mm-Wave Low Insertion Loss SIW Phase Shifter Based on Liquid Metal Technology

Shaker Alkaraki, *Member, IEEE*, Zhishu Qu, James R. Kelly, *Member, IEEE*

***Abstract*— This paper presents proof of concept of first liquid metal (LM) based millimeter-wave (mm-wave) phase shifter that have very low insertion loss (IL) performance. The proposed phase shifter has a phase shift up to 360° with a phase resolution of 45°. The phase shifter operate on 26GHz 5G band and have IL performance of lower than 2.1dB. This enables the proposed phase shifters to have an excellent figure of merit (FoM) of 174.7°/dB at 26GHz. The proposed phase shifter has several advantages including the capability to be integrated with SIW based feeding network for mm-wave phased array antennas. The phase of the phase shifters is controlled by introducing vias formed of LM. When the via is required, the via hole is filled with LM and when the via is no longer required, the holes are emptied of LM. The proposed reconfiguration approach will be also applicable within a wide range of different reconfigurable mm-wave devices.**

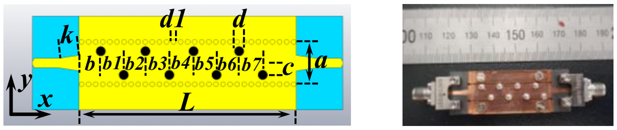
***Index Terms*— liquid metal, EGaIN, reconfigurable devices, mm-wave phase shifter, 5G, substrate integrated waveguide.**

I. INTRODUCTION

Phase shifters relied on CMOS approach are small in size and can be used in integrated circuits (ICs). However, those designs have high insertion loss (IL) and limited output power. The typical IL for a state-of-the-art CMOS based active phase shifter is much higher than 10 dB at Ka-band frequencies [1]-[4]. PIN diodes and GaAs FETs are widely used in phase shifters [5]-[6]. However, designs using GaAs FETs have limited radio frequency (RF) power handling capability [5]. Designs using PIN diodes have higher RF power handling capability, but they have relatively high IL [6]. Liquid metal (LM) attracts increasing attention due to its advantages of low IL, low harmonic distortion, and high RF power handling capability [7]-[9]. [10]-[11] has reported phase shifters using LM. For example, [10] presents a phase shifter using LM operates at 5.6 GHz with a phase shift of 67.2°. The LM phase shifter proposed in [11] achieves a limited phase shift of 180° with 2.3dB IL at 10GHz. The phase shifter in [11] employs switched line approach resulting in a complex design that has a large physical size and narrow bandwidth. One of the figure-of-merit (FoM) which is widely used to compare phase shifters [12] is given in (1).

$$FoM = \frac{\Delta\emptyset_{max}}{IL_{max}} \tag{1}$$

Where, $\Delta\emptyset_{max}$: is the maximum phase shift and IL_{max} is the maximum IL, at a particular frequency.



(a) (b)

Fig. 1. mm-wave LM phase shifter. (a)Top view of the schematic of the proposed LM mm-wave phase shifter and (b) fabricated prototype. Key: substrate = blue, copper = yellow, plated vias = yellow, LM vias = black.

TABLE I

DIMENSIONS OF THE PROPOSED PHASE SHIFTER (UNIT: MM).

a = 6.8	*L* = 34.2	*k* = 3.34	d = 1.5	*d1* = 0.8
c = 1.9	b = 3.5	b1 = 3.7	b2 = 3.5	b3 = 3.85
b4 = 3.9	b5 = 3.7	b6 = 3.65	b7 = 3.8	

This paper introduces LM based phase shifter in SIW structure, achieving a substantial 360° phase shift at mm-wave frequencies. The phase shifter is suitable for 5G, radars and satellite applications. The phase shifter surpasses competitors in IL and FoM performance, while also expected to offer improved linearity and high RF power handling capabilities. The proposed phase shifter operate on 26GHz 5G n258 band and has an excellent FoM performance of 174.7°/dB.

II. STRUCTURE, OPERATION PRINCIPLES AND DESIGN CRITERION FOR THE PHASE SHIFTERS

Fig. 1 shows the structure and prototype of the proposed phase shifter. The phase shifter is based on SIW technology and fabricated using a Rogers RO5880 substrate, which has a dielectric constant (ε_r) of 2.2, a loss tangent ($tan\delta$) of 0.0009, and a thickness (h) of 0.508mm. The width of the SIW is a and the length is L. a controls TE_{10} and TE_{20} modes which determines the upper and lower cutoff frequency of the SIW. Then, a tapered transition from microstrip to SIW is added based on the design criterion in [13]. The width of the transition is TW and the length of the transition is k. Eight LM vias are used to achieve a phase shift of ~360°. The diameter of the SIW copper vias is $d1$ and the diameter of LM vias is d. The distance between the edge of SIW and first LM via is b. The spacing between the first via and the second via is $b1$, and so on for the other vias. The distance between all LM vias and the center of the SIW in the y-direction is c. Table I gives the dimensions of the proposed phase shifter. Each single via or array of vias in an SIW can be considered as an inductive post

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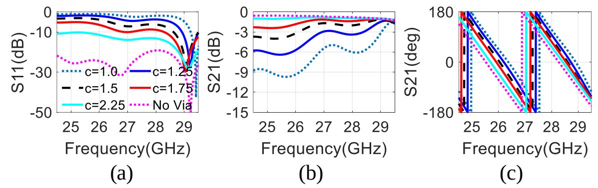


Fig. 2. Parametric study of the effect of *c* on the performance of the proposed phase shifter for a fixed via diameter of 1.5mm. (a) S_{11}, (b) S_{21} amplitude and (c) S_{21} phase. [*c* dimensions are in mm]

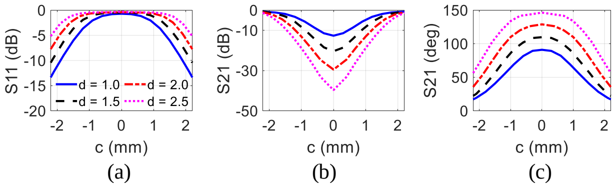


Fig. 3. Parametric study of the effect of *d* on the performance of the proposed phase shifter. (a) S_{11}, (b) S_{21} and (c) S_{21} phase.

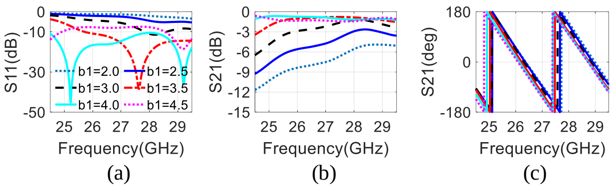


Fig. 4. Parametric study of the effect of *b1* on the performance of the proposed phase shifter. (a) S_{11}, (b) S_{21} and (c) S_{21} phase.

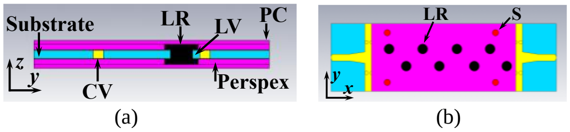


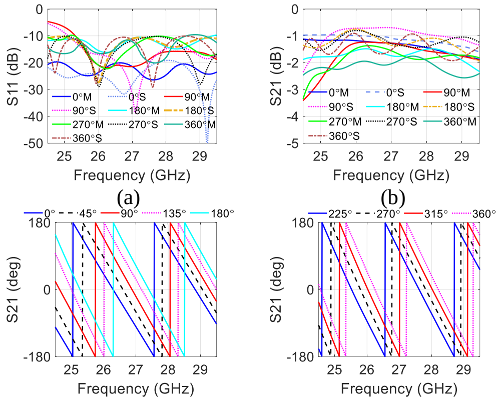
Fig. 5. Schematics of the fabricated phase shifter. (a) Top view showing Perspex and LM reservoirs and (b) cross section view showing LM vias. [Key: LR = LM Reservoir, LV = Liquid Metal Via, PC = Perspex cover, CV = Copper Plated Via, S = Screw.]

which can be represented in an equivalent T-Network high pass filter [14]. In this configuration, a high pass filter is well known to cause a phase advance, once it is used in a phase shifter topology called a switched low-pass/high-pass filter [14]. The phase shift in this topology is controlled by the position and diameter of the copper via inside the SIW. In fact, each of the vias once filled with LM behaves as a resonator in a high pass filter [14]. Specifically, adding a via will reduce the path length for the wave inside the SIW transmission line which naturally results in an advance in the phase of the wave. Fig. 2 shows the IL and phase shift with respect to different distance (*c*). Figs. 2(a) show the amplitude of S_{21} for different parameter *c*. It can be seen that the IL increases in inverse proportion to *c*. This is related to mismatch. When the via is closer to the center of the SIW transmission line, more wave is blocked, and the IL is higher. For example, the IL is 0.9dB when *c* is 2.25mm, and the IL is 9.3dB when *c* is 1.00mm. It can be seen that the phase shift is inversely proportional to *c*. The phase shift is larger when *c* is smaller. For example, Fig. 2(b) also shows that a total phase shift up to 109.4° at 26GHz with a step of ~1° can be achieved, once the first via with d = 1.5mm is introduced. This is done by gradually changing *c* from 2.25mm to 1.00mm. Vias with a larger diameter (*d*) achieve a greater overall phase shift. For example, the total phase shift is 128.8° for d = 2mm and 146.4° for d = 2.5mm, whereas it is 90.9° for d = 1mm, as illustrated in Fig. 3(c). However, for low phase shift per via (i.e., phase shift of approximately less than 70° to 80°), the via diameter has a negligible effect on the insertion loss (IL) and phase shift performance, as depicted in Fig. 3, because *c* can be adjusted to compensate for the difference in phase shift when larger or smaller vias are used. Nevertheless, the main drawback of using vias with a larger *d* (i.e., larger than 1.5mm) is that they leak RF power when they are empty of LM. In more detail, the SIW exhibits an IL of 0.53dB when there are no holes in it. However, after adding 8 holes, the IL begins to increase when *d* exceeds 1mm. For instance, the IL is 0.74dB for d = 1.5mm, 1.37dB for d = 2mm, and 2.03dB for d = 2.5mm. Adding an array of vias will further reduce the path length of the wave inside the SIW transmission line. In that case, more LM vias along x-axis direction result in a larger phase shift. As a result, we design reconfigurable phase shifters with several LM vias. By altering the states of each via, the phase shifter can have different operating states and provide an even step of phase shift. The precise steps outlining the design process of the proposed phase shifter are summarized as follows:

1. Introducing the 1st LM via: The horizontal separation between the SIW edge and the first via (*b*) does not impact the phase performance. Instead, the vertical distance (*c*) controls both the phase shift amount and the resolution. To achieve the desired phase shift, optimization of dimension *c* is essential. The dimension of *c* is chosen to achieve a ~45° phase shift. In more detail, adjusting c in 0.1mm step induces a roughly 6° phase shift. Similarly, adjusting *c* with step of 0.05mm brings about a ~3° change, which can be further refined to approximately 1° by reducing the step to 0.02mm.
2. Introducing the second LM via and fine-tuning the spacing between the first and second vias (*b1*) to achieve the desired phase increment as shown in Fig. 4. *b1* should be larger than quarter of the effective wavelength $(\frac{\lambda_g}{4})$. Smaller *b1* will obstruct the passage of the electromagnetic (EM) waves inside the SIW leading to high IL performance due to high reflection.
3. Introducing the remaining LM vias, one by one, while optimizing the spacing between vias *b2* to *b7* to get the desired phase shift in similar manner to step 2.

III. Practical Fabrication Consideration

Fig. 5 shows the channel structure, which is used to contain and guide LM. The channel structure used to contain LM consists of four layers of clear Perspex. Two Layers are used on top of the structure and two Layers on the bottom. For each of the two layers on top and bottom, the first layer incorporates eight LM reservoirs (LRs) and the second layer is used as a cover. Four metallic screws, located outside the SIW, were used to secure the layers of Perspex in position. The LM employed in this paper is based around an alloy consisting of 75.4% Gallium and 24.5% Indium. The conductivity of this LM is 3.4 × 10^6 S/m, boiling point is 2000 Celsius, thermal conductivity is 26.6 (W/(m·K)). However, the melting point of LM is 15.5



(a) (b)

(c) (d)

Fig. 6. The simulated and the measured results of the proposed LM phase shifter. (a) S_{11}, (b) S_{21} and (c-d) measured S_{21} phase. [M stands for measured results and S stands for simulated results]

Celsius which is one of its main limitations [15]-[16]. The LM was moved into (or withdrawn out of) desired portions using a syringe. This technique is widely used in the literature within proof-of-concept designs [17]-[19]. Upon removing LM from the vias, we observed no residues remain, especially that the via holes are with relatively large diameter as it easier to fill via holes having diameter larger than 1.0mm. In this paper, altering the method of actuation would have minimal effect on the RF performance of the phase shifters because the actuation components would be located beneath the ground plane, where the electric and magnetic field strengths are extremely low. Consequently, it is possible for this application to control the LM using a micropump [20] or electrochemically controlled capillary action [21]-[22].

IV. Results and Discussion

The proposed phase shifter is modelled using CST Microwave Studio 2019. Overall, an excellent agreement is found between the measured and simulated results as shown in Fig. 6. The measured IL for all 9 states is less than 2.1dB at 26GHz and it is less than 2.7dB over a -10dB S_{11} bandwidth (BW) of 4.5GHz ranging between 25GHz and 29.5GHz. In addition, the phase shifter $\pm 10°$ RMS phase BW depends on the operation state, where states with higher phase shift has lower RMS BW. For example, in worst case (i.e. state 9) the phase shifter has a BW $\pm 10°$ RMS BW of 900MHz, while the $\pm 20°$ RMS BW is 1.4GHz. Fig. 6 shows a good agreement between the simulated and measured results. The phase shifter provides a measured phase shift of $366.9°$, compared to $360.8°$ simulated phase shift. The IL of the proposed phase shifter is mainly attributed to matching and dissipation losses within the substrate. The discrepancies between the simulated and measured results of the proposed phase shifters are only attributed to PCB fabrication tolerances and manufacturing errors. In more detail: 1) The phase shift and *s*-parameters are sensitive to the vertical position of the LM via (c) as shown in Fig. 2. For instance, simulation results show that at 26GHz a tolerance of 50μm in the value of c for any of the eight LM via will cause $\approx 3°$ change in the phase shift, and 2) S_{11} and S_{22} are very sensitive to dimensions of the microstrip to SIW transition. The lower conductivity of LM does not contribute to the losses. For example, simulation analysis shows that in comparison with the use of copper vias, the use of LM vias has a negligible effect on the performance of the LM phase shifter. This is due the fact that LM has a relatively high conductivity. The proposed phase shifter has much lower IL in comparison to phase shifters in [1]-[2], [11], [23]-[26] as summarized in TABLE II. Also, the phase shifter has better FoM and higher phase shift in comparison to other LM phase shifters in [10]-[11], [27] which operate at 10GHz and 5.6GHz. In addition, the proposed phase shifter has higher FoM than phase shifters in [1]-[2], [10]-[11], [23]-[27]. Nonetheless, in contrast to CMOS and InGAS-based phase shifters in [1]-[2], [23], the suggested phase shifter presents limitations such as narrower bandwidth, reduced resolution, longer reconfiguration time, temperature limitation due to its melting point and a relatively larger physical footprint. The estimated reconfiguration time for the proposed phase shifter ranges from milliseconds to few seconds, depending on the specific technique employed to actuate LM [15], [28]-[29]. Besides, the proposed phase shifter is anticipated to effectively handle high RF power as it is based on SIW technology. Its power handling capability is likely to be limited only by that of the SIW transmission line itself, which is considerable. The reason for this is that there appears to be nothing, about LM, that should limit its power handling capability. The resolution of the phase shifter can be improved by utilizing LM vias that achieve smaller step of phase shift (i.e. 22.5°, 11.25° etc.), however, this will be at the expense of increasing the overall physical size of the phase shifter as more vias will be required to achieve the same overall phase shift. The proposed phase shifter is suitable for applications that demand both high power-handling capabilities and low IL. The LM phase shifter has a relatively small electrical size. This enables the proposed phase shifter to fit perfectly in an SIW based feeding network where it can be used to realize LM based mm-wave beam scanning phased array antenna.

TABLE II
Comparison Between the Proposed Phase Shifters and Other Phase Shifters Across Different Technologies

	f_0 (GHz)	FoM (°/dB)	IL (dB)	Phase range	Size
65nm CMOS[1]	28	10.3	17.5	180	$0.1\lambda \times 0.1\lambda$
BiCMOS[2]	28	42.4	8.5	360	$0.1\lambda \times 0.1\lambda$
In GaAS [23]	29	20.5	<8.8	180	$0.3\lambda \times 0.2\lambda$
PIN diode [24]	28	161	1.7	262	$1.3\lambda \times 1.1\lambda$
LC [26]	25	70.3	< 5.5	387	$6.1\lambda \times 1.1\lambda$
LM [10]	5.6	< 70	<1.8	67.2	NA
LM [11]	10	78.3	2.3	180	$2.9\lambda \times 2\lambda$
LM [27]	10	163.6	1.2	180	$\approx 3\lambda \times 1\lambda$
This work-LM	26	174.7	2.1	366.9	$3\lambda \times 0.6\lambda$

V. Conclusion

This paper presented a mm-Wave phase shifter operate at 25GHz with very low IL performance of 2.1dB and high FoM. The phase shifter is based on LM technology. A series of reconfigurable LM vias are located on the SIW transmission line used to reconfigure the phase of each of the phase shifters. By dynamically adding or removing via connections through the movement of LM, it is possible to achieve large phase shift using each via. The phase shift can be controlled by the position and size of the LM via.

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