Ultrawideband, Photothermally Excited mmWave Vanadium Dioxide Switches

David L. West, Graduate Student Member, IEEE, Ashley A. Goodnight, and Nima Ghalichechian, Senior Member, IEEE

Abstract—We report the first demonstration of photothermally excited vanadium dioxide (VO$_2$) RF switches. The switches operate from dc to 65 GHz. VO$_2$ is a phase-change material with a volatile insulator–metal transition (IMT) at 68 °C, and it is a promising technology for millimeter-wave (mmWave) switching applications that require low-loss performance. However, the traditional activation of VO$_2$ switches using microheaters results in undesirable parasitic capacitance. We propose heating VO$_2$ with a laser, which decouples the excitation method from electromagnetic (EM) design. The coplanar waveguide (CPW) switches exhibit low-loss, ultrawideband performance, with $<$0.43-dB insertion loss (IL) and $>$17.7-dB return loss in the ON state and $>$17.2-dB isolation in the OFF state from 10 MHz to 65 GHz. The figure of merit defined as $1/(2\cdot R_0\cdot C_{off})$ is extracted as 12.4 THz. We achieve switching times in the microsecond range using a continuous-wave 786-nm semiconductor laser.

Index Terms—Coplanar waveguide (CPW), millimeter-wave (mmWave), phase-change material (PCM), photothermal excitation, RF switches, vanadium dioxide (VO$_2$).

I. INTRODUCTION

As COMMUNICATIONS and sensing systems push into the millimeter-wave (mmWave) band, it becomes increasingly imperative to introduce wideband, low-loss switching technologies to enable reconfigurability. Semiconductor-based technologies such as p-i-n diodes or CMOS are lossy at mmWave, and MEMS switches can be complicated to fabricate and integrate. Phase-change material (PCM) switches are an attractive alternative with wideband, low-loss characteristics [1], [2]. Vanadium dioxide (VO$_2$) is a PCM that undergoes a volatile insulator–metal transition (IMT) at a low temperature of 68 °C. When VO$_2$ is heated above the transition temperature, the resistivity decreases by three–five orders of magnitude, and when cooled, the material returns to the insulating state [3]. We have shown VO$_2$ to be a highly reliable material under thermal cycling [4], and its PCM properties can be used in RF devices such as switches [1], filters [5], and power limiters [6]. VO$_2$ has also been demonstrated to have high linearity, with a third-order intercept point greater than 55 dBm [7]. For applications requiring operation above 68 °C, the transition temperature can be manipulated with various techniques, such as doping [8]. VO$_2$ can also be maintained at a lower temperature using thermal management techniques at the cost of additional power consumption, if necessary. Power handling, linearity, and transition temperature modifications were outside the scope of this study. Our group has studied the application of VO$_2$ toward phase shifters [9], filters [10], microbolometers [11], reconfigurable polarizers [12], and optical routers [13].

Typically, PCM-based RF devices are excited using integrated microheaters placed near the PCM, which heat it to the transition temperature when dc-biased. Such heaters increase the design and fabrication complexity and introduce parasitic coupling to the RF lines. Routing large numbers of bias lines on-wafer with minimal impact to electromagnetic (EM) performance is prohibitively difficult without a costly multilayer stack-up. Furthermore, additional processing steps are required for bias line isolation and heater metallization. To circumvent these limitations, we propose the use of lasers to photothermally excite the IMT of VO$_2$. Using lasers allows for heating of PCM switches in arrays without impacting the EM performance [14]. While optical pulses have previously been used to activate VO$_2$-based switches, the $S$-parameters were measured under voltage bias rather than relying on optical excitation. The laser power was not reported, but the pulses caused apparent damage to VO$_2$ film [15]. Photothermally transitioned germanium telluride (GeTe) PCM switches have been demonstrated recently, but they were only characterized up to 40 GHz and have relatively high loss [16]. The RF performance of a laser-activated, VO$_2$-based switch has yet to be characterized. In this work, we present a low-loss, ultrawideband coplanar waveguide (CPW) series switch based on VO$_2$ and, for the first time, demonstrate photothermal switching using a semiconductor laser.

II. SWITCH DESIGN

We selected a series CPW switch topology for our test vehicle. A CPW can be arbitrarily downsized for the same impedance, allowing for miniaturization of the VO$_2$ switch. The small VO$_2$ area decreases the power required for exciting the IMT. Micrographs of the device are presented in Fig. 1. A wider 50-Ω CPW line facilitates measurement of the switch using 150-μm-pitch ground–signal–ground (GSG) probes. The CPW tapers to a smaller line, and the signal trace is interrupted by a small gap with VO$_2$ inserted. When VO$_2$ is at room temperature, the switch acts as an open-circuit (the OFF state). When VO$_2$ is above 68 °C, the signal

2771-957X © 2024 IEEE. Personal use is permitted, but republication/redistribution requires IEEE permission. See https://www.ieee.org/publications/rights/index.html for more information.
which were experimentally extracted using four-point probe measurement. The sheet resistance of the blank film was measured as 221 kΩ/□ at room temperature and 12.4 Ω/□ at 100 °C. The resistivity contrast between the two states is 1.7 × 10^6. Next, we patterned VO₂ using reactive ion etching. To create the CPW lines, we deposited 1-μm-thick Cu with a 20-nm-thick Ti adhesion layer using evaporation and lift-off.

### III. Fabrication and Measurement Results

#### A. On-Wafer Fabrication

First, we deposited 320 nm of VO₂ on a 430-μm-thick, 100-mm-diameter C-plane sapphire wafer using our dc sputtering recipe [3]. Using a four-point probe, the sheet resistance of the blank film was modeled as 36 [17]. The simulated S-parameters are presented alongside measurement data in Section III-B.

#### B. Frequency-Domain Measurement

We characterized the switches using an mmWave probe station setup, as shown in Fig. 3(a). The PNA (Keysight N5227B) was calibrated using short, open, load, and thru on an impedance standard substrate. A custom 3-D-printed fixture was designed and fabricated to elevate the wafer above the vacuum chuck, providing a space for the laser and focusing elements to be placed underneath. The laser was positioned using an xyz micropositioner. Using the microscope camera, the laser spot was initially focused onto the VO₂ area. The laser position was further tuned with the GSG probes (FormFactor ACP65-AW-GSG-150) landed until we observed a change in the S-parameters when the laser was powered on. We used a commercially available laser diode operating at 786 nm, driven with dc power supply at 2.85 V, 400 mA (1.14 W), continuous wave, which was the minimum input power to achieve steady-state performance of the switch. If the laser power is too low, VO₂ at the edges of the channel does not transition, which negatively affects the IL. This power is continuous to maintain the transitioned state of VO₂. The input power requirement is primarily dependent on the efficiency of the laser, which is less than 40%, and VO₂ dimensions. Based on the refractive indices of sapphire and VO₂, less than 10% of the optical power is reflected off of the material interfaces, and more than 98% of the optical power incident on VO₂ film is expected to be absorbed.

We characterized the RF performance of the switches up to 65 GHz, which is the maximum frequency that can be measured with our probes. To reduce measurement errors, two separate measurements were conducted, covering 10 MHz–50 GHz and 50–65 GHz, respectively. The measurement results were de-embedded to the start of the taper, as indicated by the reference planes in Fig. 1(a), and are concatenated in Fig. 3(b) and (c) with comparisons to simulation. In the ON state with the laser heating VO₂, the IL is <0.43 dB, and the return loss is >17.7 dB from 10 MHz to 65 GHz. In the OFF state with room-temperature VO₂, the isolation is >17.2 dB up to 65 GHz. The discrepancies in the OFF state can be attributed to dispersive behavior in the permittivity of VO₂ at room temperature.

The switch is assumed to be comprising a capacitance \(C_{\text{on}}\) in parallel with a variable resistance, which is \(R_{\text{on}}\) in the

---

**TABLE I**

<table>
<thead>
<tr>
<th>Switch Parameters</th>
<th>(w)</th>
<th>15 μm</th>
<th>(l)</th>
<th>3 μm</th>
<th>(t)</th>
<th>50 μm</th>
<th>(g)</th>
<th>7 μm</th>
<th>(t_{\text{VO2}})</th>
<th>320 nm</th>
<th>(t_{\text{Cu}})</th>
<th>1 μm</th>
</tr>
</thead>
<tbody>
<tr>
<td>(S_{\text{12}})</td>
<td>0</td>
<td>-0.5</td>
<td>0</td>
<td>-0.5</td>
<td>0</td>
<td>-0.5</td>
<td>0</td>
<td>-0.5</td>
<td>0</td>
<td>-0.5</td>
<td>0</td>
<td>-0.5</td>
</tr>
<tr>
<td>(S_{\text{21}})</td>
<td>0</td>
<td>-0.5</td>
<td>0</td>
<td>-0.5</td>
<td>0</td>
<td>-0.5</td>
<td>0</td>
<td>-0.5</td>
<td>0</td>
<td>-0.5</td>
<td>0</td>
<td>-0.5</td>
</tr>
</tbody>
</table>

---

Fig. 1. Micrographs of the VO₂-based CPW switch. (a) Optical micrograph with dimensions labeled as given in Table I. (b) Scanning electron micrograph.

Fig. 2. Parameter sweep of \(l\) to show the effect of VO₂ length on IL and isolation. All other parameters are as listed in Table I.

---

Authorized licensed use limited to: Georgia Institute of Technology. Downloaded on July 12, 2024 at 20:55:58 UTC from IEEE Xplore. Restrictions apply.
Fig. 3. Measurement of photothermally activated VO₂ switches. (a) Image of the test setup on a probe station. The insets show an illustration and a micrograph of the switch while under photothermal excitation by the laser. (b) and (c) S-parameter data in (b) ON and (c) OFF states.

hot state and \(R_{\text{OFF}}\) at room temperature. \(R_{\text{OFF}}\) is high enough (>10 kΩ) to be negligible compared with \(C_{\text{OFF}}\), and \(R_{\text{ON}}\) dominates while the switch is ON. We extracted \(R_{\text{ON}}\) and \(C_{\text{OFF}}\) values that match the measured S-parameters using this circuit model. The measured data correspond to an \(R_{\text{ON}}\) of 3.9 Ω and a \(C_{\text{OFF}}\) of 3.3 fF. The \(1/(2\pi R_{\text{ON}} C_{\text{OFF}})\) figure of merit is estimated to be 12.4 THz.

C. Time-Domain Measurement

We measured the switching time (ON and OFF) under photothermal excitation using the PNA’s continuous-wave time sweep functionality at 40 GHz. The laser was driven by a 10-kHz square wave with a 20% duty cycle. Each pulse had the same voltage and current as in the frequency-domain measurement. The normalized \(S_{21}\) at 40 GHz is plotted versus time in Fig. 4. After the laser turns on, \(S_{21}\) quickly increases by ~20 dB, indicating that VO₂ has transitioned. As labeled in Fig. 4, the rise time, \(\tau_{\text{ON}}\), and fall time, \(\tau_{\text{OFF}}\), are taken as the time between 5% and 95% of the total change in \(S_{21}\), in the linear scale. The measured \(\tau_{\text{ON}}\) is 12.2 μs, which is similar to the microheater approach [1]. The measured \(\tau_{\text{OFF}}\) is less than 1 μs, which is limited by the turn-off time of the amplifier used to drive the laser. The response times depend on the bulk substrate, which has high thermal conductivity. The thermal time constant of the switch can be tuned using low thermal conductivity substrate, such as quartz, or using a silicon substrate and air suspension via bulk micromachining, as in our prior work [11].

IV. DISCUSSION AND CONCLUSION

Table II shows comparison of this work to other switches from the literature, showing activation method (Act.), switching time (\(\tau_{\text{ON}}, \tau_{\text{OFF}}\)), frequency range, and ON state IL and OFF state isolation (Iso.) at 40 GHz. Importantly, our switch has lower IL than other works, including optically and electrically actuated GeTe switches [16], [19], SiGe-based p-i-n diode [20], and RF-MEMS [21]. Another PCM-based switch achieved lower IL at the cost of Iso. [2]. IL can be further reduced by decreasing the channel length \(l_c\) or using thicker VO₂. Iso. can be tuned to be closer to other works at a modest cost to IL.

In this work, we presented the first demonstration of photothermal excitation of a VO₂-based CPW switch. The devices exhibit ultrawideband, low-loss performance, as shown by the measured data from 10 MHz to 65 GHz. Specifically, the ON state IL and return loss are better than 0.43 and 17.7 dB, respectively, and OFF state isolation is greater than 17.2 dB. The primary challenges for laser-based actuation are alignment of laser sources and power consumption. However, the benefit is that parasitic capacitance due to coupling between RF and dc lines can be avoided, making our approach more scalable to sub-THz frequencies.