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The study of stripline resonators and oscillatory circuits interacting through a thin metal layer

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The possibility of creating bandpass filters with an ultrawide rejection band is shown. These filters are based on resonances of odd oscillation modes of each twoconductor resonator whose stripline conductors are separated by a metal layer thinner than the skin layer at the passband frequencies. A thin metal layer weakly absorbs and reflects microwave power at the frequency of an odd oscillation mode, since in this case currents in the resonator stripline conductors are oppositely directed and, unlike the even mode, induce almost no current in the metal layer. The developed equivalent circuit on lumped elements describes the revealed effect behavior depending on the metal layer thickness. The measured frequency responses of the experimental sample of two circuits on lumped elements coupled through a metal layer, which are constructed in accordance with the equivalent circuit, are in good agreement with the calculated characteristics both with and without a metal layer.

Keywords: substrate, stripline resonator, coupling coefficient, oscillation mode.

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Metal films made of magnetic materials have attracted researchers' interest for many years because of their unique properties [1–3]. They are used as a base for weak-magnetic-field sensors [4,5], as well as in various microwave devices [6,7]. In recent years, great interest has appeared in thin layers of non-magnetic metals which are successfully used in creating bandpass filters on dielectric resonator layers separated by metal mirror films [8,9]. Studies of reflection and absorption properties of thin films made of various metals [10] were performed in a wide frequency band in view of creating on their basis coatings accumulating solar energy [11] and coatings protective against electromagnetic fields [12]. However, literature presents few studies of interaction between resonators separated by a conducting film thinner than the skin layer; just this is the subject of this paper. The results of such studies are of not only theoretical but also practical interest, for instance, in creating devices for transmitting electromagnetic energy through conductive layers, as well as innovative frequency-selective devices with improved characteristics.

Let us consider a bandpass filter consisting of three two-conductor resonators whose identical stripline structures have been constructed on one side of each of two polycor substrates having relative permittivity of $\varepsilon = 9.8$ and thickness of $h = 0.25$ mm; the substrates are suspended in a shielding case strictly opposite each other with the air gap of 1.8 mm (Fig. 1, *a*). In the middle of the gap there is a thin metal layer connected to the shield along the entire perimeter [13]. Ends of all the resonator stripline conductors on one side of the substrate are closed to the shield, while those of conductors on the other substrate side are connected to the shield through capacitors reducing the resonator's natural frequencies. Input and output ports of the structure under study have wave impedance of 50 Ω; they are connected to the outer stripline conductors located on the opposite sides of the top and bottom substrates. Obviously, the design under consideration implies predominantly inductive interaction of coupled lines both in each resonator and between resonators. As is known [14], two-conductor resonators exhibit two oscillation modes: the even one when the stripline conductor currents coincide in direction, and the odd one when the currents are oppositely directed. Therewith, mutual inductance of the stripline conductors reduces resonant frequency of the even oscillation mode f_e and increases odd oscillation mode frequency f_o in accordance with the magnitude of coupling of the strip lines forming the resonator. As shown in studying the two-conductor resonator, Q-factor of the odd oscillation mode resonance remains quite high when the metal layer thickness is less than that of the skin layer because currents induced in this layer by two resonator conductors compensate each other. Here the even mode resonance is almost not observable because of efficient microwave power reflection and absorption in the metal layer. Therefore, in tuning the considered structure only odd oscillation mode resonances are used as a bandpass filter.

Fig. 1, *b* presents frequency-response curves (FRCs) for direct loss S_{21} (solid line) and reflection loss S_{11} (dotted line) of the proposed-design filter adjusted, using the CST

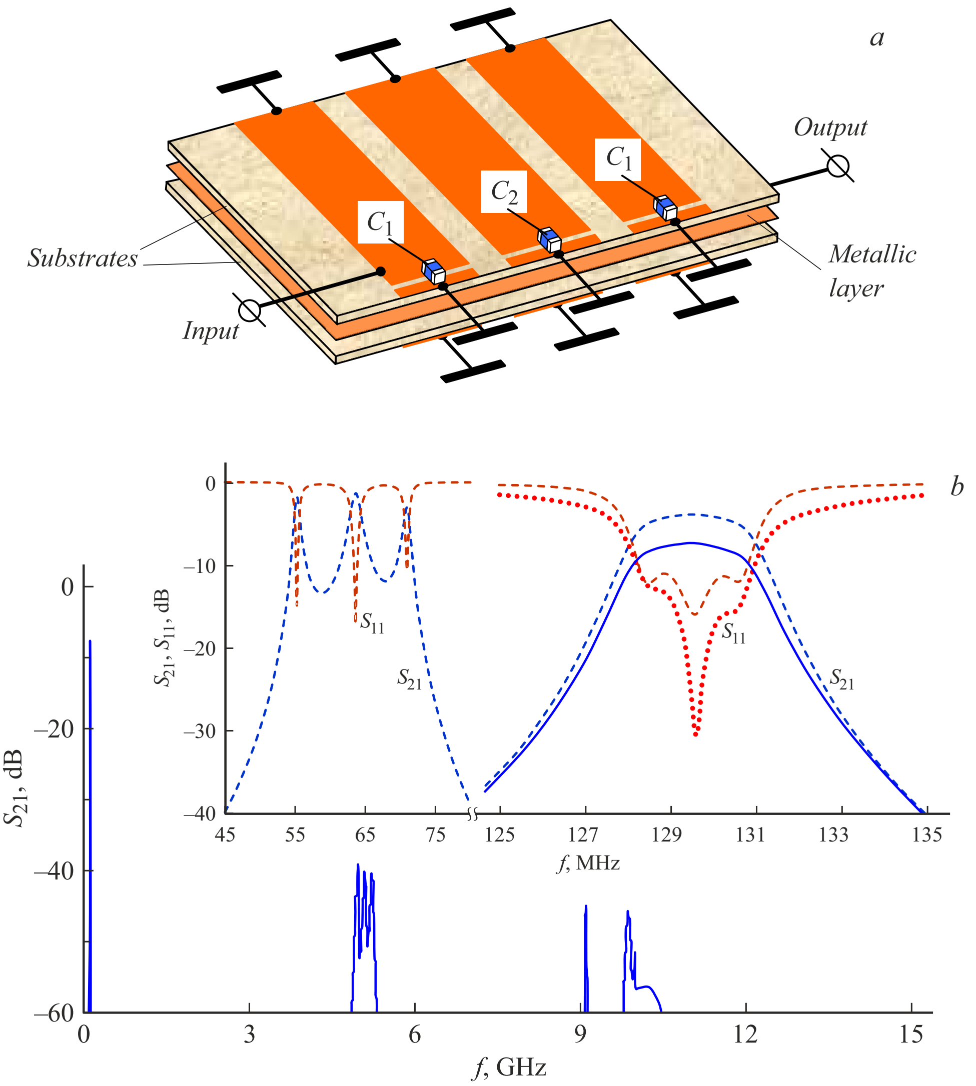

Figure 1. *a* — design of the third-order filter based on resonances of odd oscillation modes of two-conductor resonators. *b* — FRCs of the filter under study in the wide and narrow frequency ranges. Dashed lines are for the sample free of metal layer.

Studio Suite software package for electrodynamic analysis of 3D models, to central frequency $f_0 = 130$ MHz and relative width $\Delta f/f_0 = 2\%$ at the level of -3 dB. After the adjustment, the following design parameters have been obtained: width of the central resonator stripline conductor of 8 mm, that for outer resonators of 7 mm, stripline conductor length of 27 mm, gap between the conductors of 3 mm, capacities $C_1 = 500$ pF, $C_2 = 550$ pF. The metal layer $t = 36\,\mu$m in thickness is made of nichrome having specific conductivity of $\sigma = 8.93 \cdot 10^5$ S/m which is 65 times lower than that of copper. This increases the skin layer thickness at frequency $f_0 = 130$ MHz to $\delta = 47\,\mu$m. The main distinctive feature of the developed filter is the record width of rejection band extending up to the UV plasma resonances [9]. This is because the metal layer whose thickness at the passband frequencies is less than that of the skin layer becomes much thicker than the skin layer when frequency increases. Therefore, this layer serves as a good screen between the device input and output thus ensuring attenuation of ~ 40 dB at the filter's second parasitic resonance at about 5 GHz and of more than 80 dB at frequencies above 15 GHz.

In Fig. 1, *b*, dashed lines represent frequency characteristics of the studied filter without the metal layer. Evidently, the filter has retained its characteristics; the central passband frequency has remained almost unchanged, its relative width has increased only slightly from 2.0 to 2.2%; however, the minimum microwave power loss in the passband has decreased significantly (from 7.3 to 3.9 dB). Note that the filter passband losses decrease with increasing passband width both in the considered filter and in filters of conventional designs.

It is noteworthy that, in the structure without the metal layer, even-oscillation natural frequencies of two-conductor resonators also form a passband with the relative width of $\sim 28\%$, which is absent in the filter with the metal layer.

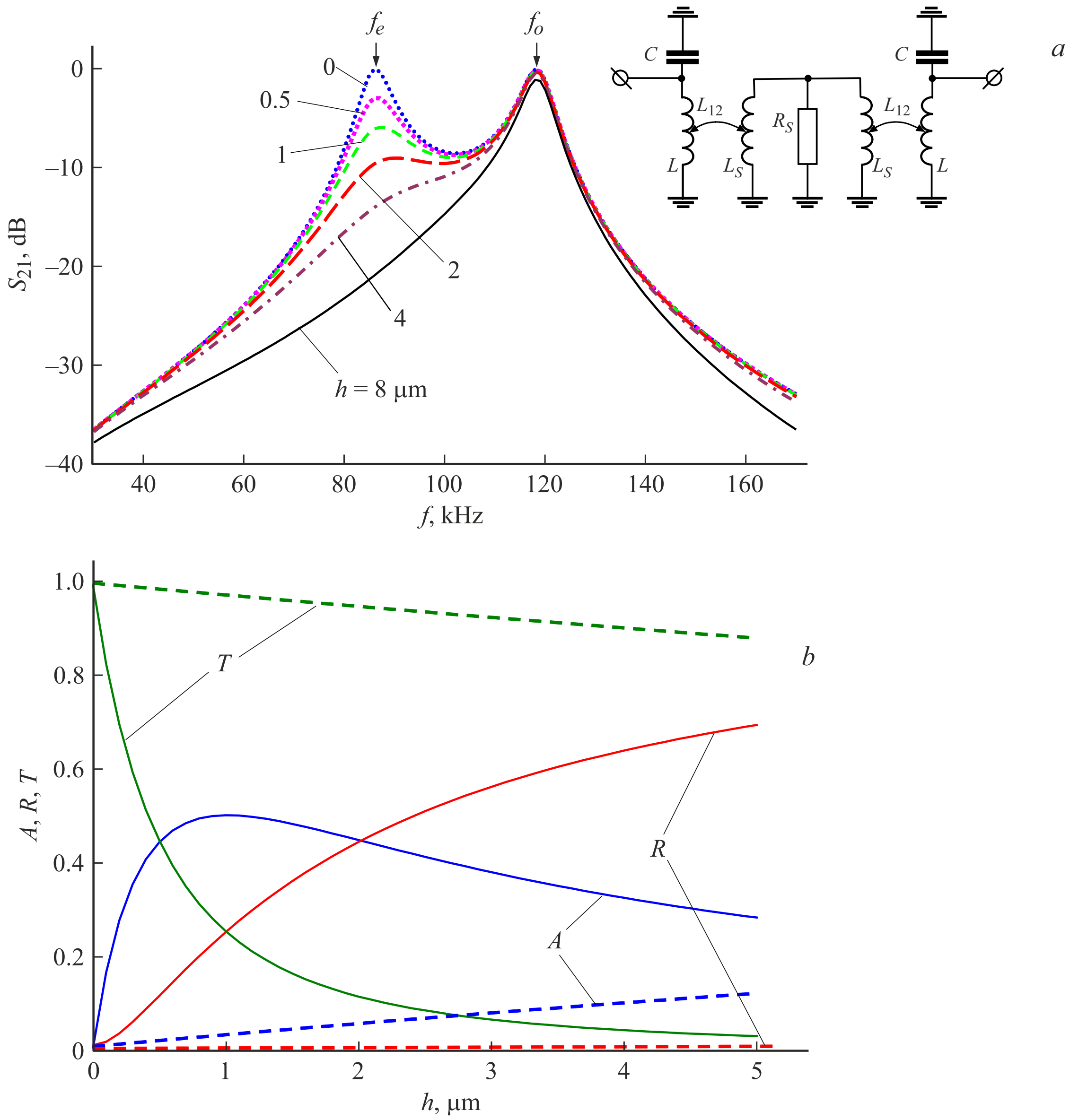

Figure 2. *a* — FRCs of the equivalent scheme consisting of two inductively coupled circuits interacting through the metal layer between them at different metal layer thicknesses (the inset depicts the equivalent scheme). *b* — dependences on metal layer thickness h of electromagnetic wave transmission coefficients T, reflection coefficients R, and absorption coefficients A at resonant frequencies of the even (solid lines) and odd (dashed lines) oscillation modes.

The bandwidth was estimated at the level of -12 dB from the minimum loss level, since this band exhibits a very high frequency response nonuniformity (above 10 dB). The passband central frequency is 61 MHz; three resonant frequencies are clearly visible in it: $f_1 = 55.3$ MHz, $f_2 = 63.7$ MHz and $f_3 = 71.0$ MHz. Obviously, such a large passband width is caused by strong coupling of resonators due to co-directionality of currents in the stripline conductors of each two-conductor resonator.

To clarify the origin of the revealed patterns of behavior of even and odd oscillation mode resonances depending on the metal layer thickness in two-conductor resonators, consider their equivalent scheme consisting of two coupled oscillatory circuits on lumped elements (inset to Fig. 2, *a*). In this scheme, the metal layer between the inductively coupled circuits will be described for symmetry by two lumped inductances L_S with connected in parallel resistance R_S that is the surface resistance of conductive layer h in thickness made of material with specific conductivity of σ:

$$R_S = \frac{1}{\sigma h}. \quad (1)$$

It is quite easy to calculate natural frequencies of such an equivalent scheme in the framework of the circuit theory; for simplicity, let us assume that $R_S = \infty$ and disconnect the input and output ports. Solving the Kirchhoff equations, obtain for this case

$$f_e = \frac{1}{2\pi\sqrt{LC}}, \quad f_o = \frac{1}{2\pi\sqrt{(L - L_{12}^2/L_S)C}}. \qquad (2)$$

It is evident that, when the circuits interact via the transformer coupling provided by inductances L_S, frequency of the lowest even oscillation mode is equal to that of the isolated circuit.

Measured capacitances $C = 505$ nF and coil inductances $L = 6.8\,\mu$H of the oscillatory circuits prepared for the experiment were chosen as nominal values of the equivalent circuit components. Note that the number of coil turns was 12, their outer diameter being 59 mm. The total loss resistance in oscillatory circuit coils and capacitances was $R = 0.04\,\Omega$. Mutual inductance L_{12} was selected so that experimentally observed resonance frequencies of even and odd oscillations coincided with calculations; inductances L_S were chosen so that experimentally observed resonance amplitudes of even and odd oscillations coincided with the calculated ones. Thus, $L_{12} = 0.197\,\mu$H, and $L_S = 12$ nH; these values remain the same regardless of the metal layer thickness.

Fig. 2, *a* shows FRCs of the studied resonance system constructed from coupled circuits depending on thickness h of the separation copper layer ($\sigma = 5.8 \cdot 10^7$ S/m); the curves have been calculated according to the equivalent scheme. Dependences at $h = 0$ clearly exhibit two resonance peaks corresponding to the frequencies of even ($f_e = 86$ kHz) and odd ($f_o = 119$ kHz) modes of the coupled circuit oscillations. The figure also shows that, as the metal layer thickness increases, insertion attenuation at the odd oscillation mode frequency varies slightly, while that at the even mode frequency (whose resonance completely disappears already at $h = 8\,\mu$m) increases rapidly.

Fig. 2, *b* presents dependences on the conductive layer thickness h of transmission coefficients T, reflection coefficients R and absorption coefficients A at the resonance frequencies of the even (solid lines) and odd (dashed lines) coupled oscillation modes. Absorption coefficient A was calculated as

$$A = 1 - T - R. \qquad (3)$$

One can see that, as the metal layer thickness increases, absorption coefficient A behaves non-monotonically at the even oscillation mode frequency and has a maximum of $A \approx 0.5$ at the copper layer thickness $h \sim 1\,\mu$m; along with this, transmission coefficient T decreases rapidly, while reflection coefficient R quickly increases. At the odd oscillation mode frequency, the T, R and A dependences vary much less with increasing h. The revealed abnormal behavior of attenuation at the odd oscillation mode resonance is explained by compensation of currents induced by coils in the metal layer, as in the case of the above-considered third-order filter on two-conductor stripline resonators.

To experimentally verify the observed effects, a sample was constructed from circuits coupled via the metal layer thinner than the skin layer; the circuits were placed in the metal case whose design is shown in Fig. 3, *a*. As an interlayer, there was used a copper layer $h = 17\,\mu$m in thickness on the Rogers 4003C ($\varepsilon = 3.55$) dielectric plate 0.5 mm thick; it was fixed between the oscillatory circuit coils (Fig. 3, *a*). Coaxial connectors with the wave impedance of $50\,\Omega$ were mounted on the device body; a tunable oscillator was connected to them at the input, a receiver was connected at the output. Note that the skin layer thickness $\delta = 189\,\mu$m calculated at the sample's odd oscillation mode frequency $f_o = 119$ kHz is an order of magnitude higher than thickness of the metal interlayer used in the experiment. Note also that, when the metal layer thickness is $h = 17\,\mu$m, the impedance is $R_S = 1.1 \cdot 10^{-3}\,\Omega$.

In Fig. 3, *b*, dots represent the measured frequency dependences of high-frequency signal transmission through the fabricated samples with and without the metal interlayer; lines represent the results of calculations performed according to the equivalent circuit. One can see a good agreement between the measured and calculated FRCs; this confirms correctness of the employed equivalent circuit. The measurements have shown that, when the copper screen thickness is $17\,\mu$m, attenuation of the transmitted electromagnetic wave at the odd oscillation mode frequency is ~ 4.5 dB, while that at the even mode frequency is ~ 26 dB; the measured resonance Q-factor at the odd mode frequency is $Q = 14$. It is obviously of interest to calculate variation in attenuation L_0 of the transmitted electromagnetic wave at the odd oscillation mode frequency with increasing loaded resonance Q-factor. This is easy to do by increasing the output wave impedance of the oscillator at the device input and that of the detector at the device output from the initial impedance of $50\,\Omega$ in order to reduce the oscillatory circuits' coupling with the input and output. Fig. 3, *c* shows the frequency response for different loaded resonance Q-factors of the odd oscillation mode calculated in the absence of inductor losses; Fig. 3, *d* presents the dependence of the transmitted power loss at the odd oscillation mode frequency on the loaded resonance Q-factor. Evidently, the transmitted power loss decreases with increasing Q-factor and reaches 0.5 dB at $Q = 110$.

Thus, the revealed in this study distinctive feature of the FRCs behavior in the case of either two-conductor resonators or a pair of oscillatory circuits, which are coupled through a metal layer thinner than the skin layer, is not only of theoretical interest, but also may find practical application. For instance, signal transmission at the frequency of 119 kHz through two circuits interacting via the metal layer $17\,\mu$m thick, which was demonstrated on the experimental sample, manifests the possibility of wireless transmission of low-frequency electrical energy to shielded devices. In addition, the revealed possibility of creating bandpass filters with a record-wide rejection band shows the potential of designing signal-frequency-selection devices based on the stripline structure in question. The origin of weak absorption of high-frequency power at the

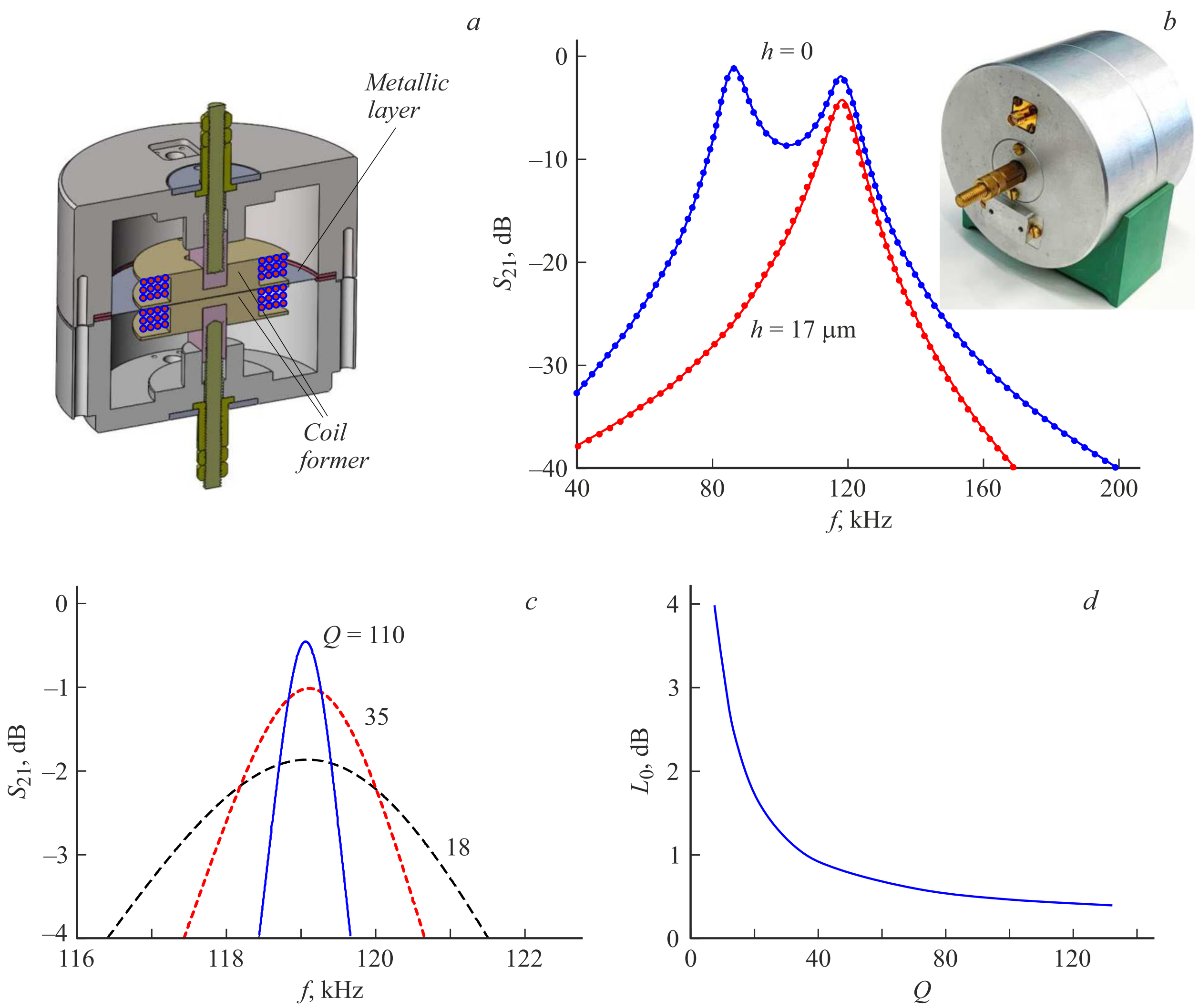

Figure 3. *a* — design of the sample consisting of two oscillatory circuits coupled through the metal layer. *b* — measured (dots) and calculated according to the equivalent circuit (lines) FRCs for the experimental sample with and without the interlayer (the inset presents a photo of the fabricated sample). *c* — FRCs at different loaded Q-factors of the odd oscillation mode resonance. *d* — insertion attenuation versus the loaded resonance Q-factor.

frequency of odd oscillation mode of the two-conductor resonator is that in this case, unlike the case of even oscillation mode, currents induced in the metal layer by two resonator conductors compensate each other since they are opposite in direction.

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Conflict of interests

The authors declare that they have no conflict of interests.

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