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RF Design, Power Handling, and Hot Switching of Waveguide Water-Based Absorptive Switches

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Abstract—This paper presents the first complete water-based waveguide absorptive switch from 25–40 GHz integrated with commercially available micropumps. The design exploits the absorptive properties of water in the microwave and millimeter-wave bands along with innovative techniques to achieve an optimized performance in both switching states. Besides its static RF performance, the hot-switching response is also experimentally characterized. Successful hot-switching measurements are presented for power levels of up to 32 and 0.16 W for circulating and noncircularizing water, respectively. This is achieved with a circulation rate of only ~20 mL/min. We also show that this power handling can readily reach 125 and 1250 W if the circulation rate is increased to 30 and 300 mL/min, respectively. In addition, the dynamic scattering matrix under hot-switching conditions is also measured and compared to the cold-switching scattering matrix. Furthermore, critical temperature effects are also studied. In particular, contrary to common wisdom, we show that increased water temperature can result in improved RF isolation with the appropriate waveguide-switching design.

Index Terms—Absorptive switch, high power, Ka-band, micropump, water, waveguide.

I. INTRODUCTION

THERE ARE mainly three types of microwave switches, which are: 1) reflective; 2) transfer; and 3) absorptive switches. Among these switches, absorptive switches are considered more suitable for high-power applications such as satellite communications, radars, and wide range Internet [1], [2]. Absorptive switches absorb the incoming waves and do not generate potentially damaging reflections.

Conventional and micromachined waveguides are excellent transmission lines for high-power RF circuits due to their low insertion loss and high power handling [3]. However, only transfer and reflective waveguide switches exist today. Although these switches typically offer excellent RF performance (0.5-dB insertion loss, 60-dB isolation, 1.15 voltage standing-wave ratio (VWSR), and 50-ms switching speed), additional protective circuits composed of circulators, terminations, etc. are needed for high-power applications [4]. These requirements come with significant additional weight, volume, and cost overhead.

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For this reason, the authors proposed the idea of the first water-based waveguide absorptive switch [5]. Similar to the water-based coplanar RF microelectromechanical systems (MEMS) absorptive switch [6], the water-based waveguide absorptive switch functions by appropriately placing water inside a waveguide to absorb the incident RF signal. Although the authors proved a good static performance in [5], this was done by manually injecting water inside the waveguide. In this paper, we present significant results in a variety of areas. As shown in Fig. 1, the switch is completed by integrating it with commercially available micropumps. We then further measure and report: 1) the water temperature effects; 2) the hot-switching response; and 3) the power handling of the switch. These measurements are significant to understanding the switch performance under high-power RF signals. Additionally, in this paper, we adopt the idea of conventional high-power microwave water-load designs [7] to substantially improve the switch power handling. Specifically, we integrate the switch with a miniaturized pump for forming a water cooling system.

This paper starts with the summary of the water dielectric properties in the microwave region in Section II. Section III describes the basic design idea of the water-based waveguide absorptive switch. In Section IV, the static RF performance, water temperature effects, and hot-switching response are reported. All measurements include the integrated micropumps. In Section V, we characterize the power handling of the switch. The concept of microwave and cooling system integration are realized to greatly improved the power handling of the switch. Finally, in Section VI, we discuss the switch power consumption and compare our results with conventional waveguide switches.
II. WATER MICROWAVE DIELECTRIC PROPERTIES

In the microwave and sub-millimeter-wave region (1–300 GHz), water is a lossy material [8]. The dielectric constant of water is frequency dependent and can be approximately expressed by the first-order Debye equation [9]

\[
\varepsilon_r = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1 + j\omega\tau},
\]

(1)

According to [8], [10], [11], and [12], \(\varepsilon_s, \varepsilon_\infty,\) and \(\tau\) are related to water temperature \((T)\). The following equations provide good approximations of these variables:

\[
\varepsilon_s = 87.9144 - 0.404399T + 9.58726 \times 10^{-6}T^2 - 1.32892 \times 10^{-6}T^3
\]

(2)

\[
\varepsilon_\infty = -2.5 + 0.023 \times (T + 273.15)
\]

(3)

\[
\tau = \frac{4.127754 \times 10^{-10}}{T + 273.15} \left(\frac{219.9074}{219.9074} - 1\right)^{-1.7313}
\]

(4)

Based on the approximation above, the \(K\alpha\)-band waveguide’s \(\text{TE}_{10}\) dielectric attenuation factors \(\alpha_{10}\) of water is plotted in Fig. 2. It is observed that: 1) the attenuation constant is increased as frequency is increased (for higher frequencies, less water volume is required to absorb the same power) and 2) the attenuation constant is decreased as water temperature is increased. Warmer water absorbs less RF power. This is a potential disadvantage, but as will be seen later, can be addressed by a proper design.

III. DEVICE DESIGN

The primary idea of our waveguide absorptive switch is to appropriately fill a waveguide section with water when the signal needs to be absorbed and remove the water when the signal needs to propagate through the waveguide. These two states are defined as “on” and “off,” respectively. To demonstrate the concept, we have considered the following design criteria in this paper:

1) on-state isolation (>20 dB);
2) off-state insertion loss (<0.5 dB);
3) on- and off-state return losses (>20 dB).

In this section, the design concept is mainly explained by a preliminary design. Subsequently, an improved design is introduced. Both designs adopt a \(K\alpha\)-band rectangular waveguide (WR-28). Therefore, the normal operating frequencies are 26.5–40 GHz. Nevertheless, the design concept can be applied to other microwave frequencies.

A. Preliminary Design

The preliminary waveguide absorptive switch is shown in Fig. 3. A reservoir is created in a \(K\alpha\)-band rectangular waveguide by inserting two thin slides. At the top and bottom of the reservoir, two holes are drilled for water access. At the on-state, water fills the reservoir through the top hole, while air escapes from the bottom one. On the contrary, at the off-state, water is withdrawn from the top hole, while air fills the reservoir from the bottom one.

The location and size of the drilled holes should be carefully decided. The holes need to be nonradiating providing the minimum possible disturbance to the current distribution on the waveguide wall. Therefore, they are drilled at the center of the waveguide long edge with a diameter of 1.59 mm. This hole size allows the insertion of standard tubing while keeping the insertion loss sufficiently low.

The inserted slides should also be carefully chosen and positioned. First, it should be a low-loss material for minimum insertion loss. Teflon is selected due to its low dielectric constant (2) and low tangent (0.00028 at 3 GHz) [14]. Second, a matching network needs to be considered at the off-state to avoid reflections due to the different dielectric constants of air and Teflon. Our design achieves this by tilting the slides at an angle of 75° and shortening their thickness to 0.5 mm. With the Teflon slides tilted, the reflected microwave signal can be minimized across the entire \(K\alpha\)-band. This angle is determined based on 3-D High Frequency Structure Simulator (HFSS) simulation results. In fact, the simulation shows that higher angles lead to even better matching networks. However, higher angles increase the volume needed for the switch. The value of 75° was chosen as a good compromise between performance and
size. This broadband matching method is inspired from the designs of conventional waveguide terminations, which are of either stepped or tapered designs [15]. It is interesting to note that this matching is also very beneficial at the on-state: water surfaces are also tilted since the reservoir is tilted.

The distance between the slides controls the maximum volume of water filled in the reservoir. This amount determines the isolation of the switch. With a distance of 17.5 mm, the volume of the reservoir is 0.45 mL and the isolation, shown in Fig. 4(b), is noticeably high (typically greater than 100 dB).

Fig. 4 shows the simulated RF performance of the preliminary waveguide water-based switch at both the on- and off-states. At the on-state, Fig. 4(a) shows an insertion loss of less than 0.1 dB and return loss greater than 20 dB. The insertion loss includes the loss of a 50-mm-long waveguide made of gold. At the off-state, with 25°C water, Fig. 4(b) shows isolation and return loss greater than 100 and 20 dB, respectively, at all operating frequencies. However, the isolation deteriorates from 112 to 90 dB at 26.5 GHz and from 149 to 133 dB at 40 GHz for water temperatures between 25°C–60°C.

Although this preliminary design has shown promising RF performance, placing and hermetically sealing thin Teflon slides at a tilted angle inside the waveguide are relatively challenging. A more practical design is introduced in Section III-B.

B. Improved Design

Fig. 5 shows the improved design. Instead of building a reservoir, several Teflon tubing sections are inserted into a waveguide. At the on-state, water fills the tubes through the top holes. On the contrary, air fills the tubes from the bottom holes at the off-state. The matching network is achieved by tilting the tubes at 75°. This network also works at both switch states.

With the tubes directly inserted, no sealing is required. Additionally, the tubes can be accurately positioned and supported by the top and bottom angled holes. However, the water volume in a single tube is limited compared to one inserted in the previously described reservoir. A switch with a single tube may not provide sufficient isolation. Therefore, several tubes are inserted so that sufficient water volume can be inserted. Nevertheless, inserting several tubes requires additional holes. As a result, a tradeoff between insertion loss and isolation has to be considered. The tubes are designed to be inserted from the center of the waveguide long edge because: 1) as mentioned above, opening holes at the center of the waveguide long edge introduces minimum radiation and 2) the tubes carry the water at the location of maximum electric field leading to the highest possible isolation.

The adopted Teflon tubing is with outer and inner diameters of 1.59 and 0.79 mm, respectively. The optimal distance between two adjacent tubes is determined by HFSS simulations. Distances from 8 to 11 mm are considered. A small resonance is observed at 26.5 GHz that slightly deteriorates the return loss at the lower band when the distance is 8 mm. This resonance can be removed as the distance increases. A distance of 9.5 mm is finally chosen in our design as a good compromise between the size, fabrication feasibility, and RF performance of the switch.
IV. RF PERFORMANCE MEASUREMENT

A. Static-State Measurement

The fabrication of our switch starts from drilling holes at a 100-mm-long (4-in long) Κα-band waveguide and then inserting the Teflon tubing. Four different pieces are fabricated with 1–4 tubing sections.

The measurement is accomplished using an Agilent 8722ES network analyzer. Two 2.4-mm coaxial-to-waveguide adapters connect the network analyzer to the waveguide switches under test. The calibration is completed at a power level of 10 dBm by a conventional waveguide calibration method using waveguide short, offset short, load, and through standards; thus, the measured reference planes are set at the end of the adapters.

With this setup, the on- and off-states are measured. Fig. 6 shows the off-state measured and simulated results. The insertion losses of the switches are less than 0.5 dB and the return losses are greater than 18 dB at 26.5–40 GHz (after [5]).

The simulated result is based on the 25 °C water model. The isolation is proportional to the number of inserted tubes. It is 11, 20, 28, and 37 dB at 40 GHz for 1–4 tubes, respectively. The return loss is greater than 20 dB at 26.5–40 GHz (after [5]).

B. Temperature Effects

The on-state performance is shown in Fig. 7. The simulated results using a 25 °C-water model are in reasonable agreement with the measured ones. The isolation of a four-tube switch is 23 and 37 dB at 26.5 and 40 GHz, respectively. It is generally proportional to the number of the inserted tubing sections. From 1–4 sections, the 40-GHz isolation is 11, 20, 28, and 37 dB, respectively. As for the return loss, S11 is nearly unrelated to the number of inserted tubes and is greater than 20 dB at the operating frequencies. These measurements show that there is minimum penalty in the insertion loss, but great benefit in the achieved isolation from increasing the number of tubing sections.

The measurement done in Section IV-A is with a static water temperature of ~25 °C. Signals with −10-dBm power have a negligible effect on the water temperature. Nevertheless, the water temperature is increased for higher power signals. This increase changes the water’s dielectric properties and affects the RF performance of the switch. This effect is investigated in this section using the setup shown in Fig. 8. Instead of heating the
water by microwave signals, water is placed in a reservoir (a beaker) and is pre-heated by a hotplate. The heated water is then withdrawn by a commercially available micropump and delivered to the waveguide absorptive switch. This pump with a size of 28 mm $\times$ 14 mm $\times$ 24 mm can offer a free flow rate up to 700 mL/min.\(^1\) A temperature sensor is connected in between the pump and switch to monitor the water temperature. The signal power is still set at $-10$ dBm during the RF measurement.

Fig. 9 shows the on-state measurement with water temperature from 22 $^\circ$C to 60 $^\circ$C. The isolation is improved by 2–5 dB when the water temperature is increased. This observation is opposite to the calculated attenuation constant $\alpha_{10}$ (Fig. 2) and the simulated results of the preliminary design (Fig. 4). This is due to the fact that, in this case, the waveguide is only partially filled with water, which leads to two competing mechanisms. On one hand, as the temperature is increased, the water dielectric properties change leading to additional microwave power entering the water volume. On the other hand, heated water absorbs less power than cold water. The net result of these two competing mechanisms is that increased RF power is absorbed for this design as the water temperature is increased. The HFSS simulated results also confirm this improvement [see Fig. 10(a)].

C. Hot-Switching Response

In this section, we measure the hot-switching response. Two micropumps are connected to propel and withdraw water from

the waveguide switch. At the on-state, water flows through the waveguide and goes back to the reservoir through the opened tubing above it. At the off-state, water in the tubing is withdrawn back to the reservoir and air fills the tubing from its opened end. This implementation is the prototype of the fully integrated water-based waveguide absorptive switch.

The employed high-power measurement setup is shown in Fig. 11. A 30-GHz sinusoidal signal generated by a continuous-wave generator is first amplified by a traveling-wave tube (TWT) amplifier, which is able to boost the signal up to 46 dBm (40 W). A protective circuit composed of a circulator and a 40-W termination is then connected. Subsequently, a 40-dB dual coupler is adopted and the coupled signals are measured by an Agilent E4419B two-port power meter so that the incident and reflective signal powers are monitored. Finally, the main high-power signal propagates through the waveguide switch. A 40-dB single coupler is then connected with its coupled signal measured by an Agilent E4448A spectrum analyzer. The remaining of the high-power signal is terminated by another 40-W termination. To observe the hot-switching response, the spectrum analyzer is set to the zero span (time domain) mode at 30 GHz.

The switch is tested with three input power levels: 20, 30, and 46 dBm. The actual incident power to the switch is about 1 dB lower due to the losses of the circulator and dual coupler. Fig. 12 shows the measured results. The isolation and return loss are measured separately. To measure the return loss, the spectrum analyzer is connected to the coupled reflective signal. The coupled transmitting signal is measured by the power meter.

Based on these measurements, we can make the following observations.

1) The temperature effects discussed in Section IV-B is observed. Water is heated up noticeably by the 46-dBm signal. The measured isolation improves from 22 to 28 dB when the input signal increases from 20 to 30 dBm. The water temperature is around 60 °C with an input signal of 46 dBm.

2) The insertion loss is typically less than 0.5 dB. Nevertheless, some random spikes showing insertion loss between 1–2 dB are observed. These spikes are due to the residual water droplets passing through the tubes. These residues can be easily eliminated by an industry-quality setup.

3) During the on–off transition time intervals, the isolation gradually changes with a ladder-like shape. This is caused by the gradual and sequential filling of the tubes with water. For this particular arrangement, the switching speed is approximately 2 s (average flow rate is ~4 mL/min). The switching speed can be greatly improved by shortening the tubing, adopting a more powerful pump, and using separate pumps to fill the individual tubing sections. Based
on the tubing selected, an average flow rate greater than 13 mL/min can fill one tube in less than 50 ms.

4) The return loss fluctuates during the transition between the on- and off-states. This is due to the fact that the impedance changes when the tubes are partially filled. In other words, while a fully filled tube is well matched to the waveguide impedance, a partially filled one is not. Fig. 13 shows the simulated return loss for various filling ratios of a single tube. Nevertheless, even during these transition times, the return loss is still greater than 10 dB.

The micropump plays a critical role of the results such as switching time and water residuals. However, the authors want to point out the absorptive property during the on–off transitions that enables the hot-switching capability of our switch. In Section V, the power handling of the switch is characterized and discussed.

V. POWER-HANDLING CHARACTERIZATION

The power handling of the water-based absorptive switch will be ultimately limited by the boiling point of water. In our switch design, vaporizing the water inside the tubes eliminates the switch absorbing characteristics. Therefore, the power handling of the switch can be characterized mainly by monitoring the isolation of the switch. Two circumstances are considered, which are: 1) water is static and 2) water is circulated at the on-state. It is worth mentioning that the second condition combines a switch design with an active cooling system (thermal radiator), which greatly improves the power handling of the switch.

The switch is tested with a 30-GHz signal using the high-power setup shown in Fig. 11 with its details described in Section IV-C. The input signal power level described in the following refer to the TWT output signals. As previously mentioned, the actual power applied to the switch is ~1 dB lower. The experiments are performed at room temperature with water originally at 22 °C.

A. Static Case: No Water Circulation

Four individual tubes filled with water are inserted into the waveguide switch before the measurement is performed. Signals with different power levels are then applied to the switch. Typically observed behaviors with input powers of 1 W (30 dBm) and 2 W (33 dBm) are shown in Fig. 14. The return loss and isolation are monitored for 2 h. An incident wave of sufficiently high power causes the switch isolation to gradually deteriorate and the return loss to fluctuate. For example, under the 2-W signal, the isolation is quickly reduced from 24.5 to 4.4 dB in 2 h. Similarly, under the 1-W signal, the isolation deteriorates from 25.8 to 24.5 dB.

To explain this phenomenon, the tubes are pulled out and the water status is inspected after the measurement. We clearly observed air bubbles in the tubes, as shown in Fig. 15. For the 2-W signal, all tubes have bubbles. For the 1-W signal, only the first two tubes (closest to the amplifier) show air bubbles. The bubbles are due to the localized microwave heating. Due to these bubbles, the amount of water inside the waveguide is reduced, which leads to a lower isolation over time. These bubbles are generated sequentially from one tube to the next so that the isolation is deteriorated gradually. While these bubbles are created, the impedance of the switch is gradually changed leading to the recorded return-loss fluctuation. When thermal equilibrium is reached, the switch behavior stabilizes.
It is also observed that the isolation does not deteriorate when the signal power is below 23 dBm (0.2 W). Considering the insertion loss of the circulator and dual coupler, the power handling of the switch with no circulation is ~0.16 W (1 dB less than 0.2 W).

B. Dynamic Case: Circulating Water

Simply combining the switch with a thermal radiator and circulating water can greatly improve the power handling. At the on-state, the microwave energy directly heats up water. With circulating water, the heated water can be cooled before it flows back into the switch. Water is one of the best coolants due to its high heat capacity (~4181.3 J/kg · K), which means water can carry more heat for a given temperature increase [16]. The increased temperature can be calculated by the following equation [17]:

\[ q = hρνΔT \]  

where \( q \) is the heat source power (W), \( h \) is the heat capacity (J/kg · K), \( ν \) is the volume flow rate (m³/s), \( ρ \) is the density of water (kg/m³), and \( ΔT \) is the average increment of temperature (K).

To measure the power handling with circulating water, we modify our experimental setup. A small radiator in the size of 42 mm × 25 mm × 9 mm with 25 fins is adopted. Two temperature sensors are connected to monitor the input and output water temperature. A flow meter is used to measure the water flow rate. Only one pump is needed since a unidirectional water flow is required here. Furthermore, in order to expedite the measurement, the tubes are connected to form a loop and the water reservoir shown in Fig. 1 is removed so that the amount of water used is minimized and the water stable temperature can be reached earlier. During the measurements, the signal power level is increased from 5 to 40 W with a step of 5 W. At each step, water is constantly circulated and the isolation, return loss, and temperature are recorded after the system reaches stability.

The recorded data are shown in Fig. 16. Circulating water at the on-state greatly improves the power handling. The switch can work properly for signals at least up to 40 W (maximum available signal in our laboratory—we predict the highest power handling for different cases at the end of this section). The return loss is maintained at 20 dB or better. The isolation shows its typical behavior as the water temperature is increased. From 5 to 40 W, the input and output water temperatures are raised from 26.06 °C to 42.2 °C and from 28.1 °C to 53.8 °C, respectively. The input and output water temperature difference at 40 W is 11.6 °C. This is 3.6 °C lower than the value calculated by (6). This difference is mainly due to the fact that this equation does not consider the heat energy spread by the tubing, temperature sensors, and the switch itself.

The high-power measurement is performed again without the radiator connected. The results are also shown in Fig. 16. Interestingly, the results are nearly identical. This is explained by the fact that the heat released from the small radiator is negligible. A typical 40-W radiator is about 28 times larger than the radiator used. Much of the heat is released from the tubing, temperature sensor, flow meter, and the switch itself. They are equivalent to the required heat sink.

The power limit of the switch can still be estimated by (6). For example, with input-water cooled down to 40 °C and flow rate set at 30 mL/min, a 125-W signal is required to boil water. Similarly, the switch can handle up to 1250 W if the flow rate reaches 300 mL/min, which may be achieved by other available micropumps. Nevertheless, microwave localized heat may generate small bubbles inside the switch even if the average water temperature is low. These bubbles could either deteriorate the impedance matching or reduce the isolation. Higher flow rate may be required to minimize the occurrence of bubbles.

VI. DISCUSSION

In this section, the power consumption and size of our switch are discussed. The adopted micropumps in the size of 28 mm ×...
14 mm × 24 mm operate at 6 V and ∼0.2 A. This constitutes the power consumption of our switch. However, this power needs to be consumed only when water flow is required. No power is needed when the switch is at either the off- or on-states if no circulation is required.

Table I compares the sizes of our absorptive switch and a conventional waveguide switch with protective circuits at 40 W. It shows that our design can be up to 40% smaller.

VII. CONCLUSION

A fully functional high-power $\ell a$-band waveguide water-based absorptive switch has been reported with integrated micropumps. The switch absorbs the RF signal by filling water into the microtubes inserted into a $\ell a$-band waveguide. With four tubes inserted, the switch shows return loss greater than 18 dB at both the on- and off-states, insertion loss less than 0.5 dB, and isolation greater than 22 dB. Besides the static RF performance, we further characterize: 1) the water temperature effects; 2) the hot-switching response time; and 3) the power handling of the switch. Due to water’s different permittivities at different temperatures, the isolation is increased when the water temperature is elevated. Hot-switching result shows that the return loss fluctuates during the transition states. It is due to the impedance change when the inserted microtubes are partially filled. However, the return loss is still greater than 10 dB. Finally, the power handling is characterized. With static water, the switch can handle RF power up to 0.16 W. This is greatly improved to more than 32 W by circulating water and integrating the switch with a thermal radiator. Based on these results, we estimate that the power handling could reach 1250 W with a water flow rate of 300 mL/min and input water temperature of 40 °C.

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