A Reconfigurable Microstrip Patch Antenna with Switchable Liquid-Metal Ground Plane

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***Abstract*—This paper presents a novel reconfigurable microstrip patch antenna that is reconfigured using liquid metal. The proposed antenna employs two approaches in unison to switch the direction of the main beam. Specifically, the antenna uses the parasitic steering approach together with a novel switchable ground plane. The antenna operates at 5.9 GHz. It consists of a driven patch surrounded by four parasitics. All five elements are circular disk resonators. Each of the parasitic resonators incorporate a drill hole. The drill holes can be filled or emptied of liquid metal to control the behavior of the parasitics. The ground plane incorporates two reconfigurable segments. The switchable ground plane can be reshaped by adding or removing the additional segments of ground plane which are formed from liquid metal. To the best of the authors' knowledge, this is the first antenna that is capable of reconfiguring its radiation pattern by reshaping the ground plane using liquid metal. A hardware prototype of the antenna was fabricated and measured. The measurement results show that the antenna can switch between five different beam directions, namely: 0°, ±20°, and ±40°. The design has only 0.5 dB of scan loss across the beam switching range.**

***Index Terms*—Beam switching, liquid metal, low scan loss, microstrip patch antenna, pattern reconfiguration, switchable ground plane, wide scan angle.**

I. INTRODUCTION

Compared to antennas with fixed beam, pattern reconfigurable antennas have attracted considerable research attention due to their advantages, including: ability to enhance communication security, improve channel capacity, and adapt to changing channel conditions [1], [2]. Microstrip patch antennas are one of the most popular forms of reconfigurable antenna due to their low cost, low profile, ease of fabrication, and conformal nature.

This work was supported in part by a grant from The United Kingdom Engineering and Physical Sciences Research Council, EPSRC, under grant number: EP/P008402/1 and EP/P008402/2, in part by the Chinese Scholarship Council who are funding the first author's PhD studentship.

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Commonly, a pattern-reconfigurable microstrip antenna may be controlled mechanically or electronically. For example, the reconfigurable pattern can be realized by mechanically changing the distance between the antenna and the reflector [3]. However, mechanical moving parts are undesirable, for many applications, because they require periodic maintenance, repair, and replacement. Electrically controlled reconfigurable antennas widely use PIN diodes or microelectromechanical switches (MEMS). These devices have fast response time but also suffer from high insertion loss and nonlinear distortion. Liquid metal as the new material could be electrically controlled, and it still has the advantages of low insertion loss, low harmonic distortion, and large tuning ranges [4]-[6].

Previous literature has reported designs which achieve pattern reconfiguration by changing the ground plane [7] – [10]. The approaches used include altering the eigenmode supported by the radiator [7], [8], or using parasitic elements to direct or reflect beams [9], [10]. For example, a reconfigurable patch antenna was proposed in [7]. By tuning on the different combinations of switches, it is possible to connect vertical metal walls to the patch antenna. The beam direction is thus altered by varying the eigenmode supported by the patch antenna. However, the antenna proposed in [7] exhibits more than 2 dB scan loss over a scan angle range of ±20º. The vertical metal walls also increase the profile of antenna. The slot antenna, proposed in [9], has low profile. It incorporates one slot which acts as a radiator together with four slits which act as parasitics. By tuning on the different switches, located within the slits, it is possible to alter the behavior of the slits and thus control the beam reconfiguration. However, the antenna can only steer its beam to a maximum angle of ±15º. We report the first antenna to employ removable sections of ground plane control in order to alter its radiation pattern. Specifically, the antenna is capable of switching the direction of its main beam. Control of the main beam direction is achieved by adding and totally removing sections of ground plane. Such an approach has never been tried before and it is only possible due to the unique properties of liquid metal. Our design also involves parasitic steering, using a technique similar to that described in [11] but that is only a minor contribution of our work. The design presented in [11] only employs parasitic patches to switch the main beam direction, whilst our design combines the use of parasitic patches with a switchable ground plane. This enables the proposed design to switch beam up to ±40º with only 0.5 dB of scan loss, while the design in [11] achieves a

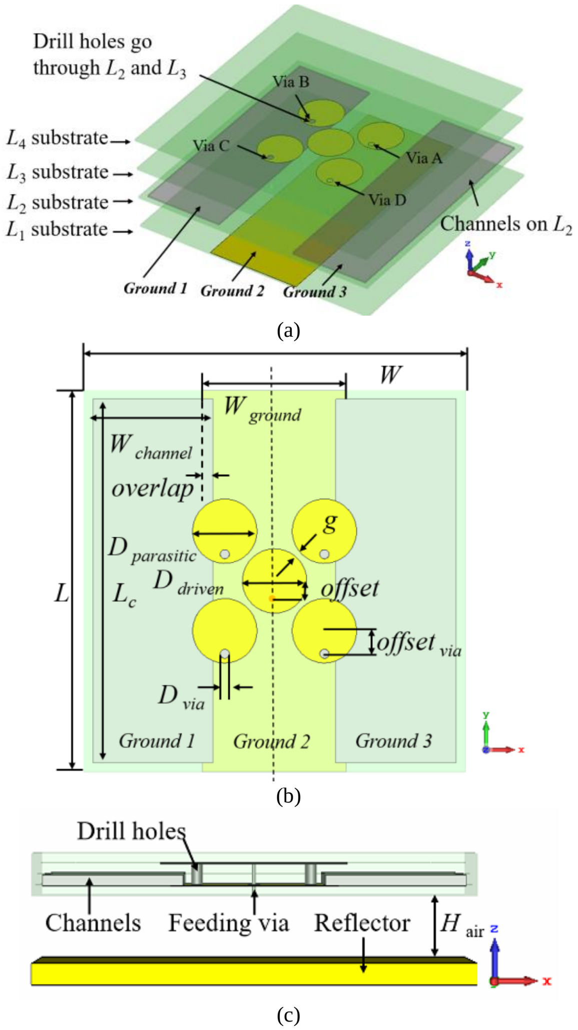

Fig. 1. Geometry and parameters of the pattern-reconfigurable antenna. (a) Perspective view; (b) Top view; (c) Side view.

TABLE I
OPTIMIZED DIMENSIONS OF THE DESIGN #1 ANTENNA (UNIT: mm)

L	***L*c**	***W***	***W* channel**	***W* ground**	***D* driven**	***D* parasitic**
83	79	83	26.1	31.26	14	14
***D* via**	***g***	***offset***	***offset* via**	***overlap***	***H* air**	
2	1.3	3.6	5	2.3	5	

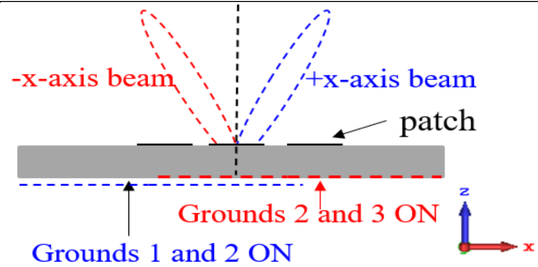

Fig. 2. The sketch of beam directions for different states.

TABLE II
STATES OF FLUIDIC CHANNELS AND RADIATION PATTERNS

State *i*	Via State				Ground State		Beam direction	Gain (dBi)	3-dB Beamwidth
	A	B	C	D	1	3			
1	Off	Off	Off	Off	On	On	0°	9	50.1°
2	Off	Off	Off	Off	Off	On	-20°	9.4	56.3°
3	Off	Off	Off	Off	On	Off	+20°		
4	On	Off	Off	On	Off	On	-40°	9.1	58.7°
5	Off	On	On	Off	On	Off	+40°		

maximum angle of ±15º with 1.3 dB of scan loss. As a result, our design differs from the designs, discussed above, in both approach and performance. The proposed antenna is fabricated and measured at 5.9 GHz. The measured results show that the antenna has good beam switching performance.

The remainder of this letter is organized as follows. Section II discusses the antenna design and reconfigurable principle. Section III explains the practical fabrication considerations and performance of the antenna. Finally, Section IV draws conclusions.

II. ANTENNA DESIGN

A. Antenna Structure

Fig. 1 shows the geometry and parameters of the antenna. Table I shows the optimized parameters of the antenna. The antenna consists of a driven patch surrounded by four parasitics. The driven patch and parasitics are all circular in shape. Energy is fed into the antenna using a coaxial fed probe. The probe is offset along the Y-axis by 3.6 mm in order to yield optimum impedance matching. The antenna is constructed using four layers of substrate, namely L_1 to L_4. Each layer of substrate is formed from a piece of Rogers RO4003c having a thickness of 0.813 mm, a permittivity of 3.55, and a loss tangent of 0.0027. Each parasitic incorporates a single drill hole which passes through substrate layers L_2 and L_3. The lowermost and uppermost layers of the substrate (i.e. L_1 and L_4) are employed as covers to prevent the liquid metal from leaking out. Two large channels are formed in substrate layer L_2. When those channels are filled with liquid metal, they form Ground 1 and Ground 3. Ground 2 is formed from copper and remains permanently in place. A metallic reflector is placed behind the antenna, as shown in Fig. 1 (c).

B. Reconfigurable Principle

The proposed antenna employs two approaches in unison to switch the direction of the main beam. The first approach, for beam switching, involves parasitic steering. In the proposed antenna, the central patch acts as the driven element and four surrounding patches act as parasitics. Each parasitic incorporates a single drill hole. The drill holes can be filled or emptied of liquid metal. When a particular drill hole is filled with liquid metal, a via is formed and the parasitic is said to be switched ON. Under this condition the associated parasitic element is connected to ground and acts as a reflector. When the drill hole is emptied, no via is formed and the parasitic is said to be switched OFF. Under this condition the associated parasitic acts as a director. With the aid of these reconfigurable vias, it is possible to reconfigure the directions of the radiation patterns. Moving the parasitics closer to the driven patch has the effect of increasing the mutual coupling between the driven element and the parasitics. In turn this leads to a lower operating frequency, a lower Side Lobe Level (SLL), and a smaller angle between the main beam and the normal direction.

The second steering approach involves altering the eigenmode supported within the radiating element. This is achieved by using liquid metal to form and reshape the ground

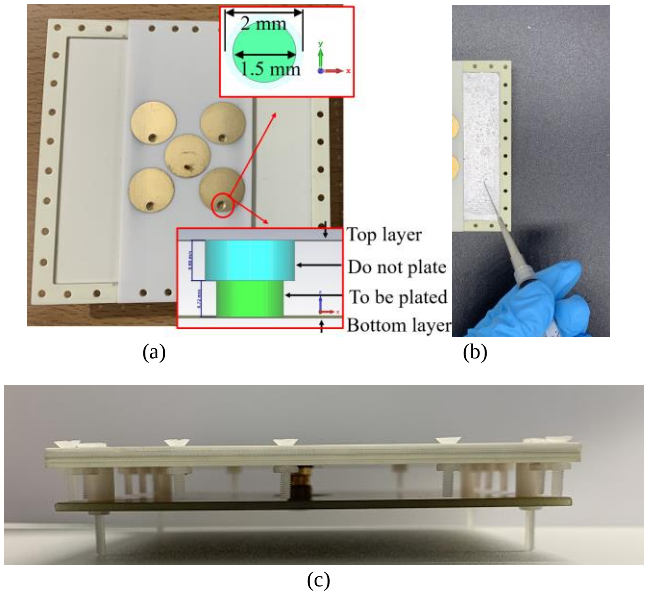

Fig. 3. Photographs of the fabricated antenna. (a) Top view without cover layer and fabrication processing for holes; (b) Ground drained by a syringe; (c) Side view of assembled antenna.

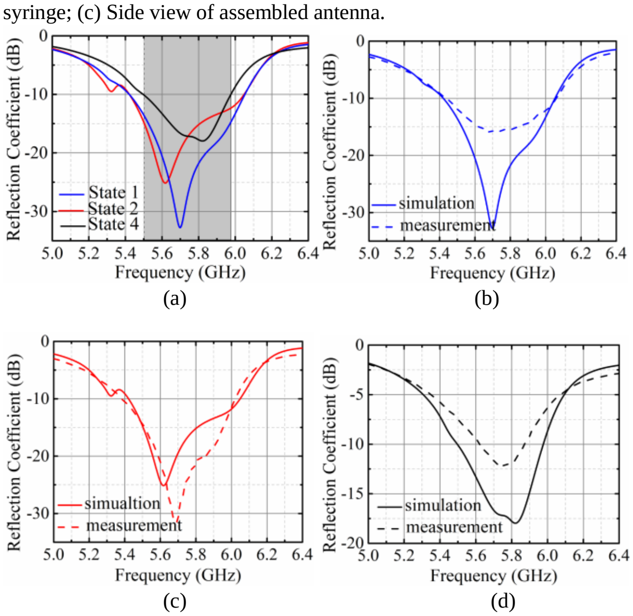

Fig. 4. The reflection coefficient of the antenna as a function of frequency for different states. (a) Simulations for three states; Comparisons between simulation and measurement for (b) State 1, (c) State 2, and (d) State 4.

plane. Specifically, whole segments of ground plane are added or removed by using liquid metal. Ground 1 and Ground 3 can be formed from liquid metal. This enables them to be added (switched ON) or removed (switched OFF) as required. Doing so influences the beam direction. In particular, the beam switches towards the direction from which the ground plane has been removed. Fig. 2 shows that directional beams are obtained by altering the shape of the ground plane using liquid metal. To our best knowledge, this is the first antenna that is capable of reconfiguring its radiation pattern by reshaping the ground plane using liquid metal.

Table II shows different operating states of the antenna. The proposed antenna is symmetrical about the Y-axis, and it provides five switchable beams in the XZ-plane. When all drill holes are empty and two ground segments are filled with liquid metal, a broadside beam is obtained. We term this known as State 1. When all drill holes are empty and one of ground segments is filled with liquid metal, a steered beam is obtained. We term those State 2 and State 3. When two drill holes and one ground segment on the same side are simultaneously filled with liquid metal, the antenna can obtain a beam directed at a larger angle. We term those State 4 and State 5.

III. Simulation and Measurement Results

All of the simulation results presented in this section were obtained using CST Microwave Studio 2019. To verify the proposed design a hardware prototype of the antenna was fabricated and measured. A vector network analyzer (Rohde & Schwarz ZNBT 8) was used for the measurement. The radiation patterns and the realized gains for the different operating states were measured using a far-field antenna test range.

A. Prototype and Injection/Removal of Liquid Metal.

Fig. 3 shows a photograph of the fabricated antenna. A series of screws, located around the edge of the substrate, were used to secure the layer L_4 in position. The layer L_4 is required to prevent the liquid metal from leaking out. The reflector was formed from a piece of FR-4 substrate incorporating copper on the upper side. A series of spacers were used to set the correct separation between the antenna and reflector. The liquid metal employed, for the work reported in this letter, is based around an alloy consisting of 75% Gallium and 25% Indium. The conductivity of this liquid metal is 3.4×10^6 S/m. It is important to ensure a good electrical connection between the liquid metal in the drill holes and the ground plane. To ensure this, we used a special channel design, see Fig. 3 (a). To ensure that the drill holes were fully filled with liquid metal, we used a multimeter to check the electrical connection between the parasitic patch and the ground plane. The liquid metal was moved into (or withdraw out of) desired positions using a syringe. This technique is widely used in the literature within proof-of-concept designs [5], [12]. Fig. 3 (b) shows the ground plane drained by a syringe.

Fig. 4 depicts the simulated and measured reflection coefficients (S_{11}) associated with the States 1, 2 and 4. It is worth noting that we measured three different operating states, which yield beams directed towards 0°, -20°, and -40° in the XZ-plane. The structure is symmetrical along the y-axis. For this reason, beams pointing towards other directions could be obtained by simply mirroring the states of vias along with the configuration of the ground plane. From Fig. 4, it can be seen that, for all states, the proposed antenna has an overlapped measured -10 dB reflection coefficient bandwidth ranging from 5.6 GHz to 5.88 GHz *(i.e. 280 MHz)*, which is narrower than the simulation but more than adequate for most applications. The discrepancies between the simulated and measured reflection coefficients are mainly caused by the offset of probe due to fabrication errors and assembly errors. Specifically, if the position of probe shifts from -3.6 m to -4 mm, the frequency of State 2 increases and the 10 dB reflection coefficient bandwidth of State 4 decreases from 480 MHz to 280 MHz.

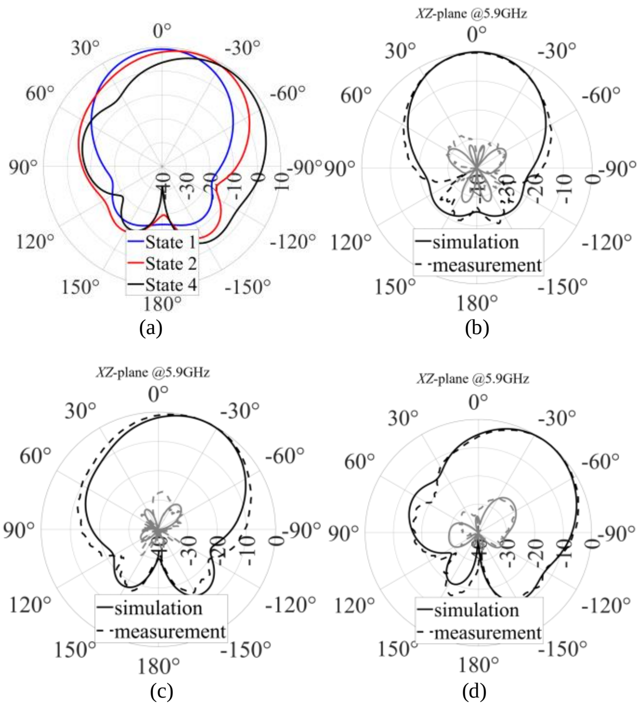

Fig. 5. Radiation patterns of the antenna working at 5.9 GHz. (a) Simulation results of three different beams. Simulation and measurement patterns for (b) State 1, (c) State 2 and (d) State 4.

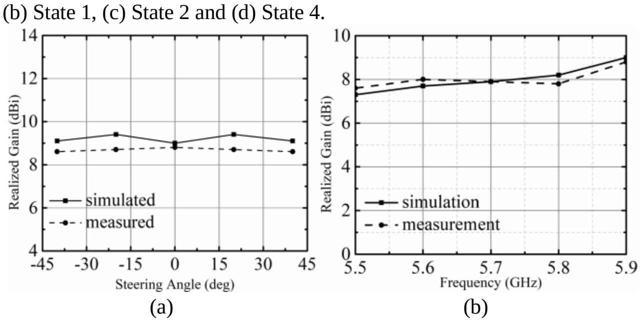

Fig. 6. Simulated gains and measured gains (a) versus steering angles at 5.9 GHz. (b) Simulated gains and measured gains of broadside beam versus frequencies.

The proposed antenna yields stable radiation performance at frequencies within the -10 dB reflection coefficient bandwidth. Fig. 5 shows the simulated and measured radiation patterns of the antenna in the XZ-plane at 5.9 GHz. From Fig. 5, it can be seen that the proposed antenna is capable of switching its beams, in evenly distributed steps, by up to a maximum angle of ±40° whilst maintaining an SLL below -10 dB. From inspection of Fig. 5 (b), (c) and (d) it is clear that there is a good agreement between the measured and simulated results. Some discrepancies between the simulation and measurement results may be attributable to fabrication errors and assembly errors.

Fig. 6 shows the simulated gains and the measured gains. Fig. 6 (a) shows the gains associated with the different beam-switchable angles. It can be seen that, the simulated gains for beams towards 0°, ±20°, and ±40° are 9 dBi, 9.4 dBi, and 9.1 dBi, respectively. The measured gains are less than 0.7 dB lower than the simulated results. The difference is due to the alignment of the measurement system. Besides, the difference between measured reflection coefficients and simulated ones also brings some errors in the reality. The measured scan loss is less than 0.5 dB across the beam switching range. Fig. 6 (b) shows the gains of State 1 at a range of different frequencies. The antenna exhibits a similar tendency when operating in the other states. Table III compares the performance of reconfigurable patch antennas reported previously in the literature against that of the antenna proposed in this letter.

TABLE III
COMPARISON FOR ANTENNA PERFORMANCE

Ref.	Frequency (GHz)	Steering angle	No. of beam	Scan loss (dB)	Radiation Efficiency	Control method
[2]	2.4	360°	4	0.5	83%	PIN
[4]	2.4	±5°	5	0.7	>60%	Liquid metal
[6]	4.5	±54°	5	3.1	>90%	Liquid metal
[11]	2.3	15°	5	2	>75%	PIN
[13]	2.45	±30°	3	1.6	Null	PIN
This Work	5.9	±40°	5	0.5	>90%	Liquid metal

B. Discussions

We actuated the liquid metal manually using a syringe. In this case, it takes approximately 20 seconds to 30 seconds to fill each drill hole and approximately 3 minutes to 5 minutes to fill each segment of ground plane. However, it is important to recognize that, for this design, altering the method of actuation would have minimal effect on RF performance because the actuation components would be located beneath the ground plane, where the electric and magnetic field strengths are minimal. Our preferred method of actuating the liquid metal would be to use a micropump [14] or electrochemically controlled capillary action [15]. The electrical technique has been shown capable of moving liquid metal at a rate of 30 cm/s [16]. If we were to employ the electrical technique to fill the channels, we estimate that it would take approximately 3 seconds to fill each drill hole and approximately 1.5 minutes to fill each segment of ground plane. The reconfiguration rate of liquid metal is not as fast as that of conventional switching and tuning devices. However, a range of important applications can tolerate slower reconfiguration rates. The intended application of the antenna could be airport radar and user terminals for satellite internet access. Both require switching speeds ranging from milliseconds to seconds but require high gain and high efficiency.

IV. CONCLUSION

This paper presents a pattern-reconfigurable patch antenna using liquid metal. A switchable ground technique is employed in the design. Specifically, whole segments of ground plane are added or removed by moving liquid metal. To the best of the authors' knowledge, this is the first time that liquid metal has been used to reshape the ground plane for pattern reconfiguration. The antenna operates at a center frequency of 5.9 GHz and provides five switchable beams. It is capable of switching its beams, in evenly distributed steps, by up to a maximum angle of ±40° with only 0.5-dB scan loss. The proposed prototype is an attractive candidate for modern wireless communications.

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