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Methods for Extending Resonance Frequency Tuning Ranges of Frequency-Selective Surfaces Using Varactors

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Abstract—Methods for tuning resonance frequencies of elements of frequency-selective surfaces with the help of varactors are considered. The varactors are placed both in breaks of the conductor inside elements and in gaps between elements. Results of the approximate calculation and measurement of resonance frequencies of elements of frequency-selective surfaces of various shapes (butterfly, loop, and snake) with different-type varactors are presented. The measurement is based on the waveguide method. It is shown that, when varactors are placed in an element, the maximum relative resonance frequency change (37%) is reached with an element having a large self-capacitance (butterfly shape) and a small-capacitance varactor (MA46H120). The efficiency of the method for extending the resonance frequency tuning range of the element by means of the inductive shunting of the varactor circuit is estimated.

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INTRODUCTION

In the recent decades, the frequency-selective surface (FSSs) technique has received substantial development. This surface is a biperiodic lattice consisting of either metallic elements on a dielectric substrate (band-reflecting FSS) or of holes in a metallic screen (band-transmitting FSS).

One of FSS applications is the frequency filtering of signals in wireless communication networks in enclosed space conditions to increase the spectral efficiency of these networks. The functional characteristics of these filters are substantially improved, when the FSSs with the resonance frequency tuning are used. Of different FSS resonance frequency tuning methods, the most promising is apparently a varactor one [1–10]. In this method, the electrically controlled capacitor (varactor) is connected either inside elements of a band-reflecting FSS [3–7, 10] or in between the elements [1, 2, 8, 9]. In the first case, the varactor is placed in the gap of the conductor forming a lattice element (e.g., in the gap of a linear dipole or in the gap of a loop). In this case, the resonance frequency of a lattice element with an incorporated varactor is slightly increased but remains comparable with the resonance frequency of the same element with a short-circuited gap. In the second case, due to the strong capacitive coupling between elements, they resonate as a single ensemble. In addition, the resonance frequency of the ensemble proves to be significantly lower than the resonance frequency of an individual element.

Thus, the FSS with elements in the form of square loops between which control varactors are placed is described in [1]. An FSS with cross-shaped elements is considered in [2]; in this structure, varactors connect the ends of adjacent crosses. The relative change of the tuned resonance frequency (relative to the average) of this FSS was ±15%. Note that the period and the dimensions of the elements of these FSSs are small as compared to the resonance wavelength. This allowed the researchers to purposefully create small-period controlled FSSs with small elements [8, 9]. In this case, the frequency tuning proved to be sufficient for implementing two operating modes: (i) band transmission and (ii) band reflection of the incident electromagnetic wave [9].

When the control varactor is connected into the gap of the conductor of an FSS element, the dimensions of elements and the period of the structure are comparable with the resonance half-wavelength, and the relative frequency tuning value proves to be small. Thus, it is proposed in [3, 4] to bring the varactors into two symmetrical gaps of a square loop that is an FSS element. The relative resonance tuning frequency value, reached in this case, does not exceed 6%. To increase the tuning range, it was proposed to connect in the break of the conductor several series varactors instead of one [6]. The achieved tuning value was about 20%. Approximately the same tuning was realized when the conductor of a varactor with a very small minimum capacitance value (about 0.1 pF) was brought into the gap.

Other possibilities of extending the FSS resonance frequency tuning range are considered in this work:

(i) the use of elements of the most appropriate shapes in an FSS;

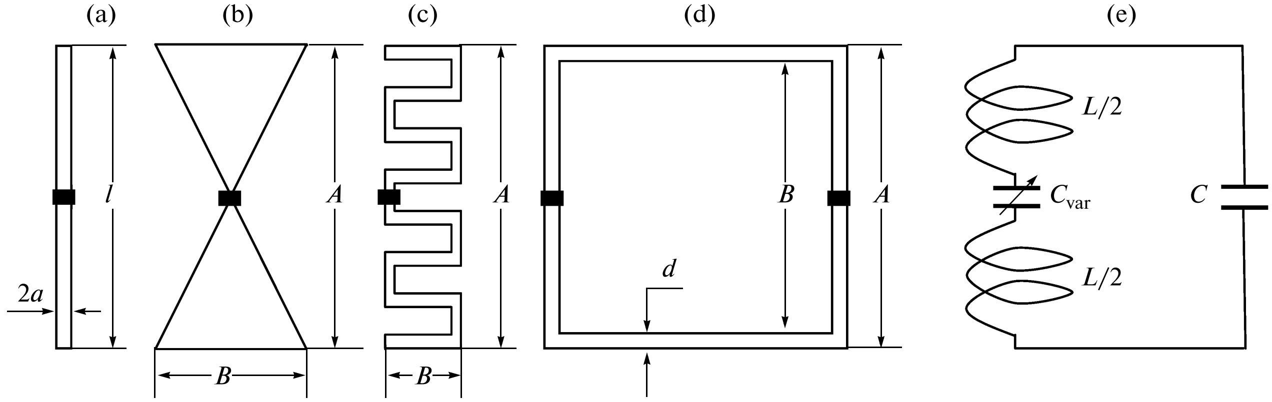

Fig. 1. FSS elements with varactors inside elements: (a) linear dipole, (b) butterfly dipole, (c) snake dipole, (d) square loop, and (e) equivalent circuit of the FSS element.

(ii) connection of an additional LC circuit in an FSS elements.

1. SELECTION OF THE SHAPE OF FSS ELEMENTS

A. Connection of Varactors in FSS Elements

Figures 1a–1d shows dipole and loop FSS elements controlled by varators (black rectangles) placed in the gaps of the conductors of these elements. The equivalent scheme of a dipole and a half-loop with varactors is shown in Fig. 1e. According to the equivalent scheme, the resonance frequency f_{rs} of the lattice element is determined by the following formula:

$$f_{rs} = \frac{1}{2\pi\sqrt{LC}}\sqrt{1+\frac{C}{C_{var}}}. \quad (1)$$

It follows from this formula that the resonance frequency tuning range depends on capacitance variation range C_{var} of the varactor and on effective capacitance value C of the FSS element. In this case, it is desirable that the C value should be as large as possible and the capacitance value of the varactor C_{var} should vary within a smaller value interval. The maximum value of the FSS resonance frequency tuning is determined by the following formula:

$$\Delta f = f_{rs\_max} - f_{rs\_min} = f_0\left(\sqrt{1+\frac{C}{C_{var\_min}}} - \sqrt{1+\frac{C}{C_{var\_max}}}\right), \quad (2)$$

where f_0 is the resonance frequency of the element, in which the varactor is short-circuited:

$$f_0 = \frac{1}{2\pi\sqrt{LC}}. \quad (3)$$

Having measured f_0 and Δf, and using reference data on C_{var_max} and C_{var_min}, it is easy to estimate the C value for various elements according to formula (2). As it was expected, the butterfly dipoles (Fig. 1b) and the loops with a wide conductor (Fig. 1d) are characterized by large C values. As an example, we report the evaluated data on C of a butterfly dipole composed of two equilateral triangles with sides equal to 11 mm. In this evaluation, a BB857 varactor with C_{var_max} = 6.6 pF and C_{var_min} = 0.52 pF was used. Measured (in the waveguide) values f_{rs_max}, f_{rs_min}, and f_0 were 5.1 GHz, 4.1 GHz, and 4 GHz, respectively. The C value calculated from formula (2) is equal to 0.26 pF. We calculate L = 6 nH from relationship (3). An element in the form of a square loop (the width of the conductor d = 3 mm) and with the same resonance frequency f_0 = 4 GHz has a smaller effective capacitance value (0.2 pF).

B. Connection of Varactors between FSS Elements

Figs. 2a–2c show FSS elements (dipole, loop, and square), between which the control varactors are connected. The equivalent circuit of one period of the structure is shown in Fig. 2d. In this circuit C and L are the self-capacitance and self-inductance values of the FSS element, and C_{cpl} is the coupling capacitance value between elements. Resonance eigenfrequency f_0 of an individual element of the FSS in the absence of adjacent elements is equal to

$$f_0 = \frac{1}{2\pi\sqrt{LC}}. \quad (4)$$

Resonance frequency f_{rs} of a serial set of coupled elements can be determined from the equivalent circuit shown in Fig. 2d. For this purpose, impedance Z is calculated for one period:

$$Z = -\frac{j}{2\pi f_{rs}(C_{var}+C_{cpl})} - \frac{j2\pi f_{rs}L}{4\pi^2 f_{rs}^2 LC - 1}, \quad (5)$$

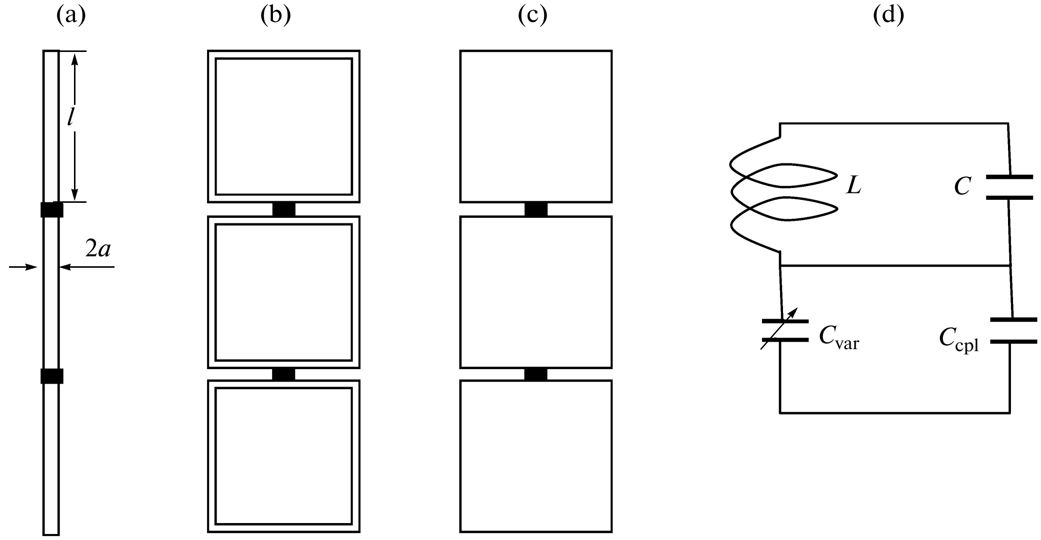

Fig. 2. FSS elements with varactors between the elements: (a) linear dipoles, (b) square loops, (c) solid squares, and (d) equivalent circuit.

which is below set equal to zero. Having solved the obtained equation, we find the following expression for resonance frequency f_{rs} of the considered structure:

$$f_{rs} = \frac{1}{2\pi\sqrt{L(C_{var} + C_{cpl} + C)}}. \tag{6}$$

It follows from formula (6) that the frequency tuning value is at maximum under the condition

$$C_{var} \gg C + C_{cpl}. \tag{7}$$

In this case, the inequality

$$f_0 \gg f_{rs} \tag{8}$$

is valid and the dimensions of the FSS element are small as compared to wavelength $\lambda_{rs} = c/f_{rs}$, where c is the light velocity.

As an example, we present the estimated parameters of the structure of dipoles with the dimensions l = 1 cm, $2a$ = 0.05 cm (Fig. 2a) connected by BB857 varactors (C_{var_max} = 6.6 pF and C_{var_min} = 0.52 pF). For narrow dipoles, capacitive coupling C_{cpl} is small. We assume that the inequality $C_{var} \gg C_{cpl}$ is valid. The resonance eigenfrequency of the dipole is $f_0 = \frac{c}{2l}$ = 15 GHz. The self-inductance of the dipole [11] is approximately $L = 2l\ln\frac{l}{a}$ = 7.38 cm = 7.38 nH, and the self-capacitance of the dipole is $C = \frac{1}{4\pi^2 f_0^2 L}$ = 1.53×10^{-2} pF. The maximal and minimal resonance frequencies of the structure are

$$f_{rs\_min} \approx \frac{1}{2\pi\sqrt{(C_{var\_max} + C)L}} = 0.72\ \text{GHz}\,,$$
$$f_{rs\_max} \approx \frac{1}{2\pi\sqrt{(C_{var\_min} + C)L}} = 2.5\ \text{GHz}\,. \tag{9}$$

Thus, in the presented example, inequalities (7) and (8) hold in the entire range of varactor capacitance C_{var}.

Under these conditions, the frequency tuning value f_{rs} is determined by the range of C_{var} as $1/C_{var}$ and can be rather large. However, in this case, the number of elements and, hence, varactors per unit FSS area is also large.

Note that here, in contrast to the case when varactors are connected into the gap of the conductor of an element, elements with a smaller self-capacitance C ensure a larger tuning of the resonance frequency f_{rs}.

2. FSS ELEMENT SAMPLES. METHOD AND MEASUREMENT OF THEIR RESONANCE FREQUENCIES

Three sets of butterfly, loop, and snake FSS elements with varactors connected into the gaps of the conductors (Fig. 1) were manufactured and studied. The table summarizes dimensions of samples, brands, and capacitance values of varactors, measured resonance frequencies, and relative tuning values.

The resonance frequency of an element was measured by the waveguide method from the frequency dependence of transmission coefficient T with an ele-

Parameters of experimental samples

Sample no.	Element type	A, mm	B, mm	Varactor type	C_{var_min}, pF (U_{cnt} = 30 V)	C_{var_max}, pF (U_{cnt} = 0 V)	f_{rs_max}, GHz (U_{cnt} = 30 V)	f_{rs_min}, GHz (U_{cnt} = 0 V)	$\frac{f_{rs\_max} - f_{rs\_min}}{f_{ra\_av}}$, %
1	Butterfly	21	11	BB857	0.52	6.6	5.2	4.1	24
2	Loop	18	10	BB857	0.52	6.6	5.6	4.7	17
3	Snake	20	4	BB857	0.52	6.6	5	4.5	11
4	Butterfly	21	11	SMY1234	1.3	9.6	4.7	4.3	09
5	Butterfly	28	14	MA46H120	0.15	1	5.4	3.7	37

ment placed in the center of the cross-section of the waveguide (except sample no. 5). Control voltage U_{cnt} in an interval of 0–30 V from a V5-44 source was applied to the varactor via thin wires through a slot in the narrow waveguide wall. To ensure high-frequency isolation from the power source, 100-kΩ resistors were soldered in two wires before the varactor. Sample no. 5 was measured in the middle of the gap of a 50-mm-long waveguide section.

The frequency dependences of transmission coefficients for samples from the table are shown in Figs. 3–7 at various control voltages. The sample numbers correspond to those listed in the table. Extreme resonance frequency values f_{rs_max} and f_{rs_min} and relative tuning values are summarized in the table. It follows from the obtained results that the shape of the butterfly element ensures a higher relative resonance frequency tuning value as compared to other shapes and that the relative resonance frequency

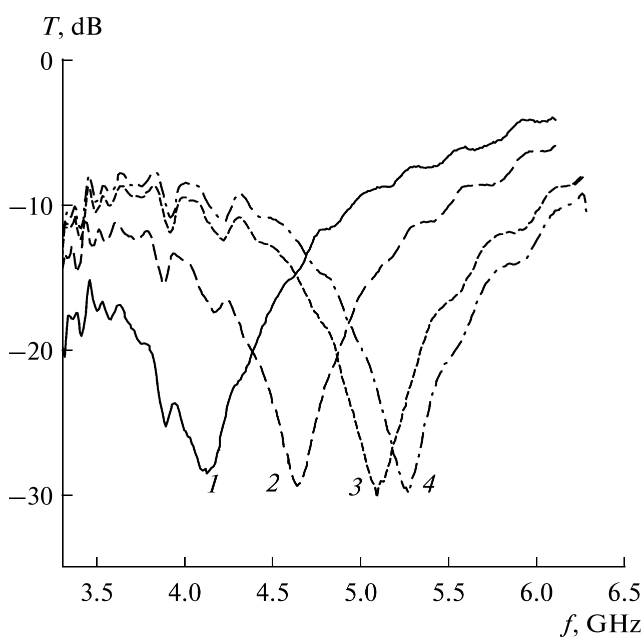

Fig. 3. Frequency dependence of the transmission coefficient for sample no. 1: curves *1–4* correspond to U_{cnt} = 0, 10, 20, and 30 V.

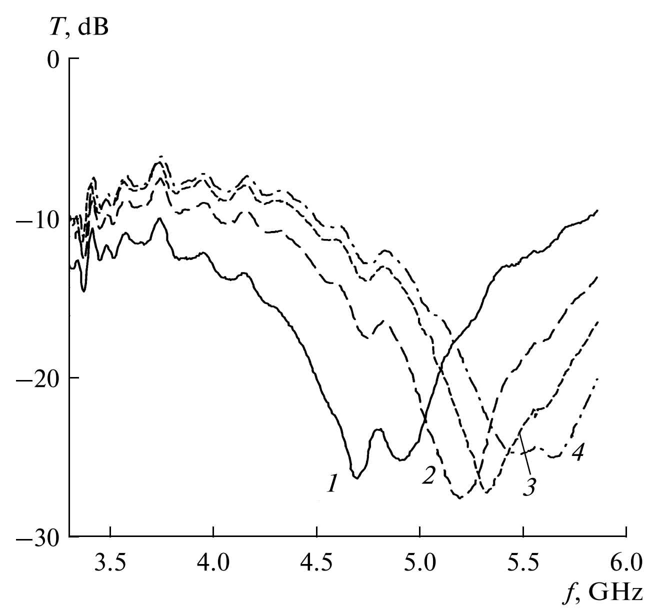

Fig. 4. Frequency dependence of the transmission coefficient for sample no. 2: curves *1–4* correspond to U_{cnt} = 0, 10, 20, and 30 V.

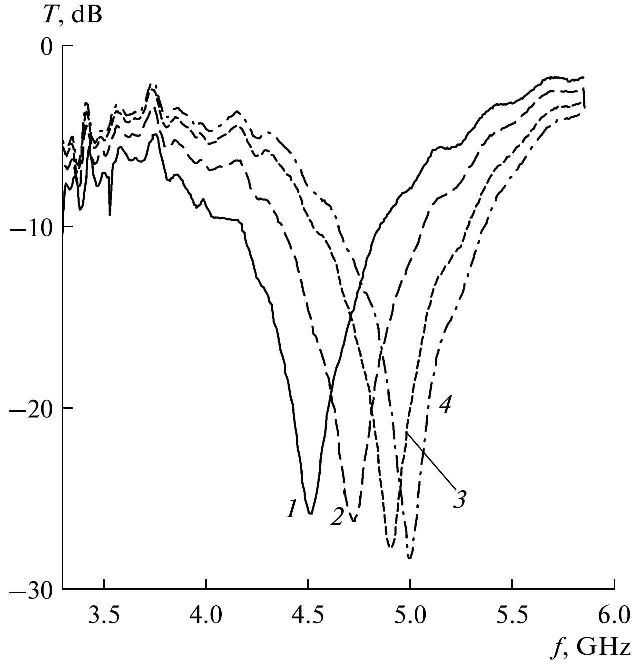

Fig. 5. Frequency dependence of the transmission coefficient for sample no. 3: curves *1–4* correspond to $U_{cnt} = 0$, 10, 20, and 30 V.

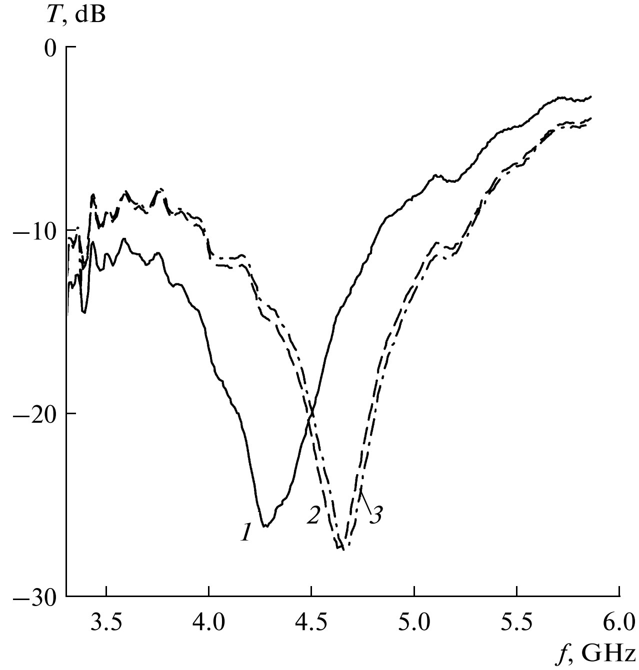

Fig. 6. Frequency dependence of the transmission coefficient for sample no. 4: curves *1–3* correspond to $U_{cnt} = 0$, 10, 20, and 30 V.

tuning value is at maximum when an MA46H120 varactor with a small capacitance is used.

The experimental results are in compliance with theoretical conclusions following from formula (2): namely, the larger the self-capacitance of an element and the smaller the minimal capacitance of a varactor, the larger the tuning range. Note, however, that the application of smaller capacitance varactors has certain drawbacks, namely: the cost of these varactors is relatively high and the practical application technology is more complex. Therefore, the search and studies of other ways of extending the tuning range seem to be urgent.

3. A METHOD FOR EXTENDING THE RESONANCE FREQUENCY TUNING RANGE OF AN FSS ELEMENT

As it has been noted above, when a varactor is placed inside an element (Fig. 8a), the smaller the minimal capacitance of the varactor and, hence, the higher its capacitive impedance, the larger the resonance frequency tuning range of the element. A natural method for increasing the impedance of the varactor circuit is to shunt the varactor capacitance C_{var} with a small inductance L_{var}. The equivalent circuit of the element with the varactor and shunting inductance L_{var} is shown in Fig. 8b. Here, C_{dbl} is a large additional capacitance disabling the short circuit for the dc voltage that controls the varactor capacitance. Equating the impedance of the equivalent circuit to zero, we obtain the equation for resonance frequency f_{rs}

$$-\frac{j}{2\pi f_{rs}C} + j2\pi f_{rs}L + \frac{j2\pi f_{rs}L_{var}}{1 - 4\pi^2 f_{rs}^2 C_{var} L_{var}} = 0. \quad (10)$$

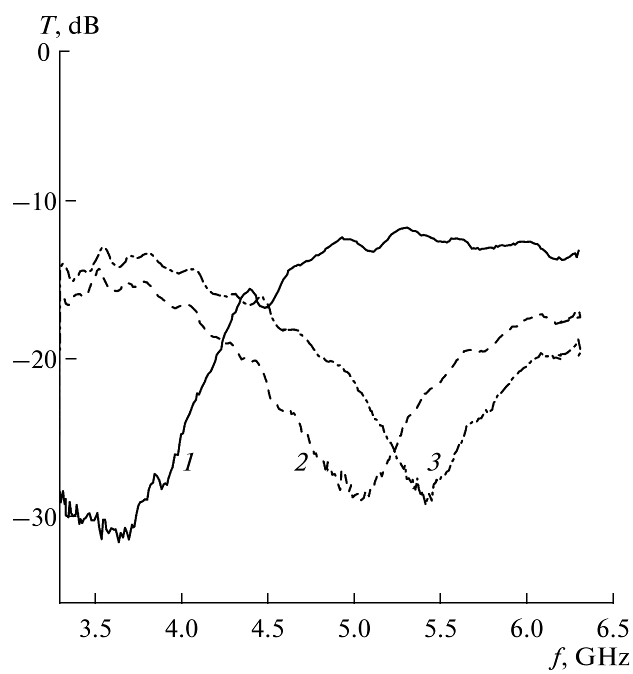

Fig. 7. Frequency dependence of the transmission coefficient for sample no. 5: curves *1–3* correspond to $U_{cnt} = 0$, 10, 20, and 30 V.

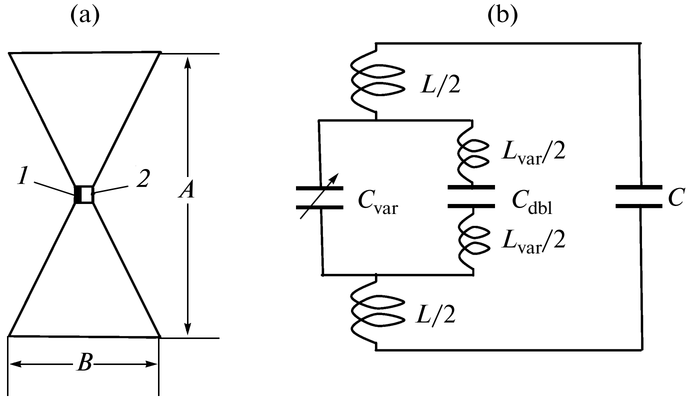

Fig. 8. Shunting the varactor circuit: (a) shunt connection circuit ((*1*) varactor and (*2*) disabling capacitor); and (b) equivalent circuit.

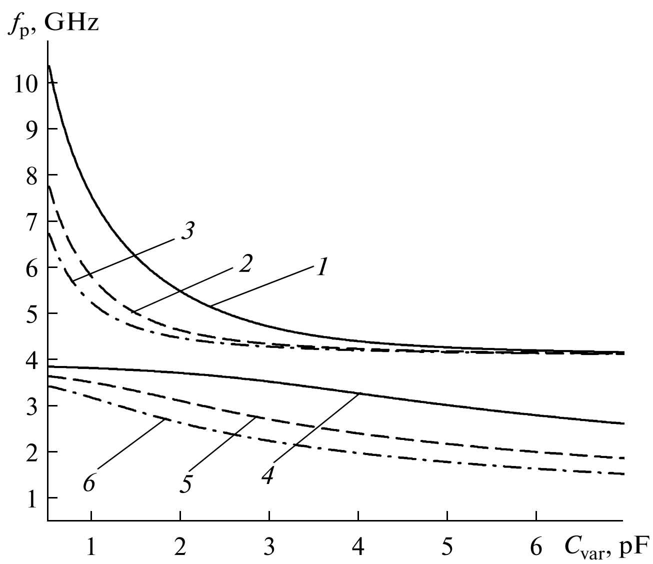

Fig. 9. Dependence of the resonance frequency on the capacitance value of the varactor C_{var} for three shunting inductances L_{var}: curves *1*, *4* correspond to $L_{var} = 0.5$ nH, curves *2*, *5* correspond to $L_{var} = 1$ nH, and curves *3*, *6* correspond to $L_{var} = 1.5$ nH.

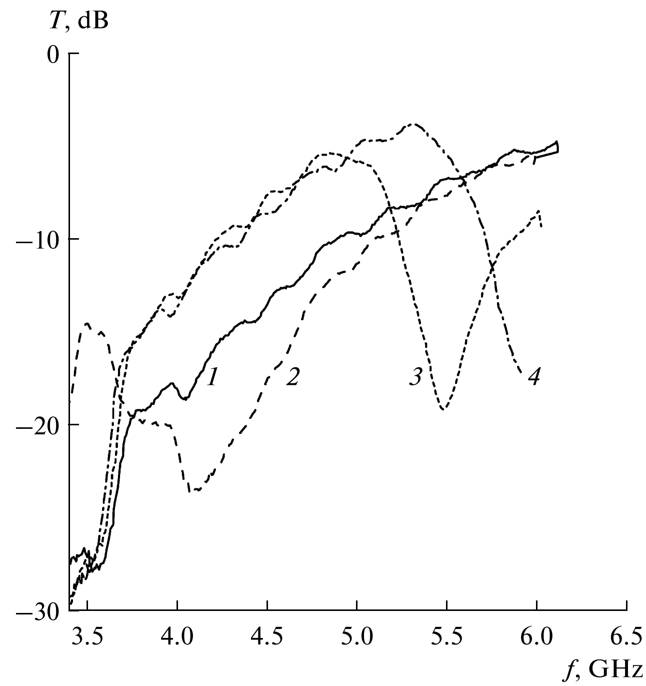

Fig. 10. Frequency dependence of the transmission coefficient for sample no. 1 with the disabling capacitor: curves *1*–*4* correspond to $U_{cnt} = 0$, 10, 20, and 30 V.

A solution to Eq. (10) has the form

$$f_{rs} = \frac{1}{2\pi}\sqrt{\frac{LC + L_{var}C_{var} + L_{var}C}{2LCL_{var}C_{var}} \pm \sqrt{\left(\frac{LC + L_{var}C_{var} + L_{var}C}{2LCL_{var}C_{var}}\right)^2 - \frac{1}{LCL_{var}C_{var}}}}. \quad (11)$$

In Eq. (10), large capacitance C_{dbl} is not taken into account, since it is assumed that its impedance is small compared to the impedance of inductance L_{var}.

Dependence of f_{rs} on C_{var} calculated from formula (11) for element no. 1 from the table ($C = 0.26$ pF, $L = 6$ nH) at $L_{dbl} = 0.5$; 1; and 1.5 nH is shown in Fig. 9. Note that two resonance frequencies correspond to each value of C_{var}, and one of them can be retuned in a rather large range. The shown dependence enables us to estimate the influence of shunting inductance L_{var} on the increase of the tuning range of resonance frequency f_{rs}. The value of this inductance is about 1 nH and even smaller. Such a small inductance value is virtually implemented as the inductance of contact connections of the varactor and disabling capacitor and the inductance of conducting gaps between the contacts (Fig. 8a).

Figure 10 shows the frequency dependence of the transmission coefficient for sample no. 1, when an 18-pF disabling capacitor is connected in parallel to the varactor. As it has been assumed above, the impedance value of inductance $L_{var} = 1$ nH at an operating frequency of 4 GHz, equal to 24 Ω substantially exceeds the capacitive impedance value of the disabling capacitor, which is equal to 2.2 Ω. The comparison of the curves from Figs. 3 and 10 shows that, in the second case, the relative resonance frequency tuning value was approximately doubled and reached 50%. However, in this case, the depth and width of resonance dips in the frequency curve noticeably decrease while the resonance frequency increases.

CONCLUSIONS

The theoretical evaluation of the FSS resonance frequency tuning with the use of varactors has demonstrated the following. When a varactor is placed in the conductor gap inside an FSS element, a wider tuning range is reached with a larger self-capacitance of the element and a smaller minimal capacitance of the varactor. When the varactor is connected between FSS elements, a wider tuning range is obtained with a smaller self-capacitance of the element and a smaller coupling capacitance between elements.

The resonance frequencies of FSS controlled elements of different shapes (butterfly, loop, and snake) have been measured by the waveguide method with varactors placed in the conductor gap inside an FSS element. The maximum relative resonance frequency tuning was 37%, and it was obtained with a butterfly element and an MA46H120 small-capacitance varactor. The method for extending the tuning range by the inductive shunting the varactor circuit has been tested. In this case, the relative resonance frequency tuning of the FSS element with a BB857 average-capacitance varactor has been increased from 24% to 50%.

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