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Low-loss reflective X-band phase shifter with wide phase control range

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Abstract. Nowadays, one of the important tasks driven by the actual society needs is the development of effective technical solutions in the field of reflective surfaces and antenna arrays for modern microwave wireless networks. They are necessary to enhance network coverage and communication stability on the way of the operating frequency increase. Their use is beneficial in highly directive wide-band radio channels vulnerable to blockage and micromobility effects. In this work, we propose a low-loss reflective X-band phase shifter with wide phase control range which can be effectively used as a part of field-programmable reflectarray for radio signal routing. Our study focuses on the influence of the errors in geometrical parameters arising during the fabrication process on the radiophysical properties of the phase shifter based on a log-periodic antenna integrated with diode. For such a design, we demonstrate geometry-defined reflection losses of less than 1 dB, and the corresponding phase control range approaching 330° with a tolerable absolute geometry deviation of up to 90 μm.

Keywords: microwave devices, reflective antenna, reflection coefficient, varactor diode

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Отражательный фазовращатель X-диапазона с низкими потерями и широким диапазоном регулировки фазы

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Аннотация. Совершенствование отражающих поверхностей и антенных решеток для беспроводных СВЧ систем представляет собой важную научно-техническую задачу. Ее решение должно позволить расширить зону покрытия, повысить стабильность связи и обеспечить эффективную работу в условиях роста рабочих частот. Особую актуальность приобретают решения для высоконаправленных широкополосных радиоканалов, где существенное влияние оказывают эффекты блокировки сигнала и микромобильности.

В данной работе представлена конструкция фазовращателя X-диапазона с широким диапазоном регулировки фазы и низкими потерями на отражение на основе логопериодической антенны, интегрированной с диодом. Основное внимание уделено исследованию влияния погрешностей изготовления геометрических параметров на радиофизические характеристики фазовращателя. Продемонстрировано, что предложенная геометрия антенны обеспечивает потери на отражение не более 1 дБ при диапазоне регулировки фазы до 330°. При этом допустимое отклонение геометрических параметров, не приводящее к заметному ухудшения характеристик, достигает 90 мкм.

Ключевые слова: СВЧ устройства, отражательная антенна, коэффициент отражения, варакторный диод

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Introduction

The development of radio access networks, in accordance with consumer demand for increased network capacity, poses urgent tasks for the scientific and technical community to develop fundamental and technical solutions in the field of antenna-feeder devices. An important part of this class of devices, which is of direct interest for use in microwave networks, are reflective antennas based on the theory of phased array antennas, i.e. with the ability to reflect an incident electromagnetic wave at a given angle, as well as with the ability to control the direction of reflection [1]. The basic unit of such antennas is a unit cell [2], in which the phase shift control allows you to control the direction of the reflected beam [3].

Numerical modeling and analytical calculations of antenna devices are undoubtedly an important design stage, however, in any case, the model represents an ideal structure without taking into account the errors that inevitably arise during manufacturing [4]. This work highlights issues related to the control of geometric parameters of antenna devices, the effect of deviation of these parameters from the nominal value on the radio frequency (RF) characteristics of the final manufactured devices both individually and as part of the antenna array. We develop our earlier reported ideas [5] and implement a low-loss reflective X-band phase shifter with wide phase control range. The details are provided below.

Design and fabrication

The initial phase of antenna array development involved numerical modeling of unit cells using the finite element method (FEM) in an electromagnetic (EM) simulation environment. Each cell is designed as a 7.5×7.5×1.524 mm parallelepiped comprising back-metallized FSD888T substrate (ε_r = 3.55) carrying a log-periodic planar spiral antenna structure as shown in Fig. 1, *a*. The spiral outer and inner arc radii R_i and r_i are defined by Eq. (1), with initial radius R_0 = 0.285 mm and growth rate τ = 0.7.

$$R_{i+1} = R_i\tau,\ r_i = R_i\sqrt{\tau}. \tag{1}$$

A diode was incorporated between the spiral arms to enable phase control by externally applied voltage. A simplified diode model was used for the initial performance evaluation. During simulation, the diode capacitance, C_{var}, was varied to analyze its effect on the phase shift of the reflected wave at 10 GHz. Using Floquet port analysis, the following characteristics were obtained for s-polarization: complex reflection coefficient's magnitude, $\Gamma = \mathrm{mag}(S_{11})$, and phase, $\varphi = \arg(S_{11})$. The results are given in Fig. 1, *b*.

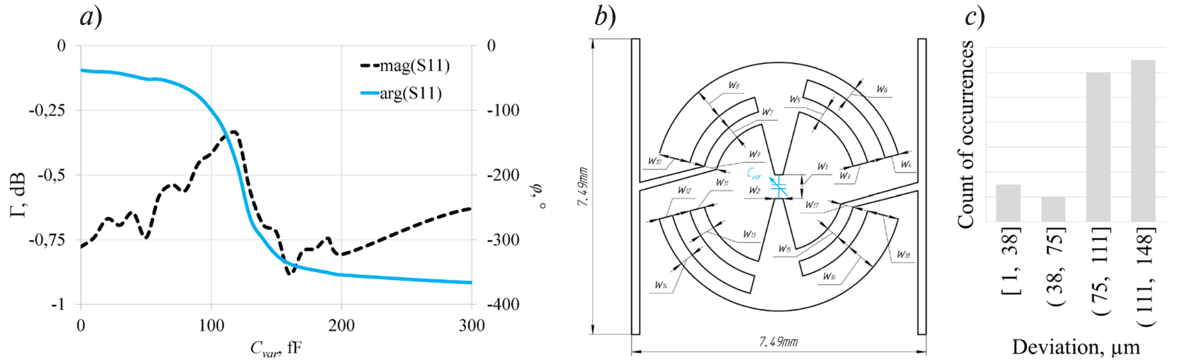

Fig. 1. Dependence of the magnitude and phase of the complex reflection coefficient on the spiral load capacitance (*a*). Unit cell design and deviations measurements (*b*). Histogram of the measured deviations of critical dimensions from their nominals (*c*)

Referring to Fig. 1, *a*, the proposed design exhibits geometry-defined reflection losses of below 1 dB with the corresponding phase control range of up to 330°. The dissipative losses in the cell are not considered at the current simulation stage.

Based on the EM model, technical drawings were generated for sample production. The samples were fabricated using direct mechanical structuring on a MITS Eleven Lab computer-driven milling machine. After the fabrication, critical dimensions Δw_i and Δr_i were measured using a Nikon SMZ745T optical microscope, equipped with an image processing system, at multiple positions as illustrated in Fig. 1, *b*. A statistical analysis of size deviations from nominal values was performed, revealing the absolute geometry deviation equal to 100 µm (Fig. 1, *c*). Fabricated sample cell was further equipped with a BAT2402LS Schottky diode by Infineon [6] and bias lines wiring as shown in Fig. 2, *a*. Conductive paste and solder were used to integrate the parts.

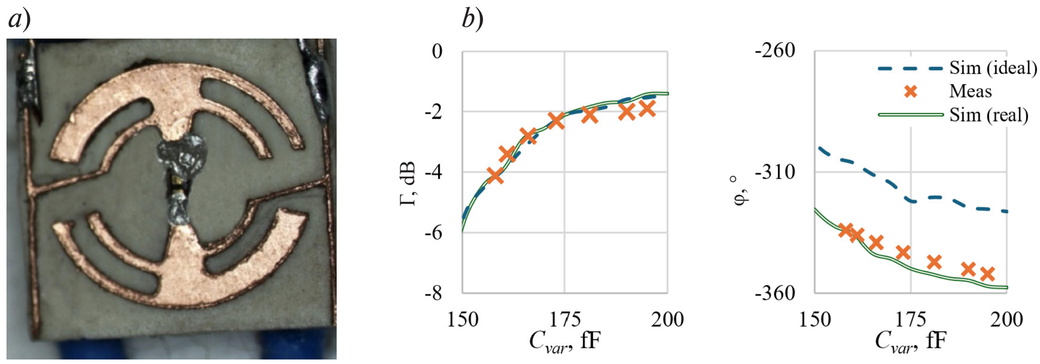

Fig. 2. Fabricated sample cell (*a*). Measured (Meas) magnitude and phase of the complex reflection coefficient compared with the model predictions without (Sim (ideal)) and with size deviations (Sim (real)) due to fabrication errors (*b*)

Following geometric inspection, we characterized radiofrequency (RF) response of the manufactured cells by measuring the magnitude and phase of the complex reflection coefficient. The measurements were performed using a Planar C4220 vector network analyzer (VNA) in single-port mode. Sample cell was installed in a holder, made using 3D-printer, ensuring precise alignment parallel to the waveguide port with a controlled gap of 1–1.5 mm. The holder was mounted at the output of a coaxial-to-waveguide junction (JCW) with a 10×23 mm waveguide cross-section, operating in the 8–12 GHz frequency range. The VNA was set to an output power of 0 dBm, and measurements were conducted across the JCW's operational bandwidth. The measurement results are presented in Fig. 2, *b* for a frequency of 10 GHz.

Results and discussion

To ensure measurement accuracy, we performed full single-port calibration (SOL: Short-Open-Load) of the VNA, applied an electrical delay of 250 ps (corresponding to the 75 mm waveguide length) to compensate for port connector misalignment and eliminate phase deviations caused by waveguide propagation of the probing 10 GHz signal.

We compare experimental results with an advanced model incorporating the diode imperfections (series resistance of 8 Ohm, capacitance tuning range of 40 fF) and the finite copper conductivity (5.8×10^7 S/m). As shown in Fig. 2, *b*, the good agreement between measurements and EM simulations is achieved. We also observe additional losses of 1.5–6 dB as compared with a simplified simulation shown in Fig. 1, *b*. This is due to the dissipative losses, the impact of the bias line termination, and the spill-over loss between the sample and the JCW. But one should keep in mind that the use of a varactor diode with wider capacitance tuning range (e.g., from 25 to 250 fF ensured by MACOM's MAVR-011020-1411) enables a phase control range of up to 330°.

Conclusion

We developed ideal and real models of a phase shifter that account for manufacturing geometry deviations. The modeled device provides a phase control range of up to 330° with an insertion loss of 1.5 to 6 dB. To validate the models, an experimental prototype was fabricated, its geometrical parameters were measured, and based on this data, simulation was performed in an RF CAE system. We observe that the mean size deviations equal 100 μm in both the antenna arcs' length and width have minimal impact on the magnitude and phase profiles of the reflected probing 10 GHz signal. Numerical analysis indicates that using a diode with 3 Ohm series resistance could significantly reduce reflection losses. The developed antenna geometry is robust and suitable for direct mechanical fabrication, making these findings valuable for low-cost X-band antenna development.

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