Glide-Symmetric Pin Phase Shifter implemented in Gap-Waveguide Technology

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***Abstract*- This paper presents a compact and low-loss waveguide phase shifter based on a pin lattice in glide-symmetric configuration. There is a significant increase in provided phase shift when using a glide-symmetric pin distribution instead of a non-glide-symmetric configuration. A prototype has been manufactured to validate the simulated results of both phase shifters: non-glide-symmetric and glide-symmetric designs. Gap-waveguide technology has been implemented for low-cost manufacturing. The measurement results demonstrate the higher performance and compactness of the glide-symmetric phase shifter. For the same phase shifter length, the glide-symmetric design provides around 80 degrees more of phase shifting compared to the non-glide-symmetric phase shifter. Both phase shifters have a good impedance matching between 46 and 60 GHz (better than -10 dB) and an insertion loss lower than 1 dB.**

***Index Terms*— Phase shifter, gap-waveguide technology, higher symmetries, mm-wave.**

I. INTRODUCTION

Radiation pattern beamforming is provoking great interest because of its advantages in wireless communications for the future transmission systems. Multibeam antennas [1]-[2] use beamforming feeding networks to produce several output signals with different phases among them. Future beamforming networks will be in the mm-wave range due to the need of greater bandwidth that allows high speed communication. Fundamental part of the beamforming network is the phase shifter which provides phase shift among the different paths of the beamforming network. Thus, there is a clear necessity to implement mm-wave phase shifter to enable the multibeam antennas.

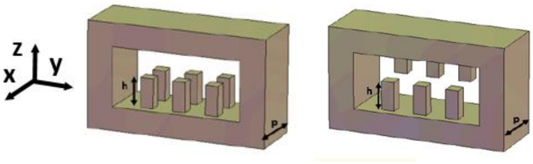
Waveguide phase shifter designs produce phase shift signal propagation with low loss at mm-wave frequencies. The waveguide phase shifter design reported in [3] uses a thin dielectric slab in the middle of the waveguide to achieve the desired phase shift. However, the use of dielectric material may be unsuitable in mm-wave frequency ranges for the losses produced in the signal at theses frequencies. In [4]-[5], phase shifters implemented in rectangular waveguide are presented. Both designs achieve a constant amount of phase shift for their whole operational frequency bands. The fundamental drawback of these phase shifters is the complex and accurate manufacturing process and therefore, its high cost. One attractive phase shifter design in hollow waveguide is the one in [6]. This phase shifter uses the groove gap waveguide technology for an easy manufacturing and metallic pins at one of the broad sides of the waveguide to obtain the desired phase shift.

The phase shifter presented in this paper is based on glide-symmetry. Glide-symmetric periodic structures are based on the existence of two mirrored periodic layers that are shifted half of the unit cell in the periodicity axis [7], [8]. In such way, our design is based on the use of metallic pins placed in a glide-symmetric configuration. The metallic pin lattice preserving glide-symmetry introduces a higher amount of phase shift, compared to non-glide-symmetric metallic pin configuration.

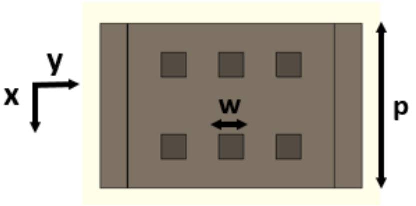
The paper is organized as follows: Section I presents the phase shifter designs reported for the mm-wave range. In Section II, a dispersion diagram study is carried out to analyze both phase shifting unit cells, non-glide-symmetric and glide-symmetric. Section III provides the designs of the phase shifters and their comparison with the non-glide-symmetric counterpart. Moreover, in this section, the manufactured prototype is shown and the measurement results are discussed. Finally, the conclusions are drawn in Section IV.

II. STUDY: DISPERSION DIAGRAMS

Applying glide symmetry to the pin lattice that composes the phase shifter, the electromagnetic performance can be significantly improved and tailored. The forming phase shifting unit cells for the different configurations are presented in Fig. 1. Two types of unit cells are depicted in 3D and top view. The non-glide-symmetric unit cell (Fig. 1(a)) is referred to the unit cell used in the phase shifter state-of-art reported in [6].



(a) (b)



(c)

Fig. 1. Phase shifting unit cells: (a) non-glide-symmetric design, (b) glide-symmetric design and (c) top view

To analyze the electromagnetic performance, some dispersion diagram studies are conducted. Dispersion diagrams allow to study the performance of a guiding structure through the distribution of the propagating modes in frequency. The location of the first propagating mode defines the working range and the forward mode dispersion properties. The dispersion diagrams of each phase shift unit cells have been performanced with the Eigenmode solver of CST Microwave Studio. The mode labelled as reference in the dispersion diagrams corresponds to the first propagating mode in a WR-15 standard waveguide. In the pin heights and pin widths dispersion diagrams comparisons, the analyzed dimension value is referred, in percentage, to the narrow and broad waveguide side dimensions, depending on the height or the width pin value respectively. Figs. 2 and 3 illustrate the mentioned dispersion diagrams studies.

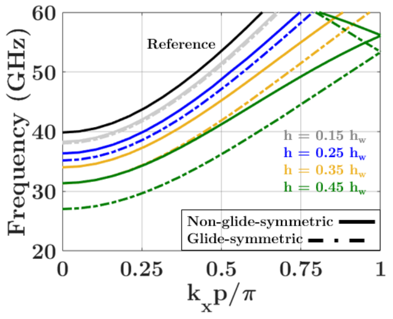


Fig. 2. Dispersion diagram comparison modifying pin height. Dimensions: p = 2.1 mm and w = 0.45 mm

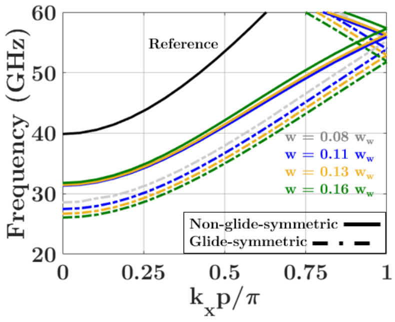


Fig. 3. Dispersion diagram comparison modifying pin width. Dimensions: p = 2.1 mm and h = 0.85 mm

The height modification of the phase shifter pin lattice has a higher effect in the dispersion behavior than the pin width modification. In addition, modifications in phase shift unit cell length (p) have been done and the dispersion diagram results are illustrated in Fig. 4. Observing these results, some conclusions can be drawn. First, the size of the phase shifting unit cell does not affect the modes distribution for the non-glide-symmetric unit cell design. Nevertheless, in glide-symmetric unit cell design, as cell length (p) is reduced, the locations of the modes decrease in frequency. Second, the position of the intersection point between the two types of cell configuration (non-glide-symmetric and glide-symmetric) is different and it is related to the cell length. It is also noticed that, for greater values of p in the glide configuration, the intersection point between modes with the same cell length is reduced.

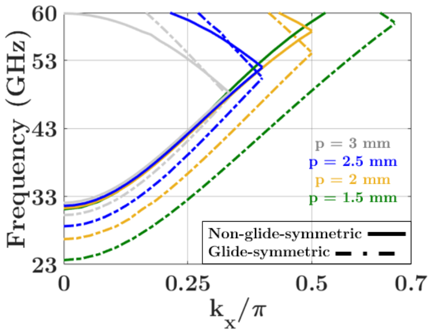


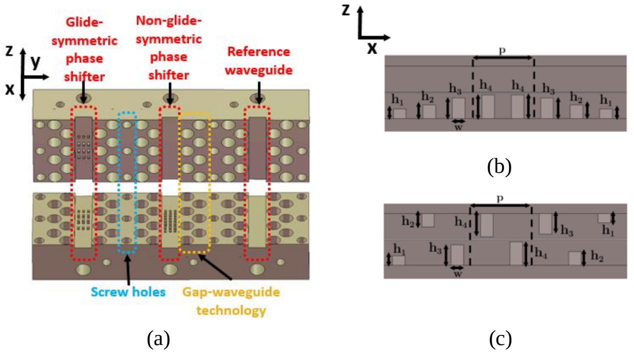
Fig. 4. Dispersion diagram comparison modifying cell length. Dimensions: w = 0.45 mm and h = 0.85 mm

III. PHASE SHIFTER DESIGN AND MEASUREMENTS

Phase shifter design is composed of phase shifting unit cells placed in cascade along the direction of signal propagation. The pin heights and cell length should be properly chosen to obtain the phase delay desired in the working frequency band of interest. In this section, the designed phase shifter provides 180 degrees of phase shift at 53 GHz (central frequency of operational frequency band) for the glide-symmetric configuration.

A. Non-glide-symmetric and Glide-symmetric phase shifter designs

Fig. 5 illustrates both phase shifter designs, non-glide-symmetric and glide-symmetric configurations. For a suitable impedance matching, the pin row heights at both ends of the phase shifter should be in a tapered design. The gap waveguide technology employed for manufacturing both phase shifters and a reference waveguide, is the glide-symmetric holey gap waveguide reported in [9]. This technology permits low manufacturing costs in gap waveguide designs.



(a)

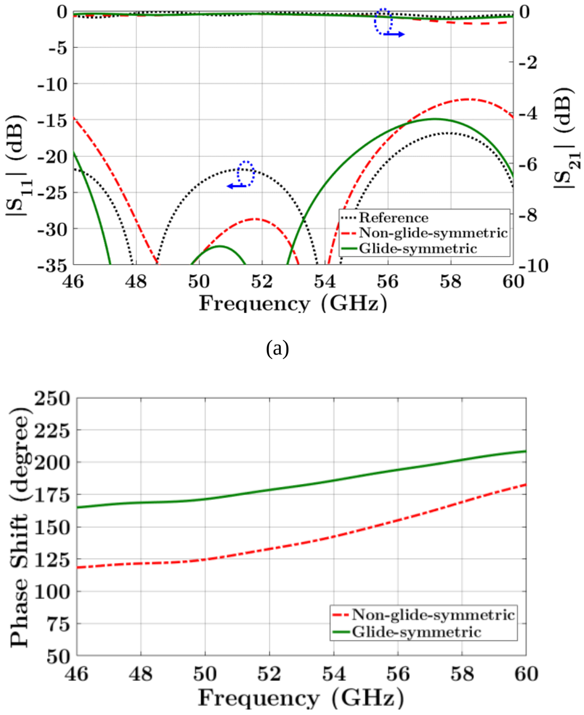
(b)

(c)

Fig. 5. Phase shifters designs: (a) upper and lower parts of the phase shifter prototype, (b) longitudinal view of the non-glide-symmetric phase shifter, (c) longitudinal view of the glide-symmetric phase shifter. Dimensions in millimeters: w = 0.45, p = 2.1, h_1 = 0.35, h_2 = 0.5, h_3 = 0.75, h_4 = 0.85.

B. *Simulation Results*

The simulation results of the phase shifters are shown in Fig. 6. Both phase shifters have a bandwidth, from 46 to 60 GHz with transmission losses below 0.4 dB. On the other hand, the glide-symmetric phase shifter produces a greater phase shift along the whole frequency band in comparison with the non-glide-symmetric phase shifter. However, this difference in phase decreases as frequency increases and the reason can be explained through the existing intersection point in the aforementioned dispersion diagrams. The glide-symmetric phase shifter provides 40 degrees more phase shift than the non-glide-symmetric phase shifter as can be observed in Fig. 6(b). This difference in phase shift was anticipated in the previous dispersion diagram study.



(a)

(b)

Fig. 6. Simulated S-Parameters of the phase shifters and reference waveguide. (a) $|S_{11}|$ and $|S_{21}|$. (b) Phase shift referred to the reference waveguide.

The non-glide-symmetric phase shifter can be designed to produce more phase shift by means of enlarging the pins. However, this phase shifter design with higher pin has a bigger phase deviation with the same reference phase degree (180 degrees at 53 GHz) regarding to the glide-symmetric phase shifter configuration. It is seen in Fig. 7. This increment in the phase deviation is due to a lower linearity behavior in the propagating mode of the non-glide-symmetric case. When the frequency increases, the glide-symmetric case keeps a propagating mode less dispersive than the non-glide-symmetric case.

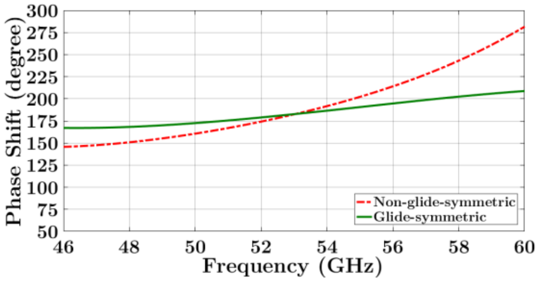


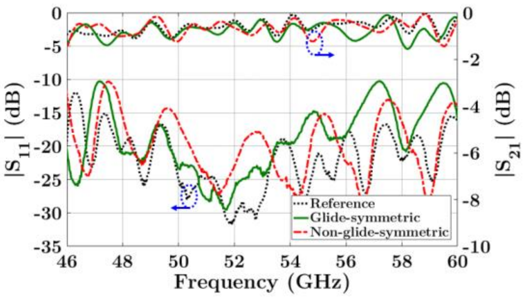
Fig. 7. Phase shift referred to the reference waveguide when non-glide-symmetric is designed to produce 180 degrees at 53 GHz.

C. *Measurements*

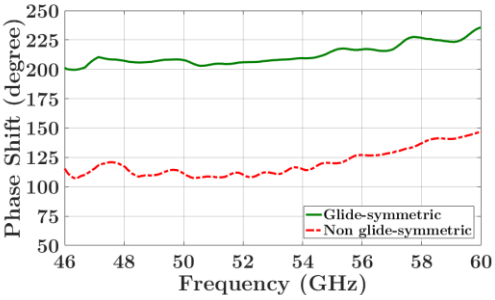
Once phase shifters are designed and simulated, the prototype has been manufactured in order to validate the simulation results. The prototype has been manufactured in aluminum and using CNC milling. It is illustrated in Fig. 8.

Fig. 8. Prototype manufactured that implemented both phase shifters design and the reference waveguide

The measured results are depicted in Fig. 9. Regarding to the scattering parameters, the reflection coefficient is lower than -10 dB in the entire frequency band for both phase shifters configurations. The maximum is 1 dB of losses in the entire operational band. Therefore, simulations and measurements are in good agreement. The increase of 0.6 dB of insertion losses compared to simulations is caused by the manufacturing process, and are negligible for the phase behavior validation. Also, the ripple presented in all of the measurements is due to the use of waveguide transitions (1.85 mm coaxial to WR-15 waveguide) in the measurement process.



(a)



(b)

Fig. 9. Measured S-Parameters of the phase shifters and the reference waveguide. (a) $|S_{11}|$ and $|S_{21}|$. (b) Phase shift referred to the reference waveguide.

The comparison between the measured phase shift produced by each phase shifter is illustrated in the Fig. 9(b). A difference in phase shift between the glide-symmetric and non-glide-symmetric phase shifter is in good agreement with the simulation results. The phase shift difference between both phase shifters is around 80 degrees. This increment, regarding to simulation results, of 40 degrees in the phase shift provided by the glide-symmetric phase shifter could be related to higher heights of the manufactured pins. A compactness of 25 degrees per millimeter can be achieved in the glide-symmetric phase shifter regarding to the 15 degrees per millimeter produced by the non-glide-symmetric version.

IV. CONCLUSIONS

It has been demonstrated that the pin configuration is the proper option for introducing higher phase shifting effect in a waveguide based system. There is significant increase in terms of phase shift when using a glide-symmetric pin distribution compared to its corresponding non-glide-symmetric configuration. A prototype has been manufactured to validate the dispersion diagram comparisons carried out for both non-glide-symmetric and glide-symmetric configurations. The measured results demonstrate the higher performance and compactness of the glide-symmetric phase shifter. Both phase shifters have proper impedance matching and are low-loss in the entire operational frequency band.

ACKNOWLEDGEMENTS

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