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Optical Actuation Performance of Phase-Change RF Switches

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Abstract—Optical actuation of GeTe-based radio frequency switches is studied for the first time at 915-nm optical wavelength. By inducing self-heating of the phase change material through light absorption, this approach removes the need for integrated micro-heaters, significantly improving the switch performances. First, laser pulse conditions required to set the RF switches in ON-and OFF-states are optimized. Then, optical actuation is performed overpassing 1500 cycles, which is much higher compared to previously reported demonstrations. Small-signal measurements show 10% lower OFF-state capacitances using optical actuation compared to electrical actuation through micro-heaters. The optical actuation demonstrated here corresponds to a standard wavelength in integrated photonic circuits and thus, this work constitutes a first step towards a CMOS compatible fully-integrated optical actuation solution for RF switches based on phase-change material.

Index Terms—Germanium Telluride, large-signal measurement, optical actuation, phase change material (PCM), radio frequency, RF switch, small-signal measurement.

I. INTRODUCTION

RADIO FREQUENCY (RF) switches based on chalcogenide phase-change material (PCM) have been widely studied in the last decade. They rely on the high resistivity ratio between the amorphous and crystalline states of the PCM that can be configured using heat pulses. Taking benefit of a low $R_{ON}C_{OFF}$ figure of merit (FoM) and high power handling performance, PCM RF switches represent an appealing solution to address sub-6G, mmW and THz applications as well as transmit-array antenna systems. In particular, many demonstrations exploiting germanium telluride (GeTe) integrated within coplanar waveguides (CPW) are reported [1], [2], [3], [4].

This paragraph of the first footnote will contain the date on which you submitted your paper for review. It will also contain support information, including sponsor and financial support acknowledgment. For example, "This work was supported in part by the U.S. Department of Commerce under Grant BS123456."

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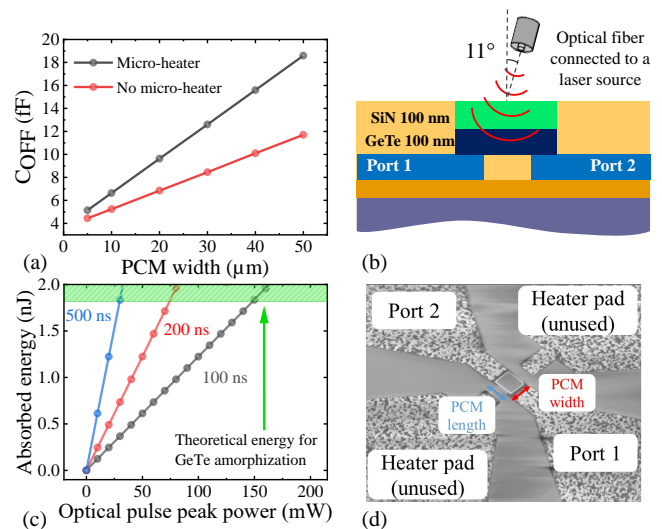


Fig. 1. (a) OFF-capacitance numerical computations for GeTe switches with/without micro-heater (2- μm long GeTe with 2- μm wide micro-heater) (b) optical actuation studied in this work using an optical fiber with a 915-nm laser source (c) 4- μm long and 5- μm wide GeTe (integrated within (b) stack) energy absorption computations when excited by a 915-nm laser source for different pulse widths (d) SEM picture of characterized devices.

Indirect electrical actuation using micro-heaters (that produces heat through the Joule effect) constitutes the main approach to perform the PCM state switching. Nevertheless, numerical computations based on an electrical model [5] presented in Fig. 1(a) show that micro-heaters and the associated biasing circuits induce significant parasitic capacitances that limit the switch RF performance [6]. Optical excitation represents another solution to address PCM RF switch actuation, relying on the high GeTe optical absorption ultimately converted into heat. Several demonstrations are reported using laser sources to actuate the PCM element [7], [8], [9]. Such approach does not require micro-heaters or extra metallic elements nearby the PCM, thus avoiding any additional parasitic RF capacitance. However, the previously reported demonstrations rely on extremely bulky and expansive ultraviolet lasers that cannot be integrated on chip, prohibiting the development of optically actuated PCM RF switches. Alternatively, integrated photonics is already a mature and industrial technology available within many CMOS foundries [10], [11], [12]. In particular, the 915-nm wavelength is standard for LiDAR

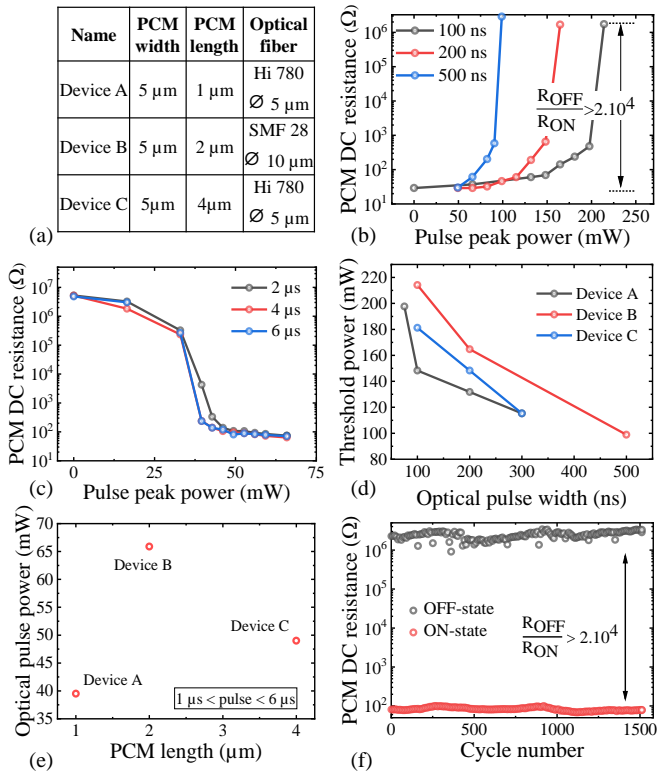


Fig. 2. (a) List of GeTe devices studied in this work and optical fibers used for actuation (b) amorphization results for different pulse widths on device B (c) crystallization results for different pulse widths on device B (d) amorphization condition summary (e) crystallization condition summary (f) cycle actuation testing on device C.

systems based on photonic circuits [13], [14] with cheap chip-scale pulsed lasers [15] that can readily be integrated on the photonic chip [16], [17]. Consequently, the co-integration of PCM RF switches and integrated photonics represents an appealing solution to address optical actuation. Besides, PCM/photonics co-integration has already been demonstrated for electro-absorption optical modulators [18], [19], [20].

In this context, we investigate experimentally and for the first time optical actuation of GeTe-based RF switches at 915 nm, paving the way for the realization of cheap and performant optically actuated RF switches.

II. TESTED DEVICES

In this work, we study RF switches made of a 100-nm thick GeTe integrated within a CPW with a 100-nm top passivation layer made of SiN (Fig. 1(b)). As a first demonstration, optical actuation is performed using an external 915-nm pulsed laser source connected to an optical fiber. The optical fiber is set 10 μm above the PCM element, with an angle of 11° to the normal of the surface (standard value used on the available fiber holders). The fiber is aligned with the PCM using micro-positioners on a standard wafer-level Cascade automatic probing station. The PCM DC-resistance is extracted through a 4-point measurement by applying 10 mV with a Keithley B2902A source connected to four probes. As shown in Fig. 1(c), numerical simulations based on the transfer matrix method (TMM) are performed in one dimension in order to es-

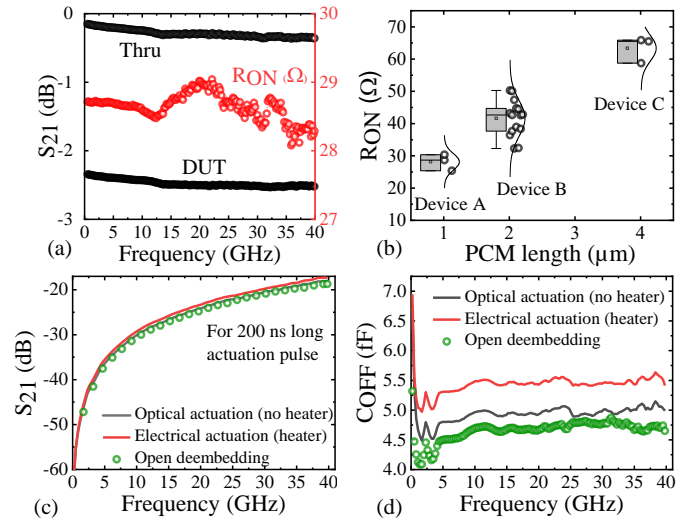


Fig. 3. (a) S_{21} parameters of optically crystallized device A and extracted R_{ON} (b) R_{ON} extraction for all optically crystallized devices at 5 GHz (c) S_{21} parameters of device A in the OFF-state (d) OFF-state capacitance extraction of device A from (c).

timate the energy absorbed by the PCM element as a function of the laser pulse characteristics, where we consider the optical properties of the GeTe provided in the literature [21], [22] and the overlap between the PCM and the Gaussian-shaped beam emitted by the optical fiber. Depending on the pulse duration (100 – 500 ns), the theoretical energy required for GeTe amorphization (~ 1.8 nJ) can be reached using optical pulses with reasonable peak power below 150 mW. Our studied devices are processed following the typical integration steps required to perform indirect electrical actuation. However, the fabrication has been stopped just before the micro-heater formation. Fig. 1(d) presents a top view of the characterized devices. In this work, three devices are studied and two types of optical fibers with different beam diameters are used. This is summarized in Fig. 2(a).

III. OPTICAL ACTUATION

At the end of the fabrication process, the PCM elements are in the crystalline state (switch in ON-state). First, the PCM amorphization is studied by applying single short optical pulses to reach the GeTe melting temperature ($\sim 700^\circ\text{C}$) with a short quenching time. The measured resistance variation of device B is shown in Fig. 2(b) for different optical pulse durations. For each curve (i.e. each optical pulse duration), a new device is used and single optical pulses are sent while sweeping the optical pulse power. Amorphization is clearly obtained with resistance ratios above 2.10^4 , corresponding to the switch OFF-state. As expected from the simulations, the pulse duration has a strong influence on the optical power required to switch the PCM. Once the PCM amorphization has been obtained, the required conditions to switch back the PCM to its crystalline state are sought. To do so, few μs long single optical pulses are applied to heat the PCM element above its crystallization temperature ($\sim 300^\circ\text{C}$). The measured resistance variation of device B relatively to the optical pulse power is shown in Fig. 2(c). The resistance significantly drops

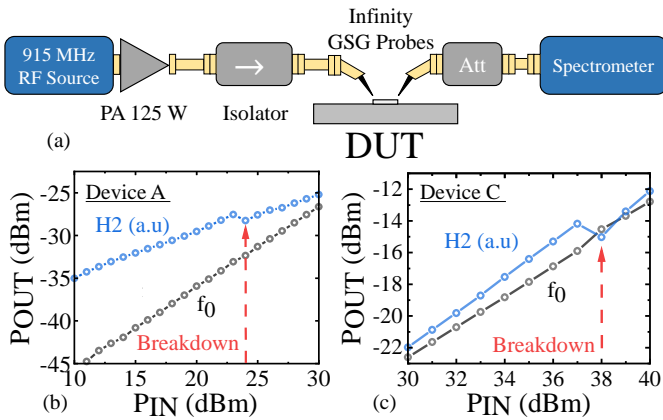


Fig. 4. RF power handling measurements for OFF-state switches amorphized with 200-ns long single optical pulses (a) experimental setup for 915 MHz fundamental frequency, second harmonic variations are measured in arbitrary unit (b) device A result (c) device C result.

for optical powers above 50 mW. Here, the optical pulse width has only a little influence on the power required for the phase transition. The conditions to perform the optical actuation are summarized in Fig. 2(d-e). Using the previously found switching conditions (amorphization: 200 ns/200 mW; crystallization: 4 μ s/50 mW), cycle testing of device C is performed with a 4 Hz repetition rate by alternately sending an amorphization pulse and then a crystallization pulse. After each of these pulses, the resistance is measured and reported. As shown in Fig. 2(f), 1500 cycles are obtained with an OFF/ON resistance ratio above $2 \cdot 10^4$. Moreover, all the actuation pulses successfully achieve the phase transition and both ON- and OFF-state DC-resistances remain stable during this test. These measurements validate that GeTe optical actuation is possible at 915-nm optical wavelength.

IV. RADIO FREQUENCY PERFORMANCE

S-parameters measurements are performed on all devices using a Keysight PNAX vector network analyzer (VNA) in a 2-port configuration. Calibration was performed from 200 MHz to 40 GHz using a commercial Impedance Standard Substrate (ISS). First, optically crystallized devices with 4- μ s long crystallization single pulse are studied. The ON-state transmission of device A is shown in Fig. 3(a) with the corresponding extracted resistance. Fig. 3(b) summarizes the extracted resistances at 5 GHz for multiple devices that have been optically crystallized. To do so, we performed optical crystallization and extracted the associated R_{ON} on several dies over a single wafer. The measured R_{ON} of device B vary from 32 Ω up to 50 Ω . This variability can be explained by an optical fiber/PCM misalignment for some dies since 1- μ m accurate stepper motors are used to achieve fiber alignment. Fig. 3(c) shows the transmission of device A in the OFF-state. Here, optically (without heater) and electrically (with heater) actuated devices are compared for 200-ns long single actuation pulses. To achieve this, we performed electrical actuation on another wafer (same technological stack) with extra fabrication steps to form the micro-heater. The corresponding OFF-state capacitances are extracted in Fig. 3(d).

As expected, the optically actuated device exhibits an OFF-capacitance lower than the electrically amorphized device by 10%. This is in perfect agreement with the simulation results shown in Fig. 1(a). Moreover, even further improvements are expected for wider devices (Fig. 1(a)), which are mandatory to handle high RF power in the ON-state. This proves that optical actuation can enhance the OFF-state capacitance and ultimately the $R_{ON}C_{OFF}$ FoM.

Finally, the power handling capability of devices in the OFF-state is measured at 915 MHz using the experimental setup shown in Fig. 4(a). Each tested point lasts 5 s, while the 2nd harmonics (H2) is also measured. Fig. 4(b-c) show the power handling results for devices A and C set to the OFF-state with a single amorphization pulse of 200 ns. The device breakdown is visible on H2 and occurs at 24 dBm and 38 dBm respectively for devices A and C. To the best of our knowledge, device C exhibits the highest reported power handling capability for a stand-alone GeTe-based RF switch in the OFF-state.

V. SUMMARY

This letter presented experimental results for optical actuation at 915 nm of GeTe-based RF switches. Switching conditions for both ON- and OFF-states were found for different PCM sizes. Cycle testing was demonstrated for at least 1500 cycles, which is the highest rate reported so far for optically actuated PCM-based RF switch. Small-signal measurements show smaller OFF-state capacitances for optically actuated devices, confirming the advantage of this method over conventional electrical actuation. A power handling capability of 37 dBm was measured in the OFF-state for a 4 μ m-long PCM device, which is the highest value reported so far for a stand-alone GeTe-based RF switch. Therefore, this work paves the way to the realization of performant RF switches that will further take benefit of CMOS integrated photonics.

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