11.1

# A high-selectivity channel bandpass filter of satellite communication Ku-band input multiplexer

© B.A. Belyaev[1,2], A.M. Serzhantov[1,2], I.E. Burlakov[2,3], A.A. Leksikov[3], Ya.F. Bal'va[3], A.A. Alexandrovsky[3], S.D. Krekov[2,3], S.A. Khodenkov[1]

[1] Siberian State University of Science and Technology, Krasnoyarsk, Russia
[2] Siberian Federal University, Krasnoyarsk, Russia
[3] Kirensky Institute of Physics, Federal Research Center KSC SB, Russian Academy of Sciences, Krasnoyarsk, Russia
E-mail: belyaev@iph.krasn.ru

*Received March 22, 2024*
*Revised April 9, 2024*
*Accepted April 10, 2024*

A design has been proposed of a 12-pole waveguide bandpass filter with additional two inductive and two capacitive cross-couplings formed by corresponding small irises in metal walls between non-adjacent resonators. The central frequency of the filter passband is $f_0 = 12.73$ GHz, and its fractional bandwidth at the level of 1 dB is only $\Delta f/f_0 = 0.3\%$ with the resonators' unloaded quality factor $Q_0 = 6 \cdot 10^3$. In a traditional Chebyshev filter the unloaded quality factor of the resonator should be five times higher to obtain such characteristics. High selectivity of the device, as well as low ripple of the transmission coefficient and group delay time in the passband, is achieved by increasing reflection losses during filter synthesis. The design of the filter is intended for creating satellite communication multiplexers on its basis.

**Keywords:** bandpass filter, waveguide, resonator, cross-coupling.

DOI: 10.61011/TPL.2024.08.58906.19927

It is known that microwave filters having a narrow passband with steep slopes of the frequency response (FR) are needed to separate closely spaced channels in satellite communication systems [1]. These devices should also be compact, have good bandpass and group delay (GD) flatness, and ensure stability of characteristics under temperature variations. The formation of transmission zeros, which are also called attenuation poles, near the passband is often used to obtain steeper passband slopes [2,3]. This approach helps improve the characteristics of devices with microstrip [3], coaxial [4,5], and waveguide [6,7] resonators and, naturally, of filters based on quasi-lumped inductive ($L$) and capacitive ($C$) elements [8]. The steepest passband slopes are formed when attenuation poles are positioned symmetrically to the left and to the right of the passband. This is achieved by introducing additional capacitive cross-coupling either between the input and the output in a 4-pole filter [2] or between the second and the fifth resonators in a 6-pole filter [2,3]. However, with a relatively low unloaded quality factor of resonators in narrow-band filters, the close positioning of transmission zeros leads to an increased ripple of the transmission coefficient and GD in the passband, which is especially pronounced at fractional bandwidth below 1%.

We have designed and fabricated a new 12-pole waveguide bandpass filter with a fractional bandwidth of 0.3% and four additional cross-couplings between non-adjacent resonators. Two of these cross-couplings are inductive and the other two are capacitive. The high pole of this filter and increased reflection losses in the passband allow us to obtain, along with fine frequency selectivity, low FR and GD ripple in the passband, even though the unloaded quality factor of resonators of relatively low.

Figure 1, *a* shows the equivalent circuit of the investigated lumped 12-pole bandpass filter with resonators positioned in series and interacting via inductive coupling. A distinctive feature of this design is the presence of four additional cross-couplings. Two of them (those between the pairs of non-adjacent resonators 4, 9 and 3, 10; $k_{C4,9}$ and $k_{C3,10}$) are capacitive, while the cross-couplings between the pairs of non-adjacent resonators 5, 8 and 2, 11 ($k_{L5,8}$ and $k_{L2,11}$) are inductive. It will be demonstrated below that this arrangement of additional cross-couplings allows one to achieve both good FR and GD flatness in the passband and high selectivity due to the formation of four transmission zeros in the frequency response of the filter.

A bandpass filter was synthesized for the given frequency response based on the equivalent circuit presented in Fig. 1, *a*. For definiteness, the technical requirements for the channel filter of a Ku-band satellite communication input multiplexer were used in synthesis of the filter. The central frequency of the filter passband is $f_0 = 12.73$ GHz, and its width measured at 1 dB from the level of minimum losses, which are set at a maximum of 10 dB by the technical specifications, is $\Delta f = 36$ MHz. The GD flatness does not exceed 40 ns. The wave impedances of ports at the input and output of the filter are 50 Ω. At ±38 MHz from center frequency $f_0$ of the passband, the attenuation level should be at least 40 dB relative to the minimum filter insertion loss. Unloaded quality factor $Q_0 = 6 \cdot 10^3$ of oscillatory

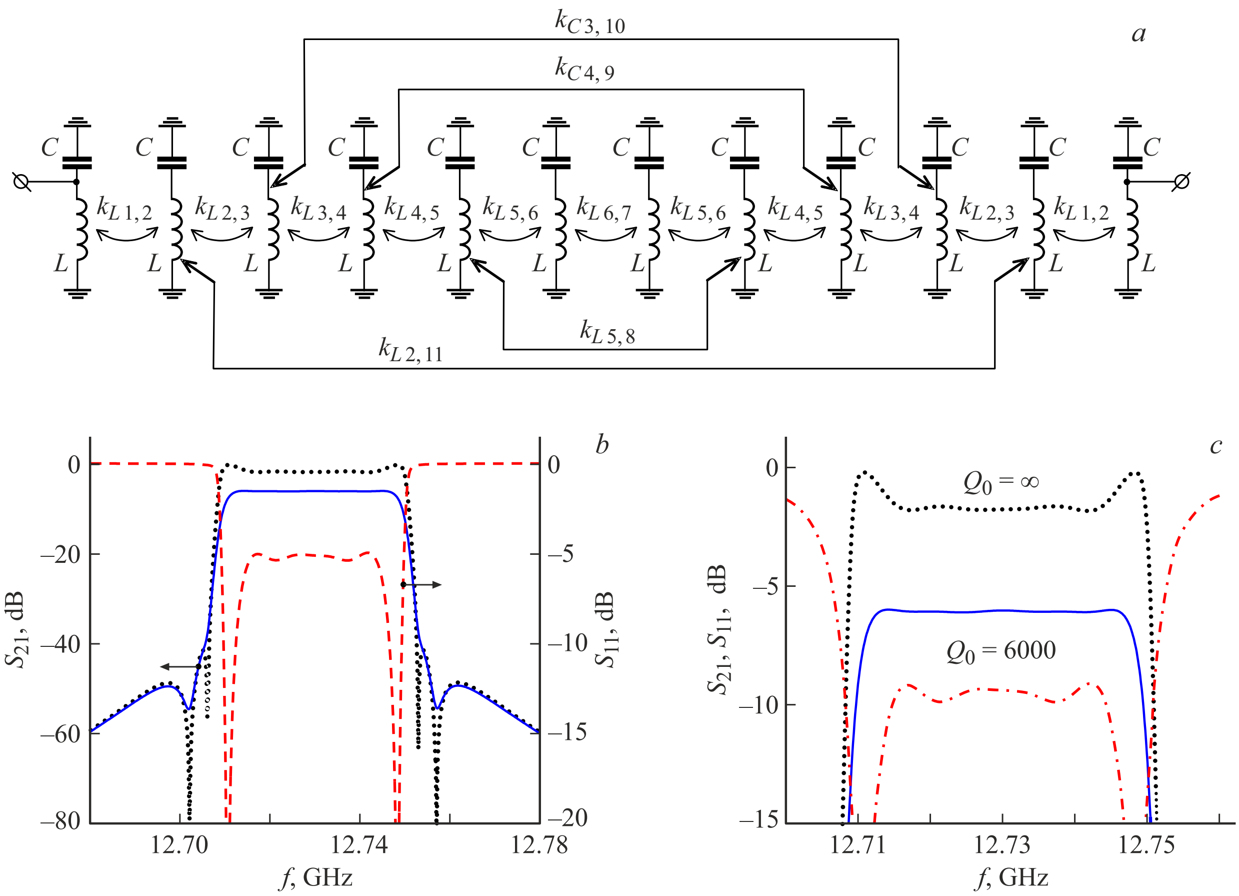


**Figure 1.** *a* — Equivalent circuit diagram of the studied lumped filter; *b*, *c* — frequency responces of insertion losses $S_{21}$ (dotted line — $Q_0 = \infty$; solid line — $Q_0 = 6 \cdot 10^3$) and reflection losses $S_{11}$ (dashed line — $Q_0 = \infty$; dash-and-dot line — $Q_0 = 6 \cdot 10^3$) of the 12-pole filter.

circuits in the equivalent circuit was chosen to be the same as that of actual hollow resonators from which the filter is constructed.

The filter poles, the central frequency of the passband $(f_0)$, the bandwidth $(\Delta f)$ at a given level, the frequencies of transmission zeros, and the unloaded quality factor of resonators $(Q_0)$ were the input parameters of the algorithm used in filter synthesis. The algorithm itself is implemented in several stages that result in the determination of the coupling matrix of resonators and the deviations of their resonant frequencies from the central frequency of the passband [1] (see the table [1,9]). The deviations of resonator frequencies from the central frequency of the passband occupy the principal diagonal of the presented matrix (italicized), and additional cross-couplings between non-adjacent resonators are found in the other diagonal (bolded).

At the initial stage, the filter is synthesized with an infinite quality factor of resonators, and reflection losses in the passband from the input and output of the device are set at the level of $-5$ dB. This level was determined in preliminary studies and is optimum for the parameters of the examined filter. At $Q_0 = \infty$, the filter insertion losses are then $\sim 1.8$ dB at the central frequency of the passband and $\sim 0.2$ dB at the edges of the band (Figs. 1, *b*, *c*). However, when the actual unloaded quality factor $Q_0 = 6 \cdot 10^3$ of resonators is introduced, the minimum insertion losses in the filter passband change to $\sim 6$ dB, and the reflection losses decrease almost to $-10$ dB (Fig. 1, *c*). The FR and GD flatness in the passband is reduced significantly in the process, and the device characteristics satisfy the technical requirements completely. It is important to note that isolators, which provide a reflection level no worse than $-25$ dB, are always installed at the input and output of channel filters in an input multiplexer.

A filter with a classical Chebyshev FR shape was synthesized for comparison based on the equivalent circuit (Fig. 1, *a*) without the additional cross-couplings. Simulation showed 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 in the rejection band of a filter with a Chebyshev FR shape. Figure 2, *a* shows the FR of two filters synthesized on the basis of equivalent circuits with two additional cross-couplings at $Q_0 = 6 \cdot 10^3$ (solid and dashed lines) and without such cross-couplings at $Q_0 = 3 \cdot 10^4$

Coupling matrix of the 12-pole filter

| | | | Resonator number | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | |
| | | Input | 1.251899 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Resonator number | 1 | 1.251899 | *0* | 1.05461 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 2 | 0 | 1.05461 | *0* | 0.668934 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | **0.011188** | 0 | 0 |
| | 3 | 0 | 0 | 0.668934 | *0* | 0.594437 | 0 | 0 | 0 | 0 | 0 | **-0.01492** | 0 | 0 | 0 |
| | 4 | 0 | 0 | 0 | 0.594437 | *0* | 0.507167 | 0 | 0 | 0 | **-0.05221** | 0 | 0 | 0 | 0 |
| | 5 | 0 | 0 | 0 | 0 | 0.507167 | *0* | 0.422829 | 0 | **0.044755** | 0 | 0 | 0 | 0 | 0 |
| | 6 | 0 | 0 | 0 | 0 | 0 | 0.422829 | *0* | **0.671303** | 0 | 0 | 0 | 0 | 0 | 0 |
| | 7 | 0 | 0 | 0 | 0 | 0 | 0 | **0.671303** | *0* | 0.423016 | 0 | 0 | 0 | 0 | 0 |
| | 8 | 0 | 0 | 0 | 0 | 0 | **0.044755** | 0 | 0.423016 | *0* | 0.507249 | 0 | 0 | 0 | 0 |
| | 9 | 0 | 0 | 0 | 0 | **-0.05221** | 0 | 0 | 0 | 0.507249 | *0* | 0.594529 | 0 | 0 | 0 |
| | 10 | 0 | 0 | 0 | **-0.01492** | 0 | 0 | 0 | 0 | 0 | 0.594529 | *0* | 0.669319 | 0 | 0 |
| | 11 | 0 | 0 | **0.011188** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.669319 | *0* | 1.054203 | 0 |
| | 12 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1.054203 | *0* | 1.251899 |
| | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1.251899 | Output |

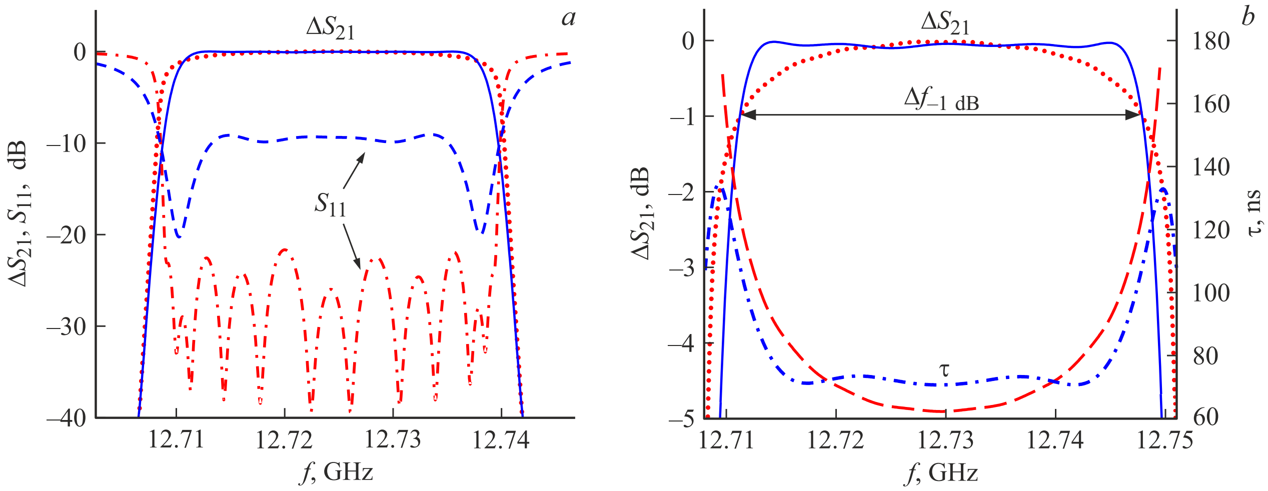


**Figure 2.** *a* — Frequency dependences of the transmission coefficient minus the insertion losses ($\Delta S_{21}(f)$) and the reflection losses ($S_{11}(f)$) of the 12-resonator filter with a Chebyshev FR shape at $Q_0 = 3 \cdot 10^4$ (dotted and dash-and-dot lines) and the filter under study at $Q_0 = 6 \cdot 10^3$ (solid and dashed lines); *b* — FR and GD ($\tau(f)$) of the filters.

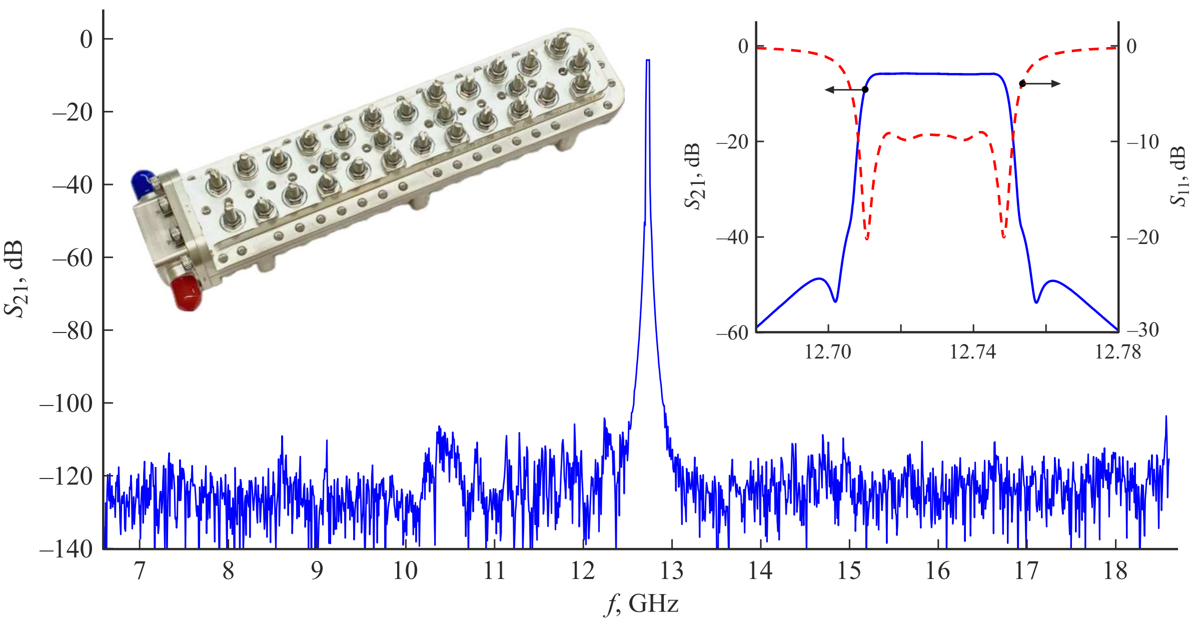


**Figure 3.** Measured characteristics of the prototype filter unit in wide and narrow (right inset) frequency ranges. The photographic image of the device is shown in the left inset.

(the filter with a Chebyshev FR shape; dotted and dash-and-dot lines). For clarity of comparison, the insertion losses at the central frequency of the filter passband were subtracted from the $S_{21}(f)$ dependences; thus, dependences $\Delta S_{21}(f) = S_{21}(f) - S_{21}(f_0)$ are actually plotted. The dependences presented in Fig. 2, *b* make it clear that the proposed multisection filter structure does not only offer the required selectivity, but also provides the needed GD flatness level, which cannot be achieved with classical solutions. The GD flatness in the passband of the proposed filter is $\Delta\tau = 40$ ns, which is 2 times better than that of the filter with a Chebyshev FR shape ($\Delta\tau = 80$ ns).

Note that the introduction of one additional coupling circuit forming one attenuation pole on the FR slopes (as was done, e.g., in [10]) relaxes only slightly the requirements as to the resonator's unloaded quality factor: $Q_0 > 2.4 \cdot 10^4$. However, it is known that the maximum unloaded quality factor of a rectangular hollow resonator made of copper and operating at the $H_{011}$ oscillation mode is $Q_0 \approx 7 \cdot 10^3$ within the considered frequency range under normal conditions. This means that traditional approaches to the design of bandpass filters cannot satisfy the requirements imposed on the characteristics of the examined device. In contrast, the solution proposed here provides an opportunity to construct a high-selectivity filter with the needed parameters at unloaded quality factor $Q_0 = 6 \cdot 10^3$ of resonators.

The coupling matrix (see the table), which was complied in the process of synthesis of a filter based on the equivalent circuit (Fig. 1, $a$), was used to design a filter with waveguide resonators with a cross section of $8 \times 16$ mm in CST Studio Suite (a software package for electrodynamic analysis of 3D models). In this design, a line of twelve resonators connected in series through inductive irises is folded into two rows of six resonators per row. This makes it easy to establish additional capacitive and inductive cross-couplings between non-adjacent resonators via small irises in metal walls. The highly selective filter was made in accordance with the obtained design parameters of Superinvar (32-Invar) with a galvanically applied silver layer $6\,\mu$m in thickness. Coaxial-waveguide adapters with SMA connectors were used at the input and output of the filter.

Figure 3 shows the characteristics of the prototype filter unit measured within wide and narrow frequency ranges; a photographic image of the filter is also provided. The filter is tuned with frequency and resonator coupling adjustment elements in the form of screws. A low FR flatness in the $\Delta f = 36$ MHz passband (1 dB) and high selectivity, which ensures a 50 dB attenuation when the device offset is $\pm 38$ MHz from central frequency $f_0 = 12.73$ GHz of the passband, are the advantages of the developed filter. Another important advantage is the small magnitude of GD variation ($\Delta\tau = 40$ ns) in the filter passband. Since the simulated and measured filter characteristics were found to agree closely, the calculated characteristics are not shown so as to avoid overloading the figure. It is important to note that the characteristics of the filter were found to be thermally stable. The range of central frequency shift is just $\pm 300$ kHz within the $\pm 30^\circ$C temperature interval.

Thus, a new 12-pole waveguide bandpass filter design with additional cross-couplings between non-adjacent resonators was developed. It features a significant level of interference suppression in rejection bands ($\sim 120$ dB) and high selectivity, which are provided by two pairs of transmission zeros located symmetrically relative to the center of the passband in the FR curve. 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. The new approach used in filter synthesis, which involves increasing the reflection losses in the passband of the device, allowed us to achieve a low FR and GD flatness in the passband (compared to traditional filter designs).

### Acknowledgments

Equipment provided by the Training Center for Collective Prototyping of Passive Electronics of the Antenna–Feeder Path (Federal Research Center „Krasnoyarsk Science Center of the Siberian Branch of the Russian Academy of Sciences") was used in the study.

### Funding

This study was supported financially by the Ministry of Science and Higher Education of the Russian Federation (state assignment FEFE-2023-0004).

### Conflict of interest

The authors declare that they have no conflict of interest.

## References

[1] M. Yu, W.-C. Tang, A. Malarky, V. Dokas, R. Cameron, Y. Wang, IEEE Trans. Microwave Theory Tech., **51** (12), 2505 (2003). DOI: 10.1109/TMTT.2003.820172

[2] J.-S. Hong, *Microstrip filters for RF/microwave applications* (John Wiley & Sons, 2011).

[3] B.A. Belyaev, Y.F. Bal'va, V.V. Tyurnev, A.A. Leksikov, R.G. Galeev, Microwave Opt. Technol. Lett., **56** (9), 2021 (2014). DOI: 10.1002/mop.28507

[4] R.M. Kurzrok, IEEE Trans. Microwave Theory Tech., **14** (6), 295 (1966). DOI: 10.1109/TMTT.1966.1126254

[5] Y. Wang, M. Yu, IEEE Trans. Microwave Theory Tech., **57** (12), 2958 (2009). DOI: 10.1109/TMTT.2009.2034221

[6] J. Kocbach, K. Folger, in *2002 IEEE MTT-S Int. Microwave Symp. Digest* (IEEE, 2002), vol. 3, p. 1449–1452. DOI: 10.1109/MWSYM.2002.1012128

[7] M. Latif, G. Macchiarella, F. Mukhtar, IEEE Access, **8** (7), 107527 (2020). DOI: 10.1109/ACCESS.2020.3000847

[8] B.A. Belyaev, A.M. Serzhantov, Ya.F. Bal'va, R.G. Galeev, An.A. Leksikov, IEEE Trans. Compon. Packag. Manufactur. Technol., **12** (7), 1186 (2022). DOI: 10.1109/TCPMT.2022.3183581

[9] R.J. Cameron, C.M. Kudsia, R.R. Mansour, *Microwave filters for communication systems: fundamentals, design, and applications* (Wiley-Interscience, 2007).

[10] B.A. Belyaev, A.M. Serzhantov, A.A. Leksikov, Ya.F. Balva, A.A. Alexandrovsky, R.G. Galeev, Tech. Phys. Lett., **49** (5), 72 (2023). DOI: 10.21883/TPL.2023.05.56034.19541.

*Translated by D.Safin*