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Liquid RF MEMS Wideband Reflective and Absorptive Switches
Chung-Hao Chen, Student Member, IEEE, and Dimitrios Peroulis, Member, IEEE

Abstract—This paper reports on the design, fabrication, and characterization of a new class of wideband liquid RF microelectromechanical-system reflective and absorptive switches. A number of different liquids are considered, including mercury, Galinstan, and ultrapure and ionic water. We first briefly review the performance of liquid–metal switches made by mercury and Galinstan. Such switches demonstrate excellent off-state insertion loss of less than 1.3 dB up to 100 GHz (the loss includes a 1500-μm-long line) and on-state isolation of better than 20 dB from 20 to 100 GHz. The main part of this paper, however, focuses on significantly transforming these designs to actually absorb and not reflect the incident power in their on-state, while at the same time maintaining their excellent off-state performance. Absorptive behavior is particularly important for high-power applications. Simpler materials such as water are proven to be very effective for wideband absorptive switches. In particular, three classes of water-based absorptive switches are discussed depending on the level of the signal coupling to water. At 10–40 GHz, the optimal design exhibits off-state insertion loss of less than 1.3 dB, on- and off-state return loss of less than 10 dB, and on-state isolation of 27.5-dB isolation at 40 GHz.

Index Terms—Absorptive switch, microfluidics, RF microelectromechanical system (RF MEMS), water, wideband.

I. INTRODUCTION

CONVENTIONAL RF microelectromechanical system (RF MEMS) microwave switches rely on metal-to-dielectric or metal-to-metal contacts [1]. Metal-to-dielectric switches, also known as capacitive switches, are typically useful for frequencies above 5–10 GHz where their down-state capacitance results in an effective short circuit. On the other hand, metal-to-metal switches, also known as dc-contact switches, cover the application range from dc to 40–50 GHz because of their ability to pass dc signals. A significant number of publications in the last 15 years have clearly demonstrated the numerous advantages of these devices in the areas of loss (0.1–0.3 dB up to 40 GHz), isolation (25–30 dB up to 40 GHz), linearity (third-order intercept point +66 dBm), and dc power consumption (2–5 nJ of switching energy) [1]. Recently, commercial switches started becoming available for medium RF power ranges (1–10 W) but only for applications requiring: 1) cold switching (i.e., RF power is cut off before the switch can change state); 2) a relatively low number of cycles (<10⁹); and 3) reflection and not absorption of the input power.¹² Absorptive switches for power ranges in excess of 0.1–1 W and reliability levels of over 10⁹ cycles remain a serious challenge primarily due to the inherent limitations of metal-to-dielectric and metal-to-metal contacts.

Several papers and reports [2]–[15] explain in detail these limitations of metal-to-dielectric and metal-to-metal contacts for high-power applications. In summary, most of the failure mechanisms can be directly linked to the following three fundamental reasons.

1) Limited contact area where current can flow through from one contact member to the other: this is very important in the down-state of metal-to-metal contact switches and is due to the roughness of the contacting solid surfaces that limits the true contact area.

2) Limited conductive volume of the switch itself: this limits the current that may flow through the switch without exceeding the critical current density or excessively raising the switch temperature [16], [17]. This is particularly relevant to metal-to-dielectric contact switches.

3) Limited heat dissipation for absorptive switches. Very few absorptive switch implementations exist today (an example is shown in [18]), but even these are not applicable to high-power applications due to the previous limitations. Absorptive switches in particular face additional limitations caused by the need to dissipate the heat associated with the absorbed power.

4) Arching that occurs during hot switching for medium- to high-power applications.

Liquid-contact switches offer numerous potential advantages in these areas including: 1) minimal contact surface damage since no excessive pressures are needed for successful contact; 2) large true contact areas because of the natural ability of liquids to conform to solid surfaces; and 3) the ability to precisely pattern and move liquids on a smooth wafer [19]. Furthermore, liquids in microfluidic channels may be circulated, which has the potential to lead to switches handling significantly improved power loads.

It is the goal of this paper to demonstrate such liquid-based designs for RF/microwave applications. In Section II, we briefly summarize the technology necessary to achieve liquid-metal reflective switches as have been reported by the authors in [19] and [20]. We subsequently investigate in Section III the potential of water being employed as an effective and simple medium for realizing absorptive switches. In this section, we also generate

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equivalent models that are utilized to facilitate advanced absorptive switch designs. Sections IV–VI introduce new classes of wideband water-based absorptive switches from 10 to 40 GHz. We present three different classes of absorptive switches depending on the level of interaction between the RF signal and the water in the switch structure.

II. REFLECTIVE SWITCHES

The authors reported in [19] and [20] two wideband reflective switches based on two different liquid metals: mercury and Galinstan\(^3\) (eutectic gallium–indium–tin alloy). In this paper, we very briefly summarize their results by paying particular attention to their differences from the absorptive switches that are analyzed in more detail in Sections III–VII.

The fundamental idea of the reflective switches is to place a liquid-metal droplet or slug in the critical path of the RF signal and thus create a short circuit. This constitutes the on-state of the switch. The droplet or slug may either be in direct contact with the solid metal [2], [5] or it could form a capacitive contact through a thin-layer dielectric [19], [20]. When the droplet or slug is removed from the RF signal path, the switch presents very low loss that is dominated by the transmission line itself. Fig. 1 shows the schematic diagram and an implementation of a mercury-based liquid switch. The mercury droplet radius is 500 \(\mu\)m and is electrostatically actuated with 110 V. For capacitive switches, the droplet size is determined by the available technology (e.g., mercury droplets with radii as small as 25 \(\mu\)m have been reported [21]), and the required isolation at a given frequency. For example, the relatively large size of the droplet in Fig. 1 is determined by the requirement of 20-dB isolation at 20 GHz. The droplet can be actuated by controlling the voltages of the actuation pad and the bias line that is in direct contact with the droplet. It is achieved by keeping the droplet staying in contact with the bias line in the on- and off-states. When actuated, the droplet moves a distance of 370 \(\mu\)m away from the RF signal path but remains in contact with the bias line. This switch presents an off-state insertion loss of less than 0.6 dB at 30 GHz, which is almost solely due to the CPW line itself. The on-state isolation is approximately 20 dB at 30 GHz, as shown in Fig. 2. While this switch exhibits many of the desired characteristics of liquid-metal switches, it is based on a toxic metal and is unpackaged.

These drawbacks are addressed in [20] where a Galinstan slug in a 500-\(\mu\)m-wide Polydimethylsiloxane microfluidic channel is employed (Fig. 3). Galinstan has the great advantage of being nontoxic and environmentally friendly. On the other hand, it is very challenging to actuate it without leaving residue due to its high adherence to most materials. This problem is addressed in [20] by actuating the Galinstan slug within a Teflon solution, which prevents it from leaving residue on any of the metallic, dielectric, or polymer surfaces. The switch on-state is capacitive due to a thin 180-nm Teflon layer \((\varepsilon_r = 1.93)\) between the Galinstan slug and coplanar waveguide (CPW) conductors. The off-state is simply implemented by removing the Galinstan slug from the CPW line and replacing it with Teflon solution. As shown in [20], the Teflon solution and the microchannel induce an insertion loss of less than 0.14 dB at 30 GHz. This switch is characterized up to 100 GHz and shows an isolation of approximately 24 dB at 30 GHz. During the measurement, the Galinstan slug was manually moved by connecting a syringe to one of the

external tube. For practical applications, an on-wafer pump or other actuation mechanism for Galinstan is needed.

A critical view of these liquid-metal implementations indicates that the off-state insertion loss is limited by the transmission line loss, while the on-state isolation is limited by the overlapping area between the liquid droplet or slug and the CPW line. For practical designs, this isolation seems to be limited to 23–26 dB for a single switch. While this performance compares favorably with conventional reflective RF MEMS switches, additional significant advantages can be gained by considering alternative architectures for liquid switches and particularly absorptive switches. In other words, an absorptive switch can maintain similar levels of isolation and insertion loss but with the additional advantage of minimum reflected power in both states. Sections III–VII further explain these advantages and provide a comprehensive design flow for obtaining optimal absorptive switches.

III. WATER FOR ABSORPTIVE SWITCHES

In addition to reflective switches, liquid metals can result in absorptive switches but with significantly added complexity. This can be achieved by replacing the solid contacts with liquid ones in traditional RF MEMS absorptive switches. For example, two liquid droplets and two 50-Ω loads can synthesize an absorptive CPW switch, as shown in [18]. In this section, we demonstrate a new way to implement absorptive switches that results in significantly smaller and simpler designs. Water is the key material in these designs, since it has the natural ability to absorb RF energy.

The conductivity of water is much lower than good metals, and so it cannot yield reflective switches. For example, the conductivity of ultrapure water is as low as $5.5 \times 10^{-6}$ S/m.\(^4\) Even the conductivity of sea water that contains many ions is less than 5 S/m. However, water exhibits a very high dielectric constant ($\sim 80$ at low frequencies) due to its large dipolar molecules. Under the influence of an electromagnetic field, these dipolar molecules attempt to continuously reorient themselves following the applied electric fields. As the frequency of the field is increased to the microwave range ($> 1$ GHz), the molecules cannot completely follow the field, which causes a phase lag that leads to energy loss usually observed as heat. This phenomenon is called dielectric relaxation [22] and can be mathematically expressed via the concept of complex permittivity. The following equation, known as the Debye equation [23], is commonly employed to express the response of the dielectric relaxation assuming ideal and noninteracting dipoles and is a good approximation up to about 80 GHz [24]:

$$\varepsilon(\omega) = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1 + j\omega\tau}$$

(1)

where $\varepsilon_\infty$ is the permittivity at the high-frequency limit, $\varepsilon_s$ is the permittivity at the low-frequency limit, $\omega$ is the angular frequency, and $\tau$ is the relaxation time given by

$$\tau = \frac{4\pi\eta r^3}{kT}$$

(2)


where $r$ is the molecular radius, $\eta$ is the viscosity, $k$ is the Boltzman constant, and $T$ is the temperature.

The fundamental idea in utilizing water for absorptive switches is to force the RF signal to propagate through a volume of water so it can be significantly attenuated. At the same time, it is important to limit the reflected power to a minimum. In this study, we discuss three different designs for accomplishing this: droplet switch, single-channel switch, and multichannel switch. These are shown in Sections IV–VI, respectively. For each design, we underline the tradeoffs between fabrication complexity, RF performance, and potential for electrothermal codesign.

IV. FIRST ABSORPTIVE SWITCH: WATER DROPLET ON CPW LINE PRINTED ON SILICON SUBSTRATE

A. Design and Fabrication

This is the simplest design where a water droplet is precisely injected onto the desired location over a CPW line printed on a silicon substrate (Fig. 4). When the droplet is over the CPW line, part of the incoming signal is dissipated due to dielectric relaxation (on-state). On the other hand, the signal can freely propagate through the CPW line if the droplet is moved away from it (off-state). Direct contact between the droplet and the actuation pads is prevented by a 1-μm-thick SiO₂ layer that covers the CPW metal lines. The droplet motion can be readily controlled with electrostatic actuation, as shown in Fig. 5. The ground planes of the CPW line as well as a separate electrode are utilized as the actuation pads in this scheme. There is also a 10-μm-wide Ti/Ni bias line between these pads that is in direct contact with the water droplet in order to provide the appropriate bias voltage. As shown in Fig. 4, motion can be achieved by switching the bias voltage of the actuation pads and the bias line. The droplet shown in Fig. 5 has a radius of 400 μm and requires an actuation voltage of 80 V. This relatively low voltage is achieved by spin-coating the wafer surface with a 0.25-μm-thick Teflon insulation layer. Teflon not only reduces the actuation voltage but also provides a hydrophobic layer that facilitates the droplet formation. With this hydrophobic layer, the contact angle of the water droplet is approximately 100°. In the absence of this Teflon layer, water spreads out easily due to the hydrophilicity of the SiO₂ surface.

B. RF Performance

Fig. 6 shows the measured on-state frequency response of the structure of Fig. 5. The off-state is identical to the one shown in Fig. 2. The droplet in this experiment is made of deionized
water. As it can be observed, the return loss remains below 10 dB for frequencies above 35 GHz. The reflected power is mainly caused by the impedance mismatch between the water and air interface due to water’s high dielectric constant. With suitable matching, the reflected power can be further reduced, as will be shown in Section VI.

The simplicity of this switch is very attractive because the obtained RF results allow us to extract a Debye-type model for the droplet that can facilitate the design of substantially improved switches. The Ansoft High Frequency Structure Simulator (HFSS) tool is used to derive the water model that fits the measured data. By employing the Debye model of (1) and by fitting its parameters to the measured data, the following expressions for the water droplet dielectric constant and conductivity can be derived:

\[
\begin{align*}
\varepsilon_r &= 8.38287 + \frac{61.6171}{1 + 3.71028 \times 10^{-21} \times f^2} \\
\sigma &= 1.24003 + \frac{2.08801 \times 10^{-19} \times f^2}{1 + 3.71028 \times 10^{-21} \times f^2}
\end{align*}
\]

where \(\varepsilon_r\) is the dielectric constant (real part), \(\sigma\) is the conductivity, and \(f\) is the frequency. This model is valid in the measured frequency range of 2–100 GHz. The fitted results are shown in Fig. 6. It is worth noting that these results are in agreement with the measured data in [25] at 25 °C.

Fig. 7 shows the dielectric constant and conductivity of water as a function of frequency using the derived equations. As this figure shows, the lossy character of water dominates after approximately 20 GHz.

Increasing the on-state isolation for this design requires injecting additional droplets on the CPW line. The line insertion loss increases from 0.8 dB at 30 GHz to 6.4, 12.9, and 20.7 dB when one, two, and three droplets are injected in series, respectively. Fig. 8 illustrates these results up to 100 GHz. The loss is generally proportional to the length of the water-covered section of the line. As these measurements indicate, at 30 GHz, the water-induced line loss is 84 dB/cm while the loss of the line itself is only 1.77 dB/cm.

V. SECOND ABSORPTIVE SWITCH: WATER SURROUNDING SUSPENDED CPW LINE

A. Design and Fabrication

A drawback of the previous design is that the droplets tend to evaporate if they are not packaged. In addition, the isolation is relatively small due to the fact that part of the wave propagates in the low-loss substrate even when the droplet is placed on the CPW line. Consequently, reasonable isolation (> 15 dB) requires long lines of the order of 2 mm for 30-GHz applications. This design can be improved if the water is also placed on the bottom part of the CPW line. This idea is depicted in Fig. 9.
Fig. 8. Measured insertion loss of water droplets on a CPW transmission line. Each droplet has a 400-μm radius. Water droplets are placed next to each other.

Fig. 9. (a) First absorptive switch: only half of the electric field is covered by the water droplet. (b) Second absorptive switch: in this improved structure, the water surrounds the CPW line, causing all of the electric field to propagate through its volume.

The fabrication process for achieving this is shown in Fig. 10 and can be divided into four main parts: substrate fabrication, microchannel construction, channel bonding, and the external tubes mounting. All steps are completed at the Birck Nanotechnology Center at Purdue University.

1) **Substrate Fabrication:** A low-stress 1.5-μm-thick Ti/Au/Ti layer is first sputter-deposited and patterned on a high-resistivity wafer to form the CPW line. The wafer is then coated with a 5000-Å-thick SiO$_2$ layer deposited by plasma-enhanced chemical vapor deposition (PECVD). This oxide layer facilitates the subsequent microchannel bonding. In order to suspend the CPW line, the oxide is wet etched from the designated microchannel area, and an additional photoresist layer is spin-coated and patterned. The silicon under the CPW line is then isotropically etched by using an XeF$_2$ etcher. With 3-torr gas pressure and 15 s/cycle, the ratio of the undercut and depth is approximately 1.1 : 2. The etch rate varies depending on the total etched area. Finally, the photoresist is removed by an acetone/isopropyl-alcohol release process combined with an O$_2$-plasma dry etch. Fig. 11 shows two representative pictures of one and two air-suspended CPW lines captured by a scanning electron microscope. The maximum channel depth is approximately 200 μm in these figures.

2) **Microchannel Construction:** To build the microchannel, an inverted mold is fabricated by a stereolithography process [26]. Dummy tubes are then inserted on the mold to build holes for later insertion of the external tubes. The polydimethylsiloxane base and its curing agent are then well mixed in a 10 : 1 ratio and poured into the mold. The polydimethylsiloxane and mold are subsequently cured overnight at room temperature. The microchannels are finally peeled off and separated.

3) **Channel Bonding:** As Fig. 10(c) shows, the polydimethylsiloxane microchannel and the CPW substrate are then aligned and bonded under a magnifying lens. This bonding is achieved through an important but simple surface treatment process. It is accomplished by bringing both bonding surfaces of the microchannel and the substrate under 20-W Ar/O$_2$ plasma. The chamber pressure is 1.7 torr and the ratio of the Ar and O$_2$ gases
Fig. 11. One and two air-suspended CPW line segments. When covered with microchannels, these silicon-etched channels can be filled with water, implementing the scheme of Fig. 9(b).

is 8:7, respectively. The treatment time is 20 s. After this treatment, a strong bonding strength forms once these surfaces are in contact [27].

4) External Tube Mounting: Teflon tubes with outer diameter of 1.1 mm and inner diameter of 500 μm are employed as the external tubes to allow water to flow in/out of the microchannel. These tubes are fit to the holes at the ends of the channels and sealed by a small amount of polydimethylsiloxane.

5) Teflon Coating: It is recommended to coat the inner microchannel and suspended CPW with a thin Teflon layer by purging the microchannel with diluted Teflon AF solution and following with at least a 2-hr 130°C oven bake. The teflon layer reduces flow resistance and avoids water residuals. It is the passivation layer that resists corrosion of the switch metals.

Fig. 12 shows the completed device. With the microchannel and the silicon-etched channel, when water flows into the switch, it completely surrounds the air-suspended CPW line segments. For mass production, it is necessary to utilize a precise method for dispensing the liquids. A great deal of progress has been made by inkjet printing companies in this area during the last two decades, so it is not expected to present a difficult challenge.

B. RF Performance

Channels of several different widths with suspended 60-/100-/60-μm CPW lines have been fabricated and measured, as shown in Fig. 13. At 30 GHz, the insertion losses are 8.6, 14.3, and 23.7 dB for 500-, 1000-, and 1500-μm-wide microchannels, respectively. These measurements yield a loss of approximately 160 dB/cm that is almost twice the calculated loss of the CPW line with water on one side only (84 dB/cm).

As Fig. 13 clearly shows, the on-state reflection coefficient is not acceptable, since it is above −10 dB for frequencies beyond 3–3.5 GHz. This is due to the fact that the suspended 60-/100-/60-μm CPW line is not a 50-Ω line when surrounded by water. As a result, although this design does provide a higher on-state isolation than the first one and it does address the droplet evaporation issue, it requires further improvements for practical implementation. These are addressed in Section VI.

VI. THIRD ABSORPTIVE SWITCH: DISTRIBUTED WATER SURROUNDING SUSPENDED CPW LINE SEGMENTS

A. Design Optimization

As already mentioned in Section V, an optimized version of the suspended CPW line requires proper matching for both the on- and off-states. While this is straightforward for narrowband designs, it is particularly challenging for wideband absorptive switches because the on-state CPW impedance is complex and varies with frequency. Fig. 14 shows the simulated characteristic impedance of a 100-/100-/100-μm CPW line when surrounded by water.

To address this issue, we propose a new design methodology based on periodic loading of CPW segments with water. This is inspired by the low-Z/high-Z low-pass filter design process [28]. The layout of the proposed design is shown in Fig. 15. The layout includes silicon-supported CPW segments (marked as low-Z sections in the figure) and air-suspended CPW segments (marked as high-Z segments). The latter segments are either surrounded by water (on-state) or by air (off-state) Fig. 11 shows two examples of such segments. The goal of the design
Fig. 13. Measured and simulated insertion loss of the CPW-suspended switches with 500-/1000-/1500-μm-wide channels.

is to find the shortest lengths for all CPW segments and their respective impedances in order to get an optimal design. A design is considered optimal when it provides the required on-state isolation and the on-/off-state return losses for the minimum possible transmission-line lengths.

As an example, we set the following goals for our design:

Required Isolation > 20 dB at \( f = 30 \) GHz \( (5) \)

Required Return Loss > 10 dB at \( f = 10 - 40 \) GHz, \( (6) \)

While brute-force optimization is possible, the following steps provide the necessary physical insight to adapt the absorptive switch design process to a variety of requirements.

1) Off-State Matching: Performing the off-state matching allows us to determine the total number of CPW segments needed and the lengths of the air-suspended segments. The lengths of the silicon-supported segments are determined by the on-state matching. The required steps are as follows.

Step 1) Considering the off-state matching problem, we observe that the air-suspended line segments are naturally high-impedance sections and can be approximated as series inductors. On the other hand, the silicon-supported segments can be fabricated as low-impedance lines and, consequently, can be approximated as shunt capacitors. The approximate inductance and capacitance values are \( [28] \)

\[
L_{\text{si}} \simeq \frac{L_s}{c} Z_h \quad (7)
\]

\[
C_{\text{sh}} \simeq \frac{L_s}{c} \sqrt{\varepsilon_{\text{eff}}} Z_l \quad (8)
\]

where \( L_{\text{si}} \) is the series inductance, \( C_{\text{sh}} \) is the shunt capacitance, \( Z_h \) is the high-Z impedance, \( Z_l \) is the low-Z impedance, \( c \) is the speed of light in vacuum, \( \varepsilon_{\text{eff}} \) is the effective dielectric constant of the low-Z CPW segments \( (\varepsilon_{\text{eff}} \simeq 6.3) \), and \( L_s \) is the length of each CPW segment, \( i = 1 \) to \( N \), where \( N \) is the total number of segments.
Step 2) We can, therefore, design the off-state matching network as a maximally flat low-pass filter [28]. Given the frequency range of interest in this example (10–40 GHz), we choose a cutoff frequency of \( f_c = 60 \) GHz for this design. For this cutoff frequency and for \( Z_0 = 50 \Omega \) system impedance, the equivalent circuit is shown in Fig. 16. Additionally, we choose a high-\( Z \) impedance of \( Z_{hi} = 145 \Omega \), which corresponds to a 100-/100-/100-\( \mu \)m air-suspended CPW. While it is certainly possible to get higher impedances in air approaching 180 \( \Omega \), it is not necessarily optimal. The reason becomes obvious from (7) where it is seen that high-impedance segments also result in shorter CPW segments. A short CPW segment, however, may not provide significant heat dissipation (isolation) when filled with water. Therefore, we compromise by selecting a lower high-impedance value that allows the suspended CPW segments to be of reasonable length.

Step 3) The final step concerns the selection of the total number of segments \( N \). This is determined by the required isolation (20 dB at 30 GHz in our example). Table I shows the maximum possible isolation for \( N \) between 3 and 9. This table also shows the computed lengths of each suspended CPW [see (7)]. As can be observed, an isolation of at least 20 dB at 30 GHz requires \( N = 9 \) segments.

2) On-State Matching: The on-state matching yields the low-\( Z \) impedance and the lengths of the silicon-supported CPW segments by performing the following steps.

Step 1) As already mentioned, the impedance of the suspended CPW line when surrounded by water is lower than 50 \( \Omega \) due to water’s high dielectric constant. At 30 GHz, it has the value \( Z_{water,\text{CPW}} = 19 + j83.3 \Omega \) (Fig. 14). For frequencies above 20 GHz, the line impedance is a weak function of frequency.

Step 2) For such high frequencies, we can assume that the first few segments (e.g., the first and third in Fig. 15) dominate the reflected power, since water is quite lossy and any power not reflected by them will be significantly attenuated by the following segments. Therefore, we can consider the relatively simple problem of choosing \( L_1, L_3, \) and \( L_5 \) for matching the impedance \( Z_{water,\text{CPW}} \) to \( Z_0 \). Simulations with the Agilent Advanced Design System yield a rather weak dependence of the reflected power on \( Z_l \) in the range of 30–40 \( \Omega \). By considering the layout limitations in our design, we chose a 30-/100-/30-\( \mu \)m silicon-supported CPW that has an impedance of \( Z_l = 40 \Omega \).

Step 3) Once the low-\( Z \) value is known, the lengths of the silicon-supported CPW segments can be calculated by (8). These values are shown in Table II.

If more accurate numbers are desired, a computer-based optimization process can be performed where the previous calculations can be used as a reasonably accurate starting point.

### B. RF Performance

1) Ultrapure Water: Figs. 17 and 18 show the measured and simulated RF performance of the implemented absorptive switch design with the values shown in Tables I and II for the off- and on-states, respectively. At the off-state, the insertion loss is less than 1.3 dB up to 40 GHz, and the return loss is lower than 10 dB. Compared with the insertion loss of a 60-/100-/60-\( \mu \)m CPW line with the same length but without the polydimethylsiloxane microchannels, we can extract the polydimethylsiloxane loss as approximately 0.3 dB. At the on-state, the isolation is 10, 15, and 27 dB at 15, 20, and 40 GHz, respectively. The reflected power is below \(-10 \) dB from 7 to 40 GHz.
Fig. 18. Measured and simulated on-state $S$-parameters for the absorptive switch of Fig. 15.

Fig. 19. Measured on-state $S$-parameters for different concentrations of ionic water in a 1500-μm-wide channel.

The small differences between measurements and simulation results (less than 3 dB) for the whole band is partly due to the approximations involved in the design process and partly due to the fact that the actual channels’ dimensions are slightly narrower (~5%) than the designed ones.

2) Ionic Water: To further improve the low-frequency isolation of the absorptive switch, the ultrapure water is replaced with ionic water. Fig. 19 shows the RF performance for different concentrations of NaCl solution in a 1500-μm-wide channel. As the figure shows, a high concentration of NaCl solution improves the isolation, but only below 20 GHz. By filling the 5 M of NaCl into the channels of the absorptive switch, the 10-dB isolation point shifts from 15 to 10 GHz (see Fig. 20).

The model of the 5-M NaCl solution shown below is derived using the same fitting method mentioned earlier. It shows that the approximate dc conductivity of this solution is 11 S/m. In order to confirm this number, the total dissolved solids (TDS) of this solution were measured using a TDS meter. The measured TDS number is 68 ppt, which can be approximately converted to electrical conductivity 10.6 S/m, which agrees with the model5

\[
\begin{align*}
\varepsilon_r & = 3.05977 + \frac{21.9402}{1 + 1.61064 \times 10^{-21} \times f^2} \\
\sigma & = 11 + \frac{4.89856 \times 10^{-20} \times f^2}{1 + 1.61064 \times 10^{-21} \times f^2}.
\end{align*}
\]

VII. PRACTICAL CONSIDERATIONS AND FUTURE RESEARCH DIRECTIONS

Although liquid switches have numerous advantages as discussed in this paper, a successful implementation needs to consider the tradeoffs associated with their liquid nature. Here, we discuss the most important of these properties and suggest areas of future research.


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A. Temperature Range

The switch-operating temperature range is limited by the freezing and boiling points of the liquid used. As shown in Table III, Galinstan is liquid in a very wide temperature range from -19 °C to 1300 °C while mercury is from -38 °C to 356 °C and water from 0 °C to 100 °C. For temperatures below their freezing points, it is may be necessary to include localized heaters around the switch area. For temperatures above the boiling points, circulating the liquid and combining it with an active cooling design may be necessary. For normal operating temperatures, it is necessary to include hermetic or nearly hermetic packaging to limit evaporation of the liquid. The package should also be bonded sufficiently well to resist the increased pressure caused by the heating or changing state of the liquid.

B. Droplet Size

The demonstrated liquid switches exhibit relatively large size. The capacitive reflective switches are around 2 mm² and the water absorptive switches are approximately 5 mm². These sizes are determined by the required isolation. While they may initially appear large, it is important to consider that liquid switches are mostly useful for high-power applications (1-100 W) where heat dissipation becomes serious and large areas are naturally required to cool the devices. In other words, liquid switches may provide an attractive solution for high-power applications (i.e., cold and hot switching) by trading off speed with power handling. The speed of our droplet switches is predicted to be ~1 ms based on the experimental results shown in [2] and [21]. The speed of the microchannel switch is predicted to be ~10 ms, assuming a reasonable average pumping speed of 1 mL/min [31]. Circulating the liquid could also combine the switching action with active cooling, which may further improve the switch power handling.

C. Actuation Mechanism

We have successfully demonstrated electrostatically actuating droplets. However, the microchannel switches were manually pumped when measured. For practical applications, an on-wafer pump is needed. There are already many useful microfluidic pump designs [31]. Electrohydrodynamic and magnetohydrodynamic pumps are considered to be particularly attractive due to their relatively fast speed, simple structure, and lack of moving parts. In particular, magnetohydrodynamic pumps have demonstrated the ability to pump liquid metals with speeds of approximately 20 cm/s [32]. The on-wafer pump type will also influence the switch power consumption. The switch consumes almost no power if it is electrostatic actuated. On the other hand, it consumes more power if it is actuated using a current-driven micropump. Therefore, the power consumption may range from 10 μW to 100 mW.

VIII. CONCLUSION AND DISCUSSION

Novel water-based wideband RF MEMS absorptive switches are designed, implemented, and characterized in this paper. Their characteristics are compared to liquid-metal switches in the areas of insertion loss, isolation, and reflected power. The study shows that the simple water-based switches are competitive with liquid-metal switches for frequencies above 20 GHz. However, this requires particular care in the design since water has a very high dielectric constant, even in microwave frequencies, and may result in mismatches if not properly accounted for. Optimal designs with distributed water microfluidic channels are presented from 10 to 40 GHz resulting in less than 1.3-dB insertion loss, better than 10-dB return loss, and higher than 27.5-dB isolation at 40 GHz. These switches clearly show the potential of coupled RF-microfluidics for high-power applications. In particular, circulated water may be used to simultaneously route RF signals and provide active wafer cooling.

REFERENCES


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