplexer. BPFs perform the function of forming frequency channels of a multiplexer and largely determine its electrical characteristics. Currently, the topology of the output multiplexer with direct coupling of the BPF through a common summing waveguide (CSW) has become the most widespread (Fig. 1). Compared with other topologies, it ensures low signal loss and good weight and size characteristics, which is critically important for the equipment of space communication systems [2].

A feature of the common summing waveguide multiplexer is the strong mutual influence of channel BPFs on each other [3–6]. The experimental setup of the BPFs as part of an CSW multiplexer is a non-trivial multiparametric optimization problem, the solution of which requires a lot of effort and time. This is attributable to the fact that it is necessary to manipulate the tuning elements of several BPFs at once for obtaining optimal electrical characteristics of one channel. For this reason it is desirable to perform the initial configuration of the channel BPFs separately from the multiplexer, and perform the final configuration with the multiplexer. Unfortunately, this approach is associated with some difficulties.

An ordinary BPF as an independent device in the vast majority of cases should have optimal Chebyshev amplitude-frequency response (AFR) of the reflectance $|S_{11}|$ and transmission coefficient $|S_{21}|$ (Fig. $2, a$). The achievement of a defined level $|S_{11}|$ in the bandwidth while preserving the Chebyshev frequency response is the main purpose of setting up such a BPF. It is possible to use one of the well-known methods for configuring.

However, the single channel BPFs of the CSW-based multiplexer often have optimal AFR of the reflectance $|S_{11}|$ of a complex shape, very different from Chebyshev AFR (Fig. $2, b$), which hinders the achievement of the final goal of tuning and significantly complicates this process. At the same time, the attempts to achieve the best fit with the reference (calculated) and measured AFR when setting up the BPF do not guarantee obtaining the required AFR of the relevant multiplexer channel.

All this implies the need to develop methods to simplify and accelerate the optimization of experimental characteristics (tuning) of channel filters of multiplexers on the CSW. We propose a method in this paper that allows for independent tuning of each channel BPF individually by simulating its operation as part of a multiplexer, which makes it possible to reproduce the AFR of the corresponding channel of the multiplexer with good accuracy. This is achieved by using an optimally selected virtual

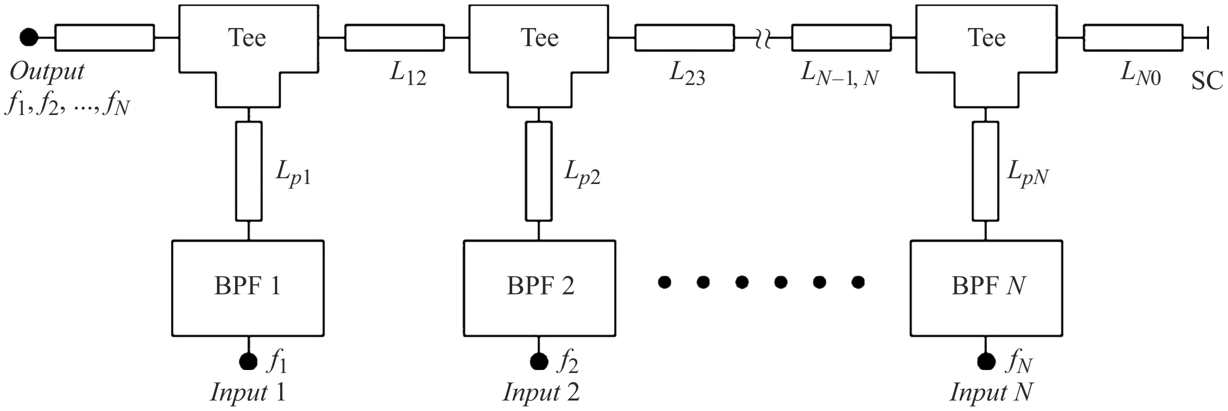

Figure 1. The topology of a multiplexer based on a common summing waveguide.

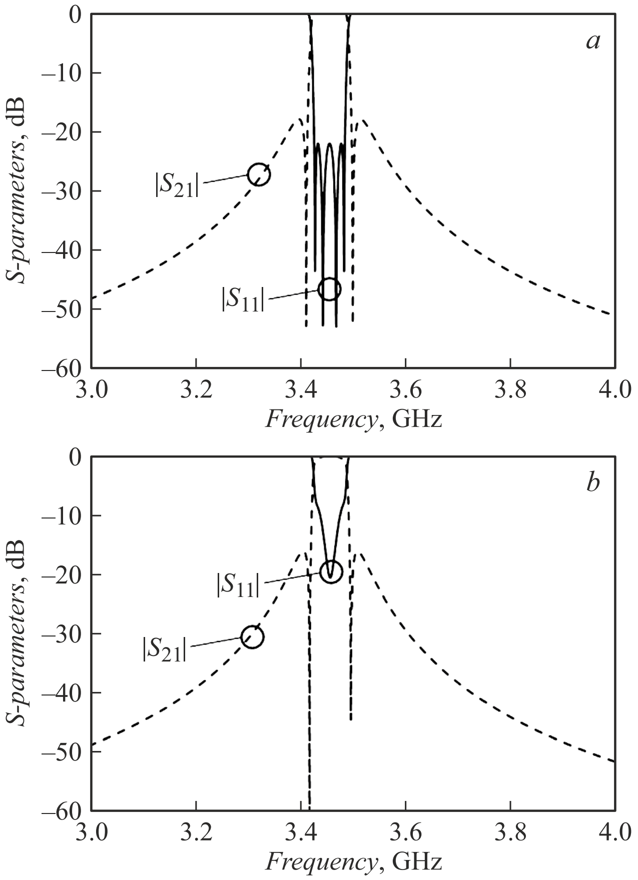

Figure 2. Optimal frequency response of a conventional BPF (*a*) and a single channel BPF (*b*).

transforming circuit i which is connected to the measured BPF using the software capabilities of the vector circuit analyzer. The proposed method was successfully tested and showed high efficiency using the example of tuning of channel BPFs intended for use in a prototype of a three-channel waveguide multiplexer of the X-frequency band.

1. Modern bandpass filter tuning methods

Tuning is a crucial stage of the production of microwave filters, including narrowband BPFs on coupled resonators. The central frequencies of each of the resonators, as well as the magnitude of the connections between them, should be very precisely tuned to achieve the required AFR. This is a rather complicated process, often requiring a lot of experience, effort and time. Let's look at some of the most common methods of setting up the BPF.

It is often difficult to track the response of each individual resonator when measuring the characteristics of a filter in the frequency domain. However, observing the characteristics of the filter in the time domain allows determining the response of each resonator. An effective BPF tuning method is based on the measurement of the reflectance in the time domain [7].

It is necessary to have a vector network analyzer (VNA) to apply this method with the option of measuring the parameters of the scattering matrix in the time domain. The central frequency of the measured VNA range should correspond to the central frequency of the filter. It is possible to set the values of the initial and final scan time on the VNA using the expressions:

$$t_1 = -\frac{2}{\pi} \cdot \frac{f_0}{\Delta f}, \tag{1}$$

$$t_2 = \frac{(2N+1)}{\pi} \cdot \frac{f_0}{\Delta f}, \tag{2}$$

where t_1 — scan start time; t_2 — scan end time; Δf — filter bandwidth; f_0 — central frequency of filter bandwidth; N — number of resonators.

The time scan of the reflectance module of the tuned filter has several responses (dips), each of which corresponds to its own resonator. The filter setup procedure is as follows. It is necessary to ensure that the first dip in the characteristic reaches a minimum value by adjusting the tuning element of the first resonator. The second, third and all subsequent resonators should be set up in the same way. The difficulty lies in the fact that the farther away the resonator is from the input, the weaker the response from it, since part of the energy is reflected from previous resonators. Thus, the probability of incorrect tuning of last resonators increases. However, this problem can be solved by simultaneously measuring the reflectances from the input and output of the filter. The time characteristic of the reflectance from the input is used for tuning of the first resonator and the last resonator is tuned using the characteristic of the reflectance from the output. Next, the second and next to the last resonators are tuned, etc. The tuning procedure can be repeated in some cases to achieve the required electrical parameters of the filter [7].

Another method for tuning the BPF is based on measuring the group delay time (GDT) associated with the reflectance from the input. It is known that the GDT describes the nonlinearity of the phase frequency response:

$$\tau_{11} = -\frac{d\varphi_{11}}{d\omega}, \tag{3}$$

where φ_{11} — phase of the reflectance from the input (S_{11}), ω — circular frequency.

The values of the GDT (τ_{11}^{i}) at the central frequency of the BPF for N of related resonators can be calculated by obtaining the values of the parameters of the low-pass prototype filter (g_i) using the known ratios [8]. The following expressions are used for this purpose [9]:

$$\tau_{11}^{1} = \frac{4g_0g_1}{2\pi\Delta f}, \tag{4}$$

$$\tau_{11}^{2} = \frac{4g_2}{2\pi\Delta f g_0}, \tag{5}$$

$$\begin{cases} \tau_{11}^{i} = \frac{4g_0(g_1+g_3+\ldots+g_i)}{2\pi\Delta f} & \text{for odd } i \text{ values}, \\ \tau_{11}^{i} = \frac{4(g_2+g_4+\ldots+g_i)}{2\pi\Delta f g_0} & \text{for even } i \text{ values}, \end{cases} \tag{6}$$

where $i = 3\ldots N$.

The tuning method includes the following steps:

— connection of the last BPF resonator using a shorted circuit;

— tuning of the first resonator so that the value of the GDT at the central frequency matches the calculated value;

— tuning of the second resonator so that the value of the GDT at the central frequency matches the calculated value, and the characteristic of the GDT is symmetrical relative to the central frequency;

— the process is repeated for all resonators except the last one;

— tuning of the last resonator based on the AFR of the reflectance module until the required characteristics are achieved. If the number of resonators is odd, then the last resonator should be opened, and if the number of resonators is even, then the last resonator should remain short-circuited [9,10].

Another method proposed by the authors of Ref. [11] allows configuring the BPF with two-mode cylindrical volumetric resonators [12–14]. The essence of the method lies in the fact that the process of tuning of the BPF with n tuning elements (screws) can be divided into stages, each of which involves only one screw. At the same time, if the optimal geometry of the BPF is already known, it becomes possible to build three-dimensional numerical electrodynamic models corresponding to each stage of tuning and differing in the number of screws:

— BPF model without screws;

— BPF model with the first screw inserted to the optimal depth H_1;

— waveguide BPF model with the first screw inserted to the optimal depth H_1 and the second screw inserted to the optimal depth H_2;

— repetition of this procedure until all screws are inserted into the BPF model to the optimal depth $H_1, H_2, \ldots H_n$ [11].

A set of $n + 1$ reference AFR is obtained after analyzing all the numerical models. Then these characteristics can be loaded into a vector network analyzer (VNA) and used for experimental tuning of the corresponding BPF using the same procedure. It is necessary to achieve a maximum match with the measured and reference frequency response at each stage, by introducing a new screw into the BPF and adjusting the screw depth. A minimum tuning is required, as a rule, to obtain the required AFR after insertion of all screws into the BPF.

2. Method for optimizing the experimental characteristics of channel filters

We propose an effective method for optimizing the experimental characteristics (tuning) of channel BPFs separately from the multiplexer. The idea of the method is to be able to simulate its operation as part of a multiplexer when measuring a single channel BPF. It is necessary to connect an optimally selected transforming circuit (TC) to the BPF for this purpose (Fig. 3).

Let's consider the structure of the multiplexer on the CSW (Fig. 1). The structure will be transformed into a two-port TC if the channel BPF 1 is removed from the multiplexer structure and an idle mode (XX) is created at the inputs of the remaining channel BPFs (Fig. 4). Now, if port 1 of the TC is connected to port 2 of the channel BPF 1 (Fig. 3), the AFR of the reflectances $|S_{11}|$ and $|S_{22}|$ of the resulting connection should reproduce as accurately as possible the AFR of the reflectances from the input

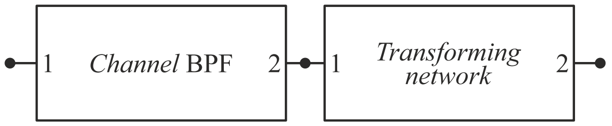

Figure 3. Single channel BPF connected to a transforming circuit.

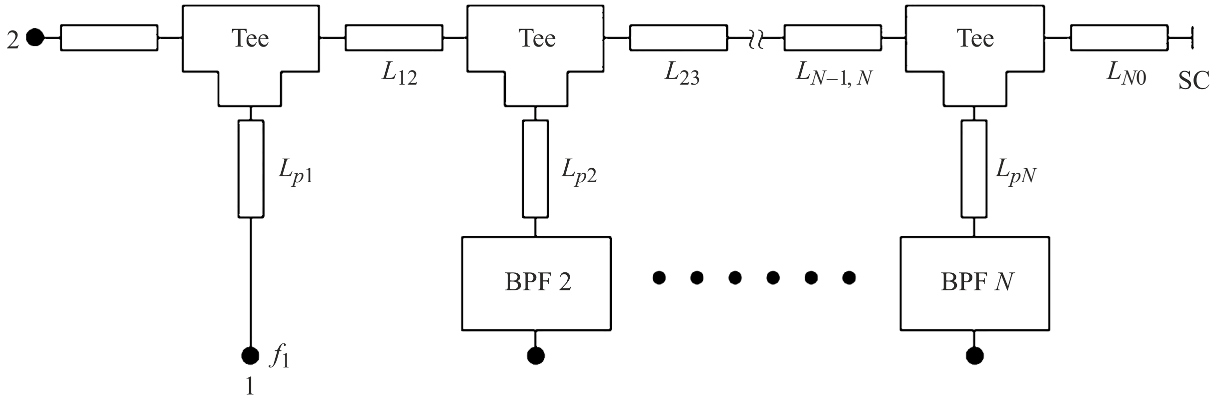

Figure 4. Transforming circuit for channel BPF 1.

and output of the corresponding channel of the multiplexer. Therefore, the purpose of setting up a solitary channel BPF becomes certain — achieving the required values of $|S_{11}|$ and $|S_{22}|$ in channel bandwidth. It is easy to see that tuning a separate channel BPF is much easier compared with a multiplexer, since the number of simultaneously variable parameters (tuning elements) is several times less.

A numerical model of the transforming circuit should be constructed in the same way for each channel BPF multiplexer. The frequency dependences of S-parameters of TC obtained after analyzing the models can be saved to files for further use in the vector network analyzer (VNA). Modern VNA have software options that allow connecting one or more virtual transforming circuits to the port(s) of the measured device and displaying the frequency characteristics of the resulting connection in real time. Therefore, it will be possible to configure the BPF in real time in case of connection to port 2 of the single channel BPF port 1 of the virtual TC (Fig. 3). Thus, the proposed method of configuring the channel BPF involves the following steps:

— coarse tuning of the BPF using well-known methods;

— connecting a virtual TC to the BPF output port by enabling the VNA software option and downloading the corresponding file with frequency dependencies of S-parameters;

— BPF tuning using AFR of the reflectances $|S_{11}|$ and $|S_{22}|$ displayed on the VNA screen for achieving a set level of $|S_{11}|$ and $|S_{22}|$ in the bandwidth of the corresponding channel of the multiplexer.

After setting up all channel BPFs and assembling the multiplexer, its frequency characteristics should be close enough to optimal, as a result of which further tuning of the multiplexer as a whole is greatly simplified.

3. Experimental testing

The proposed method has been successfully tested in the experimental tuning of channel BPFs with two-mode cylindrical resonators, which are part of the prototype of a three-channel waveguide multiplexer on the CSW of X-frequency band (Fig. 5). Bandwidth of the multiplexer channels: 7494.5−7535.0 MHz; 7402.0−7438.0 MHz; 7330.0−7371.5 MHz. Main requirements for electrical parameters: isolation between channels of more than 20 dB, direct bandwidth losses of less than 0.6 dB, reverse input and output losses of more than 20 dB.

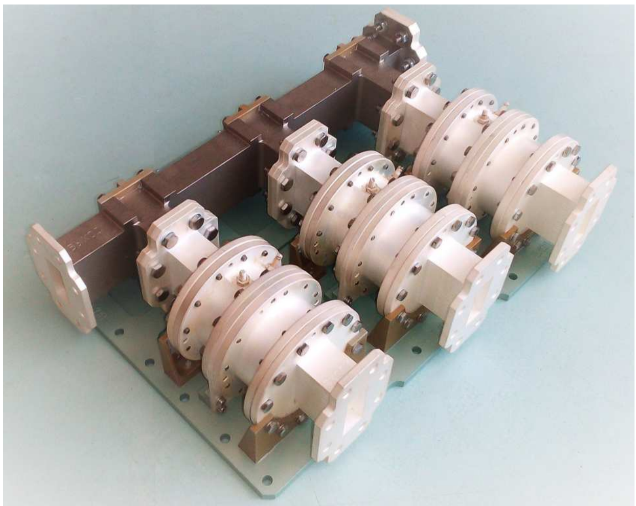

Figure 5. Prototype of a three-channel waveguide multiplexer of X-frequency band.

Each channel BPF contains two dual-mode cylindrical resonators, which is equivalent to four links of a classical filter, and also has six tuning elements (screws). This configuration is sufficient to obtain the required electrical parameters of the multiplexer, which was confirmed during its synthesis.

S-parameters of the virtual TC obtained after numerical simulation for all three channel BPFs were saved to Touchstone format files (*.s2p).

Measurements of S-parameters and tuning of the BPF were performed using the VNA „Rohde&Schwarz“ ZVA40

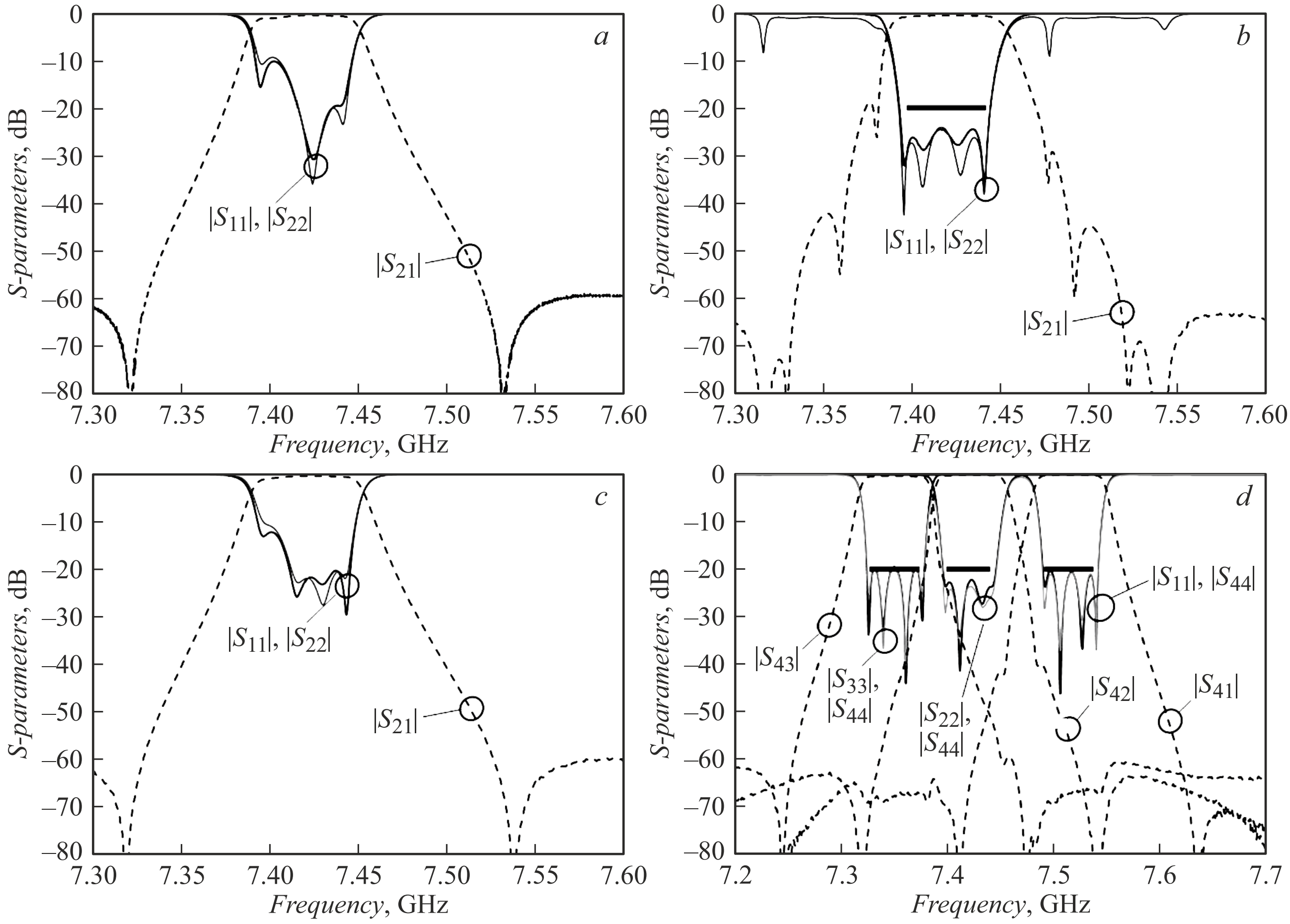

Figure 6. Screenshots of the vector analyzer of circuits with frequency response: after performing coarse tuning of the BPF (*a*); after connecting the virtual transforming circuit and fine tuning of the BPF (*b*); after disconnecting the virtual transforming circuit (*c*); multiplexer assembly (*d*).

using coaxial waveguide junctions and a waveguide calibration kit in channel WR112. A two-port calibration was performed for ensuring high measurement accuracy using the 10-component SOLT model [15].

Let us consider the setting of the BPF channel 2 as an example. First, a coarse tuning of the isolated channel BPF was carried out using the method discussed in section 1 [11]. Then a virtual TC was connected to the measured BPF by selecting the necessary option in the VNA and downloading the corresponding file. A fine-tuning of the BPF was performed after that for achieving a predetermined level (less than -20 dB) of the frequency characteristics $|S_{11}|$ and $|S_{22}|$ in the bandwidth of the corresponding channel (7399.0–7441.0 MHz, which ensures a band margin of 6 MHz). Fig. 6, *a–c* shows screenshots of the VNA with frequency characteristics $|S_{11}|$, $|S_{22}|$ and $|S_{21}|$ at different stages of tuning of a single BPF channel 2.

The time of turning of one BPF using this method was 35–40 min. A prototype multiplexer was assembled after tuning of all channel BPFs and the AFR of direct losses, reverse losses of inputs and common output were measured (Fig. 6, *d*). The most important electrical parameters obtained from the measurements of the prototype: isolation between channels more than 25.0 dB, direct bandwidth losses ($|S_{41}|$, $|S_{42}|$, $|S_{43}|$) less than 0.4 dB, reverse losses of inputs ($|S_{11}|$, $|S_{22}|$, $|S_{33}|$) and outputs ($|S_{44}|$) exceed 19.4 dB. Four-port SOLT-calibration of VNA was performed to ensure high accuracy of measurement of S-parameters of the multiplexer. No additional tuning of the multiplexer was required.

Conclusion

Modern methods of BPF tuning are considered. The proposed method makes it possible to speed up the tuning of channel filters and multiplexers with a common summing waveguide. The method allows obtaining electrical characteristics of the multiplexer that are close to optimal, while each channel filter is configured separately from the multiplexer. Thus, the complex task of configuring a multiplexer is divided into several simpler ones. The method showed high efficiency of tuning of channel BPFs for a prototype of a three-channel waveguide multiplexer of

X-frequency band. The time of tuning time of one channel filter was 35–40 min.

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Conflict of interest

The authors declare that they have no conflict of interest.

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