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A Ka-band Waveguide Water-Based Absorptive Switch with an Integrated Micropump

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Abstract—A new water-based waveguide absorptive switch is developed and reported. The switch functions by controllably inserting water inside a conventional Ka-band waveguide. In particular, three Teflon-made circular cylinders with a diameter of 1.59-mm are placed inside a 50-mm-long waveguide section at an angle of 75° and can be filled with water by micropumps. The water-filled tubes offer a measured isolation of 18 and 28 dB at 26.5 and 40 GHz respectively. When water is removed the total insertion loss is measured at less than 0.5 dB across the whole band. This number includes the effects of a) the 50-mm long waveguide section, b) the holes for inserting the teflon tubes, and c) the tubes themselves. In addition, the measured switch return loss is greater than 18 dB at both states from 26.5 to 40 GHz. Water can be inserted and removed at a simulated speed of less than 50 ms. The proposed design requires approximately 40% less volume than conventional waveguide absorptive switches.

Index Terms— Absorptive switch, water.

I. INTRODUCTION

High-power microwave applications are dominant in many fields including satellite communications, radars, and wide-range internet [1]. Conventional and micro-machined waveguides result in devices with the lowest possible loss for their respective dimensions. Their power handling is only limited by the breakdown strength of the dielectric filling material [2]. Unlike low-power designs, conventional reflective solid-state or MEMS switches are not particularly useful for high-power applications since the reflected signal can adversely affect the circuit performance or lead to catastrophic failures.

Two main approaches exist today for waveguide switches: a) a shutter switch that creates a physical short to block the signal along with a circulator and a high-power termination (Fig. 1a); and b) a transfer switch that mechanically transfers the input signal from the through port to high-power terminations (Fig. 1b) [3]. Typically these switches offer excellent RF performance: 0.5-dB insertion loss (not including the circulator loss), 60-dB isolation, 1.15-VSWR, and 50-ms switching speed [4]. This, however, comes with significant additional weight, volume and cost due to the required bulky components required (circulator, terminations etc).

In this paper we demonstrate an alternative approach by exploiting the absorptive properties of water in the microwave and sub-mm wave bands. This approach can now be made practical due to the recent significant advances in the microfluidics domain that has resulted in powerful miniaturized pumps with excellent performance [5]. Although this paper focuses on the RF design of the water-based switch, the design is

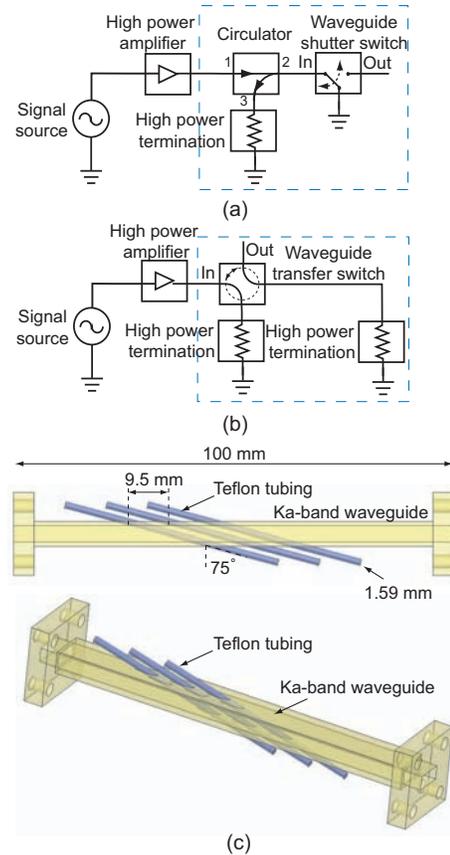


Fig. 1. (a) and (b) Conventional implementations of virtual waveguide absorptive switches. A waveguide shutter switch is used in (a) while a waveguide transfer switch is used in (b). In this paper, a single-device waveguide absorptive switch using water is proposed as shown in (c). Water can be controllably inserted and removed from the Teflon tubes leading to excellent on- and off-states.

accomplished by keeping in mind the limitations imposed by miniaturized pumps.

II. WATER MICROWAVE PROPERTIES

The inability of water dipoles to follow the rapid changes of high-frequency electric fields is the primary basis of microwave heating [3]. This reorientation lag depends on the frequency of the applied field and the size of the dipoles. In the microwave region and sub-mm wave region (1-300 GHz), water is a relatively lossy material with a complex dielectric

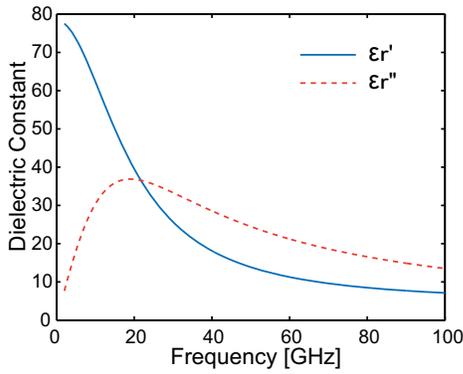


Fig. 2. Water's dielectric constant at 25°C [6]. Water is utilized as the absorptive material in our waveguide absorptive switch because it is highly lossy in the microwave range.

constant that can be approximated with the well-known first order Debye equation [3]

$$\epsilon_r = \epsilon_\infty + \frac{\epsilon_s - \epsilon_\infty}{1 + j\omega\tau} \quad (1)$$

where ϵ_s and ϵ_∞ are the dielectric constants at DC and very high frequencies respectively, and τ is the relaxation time of the system which controls the build up and decay of the polarization. Separating the real and imaginary parts yields

$$\epsilon_r' = \epsilon_\infty + \frac{\epsilon_s - \epsilon_\infty}{1 + \omega^2\tau^2} \quad (2)$$

$$\epsilon_r'' = \frac{(\epsilon_s - \epsilon_\infty)\omega\tau}{1 + \omega^2\tau^2} \quad (3)$$

According to [6] and [7] the values $\epsilon_s=78.32$, $\epsilon_\infty=4.57$, and $\tau=8.38$ ps result in a good approximation of water's dielectric constant at 25°C. Fig. 2 plots these two equations from 2 to 100 GHz.

In this paper, this model is entered and used in Ansoft HFSS 3-D FEM simulation software [8] to predict the RF performance of our waveguide absorptive switch.

III. DEVICE DESIGN

The primary idea for the presented 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. In this paper we have considered the following design criteria: a) on-state isolation (> 20 dB), b) off-state insertion loss (< 0.5 dB), and c) on- and off-state return losses (> 20 dB).

The design concept of the waveguide switch is shown in Fig. 1c. Several tubing sections are inserted into a Ka-band waveguide section through appropriately drilled holes at its top and bottom surfaces. At the on-state, water fills the tubes through the top holes while air escapes from the bottom ones. On the contrary, at the off-state, water is withdrawn from the top holes while air fills the tubes from the bottom ones.

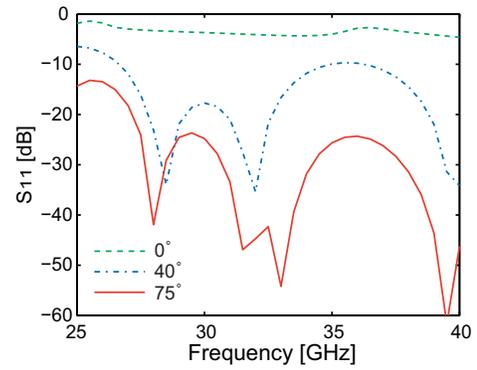


Fig. 3. Simulated return loss of waveguide section when three tubes are inserted at different angles.

The tubing needs to be carefully chosen and positioned. First, it should be made with a low-loss material so that the switch insertion loss can be minimized. Teflon is selected in our design due to its low dielectric constant ($\epsilon_r = 2$) and loss tangent ($\tan \delta = 0.00028$ at 3 GHz) [9]. Second, a matching network needs to be considered in the off-state to avoid reflections due to different dielectric constants between air and the tubing material. Our design achieves this by tilting the tubes at an angle of 75°. With the Teflon tubes tilted at this angle the reflected microwave signals can be minimized across the whole TE₁₀ mode band. This angle is determined based on 3-D HFSS simulation results shown in Fig. 3. In fact the simulation shows that higher angles lead to even better matching networks. However, drilling the necessary holes at very high angles becomes particularly challenging. The value of 75° was chosen as a good compromise between performance and practicality. This broadband matching method is inspired from the design of conventional waveguide terminations [10]. It is interesting to note that this matching is also very beneficial at the on-state: water shapes as a tilted cylinder as it fills the interior of the tubing.

The location and size of the drilled holes should be carefully decided as well. The tubing is inserted through the center of the waveguide long edge for the following reasons: a) The drilled holes need to be non-radiating holes providing the minimum possible disturbance to the current distribution on the waveguide wall; and b) The tubes carry the water at the location of maximum electric field leading to the highest possible isolation.

To satisfy the isolation requirement and also facilitate the device fabrication we chose to insert an array of tubes, each with outer and inner diameters of 1.59 and 0.79 mm respectively. More tubes introduce more water inside the waveguide so that more energy can be absorbed and higher isolation can be achieved. The distance between two successive tubes is simulated in HFSS for values between 8 and 11 mm. For 8 mm, a small resonance is observed at 26.5 GHz that slightly deteriorates the return loss at the lower band. This resonance is removed as the distance increases. The number of 9.5 mm is chosen in our design in order to compromise

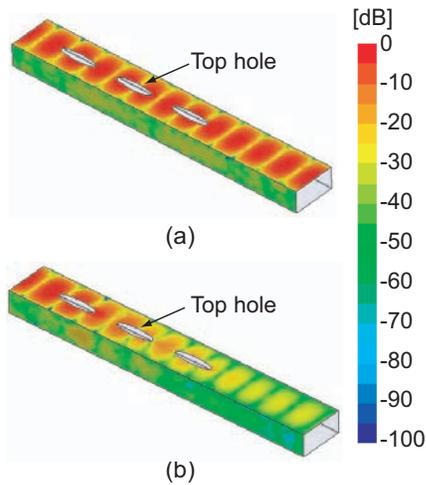


Fig. 4. Simulated normalized 40-GHz E-field plots of the TE₁₀ propagating wave in our waveguide section: (a) off-state, (b) on-state.



Fig. 5. The completed water-based waveguide absorptive switch. One, two and three tubing sections are shown.

the size, fabrication feasibility, and the RF performance. The propagating electric fields inside the waveguide are plotted in Fig. 4 for both states. No standing wave is observed in the off-state and the field energy is successfully absorbed by water at the on-state.

IV. MEASUREMENTS

Three completed waveguide absorptive switches are shown in Fig. 5. The fabrication starts from drilling holes at a 100-mm (4") long Ka-band waveguide and then inserting the Teflon tubing. Three different pieces are fabricated and tested with one, two and three tubing sections.

The measurement is accomplished using an Agilent 8722ES network analyzer with the setup shown in Fig. 6. Two 2.4-mm coaxial-to-waveguide adapters connect the network analyzer to the waveguide switches under test. The switches are measured from 25 to 40 GHz. The calibration is completed at -10 dBm power by conventional waveguide calibration using waveguide short, offset short, load, and through; thus, the measured reference planes are set at the end of the adapters.

With this setup the on- and off-states are measured. Fig. 7 shows the off-state measured and simulated results. The insertion losses of the switches are less than 0.5 dB and the

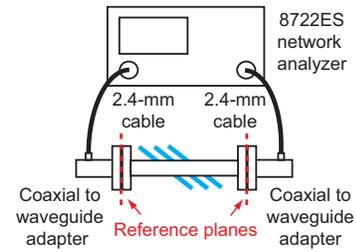


Fig. 6. Measurement setup. 2.4-mm coaxial-to-waveguide adapters are used to measure our waveguide absorptive switch. The calibration reference planes are set at the end of the adapters (red dash lines).

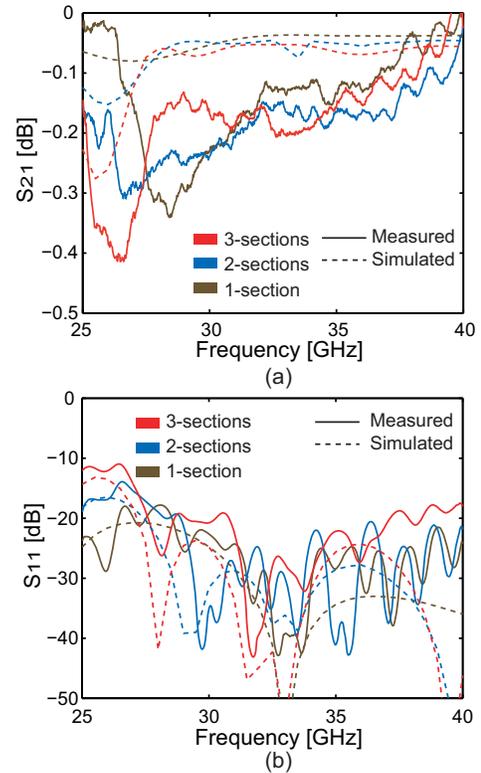


Fig. 7. Measured and simulated off-state results of the water-based waveguide absorptive switches with 1-3 sections of tubing: (a) S_{21} , (b) S_{11} . The insertion losses are less than 0.5 dB while the return losses are greater than 18 dB at 26.5-40 GHz. The coaxial-to-waveguide adapters used are designed only for Ka-band, 26.5-40 GHz.

return loss is typically better than 18 dB at Ka-band, 26.5-40 GHz. It is observed that the insertion and return losses are worse at lower frequency, 26.5 GHz, because the tilted matching performs better at higher frequency.

The on-state performance is shown in Fig. 8. The adopted water model is in reasonable agreement with the measurement results. With three tubing sections, the isolation of the switch is 18 and 28 dB at 26.5 and 40 GHz respectively. As expected the isolation is generally proportional to the number of inserted tubing sections. From one to three sections, the isolation is increased from 11 to 28 dB at 40 GHz respectively. As observed from Figs. 7 and 8, there is minimal penalty in the insertion loss but great benefit in the achieved isolation from

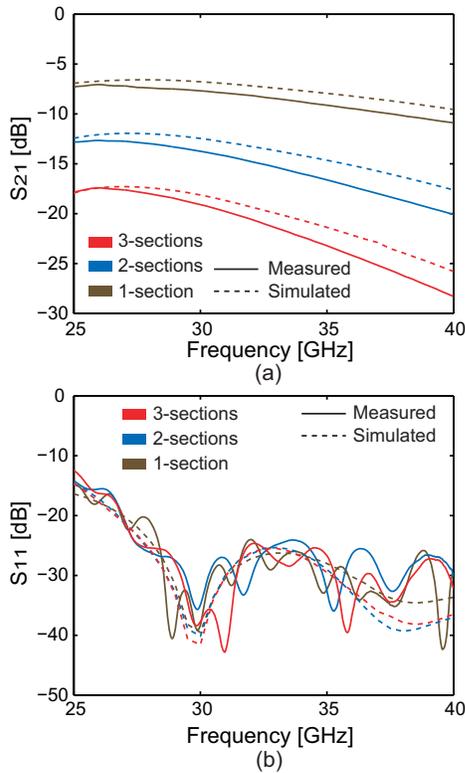


Fig. 8. Measured and simulated on-state results of the water-based waveguide absorptive switches with 1-3 sections of tubing: (a) S_{21} , (b) S_{11} . The isolation is generally proportional to the number of tubing sections inserted while the return loss is greater than 18 dB at 26.5-40 GHz.

increasing the number of tubing sections.

V. DISCUSSION

In this section, the switching speed, power consumption, and size of our switch are discussed. Based on the tubing selected, 0.01 ml water is required to fill each inserted tube. Therefore, a micropump with average flow rate greater than ~ 13 ml/min can fill one tube in less than 50 milliseconds. This flow rate is achievable from many micropumps designs [5]. A commercially-available micropump is adopted in our design (Fig. 9). This pump can offer free flow rate up to 700 ml/min. The pump operates 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. Future implementations will investigate the relationship between flow rate and power handling. Table I compares the sizes of our and conventional waveguide absorptive switches at 40 W. It shows that our switch can be up to 40% smaller.

VI. CONCLUSION

The design and implementation of a waveguide absorptive switch is presented in this paper. Water is adopted as the absorber of the switch so that the microwave signal is blocked if water flows into the waveguide. The prototype water absorptive switch is fabricated and measured. With three

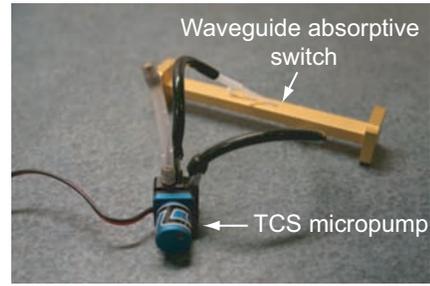


Fig. 9. The adopted TCS micropump [11]. Its size is 28 mm \times 14 mm \times 24 mm with free flow rate up to 700 ml/min.

TABLE I

VOLUME COMPARISON OF THE WATER-BASED AND CONVENTIONAL WAVEGUIDE ABSORPTIVE SWITCHES [4] FOR 40-W POWER HANDLING

	Conventional (in ³)	Water-based (in ³)
Switch itself	20	2.25
Circulator	1	Not needed
Water and tubing	Not needed	4.5
Micropump	Not needed	0.6
40-W radiator or termination	16	16
Total size	37	23.35

sections of Teflon tubing inserted the isolation is between 18 to 28 dB at Ka-band. Its return loss is below 18 dB at both states. Further isolation improvement could be achieved by inserting additional segments of tubing. Implementations details are discussed related to the micropumps required for practical applications.

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REFERENCES

- [1] R. J. Barker et al., *Modern Microwave and Millimeter-Wave Power Electronics*. Wiley-IEEE Press, 2005.
- [2] Microwave101.com (2006, July), Waveguide primer. [Online]. Available: <http://www.microwave101.com/encyclopedia/waveguide.cfm>
- [3] A. C. Metaxas and R.J. Meredith, *Industrial Microwave Heating*. London, UK: Peter Peregrinus, 1983.
- [4] QuinStar Technology, Inc., http://www.quinstar.com/qwz_electromechanical_waveguide_switches.html
- [5] D. J. Laser and J. G. Santiago, "A review of micropumps," *Journal of Micromechanics and Microengineering*, vol. 14, 2004, pp. R35-R64.
- [6] R. Buchner, J. Barthel, and J. Stauber, "The dielectric relaxation of water between 0°C and 35°C," *Chemical Physics Letters*, vol. 306, issues 1-2, June 1999, pp. 57-63.
- [7] M. Chaplin (2007, March), Water structure and behavior. [Online]. Available: <http://www.lsbu.ac.uk/water/microwave.html>
- [8] Ansoft Corporation, <http://www.ansoft.com/>
- [9] RF Cafe, Dielectric constant, strength, & loss tangent. [Online]. Available: http://www.rfcafe.com/references/electrical/dielectric_constants_strengths.htm
- [10] I. Chang, *Encyclopedia of RF and Microwave Engineering*. New Jersey: John Wiley & Sons, Inc, 2006.
- [11] TCS Micro Pumps Limited, <http://www.micropumps.co.uk/index.html>