Liquid metal enabled SIW vias and RF blocking walls for reconfigurable antennas

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Liquid Metal Enabled SIW Vias and RF Blocking Walls for Reconfigurable Antennas

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***Abstract* — This paper presents a method for designing reconfigurable microwave devices based on substrate integrated waveguides (SIW) technology. The method involves forming walls from drill holes that can be filled with liquid metal to form vias. Furthermore, the proposed method is validated by designing and testing several reconfigurable radio frequency (RF) switches. The switches are intended to be used for reconfigurable antenna applications. The measured results for the proposed devices are in good agreement with the simulated results and they show wideband operating bandwidth with highly efficient performance. The proposed method will find application within a wide range of different reconfigurable microwave devices and circuits.**

***Keywords* — Liquid metal, Gallium-Indium eutectic, fluidic devices, reconfigurable devices, microwave switches.**

I. Introduction

Substrate integrated waveguide (SIW) technology is a powerful technology that enables the mass production of microwave and mm-wave devices that are compact, efficient, and low cost. SIW technology is a reliable alternative to the traditional metallic waveguide which, by comparison, is bulky and expensive. SIW technology can be used to produce: filters [1], phase shifters [2]-[3], multiplexers [4], diplexer [5], power divider/combiner [6], couplers [7] and antennas [8].

In this paper, we present a method which enables an engineer to create a wide range of microwave devices and antennas based on SIW structures. The devices can be reconfigured using liquid metal vias. The proposed method is validated numerically and experimentally by designing and measuring a SIW waveguide wall that block radio frequency (RF) transmission. Furthermore, the method is tested by developing three type of microwave switches that can be reconfigured using liquid metal vias. This includes a: single-pole single-throw (SPST) switch, single-pole double-throw (SPDT) switch, and single-pole triple-throw (SPTT) switch. The proposed switches were developed in order to demonstrate the potential of the proposed method for reconfiguring SIW based devices. The proposed method will broaden the horizon for microwave, mm-wave and RF engineers to realize various reconfigured SIW based devices such as: reconfigurable filters, reconfigurable power dividers and combiners, reconfigurable diplexer and multiplexer, and reconfigurable couplers.

II. Concept and Design Structure

A. SIW SPST Incorporating One RF Blockage Wall.

Fig. 1 shows the structure of the proposed SIW transmission line incorporating an RF blocking wall. The dimensions of the waveguides together with the microstrip to SIW transitions were designed based on the guidance provided in [9]. The number of liquid metal vias and their dimensions were studied numerically to determine the minimum number of liquid metal vias required to deliver certain level of isolation between a pair of ports. The isolation between both ports is determined by the ratio of the distance between the liquid metal vias (denoted d) and via diameter (denoted r). We discovered that the isolation is less than -30 dB when $\frac{d}{r} \leq 2.5$, while the isolation is less than -40 dB for $\frac{d}{r} \leq 2$ and it is less than -50 dB once $\frac{d}{r} \leq 1.5$. The RF blocking wall is formed from 5 drill holes. When the drill holes are filled with liquid metal the wall is said to be turned ON. When the drill holes are emptied of liquid metal the wall is said to be turned OFF, see Fig. 2. The structure behaves as an SPST switch. It is fabricated on an RO4003C substrate having a thickness of $1.524\ mm$, a dielectric constant of 3.55, and a loss tangent of 0.009. Table 1 gives the dimensions of the proposed SPST switch.

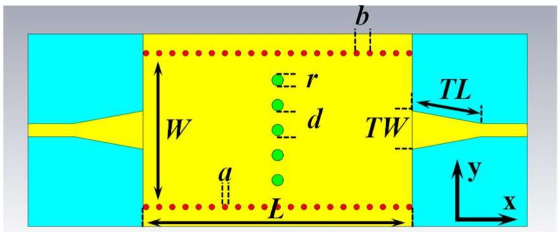
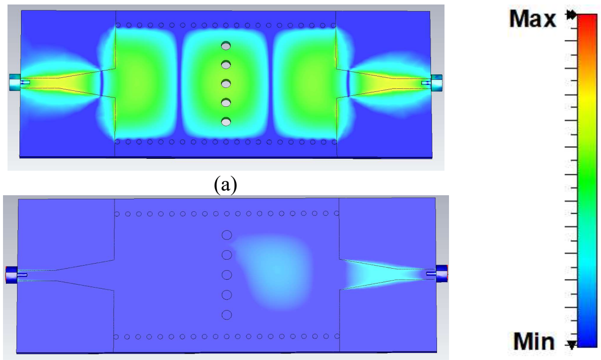


Fig. 1. Schematic of the proposed SIW SPST switch incorporating an reconfigurable RF blockage wall formed from liquid metal (shown in green)

Table 1 The dimensions (in mm) of the proposed switches.

$TL = 18.3$	$W = 38.5$	$a = 1.5$	$TW1 = 5.25$	$TL1 = 8.05$
$TW = 10$	$L = 70$	$r = 3$	$b1 = 2.13$	$r1 = 2.5$
$b = 3.43$	$d = 6.6$	$W1 = 20$	$W2 = 100$	$L2 = 90.6$
$d1 = 4.47$	$L1 = 61.1$			



(a)

(b)

Fig.2. The electric field (E-field) distribution, at 3.5 GHz, inside the proposed SIW SPST switch. (a) Wall OFF, and (b) wall ON.

B. *SPST Switch Incorporating Two RF Blocking Walls.*

Fig. 3 shows the SPDT switch that was designed to validate the proposed liquid metal RF blocking wall concept. TABLE.II summarizes the operating states of the switch. State A occurs when there is no liquid metal in the RF blocking wall between ports 1 and 2 but there is liquid metal in the RF blocking wall between ports 1 and 3. Under this condition there is full transmission between ports 1 and 2. State B is the opposite of state A, and as such there is full transmission between ports 1 and 3 but no transmission between ports 1 and 2.

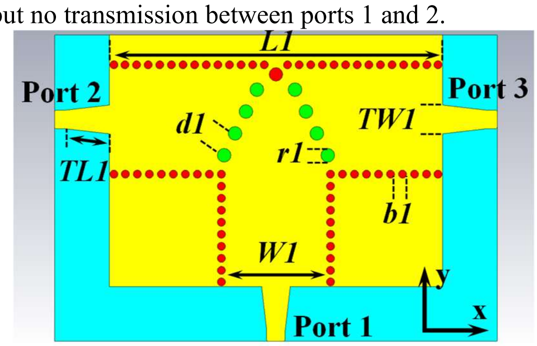


Fig. 3. The schematics of the proposed SPDT switch. Note that liquid metal is shown in green.

Table 2 Operating states associated with the SPDT switch.

State	Connected Ports
A	1 and 2
B	1 and 3

C. *SPDT Switch Incorporating Four RF Blocking Walls.*

Fig. 4 shows the schematic of the proposed SPTT switch. The switch operates in three states, as summarized in Table 3. State A corresponds to the situation that port 1 is connected to port 2, while state 2 corresponds to the situation that port 1 is connected to port 3. Finally, state C corresponds to the situation that port 1 is connected to port 4.

Table 3 Operating states associated with the proposed SPTT switch.

State	Connected Ports
A	1 and 2
B	1 and 3
C	1 and 4

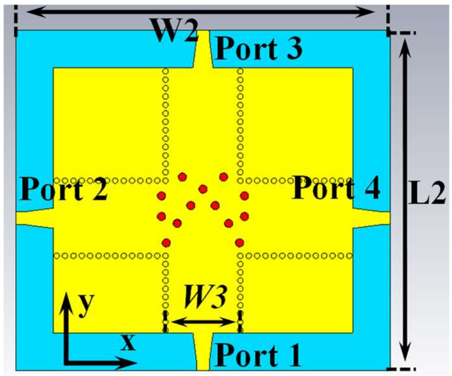
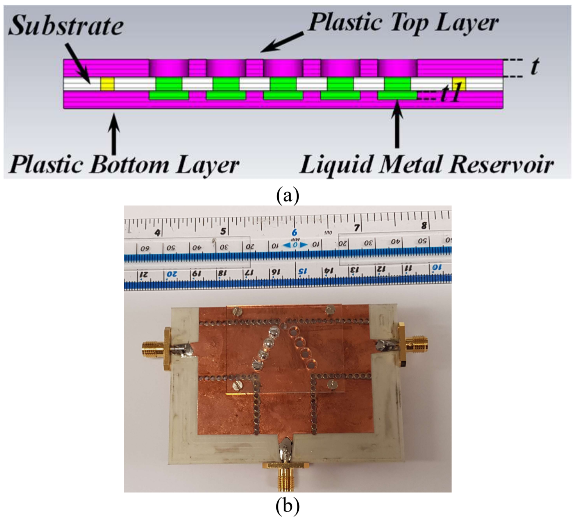


Fig. 4. The schematics of the proposed SPTT SIW switch. Note that liquid metal is shown in green.

III. MECHANICAL AND FABRICATION CONSIDERATION

A two layer plastic structure consisting of clear Perspex with thickness of $t = 2\,mm$ was designed to hold the liquid metal inside the drill holes to form vias, as shown in Fig. 5. Holes were cut through the top layer Perspex. This was necessary to enable injection of liquid metal into each drill hole using a syringe. Cylindrical groves were engraved into the bottom layer of Perspex. The groves were cut to a depth of $t1 = 0.5\,mm$. The holes and groves were formed in the Perspex using a laser machine. Both Perspex layers are attached to the RO4003C substrate using metallic screws. The liquid metal is injected to each via separately using a syringe. This approach for actuation is commonly employed in the literature [10]. Alternative methods of actuation have been reported in the literature, including electrochemically controlled capillary action [1] and the use of a micropump [12].



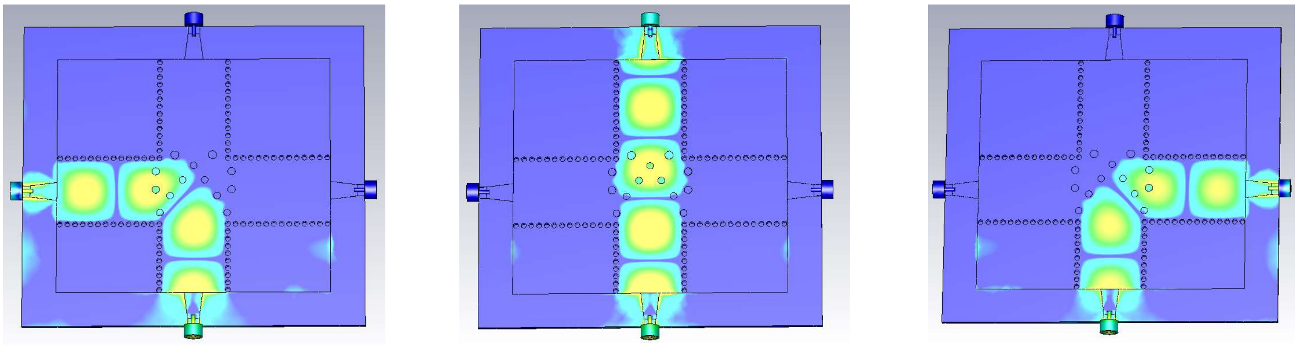
(a)

(b)

Fig. 5. The schematic of the proposed SPST switch. (a) Cross section of SIW with reconfigurable wall with Perspex material, and (b) fabricated prototype.

IV. DISCUSSION AND RESULTS

The proposed SPST switch was designed to operate from 2 GHz to 4.5 GHz. Whereas both the SPDT and SPTT switches were designed to operate from 4 GHz to 8 GHz, in order to validate the suitability of the proposed method for use at higher frequencies. Fig. 2 and Fig. 6 shows the E-field distribution for the SPST and SPTT switch, respectively. It is clear that the wall



(a) (b) (c)

Fig. 6. The E-field distribution of the proposed reconfigurable liquid metal SPTT at 6 GHz. (a) state A, (b) state B and (c) state C.

(a) (b)

Fig. 7. The measured and simulated S-parameters of the SIW with no liquid metal i.e. with wall in OFF state. (a) reflection coefficients (S_{11} and S_{22}) and (b) transmission coefficient (S_{21} and S_{12}).

(a) (b)

Fig. 8. The measured and simulated S-parameters of the SIW with liquid metal i.e. with wall in ON state. (a) transmission coefficient (S_{21} and S_{12}) and (b) reflection coefficients (S_{11} and S_{22}).

provides effective blockage the RF signal when it is in place, as shown in Figs. 2(b) and Fig. 6. Prototypes for the SPST and SPDT were fabricated. Figs. 7 and 8 show measurement results for the SPST switch. Figs. 9 and 10 show measurement results for the SPDT switch, along with simulation results for the SPTT switch, respectively. Fig. 7 shows measured results for the proposed SPST. When the switch is in OFF state (i.e. no liquid metal in the drill holes) the -10 dB bandwidth is 1.9 GHz (ranging from 2.4 GHz to 4.3 GHz). The transmission coefficient (i.e.S_{12}) is approximately -0.5 dB. However, once the liquid metal is inserted into the drill holes to form the RF blocking wall, the signal transmission between both ports, is blocked. Under this condition the values of S_{21} is below approximately -30 dB over the entire operating band, as shown in Fig. 8 (a). Complete reflection is achieved at ports 1 and 2 (i.e. S_{11} is approximately -0.5 dB), as shown in Fig. 8 (b). In addition, the measured result show that the SPDT switch operates efficiently in both states A and B, as shown in Fig. 9. For both cases, a very good agreement is found between the simulated and measured results. The SPDT switch operates efficiently with a bandwidth of 2.7 GHz ranging from 4.6 GHz and 7.3 GHz. In state A, S_{21} is approximately -0.6 dB, as shown in Fig. 9(b).

The isolation between ports 1 and 3 as well as between ports 2 and 3 is below -40 dB, as shown in Fig. 9(c-d). Similarly, the measurement results for state B are a mirror image of those for state A with the transmission coefficient S_{31} approximately 0.65 dB with isolation of less than -40 dB between ports 1 and 2 as well as between ports 3 and 2. The simulation results for the SPTT switch in state B are shown in Fig. 10. In all operating states, the SPTT switch has a bandwidth ranging from 4.7 GHz to 8 GHz. The insertion losses of the SPTT switch is below 1 dB over a 2 GHz bandwidth ranging from 4.7 GHz to 6.7 GHz and the insertion losses are below 1.5 dB in the frequency range 6.8 GHz to 8 GHz. Finally, for all of the proposed switches the isolation between all non-connected ports is lower than -23 dB for all operating states.

Note that all of the switches are symmetrical and reciprocal and so their forward scattering parameters are approximately equal to their reverse scattering parameters (e.g. $S_{11} \approx S_{22}$).

V. Conclusion

This paper presented a method to develop reconfigurable microwave devices by using liquid metal vias. Liquid metal is used to reconfigure an RF blocking wall in an SIW structure. The proposed method was validated numerically and experimentally by develop and testing microwave switches.

Acknowledgment

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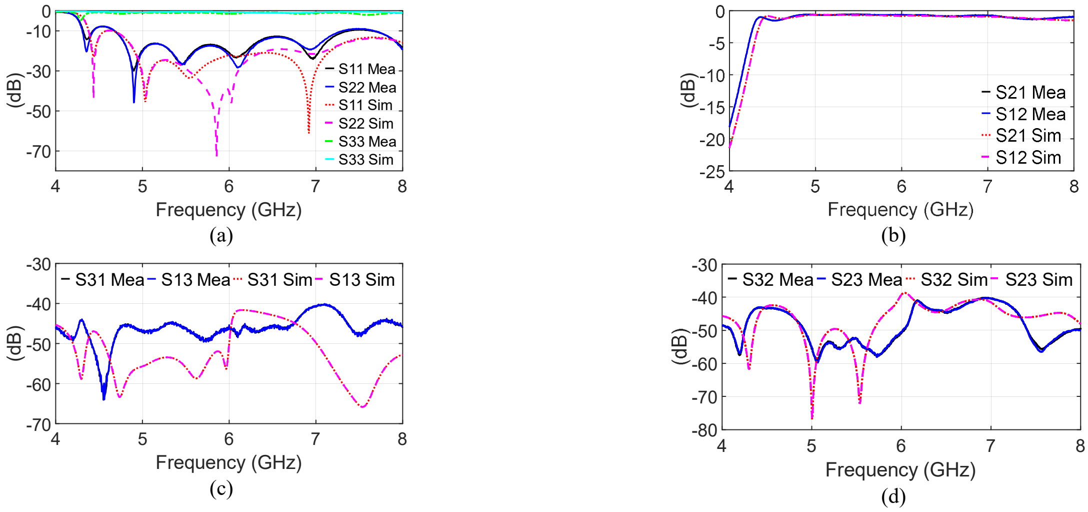

Fig. 9. The measured and simulated s-parameters for the SPDT switch in operating state A. (a) reflection coefficients and (b) transmission coefficients (S_{21} and S_{12}), (c) isolation between ports 1 and 3 and (d) isolation between ports 2 and 3.

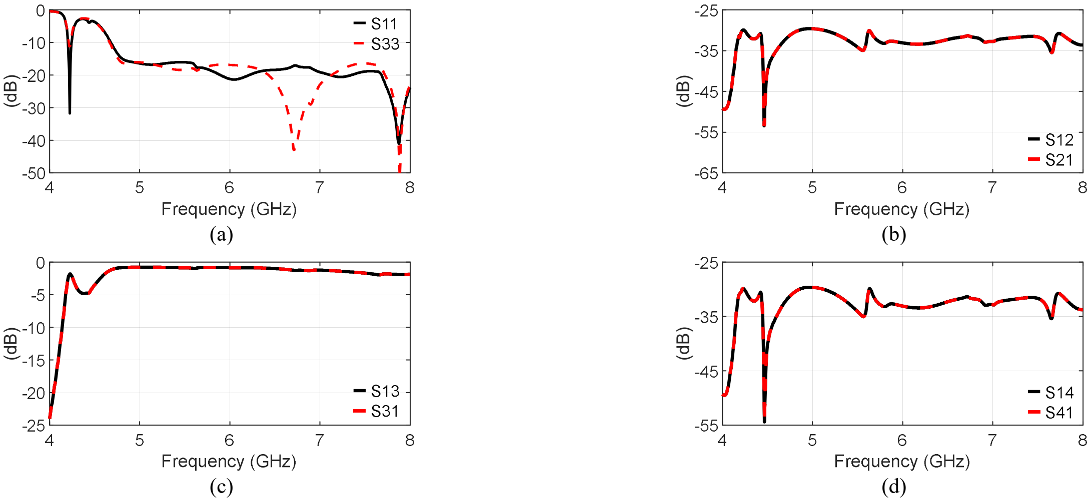

Fig. 10. The simulated s-parameters for the SPTT switch in operating state B. (a) reflection coefficients (S_{11} and S_{33}), (b) isolation between ports 1 and 2, (c) transmission coefficients (S_{13} and S_{31}), and (d) isolation between ports 1 and 4.

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