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COMMUNICATIONS

Phase shifter based on the substrate integrated waveguide technology

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Substrate integrated waveguide (SIW) technology is widely known transmission line technology adapted for use in various types of microwave circuits. This article deals with the analysis and design of a phase shifter based on the SIW technology. With simulation and measurement results obtained from the phase shifter with using air holes inside the structure, a test circuit was designed and manufactured. Results show that a phase balance of less than 10° is achieved with the experimental setup. The return loss value is better than 15 dB for working frequency band 8.85 GHz − 9GHz. The main benefit of this work is the easy of implementation air holes inside the structure and also the easy of manufacture of the circuits for antenna arrays, where a certain number of identical circuits is usually needed.

K e y w o r d s: waveguide, SIW, phase shifter, TRL calibration

1 Introduction

Transmission line based on SIW technology [1-3] are widely used in the development of RF front-end components. The geometry of the structure as shown in Figure 3 allows for the propagation of the dominant TE10 mode inside the substrate within the two rows of metallic vias which ensures that the electromagnetic field does not emit radiation into the environment. This is particular useful in event where several microwave circuits are placed close together, for example, in phased array antennas which consist of several feeding network [4].

The feeding network of the phase array antenna is a microwave structure, which consists of power dividers and phase shifters. Using microwave power dividers and phase shifters, amplitude and phase values are set on the individual antenna element. The amplitude and phase values, on the antenna aperture, form the shape of the radiation pattern.

The design choice of transmission line technology (for example microstrip line, strip line, coplanar, SIW technology) suitable for feeding network design is very important. Different methods to implement phase shift in SIW technology have been explored in [1-3, 5-6].

For a passive phase shifter using SIW a classical example as presented in [9] uses varying lengths of SIW to achieve the required phase shift. However, this increases the size of the physical circuit. Unlike [8] where via post are used to create the phase shift effect, more compact means presented in [1,7] uses alternative rows of vias within the SIW to create the phase shift.

This article continues on from previous research [4], which focused on the design of a feeding network based on the SIW technology for a phase antenna array operating at frequency band X (from 8.85 GHz to 9 GHz). In [4], the experimental hybrid structure of the feeding network has been designed. The power divider part is based on the SIW technology and the phase shifter part is based on the microstrip line technology. The microstrip line technology and transition between SIW and microstrip transmission lines emits undesired radiation, which may change antenna array parameters.

The motivation of research [4] was to design the feeding network with ease of construction and very low value of undesired radiation. This article presents another way of feeding an array network with the implementation of a SIW phase shift using air holes. The requirements on phase shifter design are low insertion loss value, easy construction and low level of parasitic radiation. These requirements of the SIW technology are satisfied.

2 Comparison of phase shifters

Several types of microwave phase shifter have been implemented in literature depending on the application [1-3, 5-6, 8-10]. Phase shift can be achieved by inserting a dielectric material into the structure, as in the case of a metallic waveguide. As shown in Fig. 1(b), a Teflon dielectric was inserted within the waveguide and due to the different values of the relative permittivity, the wavelength inside the waveguide can be changed.

In SIW technology, phase shift could also be implemented by adding air holes to change the dielectric prop-

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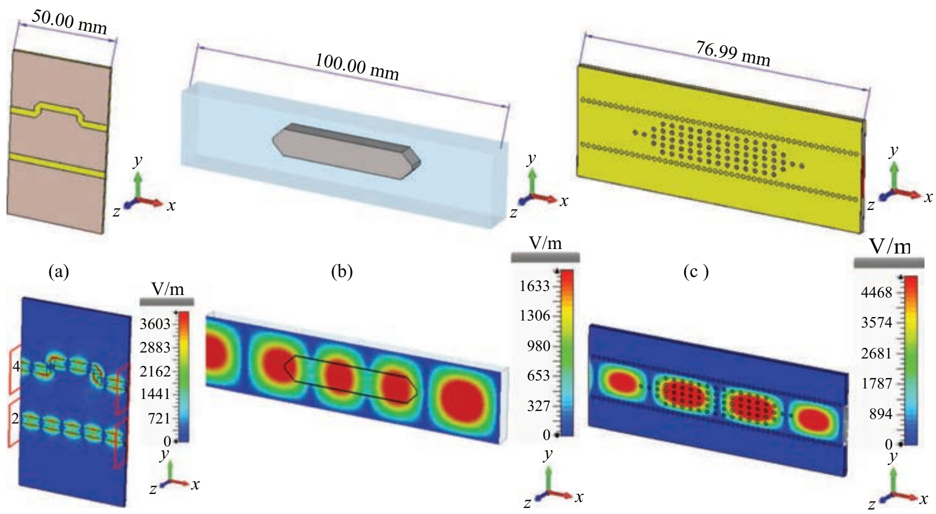

Fig. 1. An example of phase shifters: (a) – microstrip line, (b) – metallic waveguide, and (c) – SIW technology, simulated at 8.925 GHz

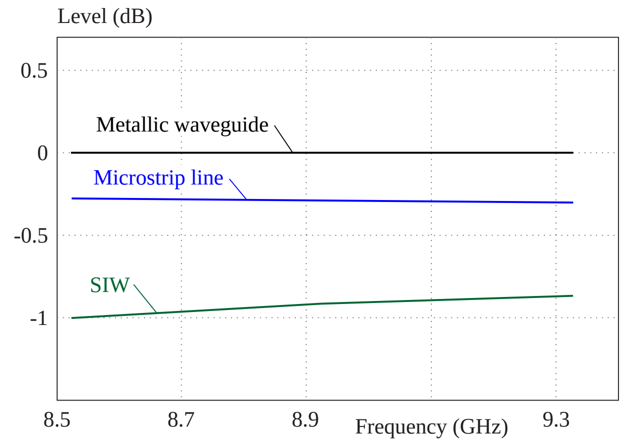

Fig. 2. Frequency response of transmission coefficient: metallic waveguide (black), microstrip line (blue), SIW (green)

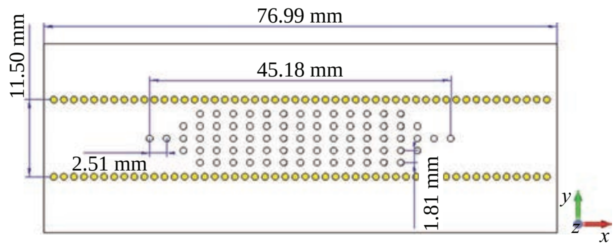

Fig. 3. The simulation model of the phase shifter based on the SIW technology with an initial density of the array holes

erties of the waveguide. In [11], an example of a phase shifter with air holes has been described.

In this article, three kinds of phase shifters are implemented using a microstrip line, metallic waveguide and SIW technology as shown in Fig. 1, with the results presented in Fig. 2. It can be observed that the metallic waveguide has low losses. Planar structures such as the microstrip line and SIW technology in Fig. 1 are compact, although with loss higher than the metallic waveguide as depicted in Fig. 2. The same dielectric substrate, RO4350B is used for both planar structures with a thickness of 1.524 mm.

The application of the planar structure and the resulting weight of the complete system (*eg* the full antenna array) must be considered. For the feeding network design of antenna array, the SIW technology was selected. In comparison with the microstrip line structure, the SIW technology does not need to suppress undesired radiation such as waveguide with metallic walls.

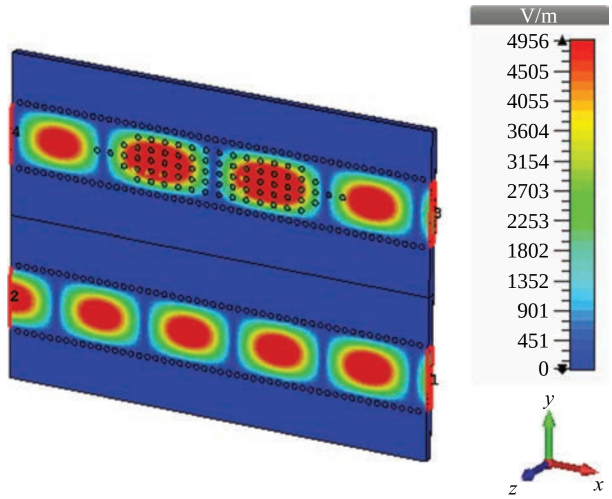

Fig. 4. The E-field simulation the phase shifter based on the SIW technology

3 Analysis and design of the phase shifter

The concept of changing the dielectric property inside the planar substrate was adopted. An array of air holes inside the SIW structure was introduces. Figure 3 and Fig. 4 show the model of the SIW phase shifter. The results of the phase shifters simulation with the reference simulation model of waveguide were compared.

The dielectric constant of the air is $\varepsilon_r = 1$ and the substrate RO4350B has $\varepsilon_r = 3.48$, $(\tan\delta = 0.0037)$.

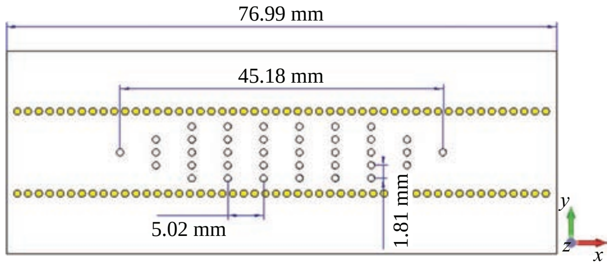

Fig. 5. The simulation model of the phase shifter - layout of the air holes in xy plane

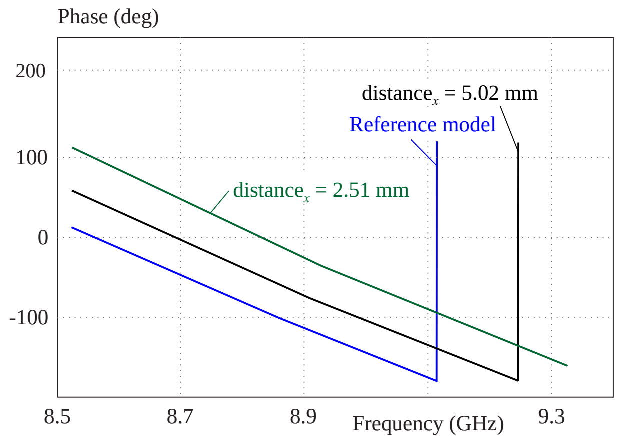

Fig. 6. Simulated frequency response of phase shift for different distance of vias: $\Delta x = 5.02$ mm (black), $\Delta x = 2.51$ mm (green), reference (blue)

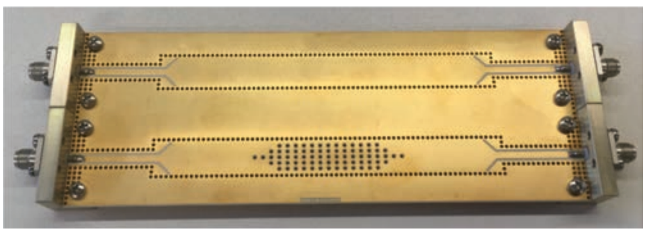

Fig. 7. Fabricated prototype of the phase shifter (down) and the reference waveguide (up)

The diameter of the metal vias is 1 mm and the distance between vias is 1.51 mm. The width of the waveguide is 11.5 mm for all models. The diameter of the all air holes is 1 mm with the spacing between air holes in the x-axis equal to 2.51 mm and in the y-axis equal to 1.81 mm. First, the length and the density of the array of air holes were experimentally chosen with respect to the maximum waveguide length. Then, a length of 45.18 mm (x-axis spacing of air holes) was found to correspond to the given phase value. The value of wavelength inside the reference model of waveguide is equal to 32.8 mm. This value was obtained using the value of phase constant ($\beta = 191.7\,1/\mathrm{m}$), that was achieved by using mode analysis in a CST Design studio.

Figure 4 shows the electric field simulation (E-field). The model consisted of the phase shifter and the reference waveguide.

Figure 5 shows the SIW phase shifter with a larger horizontal spacing between the air holes. The value of the distance is increased to 5.02 mm. The distance between the y-axes remains unchanged.

The results as presented in Fig. 6 shows that the phase change as the distance between the air holes increases. The simulated phases with the phase value of the reference waveguide were compared. The value of the phase difference between the reference model and the model with the distance 5.02 mm between air holes, is equal to $40°$. With the distance between air holes of 2.51 mm, the phase difference is equal to 88 degrees. With the high density of the air holes inside the SIW, we can expect a higher phase change value. Based on the previous analyzes, the prototype of a $60°$ phase shifter has been made, see Fig. 7. In Fig. 8, comparison of the simulation and measurement results are shown. During the measurement, the TRL calibration [12], see Fig. 13, was applied. The main purpose of using the TRL is to compensate the transition part of the microstrip line to the SIW.

In the working frequency band (8.85 GHz 9 GHz), the reflections coefficient of the phase shifter are less -15 dB. At center frequency of 8.925 GHz, the phase shift between the reference waveguide and phase shifter is equal to $60.3°$, see Fig. 8.

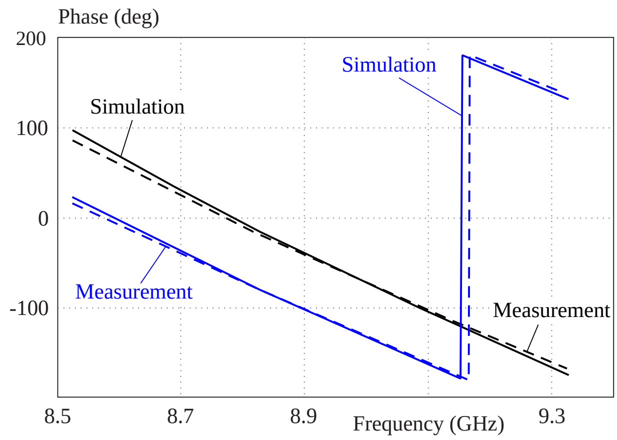

Fig. 8. Frequency response of phase shift: simulation (solid), measurement (dashed)

4 Design of the test prototype

Figure 9 shows the simulation model of the reference test circuit without phase shifters. The test circuit consists of a Wilkinson power divider and 3-port Hybrid power dividers. The circuit has symmetrical amplitude distribution. In Table 1, the desired amplitude and phase values at the outputs of the test circuit are shown. In [10] the microwave circuits, based on the SIW technology (Wilkinson and 3-port Hybrid divider), were described. The test circuit is the 5-port symmetrical power divider. The 3-port Hybrid power divider, caused a phase change of 90 degrees at the outputs, see Fig. 11. To achieve the desired phase distribution at the output ports according Tab. 1, the phase shifter has been applied, see Fig. 10.

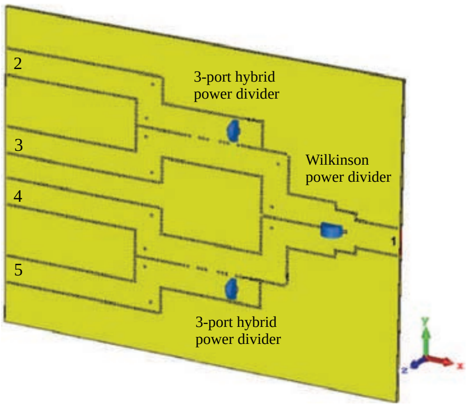

Fig. 9. The simulation model of the reference test circuit

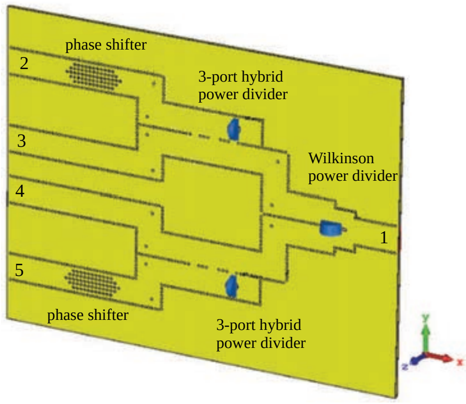

Fig. 10. The simulation model of the test circuit

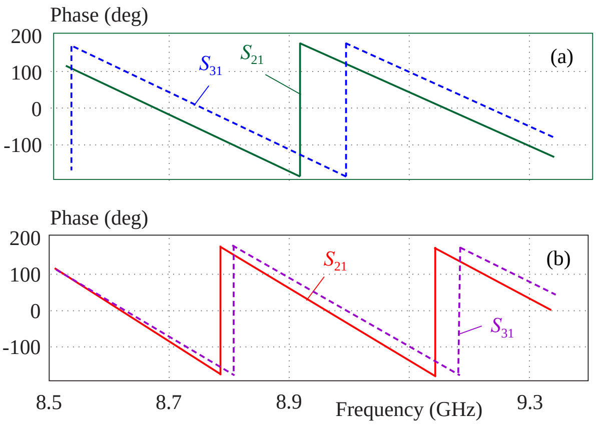

Fig. 11. Simulated phases of the reference test circuit (a) – without phase shifter, and (b) – the test circuit with the phase shifters

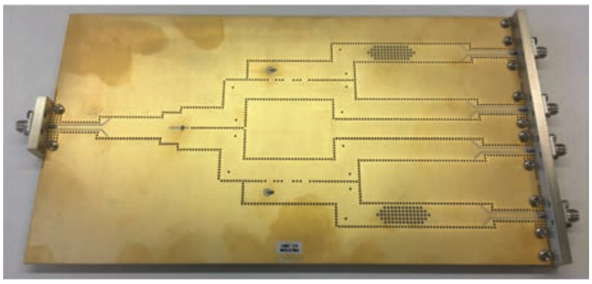

Fig. 12. Fabricated prototype of the test circuit

Table 1. Amplitudes and phases of the test circuit

Number of ports	2	3	4	5
Amplitudes (dB)	-13	0	0	-13
Phases (degrees)	-30	0	0	-30

Figure 10 shows the simulation model of the test circuit with the phase shifters implemented. To achieve the desired phase value at the outputs of the test circuit, the air hole density, and distance between air holes in x-axes and y-axes were set. In Figure 11, the simulation results of the proposal reference circuit and test circuit are shown. At center frequency of 8.925 GHz, the phase difference between port 2 and port 3 is equal to 25 °, see Fig.11.

5 Measurement of the prototype

The fabricated test circuit prototype is shown in Fig. 12. A thru-line-reflect (TRL) calibration (Fig. 13) was designed and use to de-embedded the effects of the transition.

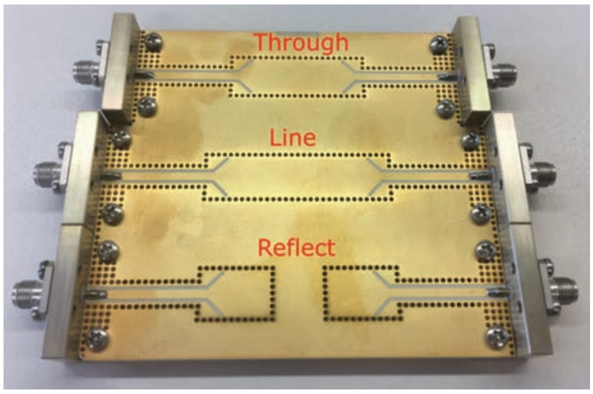

Fig. 13. TRL calibration set

In Figure 14, the measurement results of the test circuit are shown. At center frequency of 8.925 GHz, the value of the phase shift between port 2 and port 3 is equal to 32°. In working frequency band (8.85 GHz – 9 GHz), the phase balance is less than 10 the reflection coefficients, Fig. 15, are less than −10 dB and −15 dB at center frequency 8.925 GHz (for all ports).

6 Conclusion

The aim of this work was to analyze, and design a phase shifter based on the SIW technology. The proposed phase shifter was implemented in the test circuit. The parameters comparison of several circuits is show in Table 2. The proposed circuits were fabricated and measured.

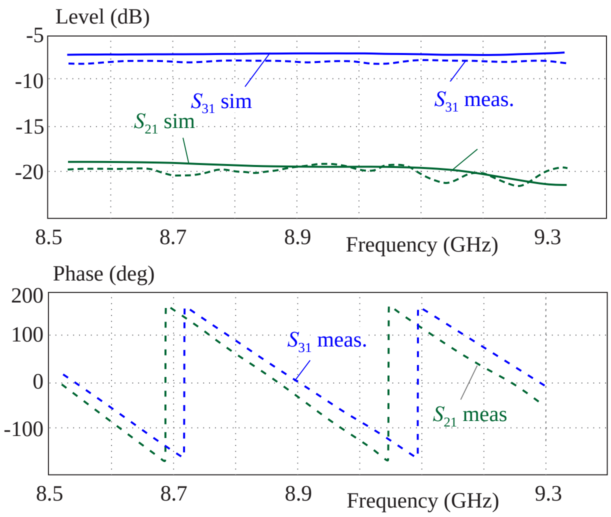

Fig. 14. Frequency response of the test circuits: top – simulated and measured coefficients of the transmission, bottom – measured phase

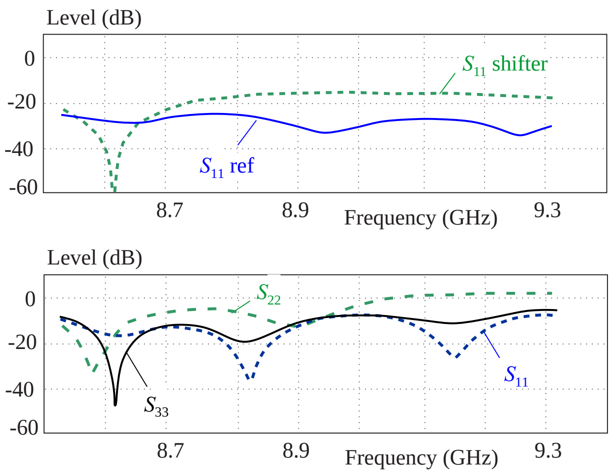

Fig. 15. Measured reflection coefficients: (top) – reference waveguide and phase shifter, (bottom)- -test circuits

Table 2. Comparison of phase shifters parameters; ϕ - phase shift, $\Delta\phi$ - phase shift range

Ref	Freq (GHz)	ϕ (deg)	$\Delta\phi$ (deg)	RL (dB)	No of Layers
[2]	4.48 8.35	45	$\pm$2.5	-15	3
[7]	10	11	$\pm$1.5	-14	1
[3]	13.1	83.2			10
[9]	10.2 - 18.85	45	$\pm$2.5	-15	
This work	8.85 - 9	30	$\pm$5	-15	1

During the measurements, a TRL and standard calibration techniques have been applied. Based on the measurement results of the test circuit, the phase balance can be less than 10. The phase shifter can be used for phase antenna design at the cost of achieving larger sizes than microstrip structures. A major advantage of this structure is very easy construction.

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