Continuously Tunable Frequency Reconfigurable Liquid Metal Microstrip Patch Antenna

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Abstract—This paper presents a continuously tunable microstrip patch antenna formed from liquid metal (eutectic gallium indium). The concept and design of the antenna have been validated through computer simulation. The antenna is capable of reconfiguring its operating frequency in a continuous manner. The proposed design consists of a microstrip patch which is excited via aperture coupling. The EGaIn liquid metal is contained within a microfluidic channel which is formed within a polydimethylsiloxane (PDMS) substrate. Frequency tuning is achieved by altering the amount of fluid within the channel to vary the electrical length of the antenna. The simulated antenna provides a frequency tuning range of approximately 104% and a total usable spectrum ($S_{11} < -10$ dB) of 105%. The antenna can be tuned from 3.21 GHz to 10.12 GHz. The maximum realized gain is 6.9 dBi and the total efficiency is 82%.

Keywords—aperture-coupled patch antenna; continuous tuning; frequency reconfigurable; liquid metal; microfluidics

I. INTRODUCTION

Reconfigurable antennas are an enabling technology for the kind of intelligent, self-aware, self-configuring systems that are required within future telecommunications networks as well as within industry 4.0. Various techniques have been applied to achieve frequency reconfigurability. Most conventional reconfigurable antennas are unable to support continuous tunability due to the on/off nature of switches. The use of liquid metal to produce a reconfigurable antenna represents an entirely new approach which promises important performance advantages compared with conventional reconfigurable antennas, including: improved linearity and higher power handling together with the possibility of achieving continuous tuning and lower overall power losses/consumption. A number of frequency reconfigurable microstrip patch antennas have been demonstrated in the literature. In [1] the antenna incorporates channels which can be filled with liquid metal and used as switches to reconfigure the operating frequency of the antenna between two discrete values. The antenna in [2] is reconfigured by varying the location of a shorting pin. In this way the operating frequency can be tuned between two discrete values. A frequency tunable microstrip patch antenna is presented in [3]. A U-shaped slot is incorporated within the ground plane. By partially filling the slot with liquid metal it is possible to alter the length of the current path and thus vary the

operating frequency. The antenna achieved a tuning range from 1.85 GHz to 2.07 GHz. Reference [4] presents a patch antenna formed from liquid metal and embedded within a silicon substrate. The operating frequency of the antenna can be varied continuously from 1.3 GHz to 3 GHz ($S_{11} < -6$ dB) by mechanically stretching the antenna. Unfortunately [4] suffers from low efficiencies at the lower end of the tuning range. Additionally the instantaneous operating bandwidth of each reconfigurable state was narrow.

This paper describes a continuously frequency tunable patch antenna whose operating frequency can be varied from 3.21 GHz to 10.12 GHz using EGaIn ($\sigma = 3.4 \times 10^6$ S/m) liquid metal. This equates to a tuning range of approximately 104% and a total usable spectrum ($S_{11} < -10$ dB) of 105%. The paper begins by describing the design of the antenna. Then simulation results are presented and discussed. Finally comparisons are drawn between this work and other frequency reconfigurable patch antennas using liquid metal [1-4].

II. ANTENNA AND MICROFLUIDIC CHANNEL DESIGN

EGaIn reacts with common metals, for this reason the proposed antenna uses aperture coupling to avoid direct contact between the EGaIn and copper. In addition this feeding method allows more freedom when selecting the substrate material for the feed while isolating it from the radiating element. Finally the aperture feeding approach avoids the need for the feeding probe to puncture the polydimethylsiloxane (PDMS) which ensures a more mechanically reliable and hermetically sealed structure. The antenna, shown in Fig. 1, consists of two parts. The lower part is the feed substrate made of 0.8 mm-thick FR-4 ($\epsilon_r = 4.55$ and $\tan\delta = 0.0175$) while the top part is a 1.6 mm-thick PDMS substrate ($\epsilon_r = 2.67$ and $\tan\delta = 0.001$) incorporating a microfluidic channel to contain the EGaIn.

The width of the channel and the diameter of the posts are 1 mm and 0.1 mm respectively and were designed by referring to [5]. The microfluidic channel is laid out in a cavity with an overall length of 26.3 mm (L_R) and a width of 17.9 mm (W_R). In other words, the antenna length can be increased continuously up to 26.3 mm leading to a continuous frequency tunability. There are two connectors for inlet/outlet to allow control of the liquid length. A carrier liquid, namely: Hydrocal 2400 ($\epsilon_r = 2.31$ and $\tan\delta = 0.05$), is used to facilitate moving

Fig. 1. Outline of antenna and feed substrates, $W = 50$ mm, $L = 50$ mm, $W_R = 17.9$ mm, $L_R = 26.3$ mm, $W_A = 7.75$ mm, $L_A = 0.775$ mm, $W_F = 1.5$ mm, and $L_S = 6$ mm. Ant_L represents variable length of liquid metal radiator.

the EGaIn. Due to a thin oxide skin formed on EGaIn surface, it does not flow between the posts until the applied pressure exceeds critical pressure of the inter-posts paths [5]. EGaIn and carrier liquid can be retracted in a reversible process to allow a continuous frequency tunability in both directions.

III. SIMULATION RESULTS

Fig. 2 depicts the simulated frequency response, of the proposed antenna for values of Ant_L ranging from 6.5 mm to 26.3 mm. Fig. 3 shows simulated radiation patterns (realized gain) corresponding to three different values of Ant_L . The variations in the radiation pattern caused by changing Ant_L are minor. The antenna yields its maximum realized gain of 6.9 dBi (corresponding to a total efficiency of 82%) at 5.85 GHz, i.e. when $Ant_L = 13.1$ mm. The antenna yields its minimum realized gain of 4.97 dBi (corresponding to a total efficiency of 66%) at 10.12 GHz, i.e. when the antenna length is $Ant_L = 4.3$ mm plus half-filled adjacent channel segment.

Table I compares the performance of the proposed antenna with that of published designs, from the literature, for frequency reconfigurable liquid metal patch antennas.

Fig. 2. Reflection coefficient of EGaIn patch antenna when varying Ant_L .

Fig. 3. Radiation patterns (realized gain) of EGaIn patch antenna for three different Ant_L values. (a) E-plane ($\varphi = 0^\circ$). (b) H-plane ($\varphi = 90^\circ$).

TABLE I. COMPARISON OF THIS WORK TO OTHER PUBLISHED FREQUENCY RECONFIGURABLE LIQUID METAL MICROSTRIP PATCH ANTENNAS

Reference	Frequency Range (GHz)	Tuning Range (%)	Realized Gain (dBi)	Total Efficiency (%)
This work	3.21 – 10.12	103.68	4.97 – 6.9	66 – 82
[1]	1.59 & 2.41	41	4.09 & 5.54	60.6 & 75.1
[2]	4.8 & 5.4	11.76	-	-
[3]	1.85 – 2.07	11.22	2.1 – 4.1	-
[4]	1.32 – 2.84	73.08	$\approx 6 - 8$	≤ 80

IV. CONCLUSION

The paper presents a continuously tunable microstrip patch antenna formed entirely from liquid metal. The simulated antenna is capable of continuously reconfiguring its operating frequency from 3.21 GHz to 10.12 GHz. This equates to a tuning range of approximately 104% and a total usable spectrum ($S_{11} < -10$ dB) of 105%. A maximum simulated realized gain of 6.9 dBi and 82% total efficiency are obtained.

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