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RESEARCH ARTICLE

Low-Loss Mechanically Tunable Resonator and Phase Shifters in Groove Gap Waveguide Technology

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ABSTRACT This research is focused on the design and realization of high-performance high-power variable phase shifters in groove gap waveguide technology. Specifically, it is shown that the unique characteristic of groove gap waveguides, which is its proper operation without the need for electrical connection between the top and bottom sections of the waveguide, can be used to design mechanically tunable devices. Using the proposed method, a mechanically tunable cavity resonator and phase shifters with a wide range of achievable phase shifts are presented. To validate the concept, a phase shifter with 540 degrees relative phase shift at 15 GHz is designed, fabricated, and measured. Moreover, a multi-layer version of the proposed phase shifter with stationary feed ports and improved performance is presented.

INDEX TERMS Mechanically tunable, cavity resonator, phase shifter, variable phase shift, GGWG technology.

I. INTRODUCTION

Variable phase shifters are used to achieve a dynamically tunable phase shift, which is required in many applications. A comprehensive comparison between mechanically and electronically variable phase shifters that highlights the pros and cons of each method is presented in [1]. In short, electronic variable phase shifters based on solid-state devices, ferrites or ferroelectric materials such as liquid crystals provide very fast switching [2], [3], however, they suffer from low power-handling and high insertion loss that can be as much as 4-6 dB in Ku band [2]–[5]. In contrast, the main limitation of mechanically tunable phase shifters is their relatively long switching time, which makes them inappropriate for fast military or airborne applications. However, phase shifters based on this method benefit from

low-loss, wide-band performance, high linearity, and high power-handling capability [1], which are desirable in many applications.

The application of metallic hollow waveguides for the realization of mechanically tunable devices results either in poor performance due electromagnetic (EM) power leak or complicated and costly structures [6]. To tackle the problem, tunable phase shifters based on groove gap waveguide (GGWG) technology have been presented, recently [7]–[10]. GGWGs loaded with slabs of dielectric or liquid crystal were presented in [7] and [8], respectively. However, the proposed phase shifters suffer from a relatively high insertion loss. To address this issue, variable phase shifters based on changing the width (and as a result, the phase constant) of GGWGs were presented in [9] and [10]. The main limitations of these phase shifters are: 1) To achieve high values of phase shift the width of the waveguide has to be drastically changed, which results in a significant discontinuity and impedance

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mismatch. 2) Reducing the width of the waveguide also increases the cutoff frequency and consequently reduces the single-mode operating bandwidth of the device. 3) To avoid the mismatch and limited bandwidth a relatively long waveguide has to be used. 4) Achieved phase shift is a non-linear function of the waveguide width, which is generally not desirable.

The phase of the transmission coefficient of a transmission line or waveguide can be changed either by changing the phase constant β or changing their physical length. While the first method has been widely used both in transmission line and waveguide technologies, the latter method has rarely been used in waveguides. This is because changing the length of a waveguide to achieve a mechanically tunable resonator or phase shifter, while a theoretically trivial method, its practical implementation is not as trivial, and may result in the leak of EM power from the structure and need for a movable output port. To address this issue, recently an array of mechanical phase shifters based on changes in the length of a vertical GGWG has been proposed in [11] and [12]. However, the work is thoroughly focused on the realization of an array of phase shifters for feeding a waveguide slot array antenna, resulting in the following limitations and complexities: 1) To achieve a phase shift, the lower metallic surface and as a result, the input feed port needs to be rotatable. Using a flexible coaxial cable between the signal source and the input port may not be a good solution since the cable and the connections may wear over time due to the movements. An alternative is to use a rotary joint, which adds to the cost and complexity of the structure. 2) A two-layer gap waveguide, composed of a vertical GGWG in the lower layer and a ridge gap waveguide (RGWG) for the upper layer, is used. Hence, an elaborate two-level GGWG-RGWG transition is required to transform the horizontally polarized EM field in the vertical GGWG, to the vertically polarized EM field in the upper RGWG. 3) The required sliding short-circuit termination is formed using an E-shape stopband filter, which adds to the complexity of the design.

Considering the limitations of the phase shifters presented in [9]–[12], this research is focused on the design and realization of simple mechanically tunable phase shifters in which:

- 1) The issue of the EM power leak from the sliding termination in conventional waveguides is addressed by using GGWGs rather than conventional rectangular waveguides.
- 2) The need for a movable output port, which is not easily realizable in conventional waveguides, is addressed.
- 3) Even the need for a movable input/output port is bypassed by proposing a multi-layer GGWG phase shifter.
- 4) A perfect linear relation between the phase shift and actuation is attained.
- 5) In contrast to the phase shifters presented in [9], [10] where attaining a phase shift by changing the waveguide width results in a narrower operating

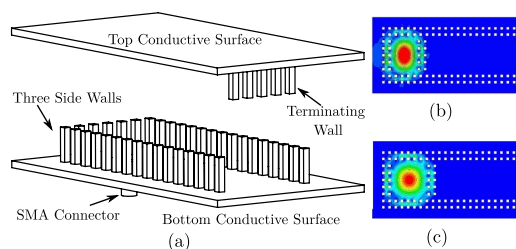


FIGURE 1. (a) An illustration of the proposed tunable GGW cavity resonator, and the electric field distributions (using eigen analysis) of the tunable resonator for two different lengths corresponding to different resonance frequencies at (b) $f = 14.3$ GHz and (c) $f = 12.6$ GHz.

bandwidth, the phase shifters proposed in this study benefit from fixed operating bandwidths.

- 6) Last but not least, the proposed phase shifters benefit from an extremely simple structure and relatively compact size.

II. MECHANICALLY TUNABLE RESONATOR AND PHASE SHIFTER IN GAP WAVEGUIDE TECHNOLOGY

As mentioned in the introduction, to address the difficulties associated with the fabrication of the classical waveguides, several variations of gap waveguides including GGWG have been proposed. The principle of operation in all variations is to replace the sidewalls of a conventional waveguide with a parallel PEC-PMC structure. Normally, the required PMC sections are realized by implementing arrays of quarter-wavelength metallic pins on one of the parallel plates (say bottom plate) of the waveguide while the other parallel plate is left as a bare PEC surface [13]. Therefore, as long as the vertical distance between the two plates is fixed, a relative horizontal displacement between the top and bottom sections of the gap waveguide does not affect its waveguiding behavior. However, as will be shown in the following as a general method for the realization of mechanically tunable devices, if part of the PMC array that forms a gap waveguide structure is implemented on one of the conductive surfaces and the rest of the PMC array is implemented on the other conductive surface, a relative mechanical displacement of the two parallel conductive surfaces can be used to change the shape, size, or some other geometrical properties of the structure. Accordingly, the EM characteristics of the device can be mechanically altered.

For instance, a tunable GGWG cavity resonator based on the proposed method is illustrated in Fig. 1(a). The coaxial input port and the three PMC sidewalls of the cavity are implemented on the bottom surface, whereas the PMC array that forms the terminating sidewall is realized on the top plate. In this configuration, a relative displacement of the top and bottom plates in the waveguide longitudinal direction x changes the length of the gap waveguide cavity. Therefore, its resonance frequency is altered. In other words, the structure is a simple mechanically tunable resonator, which is appropriate for high-power low-loss applications with very wide frequency tunability. Note that to have an acceptably

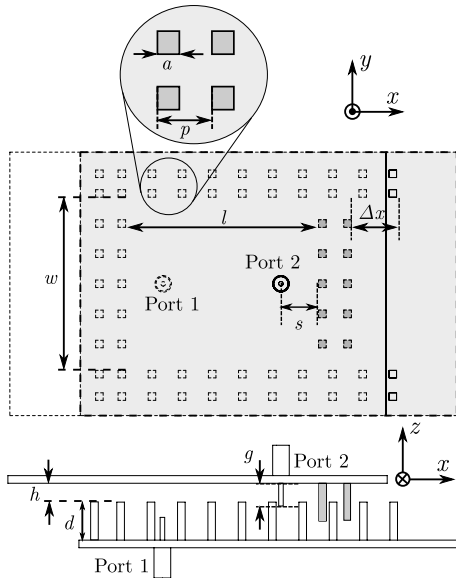


FIGURE 2. An illustration of the top and side views of the proposed transmission-type phase shifter.

low leak from the sidewalls, usually at least two rows of pins are required. However, to have a clear demonstration, only one row of pins is illustrated in this figure. Simulated electric field distributions of the tunable resonator for two different lengths corresponding to two different resonance frequencies are shown in Figs. 1(b) and (c).

With a simple but efficient modification, the structure can be converted to a variable phase shifter. Illustrations of the top and side views of such a phase shifter are depicted in Fig. 2, where three sidewalls and the input port are implemented on the bottom conductive surface, whereas the output port and the terminating wall are devised on the top conductive surface of the structure. In this configuration, the distance between each port and its corresponding terminating wall is fixed. However, a relative displacement Δl of the top and bottom surfaces changes in the length of the waveguide and consequently a phase shift $\Delta\phi$ is achieved that can be analytically calculated as

$$|\Delta\phi| = \sqrt{\left(\frac{2\pi f}{c}\right)^2 - \left(\frac{\pi}{w_{eff}}\right)^2} \times \Delta l, \quad (1)$$

where

$$w_{eff} = \frac{\pi}{\sqrt{k_0^2 - \beta^2}}. \quad (2)$$

is the effective width of the GGWG. The equation shows that the phase shift is a linear function of the actuation distance Δl .

III. NUMERICAL AND EXPERIMENTAL RESULTS

To validate the concept, a Ku-band variable phase shifter is designed, and its performance is numerically studied. The designed structure is also fabricated, and measured.

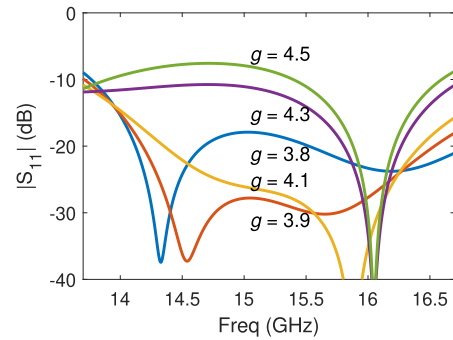


FIGURE 3. Input impedance matching of a pair of coaxial-to-GGWG transitions for different values of the probe length g while $s = 3.5$ mm.

A. GGWG DESIGN AND COAXIAL-TO-GGWG TRANSITION

A preliminary step for presenting the numerical and experimental performance of the proposed phase shifter is the design of a GGWG structure with appropriate behavior across the frequency band of interest. Therefore, the dimensions and period of array of pins should be accurately designed to achieve a bandgap over the operating frequency of the phase shifter, which is considered to be from 14.5 GHz to 15.5 GHz. The dimensions of the bed of nails and the GGWG are determined following the practical guidelines presented in [14], [15]. The dimensions as denoted in Fig. 2 are: pin width $a = 1$ mm, pin height $d = 6.25$ mm, period $p = 2.7$ mm, $h = 1$ mm. Then, the gap waveguide is formed by introducing a groove of width $w = 15.8$ mm, which corresponds to a WR62 standard rectangular waveguide for operation in the frequency range of 12.4-18 GHz. The dispersion diagram of the bed of nails and the GGWG are identical to those presented in [16], [17].

Once the GGWG is designed, suitable feed structures also must be devised. As will be shown in the following, using a pair of coaxial-to-waveguide transitions can be a simple and efficient method for feeding the GGWG. Such transitions are shown as part of the illustration of Fig. 2. The effect of several parameters, such as the length and shape of the probe, and its spacing from the terminating wall of the waveguide as well as the length of probe that is covered with Teflon can be studied to optimize the impedance matching. In this case, however, a bare probe is used and only the length of the probe g and its spacing from the terminating wall s are utilized. For demonstration, the input impedance matching of the coaxial-to-GGWG transition for different values of the probe length g while $s = 3.5$ mm is shown in Fig. 3. Considering the presented parametric study, $g = 3.9$ mm and $s = 3.5$ mm are chosen for the length and the position of the coaxial probes.

B. VALIDATION OF THE PROPOSED PHASE SHIFTER

Photographs of the fabricated prototype are depicted in Fig. 4. Note that the bottom surface of the structure is also equipped with a pair of corrugated rims to maintain the fixed gap between the top and bottom surfaces while allowing displacement only in the longitudinal direction of

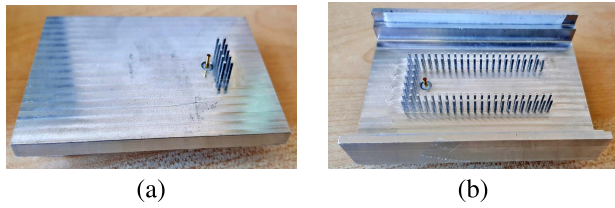


FIGURE 4. Photographs of the (a) Upper section, and (b) bottom section of the fabricated prototype.

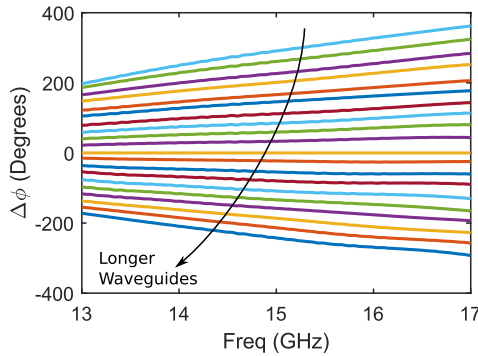


FIGURE 5. Measured phase shift $\Delta\phi$ of the proposed phase shifter for different values of waveguide length l from 2 mm to 40 mm in steps of 2 mm.

the waveguide. Note that since the required mechanical motion is a simple one-dimensional linear displacement, it can be easily achieved by a custom-made setup that includes a stepper motor. Alternatively, one can use an off-the-shelf 1D motorized translation stage. With the aim of providing a proof of concept, and also to accurately measure the relation between the achieved phase shift and the amount of displacement, a manual translation stage is used to displace the top movable section of the prototype.

The measured phase shifts $\Delta\phi$ of the prototype for different lengths l from 2 mm to 40 mm with respect to a reference gap waveguide with a length of $l = 20$ mm is shown in Fig. 5. For comparison, the absolute values of measured and simulated phase shifts $|\Delta\phi|$ at $f = 15$ GHz versus the longitudinal displacement is also depicted in Fig. 6. The figure shows very good agreement between the simulated and measure phase shifts. Moreover, the results clearly show an achievable phase shift of 540 degrees at 15 GHz, which is sufficient for most applications. Note that the limited achievable phase shift is due to the limited length of the fabricated prototype. In other words, much higher ranges of phase shift can be achieved provided a longer waveguide is used. The figure also shows that the phase shift has good linearity and a low slope over the frequency band, especially for smaller values of the phase shifts. It should be borne in mind that the demonstrated frequency band is extremely wide. Practical applications at the Ku band are limited to much narrower bandwidths over which the achieved phase shift versus frequency is almost constant.

Fig. 7 shows the measured transmission and reflection coefficients of the fabricated prototype for different lengths l of the waveguide from 2 mm to 40 mm. The results show

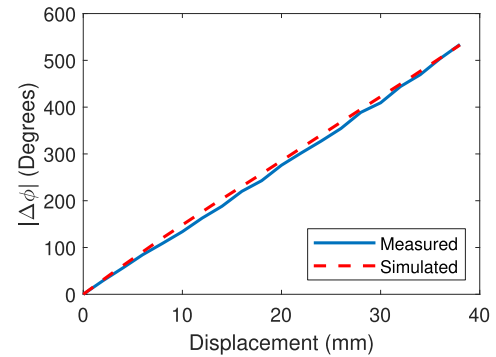


FIGURE 6. Measured phase shift $\Delta\phi$ of the proposed phase shifter for different values of waveguide length l from 2 mm to 40 mm in steps of 2 mm.

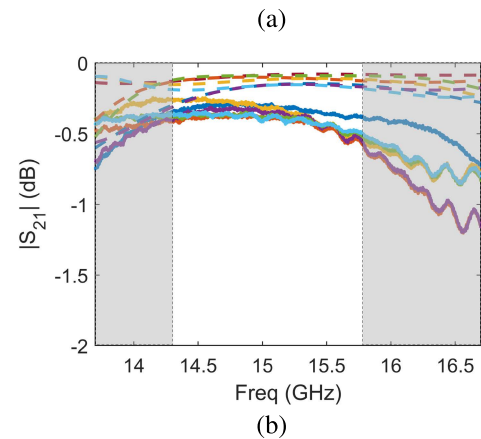
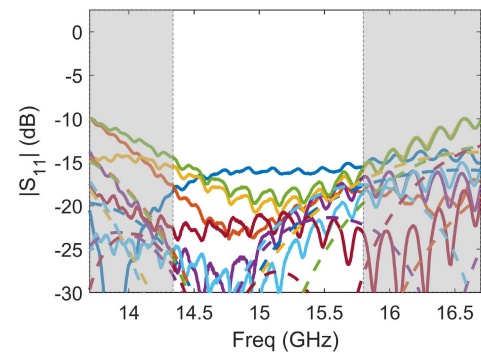


FIGURE 7. (a) Transmission coefficients, and (b) reflection coefficients of the proposed phase shifter for different lengths of the waveguide from 2 mm to 40 mm. Measurement results are shown by solid lines, while simulation results are depicted using dashed lines.

that the structure provides a measured return loss (RL) better 15 dB over a 1.4 GHz frequency band from 14.35 GHz to 15.75 GHz (and RL better than 10 dB over a 3 GHz band from 13.7 GHz to 16.7 GHz). The measured insertion loss (IL) over the frequency band of 14.35-15.75 GHz is better than 0.5 dB (and better than 1.2 dB over the frequency band of 13.7-16.7 GHz). It is important to note that much better return loss can be achieved if a smaller range of phase shifts is required.

Analysis of the peak power handling capability (PPHC) due corona discharge effect is another important topic that will be briefly covered in the following. Due to the presence

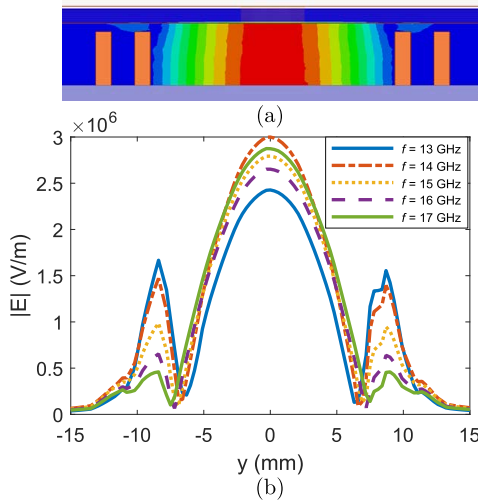


FIGURE 8. Distribution of the electric field at $f = 14$ GHz and input power $P = 470$ kW in the (a) cross section of the waveguide, and (b) along a line above the bed of nails at different frequencies.

of a strong electric field in the free space above the bed of nails the PPHC of a GGWG can be much lower than that of a conventional waveguide with the same dimensions [18]. To avoid this issue, in this work, the dimensions and period of the bed of nails are selected such that the field above the bed of nails is much smaller than the maximum E_{10} field inside the groove waveguide (See Fig 8(a)). Therefore, the PPHC of the phase shifter can be calculated using

$$P = \frac{1}{4} \frac{\sqrt{1 - k_c/k_0}}{\eta_0} |E_{10}|^2 \times w_{eff} \times (d + h), \quad (3)$$

where the effective width w_{eff} is found from (2). For the GGWG used in this study, at $f = 14$ GHz the effective width is $w_{eff} = 15.25$ mm. Ionization breakdown in dry air occurs when a critical field strength, which is 3 MVolts/m at 1000 mbar, is exceeded. Considering this critical field strength the calculated PPHC of the phase shifter using (3) is 470 kW, which is only 6% less than the PPHC of the WR62 waveguide. To validate (3) and the calculated PPHC value, EM simulation of the structure when an input power of $P = 470$ kW is applied is conducted, and the E fields in the cross-section of the waveguide at different frequencies are observed. As shown in Fig 8(b), at $f = 14$ GHz, the maximum electric field is $E = 3$ kV/m, which is exactly equal to the critical field strength of dry air at 1000 mbar. In short, the PPHC of the phase shifter calculated using (3), which is confirmed by the EM simulations, is 470 kW.

IV. MULTI-LAYER TUNABLE PHASE SHIFTER

Despite achieving literally unlimited phase shift, high power-handling, and relatively low insertion loss, the proposed phase shifter in the previous section (as well as those presented in [11], [12]) have an important practical limitation. In the presented structures, the input or output port is mounted on a moving conductive plate. That means the phase shifter cannot be directly connected to a pair of fixed devices. Using flexible

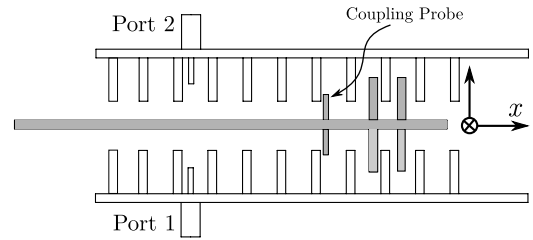


FIGURE 9. An illustration of the side view of the proposed improved phase shifter with stationary ports.

coaxial cables might address this issue for applications where occasional low-speed phase shifts are required, however, the method is not appropriate when high-speed or frequent phase shifts are needed. To overcome this problem, and also to improve the performance of the phase shifter in terms of the achieved phase shift versus actuation $\Delta\phi/\Delta x$, a multi-layer phase shifter is presented in this section.

An illustration of the proposed phase shifter is shown in Fig. 9. The structure is composed of three conductive surfaces. Similar to the phase shifter of Fig. 2, arrays of pins are implemented on the bottom conductor to form the three sidewalls of a GGWG, whereas the terminating wall is implemented on the middle conductive layer. Similarly, another GGWG is formed between the middle and the top conductive surface. Three sidewalls of this gap waveguide are implemented on the top plate, whereas the terminating wall is mounted on the middle plate. Therefore, two identical waveguides are formed between the three plates. The lower waveguide is fed from Port 1, which is mounted on the bottom plate. The wave propagates along the waveguide and is coupled to the upper waveguide through a pair of coupling probes, and finally, it reaches Port 2.

In this configuration, the middle plate together with the waveguides' terminations and the coupling probes, which are implemented on this plate can be moved freely in the x direction. Therefore, the overall path of the guided wave, and thereby the phase of the transmitted wave from Port 1 to Port 2 is changed. It is very important to note that in contrast to the phase shifters presented in [11], [12], in this configuration both input and output ports are stationary, thus no need for flexible cables or expensive rotary joints. It is also worth highlighting that, in this structure, when the middle plate is displaced for a distance Δx , the variation of the waveguide's length Δl is twice that, i.e., $\Delta l = 2\Delta x$. That means the rate of phase shift versus displacement $\Delta\phi/\Delta x$ in the proposed two-layer phase shifter is double that of its single-layer counterpart presented in the previous section. As a result, a phase shift of 540 degrees at $f = 15$ GHz is obtained by a displacement of $\Delta x = 20$ mm (rather than 40 mm). Note that the required actuation distance for the phase shifters based on the waveguide width [9], [10] is relatively smaller. However, this feature is achieved at the cost of using a much longer waveguide. In contrast, the phase shifters presented in this study are much shorter.

TABLE 1. A comparison between the proposed phase shifter and state-of-the-art low-loss high-power-handling variable phase shifters.

Reference	Technology	Frequency (GHz)	FBW (%)	RL (dB)	IL (dB)	$\Delta\phi_{max}$ (Degrees)	Fabrication Complexity	Scalability	Active length for 360° phase shift †
[6]	Hollow Waveguide	15	-	15	0.25	360	Relatively Complex	Relatively Difficult	$6.95 \lambda_0$
[8]	RGWG + Liquid Crystal	21-27	25	12	5.5	387	Moderate	Very Lossy	$4.9 \lambda_0$
[9]	GGWG	64-75	16	12	3	250	Moderate	Relatively Difficult	$7.4 \lambda_0$
[10]	GGWG	12-17	34.5	15	0.6	524	Low	Easy	$4.5 \lambda_0$
[11], [12]	GGWG	29-31	7.5	12	1	180	Relatively Complex	Easy	$1.36 \lambda_0$
This work	Single-Layer GGWG	14.35-15.75	9.3	15	0.5	540*	Low	Easy	$1.22 \lambda_0$
This work	Two-Layer GGWG	14.3-15.8	10	15	0.25	540*			$0.66 \lambda_0$

*This is the maximum phase shift achieved by the fabricated prototype. The actual maximum achievable phase shift is literally unlimited.

† The length of waveguide excluding the waveguide-to-coaxial adapters.

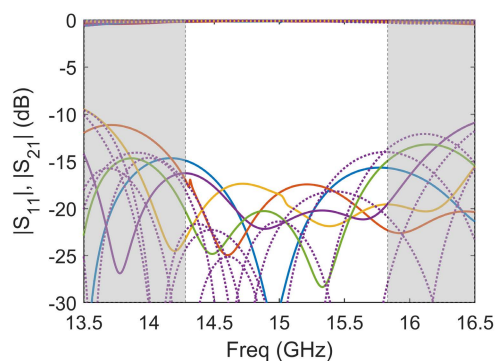


FIGURE 10. Simulated transmission and reflection coefficients of the proposed two-layer phase shifter for different lengths of the waveguide from 2 mm to 20 mm. Solid lines are obtained using HFSS, while dotted lines are from CST Microwave Studio.

Fig. 10 shows the simulated transmission and reflection coefficients of the proposed two-layer phase shifter for different lengths of the waveguide from 0 mm to 20 mm. The simulation results using HFSS show a return loss better 15 dB and an insertion loss better than 0.25 dB over a 1.5 GHz frequency band from 14.3 GHz to 15.8 GHz. The phase shifter can be used over a much wider bandwidth of 3.3 GHz (13.6 GHz-16.9 GHz) with a return and insertion losses better than 10 dB and 0.6 dB, respectively. To confirm the validity of the HFSS results, the structure is also simulated using a CST Microwave Studio. The results obtained from CST, which are shown with dotted lines in Fig. 10, are in good agreement with those from HFSS (shown with solid lines).

A brief comparison between the proposed phase shifters in this work and variable high-power phase shifters in most recent studies is presented in Table 1. In short, the comparison shows that the characteristics of the proposed phase shifter are comparable to the state-of-the-art phase shifters while providing a superior achievable phase shift, having simple design, high power-handling, stationary ports, and linear and wideband behavior. Note that the maximum phase shift of 540 degrees corresponds to the fabricated prototype. The phase shifter can be designed for a longer length to achieve much higher phase shifts. The limitation would be the maximum tolerable insertion loss. However, since the waveguide structure is very low-loss, the actual maximum

achievable phase shift is literally unlimited. The last column of the table compares the active length of a 360° phase shifter, i.e. the length of the phase shifter (excluding the waveguide-to-coaxial adapters) to achieve a 360° phase shift. To have a fair comparison, the lengths are expressed in terms of the free space wavelength λ_0 . The comparison shows that the proposed phase shifter, especially the two-layer variant, benefits from a significantly smaller size.

V. CONCLUSION

A novel method for the realization of mechanically tunable passive microwave devices based on gap waveguide technology has been presented. It has been shown that the unique feature available in gap waveguide technology, i.e., proper waveguiding without the need for electrical connection between the top and bottom conductive surfaces of the waveguide, can be used for the design of mechanically tunable microwave devices. On that basis, a cavity resonator with tunable resonance frequency as well as reflection- and transmission-type variable phase shifters with literary unlimited phase shift have been presented. To validate the concept, a transmission-type phase shifter with a minimum variable phase shift of 540 degrees at 15 GHz has been designed and fabricated, and its performance has been experimentally measured. Furthermore, a multi-layer version of the phase shifter with stationary input and output ports and improved performance has been demonstrated.

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