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Miniature Coaxial Resonator and Related Bandpass Filter with Ultra-Wide Stopband

B. A. Belyaev*, A. M. Serzhantov, V. V. Tyurnev, A. A. Leksikov, and An. A. Leksikov

L.V. Kirensky Institute of Physics, Siberian Branch, Russian Academy of Sciences, Krasnoyarsk, 660036 Russia
Institute of Physical Engineering and Radioelectronics, Siberian Federal University, Krasnoyarsk, 660074 Russia
Reshetnev Siberian State Aerospace University, Krasnoyarsk, 660014 Russia
**e-mail: belyaev@iph.krasn.ru*

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Abstract—Resonator of a new type is described, which is formed by two coaxial conductors applied onto the internal and external surfaces of a ceramic tube arranged in a metal case. An equation for the resonant frequencies is derived. In comparison to a standard coaxial quarter-wave resonator, the proposed device has a shorter length and manifold increased ratio of frequencies of the second resonance to the first resonance. The new resonator can be used for the creation of bandpass filters with ultra-wide stopband. The frequency response of a working prototype four-resonator filter is presented, in which the stopband at a –90 dB level extends up to a frequency that is 47 times greater than the central frequency of the passband.

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The progress in wireless communications requires the development of microwave filters possessing improved characteristics, smaller dimensions, and lower cost. Depending on particular requirements, these filters can be based on the electromagnetic resonators of various types.

As is known, waveguide filters are characterized by minimum loss in the passband. These filters are well suited for stationary equipment, where the requirement of low loss is more important than the device weight and size parameters. However, these devices are difficult to manufacture, expensive, and large-sized, especially those intended to operate in the frequency range of several hundred megahertz.

Miniature filters are represented by those designed as microstrip and strip lines on suspended substrates [1–4]. Important advantage of these devices is the possibility to arrange more complicated functional units implemented as integrated and hybrid circuits. Unfortunately, microstrip resonators possess relatively low Q that hinders the creation of narrow-band filters with low loss in the passband. This problem can be solved by using high-temperature superconductor films [1, 5, 6], but their application requires special cooling systems.

Filters based on dielectric resonators are characterized by a combination of electrical properties and size parameters such that these devices occupy intermediate positions between filters based on hollow metal waveguides and those based on mictrostrips.

One of the main disadvantages of all filters mentioned above is a narrow stopband, which amounts in the best cases to two octaves (i.e., $4f_0$ at a level of –60 dB).

Among a large variety of electromagnetic resonators used at frequencies from several hundred megahertz to several gigahertz, metal–dielectric resonators (also called coaxial dielectric resonators [7–9]) find increasing application in recent years. Filters based on these resonators are among the best with respect to the combination of characteristics. In particular, the stopband width of these filters can reach several octaves (up to $8f_0$ at a level of –60 dB) [10–12]. However, modern wireless communication systems frequently require even greater stopband widths in combination with small size and high selective properties.

This Letter describes a coaxial dielectric resonator of new design, which makes possible the creation of bandpass filters with ultra-wide stopbands (up to $47f_0$ at a no less than –90 dB level). At the same time the proposed filters exhibit high selectivity and have small dimensions even if designed to operate at several hundred megahertz.

The proposed resonator consists of two tubular coaxial thin-film conductors applied onto the internal and external surfaces of a ceramic tube arranged in a metal case. The conductors are connected by one end to opposite walls of the metal case. In an analysis of the resonator model, it will be assumed that the metal case has a cylindrical shape (Fig. 1a), Figure 1b shows an equivalent circuit of the resonator, which represents three serially connected segments of two-wire transmission lines, one of which with length l_{12} has an open end. Two segments of transmission lines (with lengths l_2 and l_{12}) are homogeneous and, hence, their funda-

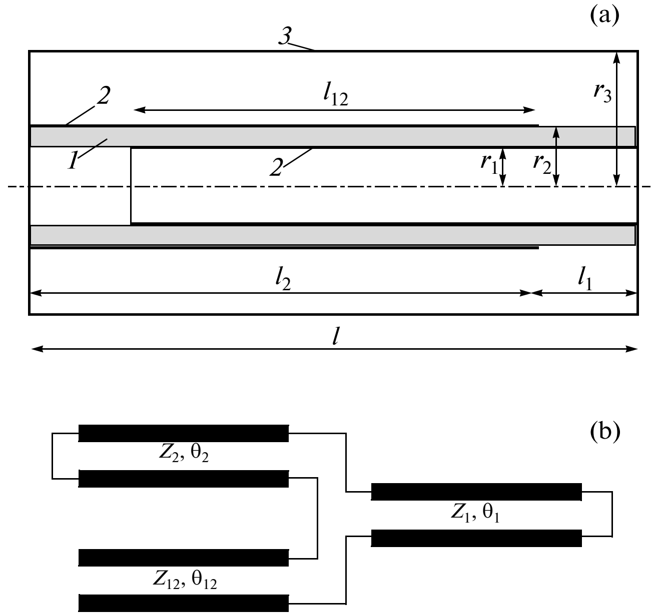

Fig. 1. Coaxial resonator arranged inside a metal case: (a) longitudinal section; (b) equivalent circuit of coaxial resonator arranged inside a metal case: (*1*) ceramic tube; (*2*) metallization; (*3*) metal case.

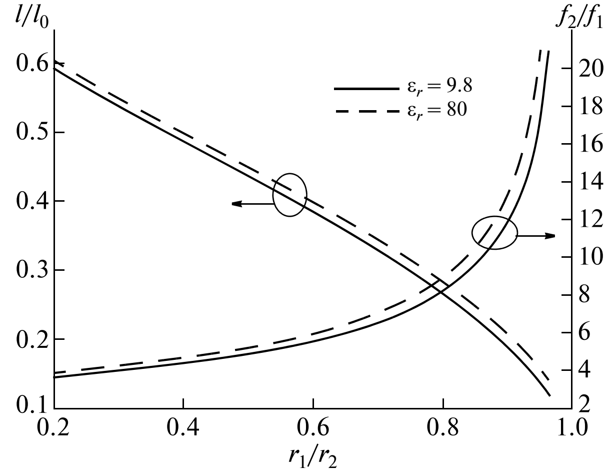

Fig. 2. Plots of the relative length l/l_0 and frequency ratio f_2/f_1 versus internal radius r_1 of ceramic tube (for r_2 = 2.8 mm and r_3 = 10 mm).

mental modes represent TEM waves. For the line with length l_1, the fundamental mode is a quasi-TEM wave.

The parameters of fundamental modes in the transmission lines can be calculated using the following quasi-static formulas:

$$\varepsilon_1 = \left[\frac{\ln(r_3/r_1)}{\ln(r_2/r_1)/\sqrt{\varepsilon_r} + \ln(r_3/r_2)}\right]^2,$$
$$Z_1 = \frac{1}{2\pi}\sqrt{\frac{\mu_0}{\varepsilon_0}}\left[\frac{\ln(r_2/r_1)}{\sqrt{\varepsilon_r}} + \ln(r_3/r_2)\right], \tag{1}$$

$$\varepsilon_2 = 1, \quad Z_2 = \frac{1}{2\pi}\sqrt{\frac{\mu_0}{\varepsilon_0}}\ln(r_3/r_2), \tag{2}$$

$$\varepsilon_{12} = \varepsilon_r, \quad Z_{12} = \frac{1}{2\pi}\sqrt{\frac{\mu_0}{\varepsilon_0}}\frac{\ln(r_2/r_1)}{\sqrt{\varepsilon_r}}, \tag{3}$$

where ε_r is the permittivity of the ceramic tube. The system of Kirchhoff equations written for nodes of the equivalent circuit leads the following expression for the resonant frequencies of the coaxial resonator:

$$Z_2\tan\theta_2 + Z_1\tan\theta_1 - Z_{12}\cot\theta_{12} = 0, \tag{4}$$

where θ_1, θ_2, and θ_{12} are the electrical lengths and Z_1, Z_2, and Z_{12} are the impedances of the transmission line segments that form the resonator. Equation (4) is also valid for decaying oscillations, in which case all coefficients are complex quantities.

Let us compare the proposed resonator to a standard dielectric-filled coaxial quarter-wave resonator in a particular case with the first resonant frequency f_1 = 100 MHz, external conductors of radius r_3 = 10 mm, internal conductors of radius r_2 = 2.8 mm, and first segment length $l_1 = r_2$. One can readily check that the selected r_3/r_2 ratio corresponds to the maximum unloaded Q of the standard resonator.

Figure 2 shows calculated dependences of two important parameters of the proposed resonator on the internal radius of the ceramic tube. The first parameter is defined as the ratio of the length (l) of the proposed resonator to that (l_0) of a standard coaxial resonator. The latter value is assumed to be $\lambda_g/4 + r_2$, where λ_g is the intrinsic wavelength in the coaxial line. The ratio l/l_0 characterizes the degree of miniaturization of the resonator.

The second parameter plotted in Fig. 2 is the ratio of the second resonant frequency (f_2) to that of the first resonance (f_1). For the standard coaxial resonator, this ratio is constant and amounts to $f_2/f_1 = 3$. The value of f_2/f_1 characterizes the relative decrease in the fundamental resonant frequency, which determines the relative width of the stopband.

As can be seen, an increase in the internal radius of the ceramic tube leads to a manifold decrease in the resonator length and the ratio of the fundamental resonant frequency to those of higher resonances, that is, both parameters are improved. Note that this is accompanied by an increase in unloaded Q of the resonator, which approaches that of the standard coaxial device. This result follows from the numerical solution of Eq. (4) with complex frequency and parameters of the equivalent circuit.

Figure 3a presents photograph of a working prototype of the bandpass filter that was developed based on the proposed resonator, and Fig. 3b shows a measured

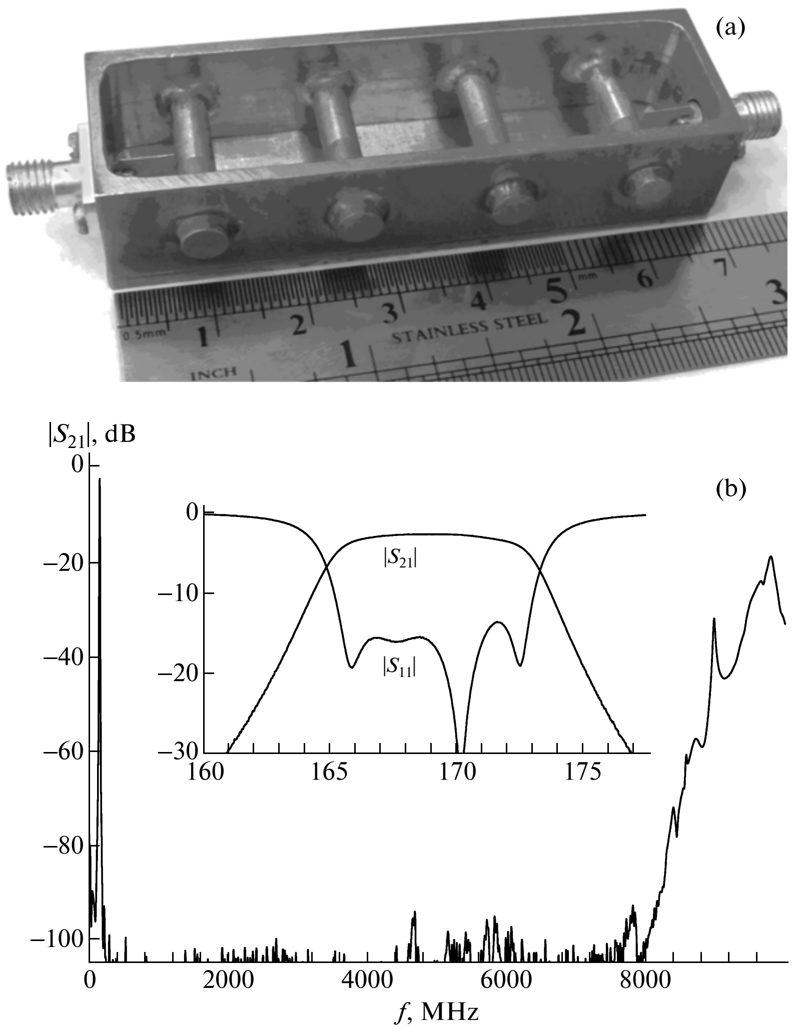

Fig. 3. Coaxial four-resonator filter: (a) general view of a working prototype; (b) measured frequency response. The inset shows a fragment of the passband.

frequency response of this device. The filter has a central frequency of f_0 = 169 MHz, a pass bandwidth of Δf = 7.9 MHz (4.7%) at a –3 dB level, the maximum reflection in the passband –13.6 dB, and a minimum insertion loss of 2.7 dB. The stopband width at a –90 dB level extends up to 8 GHz (i.e., up to $47f_0$). This is achieved not only due to a relative decrease in the fundamental resonant frequency, but also due to a significant decrease in the coupling at higher resonant frequencies. The filter case has internal dimensions 67 × 17 × 14 mm; the tubes are made of ceramics with ε_r = 50 and dimensions l = 17 mm, r_1 = 1.7 mm, and r_2 = 2.0 mm.

Thus, we have proposed coaxial resonator of a new type with $l \ll \lambda_g$ and resonant frequencies $f_1 \ll f_2$, which can be used to develop miniature bandpass filters with ultra-wide stopband. A working prototype four-resonator filter has been designed and manufactured, which has dimensions 0.038λ × 0.0096λ × 0.0079λ and a stopband width of up to $47f_0$ at no less that –90 dB level.

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