Four-State Full Q-Band Phase Shifter Using Smooth-Ridged Waveguides

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***Abstract*— A novel four-state full Q-band waveguide phase shifter based on smooth-ridged sections is presented. The waveguide structure combines differential 90° and 180° phase shifters, whose combination provides the four-phase states (0°, 90°, 180°, and 270°) by appropriately controlling a set of millimeter-wave switches. Each differential phase shifter is performed using an E-plane continuous profile ridge to reach the 90° or 180° phase shift, respectively. The phase shifter module provides outstanding performance covering the full Q-band (33–50 GHz) with average phase results of 93.5°, 182.8°, and 270.6°.**

***Index Terms*— Millimeter-wave circuit, phase shifter, waveguide, wideband.**

I. Introduction

COMMUNICATION systems commonly require phase shifters, and their accuracy typically defines the goodness of the implemented system, not only referring to its differential phase, but also the balance between the shifting amplitudes. These concerns are remarkable when large operation bandwidths are involved, since the feasibility of obtaining flat and low-error phase performances and balanced amplitudes between states over the band becomes a harsh issue.

Broadband differential phase shifters can be designed implementing quite different solutions and technologies. Stepped-ridged [1], corrugated [2], or stub-loaded [3] waveguide solutions regarding a straight section cover great bandwidths in different frequency bands with significant results. Competitive alternatives are developed using planar technologies, such as microstrip lines [4], [5] or substrate-integrated waveguide [6], [7], working in millimeter-wave frequencies. Monolithic solutions are also developed, with good results in Q-band but narrower bandwidth [8].

Consequently, a crucial fact for selecting the design technology is the intended wide operation frequency band. The implementation of all those waveguide solutions arises manufacturing difficulties due to the required accurate dimensions and tight mechanical tolerances to increase the bandwidth, since several waveguide steps are demanded. On the other hand, in planar hybrid technology the assembly becomes critical for the performance at millimeter-wave frequencies.

Therefore, an innovative solution in waveguide technology is presented in this letter. 90° and 180° phase shifters based on E-plane continuous profile ridges are described, overcoming both mechanical constraints and assembly or interconnection issues. Furthermore, the combination of both phase shifters composes a four-phase state module, which provides full switching operation through monolithic pin diode-based single-pole double-throw (SPDT) switches, exhibiting an outstanding performance over the full Q-band.

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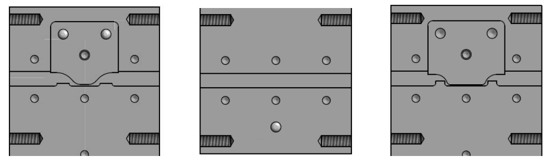

(a) (b) (c)

Fig. 1. Proposed Q-band phase shifters artistic views. (a) 90° phase shifter. (b) E-plane WR22 reference section (30 mm of length). (c) 180° phase shifter.

II. Differential Phase Shifters

Two broadband 90° and 180° differential phase shifters that enable full Q-band operation are presented. WR22 standard waveguide technology is proposed, using smooth-profile ridges to fulfill each phase requirement related to same length straight waveguide sections. Artistic views of both phase shifters are shown in Fig. 1.

A continuous profile ridge is considered for the designs, which enable an easier manufacturing process both for the phase shifting ridge and for the whole waveguide structure. The proposed shapes improve the stepped-ridged solution in terms of fabrication and cost purposes. Then, metallic sheets with these profiles are individually milled in 1-mm-thick aluminum, and the phase shifting waveguide structures have half-thick depth slots to insert them. A pair of alignment pins is located in each sheet to easily attach them to the structure. Then, to perform the phase shifts, the sheets are directly placed in the slots and, by closing the waveguide structures, the sheets are correctly placed. Furthermore, to enhance the impedance matching results and minimize the phase deviations, a pair of symmetric simple corrugations is placed in the opposite waveguide face and at both sides of the sheet.

A. Smooth-Ridged Waveguide Model

The smooth-profile ridges are considered as multiple cascaded discrete ridges of tiny dimensions. Considering this, the steps can be approximated by a continuous profile.

The height of the smooth-ridged waveguide is modeled using a sum of sines, considering a half-length mirror symmetry of their full lengths. So, it is defined as

$$y = \sum_{i=1}^{N} a_i \cdot \sin(b_i \cdot x + c_i) \qquad (1)$$

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TABLE I
COEFFICIENTS FOR THE MODELS OF EACH SMOOTH RIDGE

Coeff.	Value		Coeff.	Value		Coeff.	Value	
	90º	180º		90º	180º		90º	180º
a_1	4.351	2.672	b_1	0.468	0.272	c_1	0.521	0.293
a_2	2.962	1.192	b_2	0.606	0.487	c_2	3.759	3.595
a_3	0.124	0.396	b_3	2.189	1.438	c_3	1.201	1.068
a_4	-	0.111	b_4	-	2.575	c_4	-	2.879

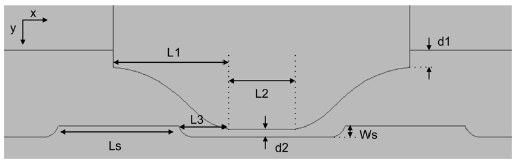

Fig. 2. E-plane cross section of the 90° phase shifter ridge. Dimensions (in mm): $L_1 = 4.01$, $L_2 = 1.72$, $L_3 = 1.88$, $Ls = 3.95$, $d_1 = 0.758$, $d_2 = 0.559$, and $Ws = 0.37$.

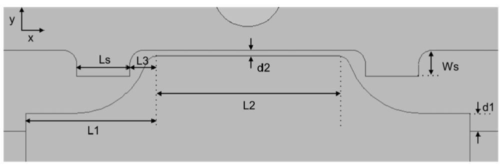

Fig. 3. E-plane cross section of the 180° phase shifter ridge. Dimensions (in mm): $L_1 = 4.64$, $L_2 = 6.38$, $L_3 = 0.973$, $Ls = 1.87$, $d_1 = 0.804$, $d_2 = 0.539$, and $Ws = 0.92$.

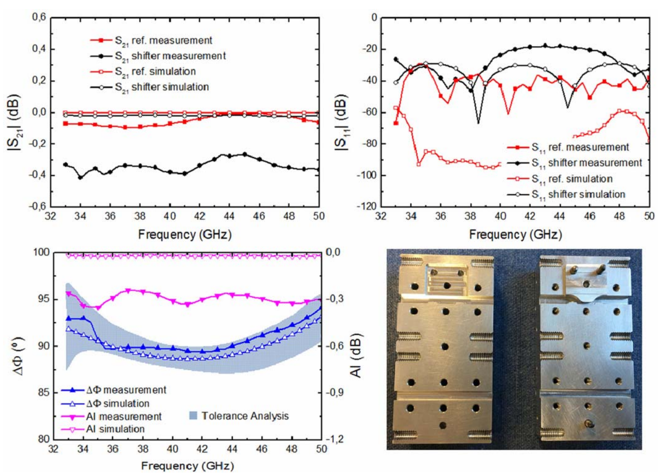

Fig. 4. 90° phase shifter: comparison between measurements and simulations of insertion loss, phase difference and AI over the band, and tolerance analysis of the phase difference sweeping dimensions (shaded area).

where y is the height of the ridge, x is the length across the waveguide (both in mm), a_i, b_i, and c_i are the coefficients, and N is the number of terms.

The 90° and 180° phase shifter ridges are modeled using three- and four-term series, respectively. Once the sheets are implemented in a 3-D electromagnetic simulator using these series, and the coefficients of each ridge are obtained after an optimization process. Their values are listed in Table I. Detailed views of the profiles of the ridges are shown in Figs. 2 and 3, respectively.

A tolerance analysis of the dimensions for the 90° phase shifter is performed, obtaining that deviations in the dimensions lower than 25 μm do not severely affect the behavior. The results of the analysis are shown in Fig. 4 in terms of the phase difference.

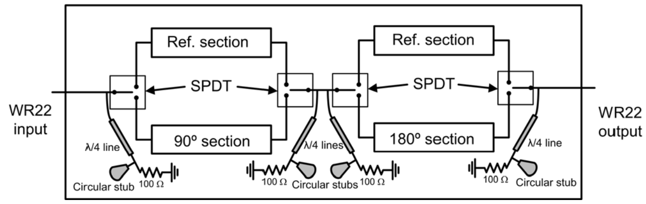

Fig. 5. Schematic of the proposed four-state phase shifting module.

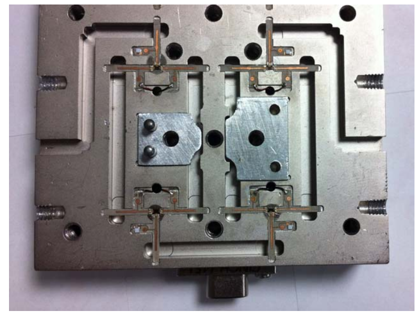

Fig. 6. E-plane top view of the assembly of the four-state phase shifting WR22 module: the 90° phase shifter (left); the 180° phase shifter (right). Size: 65 mm × 47.5 mm × 15 mm.

B. 90° Phase Shifter Prototype

To validate the methodology and the performance, only one of the phase shifters is manufactured since both of them are based on the same basis. Thus, the manufactured prototype of the 90° phase shifter together with its performance tested over the Q-band is shown in Fig. 4, compared with the simulations. An average phase difference ($\Delta\Phi$) of 90.83° and amplitude imbalance (AI) of 0.3 dB are provided, with an input matching $|S_{11}|$ better than -20 dB for both waveguide sections. These significant results validate the proposed design, since low in-band errors in $\Delta\Phi$ and AI are obtained.

III. FOUR-STATE PHASE SHIFTING MODULE

A. Design and Assembly

A WR22 waveguide module is designed containing both phase shifters which provides full switching capability. A schematic of the module is shown in Fig. 5. A set of four pin diode-based monolithic SPDT switches, model MA4AGSW2 from MACOM Technology Solutions, is used. To control their switching state, MADRCC0005 drivers, from MACOM Technology Solutions, are configured to be controlled by TTL signals. WR22 waveguide-to-microstrip transitions are designed using 0.254-mm-thick CLTE-XT substrate from Rogers. The dc networks of the switches consist of radio frequency choke quarter-wavelength lines, directly etched in the substrate, and open-ended circular stubs, which perform virtual short circuits in the band. Moreover, the dc return path for the switches is done through 100-Ω resistors. Additional waveguide sections are configured to connect both phase shifters, as well as the access to the switches. An E-plane top view of the module inside is shown in Fig. 6.

B. Experimental Characterization

A vector network analyzer is used to perform the measurement of the module over the Q-band. It is biased with a dc voltage of ±5 V with a consumption of 38 mA. The S-parameters

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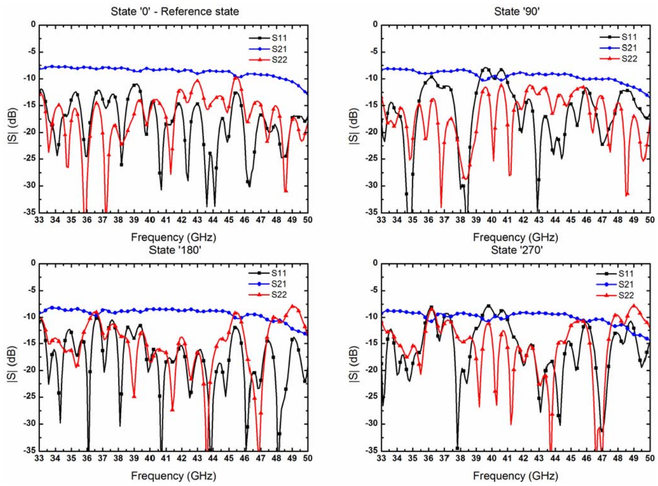

Fig. 7. Measured *S*-parameters for the different phase states in the module.

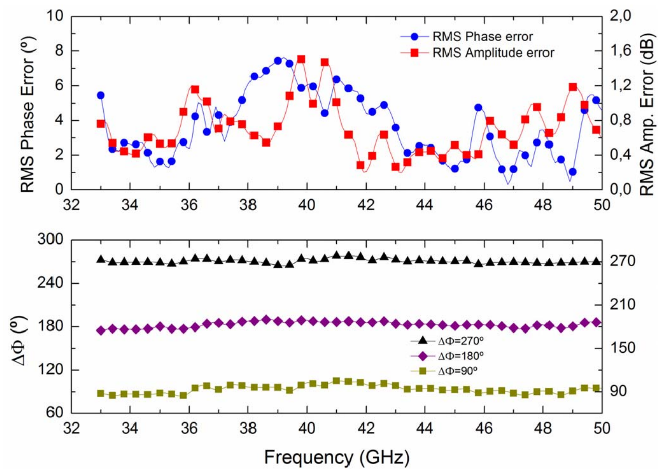

Fig. 8. Measured performance of the module over the Q-band: rms amplitude and phase errors and phase difference ($\Delta\Phi$) in each state.

for the different phase states are shown in Fig. 7 and the phase difference ($\Delta\Phi$) in Fig. 8, together with the calculated root-mean-square (rms) phase and amplitude errors, calculated as the square root of the sum of the square individual errors divided by the number of considered errors. The module shows average insertion loss of 9 dB (each SPDT with transitions $\sim$2 dB and each reference or shifter waveguide section $\sim$0.1 or $\sim$0.4 dB) and average phase shifts of 93.5°, 182.8°, and 270.6° within the band. The rms phase and amplitude errors are less than 7.5° and 1.5 dB, respectively, in the band. The module does not show compression for input powers up to +10 dBm for any phase state, providing stable phase differences and AIs.

Finally, Table II shows a comparison of the performance achieved in this letter with other reported broadband phase shifters, operating at Q-band and other frequency ranges and implemented in different technologies. The proposed solution has the advantage of being adaptable to achieve different phase shifts modifying only the profile of the sheet, as an individual part. Moreover, the integration of switches provides to the module full functionality to obtain the phase states. The module in this letter covers a full standard waveguide band with full switching capability, providing a very flat phase shift response with low errors over the band, improving the relative bandwidth covered.

TABLE II

COMPARISON OF PROPOSED CIRCUIT WITH OTHER REPORTED WORK

Ref.	Freq. (GHz)	Ph. States	RMS Ph./Amp Error (º)	Ph. Error (º)	I. L. (dB)	Technology
[1]*	10-15	2	-/-	<4	<0.1	Ridged waveguide
[2]*	85-115	1	-/-	<4	0.2	Corrugated waveguide
[3]*	26.5-40	4	-/-	<3	0.1	Stub-loaded waveguide
[4]	35-47	4	<8/<2	<2	7.4	Microstrip
[6]*	31.5-35.6	1	-/<	<5	<0.6	SIW
[7]*	25.11-39.75	1	-/<	<2.5	0.2	SIW
[8]	46-49	16	<7./<1.2	-	<6.1	MMIC
This work	33-50	4	<7.5/<1.5	<4	<9	Smooth-ridged waveguide

*no switch integrated

IV. CONCLUSION

A Q-band four-state phase switching circuit designed in waveguide technology using novel smooth-ridged sections has been described. The proposed structure is easy to manufacture and a low-cost solution. The outstanding flat phase performance of the circuit has shown average values of 93.5°, 182.8°, and 270.6° over the full Q-band, with rms phase and amplitude deviations lower than 7.5° and 1.5 dB, respectively. The circuit has shown return loss better than 9 dB within the band, with average insertion loss of around 9 dB.

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