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Controlled Bandpass Frequency-Selective Surfaces

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Abstract—Bandpass frequency-selective surfaces (FSSs) controlled by varactors and representing biperiodic lattices formed from slotted squares in a thin metallic screen are considered. Main factors affecting the FSS tuning range with different circuits for connection of control varactors are experimentally evaluated. Experimental results obtained by the waveguide method of measuring the transmission coefficient through samples of both individual FSS elements loaded with varactors of various types and lattices consisting of these elements at microwave frequencies are presented. Based on the measured data, attainable values of the relative tuning of the FSS resonance frequency are evaluated: $f_{max}/f_{min} = 1.4$ for control circuits with two MA46N120 low-capacitance varactors in each FSS element and $f_{max}/f_{min} = 1.5$ for control circuits with one VV857 medium-capacitance varactor.

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INTRODUCTION

At present, frequency-selective surfaces (FSSs) are used in a broad class of electronic devices. The functional capabilities of these devices are substantially improved if they use FSSs with tuned resonance frequency. In the last 10–15 years, many studies devoted to the design of band-stop FSSs controlled by varactors were published. In these FSSs, the varactors are included either into breaks of the conductor inside metal elements of FSSs [1–7] or between elements [8–11]. At the same time, controlled bandpass FSSs are also of interest for practical applications, namely, in frequency filters ensuring optimal conditions for propagation of radio waves inside building structures [12–14], in systems controlling the direction of the radio beam [15, 16], and in antenna radomes with a limited passband [17].

The bandpass FSSs are usually implemented as a periodic lattice of resonance holes in a thin metal screen. The resonance frequency and the Q factor of the lattice depend on the shape and dimensions of the holes and the lattice period. Usually, the holes in a controlled FSSs have the shape of either straight slots [13, 15] or slotted squares and circles [14, 18–20]. Electronic control is carried out by p–i–n diodes or varactors inserted between the slot edges.

The quality of control can be evaluated by the two parameters: (i) the tuning range of the FSS resonance frequency and (ii) the loss of the wave passing through the FSS at the resonance frequency. These parameters depend on many factors, namely, the interval of operating capacitances of varactors, shapes and dimensions of slotted elements, circuits used for connection of varactors to the slotted elements of the FSS, the thermal loss in varactors, etc. For example, the FSSs in the form of periodic lattices consisting of straight slots controlled by varactors, which are located in the midpoints of the slots were considered in [13, 15]. These lattices were designed for control of propagation of radio waves in closed premises with numerous wireless communication devices. The maximum relative frequency tuning, implemented in [13], was 1.7. In this case, at the minimum frequencyof the tuning range, the loss of the wave transmitted through the FSS exceeds 6 dB. In [15, 16], it is assumed to use such FSSs in a system controlling the direction of the radio beam. For an acceptable loss level, the relative tuning range of the resonance frequency of the FSS does not exceed 1.3 and can be implemented by changing capacitances of varactors within 0.14–0.3 pF [15]. As it was noted in [16], further increase in the capacitance value leads to a disastrous decrease in the value of the signal transmitted through the FSS and an increase in the loss level.

Bandpass FSSs in the form of periodic lattices consisting of slotted squares with p–i–n control diodes [14] and varactors [18] inserted between of opposite sides of the slot in its midpoint were studied in some works [14, 18]. A controlled lattice [14] is a spatial switch between reflection and transmission modes for some specified frequency band. It was shown [18] that a relative resonance frequency tuning of 1.3 is reached when the capacitance of the varactors varies in an interval of 0.3–0.7 pF with an insignificant loss (below 1 dB). Papers [19, 20] give the results of numerical calculation of the reflection coefficient of periodic lattices consisting of ring slots in a thin metallic screen with lossless variable capacitances connected to the slots.

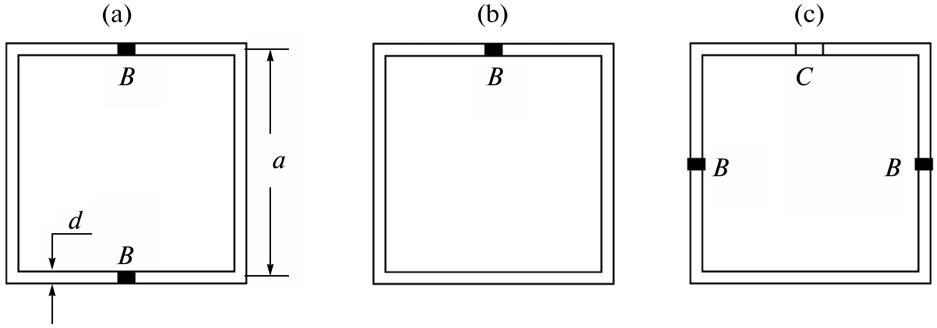

Fig. 1. Circuit of connection of capacitive loads to the slotted element: (*B*) varactor and (*C*) constant-value capacitor.

For eaxmple, the case of connection to diametrically opposite areas of the slot of two capacitors with capacitances varying in an interval of 0.05–0.3 pF and ensuring a relative resonance frequency tuning of about 1.7 was considered in [19]. Connection of one capacitor with a capacitance varying from 0.2 to 1.0 pF and ensuring a relative resonance frequency tuning of 1.4 was considered in [20].

In many controlled band-transmitting FSSs described above, a decrease in the resonance frequency is accompanied by an increase in the loss level at the resonance frequency and narrowing of the bandwidth. Another negative factor is that an efficient control of the resonance frequency of a FSS with small loss at the resonance frequency takes place only in an interval of small control capacitances (below 1 pF).

The purpose of this study is to evaluate the tuning range of the resonance frequency of a bandpass FSS as a function of the type of varactors and the circuit used for their connection to the elements of a lattice in the form of slotted squares. As is well known [17], an advantage of a lattice with elements of this shape is a high angular stability of their frequency characteristics.

1. CIRCUITS FOR CONNECTION OF VARACTORS TO THE FSS ELEMENTS

Figs. 1a–1c show the basic considered circuits for connection of varactors to the slotted element of the FSS, where *B* is the varactor and *C* is the constant-capacitance varactor. The circuit in Fig. 1 with two varactors seems to be the most universal, since it is simple to modify it for application in a circuit operating with an arbitrary polarization of the incident wave. The circuits in Figs. 1b and 1c are designed for operation with the only polarization of the incident wave. The distribution of the electric field of the fundamental mode in a slotted element without varactors and the capacitor is shown in Fig. 2. This field can be represented as a sum of two gap waves, traveling towards each other. After rotation through 360°, the field amplitude in the slot passes two maxima and two nulls. In circuits shown in Figs. 1a and 1b, varactors are connected at the points of maxima of the electric field, which is natural. In the circuit in Fig. 1c, in the absence of capacitor *C*, the varactors would be at the points where the electric field was equal to zero. However, connection of the capacitor creates finite-amplitude field at these points.

The connection of a capacitive load in the form of a varactor or a constant-value capacitor to the slotted element changes not only the resonance frequency of the element but also the distribution of the electromagnetic field in it. For example, in the circuit in Fig. 1a, a significant increase in the capacitance of the capacitive loads, which, in the limit, is equivalent to short circuits, efficient excitation of the fundamental gap mode becomes impossible, and, hence, the transmission coefficient of the FSS decreases at the resonance frequency. Another important factor affecting the transmission coefficient of the FSS is the scattering of the slot wave, including the thermal scattering on the capacitive element. Both this factor and the factor of largr capacitance really limit the tuning range of the resonance frequency of the bandpass FSS. Comparative evaluation of tuning ranges was performed using measurements carried out according to the waveguide method [4] for circuits in Figs. 1a and 1b and different types of the capacitive load (constant-value capacitors and varactors). Measurements with constant-value capacitors, which have knowingly small thermal loss, were performed for evaluation of

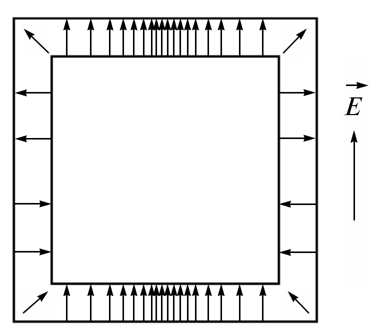

Fig. 2. Distribution of the electric field in the unloaded square slotted element.

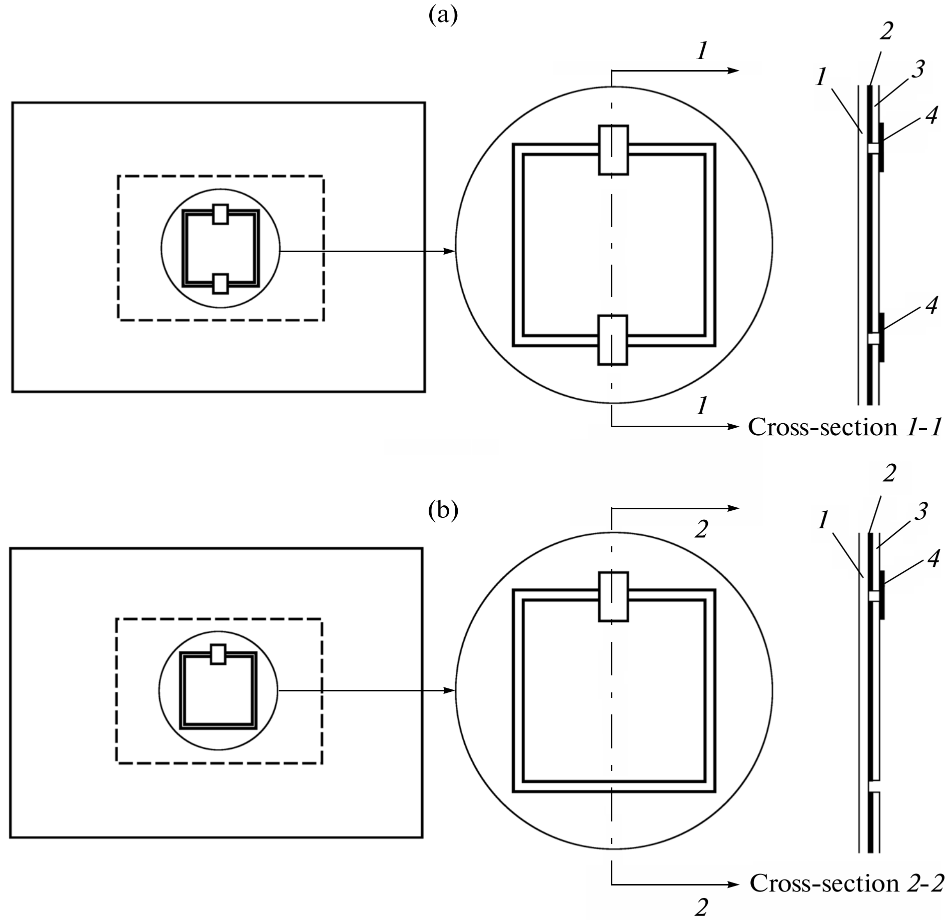

Fig. 3. Slotted element with (a) two and (b) one constant-capacitance loads.

the effect of the factor of the load capacitance on the transmission coefficient.

2. MEASUREMENT OF THE RESONANCE FREQUENCY OF THE SLOTTED ELEMENT LOADED BY A CONSTANT-VALUE CAPACITOR

The resonance frequency of the slotted element of the FSS and the transmission coefficient at this frequency were determined by the waveguide method from the frequency dependence of transmission coefficient $T(f)$ for the case when the element is placed at the center of the waveguide cross-section.

The measurements were performed for the sample of a slotted element loaded by two (Fig. 3a) and one (Fig. 3b) constant-value capacitors. Square slotted elements were manufactured from a three-layer film: the first layer was 50-μm-thick lavsan, the second layer was 20-μm aluminum foil, and the third layer was 50-μm polyethylene. The slot width d was 0.5 mm and the average length a of the square side was 10 mm. The capacitive load was rectangular fragment *4* of the aluminum foil placed on the slot and forming two flat series capacitors.

Capacitive load C was calculated in accordance with the known formula for flat capacitors:

$$C = \frac{S\varepsilon}{8\pi l}\ [\mathrm{cm}], \qquad (1)$$

where S is the capacitor area, $\varepsilon = 2.25$ and $l = 0.005$ cm are the permittivity and thickness of the polyethylene layer, respectively. Here, it is taken into account that the capacitance of the load is equal to the halved capacitance of two identical capacitors.

In the process of measurements,, the sample was placed between two waveguide flanges. The dotted line in the figure shows the cross-section of the waveguide.

Tables 1 and 2 summarize the results of measurements of the resonance frequency and the transmission coefficient in accordance with the circuits in Figs. 3a and 3b for different capacitive loads. In the case of two capacitive loads (Fig. 3a, Table 1), the transmission coefficient rapidly decreases when the capacitive load exceeds 3 pF. This behavior of the transmission coefficient is explained by lowering of the impedance of the capacitive load to values below 20 Ω. The relative tun-

Table 1. Results of the measurements of the resonance frequency and the transmission coefficient in accordance with the circuit in Fig. 3a

Side of the square slot, mm	Cross-section of the waveguide, mm^2	Load capacitance, pF	Resonance frequency, GHz	Transmission coefficient, dB
10	35 × 15	0	7.5	–1.0
10	48 × 24	0.25	5.7	–3.0
10	48 × 24	0.5	5.2	–4.0
10	48 × 24	1.0	3.5	–5.0
10	72 × 34	2.0	2.85	–5.5
10	72 × 34	3.0	2.44	–7.5
10	72 × 34	4.0	2.18	–15.0

Table 2. Results of the measurements of the resonance frequency and the transmission coefficient in accordance with the circuit in Fig. 3b

Side of the square slot, mm	Cross-section of the waveguide, mm^2	Load capacitance, pF	Resonance frequency, GHz	Transmission coefficient, dB
10	35 × 15	0	7.5	–1.0
10	35 × 15	0.25	7.0	–1.0
10	35 × 15	0.5	6.6	–1.0
10	35 × 15	1.0	5.4	–1.0
10	35 × 15	2.0	5.2	–2.0
10	48 × 24	4.0	4.3	–3.0
10	72 × 34	7.0	4.2	–4.0

ing of the resonance frequency f_{max}/f_{min} is about 3 when the capacitive load varies from 0 to 3 pF. In the case of two capacitive loads (Fig. 3b, Table 2), when the capacitive load varies from 0 to 7 pF, variation of the transmission coefficient is comparatively small (from –1 to –4 dB). In this case, the relative tuning of the resonance frequency f_{max}/f_{min} is about 1.8. Note that, when the slot is short-circuited, the resonance frequency varies comparatively little as compared to the case when the load is 7 pF (from 4.2 GHz to 3.75 GHz).

3. MEASUREMENT OF THE FREQUENCY DEPENDENCE OF THE TRANSMISSION COEFFICIENT FOR THE SLOTTED ELEMENT OF THE FSS LOADED BY VARACTORS

As variable-capacitance loads, two types of varactors were used: BB857 medium-capacitance varactor (INFINEON Technologies) and MA46H120 low-capacitance varactor (MACOM). Slotted elements were of two standard dimensions: (a = 10 mm, d = 0.5 mm) and (a = 7 mm, d = 0.5 mm). The resonance frequency of the element and the transmission coefficient at the resonance frequency were determined from the frequency dependence of the transmission coefficient, which was measured by the waveguide method. Frequency dependences of transmission coefficients T for the circuit shown in Fig. 1a, two standard dimensions of the slotted elements, and two types of varactors are shown in Figs. 4–7. Figures 4 and 5 show the frequency dependences of the transmission coefficients for the BB857 varactor and slotted elements with a = 10 mm and a = 7 mm, respectively. In accordance with the design data, the capacitance of the varactor at 1 MHz varies from 7 to 0.5 pF when the control voltage varies from 0 to 29 V. As follows from Figs. 4 and 5, strong lowering of the transmission coefficient takes place already when the control voltage at the varactor decreases to 10 V, which corresponds to a capacitance of 1 pF. Note that, when the capacitive loads are capacitors with small thermal loss, significant decrease in the transmission coeffi-

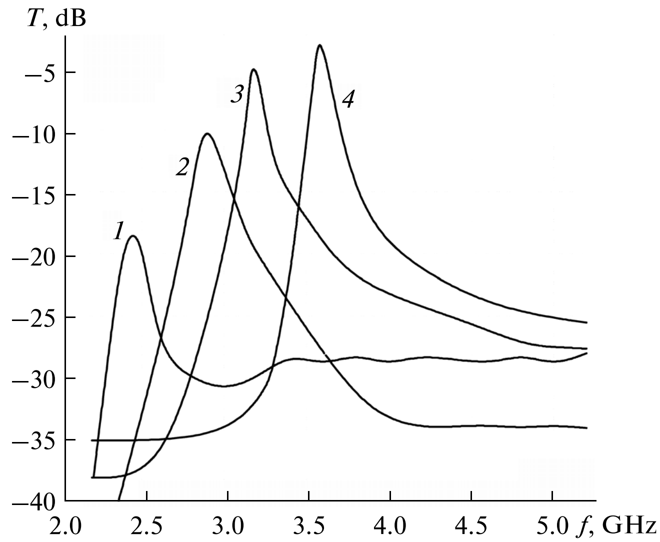

Fig. 4. Frequency dependence of the transmission coefficient of a square slotted element with side $a = 10$ mm loaded by two BB857 varactors. Curves *1*, *2*, *3*, and *4* correspond to a control voltage at varactors of 10, 15, 20, and 29 V.

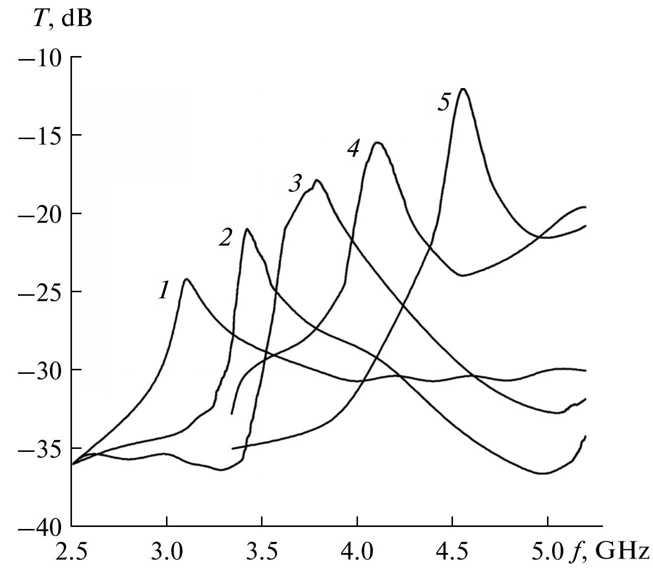

Fig. 5. Frequency dependence of the transmission coefficient of a square slotted element with side $a = 7$ mm loaded by two BB857 varactors. Curves *1*, *2*, *3*, *4*, and *5* correspond to a control voltage at varactors of 10, 13, 15, 20, and 29 V.

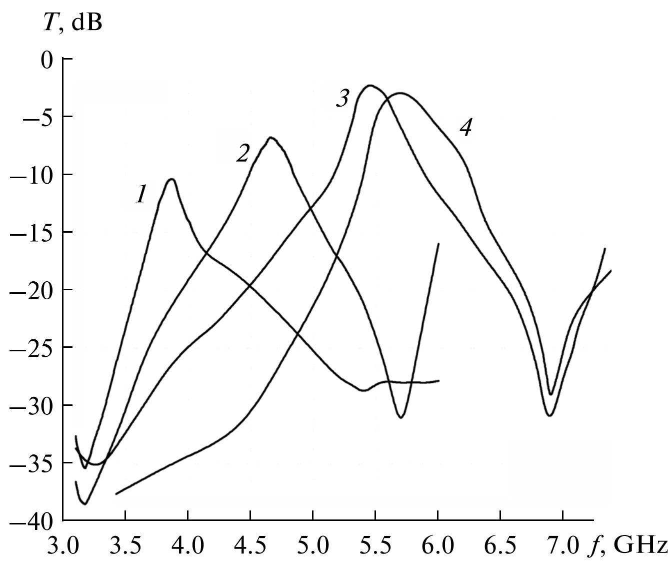

Fig. 6. Frequency dependence of the transmission coefficient of a square slotted element with side $a = 10$ mm loaded by two MA46H120 varactors. Curves *1*, *2*, *3*, and *4* correspond to a control voltage at varactors of 0, 2, 15, and 20 V.

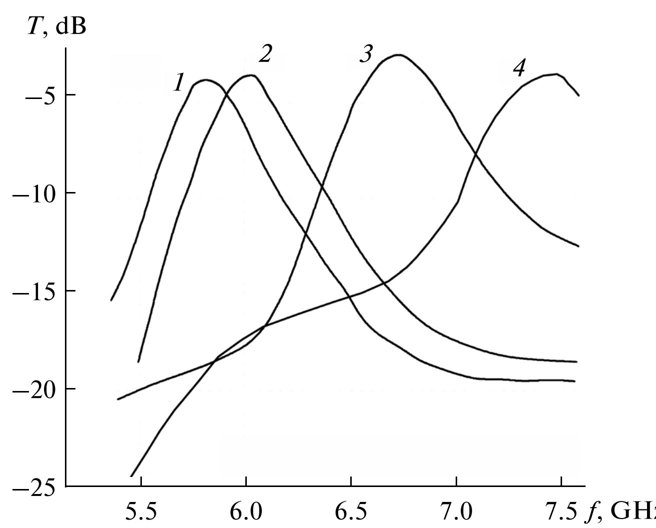

Fig. 7. Frequency dependence of the transmission coefficient of a square slotted element with side $a = 7$ mm loaded by two MA46H120 varactors. Curves *1*, *2*, *3*, and *4* correspond to a control voltage at varactors of 6, 7, 10, and 20 V.

cient takes places for a capacitance of 3–4 pF. This difference in the transmission coefficients can be attributed to the scatter of the thermal energy at the varactor, which increases with the varactor capacitance and, hence, with the high-frequency current through the *capacitive* + *active resistance* series circuit of the varactor.

Figures 6 and 7 show the frequency dependences of transmission coefficients for MA46H120 varactors. In accordance with the design data, the capacitance of the varactor of this type at 1 MHz varies from 1.1 to 0.15 pF when the control voltage varies from 0 to 20 V. As follows from Figs. 6 and 7, transmission coefficients of these varactors are higher in the whole interval of control voltages and the relative tuning of the resonance frequency $f_{max}/f_{min} = 1.5$. This fact can be attributed to both smaller capacitance values and

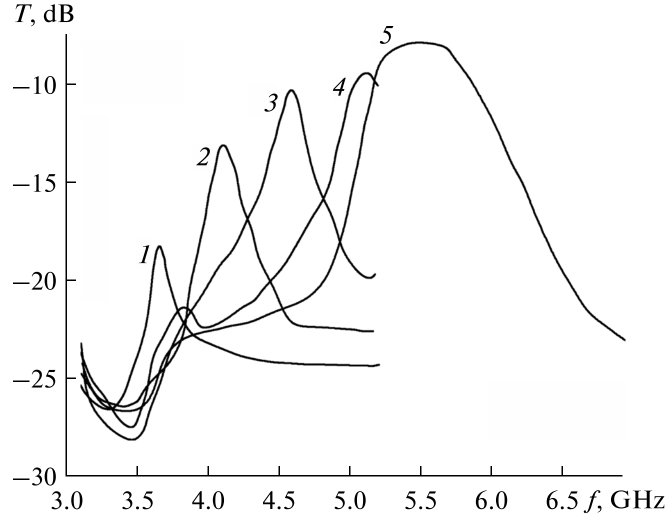

Fig. 8. Frequency dependence of the transmission coefficient of a square slotted element with side $a = 10$ mm loaded by one BB857 varactor. Curves *1*, *2*, *3*, *4*, and *5* correspond to a control voltage at varactors of 0, 5, 10, 20, and 29 V.

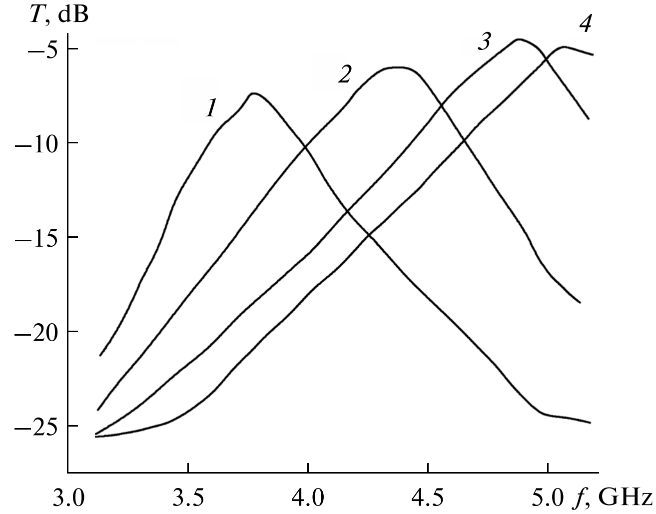

Fig. 9. Frequency dependence of the transmission coefficient of a square slotted element with side $a = 17$ mm loaded by two BB857 varactors and a 0306 capacitor (30 pF). Curves *1*, *2*, *3*, and *4* correspond to a control voltage at varactors of 0, 10, 20, and 29 V.

smaller thermal loss in the varactor. This result does not contradict the measurement results of the lattice consisting of eight square slotted elements, each being controlled by two varactors with characteristics close to the characteristics of MA46H120 [18].

Figure 8 shows the frequency dependence of the transmission coefficient for the circuit shown in Fig. 1b with the BB857 varactor. As could be expected, the tuning range lies inside the frequency interval, which is bounded from above by the condition of the absence of the capacitive load and bounded from below by the short-circuit condition of the load. The boundaries of this interval are equal to 7.5 GHz and 3.7 GHz, respectively. As in the case of the circuit with two BB857 varactors, the transmission coefficient rapidly decreases as the control voltage is below 10 V.

Figure 9 shows the frequency dependence of the transmission coefficient for the circuit, shown in Fig. 1c with the BB857 varactor and the following parameters of the slotted elements: $a = 17$ mm and $d = 1$ mm and capacitance C of the 0603 type capacitor is 30 pF. It is clear from the figure that, when the control voltage at the varactors varies from 29 V to 0, the resonance frequency varies from 5 GHz to 3.8 GHz and the transmission coefficient at the resonance frequency varies from −6 dB to −10 dB.

4. MEASUREMENT OF THE TRANSMISSION COEFFICIENT OF THE LATTICE CONSISTING OF SLOTTED ELEMENTS OF THE FSS LOADED BY VARACTORS

The experimental results of the transmission coefficient of the samples of the individual slotted elements obtained by the waveguide method differ from the experimental results for the transmission coefficient of biperiodic lattices consisting of a great number of elements in free-space conditions. To maximally decrease this difference, the transmission coefficient of the lattices of eight elements loaded with either two or one BB857 varactors was measured using the same waveguide method. The appearance and dimensions of lattices are given in Figs. 10a and 10b. The frequency dependences of the transmission coefficients of the lattice samples with elements loaded with two and one BB857 varactors, are given in Figs. 11 and 12, respectively. As it is clear from comparison of the frequency dependences of the transmission coefficients for lattices (Figs. 11 and 12) and isolated elements (Figs. 5 and 8), corresponding resonance frequencies do not virtually differ but the transmission coefficients at these frequencies are substantially higher for lattices. The latter especially true for the elements loaded with one varactor. Thus, when the resonance frequencies are tuned from 5.5 GHz to 3.6 GHz, the transmission coefficient at these frequencies varies from −1 to −4 dB for the lattice and from −8 to −18 dB for the isolated element.

The efficiency of control of the resonance frequency of the lattice can be evaluated as the relative frequency tuning range f_{max}/f_{min} in which the transmission coefficient varies within 3 dB. For the lattice loaded with two varactors, f_{max}/f_{min} ratio = 1.15 and, for the lattice loaded by one varactor, it is 1.5. Note that the relative frequency tuning range of even not a lattice but an isolated slotted element loaded with two MA46H120 low-capacitance varactors is 1.28.

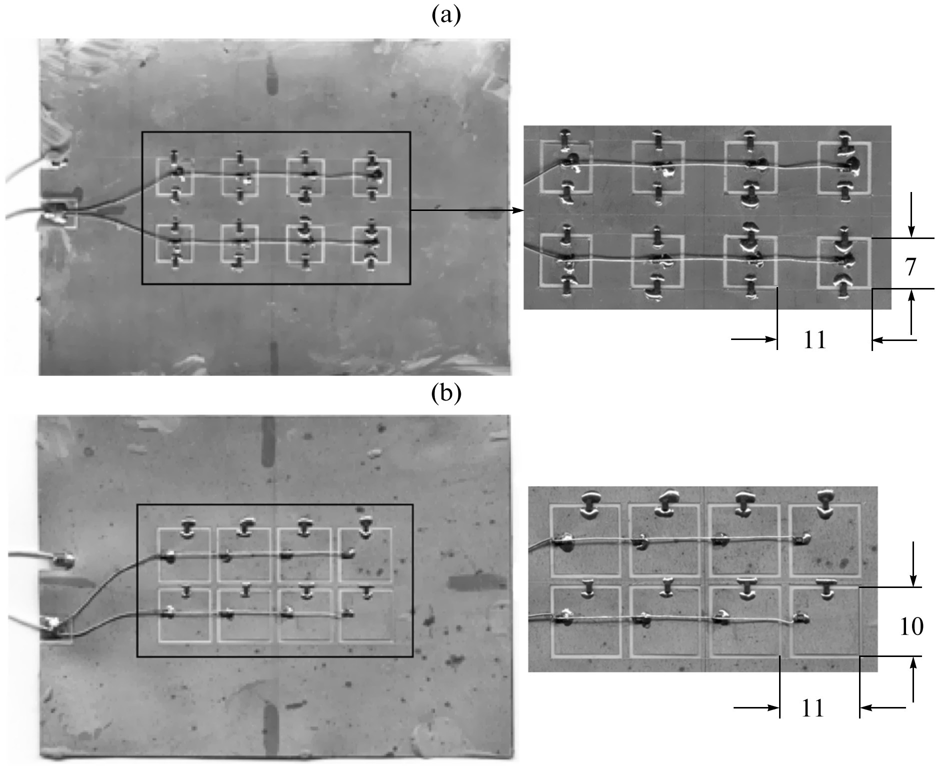

Fig. 10. Outward appearance of the lattices consisting of square slotted elements loaded by (a) two and (b) one BB857 varactors.

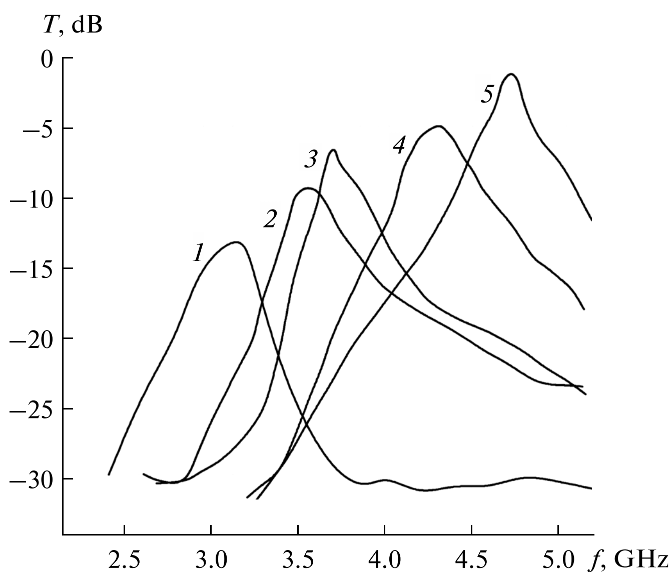

Fig. 11. Frequency dependence of the transmission coefficient of a lattice consisting of eight square slotted elements with side $a = 7$ mm loaded by two BB857 varactors. Curves *1*, *2*, *3*, *4*, and *5* correspond to a control voltage at varactors of 10, 13, 15, 20, and 29 V.

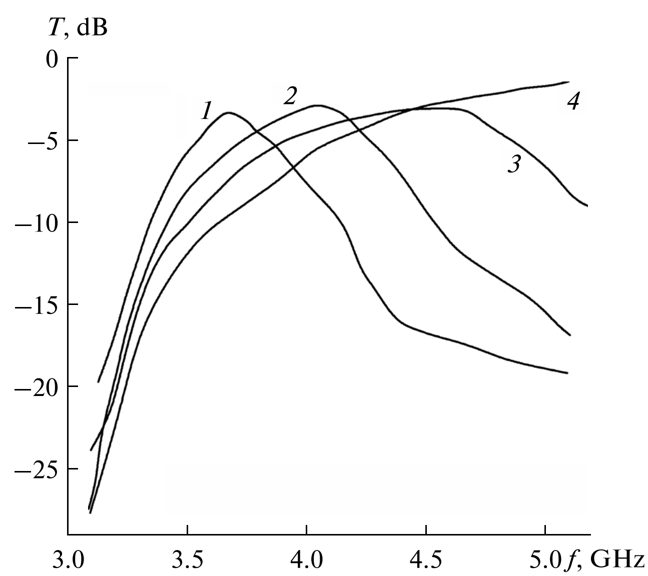

Fig. 12. Frequency dependence of the transmission coefficient of a lattice consisting of eight square slotted elements with side $a = 10$ mm loaded by one BB857 varactor. Curves *1*, *2*, *3*, and *4* correspond to a control voltage at varactors of 0, 5, 10, and 20 V.

CONCLUSIONS

Three possible circuits for connection of control varactors to slotted elements of the bandpass FSS have been considered: (i) a circuit with two varactors, (ii) a circuit with one varactor, and (iii) a circuit with two varactors and a constant capacitance. A set of measurements of the transmission coefficient of the samples of elements loaded with film capacitors having different capacitances with knowingly small thermal loss has been performed in order to evaluate the potentialities of the resonance frequency tuning of the FSS elements with different circuits for connection of varactors. Measurements have shown that, in a circuit with two capacitors, the transmission coefficient at the resonance frequency starts to decrease rapidly when the capacitance exceeds 3 pF. This fact can be attributed to cardinal rearrangement of the electromagnetic field in the slotted element. When the capacitance varies in an interval of 0.25–3 pF, the relative frequency tuning range is 2.3. In a circuit with one capacitor, when the capacitance varies from 0.25 to 7 pF, the transmission coefficient at the resonance frequency decreases by only 3 dB. In this case, the relative frequency tuning range is about 1.7.

The results of the measurement of the transmission coefficients of the element samples loaded with varactors have demonstrated substantially smaller frequency tuning ranges. This is especially valid for the connection circuit with two BB857 medium-capacitance varactors. Rapid decrease in the transmission coefficient occurs at a control voltage of $\leq$10 V, which approximately corresponds to a varactor capacitance of $\geq$1 pF. The relative frequency tuning range at which the transmission coefficient varies by no more than 3 dB is 1.1. When MA46H120 low-capacitance varactors are applied in this circuit, the relative frequency tuning range increases up to 1.3.

When the transmission coefficient of the lattices consisting of eight slotted elements loaded with BB857 varactors was measured, the values of the frequency tuning range of 1.15 and 1.5 were obtained for circuits with two and one varactors, respectively.

The results of the measurement of the characteristics of isolated slotted elements and lattices consisting of these elements allow one to evaluate attainable values of the resonance frequency tuning range of the bandpass FSSs as follows: 1.4 and 1.5 for the FSS with elements controlled by two MA46H120 low-capacitance varactors and by one BB857 medium-capacitance varactor, respectively.

REFERENCES

1. C. Mias, Electron. Lett. **39**, 850 (2003).
2. C. Mias, Electron. Lett. **39**, 1060 (2003).
3. C. Mias, Microwave Opt. Technol. Lett. **43**, 508 (2004).
4. C. Mias, Microwave Opt. Technol. Lett. **44**, 412 (2005).
5. C. Mias, IEEE Microwave Wireless Components Lett. **15**, 570 (2005).
6. Yu. N. Kazantsev, G. A. Kraftmakher, and V. P. Mal'tsev, J. Commun. Technol. Electron. **58**, 933 (2013).
7. G. A. Kraftmakher, V. S. Butylkin, and Yu. N. Kazantsev, Tech. Phys. Lett. **39**, 505 (2013).
8. T. K. Chang, R. J. Langley, and E. A. Parker, IEEE Microwave and Guided Wave Lett. **3**, 387 (1993).
9. W. A. Shiroma, S. C. Bundy, S. Hollung, et al., IEEE Trans. Microwave Theory Tech. **43**, 2904 (1995).
10. F. Bayatpur and K. Sarabandi, IEEE Trans. Microwave Theory Tech. **57**, 590 (2009).
11. F. Bayatpur and K. Sarabandi, IEEE Trans. Microwave Theory Tech. **57**, 1433 (2009).
12. B. Sanz-Izquierdo, L. T. Ekpo, J. B. Robertson, et al., Electron. Lett. **44**, 1268 (2008).
13. B. Sanz-Izquierdo, E. A. Parker, J. B. Robertson, et al., Electron. Lett. **45**, 1107 (2009).
14. B. Sanz-Izquierdo, E. A. Parker, and J. C. Batchelor, IEEE Trans. Antennas Propag. **59**, 2728 (2011).
15. L. Boccia, I. Russo, G. Ameudola, et al., Electron. Lett. **45**, 1213 (2009).
16. I. Russo, L. Boccia, G. Amendola, et al., in *Proc. Fourth European Conf. on Antennas and Propagation (EuCAP 2010), Barcelona, Apr. 12–16, 2010* (IEEE, New York, 2010), p. 235.
17. B. A. Munk, *Frequency Selective Surfaces. Theory and Design* (Wiley, New York, 2000).
18. C. Mias and C. Tsakonas, Microwave Opt. Technol. Lett. **45**, 62 (2005).
19. A. E. Martynyuk, J. I. M. Lopez, and N. A. Martynyuk, Electron. Lett. **41**, 2 (2005).
20. J. L. Durbin and M. A. Saed, Progr. Electromagn. Res. Lett. **29**, 43 (2012).

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