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Mechanically controlled Ku-band phase shifter

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The paper is devoted to the study of mechanically controlled phase shifter based on gap-waveguide with transitions to standard waveguide cross section. The paper presents the results of electrodynamic modeling of a broadband transition from a P-section gap-waveguide to a WR-75 waveguide section. The results of measuring the characteristics of the phase shifter mockup fabricated according to the results of electrodynamic modeling showed good agreement with the calculated values. The standing wave coefficient of the phase shifter was not more than 1.5 in the frequency range of 10.7–14.5 GHz. The maximum value of total loss was 0.3 dB. The phase adjustment range was slightly lower than calculated and amounted to 351° at the lower frequency of the range and 517° at the upper frequency. The considered phase shifter can be used as a part of antenna arrays with mechanoelectric scanning for operation in satellite communication networks.

Keywords: gap-waveguide, phase shifter, mechanoelectric scanning.

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Rapid development of satellite systems utilizing low-altitude, medium-altitude, and highly elliptical spacecraft makes it necessary to maintain continuous reception and transmission of signals by antenna systems (ASs) for both mobile and stationary objects. One solution to this problem is the use of scanning ASs. Several approaches to adjusting the spatial position of an antenna beam (namely, mechanical, electronic, and mechanoelectric scanning) are known.

In the first case, scanning is achieved by rotating the entire antenna. This makes it difficult to design low-profile ASs with high performance for on-the-go communications.

ASs with electronic scanning [1] are distinguished by their small dimensions and high performance. One of the main disadvantages of ASs with electronic scanning is their high cost.

The use of mechanoelectric systems [2,3] is one possible compromise that allows one to design equipment with small dimensions, high performance, and low cost. Phase shifters (PSs) are an integral part of these ASs [4]. In addition, mechanically controlled low-loss PSs may be used for non-mechanical adjustment of the radiation pattern position in base station antennas of modern cellular communication systems [5].

A low-loss transmission line without the need for electrical contact between moving parts is required to build a mechanically controlled PS. The development of a new type of transmission line, „gap waveguide“ [6], opens up the possibility of fabrication of low-cost mechanically controlled elements for use in scanning antenna systems. A gap waveguide operates by establishing high-impedance conditions in a certain frequency band, suppressing the propagation of plane-parallel modes in unwanted directions [7]. Periodically arranged metal pins may serve as a high-impedance structure.

Symmetrical milled holes were used as a periodic rejection structure in [8]. A dielectric plate was positioned parallel to the electrical field lines of a gap waveguide. When this plate was moved, the phase constant in the waveguide changed. This PS provides an acceptable level of matching only in a narrow frequency band, and losses exceed 0.6 dB.

The phase shift mechanism proposed in [9] consists in adjusting the position of the side wall of a gap waveguide to alter the propagation constant. This PS has significant variations in frequency response and losses as high as 0.6 dB.

In the present study, a mockup of a mechanically controlled gap-waveguide PS, which is based on the design developed earlier [10], was fabricated and examined. Transitions to standard waveguide sections or coaxial connectors are needed to use a PS as part of scanning systems or connect it to measuring equipment. We studied the transition from a U-section gap waveguide to a standard WR-75 rectangular waveguide.

Transitions discussed in literature are notable for their narrow operating frequency band [11], which is insufficient to ensure the operation of a PS within the entire required range. Other transition configurations make it significantly more difficult to operate a PS, since they are to be located on the upper wall of a gap waveguide [12] and, in the case under study, make it hard to shift the retardation line while keeping the transition stationary.

The proposed transition consists of three parts (Fig. 1, *a*): a U-section gap waveguide (the upper wall of the gap waveguide is not shown) (*1*), a metal WR-75 hollow

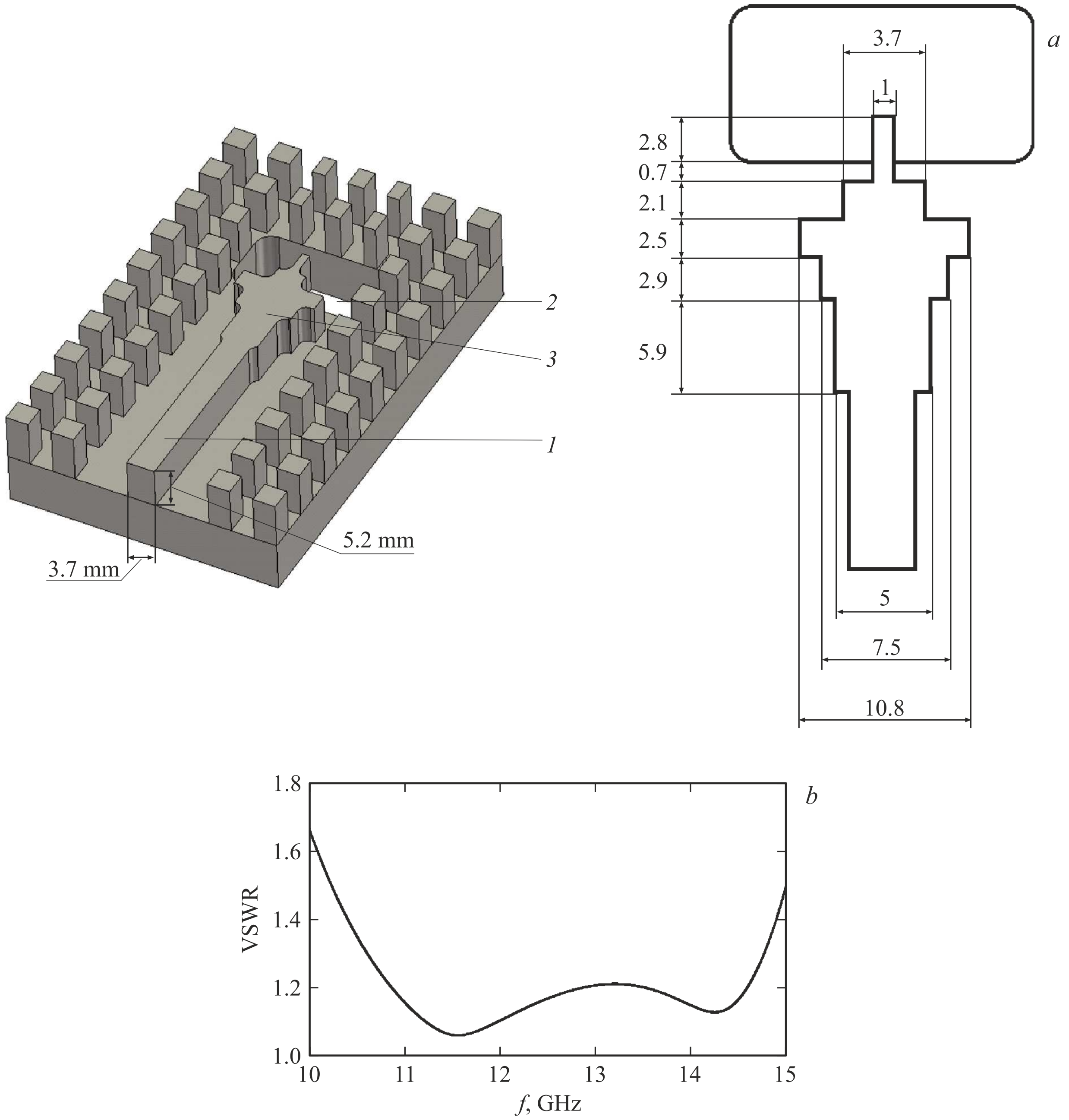

Figure 1. *a* — Design of the transition. *1* — U-section gap waveguide, *2* — rectangular waveguide, and *3* — matching part. The outside dimensions (mm) of transforming steps. *b* — Frequency dependence of the transition VSWR.

waveguide (*2*), and a matching part that acts as a multistep impedance transformer (*3*).

This transition has an operating bandwidth of more than 30% at a voltage standing wave ratio (VSWR) level of 1.2 (Fig. 1, *b*), covering the entire communication Ku band (10.7–14.5 GHz). The operating frequency band was extended by introducing nonuniformities, which produced additional resonances in this band, into the transformer structure. The number of transforming stages and their overall dimensions (shown on the right in Fig. 1, *a*) were determined in the course of numerical optimization according to the criterion of VSWR < 1.3 in a given operating frequency band.

The PS model with built-in transitions is shown in Fig. 2, *a*. The PS operation relies on displacement of slow-wave structure *2*, which is located on upper movable cover *1* of U-shaped gap waveguide *3*, from the gap with the maximum field strength; in this way, the degree of influence of the slow-wave system on a wave, and, accordingly, the phase of the transmitted wave is adjusted. Figure 2, *b* shows the PS mockup fabricated by milling. The overall dimensions of the device were $195.0 \times 85.0 \times 17.5$ mm.

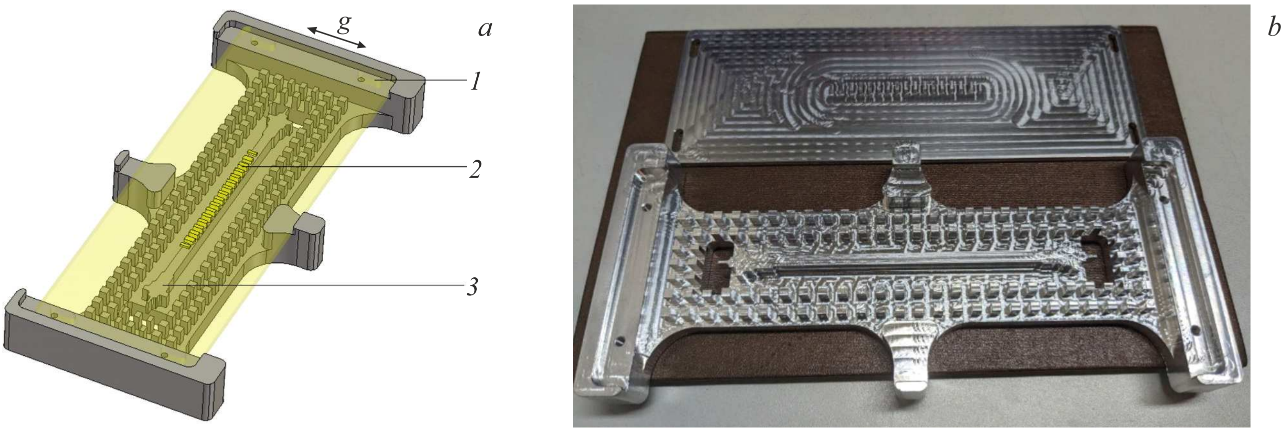

Figure 2. *a* — Phase shifter model. *1* — Cover, *2* — slow-wave structure, and *3* — U-waveguide with a transition. *b* — Phase shifter mockup.

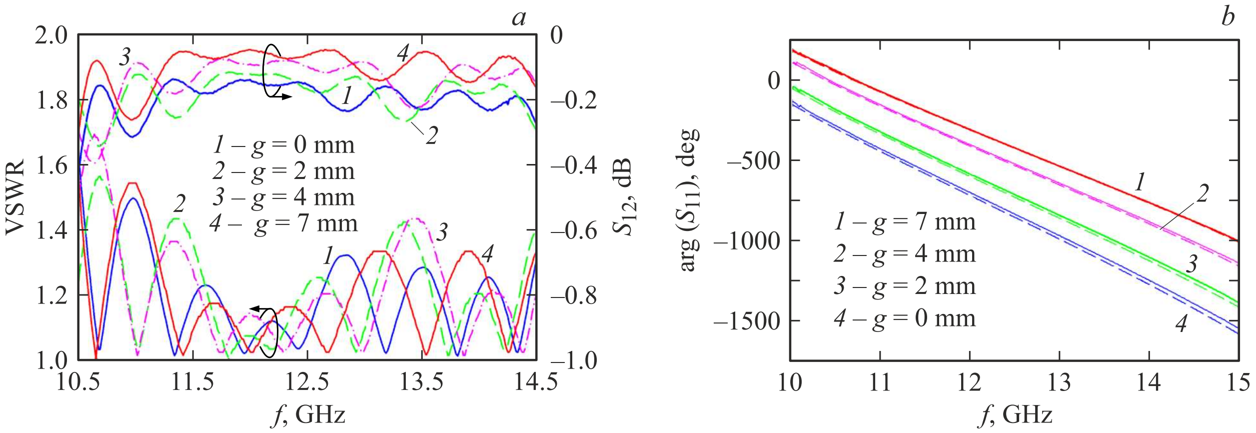

Figure 3. *a* — Measured frequency dependences of VSWR (lower curves) and the transmission coefficient (upper curves). *b* — Measured (solid curves) and calculated (dashed curves) frequency dependences of the transmission coefficient phase.

The PS mockup has two component parts. The first part features two transitions from the rectangular waveguide to the gap one, the gap waveguide ridge with a rejection system of pins, and a cradle for the upper cover. The second part is a mechanical sliding cover that carries the slow-wave structure. This design does not require contact between the two components, and the contact at points where these parts are closely adjacent to each other does not affect the device parameters.

Figure 3, *a* shows the measured frequency dependences of VSWR and the transmission coefficient at various magnitudes of displacement g. The maximum total loss value (0.3 dB) is achieved when the slow-wave structure is located above the transmission line ($g = 0$). The mean attenuation is just 0.2 dB. When the slow-wave structure is displaced by 7 mm relative to the central position, the mean loss level changes to 0.1 dB. The total losses calculated with account for the conductivity of aluminum and a surface roughness of 1 μm were below 0.35 dB, which agrees closely with experimental data.

The VSWR value (slightly higher than 1.5) was marginally worse than the calculated one at the start of the frequency range. In the remaining part of the range, experimental values agreed with the calculated ones.

Figure 3, *b* shows the frequency dependences of phase of the transmission coefficient at various displacements of the slow-wave structure. The adjustment range of the mockup was narrower than the one of the model (by 16° at a frequency of 10.7 GHz and by 30° at a frequency of 14.5 GHz). This narrowing of the adjustment range is attributable to manufacturing errors (namely, deformation of the plate with the slow-wave structure) that led to the slow-wave structure being positioned at a greater-than-nominal distance from the waveguide ridge. That said, the range of phase adjustment of the experimental prototype varied from 351° at the lower boundary of the range to 517° at the upper boundary. The range of phase adjustment expands with increasing frequency: the studied PS acts as a delay line. This enables the use of such a device in broadband antenna systems.

The obtained results demonstrate the feasibility of fabrication of efficient mechanically controlled microwave devices based on a gap waveguide. The designed transition and PS feature minimal losses and fine matching throughout the entire range of Ku band frequencies used in satellite communications. The adjustment range of this PS is sufficient for its use in scanning antenna devices for satellite communications. The final design of the PS may be corrected to tailor it to specific installation, weight, and size requirements.

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Conflict of interest

The authors declare that they have no conflict of interest.

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