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A Ku-band satellite communication input multiplexer based on twelfth order waveguide bandpass filters

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A four-channel Ku-band multiplexer for a satellite communication system has been developed, based on domestically produced components. The central frequencies of the channel passbands are 12.70, 12.74, 12.78 and 12.83 GHz, and their fractional bandwidths are $\sim 0.29\,\%$, measured at a level of -1 dB from the minimum loss level. High frequency selectivity of the channels in the multiplexer is achieved by using twelfth-order waveguide bandpass filters, in which two attenuation poles are formed to the right and left of the passband to increase selectivity. A miniature input filter of the multiplexer with a passband of $11.8-13.7$ GHz, manufactured on coaxial resonators, provides an extended (over 35 GHz) high-frequency stopband with a suppression level of at least 60 dB. The results of mechanical and climatic tests of the created multiplexer confirm its compliance with the requirements for onboard satellite communication devices.

Keywords: multiplexer, band-pass filter, coaxial resonator, circulator, isolator.

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Onboard repeater systems are one of the most important types of payload for current spacecraft. This radio equipment is installed on satellites and designed to receive signals from transmitting earth stations of satellite communication systems, amplify these signals, and transmit them in the direction of receiving earth stations. Most modern onboard repeater systems are multi-channel. Channels are understood here as a set of receiving and transmitting equipment that retransmits signals in specified frequency bands formed by channel band-pass filters (BPFs), which serve as the basis for input and output multiplexers [1–4]. As is known, when data are transmitted via narrow-band channels, the requirements for linearity of the characteristics of high-power output amplifiers are relaxed significantly, allowing repeaters to operate with a relatively high efficiency. It is evident that the requirements for the characteristics of output multiplexers are also relaxed in this case. However, particularly high requirements are imposed on the selectivity of channel filters of input multiplexers and on the linearity of their phase-frequency characteristics. In the present study, we report the results of examination of a Ku-band four-channel input multiplexer built from components produced in Russia. These multiplexer is specific in using highly selective twelfth-order channel BPFs [5] and a miniature input fourth-order harmonic filter of an original design [6]. The metal case of the harmonic filter houses metal resonator rods that are connected at one end to the case. The open ends of metal rods are inserted with a small gap into blind holes on the opposite side of the case that are coaxial with these rods.

The structural diagram of the designed multiplexer is shown in Fig. 1. The received group signal goes through the input isolator to the input BPF (its photographic image is shown in inset *a*), which ensures signal transmission with minimal losses of 0.16 dB in the operating $12.6-12.9$ GHz frequency band. At the same time, it provides suppression of high-frequency interference up to frequencies above 35 GHz with an attenuation level no lower than 60 dB. The signal is then divided by the designed two-section bridge power divider (its photographic image is shown in inset *b*) into two equal parts and is fed to the upper and lower arms of the circuit (Fig. 1). Note that matched load is connected to the fourth connector visible in the photo of the divider. Circulators and channel band-pass filters (a photographic image of one of them is shown in inset *c*) are then used to isolate odd and even channels from the upper and lower arms, respectively. Note that FKVN2-71 circulators and isolators based on them were produced by the Ferrite-Domen Scientific Research Institute (St. Petersburg, Russia).

The main purpose of channel BPFs is maximum suppression of closely located adjacent channels, which is achieved through the use of filters with frequency responses (FRs) with steep slopes. Channel filters should also feature minimum FR ripple in the operating frequency band and high linearity of the phase-frequency characteristic; i. e., minimum unevenness of the group delay (GD) must be provided. When an input multiplexer is designed, the above characteristics of channel filters are normally prioritized over

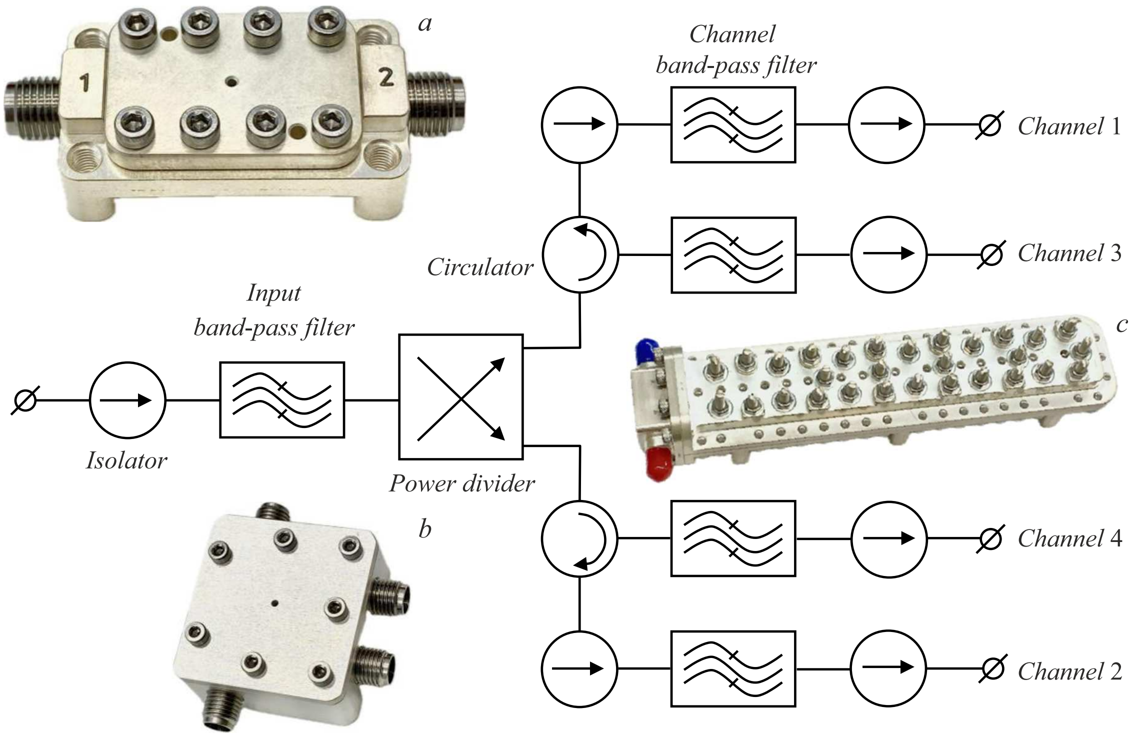

Figure 1. Structural diagram of a four-channel satellite communication multiplexer. Insets *a*, *b*, and *c* present photographic images of the fourth-order input filter, the two-section bridge divider, and the twelfth-order channel filter, respectively.

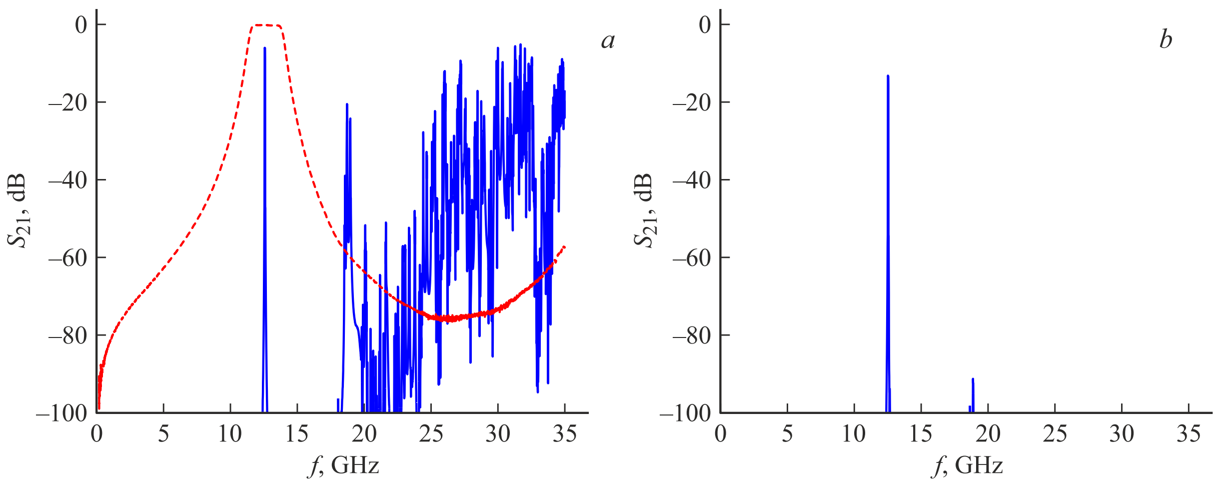

Figure 2. *a* — Measured FR of the channel (solid curve) and input (dashed curve) BPFs; *b* — measured FR of the first channel of the multiplexer.

the magnitude of signal attenuation in the operating frequency band. As a result, the total active losses in channels may exceed 10 dB. They are a combination of losses in the input filter, the bridge divider (≥ 3 dB), circulators (0.4 dB), isolators (0.4 dB), channel filters (~ 6 dB), and connecting coaxial lines. However, since that the input multiplexer is located after the low-noise amplifier, its thermal noise does not produce a significant contribution to the overall noise temperature of the device.

The need to suppress parasitic passbands of channel filters, which, as is known, are located relatively close to the passband if these devices are built based on waveguide resonators, is one of the major problems in the design of input multiplexers. Figure 2, *a* shows the FR of a single channel filter (solid curve) measured within a wide frequency range. It can be seen that the first parasitic passband is located at a frequency of approximately 18 GHz, while the central frequency of the operating passband of the chosen filter is 12.7 GHz. However, the high-frequency stopband of the channels of the designed multiplexer is subject to rather strict requirements: it must extend to a frequency of 35 GHz with an attenuation level of more

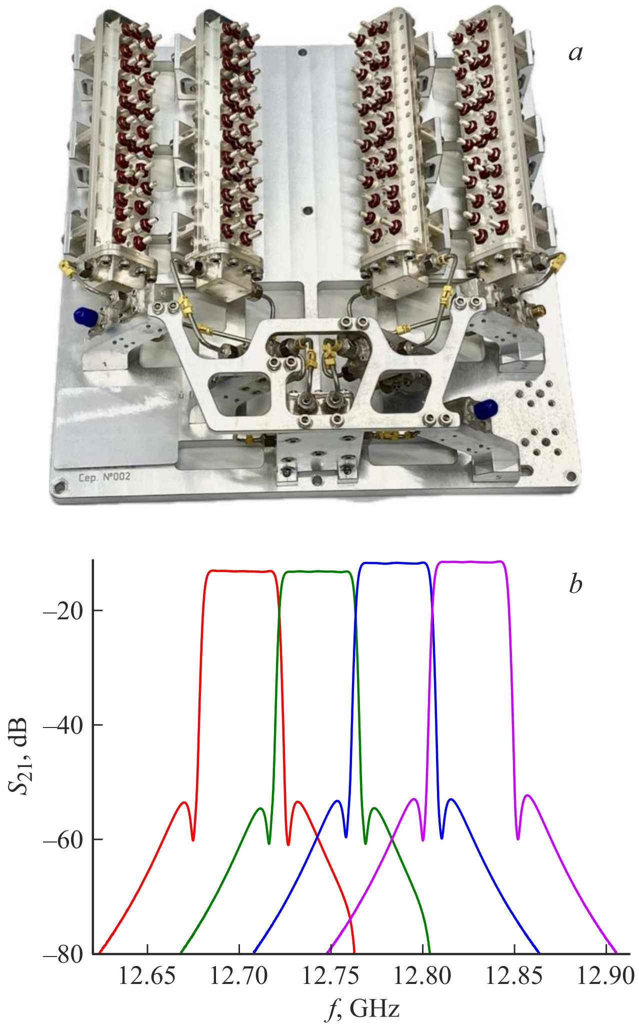

Figure 3. *a* — Photographic image of the fabricated four-channel satellite communication multiplexer; *b* — FRs of its channels measured within a narrow frequency range.

than 60 dB relative to the attenuation in the passband of multiplexer channels.

An original four-section BPF based on coaxial resonators [6], which is installed at the input of the multiplexer, was designed in order to solve this problem. The dashed curve in Fig. 2, *a* shows the measured FR of the developed input filter with fractional bandwidth $\Delta f / f_0 = 18\,\%$ and central passband frequency $f_0 = 12.7$ GHz. The minimum insertion loss in the filter passband is only 0.16 dB, while the VSWR (voltage standing wave ratio) is < 1.2. The input BPF was made of aluminum with galvanic coating of the surface with a layer of silver 6 μm in thickness. The dimensions of the filter are $30 \times 15 \times 15$ mm, and its mass is just 15 g.

Figure 2, *b* shows the FR of the first channel measured after assembling the multiplexer. It can be seen that the use of an input BPF with the above characteristics provides an attenuation level of more than 80 dB in the high-frequency stopband at frequencies up to and exceeding 35 GHz. Note that all four channels of the multiplexer have the same characteristics of the high-frequency stopband. It is also important to note that the suppression of interference in the high-frequency stopband is facilitated by attenuation introduced by circulators and isolators outside of their operating 12.6–13.3 GHz frequency band.

Figure 3, *a* shows the photographic image of the fabricated multiplexer, and Fig. 3, *b* presents the FRs of its channels measured within a narrow frequency range. High channel selectivity is achieved not only through the use of twelfth-order waveguide BPFs, but also due to the formation of two pairs of attenuation poles in the FR located symmetrically relative to the center of the passband [5]. This symmetry of positioning is ensured by four additional cross-couplings between pairs of non-adjacent resonators; two of these cross-couplings are capacitive, and the other two are inductive.

A special approach [4,5,7], which involves a certain enhancement of reflection losses in the passband of the device („predistortion technique"), was used to synthesize the FR of channel filters. It allows one to minimize FR and GD ripple ($\Delta\tau = 40$ ns) in the passband with a relatively low unloaded quality factor of rectangular waveguide resonators $Q_0 \sim 7 \cdot 10^3$ at the operating oscillation mode H_{011}. To ensure the stability of multiplexer characteristics in the operating temperature range, the channel filters were made of superinvar (32NKD steel) with a galvanically applied silver layer 6 μm in thickness. The photographic image of the fabricated channel filter is shown in inset *c* in Fig. 1.

Note that unloaded quality factor $Q_0 > 3 \cdot 10^4$ of resonators is needed to achieve the required levels of transmission coefficient ripple in the passband and suppression of interference in the stopbands if a classical twelfth-order filter with a Chebyshev FR shape is used.

Sections of semi-rigid coaxial cable with SMA connectors at the ends were used to connect all the multiplexer elements together. The base of the multiplexer is an 8-mm-thick aluminum plate, which provides the necessary structural strength under impact and vibration exposure aboard spacecraft. The dimensions of the fabricated multiplexer were $255 \times 250 \times 90$ mm, and its mass was 3.5 kg.

Thus, a Ku-band four-channel satellite multiplexer has been designed and fabricated. The device has successfully passed electrical, climatic, vibration, and impact tests. The required high levels of frequency selectivity of multiplexer channels were achieved through the use of twelfth-order waveguide band-pass filters with two attenuation poles formed on the passband slopes to increase selectivity. An extended high-frequency stopband was formed by connecting a miniature band-pass filter of an original design based on coaxial resonators to the multiplexer input. The results of a complete cycle of electrical, vibration, impact, and climatic tests confirmed that the fabricated multiplexer complies fully with the requirements imposed on onboard devices of communication satellites.

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Conflict of interest

The authors declare that they have no conflict of interest.

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