Liquid Metal Reconfigurable Phased Array Antenna

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Abstract —**A design for a phased array antenna using liquid metal (LM) technology is presented. The phased array antenna uses substrate integrated waveguides (SIW) feeding structure to excite a 1×4 printed dipole antenna array. The phase distribution on SIW power dividers is manged using LM shorting vias inside the SIW. The integrated LM vias offers an extensive phase tuning range of 360° delivering stable, low-loss, and wide bandwidth. In more detail, the reconfigurability of phase control within the array can be realized by manipulating the presence or absence of liquid metals in designated vias in the SIW. A prototype of the LM phased array antenna, operating at 10 GHz, has been measured, demonstrating an impedance bandwidth exceeds 10% with maximum gain of higher than 8 dBi and a scanning range of approximately ±40° along the end-fire direction. This technology holds promise as a reliable and cost-effective solution for wideband phased array applications.**

Keywords — **phased antenna arrays, phase shifters, Gallium, reconfigurable devices, SIW.**

I. INTRODUCTION

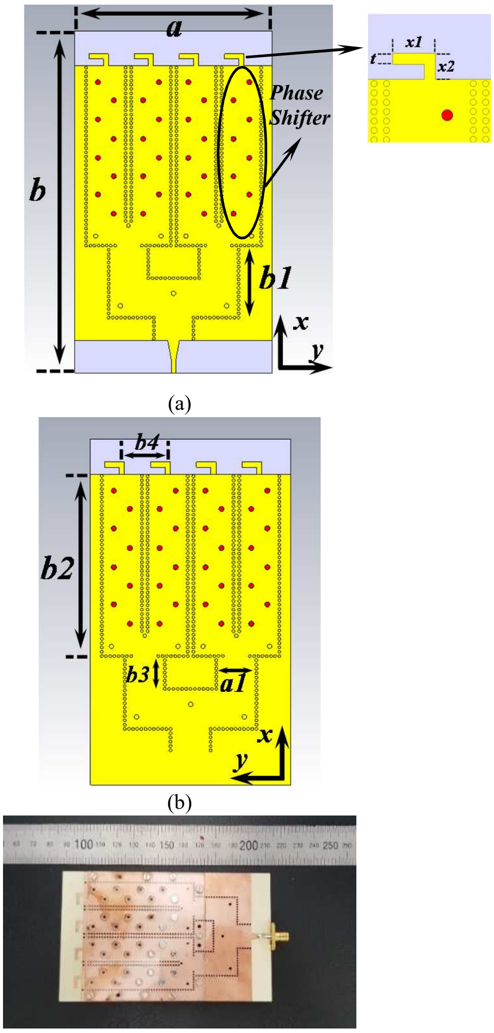
Phased array antennas, as discussed in [1]-[2], offer a great advantage by enabling precise electronic beam steering in fine angular increments. However, the technology depends on the use of a signal distribution network that incorporates phase shifters and, in some cases, adjustable attenuators [1]-[2]. This type of signal distribution network adds complexity to the design of the array and contributes to the fabrication cost. Furthermore, analogue phased array antennas often rely on phase shifters that tend to exhibit significant insertion losses, particularly at millimeter-wave frequencies.

Moreover, researchers have explored various approaches for phase shifters and phased antenna array design. This includes the utilization of Ferroelectric Ceramics [3], Liquid Crystals [4], and Micro-electromechanical systems (MEMS) [5]. These different technologies have been particularly promising for applications spanning from the low GHz to millimeter-wave frequencies. While these methods offer the potential for low-power consumption in large active antenna arrays, they do present certain challenges. Besides, these approaches often have limitations in terms of the total achievable range of phase tuning, and the structures of such antenna arrays are complicated. Furthermore, one of the most popular technologies for designing phase shifters are PIN diodes, Gallium Arsenide Field-Effect Transistors (GaAs FETs), and Complementary Metal-Oxide-Semiconductor (CMOS) technology. However, each of these technologies has some limitations. For example, phase shifters based on PIN diodes tend to have poor insertion loss performance, while those employing GaAs FETs offer better insertion loss performance but are constrained in terms of radio frequency (RF) power handling capability [6]-[7].

Phase shifters based on CMOS technology are known for their compact size, high resolution, and accuracy. However, their limitations such as restricted output power and amplitude losses, often resulting in a relatively poor noise figure. This is due to high insertion loss and nonlinearity. For instance, a typical X-band state-of-the-art CMOS-based active phase shifter often demonstrates an insertion loss exceeding 10 dB [8]-[9].

There is a growing interest in developing low-loss phase-shifting technology, which serves as the central focus of this paper. Previous research, has shown the possibility of using Liquid Metal (LM) in designing a range of microwave devices, including antennas, filters, resonators, phase shifters, and RF switches [10]-[23]. However, there is a gap in the existing literature to develop phased array antenna enabled by Liquid metal.

This paper presents a new approach to enhance the phase tuning range in a phased antenna array. We introduce the use of LM, specifically Gallium-based alloys, for phase control in a Substrate Integrated Waveguide (SIW) structure. This technique enables beam steering in a 1×4 antenna array. The proposed phased array features a LM phase shifters, representing a tuning range of up to 360°, while maintaining very low insertion loss (IL) and a compact physical size. Besides, an additional advantage of the used LM phase shifter used within the phased array architecture is its compact overall



(a)

(b)

(c)

Fig. 1. Liquid Metal X-band Reconfigurable phase array. (a) top view, (b) bottom view and (c) fabricated prototype.[*m* =mm, c8 = 6.2 mm, L1= 67.7mm, *m1*= 3.5mm, *b2* = 6mm, *b3* = 5.7mm, *b4* = 5.7mm , *b5* = 6.8mm , *b6* = 5.5mm , *b7* = 5.8mm, *b8* = 5.6mm , *b9* = 5.4mm, *b10* = 5.4 mm].

electrical length, making it highly suitable for integration within an SIW feeding network. This characteristic greatly facilitates the realization of a beam-scanning phased array. Furthermore, the utilization of liquid in-and-out controls in the LM phase shifter has the potential to facilitate various beam configurations for the phased antenna array. In addition, the LM phased array has the capacity to effectively manage high levels of RF power. This is based on the absence of limiting factors within the LM that might otherwise impede its RF power-handling capabilities. Also, we anticipate that LM phased array will exhibit significantly enhanced linearity performance [23]. Ultimately, the suggested LM phased array antenna represents an excellent choice for applications that require a combination of low loss performance and robust RF power-handling.

II. Concept And Structure

Fig. 1 shows the configuration of the LM phased array antenna, providing both its conceptual design and the physical prototype that has been fabricated. The proposed phase array antenna consists of 1x4 printed dipole antenna fed using substrate integrated waveguide (SIW) feeding structure. The feeding structure consists of SIW based power dividers and four different liquid metal based phase shifters as shown in Fig. 1(a). Also, the phase shifters are integrated within the SIW feeding structure to realize complete phased array antenna system. Each phase shifter consists of eight liquid metal vias that are arranged in series to achieve a total phase shift of 360°, where each via contribute to a phase shift step of 45°. In more detail, the phase of the phase shifters is controlled by introducing vias formed of liquid metal. When the via is required, the via hole is filled with liquid metal and when the via is no longer required, the holes are emptied of liquid metal. This enables each of the phase shifters to have nine different reconfigurable operation states ranges between 0° and 360° with a resolution of 45° as explained in Table. I.

TABLE I
RELATIONSHIP BETWEEN ACTIVE LM VIAS AND PHASE OF EACH OF THE PHASE SHIFTERS

Active Liquid Metal Via	Achieved Phase
0	0
1	45°
2	90°
3	135°
4	180°
5	225°
6	270°
7	315°
8	360°

Conventional theory demonstrates that a phase shift can be induced through the utilization of a high-pass filter within configuration known as the switched high-pass/low-pass [24]-[27]. An in-depth examination of one of these high-pass filter configurations is presented in [24], [27]-[28], which focuses on a cylindrical conductive post (or an array of such posts) placed within a rectangular waveguide. These conductive posts can be linked to vias in an SIW transmission line as discussed in detail in [10]-[11], [19]. In the case of a single liquid metal via, the phase shift is primarily influenced by the via diameter and its horizontal positioning relative to the E-plane wall of the SIW waveguide. Furthermore, this single liquid metal via can be equivalently represented by a lumped element circuit, comprising a T-network of components.

The incorporation of one LM via into an SIW transmission line yields a phase shift that has direct proportionality to the diameter of the via and an inverse relationship with the separation distance between the center of the SIW transmission line and the placement of the via along the y-axis orientation [10]-[11], [19]. In more detail, a single via introduces a phase advance to the electromagnetic (EM) wave as it propagates through the SIW transmission line. More precisely, the addition of the via shortens the electrical length of the SIW, resulting in a naturally reduced electrical path, and consequently, an advancement in the phase of the EM wave as explained in detail in [10]-[11], [19].

Liquid metal is inserted into and extracted from the via holes to form the via connection using a syringe. Two layer of transparent Perspex are attached. The first layer is located on the top of the phased array and the other layer is on the bottom of the phased array to form reservoir to contain Liquid Metal as shown in Fig. 2. In addition, an additional two layers of Perspex are attached on top of these layer to form a protective cover. This approach has been widely used especially in proof of concept design such as the ones shown in [10],[12],[16]-[18]. However, it is possible to move liquid metal in the vias utilizing micropumps in similar manner to designs shown in [10], [14], [20]-[21] or by electrochemically actuation such as designs shown in [22], [30]. Both methods can be implemented with the phased array as there is no electric field outside the SIW feeding structure and a pump or electrochemically based actuation circuit can be attached on top or bottom of the SIW feeding structure without affecting its RF performance.

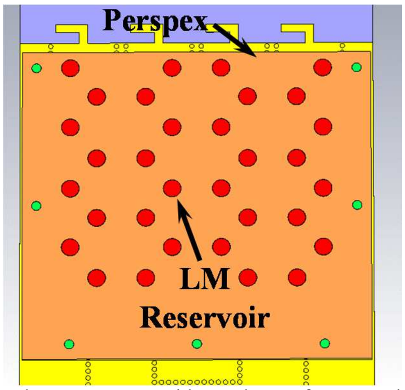
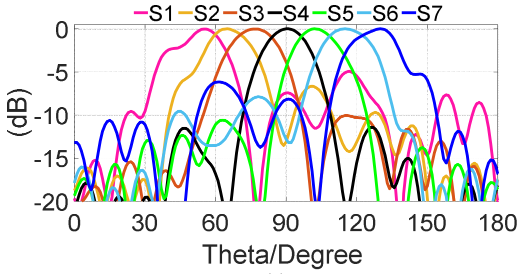


Fig. 2. The phased array antenna with one layer of perspex that contains LM reservoirs.

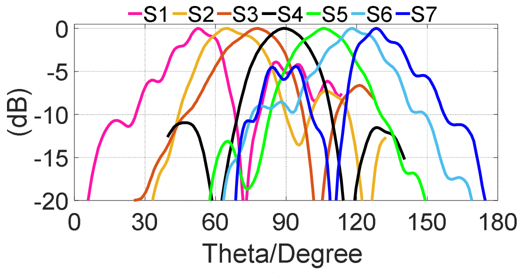
III. Simulated and Measured Results

Utilizing the array of 1×4 printed dipoles, we generate a beam that can be steered within the end-fore direction particularly in x-y plane. The phased array's performance was simulated using computer simulations in CST Microwave Studio. We carried out multiple tests on the phased array, enabling beam steering within a range of up to ±40° in the end-fire direction. It is essential to note that the electric field radiation pattern (E-field) exists within the x-y plane, while the magnetic field radiation pattern (H-field) is confined to the x-z plane. The proposed phased array's beam can be steered within the x-y plane, similar to traditional phased array beam scanning.

Fig. 3 shows the radiation patterns of the phased array at 10GHz and Fig. 4 shows the S_{11} performance. The measurement and simulation results are in good degree of agreement with each other. The proposed phased array is evaluated across seven reconfigurable steered angles, denoted as State 1 to State 7 (S1 to S7). The corresponding beam steering angles, are also explained in Table II. Experimental results indicate that the primary beam of the proposed phased array antenna can be steered within the x-y plane, covering an angular range of ±38 degrees.



(a)



(b)

Fig. 3. Radiation patterns of the reconfigurable X-band Array. (a) Simulated, (b) measured. [S in the caption stands for State]

TABLE II
Operation States of the Proposed LM Reconfigurable Phased Array

State (S)	Phase difference between phase shifters	Beam Angle/Simulated	Beam Angle/Measured
S1	135°	55°	52°
S2	90°	65°	64°
S3	45°	77°	78°
S4	0°	91°	89°
S5	−45°	102°	106°
S6	−90°	115°	117°
S7	−135°	130°	128°

TABLE III
Configuration of Each of the Individual Phase Shifters in Each Operation State

State	Number of active LM via in phase shifter 1 (Phase shift)	Number of active LM via in phase shifter 2 (Phase shift)	Number of active LM via in phase shifter 3 (Phase shift)	Number of active LM via in phase shifter 4 (Phase shift)
S1	3 (≈ 135°)	5 (≈ 270°)	1 (≈ 45°)	4 (≈ 180°)
S2	2 (≈ 90°)	4 (≈ 180°)	6 (≈ 270°)	8 (≈ 360°)
S3	1 (≈ 45°)	2 (≈ 90°)	3 (≈ 135°)	4 (≈ 180°)
S4	0 (0°)	0 (0°)	0 (0°)	0 (0°)
S5	4 (≈ 180°)	3 (≈ 135°)	2 (≈ 90°)	1 (≈ 45°)
S6	8 (≈ 360°)	6 (≈ 270°)	4 (≈ 180°)	2 (≈ 90°)
S7	4 (≈ 180°)	1 (≈ 45°)	6 (≈ 270°)	3 (≈ 135°)

Table II provides a summary of the phase differences between the phase shifts employed by the four LM phase shifters to achieve specific beam angles. In State 4 (S4), the phased array radiates in the end-fire direction without any beam steering, i.e., directed at 91°. In this instance, the phase difference between the LM phase shifters is 0°. For S3 and S5, the phase difference between consecutive LM phase shifters is ±45°, respectively. In

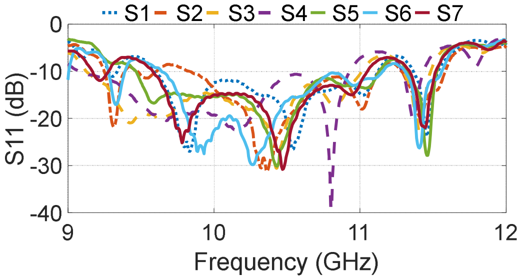


Fig. 4. Measured S_{11} of the reconfigurable X-band LM phased array antenna. [S in the caption stands for State]

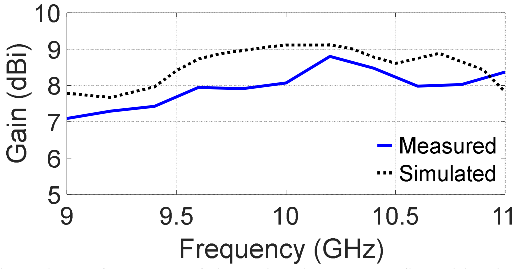


Fig. 5. The gain performance of the X-band LM reconfigurable phased array antenna.

S2 and S6, the phase difference between consecutive LM phase shifters is ±90°, respectively. Lastly, in S1 and S7, the phase difference between consecutive LM phase shifters is ±135°. An evident level of similarity is observed between the simulated and measured radiation pattern and side lobe level (SLL) performance across all seven steering angles as shown in Fig. 3. For instance, the measured SLL of the phased array are: -11.1 dB in S4, -12.5 dB in S5, -8.6 dB in S6, and -4.9 dB in S7. The measured SLL is recorded at -7.1 dB in S3, -7.3 dB in S2, and -4.5 dB in S1.

The reconfigurable LM phased array is with a measured gain of 8.3 dBi at 10 GHz as explained in Fig. 5. This is 0.8 dB lower than the corresponding simulated gain. The peak measured gain of 8.5dBi is achieved at 10.2 GHz. In summary, the measured gain of the proposed phased array consistently exceeds 7.9 dBi across a bandwidth spanning over 1 GHz, ranging from 9.6 GHz to 10.8 GHz.

The minor disparities observed in the gain and radiation pattern performance of the proposed phased array antenna, as compared to the results obtained from simulation and measurement, can primarily be attributed to errors arising during the printed circuit board (PCB) manufacturing process. Note that the variance between the simulated and measured gain of the array falls within a range of 0.2dB to 0.8dB across the array bandwidth. This difference is relatively small and is due fabrication tolerances related to the positioning of LM vias, the dimensions of the feeding networks and the dipole antenna, as well as the dimensions of the microstrip to SIW transition.

IV. CONCLUSION

This paper presents design and prototype that utilizes liquid metals (LM) to achieve versatile phase control for the design of a substrate-integrated waveguide (SIW) phased antenna array. The proposed phased array is centered around SIW technology, which excites an array of printed dipole antenna array. It offers a cost-effective solution with low loss and wideband performance compared to existing technologies. The innovation lies in the integration of LM-based phase shifters with SIW power dividers to effectively manage phase distribution within the SIW, enabling a substantial phase tuning range of 360°. Four LM phase shifters are incorporated into the SIW feeding structure, each with eight LM vias, allowing for phase adjustments in approximately 45° steps by adding or removing LM vias. The measured and simulated results in the paper demonstrate the excellent performance of the proposed phased array antenna. Operating at 10 GHz, it provides a scanning range of ±38° along the end-fire direction, an impedance bandwidth exceeding 10%, and a peak gain of 8.3 dBi. Notably, this phased array offers advantages such as low insertion loss, wideband performance, and the potential for high power handling capability, surpassing existing technologies.

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