PHASE SHIFT CONTROL USING WAVEGUIDE-SLOT PHASE SHIFTER

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Some specific electrical properties of a waveguide-slot phase shifter have been studied in the paper. We propose to use waveguide-slot phase shifter as a controlled coupler in the switchgears of phased arrays with series feeding and *p–i–n*-diodes control. The characteristics of the waves transmitted through the waveguide and their dependences on the slot's position and dimensions were considered. The slot of special form was cut through the waveguide wide wall. We succeeded in obtaining the phase shift up to 360 degrees by the lengthwise variation in the slot's position in a coupling window and by the slot's displacement specularly relative to the waveguide's axis line. The study of the problem was conducted experimentally and by simulation technique. The simulation results were verified by experimental data. The proposed phase-shifter can be also used in switchgears of phased arrays with a locked beam.

Key words: waveguide; slot in waveguide; antenna; phased array; phase shifter

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Introduction

Phased arrays (PAs) are increasingly used as radar antennas for different ranges and applications. Series-fed arrays are one possible configuration for these devices. Examples of antennas with series feeding serving as PAs were proposed in [1 – 7]. Any phased array includes a switchgear that supplies power to the radiating elements with the required phase and amplitude.

In most cases, phase shifters with individual driver circuits for each element are used to control PAs. A series-fed PA uses a ferrite phase shifter to form an amplitude-phase distribution of the field of radiating elements. The driver circuit of a ferrite phase shifter is usually cumbersome and power-consuming [6, 8 – 10], which limits potential applications of such devices.

In this paper, we have studied the characteristics of a slot-waveguide phase shifter which at the same time can be used as a controlled coupler in PA switchgears with serial feeding and *p–i–n*-diode control.

Design of the phase shifter and its operating principles

The design of the slot-waveguide phase shifter is shown in Fig. 1. Two waveguides are connected by a longitudinal slot similar to that used as the radiating element of the slot-waveguide array.

The concept we propose in this study is that varying the position of the slot allows controlling the phase shift of the electromagnetic field. If the longitudinal position of the slot is changed, then the phase of the field changes. An additional phase shift of 180 degrees is achieved when the slot is moved to the other side of the center line. If the slot detuned from resonance, it should beis possible to gain some extra phase shift. Slots are formed by turning *p–i–n*-diodes on or off.

Thus, we have an opportunity to control the phase of the coupled electromagnetic field.

Simulation results

In this section we present the simulation results for a slot-waveguide phase shifter. Fig. 2, *a* shows the frequency dependences of the coupling coefficient S_{31} from the source port to the radiator for different positions of the slot. The S_{31} magnitudes are usuallyfrom –20dB to –10dB. EThe exact value is determined by the number of elements in the series-fed antenna, as well as by the shape of the required amplitude distribution. The coupling coefficient S_{31} can be varied by shifting the slot from the center line of the waveguide, and also by detuning it from the resonance. It

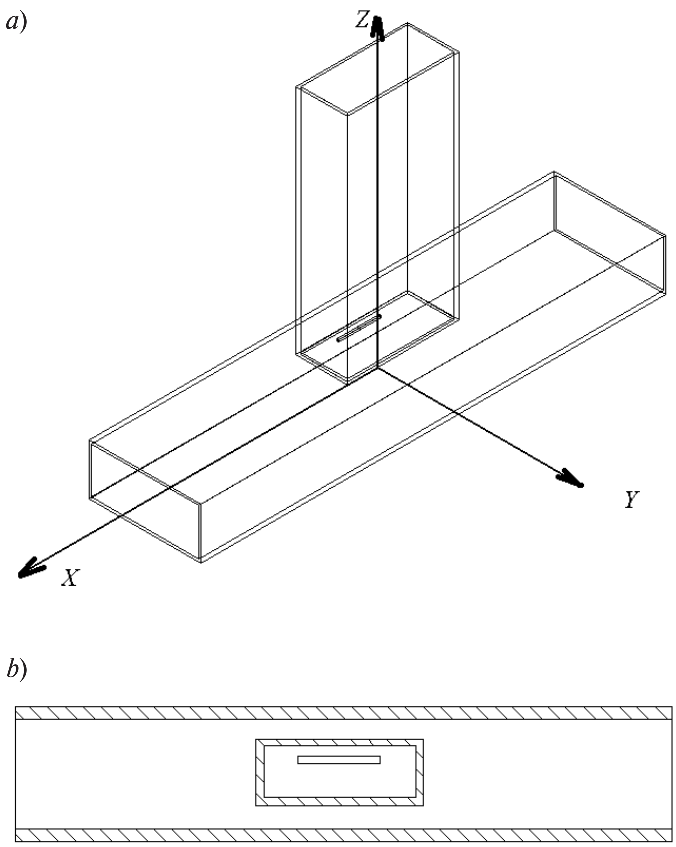


Fig. 1. Schematic of the slot-waveguide phase shifter: general view *a*, cross-section in the *xy* plane (plane of contact of the waveguides) *b*

can be seen from belowFig. 2 that the resonance frequency slightly increases when the center of the slot is shifted relative to the symmetrical position.

Fig. 2, *b* shows the frequency dependences of the phase shift of the electric field (relative to the input port) for the fixed position of the slot. It can be seen that the maximum phase shift is 62° at 9.50 GHz.

To increase the phase shift, we propose using an inverted-L-shaped slot near the edges of the waveguide's cross-port. Fig. 3 shows a sketch of the slot of the phase shifter being considered. The radiating inverted-L-shaped slots are formed by turning the *p–i–n*-diodes in the inverted-U-shaped slot on or off. We simulated different positions of the slot, including two near-edge positions.

Fig. 4 shows the simulation results of the E field distribution along the slot. It can be seen that the distribution of the electric field amplitude over the inverted-L-shaped slot is close to sinusoidal, the same as for the rectangular slot.

Fig. 5, *a* shows the phase shift of two inverted-L-shaped slots against the radiation frequency. The maximum phase shift is 177°, which is enough to create a fully functioning phase shifter for a scanning PA (taking into account a 180-degree shift of the slot that is symmetric with respect to the waveguide axis, the maximum phase shift obtained is about 360°).

The transmission coefficients S_{31} (Fig. 5, *b*) varies less than 10 dB over the operating range for two slot positions.

Experimental results and discussion

To test the simulation results, we have builtcreated two models of phase shifters and two sets of slots. Laser cutting and milling were used to cut the slots in the first and the second sets, respectively.

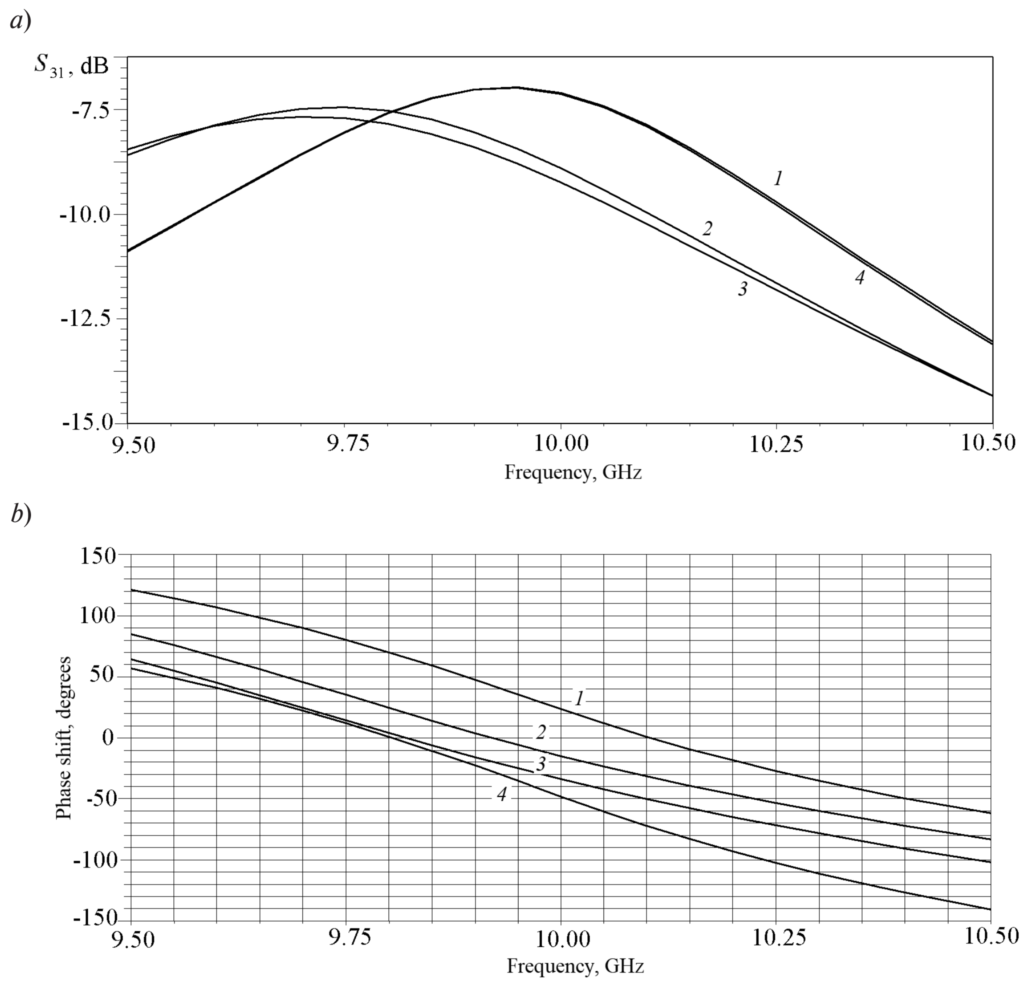


Fig. 2. Frequency dependences of the coupling coefficient S_{31} (*a*) and the phase shift relative to the input terminal arg(S_{31}) (*b*) for different shifts of the slot center along the *x* axis with respect to the origin:
−4 mm (curve *1*); 0 mm (*2*); +2 mm (*3*); +4 mm (*4*)

Fig. 6 shows the experimental dependences of the phase shift against the position of the slot for model 1. The curves depicted in Fig. 6, *b*, are the results of measurements for the slots located on the other side of the waveguide's center line (bottom row), compared to the slots in Fig. 6, *a* (top row). This produces an additional phase shift of 180°. This phase shift was taken into account in the results shown in this figure (180° were subtracted from the data in Fig. 6, *b*). Therefore, according to theory, the

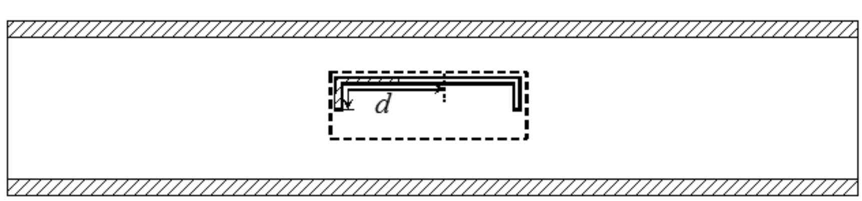


Fig. 3. Schematic of the proposed shape of the radiating slot of the given phase shifter (the non-radiating part of the slot is shaded)

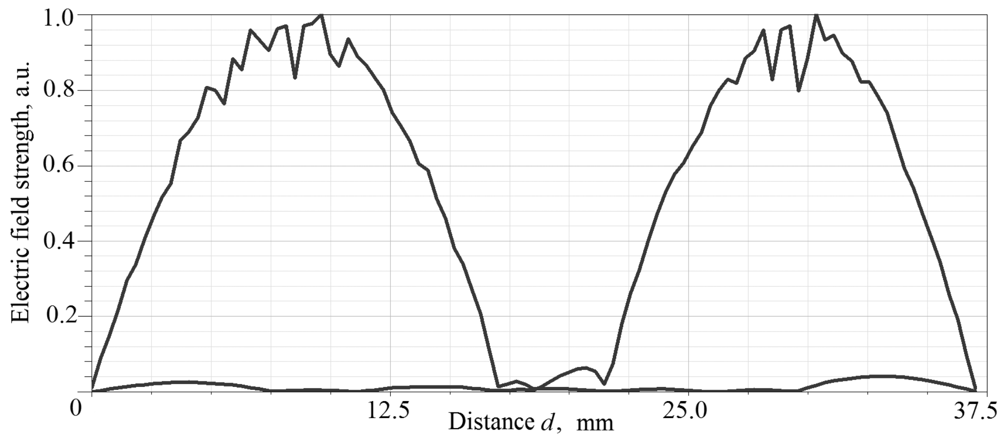
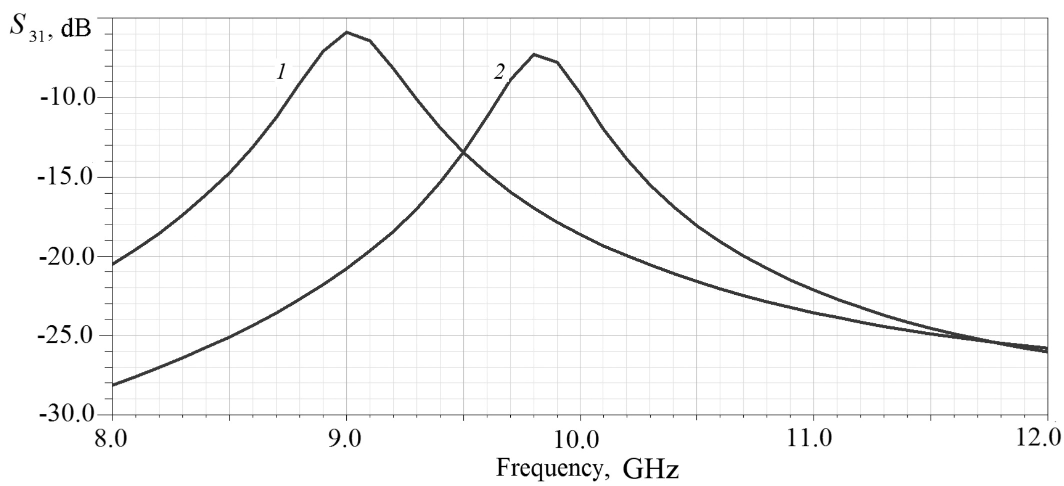


Fig. 4. Distribution of the electric field strength along the inverted-L-shaped slot for two states of *p*—*i*—*n*-diodes (the distance *d* is shown in Fig. 3)

a)



b)

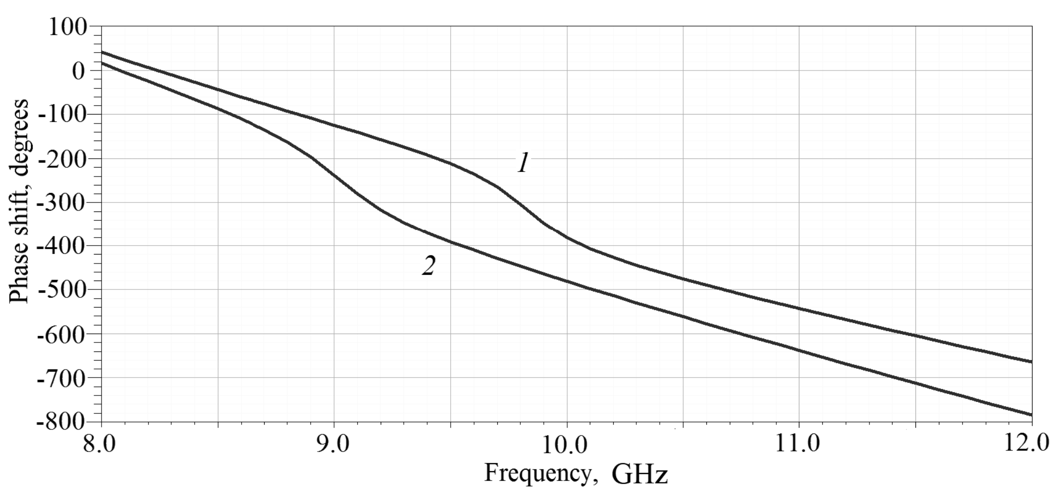


Fig. 5. Frequency dependences of the transmission coefficient (*a*) and the phase shift (*b*) of two inverted-L-shaped slots for their extreme left (curve *1*) and extreme right (curve *2*) positions

curves in Fig. 6, *b* should coincide with the curves in Fig. 6, *a*. The differences in these graphs can be used to estimate the error in the measurements, as well as the error of positioning the aperture.

Photos of both models are shown in Fig. 7. The results of measurements for model 2 turned out to be close to those for model 1, which proves that both laser cutting and milling are suitable technologies for cutting inverted-L-shaped slots.

Conclusion

We have studied some specific properties of a slot-waveguide phase shifter, which is proposed to be used as a controlled coupler in switchgears of phased array antennas with serial feeding and *p–i–n*-diode control. We have considered the characteristics of the wave transmitted through the waveguide and their dependences on the position and size of the slot cut in the waveguide's wide wall. To test the simulation results, we have built experimental models of the phase shifter, equipped with inverted-L-shaped slots. We have measured the characteristics for two types of phase shifter layouts.

The experimental data obtained generally

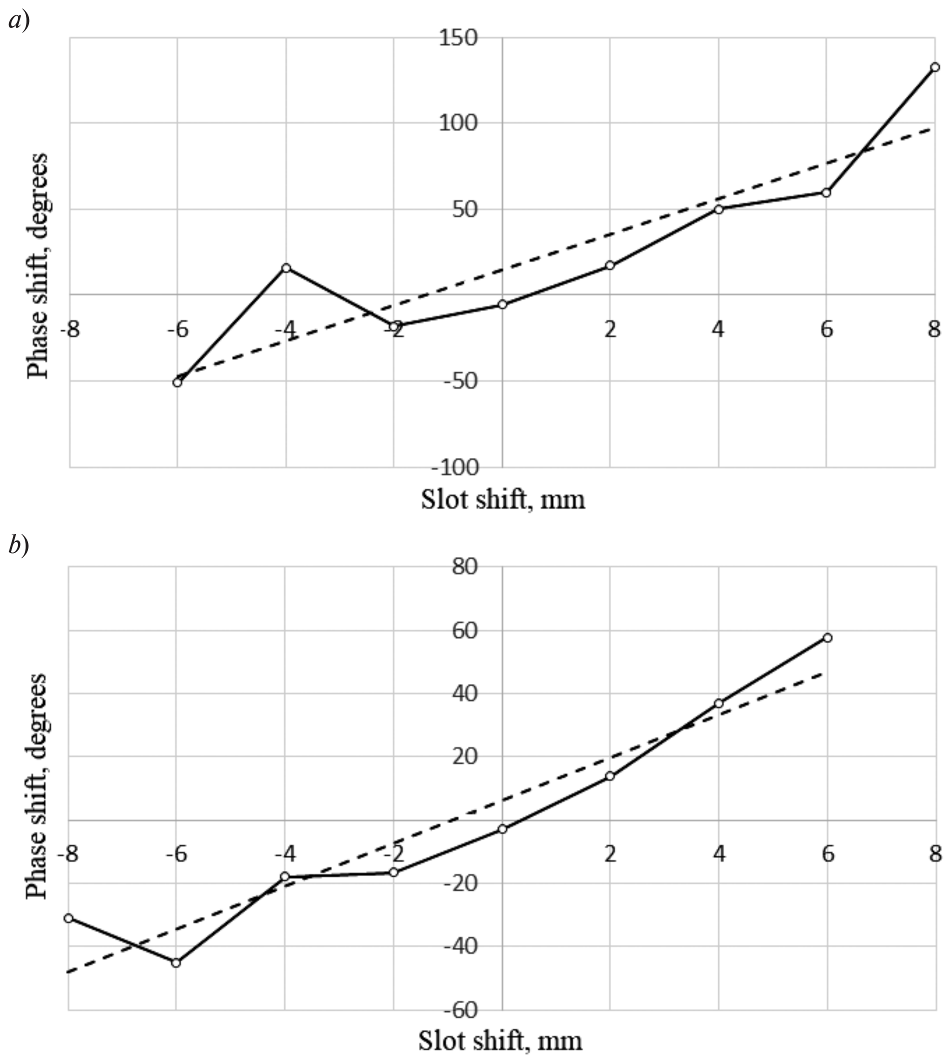


Fig. 6. Experimental dependences of the phase shift on the position of the inverted-L-shaped slot for the top (*a*) and bottom (*b*) rows (see the explanations in the text) for experimental model 1 (see Fig. 7,*a*), and linear approximations of the data (dashed lines).
The frequency of microwave radiation is 10 GHz

a) *b*)

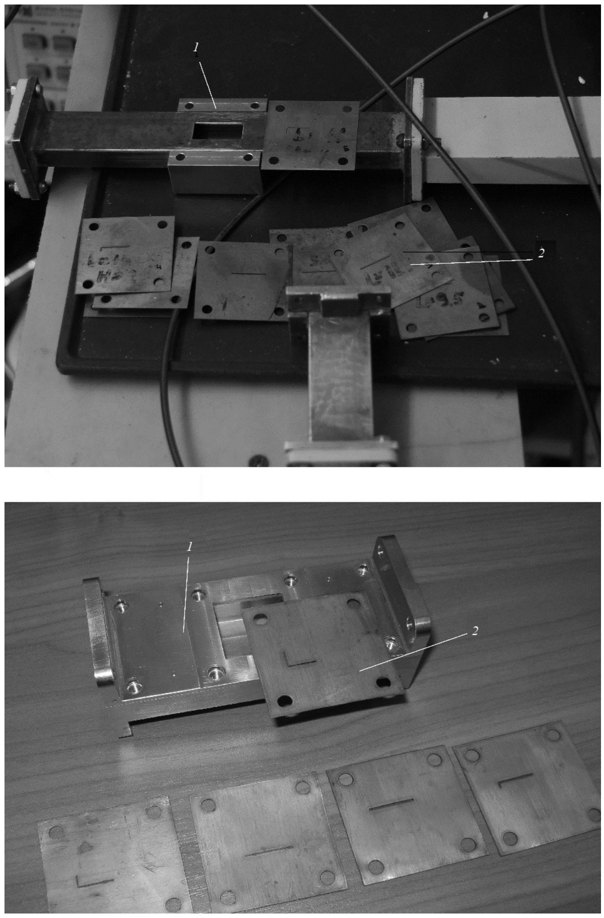


Fig. 7. Photographs of models 1 (*a*) and 2 (*b*) of the phase shifters (*1*) and inverted-L-shaped slots (*2*) attached to the phase shifters

confirmed the simulation results. Thus, we have proved that it is possible to use a slot-waveguide phase shifter as a switchgear element of a phased array with series feeding.

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