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Variable High Precision Wide D-Band Phase Shifter

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ABSTRACT This paper proposes a new concept of designing compact high precision millimeter-wave wideband variable phase shifters. The phase shifter is implemented with a stacked shim with extremely short length of 0.9 mm and two waveguide flange adaptors with length of 0.5 mm. High precision phase shifting is achieved over entire D-band (110–170 GHz) by rotating the shim 90 degrees from aligned to perpendicular with consistent impedance matching performance. In addition, a glide-symmetric holey electromagnetic bandgap (EBG) structure is adopted to avoid wave leakage from the gap between the shim and the flange adaptors. A proof-of-concept (PoC) demonstrator is designed, manufactured, and tested. The measured results show that the designed stacked shim phase shifter with embedded EBG structure ensures return loss higher than 10 dB across 110–170 GHz with a 75 μm airgap between waveguide flanges. The studied phase shifter provides a 0.88° phase shifting with each degree of mechanical rotation. The fabricated PoC phase shifter has a worst-case insertion loss of 0.92 dB and a return loss of 20 dB across the entire 110–170 GHz band and a maximum phase shift of 30°. At 10° phase shifting, the measured insertion loss is lower than 0.52 dB, and return loss is higher than 23 dB, respectively.

INDEX TERMS D-band, electromagnetic bandgap (EBG), glide-symmetric, millimeter-wave, phase shifter.

I. INTRODUCTION

Nowadays, cost-sensitive industries such as telecommunication, autonomous vehicles, security imaging have started investigating systems working on frequencies in D-band from 110 to 170 GHz to achieve higher data rate or higher resolution performances. The operation frequency is approaching half f_{MAX} value of most commercial semiconductor processes in D-band frequencies, where f_{MAX} is the frequency at which the transistor's power gain is equal to one. Operating at such bands results in lower energy efficiency and higher design costs, and the output power P_{out} reduces dramatically following that $P_{\text{out}} \propto f^{-2} \sim f^{-3}$, where f is the operating frequency [1]. New transmission line technology in D-band frequencies with low loss and low cost is a key point to be studied for commercializing millimeter-wave applications.

Substrate based transmission lines such as microstrip lines and substrate integrated waveguides (SIW) usually suffer from relatively high loss. The dielectric constant variations of microwave substrate contributes to the system performance and affects the yield of the final product [2]. In order to get the lowest loss of transmission lines in the millimeter-wave band, air-filled waveguides are the preferential and advantageous choice for space communication systems, high precision instrumentations, and radar applications, because of their substrate-less property.

However, waveguide sections are often manufactured with expensive metal machining process to avoid airgap. One approach to reducing cost is to use a micro-electromechanical system (MEMS) technology of excellent geometry accuracy and surface roughness. For example, a phase shifter up to 550 GHz has been demonstrated [3]. Nevertheless, it only becomes cost-effective when the processing volume is large enough to cover the cleanroom operation expense.

Another cost reduction approach is to incorporate an electromagnetic bandgap (EBG) structure into the design. A lower precision and cheaper machining process can be used to fabricate the design, which can suppress unwanted

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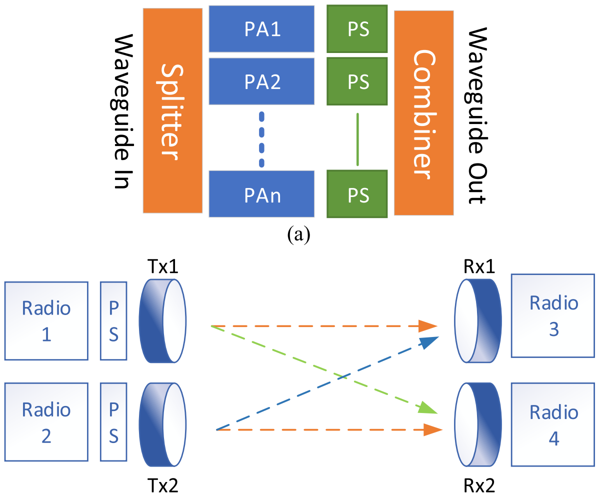


(a)

(b)

FIGURE 1. **Applications for compact, high precesion PSs: (a) High order power combined PA modules; (b) LoS MIMO Links.**

leakage radiation. Gapwave technologies are proposed and a bed of nails structure is introduced to guide the wave in waveguides [4]. When the frequency is above 100 GHz, the size of nails shrinks thus the cost and manufacture difficulty increases accordingly. Glide symmetric holes is an alternative EBG structure to suppress the unwanted wave propagation [5]. It is easier to manufacture the holes by chemical etch with lower manufacturing cost. A planar waveguide is demonstrated at D-band [6].

Wideband phase shifter is important in modern millimeter-wave systems, which can be elaborated with two examples. First, the power combing module is often of great interest to achieve higher output power in millimeter-wave band. As shown in Fig. 1(a), multiple power amplifier Monolithic Microwave Integrated Circuits (MMIC) are packaged with a power splitter and a combiner to achieve high output power. Practical issues such as wirebond inconsistency, process variations, and assembly accuracy will affect the output waveform phase of each packaged MMIC. Even several degrees of phase mismatch between each MMIC output waveform will result in a decrease of final output power. In this case, a compact mechanical turned high precision phase shifter is usually adopted for post-assembly adjustment to maximize the power combing efficiency. The phase shifter can significantly minimize the loss of the whole MMIC, the overall size, and the cost of the power combined amplifier module.

Secondly, the compact phase shifter also finds its applications in line of sight (LoS) MIMO systems, where several radios and antennas are used to reach high link capacity. As demonstrated by Ericsson, an 8 × 8 LoS MIMO is established with over 100 Gbps [7]. The antennas must be placed accurately with a certain separation distance. With such deployment, receiver 1 (Rx1) receives signals from transmitter 1 (Tx1) and transmitter 2 (Tx2) with 90-degree out-of-phase, thus these radios (radio 1 and radio 2) are orthogonal due to spiral separation. The capacity (in bits/s/Hz) of the LoS MIMO can be written as:

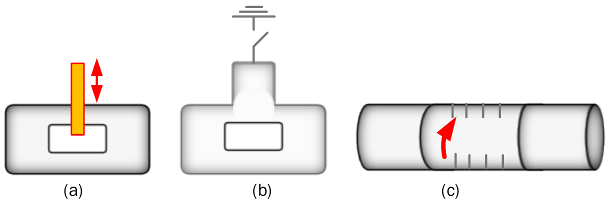


FIGURE 2. **Different mechanical tuned waveguide phase shifter principles.**

$$C = log_2(det(I_N + \rho HH^T/N)), \tag{1}$$

where I_N is the N × N identity matrix, ρ corresponds to the signal-to-noise ratio (SNR), H is the normalized free-space channel response matrix, and T denotes the conjugate transpose [8]. However, even though MIMO equalizer is often used to cancel the non-orthogonal interference introduced by non-ideal antenna installation [9], the capacity is reduced and cannot be regained by any process when the phase shift is non-ideal. The phase mismatch from deployment inaccurate can be adjusted post-installation with high precision by inserting the phase shifters between transmitter radios and antennas to optimize system performance, as shown in Fig. 1(b). In this circumstance, the group delay property is important for such phase shifter to avoid introducing dispersion to the wideband modulated signal.

It should be noticed that a small phase adjustment less than 10° is sufficient for both cases. Therefore, high precision is sometime more important for the phase shifter rather than the maximum turning range. Furthermore, because the phase shifting is only required once at the installation/calibration stage, the mechanically tuned phase shifter is preferred over electrical phase shifter for cost consideration.

Air-filled waveguide phase shifters made with different principles are illustrated in Fig. 2. One method to make it is inserting a dielectric fin [10], a metal fin [11] or an EBG structure [12] into the waveguide. The insertion depth of the fin determines the additional phase shifting in the waveguide as shown in Fig. 2(a). The phase shift is not linearly proportional to the insertion depth. Several micrometers offset of the fin at a certain position can result in tens of degree of phase shifting. This makes it difficult to achieve high precision adjustment in the field. The size of the fin is comparable or larger than the waveguide cross-section, thus it is hard to make it compact. MEMS technology is used to implement phase shifter by switching different open/short stub sections in order to apply phase shifting, as shown in Fig. 2(b) [3]. Another phase shifter based on waveguide rotation is introduced in [12]. In this phase shifter, several quarter-wavelength sections with iris corrugation are required as shown in Fig. 2(c), which is hulking for some applications.

In this paper, we presented a novel phase shifter concept based on twist metal shim principle. A proof-of-concept high precision phase shifter demonstrator is designed, fabricated, and tested in D-band from 110 to 170 GHz with a

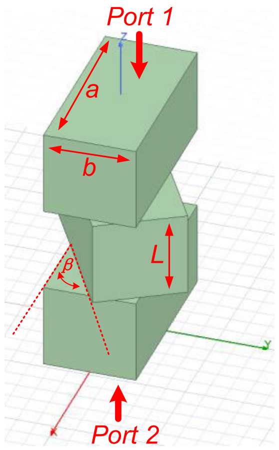


FIGURE 3. Proposed rotational waveguide phase shifter simulation mode.

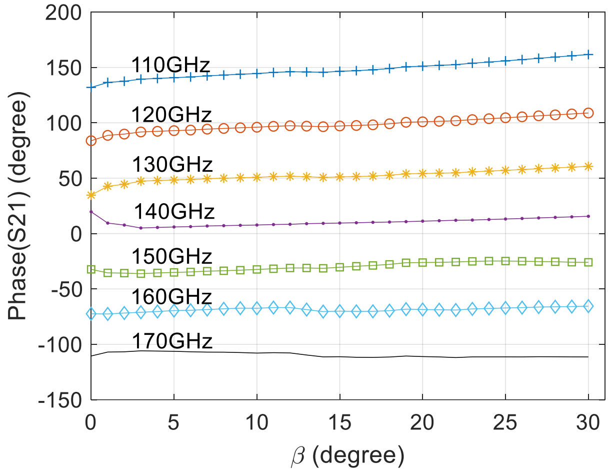
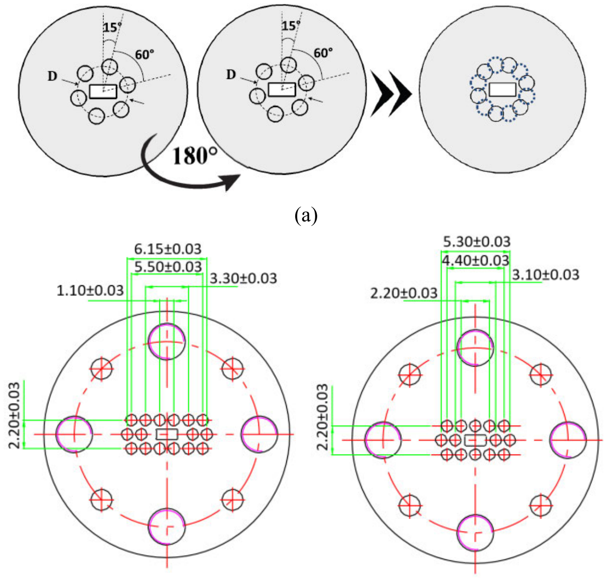


FIGURE 4. Simulated phase shift at different rotation angles of the proposed twisted waveguide phase shifter.

state-of-the-art compactness of 0.9 mm, which corresponds to an electrical length of 0.8λ, where λ is the guided wavelength. The paper is organized as follows: the principle of the twisted waveguide phase shifter is explained in section II after the introduction. In section III, the laboratory verification result is presented and discussed. Finally, the paper is concluded in section IV.

II. TWISTED WAVEGUIDE PHASE SHIFTER DESIGN

The basic idea of the phase shifting concept is shown in Fig. 3, where the air-filled inner wall is presented. A small section of a rectangular waveguide with a length L of 0.88 mm is inserted between standard waveguide flanges (a = 1.65 mm, b = 0.825 mm). When this section is rotation along the wave propagation axis Z with an angle β. The rotation of the middle section increases the length of wave travel path, thus phase shifting is introduced. Simulation is performed by using of Ansoft HFSS software based on this ideal model and the results are plotted in Fig. 4



(a)

(b)

FIGURE 5. EBG holes for millimeter wave leakage suppression for airgap between waveguide flanges. (a) rotational EBG holes [5]; (b) proposed offset EBG hole configurations (unit:mm).

To allow free rotation of the center section, air gaps will appear at both sides of the movement section, which will cause electromagnetic wave leakage. Even several micrometer air gap can result in bandwidth reduction and huge loss in D-band frequencies. A glide symmetry holes are milled on both flanges with a rotational offset relative to each other as illustrated in Fig. 5(a) [5]. In our case, such concept is not applicable because the rotation of the section would break the electrical bandgap.

We have proposed a modified EBG structure for our phase shifter, as shown in Fig. 5(b). There are two EBG hole configuration A (left) and configuration B (right). The EBG holes are placed around a standard WR-6.5 waveguide opening (1.65mm × 0.88mm) and the pitch of the holes are marked in this figure. Configuration A and B has different hole placements. When these two sides facing toward each other, all holes are offset toward its counterpart at arbitrary β to maintain EBG. The diameter and the depth of EBG holes are 0.9 mm and 0.4 mm, respectively. The rotation section metal shim thickness is 0.9 mm with different EBG hole configurations on both sides. The EBG holes can be realized either by drilling [5] or chemical etching [6]. The fabricated PoC photo is shown in Fig. 6. The diameter of the shim is 19 mm. Several through holes are opened for alignment pins and screws, so the shim can be easily attached to a standard waveguide flange.

Simulation is performed when waveguide flanges are placed with 75 μm airgap in between. The simulated S-parameter results are plotted in Fig. 7. When no EBG holes are embedded, return loss is lower than 15 dB at 135 GHz, 150 GHz and 170 GHz, respectively, due to unwanted radiation between the airgap. When EBG structure is used, return loss remains higher than 20 dB through entire waveguide band 110-170 GHz. The insertion loss with or without the EBG holes keeps the same. This evidences the effective

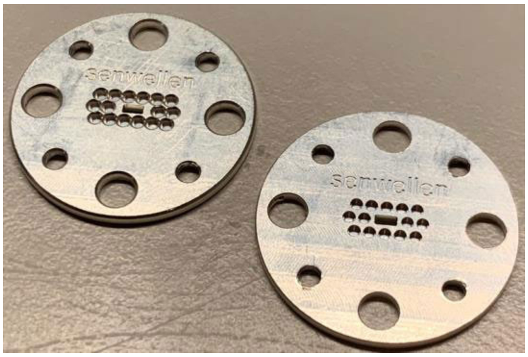


FIGURE 6. A photo of fabricate phase shifter.

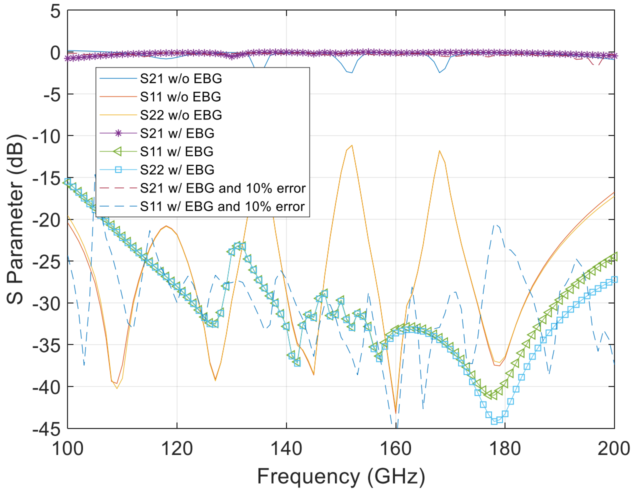


FIGURE 7. Simulated S-parameter with and without EBG holes with 75 μm airgap between flanges.

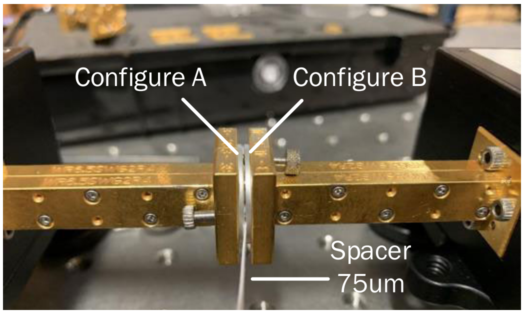
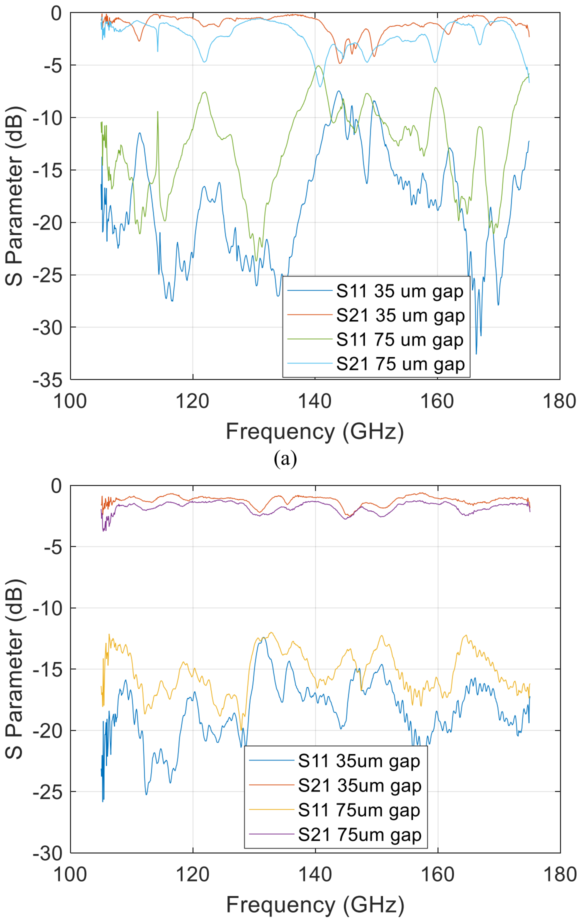


FIGURE 8. A photo of measurement setup with 75 μm air gap.



(a)

(b)

FIGURE 9. Measured S-parameter results: (a) without, and (b) with the proposed EBG structure.

leakage suppression by using proposed EBG structure. 10% over etching on all EBG holes is also simulated to see how the performance changes with errors. It turns out the insertion loss and return loss keep almost the same when there is 10% manufacturing error.

III. LABORATORY VERIFICATION

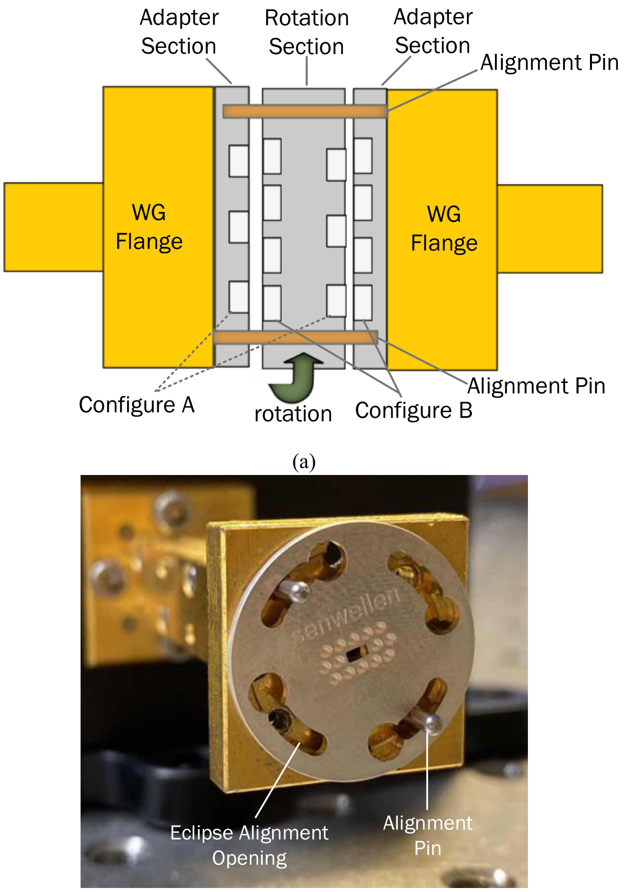
The manufactured PoC phase shifter is verified in two steps. Firstly, the proposed EBG holes are tested to check if that can ensure transmission when air gap is presented in an actual assembly. Secondly, the phase shifter is measured to examine the principle of twisted waveguide phase shifting.

A. LEAKAGE SUPPRESSION VERIFICATION

Two 450 μm thin metal shims with EBG hole configure A and hole configure B are attached to VDI WR-6.5 millimeter-wave extenders. A paper spacer is inserted between two metal shims and S-parameter is measured use Keysight PNA-X vector network analyzer. The photo of the measurement setup is shown in Fig. 8.

As a reference, the paper spacer is inserted between extender flanges without EBG shims. The measurement results when 35 μm and 75 μm are presented in Fig. 9(a). With 35 μm paper spacer, return loss is lower than 10 dB at 150 GHz and also an insertion loss of 5 dB is observed. For 75 μm paper spacers, both insertion loss higher than 5 dB and return lose lower than 10 dB can be seen at several frequencies within the waveguide band. The main cause of this poor performance is the radiation via airgap between flanges.

When the proposed EBG structure is used, as shown in Fig. 8, the measurement result is plotted in Fig. 9(b). For both 35 μm and 75 μm air gap cases, return loss is higher than 10 dB over the entire waveguide band 110-170 GHz. This test confirms the proposed EBG structure can be used to suppress unwanted leakage via the air gap between flanges.



(a)

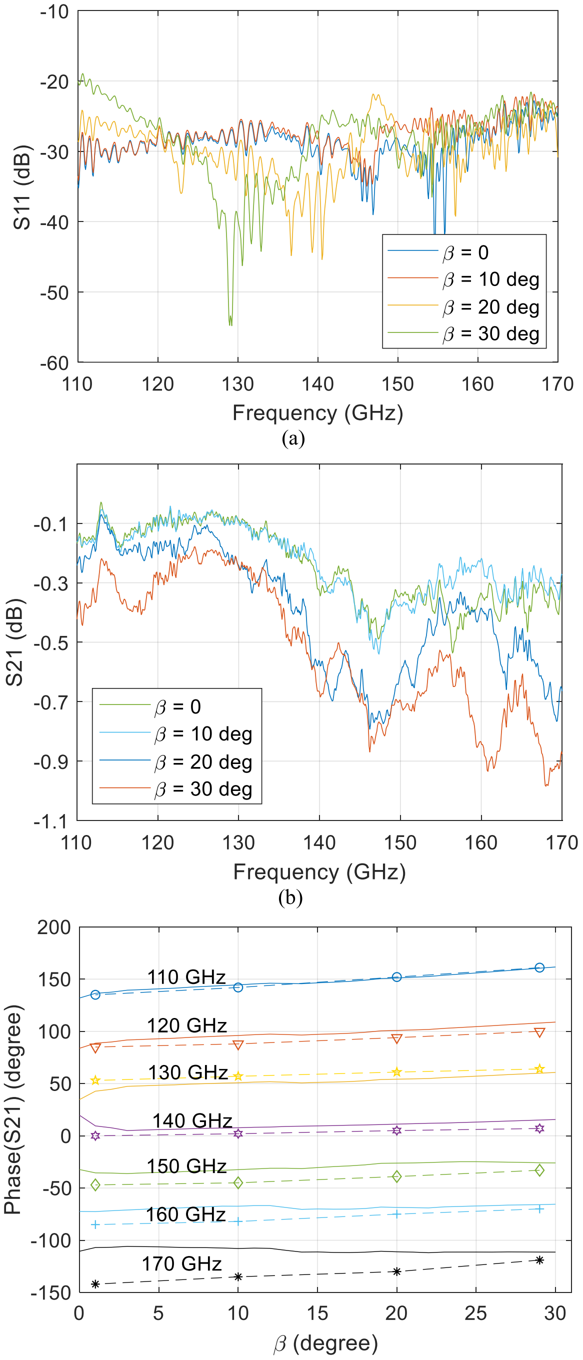
(b)

FIGURE 10. Diagram and photo of proposed PS: (a) diagram of proposed phase shifter using three SHIMs; (b) photo of the rotation section of the phase shifter.

In practice, air gap would be less than 20 μm [5] when the structure is carefully assembled.

B. PHASE SHIFTING VERIFICATION

The phase shifter PoC demonstrator (same dimension as previously mentioned leakage suppression shim) is fabricated and tested. It comprises three metal shims as shown in Fig. 10(a). Two 500 μm adapter sections have EBG holes at only one side and the other side is secured at extender flanges. Between these two adapter sections, there is a 900 μm rotation section with EBG holes at both sides. Between the adapter section and rotation sections, complementary EBG configurations are used to ensure leakage suppression. Alignment Pin from standard WG-6.5 waveguide flange (UG385) is used to keep these shims in place. The photo of the rotation section is shown in Fig. 10(b), eclipse shape opening is added on the rotation section, so this section can rotate 30 degrees along the wave propagation direction. As mentioned in previous sections, such rotation would introduce the wanted phase shift to the millimeter-wave signal. When a higher phase shifter is required, more rotation section can be used in cascade.



(a)

(b)

(c)

FIGURE 11. The measurement results of the proposed phase shifter: (a) return loss at different rotation angles; (b) insertion loss at different rotation angles; (c) normalized phase shift at different rotation angles.

The measurement result is shown in Fig. 11 when the rotation section is turned with $\beta = 0, 10, 20$ and 30 degrees, respectively. In Fig. 11(a), the measured S_{11} is shown. The return loss ($-S_{11}$) is higher than 20 dB for all the β in the entire waveguide band. This result is better than the previous case because the PoC is assembled carefully to avoid unwanted air gaps.

A higher β introduces more phase shifter but also higher insertion loss ($-S_{21}$) as shown in Fig. 11(b). The measured phase shift is presented in Fig. 11(c), different colors represent different frequency points from 110-170 GHz with

TABLE 1. **Comparison with other published millimeter wave phase shifters.**

Ref.	[12]	[14]	[3]	[11]	[13]	This Work
Frequency (GHz)	46-60	85-115	500-550	33-50	80-95	**110-170**
Phase shift range (degree)	180	90	315	0-360	0-150	**0-30**
Tuning Resolution	Fixed	Fixed	3.3-bit	2-bit	γ =2	**γ =0.82-0.9**
Insertion Loss (dB)	1	1.8	2-6	9	0.3	**0.52, β=10 °** **0.92, β=30 °**
Return Loss (dB)	14	10	17	8	18	**20**
Length (mm)	9	12.7	6.8	11.4	52	**1.9**
Electrical Length	1.59λ	4.2λ	11.9λ	1.57λ	15λ	**0.8λ**
Topology	Dielectric slab + EBG	Corrugated square wave	MEMS switch waveguide stub	PIN diode Switch	Rotate λ/4 Section	**Twisted SHIM**

10 GHz space. The phase shift is normalized with $\beta = 0°$ at 140 GHz as a reference. The solid lines are the simulated results (with 5 μm airgap) and the dashed lines with markers are measured results.

The measurement results deviated from the simulated ones due to the difficulty of estimate the airgap and shims relative position in practice. We define a ratio $\gamma = \Phi_{\mathrm{EM}}/\Phi_{\mathrm{mech}}$, where Φ_{EM} is the signal phase shifting and Φ_{mech} is a mechanical rotation angle. The measurement result shown from 110-160 GHz, the phase shift is linear with $\gamma = 0.82 - 0.9$. At the high end of the waveguide band 170 GHz $\gamma = 0.76$, which due to higher mode than TE10 starts to appear when $\beta > 15$ degree. The measurement result confirms the phase shifter concept can be used to provide high precision phase shifter across the entire waveguide band with very loss insertion loss.

The PoC phase shifter is compared with previously published results in Table. 1. In this table, fixed phase shifters [12], [14], discrete-state phase shifters [3], [11] and variable phase shifters [13] are included. This work exhibits the best compactness among these works. The total length is only 1.9 mm including waveguide flanges (0.9 mm excluded flanges) that corresponds to an electrical length of 0.8λ. The tuning resolution of discrete-state phase shifters is not sufficient for the application cases mentioned in the introduction. Both [13] and this work rotating a mechanical part to achieve phase shifting.

IV. CONCLUSION

In this paper, a novel millimeter-wave phase shifter concept is proposed. The proposed concept has a low loss due to its state-of-the-art compactness. Furthermore, EBG structures are used to eliminate unwanted leakage due to assembly and manufacture error. Therefore, this phase shifter can be manufactured with reduced cost and reach high production yield. We defined a ratio $\gamma = \Phi_{\mathrm{EM}}/\Phi_{\mathrm{mech}}$. For high precision adjustment, a small γ is preferred, so several degree adjustment is possible with limited mechanical rotation accuracy. Compared with the previous reported works, the proposed work has less phase shifter range but higher adjustment accuracy. In addition, when a greater tuning range is required, the proposed phase shifter can be easily cascaded into several stages. Even with 5-stages in use, the overall electrical length is only 4λ. The proposed concept is also applicable at sub-THz by scaling EBG holes, where alignment and assembly are more challenging in practice.

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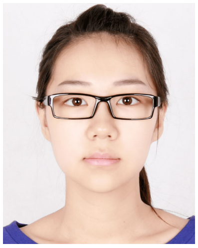

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