Circuits and Antennas Reconfigured using Gallium-based Liquid Metal

Abstract—**Wireless telecommunication systems incorporate a range of components (or circuits), including: filters, power splitters, couplers, etc.. They also require antennas to launch electromagnetic energy into the air. Typically, the performance parameters of these circuits and antennas is fixed at the time of manufacture. Reconfigurable circuits and antennas are useful as a way of mitigating for dynamic changes in interference. They also enable systems to respond to changes in network traffic and user requirements. The paper discussed a range of circuits and antennas that can be reconfigured using Gallium-based liquid metal, including: switches, phase shifters, and a beam steerable/switchable antenna. The paper shows that, from the RF perspective, liquid metal is a good approach for reconfiguring circuits and antennas.**

Keywords— ***Reconfigurable circuits and antennas, Microwave Switches, Microwave Phase Shifters, Millimeter Wave Phase Shifters, Beam Steerable Antennas, Beam Switchable Antennas, Gallium-based liquid metal, EGaIn.***

I. INTRODUCTION

Today the radio frequency spectrum is more congested than ever before. At the same time applications such as video streaming and computer gaming have driven the need for communication at higher data rates. The Shannon–Hartley equation tells us that to achieve this we require more bandwidth, than would have been the case in the past, along with a good signal-to-noise-plus-interference ratio. Directional antennas, having low side-lobe-levels, can be helpful in that regard. In an environment where interference changes dynamically, reconfigurable circuits and antennas are helpful. Reconfigurable circuits and antennas also enable systems to respond to changes in traffic levels on a network and to changes in individual user requirements (i.e. desire for more or less data rate depending on the activity being performed at the time). In comparison with alternative approaches (e.g. switchable banks of hardware or broadband systems), this produces more compact systems. Additionally, there is less need for performance compromises. There are 3 main techniques for reconfiguring circuits/antennas: 1) switches/tuning elements, 2) mechanical movement, 3) tunable materials that can vary their bulk properties. Today the most popular technique for reconfiguring circuits and antennas is to use semiconductor switches/tuning elements and this technology is quite mature. However, it suffers from several important limitations including: 1) complexity of the biasing and control circuits, 2) significant overall power consumption, 3) poor harmonic performance, 4) limited tuning range, 5) complex design process created by the frequency dependent input impedance, 6) spurious effects due to isolated areas of metallisation. Around 2014, interest started to grow in liquid metals based on alloys of Gallium which can potentially address all of these issues. Gallium-based liquid metals exhibit attractive properties [1]. They show good electrical conductivities (approx. 17 × lower than that of Copper) and low-toxicity. Their melting points are close to room temperature, making them flexible, stretchable, and reformable; working like 'liquid wires'. In 2018 Wang et al [2] showed that a Gallium-based liquid metal monopole has comparable linearity to a monopole formed from solid Copper. They showed that the linearity of an electrically tunable Gallium-based liquid metal monopole was at least 40 dB better than that of a monopole incorporating varactor diode tuning. The paper also showed that a tunable Gallium-based liquid metal antenna could handle more power (31 dBm) than a varactor-tuned antenna (24 dBm). Antennas incorporating Gallium-based liquid metal have been demonstrated with tuning ranges of >3 octaves [3].

II. SUBSTRATE INTEGRATED WAVEGUIDED (SIW) SWITCHES AND PHASE SHIFTERS

Our team at Queen Mary University of London has devised several switches and phase shifters whose operating states can be reconfigured using a commercially available Gallium-based liquid metal known as EGaIn. These switches and phase shifters were based on substrate integrated waveguide (SIW) technology. The proposed switches have low insertion losses. Devices formed from SIW also have the potential to handle moderately high levels of radio frequency (RF) power. We use two approaches to vary the operating state of a switch or phase shifter, formed from SIW technology. Both approaches rely on adding drill holes into the structure. When a particular drill hole is filled with Gallium-based liquid metal it forms a via. When the drill hole is emptied of liquid metal the via is removed. The location of the drill hole then determines its effect. Drill holes positioned close to the edges of the SIW waveguide tend to act as reactive loading. On the other hand, if a series of drill holes are formed across the transverse cross section of the waveguide they will act as a blocking wall. By opening and closing different combinations of walls it is possible to alter the routing of signals within a branching waveguide.

A. *Single Pole Double Throw (SPDT) Switch*

Fig. 1 shows a single pole double throw (SPDT) switch [4]. The operating mode of the switch is reconfigured by opening and closing a series of walls within a branching waveguide.

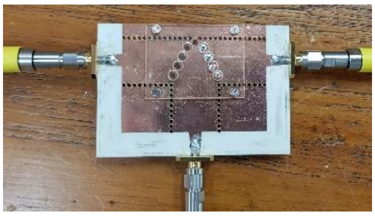
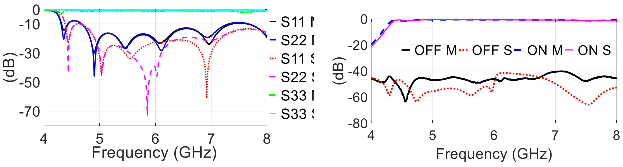


Fig. 1. Single pole double throw switch based on SIW technology.

In Fig. 1 the drill holes are the larger set of holes located beneath the Perspex cover. Fig. 2 illustrates the scattering parameter performance of the switch. It is clear that the switch operates over a wide bandwidth with low insertion loss ≤ 0.7 dB.



(a) (b)

Fig. 2. Scattering parameter performance of the single pole double throw switch, shown in Fig. 1. (a) Return loss curves. (b) Insertion loss curves.

B. Single Pole Triple Throw (SPTT) Switch

Fig. 3 shows a single pole triple throw switch (SPTT) [5]. The operating mode of the switch is reconfigured by opening and closing a series of walls within a branching waveguide. In Fig. 3 the drill holes are the larger set of holes located beneath the Perspex cover. Figs. 4 and 5 illustrate the scattering parameter performance of the switch.

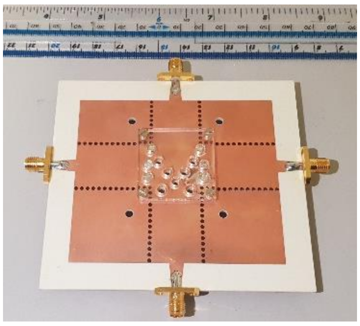
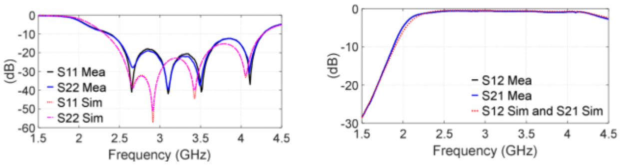


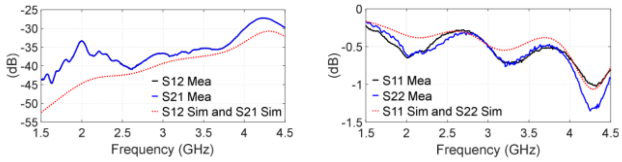
Fig. 3. Single pole triple throw switch based on SIW technology.



(a) (b)

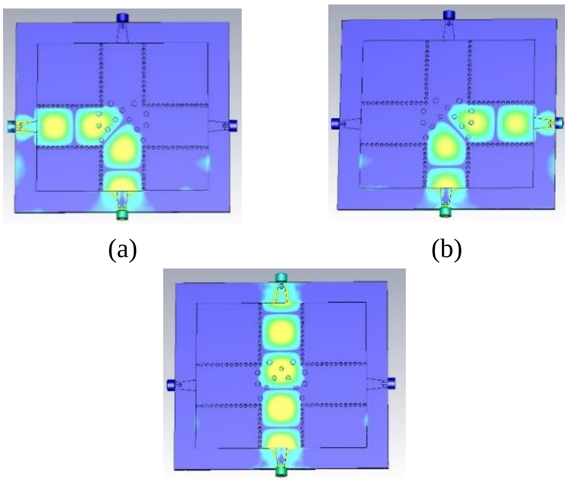
Fig. 4. The measured and simulated S-parameters of the SPTT, shown in Fig. 3, with no liquid metal i.e. with wall in OFF state. (a) reflection coefficients (S_{11} and S_{22}) and (b) transmission coefficient (S_{21} and S_{12}).

The switch operates over a one octave bandwidth with low insertion loss ≤1 dB. Fig. 6 shows the magnetic field distributions associated with the device when it is configured to operate in various different states.



(a) (b)

Fig. 5. 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}).



(a) (b)

(c)

Fig. 6. Magnetic field distributions associated the single pole triple throw switch, shown in Fig. 3.

C. 180° X-Band Phase Shifter Providing both Coarse and Fine Adjustment of Phase

Fig. 7 shows a phase shifter, based on SIW, technology that can provide a phase shift of up to 180° [6]. The device operates at X-Band frequencies (i.e. 10 GHz). It enables both coarse and fine control over the phase shift. Coarse control (in steps of about 60°) is achieved using a switched line approach. This is achieved by altering the route taken by microwave energy as it passes through the device. To do this we employ a series of walls within a branching waveguide. By adding and removing those walls we can vary the route taken by the microwave energy. In Fig. 7 the drill holes, forming those walls, are surrounded by red boxes. Fine control (in steps of 10°) is achieved through the use of drill hole located close to the edges of the waveguide. When the drill holes are filled with liquid metal they form vias that introduce reactive loading into the transmission line. This has the effect of altering the phase shift. In Fig. 7 the drill holes, used to introduce reactive loading, are surrounded by red boxes. The device enables control of the phase in 10° steps from 0° to 180°. Fig. 8 illustrates the scattering parameter performance of the phase shifter. Due to limited space in this paper we are only able to show the operation in Stage A (i.e. a coarse phase shift of 60°). Fig. 9 shows the magnetic field distributions associated with the device when it is configured to operate in various different states. The phase shifter provides a low insertion loss ≤ 2.3 dB.

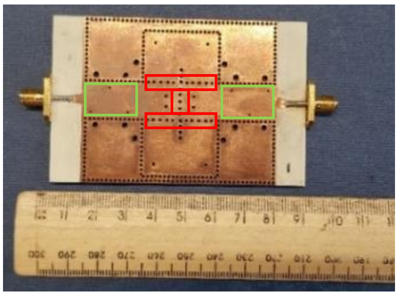
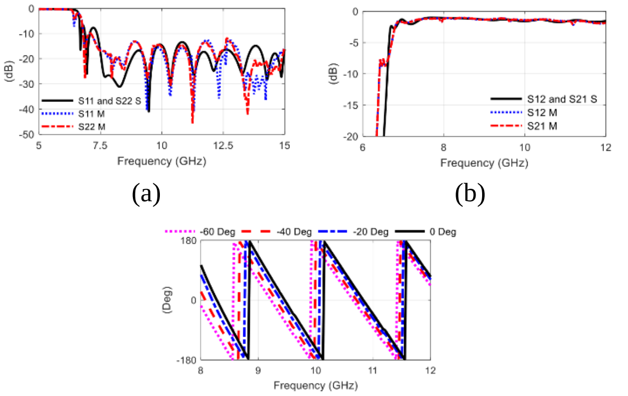


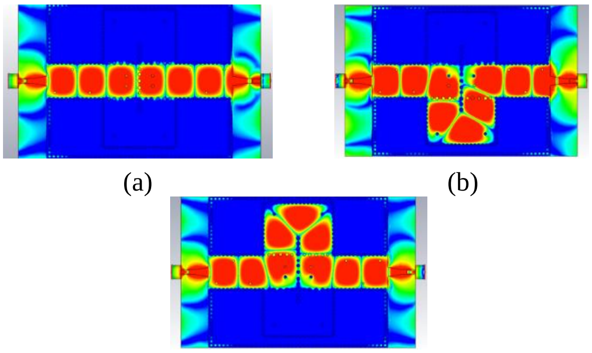
Fig. 7. 180° X-band phase shifter based on SIW technology.



(a) (b)

(c)

Fig. 8. Measured and simulated scattering parameter for 180° X-band phase shifter, shown in Fig. 7, and associated with State A (-60°). (a) S_{11} and S_{22}. (b) S_{21} and S_{12}. (c) Phase of S_{21}.



(a) (b)

(c)

Fig. 9. Magnetic field distributions associated the 180° X-band phase shifter, shown in Fig. 7. The field distributions correspond to states: (a) A = - 60°, (b) B = - 120°, and (c) C = - 180°.

D. 360° X-Band Phase Shifter

Fig. 10 shows a phase shifter, based on SIW, technology that can provide a phase shift of up to 360° [7]. The device operates at X-Band frequencies (i.e. 10GHz). It enables control over the phase shift (in steps of 45°). This is achieved through the use of drill hole located close to the edges of the waveguide. The drill holes are uniformly distributed within the SIW. When the drill holes are filled with liquid metal they form vias that introduce reactive loading into the transmission line. This has the effect of altering the phase shift. In Figs. 10 and 12 the drill holes, used to introduce reactive loading, are filled with liquid metal giving a silver appearance. The device enables control of the phase in 45° steps from 0° to 360°. Fig. 11 illustrates the scattering parameter performance of the phase shifter. The phase shifter provides a low insertion loss ≤ 2.5 dB.

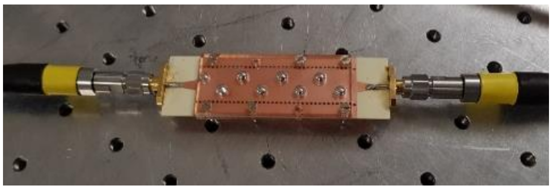
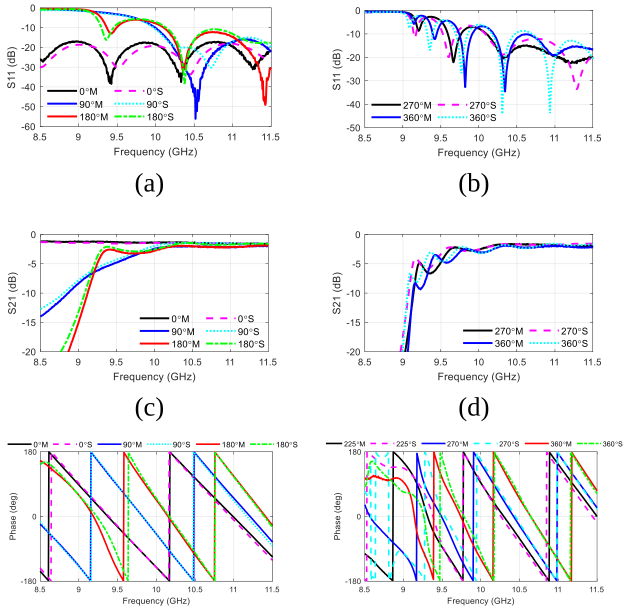


Fig. 10. 360° X-band phase shifter based on SIW technology.



(a) (b)

(c) (d)

(e) (f)

Fig. 11. Scattering parameter performance of the 360° X-band phase shifter, shown in Fig. 10. (a-b) S_{11} and (c-d) S_{21}. (e) phase of S_{21} (0° to 180°) and (f) phase of S_{21} (180° to 360°). Note: M stands for measured results and S stands for simulated results.

E. 360° Millimeter Wave Phase Shifter

Fig. 12 shows a phase shifter, based on SIW, technology that can provide a phase shift of up to 360° [8].

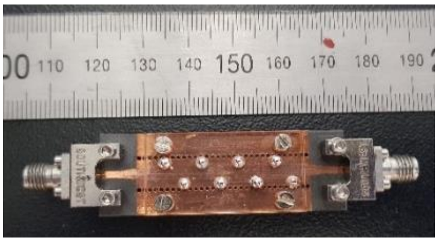


Fig. 12. 360° millimeter wave phase shifter based on SIW technology.

The device operates at millimeter wave frequencies (i.e. 26 GHz). It enables control over the phase shift (in steps of 45°). This is achieved through the use of drill hole located close to the edges of the waveguide. When the drill holes are filled with liquid metal they form vias that introduce reactive loading into the transmission line. This has the effect of altering the phase shift. The device enables control of the phase in 45° steps from 0° to 360°. Fig. 13 illustrates the scattering parameter performance of the phase shifter. The phase shifter provides a low insertion loss ≤ 2.4 dB.

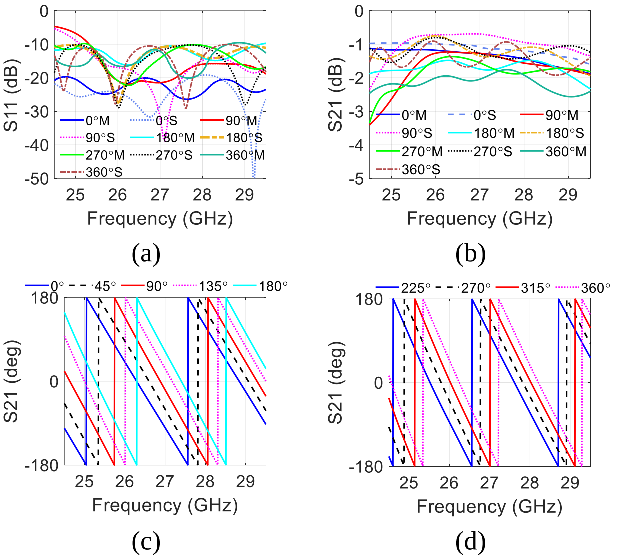


Fig. 13. The simulated and the measured results for the 360° millimetre wave phase LM shifter, shown in Fig. 12. (a) S_{11}, (b) S_{21} and (c-d) measured S_{21} phase. Note: M stands for measured results and S stands for simulated results.

III. BEAM SWITCHABLE/STEERABLE ANTENNAS

Our team at Queen Mary University of London has devised several antennas whose main beam direction can be reconfigured using EGaIn metal. In this section we will show one example to illustrate the work.

A. Phased Array

Fig. 14 shows a phased array antenna [9]. The feed network for the antenna is based around SIW. The feed network incorporates a 1 to 4-way power splitter along with four phase shifters. The phase shifters are closely based around the design discussed in Section II, Part D. The antenna was the world's first phased array antenna incorporating phase shifters reconfigured using EGaIn liquid metal. Fig. 15 illustrates the S-parameter performance of the antenna.

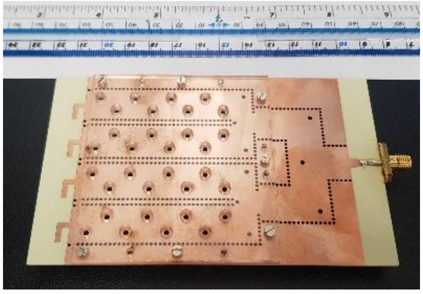


Fig. 14. Phased array antenna incorporating an SIW feed network.

Fig. 16 illustrates the radiation patterns associated with the antenna, for different modes of operation. The antenna has a scan angle range of ±38° for a side-lobe level (SLL) of 6 dB. The scan loss is 1.5 dB.

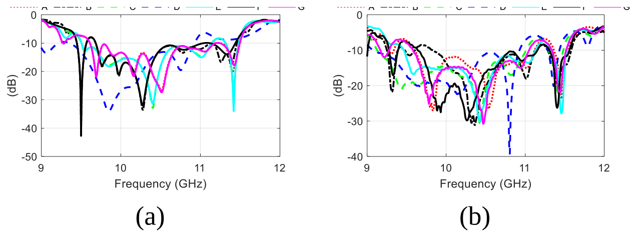


Fig. 15. Reflection coefficients (S_{11}) associated with the LM phased array antenna, shown in Fig. 14, in all states. (a) Simulated result and (b) measured result.

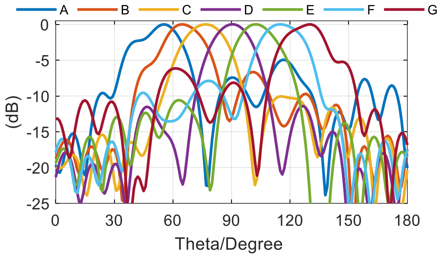


Fig. 16. Radiation pattern performance of the phased array antenna, shown in Fig. 14.

IV. CONCLUSION

This paper has presented a range of circuits and antennas whose operating parameters can be reconfigured with the aid of a Gallium-based liquid metal called EGaIn. Gallium-based liquid metal enables forms of reconfiguration (e.g. continuous length control over an unlimited range) that are impossible using conventional approaches. This helps to ensure a wider tuning range than can be achieved using semiconductor based switching and tuning elements. The circuits and antenna presented in the paper have good performance. Typically, the phase shifters and switches have insertion losses on the order on 2.5 dB. It is important to realise that there is almost no dissipation of RF power in the liquid metal. Also, liquid metal has a purely real impedance that does not depend on frequency. For this reason the approaches discussed in this paper can be applied at very high frequencies without incurring additional losses. In particular Further work is needed to devise practical ways of moving liquid metal around in order support truly dynamic reconfiguration.

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