Wideband Gap-Waveguide Phase Shifter Based on a Glide-Symmetric Ridge

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Abstract

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Abstract—This letter presents a gap-waveguide phase shifter based on ridged unit cells with glide-symmetric configuration. The proposed unit cell design provides a higher stable phase shift compared to a conventional ridged unit cell whose ridge height and waveguide width are tuned to achieve a stable phase shift. Through the insertion of glide-symmetric holes with semicircle base in the ridged waveguide, a stable phase shift in a wide frequency range is achieved. Depending on the radii of the holes, the operating frequency range of the phase shifter can be tuned. A 90° phase shifter in millimeter-wave range is designed and manufactured to validate the analysis. The experimental results reveal a 85°± 5° phase shift from 33 GHz to 43 GHz (26.3% bandwidth). In this bandwidth, the reflection coefficient is below -10 dB with a maximum insertion loss of 0.7 dB.

Index Terms—Glide symmetry, millimeter-wave frequencies, phase shifter, ridge gap-waveguide, wideband.

I. INTRODUCTION

Phase shift in multi-beam antennas is a critical mechanism to achieve the adequate performance of this kind of radiating systems. One of the most attractive network to produce multi-beam radiation is the Butler matrix. For millimeter-wave applications, this beamforming network has been implemented in different waveguide technologies such as substrate integrated waveguide [1], rectangular waveguide [2], groove gap waveguide (GGW) [3] and printed ridge gap waveguide (PRGW) [4]. In all the previous works, a phase shifter in the corresponding technology had to be designed. Ridge waveguide (RW) technology and its evolution in gap waveguide [5] have gained interest to develop millimeter-wave antennas [6] and multi-port components [7], [8]. Nevertheless, there are few reported ridge gap-waveguide (RGW) phase shifters in the literature. A RW phase shifter based on multiple steps is proposed in [9], while [10] proposes an approach based on a optimization of a smooth-ridge waveguide model. However, the phase shift is calculated considering another waveguide technology (rectangular waveguide) as a reference and gap-waveguide technology is not employed. The insertion of materials with different permittivity in the RW is another way to introduce phase shift. In [11], the propagation constant is modified in the RW through the rotation of a dielectric slab placed atop the ridge. Liquid crystal (LC) is used in [12] inside a gap-waveguide to properly bias the material but the phase shift has no ability to be stable in frequency and also has large insertion losses. Materials with different relative permeability are also employed in the design of phase shifter in ridge gap waveguide [13]. Additionally, mechanical approach by taking advantage of the gap-waveguide technology is applied in [14] to vary the waveguide length and produce the phase shift. Waveguide phase shifters loaded with pins [15] and holes [16] that present glide symmetry have demonstrated the benefits for producing and tuning phase shift in waveguides. This kind of higher symmetry greatly enhances the performance of radio-frequency devices [17]. In this letter, we present a gap-waveguide phase shifter that exploits the use of ridged unit cells with glide symmetry to produce a stable phase shift response over a wide bandwidth in millimeter waves.

II. GLIDE-SYMMETRIC RGW UNIT CELL

The proposed ridge gap-waveguide phase shifter is illustrated in Fig. 1. It is composed by glide-symmetric ridged (GSR) waveguide unit cells and two rectangular waveguide to ridge gap-waveguide transitions inspired by [18] to design a back-to-back device. The electromagnetic bandgap pin lattice provides a stopband from 12 GHz to 61 GHz that allows the proper operation of the RGW in the WR22 frequency range. The insertion of glide-symmetric holes with radius $r_2=0.3$, $p=3.6$, $d_x=0.9$, $r_h=0.6$, $w_{L1}=1.3$, $w_{T2}=3.6$, $h_r=1.55$, $h_p=2.37$, $p_y=2.7$, $w_p=1.2$, $g=0.03$.

Fig. 1: Proposed gap-waveguide phase shifter with glide-symmetric ridged unit cells. Planar view of the rectangular waveguide to ridge gap waveguide transition. Dimensions (in mm): $w=5.69$, $h=2.845$, $w_1=0.725$, $L_{11}=1$, $L_{12}=1.1$, $L_{13}=3.5$, $r_2=0.3$, $p=3.6$, $d_x=0.9$, $r_h=0.6$, $w_{L1}=1.3$, $w_{T2}=3.6$, $h_r=1.55$, $h_p=2.37$, $p_y=2.7$, $w_p=1.2$, $g=0.03$. Dimensions (in mm): $w=5.69$, $h=2.845$, $w_1=0.725$, $L_{11}=1$, $L_{12}=1.1$, $L_{13}=3.5$, $r_2=0.3$, $p=3.6$, $d_x=0.9$, $r_h=0.6$, $w_{L1}=1.3$, $w_{T2}=3.6$, $h_r=1.55$, $h_p=2.37$, $p_y=2.7$, $w_p=1.2$, $g=0.03$. Dimensions (in mm): $w=5.69$, $h=2.845$, $w_1=0.725$, $L_{11}=1$, $L_{12}=1.1$, $L_{13}=3.5$, $r_2=0.3$, $p=3.6$, $d_x=0.9$, $r_h=0.6$, $w_{L1}=1.3$, $w_{T2}=3.6$, $h_r=1.55$, $h_p=2.37$, $p_y=2.7$, $w_p=1.2$, $g=0.03$. Dimensions (in mm): $w=5.69$, $h=2.845$, $w_1=0.725$, $L_{11}=1$, $L_{12}=1.1$, $L_{13}=3.5$, $r_2=0.3$, $p=3.6$, $d_x=0.9$, $r_h=0.6$, $w_{L1}=1.3$, $w_{T2}=3.6$, $h_r=1.55$, $h_p=2.37$, $p_y=2.7$, $w_p=1.2$, $g=0.03$. Dimensions (in mm): $w=5.69$, $h=2.845$, $w_1=0.725$, $L_{11}=1$, $L_{12}=1.1$, $L_{13}=3.5$, $r_2=0.3$, $p=3.6$, $d_x=0.9$, $r_h=0.6$, $w_{L1}=1.3$, $w_{T2}=3.6$, $h_r=1.55$, $h_p=2.37$, $p_y=2.7$, $w_p=1.2$, $g=0.03$. Dimensions (in mm): $w=5.69$, $h=2.845$, $w_1=0.725$, $L_{11}=1$, $L_{12}=1.1$, $L_{13}=3.5$, $r_2=0.3$, $p=3.6$, $d_x=0.9$, $r_h=0.6$, $w_{L1}=1.3$, $w_{T2}=3.6$, $h_r=1.55$, $h_p=2.37$, $p_y=2.7$, $w_p=1.2$, $g=0.03$. Dimensions (in mm): $w=5.69$, $h=2.845$, $w_1=0.725$, $L_{11}=1$, $L_{12}=1.1$, $L_{13}=3.5$, $r_2=0.3$, $p=3.6$, $d_x=0.9$, $r_h=0.6$, $w_{L1}=1.3$, $w_{T2}=3.6$, $h_r=1.55$, $h_p=2.37$, $p_y=2.7$, $w_p=1.2$, $g=0.03$. Dimensions (in mm): $w=5.69$, $h=2.845$, $w_1=0.725$, $L_{11}=1$, $L_{12}=1.1$, $L_{13}=3.5$, $r_2=0.3$, $p=3.6$, $d_x=0.9$, $r_h=0.6$, $w_{L1}=1.3$, $w_{T2}=3.6$, $h_r=1.55$, $h_p=2.37$, $p_y=2.7$, $w_p=1.2$, $g=0.03$. Dimensions (in mm): $w=5.69$, $h=2.845$, $w_1=0.725$, $L_{11}=1$, $L_{12}=1.1$, $L_{13}=3.5$, $r_2=0.3$, $p=3.6$, $d_x=0.9$, $r_h=0.6$, $w_{L1}=1.3$, $w_{T2}=3.6$, $h_r=1.55$, $h_p=2.37$, $p_y=2.7$, $w_p=1.2$, $g=0.03$.
The use of GSR unit cells instead of conventional RGW unit cells with modified parameters provides an advantage in the design of phase shifters. The proposed glide-symmetric configuration is the one that produces the largest bandwidth regarding other hole configuration in the unit cell. This can be observed in the dispersion diagram of Fig. 2(c) since stopbands do not appear for GSR unit cell. The parameter $d_x$ in Fig. 2(c) stands for the distance between the center of the holes and that of the unit cell. This parameter is of special attention to preserve the glide symmetry configuration. If $d_x$ is not equal to a quarter of the period of the unit cell, the distance between hole centers is not equal to half of the unit cell period and a stopband appears. This implies a reduction of the operating frequency range and also a loss of linearity of the propagating mode near the stopband [19]. Note that the glide-symmetric configuration of the holes makes the stopband to vanish while the mirror-symmetric configuration ($d_x = p/2$) provides the widest stopband according to the results discussed in [16].

Figs. 2(d) and 2(e) present the dispersion diagram and the produced phase shift of the GSR unit cell. The ridge height of the GSR unit cell must be slightly higher than the reference RGW unit cell to reduce the cutoff frequency and achieve the desired effect of the glide-symmetric holes. The increase in ridge height leads to set a higher offset in the produced phase shift of the GSR unit cell. The ridge height of the reference RGW unit cell corresponds to $h_r = 1.4$ mm and $w_{y2} = 3.6$ mm. The other dimensions can be found in Fig. 1.
The modification in the slope of the mode is mainly from 30 GHz onwards. As the hole radius increases, a lower slope is obtained in the dispersion diagram regarding of GSR unit cells. This relevant effect enables a stable and higher phase shift depending on the selected hole radius as illustrated in Fig. 2(e). In this figure, three different ranges of frequencies with phase-stable behavior are achieved. The smaller the radius, the smaller the phase shift produced by the unit cell but the produced stable phase shift has a higher value than the one obtained for the best case in Fig. 2(b) (yellow line).

III. PHASE SHIFTER DESIGN AND EXPERIMENTAL VALIDATION

Based on the proposed GSR unit cell, a 90° phase shifter has been designed by the concatenation of eight unit cells whose dimensions are in the caption of Fig. 1. A RGW reference line with the same length of the phase shifter has also been designed. The dimensions of the unit cell employed in the RGW reference line correspond to the unit cell with \( h_x = 1.4 \) mm and \( w_{1/2} = 3.6 \) mm in Fig. 2(a). The manufactured back-to-back designs of the RGW reference line and phase shifter are displayed in Fig. 3(a). Same transitions have been used in both designs to accurately measure the phase shift. The simulation of this design has been performed with CST Studio Suite where the metal considered in the structure is aluminum, the same metal as used in the prototype. In Fig. 3(b), the simulated and measured \( |S_{21}| \) and \( |S_{11}| \) of the RGW reference line and phase shifter are shown. The experimental results show a common impedance bandwidth where \( |S_{11}| \) is below -10 dB from 33 GHz to 43 GHz with a maximum insertion loss of 0.7 dB. Tolerances of ±75μm in the position of the holes due to manufacturing has also been studied in simulation but the effect of possible stopband in the transmission coefficient is negligible. In the impedance bandwidth, the output phase difference between the reference line and phase shifter is calculated and presented in Fig. 3(c). The expected phase shift from the simulated result was approximately 90°±2° in the bandwidth under consideration. Measured results reveal a phase shift of 85°±5°. A further study has been carried out to find out the cause of this slight difference between simulated and measured results. The parameter \( g \) (see Fig. 1) has been varied and the simulated results are shown in Fig. 3(c). The larger the air gap \( g \), the greater the variation in the phase shift, besides a reduction in the average phase shift in the considered bandwidth. Nevertheless, the phase shifter design can be considered robust under this gap tolerance.

Finally, Table I presents a comparison with other related waveguide phase shifters found in the literature. The proposed RGW phase shifter provides a wideband performance comparable to other state-of-the-art waveguide phase shifters. Specifically, if we compare with the other wideband ridge waveguide phase shifter [10], it uses a rectangular waveguide as a reference while in the proposed design the reference is a ridge waveguide. This is of interest when the same waveguide technology is required in a more complex circuit. Furthermore, the phase shifter design in [10] relies on an optimization process as opposed to the one presented in this work, which is based on dispersion diagrams. This provides greater physical insight and lower computational cost but with lower compactness in the phase shifter.

### Table I: Comparison of phase shifters in mm-wave band with this work

| Ref. | Frequency (GHz) | Waveguide Technology | Max. IL (dB/°) | Stable Phase Shift (°/λ) \( \dagger \) | Compactness \((°/λ)^{1}\) |
|------|----------------|----------------------|----------------|---------------------------------|-----------------|
| [4]  | 33-35 (21.78%) | PRGW                 | 8.85·10\(^{-3}\) | Yes (45°±2°)                       | 30              |
| [10] | 33-50 (40.1%)  | RW                   | 4.44·10\(^{-3}\) | Yes (92°±2°)                      | 48.58           |
| [12] | 20-27 (29.78%) | RGW & LC             | 14.3·10\(^{-3}\) | No                               | 58.92           |
| [14] | 75-76.5 (1.98%)| RGW                  | 8.33·10\(^{-3}\) | No                               | 197.37          |
| [15] | 46-60 (26.41%) | GGW                  | 4.85·10\(^{-3}\) | No                               | 141.5           |
| [16] | 56.5-74.5 (27.5%)| GGW                   | 11.11·10\(^{-3}\) | Yes (180°±5°)                      | 31.22           |
| This work | 33-43 (26.3%) | RGW                  | 8.24·10\(^{-3}\) | Yes (85°±5°)                      | 24.67           |

\( ^\dagger \) Simulated results.

At center frequency.

IV. CONCLUSION

This paper presents a RGW phase shifter with a stable phase shift response in a wide frequency range. By tuning the radii of the glide-symmetric holes and the height of the ridge of the unit cell, a stable phase shift can be achieved in a desired frequency range. A 90° phase shifter is designed and manufactured. The measured results reveal a low loss and wideband phase shifter whose produced phase shift is 85°±5° from 33 GHz to 43 GHz. The RGW phase shifter enables the potential development of cost-effective Butler matrix in ridge waveguide. Additionally, the GSR unit cell allows a wideband control of the \( \beta \) which can potentially be used for the design of leaky-wave antennas in ridge waveguide.
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