Low-Loss Reconfigurable Phase Shifter in Gap-Waveguide Technology for mm-Wave Applications

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\textbf{Abstract:}
In this paper, we present a low-loss mechanically reconfigurable phase shifter implemented in gap-waveguide technology for mm-wave frequencies. The proposed design gives a practical implementation of tuning elements inside the waveguide providing alternatives to the use of the E-plane split waveguide at high frequencies in order to avoid leakage losses. The depicted phase shifter design is based on a H-plane split waveguide. The phase shift is controlled by means of a tuning screw, which exerts pressure on a flexible metallic strip inserted inside the waveguide. The flexible strip bends with different curvature radii and determines the phase shift at the output port. Cost-effective manufacturing and simple implementation of the flexible metallic strip are achieved by means of the gap-waveguide design. A prototype has been manufactured for validation purposes. Good impedance matching is achieved from 64 GHz to 75 GHz providing a 15.8% impedance bandwidth. The results show a maximum phase shift of 250° with a maximum and mean insertion loss of 3 dB and 1.7 dB, respectively.

1. Introduction

Reconfigurability is playing a fundamental role in present and future mm-wave communication systems. Thus, reconfigurable phase shifters are necessary to provide beamforming capabilities to the antennas [1]. However, this kind of phase shifters have to be implemented in a proper technology to present low losses and fulfill demanding requirements. Waveguide technology is a good candidate since it provides reduced losses in the mm-wave frequency range. Some examples of mechanically reconfigurable phase shifters in waveguide technology at K-band can be found in [2, 3]. In both designs, short waveguide couplers with mechanical reconfigurable elements at the output ports have been used to achieve the desired phase shift in reflection. Another solution in waveguide technology is presented in [4], where the wide side of the waveguide is adjustable to achieve the desired phase shift at the output port of the waveguide. Similarly, [5] shows a reconfigurable phase shifter based on a piezoelectric actuator, where the side wall of the waveguide is in this case a perfect magnetic conductor (PMC). Other approaches to obtain phase shift employ PIN diodes [6, 7, 8, 9, 10, 11, 12]. Nevertheless, PIN diodes suffer from high losses in mm-wave regime. Some reconfigurable material such as liquid crystals [13, 14, 15, 16, 17] or ferroelectrics [18, 19, 20] are also used to vary the phase shift. These approaches are currently attractive but present some drawbacks such as complex implementation in waveguide and high insertion losses incurred when the frequency increases.

Waveguide technology has evolved in order to provide a less demanding manufacturing process. Gap-waveguide technology [21] enables the waveguide fabrication in two separate parts with no mandatory perfect electrical contact in the assembly, avoiding possible leakage throughout the gap. This fact permits to relax the
requirements of manufacturing providing a low-cost fabrication. Besides, taking advantage of the waveguide fabrication in split parts, tuning elements can be easily implemented inside the waveguide in order to modify the phase of the propagating signal. For example, in [22] and [23], gap-waveguide based on glide-symmetric holes [24] has been used to design a mm-wave phase shifter inserting a dielectric slab and pinned structures, respectively. This work presents a tunable phase shifter based on gap-waveguide technology. The reconfigurable behavior of the phase shifter is achieved by means of a flexible metallic strip inserted in the side wall of the waveguide. The variation of the curvature radius of the flexible metallic strip is produced by a tuning screw that exerts a pressure on the center of the strip. It allows to narrow the wide side of the waveguide and modify the propagation constant ($\beta$), producing an adjustable phase shift. Figure 1 depicts the design of the proposed tunable phase shifter. Some patents about mechanically tunable phase shifter in waveguide are in [25, 26]. However, no in-depth details are provided about the manufacturing issues and performance of a real prototype. Moreover, their designs are intended for the conventional waveguide technology. There exist examples of commercially available phase shifters in waveguide technology [27, 28]. Nevertheless, their designs have not been reported and the implementations to achieve the phase shift in waveguide are not known. In addition, they are bulky designs in order to implement the phase shift mechanism. The design phase shifter design exploits the advantages of the gap-waveguide technology to allow a cost-effective device with low losses. To the best of the authors’ knowledge, this is the first reported mechanically reconfigurable gap-waveguide phase shifter in mm-waves frequencies.

![Figure 1: Tunable phase shifter design model.](image)

The paper is organized as follows. Section II presents the phase shifter design and its reconfigurable behavior. Section III shows the experimental results obtained with the prototype as well as the comparison with the simulation results. Finally, conclusions are provided in Section IV.

2. Phase Shifter Design

A planar view of the proposed phase shifter is illustrated in Fig. 2. The contour of the metallic strip can be modeled with an elliptical profile, whose semi-major axis $a_e$ is fixed and whose semi-minor axis $b_e$ depends on the position of the tuning screw. The more pressure the screw exerts, the larger $b_e$ is. This implies a variation in the propagation constant $\beta_g$ when the signal propagates along the waveguide [29]. At each position $x$ of the waveguide, $\beta_g(x, b_e)$ has a value that depends on the profile of the ellipse $h_e(x, b_e)$. The expressions for $\beta_g(x, b_e)$ and the approximated total phase shift $\phi$ obtained along the waveguide are represented as:

$$\beta_g(x, b_e) = \frac{2\pi}{\lambda_g(x, b_e)} = 2\pi \sqrt{1 - \left(\frac{\lambda_o}{2(w - h_e(x, b_e))}\right)^2}$$

$$\phi(b_e) = \int_{a_e}^{a_e} \beta_g(x, b_e) \, dx$$

where $\lambda_o$ is the free-space wavelength and $w$ is the size of the broadside in WR15 waveguide. From Eqs. (1)-(2), it is clear that a variation in the profile of the ellipse produces a modification in the total phase shift. The results provided by this model are shown at the end of this section in comparison with the simulations in CST Microwave Studio.
Figure 2: Description of the upper layer of the phase shifter. Dimensions: $a = 11\, \text{mm}$, $b_e = 0.55\, \text{mm}$, $w = 3.76\, \text{mm}$, $a = 3.22\, \text{mm}$, $r = 1.25\, \text{mm}$, $w_{corr} = 0.6\, \text{mm}$, $h_{corr} = 0.25\, \text{mm}$, $p_{corr} = 2\, \text{mm}$, $L_{corr} = 1.8\, \text{mm}$, $h_1 = 1.8\, \text{mm}$, $p_1 = 1.1\, \text{mm}$, $w_1 = 0.8\, \text{mm}$.

In order to allow an easy implementation of the metallic strip inside the waveguide, gap-waveguide technology based on glide-symmetric holes is chosen [24]. The dimensions for the glide-symmetric holes are depicted in Fig. 2, where the gap height and the depth of the holes are set at 0.05 mm and 3 mm, respectively. This electromagnetic bandgap (EBG) structure provides a stopband for the gap leakage from 45 GHz to 85 GHz, covering the frequency range of the waveguide standard WR15. Figures 3(a) and 3(b) show the effect of the gap-waveguide technology in the proposed phase shifter. It is observed how the phase shift can be controlled by changing the curvature radius of the metallic strip.

Figure 3: Amplitude of the E-field distribution: (a) top view of the gap between layers at 65 GHz when the tuning screw does not exert any pressure, (b) when the tuning screw exerts a pressure. The phase changes as a consequence of the tuning screw. (c) 3D views of the selected cutting planes and transversal cut of the phase shifter showing the fundamental propagative mode.

In order to prevent undesired resonances between glide-symmetric EBG holes and the waveguide, corrugations are implemented to avoid resonant fields [30],[31]. In addition, a vertical thin gap should exist between the long side of the metallic strip and the upper and lower surface of the waveguide to permit the flexible movement of the metallic strip. These thin gaps may cause resonant fields in the same manner as previous situation. For that reason, the flexible metallic strip has also a corrugated shape in order to prevent resonances. A transversal cut of the phase shifter is illustrated in Fig. 3(c), where 50 $\mu$m gaps are included in both sides of the metallic strip to observe the E-field distribution in presence of an imperfect electrical contact between the metallic strip and the waveguide walls. No resonances are observed, since the electric field is confined in the
waveguide despite the existence of thin air gaps. Figure 4 illustrates the simulated $|S_{21}|$ of the phase shifter for a design with and without corrugations. These corrugations, on both the metallic strip and the waveguide wall, enhance the transmission in the entire operating frequency range. When the strip corrugations are not included (blue lines), peaks in the upper part of the frequency range begin to appear due to resonances. Other deeper peaks in transmission show up in the case of not implementing the wall corrugations.

![Figure 4: Simulated transmission coefficient with (w/) and without (w/o) strip and wall corrugations for different curvature radii (different $b_e$ values).](image)

The simulated phase shift results are presented in Fig. 5 along with the results provided by the model. Good agreement is observed between the simulation and the model results, providing more phase shift dispersion when the radius of curvature increases. For lower curvature radii, which entail larger broadside waveguide, the deviation of the phase shift tends to decrease. This is because of the resulting propagation constant, which is less dispersive when the screw does not increase the curvature radius (reference position). According to this effect, a less dispersive phase shifter can be designed by extending the phase shift area (i.e. enlarging the range of the semi-major axis $a_e$) and employing smaller curvature radii.

3. Experimental Validation

In order to validate the simulation results, a prototype of the proposed phase shifter was manufactured in CNC (Computer Numerical Control) technology. Figure 6(a) shows the forming layers of the reconfigurable phase shifter, as well as the final assembly. Figure 6(b) shows the effect of the pressing screw over the metallic strip. The flexible metallic strip has been manufactured in FR4 (substrate thickness of 0.4 mm and $\varepsilon_{r} = 4.5$) to obtain the desired flexible behavior to implement the reconfigurability in the phase shifter. The gaps between the metallic strip and the lower and upper surface of the waveguide were measured to assess the correct assumption of gap sizes. The measured gaps have a size of $25\mu m \pm 10\mu m$. For gap sizes bigger than $100\mu m$, the gaps are expected to have a significant effect in the performance of the phase shifter. Since the measured gaps are less than this value, the electric field remains confined by the metallic strip, similar to what shown in Fig. 3(c).

The scattering parameters, for the complete range of curvature radius, have been measured using the R&S-ZVA67 VNA and they are shown in Fig. 7(a). The simulated results are also included in this figure. A frequency range from 63 to 75 GHz is established. The measured results show a shift in the lowest limit frequency, achieving a $|S_{11}|$ lower than -10 dB from 64 to 75 GHz (15.8% impedance bandwidth). These values obtained for the measured reflection coefficient are greater than the simulation results. The reason is that the
Figure 6: Manufactured prototype: (a) forming layers and assembled prototype, (b) detail of the modification of the curvature radius by the pressing screw.

Figure 7: Measured S-parameters: (a) magnitude of the phase shifter for the complete range of radius of curvature and comparison with the simulated results and, (b) measurement setup in WR10.

measurement setup in WR15, which uses 1.85mm coaxial to WR-15 waveguide transitions, is limited up to 66.5 GHz. Therefore, a measurement with the ZVA-Z110E Converters in WR10 has been carried instead, as it is shown in Fig. 7(b). An increase in the $|S_{11}|$ is expected because of the transitions between WR10 and WR15. For the sake of validation, a measurement with the setup in WR15 has also been done, in the range of 63 to 66.5 GHz, and it is observed the decrease in the reflection value approaching to simulation levels (green line in Fig. 7(a)). Furthermore, low insertion losses are obtained with a mean value of 1.7 dB and lower than 3 dB in the impedance bandwidth.

The measured phase shift is shown in Fig. 8. In order to assess the repeatability of the prototype, three consecutive measurements have been carried out. This test ensures that the metallic strip returns to its original position after being deformed by the tunning screw. The screw has a standard metric M1.6, whose pitch thread is 0.35 mm. Therefore, an increment in $b_{\text{ellipse}}$ of 0.05 mm implies approximately 0.14 screw turns. The measurement results present a good agreement with the simulation results providing the same dynamic range for the phase shift. The small discrepancies evidenced could be associated to approximating the real deformation of the metallic strip with an elliptical profile. Moreover, the repeatability of the measurements show the good performance of the flexible metallic strip to set the desired phase shift.

Finally, a comparison between the proposed phase shifter and other reconfigurable phase shifters in mm-wave
frequencies is illustrated in Table 1. The proposed reconfigurable phase shifter achieves a better performance in insertion losses and FoM (figure-of-merit) along the operating frequency than some of the reported tunable phase shifters. Some of them require a complex setup or a more complicated implementation of the tuning elements in the waveguide. By applying the gap-waveguide technology in the phase shifter design, more options in the location of the gap for the split waveguide is achieved in contrast with the traditional implementation using E-plane split waveguide. In addition, the required volume of the device is reduced compared to the commercial devices.

4. Conclusion

This paper presents the first mechanically reconfigurable phase shifter design in gap-waveguide technology for mm-wave frequencies. The gap-waveguide technology enables a low-complex prototype that allows the inclusion of a flexible metallic strip inside the waveguide. This element provides the reconfigurability behavior of the phase shifter. A prototype has been manufactured to validate the simulation design. The experimental results show an operational frequency bandwidth from 64 to 75 GHz with averaged insertion loss of 1.7 dB and a maximum dynamic phase shift of 250°.

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