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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 unsuitable 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 for designing compact BPF was chosen. A 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 $\varepsilon = 80$, thickness 0.5 mm, lateral sizes $0.13\lambda_g \times 0.09\lambda_g$ (18.7 mm × 13.2 mm). The central frequency is 305 MHz; bandwidth is 39 MHz; passband minimum insertion loss is 2.0 dB; passband return loss is less −14.6 dB; −40 dB stopband width is 480 MHz.

1. INTRODUCTION

Bandpass filters (BPF) are important devices in telecommunications, radio navigation, radiolocation systems, etc. Filters often determine the 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 been wide spread [1, 2]. They satisfy the above mentioned requirements in many aspects. Application of substrates having high dielectric constants ($\varepsilon = 20 \ldots 80$) has allowed them to penetrate in low part of a band UHF [3, 4]. But at frequencies lower ~ 500 MHz their sizes become, as a rule, unacceptably large, even on a substrate having $\varepsilon = 80$.

An invention of a two-conductor strip resonator on a suspended substrate [5, 6] has opened a way for application strip technology in filters' design and fabrication 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 [7, 8] and ultra-wideband filters [9].

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 decrease in size. We use the same method for miniaturization of two-conductor suspended-substrate filters. Several different structures of resonators are considered. Their unloaded quality factors and frequencies ratio are investigated. Coupling between the resonators is also 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.

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Good agreement between the simulated data and measured ones was achieved. The central frequency and bandwidth of filter were chosen to correspond to Terrestrial Trunked Radio (TETRA) band application [10, 11]. For ensuring the most compact device, the substrate with $\varepsilon = 80$ and thickness $= 0.5$ mm was taken to design the filter.

2. FOLDED TWO-CONDUCTOR RESONATOR ON SUSPENDED SUBSTRATE

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

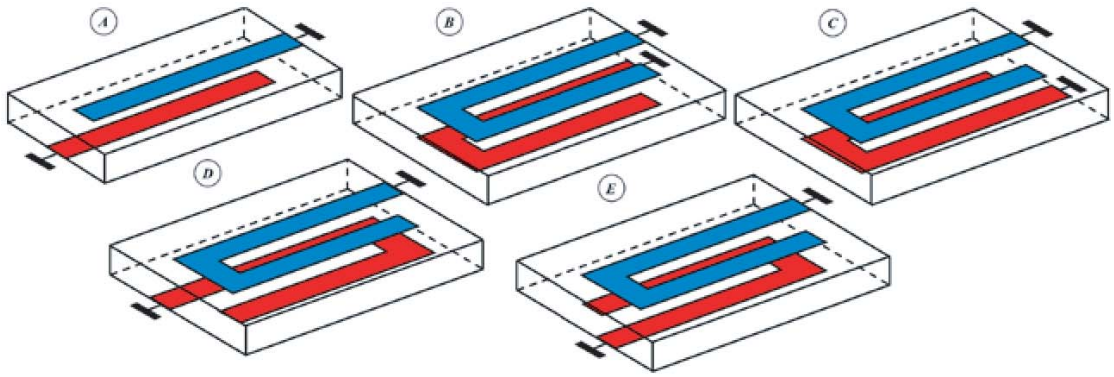


Figure 1. Structures of the investigated resonators.

The resonator of structure **E** was earlier proposed in [12]. However, as it will be seen then, such a resonator is worse compared to 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 a well-known formula [2]:

$$Q_0 = 2\pi f_r \frac{W_{st}}{P_J + P_D} \tag{1}$$

where f_r is the resonant frequency; W_{st} is the electromagnetic energy, stored by a resonator; P_J is the a power of Joule loss; and P_D is a power of dielectric loss. It should be mentioned that for strip-line resonators we can express Q_0 as follows:

$$Q_0 = 2\pi f_r \frac{W_{st}}{P_J + P_D + P_R}, \tag{2}$$

where P_R is a power of radiation loss. In a case of strip-line resonator substrate material has very low dielectric loss, $\mathrm{tg}\delta \sim 10^{-4}$, and in the case of, for example, shielded microstrip resonator radiation loss is negligible, then

$$Q_0 = 2\pi f_r \frac{W_{st}}{P_J}. \tag{3}$$

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

$$Q_0 = 2\pi f_r \frac{W_{st}}{a\sqrt{f_r}} = q\sqrt{f_r}, \tag{4}$$

where a and q are constants.

In order to find if this formula is valid in the case of a two-conductor resonator on suspended substrate, we determined with a help of simulating frequency dependence of the Q-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 every specific ε, a 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 and round markers with the frequency dependence obtained as an approximation by Equation (4) where $q = 14.42\,1/(\text{MHz})^{1/2}$, red curve.

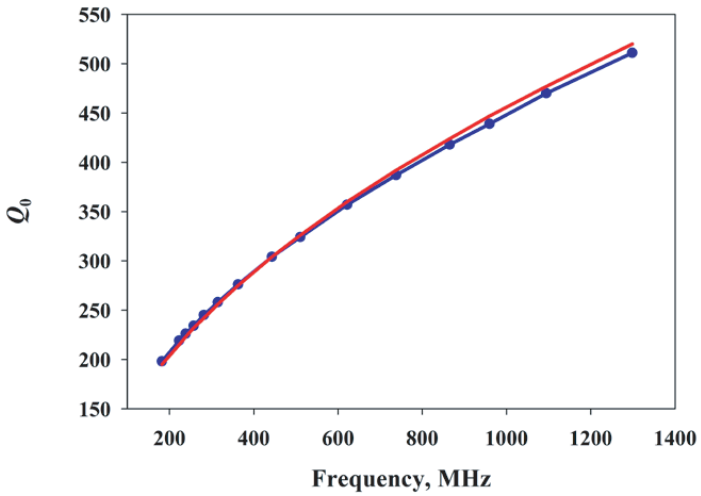


Figure 2. Q-factor of the two-conductor resonator on a suspended substrate vs resonant frequency. Blue line is a result obtained with a help of simulation, red curve is an approximation by the formula (4).

It is seen that the dependencies are in good agreement, and the frequency dependence of a two-conductor suspended substrate resonator's Q-factor obeys the square root law. This circumstance allows us to compare Q-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 $\varepsilon = 80$. 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.

We have used above mentioned method 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 Equation (5):

$$Q_{ri} = Q_{0i}/k_i \tag{5}$$

where

$$k_i = \sqrt{f_i/f_A} \tag{6}$$

Q_{0i} is the unloaded Q-factor of the i-th resonator; ($i = B$, C, D or E); Q_{ri} is the reduced Q-factor of the 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 an important parameter of a resonator: it shows how wide upper stopband of a filter based on the resonator may be.

Table 1. 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

The obtained data are collected in Table 1.

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

Resonant frequencies of resonators **B** and **E** are higher than resonators **C** and **D** because 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 whether 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.

3. INVESTIGATION OF INTERACTION BETWEEN SUSPENDED-SUBSTRATE FOLDED RESONATORS

The coupling coefficients were determined with a help from a well-known method used for the example in [13]. 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 a large external Q-factor is shown. In the figure f_e and f_o are frequencies of even and odd modes, respectively, and coupling coefficients

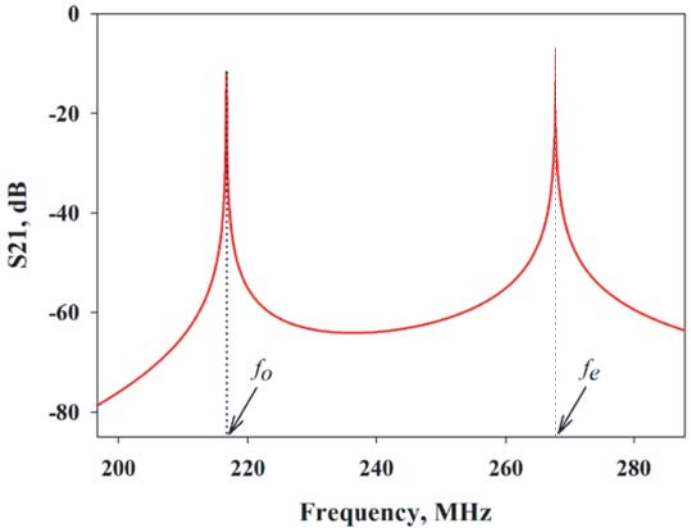


Figure 3. Typical response of a two-resonator section having large external Q-factor.

are calculated by the formula [13]:

$$k = \frac{|f_e^2 - f_o^2|}{|f_e^2 + f_o^2|} \tag{7}$$

Since resonators **B** and **E** are inapplicable to 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 Figs. 4(a) and (b) for resonator **C**; (c) and (d) are the same for 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.

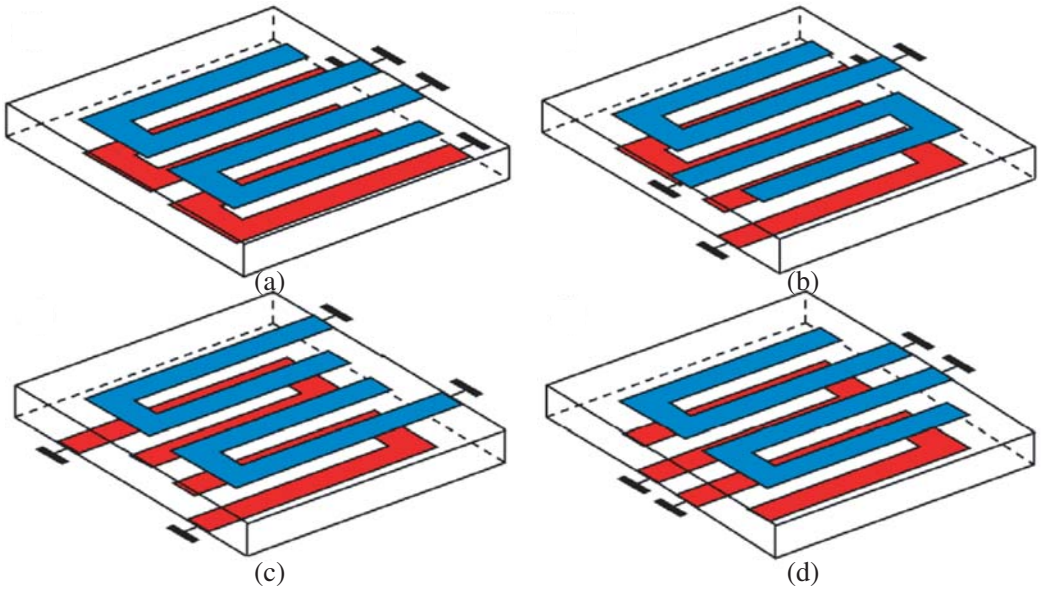


Figure 4. Two-resonator sections: (a) and (b) are two arrangements of the resonators **C**; (c) and (d) are two variants of the section consisting of the resonators **D**.

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 of their arrangement in the section. Their behaviors on changing S and H_a are similar too. On the 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 so weak that we could hardly obtain a curve of the coupling coefficient vs S. Dependence of the coupling coefficient on the shielding height H_a appears insignificant. It is known [14] that such a behavior is inherent in a case of mainly capacitive interaction between stripline resonators. On the contrary, interaction in the section of Fig. 4(d) is strong and has mainly inductive nature. So, these circumstances make resonator **D** unsuitable for designing multi-resonator filters.

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

4. SIMULATION AND EXPERIMENTAL RESULTS

Based on 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 $0.13\lambda_g \times 0.09\lambda_g$ ($18.7\,\text{mm} \times 13.2\,\text{mm}$) where λ_g represents

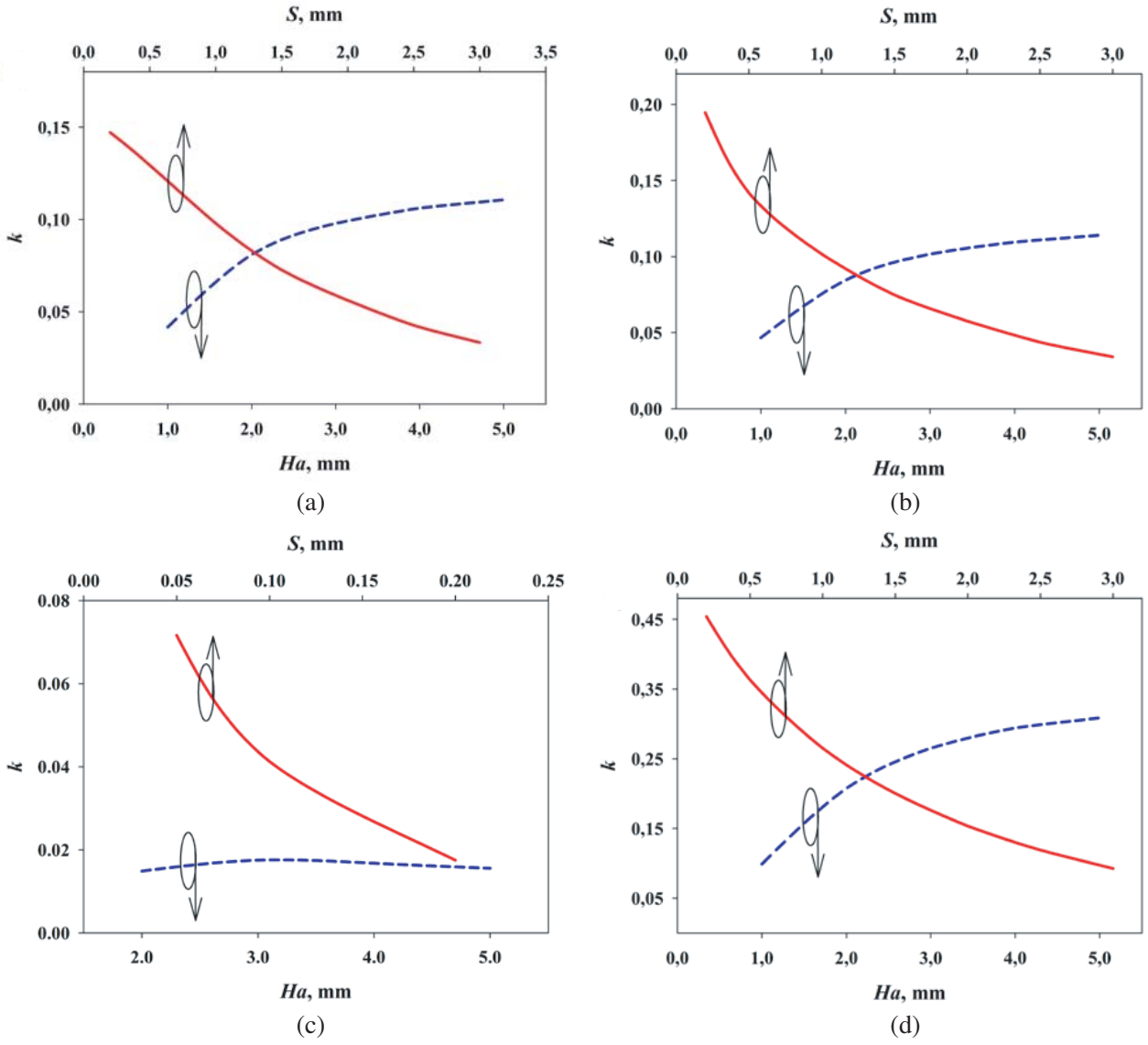
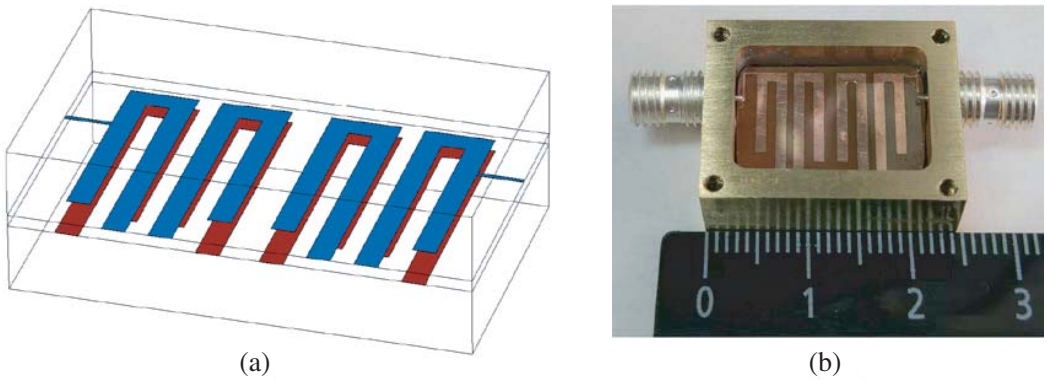


Figure 5. Dependencies of the coupling coefficient vs space S between resonators (red solid curve) and a distance from substrate's faces to shielding covers (blue dashed curve). (a) and (b) for the sections consisting of resonators **C**; (c) and (d) for the sections consisting of resonators **D**.

the guided wavelength of a microstrip line on the used substrate at filters' center frequency; its thickness is 0.5 mm; conductors' width is 1 mm; inner gap of a resonator is 1 mm; spaces between outer and inner resonators 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 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 is located at a distance of 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 and green dashed curve) and measured (red and brown solid curve) frequency responses of the filter are depicted. The inset in Fig. 7 shows the frequency responses of the filter in vicinity of its passband. Good agreement is observed between simulated and measured results, especially in the range of the passband and its vicinity. Centre frequency of the passband $f_0 = 305$ MHz; -3 dB level $\Delta f = 39$ MHz; fractional bandwidth (FBW) is 12.8%; the maximum and minimum insertion losses in passband filter are obtained as 5 and 2 dB; passband return loss is less than -14.6 dB; -40 dB stop bandwidth is 480 MHz.



(a) (b)

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

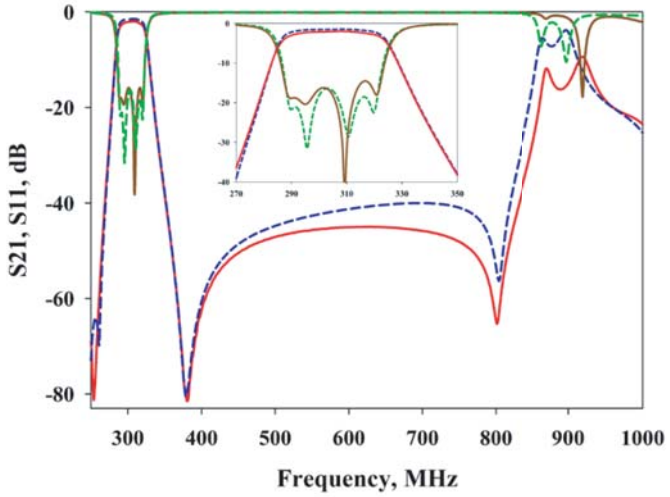


Figure 7. Simulated (blue and green dashed curve) and measured (red and brown solid curve) frequency responses of the filter.

Two transmission zeros symmetrically placed on the slopes at 253 MHz and 378 MHz with 80 dB attenuation ensure parameter BW (3 dB)/BW (20 dB) = 0.68 that is better than the one in the referenced work [10]. Table 2 provides the comparison of the proposed filter performance with other filters working in a close frequency range. It can be seen that the designed device in this work has compact size and possesses a better selectivity of passband than filters from recently reported works. Also the out-of-band rejection of proposed filter is better than 40 dB up to $2.7f_0$.

Table 2. Comparison of the proposed work with early reported works.

	f_0/FBW	IL	HS	BW (3 dB)/ BW (20 dB)	Size ($\lambda_g \times \lambda_g$)/mm
[10]	0.34/10	1.2	$4.9 * f_0$ (−27.5 dB)	0.609	$0.078 \times 0.082/26.3 \times 27.7$
[11]	0.33/20.5	0.6	$4.5 * f_0$ (−32 dB)	-	$0.12 \times 0.13/42 \times 44$
This work	0.305/12.8	2	$2.7 * f_0$ (−40 dB)	0.68	$0.13 \times 0.09/18.7 \times 13.2$

f_0 is center frequency of the passband (MHz); FBW is −3 dB fractional bandwidth (%), IL is insertion loss (dB), HS is harmonic suppression.

5. CONCLUSION

The main purpose of the work is miniaturization of filters based on two-conductor suspended-substrate resonators. Four types of two-conductor suspended-substrate resonators 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 second modes are found. Their comparison has shown two types of the resonators are not suitable in designing compact filters, because they have too high frequency of the fist modes. Two other types of the resonators 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 are obtained. Analysis of the dependencies has shown the only type of two-conductor suspended-substrate resonator suitable for designing a compact bandpass filter on its base. Four-pole BPF was designed and fabricated. Central frequency and bandwidths of the BPF are 305 MHz and 39 MHz correspondingly. Substrate's lateral sizes are $0.13\lambda_g \times 0.09\lambda_g$ ($18.7\,\text{mm} \times 13.2\,\text{mm}$). Estimation has shown that 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 noted that such sizes are unprecedentedly small for a strip-line technology.

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