Miniaturized Suspended-Substrate Two-Conductors Resonator and a Filter on its Base

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Abstract–The paper is devoted to an investigation of two-conductor suspended-substrate resonators. For the purpose of miniaturization conductors of a resonator are folded. Four types of the resonator differing in conductors' configurations were considered. Their Q_0-factors and resonant frequencies were studied. Based on results of the study two types of the resonator appeared to be suitable for an application in compact filters. Two other types were investigated in concern of their interaction: dependencies of coupling coefficients versus space between resonators and versus distance from substrate's surfaces and package's covers were obtained. Based on the dependences a type of the resonator suitable in designing compact BPF was chosen. Four-pole BPF was simulated and fabricated. Good agreement between simulated and experimental results is observed. The main filter's characteristics are the next: substrate has ε=80, thickness 0.5 mm, lateral sizes 17.7 mm × 12.0 mm. The central frequency is 282 MHz; bandwidth is 28.7 MHz; passband minimum insertion loss is 1.8 dB, passband return loss is less –14.6 dB; –40 dB stopband width is 480 MHz.

Key words: Two-conductor suspended-substrate resonator, bandpass filters, Q_0-factor, coupling coefficients

I. INTRODUCTION

Bandpass filters (BPF) are important devices in telecommunications, radio navigation and radiolocation systems, and so on. Often filters determine size of radio equipment, its weight and quality. Therefore a task of finding compact resonator structures and developing filters on their base is extremely urgent. Also, selectivity, insertion loss, manufacturability, and low cost remain important issues.

In this concern, microstrip filters have got wide spread [1]. They satisfy the above mentioned requirements in many aspects. Application of substrates having high dielectric constants (ε=20…80) has allowed them penetrating in low part of a decimeter band [2, 3]. But at frequencies lower ~500 MHz their sizes become, as a rule, unacceptably large, even on substrate having ε=80.

An invention of two-conductor strip resonator on a suspended substrate [4, 5] has opened a way for application strip technology in filters designing and fabricating for frequencies <500 MHz. Such filters appeared to be better microstrip ones in many aspects. They are more compact, have less insertion loss and wider stopband at the same conditions. Besides, a number of specialized filters were invented on their base, for example, harmonic filter [6, 7] and ultra-wideband [8] filters.

This work deals with further miniaturization of strip-conductors filter. In microstrip technology conductors folding is one of the commonly used methods for filter's decreasing in a size.

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The same method we use for miniaturization of two-conductor suspended-substrate filters. Several different structures of resonator are considered. Their unloaded quality factors and frequencies ratio are investigated. Also, coupling between the resonators is studied. With a help of the obtained results an optimal structure of the resonator was chosen and on its base four-pole BPF was simulated and fabricated. Good agreement between the simulated data and measured ones is achieved.

II. FOLDED TWO-CONDUCTOR RESONATOR ON SUSPENDED SUBSTRATE

In Fig. 1 various configurations of the resonator are shown. The structure ***A*** is a base resonator, having straight strip conductors. The structures ***B***, ***C***, ***D*** and ***E*** represent four possible configurations of the resonator with folded strip conductors.

Resonator of structure ***E*** was earlier proposed in the paper [9]. But, as it will be seen then, such resonator is the worst among the other ones. It has high frequency and low Q_0-factor.

In order to determine, what type of the resonator is suitable for designing compact filters, investigations were carried out with a help of electromagnetic simulation, using Sonnet Software, which allowed comparing properties of the resonators, such, as unloaded Q-factors and frequencies of two first modes.

As unloaded Q-factor depends on frequency and size (volume) of resonators, it will not be correct to compare their values exactly. Therefore we applied the next approach.

Unloaded quality factor of a resonator is described by well-known formula:

$$Q_0 = 2p\, f_r \frac{W_{st}}{P_J + P_D + P_R}, \qquad (1)$$

where f_r is resonant frequency, W_{st} is electromagnetic energy, stored by a resonator, P_J is a power of Joule loss, P_D is a power of dielectric loss, and P_R is a power of radiation loss. In a case of strip-line resonator substrate material has very low dielectric loss, tgδ~10^{-4}, and in the case of, for example, shielded microstrip resonator radiation loss is negligible, then

$$Q_0 = 2p\, f_r \frac{W_{st}}{P_J}. \qquad (2)$$

Joule loss is proportional to surface resistance of a conductor, that in own turn is proportional, as is known, to square root from frequency of MW current. Finally, we can write

$$Q_0 = 2p\, f_r \frac{W_{st}}{a\sqrt{f_r}} = q\sqrt{f_r}, \qquad (3)$$

where q is a constant.

In order to find out is this formula valid in the case of two-conductor resonator on suspended substrate, we determined with a help of simulating frequency dependence of the Q_0-factor of the type A resonator. The resonator had the next structural parameter. Inner sizes of the package are 22 mm × 6 mm × 6.5 mm; substrate thickness is 0.5 mm; length of the resonator strip conductors is 21 mm and width is 1 mm.

Frequency changing was carried out by varying a dielectric constant of the substrate from 2.2 to 120. At an every specific ε, resonant curve of the resonator “connected” with weak coupling to “a measuring tract” was obtained, and from that unloaded Q-factor was derived by the commonly known way. The dependence is shown In Fig. 2 by the blue curve along with the frequency dependence obtained as an approximation by the formula (3), where q= 14.42 $(\text{MHz})^{-0.5}$, red curve.

It is seen, the dependencies are in good agreement, and then frequency dependence of a two-conductor suspended substrate resonator’s Q_0-factor obeys the square root law. This circumstance allows us comparing Q_0-factors of the resonators, having equal volumes and different resonant frequencies.

For this purpose we simulated five resonators ***A***, ***B***, ***C***, ***D*** and ***E*** (Fig. 1), having equal inner sizes of the package, 22 mm × 6 mm × 6.5 mm, and other structural parameters: substrate of a thickness 0.5 mm has ε=80. It is suspended in a middle plane of the package. Width of the resonators' strip conductors is 1 mm; inner gap (for resonators ***B***, ***C***, ***D***, ***E*** only) between folded conductors is 1 mm, and a space between opened ends of the resonators' conductor and a wall of the package is 0.1 mm.

Above mentioned method we have used to determine Q_{0i}-factors and frequencies of two first modes of the resonators. After that, we reduced Q_{0i}-factors in accordance to the resonant frequency, using formula (4):

$$Q_{ri} = Q_{0i} / k_i , \qquad (4)$$

where

$$k_i = \sqrt{f_i / f_A} . \qquad (5)$$

Q_{0i} is unloaded Q-factor of ***i***-th resonator; (***i***=*B, C, D* or *E*); Q_{ri} is reduced Q-factor of ***i***-th resonator; f_i is its first resonant frequency; and f_A is the first resonant frequency of the resonator ***A***, which is taken here as an etalon. Using reduced Q-factors, we can more impartially compare lossy properties of the resonators.

Besides, frequencies of the first f_1 and the second f_2 modes were determined, as their ratio f_2/ f_1 is important parameter of a resonator: it shows, how wide upper stopband of a filter based on the resonator may be.

The obtained data are collected in Table I.

It is seen from the Table, the resonators ***B*** and ***E*** have the frequencies being higher, than that of the resonator ***A***, and therefore they are not suited for designing compact filters. Moreover, filter ***E*** has the least reduced Q-factor and frequency ratio. The resonators ***C*** and ***D*** have resonant frequencies which are considerably less, than those of resonator A, and therefore they are suitable for designing more compact filters.

Resonant frequencies of resonators ***B*** and ***E*** are higher as compared to resonators ***C*** and ***D*** due to MW currents in neighboring conductors of ***B*** and ***E*** run in opposite directions at a resonant frequency, thus lowering inductance of resonant system of a resonator.

In order to decide, what resonator, ***C*** or ***D*** should be chosen for designing a compact filter, it is important to investigate their coupling coefficients, i.e., their behavior on changing a distance between them, and a distance from substrate faces to a shielding cover, etc.

III. INVESGATION OF INTERACTION BETWEEN SUSPENDED-SUBSTRATE FOLDED RESONATORS

The coupling coefficients were determined with a help of well-known method used, for example, in [10]. In the method, frequency response (Fig. 3) of a two-resonator section having weak coupling with "a measuring tract" is determined, and from that frequencies of odd and even modes are extracted.

In Fig. 3 a typical response of a two-resonator section having small external Q-factor is shown. In the figure f_e and f_o are frequencies of even and odd modes respectively, and coupling coefficients are calculated by the formula

$$k = \frac{f_e^2 - f_o^2}{f_e^2 + f_o^2} \qquad (6)$$

Since resonators ***B*** and ***E*** are inapplicable for designing compact filters, only resonators ***C*** and ***D*** were studied in concern of their coupling.

Both resonators allow two types of an arrangement in the section, and these are presented in Fig. 4, (a) and (b) are two possible arrangements for the resonator ***C***; (c) and (d) are the same for the resonator ***D***. In the section of Fig. 4 (a) conductors of both resonators are short-circuited at the same wall of the package, whereas in the section of Fig. 4(b) conductors of the second resonator are short-circuited at the opposite walls of the package. The sections depicted in Fig. 4(c) and 4(d) differ in resonator ***D*** arrangement.

Results of investigation are shown in Fig. 5, where dependencies of coupling coefficient on a space *S* between resonators (red solid curves) and on a distance H_a from a substrate's faces to shielding covers (blue dashed curves) are represented.

As one can see from the Figure, a value of interaction between resonators ***C*** is practically the same, independently on their arrangement in the section. Their behaviors on changing *S* and H_a are similar too. On contrary, in the case of resonators ***D*** strong influence of their arrangement on the interaction is observed. The interaction in the section from Fig. 4(c) is such weak, so we could not obtain a curve of the coupling coefficient vs *S*. Dependence of the coupling coefficient on the shielding height H_a appears to be insignificant. It is known [11], such behavior is inherent in a case of manly capacitive interaction between stripline resonators. On contrary, interaction in the section of Fig. 4 (c) is strong and has manly inductive nature. So, these circumstances make a resonator ***D*** unsuitable in designing multi-resonator filters.

Thus, only a resonator of ***D*** type is applicable in designing multi-resonator filters.

IV. SIMULATION AND EXPERIMENTAL RESULTS

On the base of the resonator ***C*** a 4-pole filter was simulated and fabricated. Simulation was carried out with a help of *Sonnet* software, and its final tuning was fulfilled with a help of *CST STUDIO*. Fig. 6 (a) shows structure of the simulated filter, and in Fig. 6 (b) its photo is presented Structural parameters of the filter are the next: substrate's lateral sizes are 18.7 mm × 13.2 mm; its thickness is 0.5 mm; conductors' width is 1 mm; inner gap of a resonator is 1 mm; spaces between outer and inner resonator are 0.75 mm, a space between inner resonators is 1.3 mm; resonator's length is 11.9 mm; gap between unclosed end of a resonator's conductor and the package wall: in inner resonators it is 2.35 mm, and that of an outer resonator is 3.25 mm; a width of tapping lines is 0.2 mm; a tapping point locates at a distance 8.85 mm from the unclosed ends of the outer resonators' conductors. Distances from the substrate surfaces and upper and bottom covers of the package are 3.5 mm

In Fig. 7 simulated (blue dashed curve) and measured (red solid curve) frequency responses of the filter are depicted. Good agreement is observed between simulated and measured result, especially in the range of the passband and its vicinity. Two transmission zeros symmetrically placing on the slopes considerably enhance selectivity of the filter. Centre frequency of the passband f_0=282 MHz; –3 dB level Δf=28.7 MHz; fractional bandwidth is 10.2 %; minimal passband insertion loss is 1.8 dB; passband return loss is less –14.6 dB; –40 dB stop bandwidth is 480 MHz.

V. CONCLUSION

The main purpose of the work is miniaturization of filters based on two-conductor suspended-substrate resonator. Four types of two-conductor suspended-substrate resonator are considered and their characteristics are studied. Resonators differ in a manner of their conductors folding. Resonators' Q_0-factor and frequency ratio of the first and the second modes are found. Their comparison has shown two types of the resonator are not suitable in designing compact filters, because they have too high frequency of the fist modes. Two other types of the resonator were investigated from the point of view of their interaction. Dependencies of coupling coefficients on a space between the resonators and on a distance from substrate's surfaces to package's shielding covers re obtained. Analysis of the dependencies has shown the only type of two-conductor suspended-substrate resonator is suitable for designing a compact bandpass filter on its base. Four-pole BPF was designed and fabricated. Central frequency and bandwidth of the BPF are 282 MHz and 28.7 MHz correspondingly. Substrate's lateral sizes are 18.7 mm × 13.2 mm. Estimation has shown, the substrate's area is practically a half of that for a filter based on a suspended-substrate resonator having straight conductors. It should be note, such sizes are unprecedentedly small for a strip-line technology.

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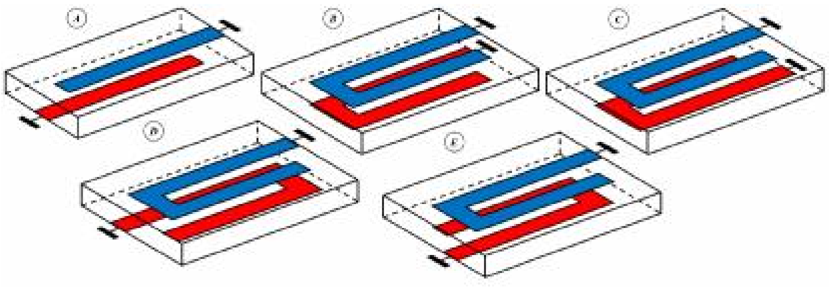

Figure 1. Structures of the investigated resonators.

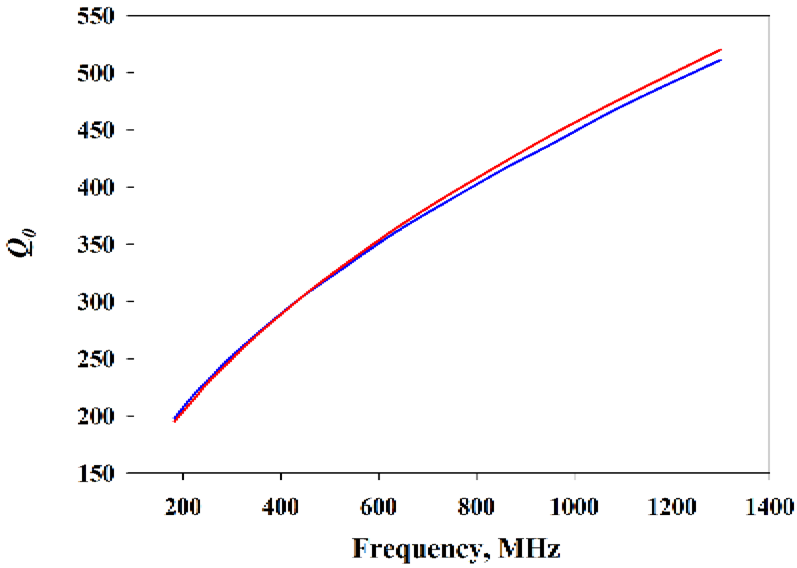

Figure 2. Q_0-factor of the two-conductor resonator on a suspended substrate vs resonant frequency. Blue line is a result obtained with a help of simulation, red curve is an approximation by the formula (3).

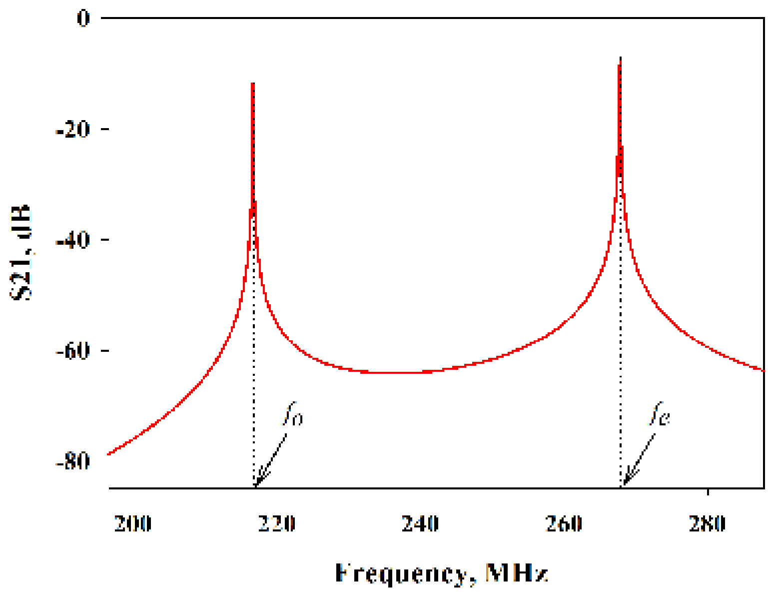

Figure 3. Typical response of a two-resonator section having small external *Q*-factor.

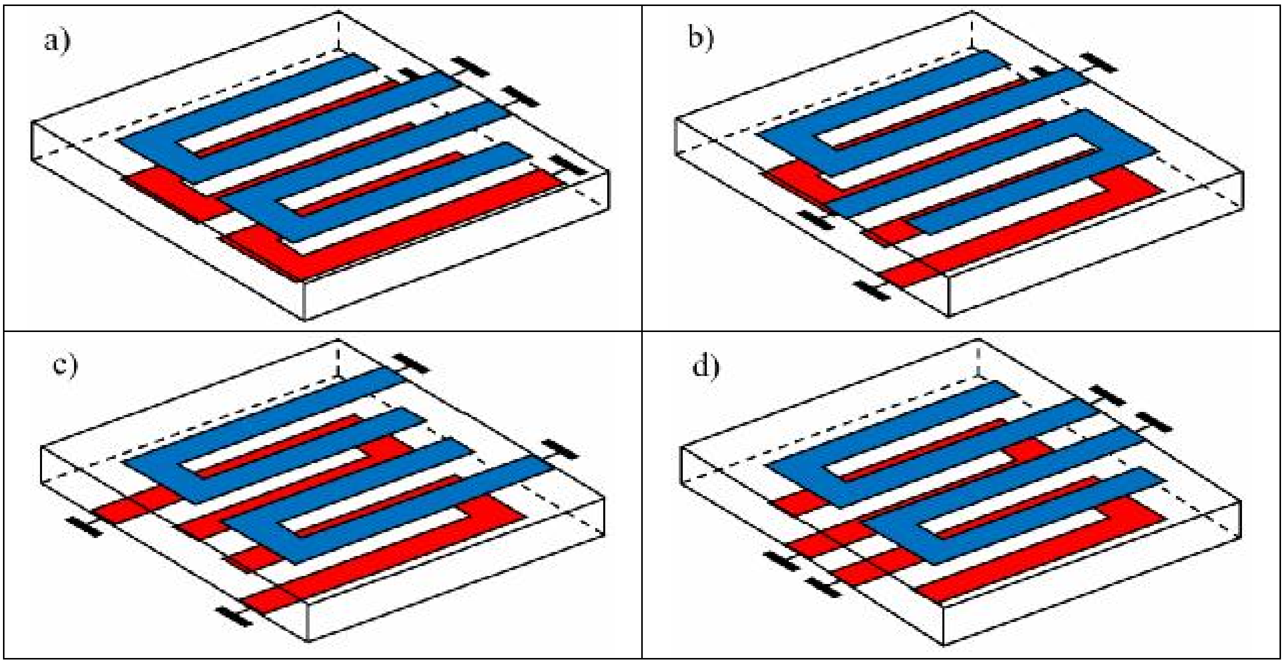

Figure 4. Two-resonator sections: (a) and (b) are two arrangements of the resonators ***C***; (c) and (d) are two variants of the section consisting of the resonators ***D***.

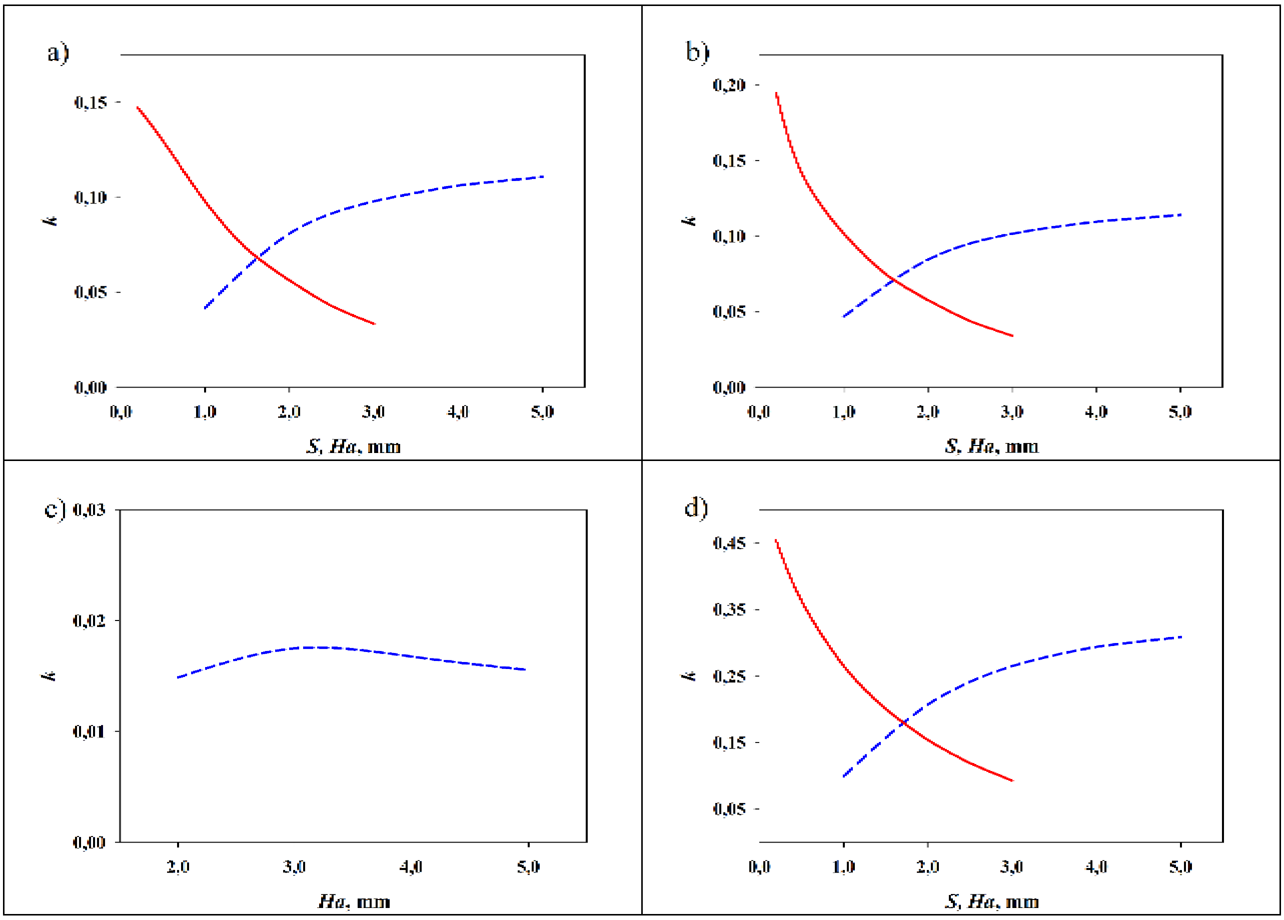

Figure 5. Dependencies of the coupling coefficient vs space *S* between resonators (red solid curve) and a distance from substrate's faces to shielding covers (blue dashed curve). (a) and (b) for the sections consisting of resonators ***C***; (c) and (d) for the sections consisting of resonators ***D***.

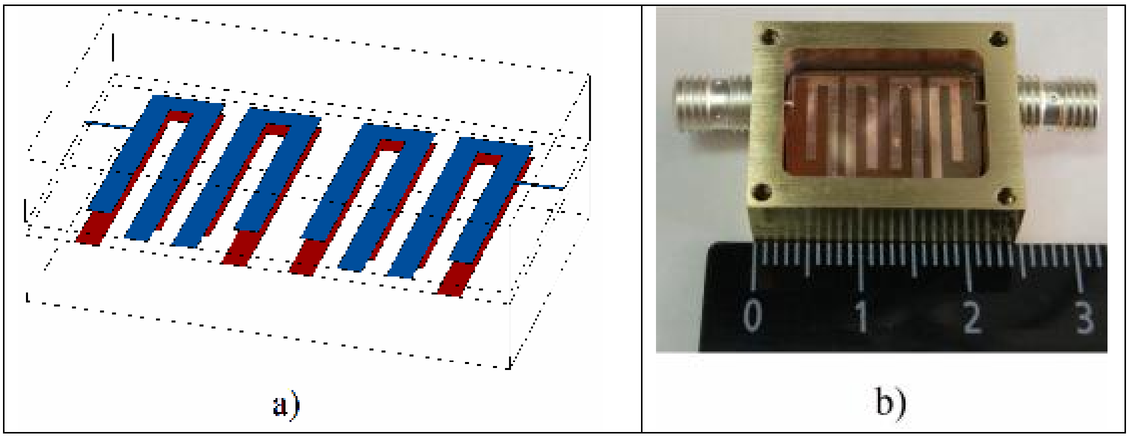

Figure 6. (a) Structure of the proposed 4-pole filter based on the resonator of the type ***C***, (b) Photo of the fabricated filter.

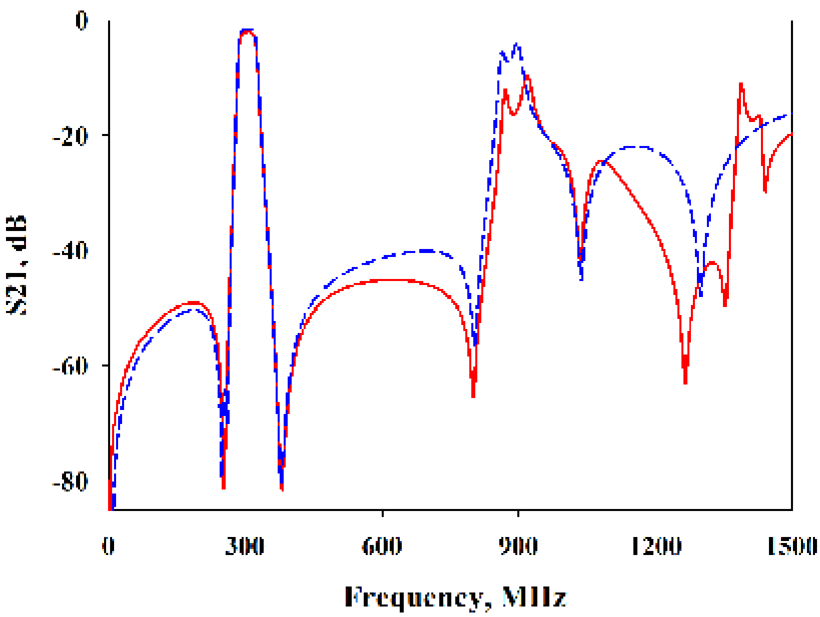

Figure 7. Simulated (blue dashed curve) and measured (red solid curve) frequency responses of the filter.

Table I. Main parameters of the investigated resonators.

Structure	f_1, MHz	f_2, MHz	Q_{0i}	k_i	Q_{ri}	f_2/f_1
A	471	1449	231	1	231	3.08
B	687	1516	205	1.21	170	2.21
C	287	718	113	0.78	145	2.50
D	246	900	122	0.72	169	3.66
E	1819	2477	162	1.96	83	1.36