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A memristor-controlled multilevel non-volatile phase shifter for photonic integrated circuits

Student paper

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Programmable Photonic Integrated Circuits (PIC) are a rapidly growing field promising energy-efficient high-speed signal processing. To connect various information processing elements and perform operations, an efficient, reprogrammable non-volatile optical phase shifting element with high retention is needed. In this work, we demonstrate a Mach-Zehnder Interferometer (MZI) controlled by a non-volatile, multi-level memristor.

Keywords: *PIC, Memristor, Non-volatile, Integrated optics, Phase Shifter*

INTRODUCTION

Field-Programmable Gate Arrays (FPGAs) have revolutionized the semiconductor industry, allowing for reconfigurable and multi-purpose hardware. Another implementation, Application Specific Integrated Circuits (ASICs), offer better performance overall, at the cost of design and fabrication overhead due to their limited purpose [1]. Current integrated photonics solutions are ASIC-like, missing their programmable counterpart.

With the refinement of the design, manufacturing and testing processes of silicon integrated photonics, new implementations based on an increasing number of optical components are emerging, ranging between multipurpose photonic signal processors ([2], [3]), optical quantum computers ([4]) and machine learning accelerators ([5]). A key component shared between all PICs are optical phase shifters. Non-volatile phase shifters could prove to be beneficial for the upscaling and efficiency of reprogrammable integrated photonic circuits [6], simplifying the electro-optical control of photonic circuits.

In this work, an implementation of a basic building block for programmable photonic integrated circuits is demonstrated. Previous works have shown the exploitation of ferroelectric material to achieve multi-level, non-volatile phase shifters [7]. Here, we demonstrate a multi-level optical phase shifting element utilizing the non-volatility of filamentary metal-oxide based memristors. By combining a memristor-controlled voltage divider, an amplification stage and a thermo-optic phase shifter, we show that this implementation allows to obtain many non-volatile optical transmission states of an integrated photonic Mach-Zehnder Interferometer (MZI).

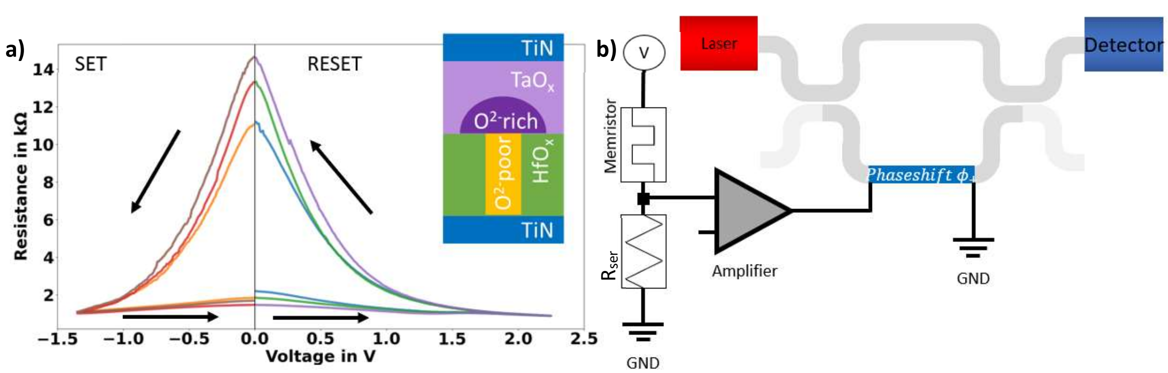

Fig. 1. a) *Memristor resistance versus the applied voltage. Multiple curves are shown, with different maximum voltage V_{Max}. The inset in the top right schematically shows the material stack of the memristive device [8].* ***b)*** *Schematic of the experimental setup linking the memristor to the optical phase shifter. The memristor is integrated in a voltage divider configuration as depicted on the left. The ratio of the two resistors defines the output voltage of the divider and so controls the output signal of the amplifier, driving the thermo-optic phase shifter. Continuous wave laser light is used to read out the phase shift via an integrated photonic MZI.*

EXPERIMENT

The filamentary memristor stack exploited in this work consists of 25nm TiN/ 20nm TaO_x/5.7nm HfO_2/25nm TiN (inset fig. 1a) fabricated on a Si++ doped substrate (bottom electrode BE), with an additional W plug as top contact (top electrode TE). The conductive filament is formed in previously pristine devices by applying a positive voltage sweep up to 5.5 V between TE (V+) and BE (ground). When reaching the breakdown voltage, a conductive filament forms in the HfO_2. TaO_x is substoichiometric, therefore it can oxidize through the electrically induced O^{2-} ions from the HfO_2 filament (see [8, 9]).

A negative voltage induces an electric field across the memristor, pushing the oxygen ions back into the HfO_2 layer, causing a reduction of the resistance, whereas a positive voltage drives the ions into the TaO_x layer, thus increasing the resistance. A fine tuning of the maximum applied voltage enables a gradual transition between Highest Resistive State (HRS) and Lowest Resistive State (LRS) (fig. 1a).

The measurement setup is shown in fig. (1b). The memristor and a fixed 4.7 kΩ resistor R_{ser} placed in series act as a voltage divider. The memristive state is read out at a constant bias of 0.4 V. The low voltage guarantees long resistive retention, as it is well-below the switching threshold of the device. The output signal of the voltage divider depends on the ratio of the two resistors. To allow high voltage applications, we link the voltage divider with an amplifier (A=10x) to the thermo-optical phase shifter (fig. 1b). The discrete elements and memristors are mounted on a Printed Circuit Board (PCB). Individual memristive devices are connected via wire bonds. The supply voltage of the amplification stage is set to 12 V.

The symmetric MZI is processed on an SOI-Wafer. Tungsten lines on top of the patterned Si-waveguides are utilized as joule heaters. Grating couplers are used to in- and output laser light from a tunable laser at 1550nm wavelength. The transmission of a MZI driven by a thermal phase shifter is given in Eq 1 ([13]),

$$T = a \cdot \cos\left(\frac{1}{t} \cdot P + \phi_0\right) + O \quad \text{(Eq 1)}$$

where a is the amplitude, O is a constant offset, t is the power for a 2π phase shift, P is the power applied and ϕ_0 the phase shift at 0V.

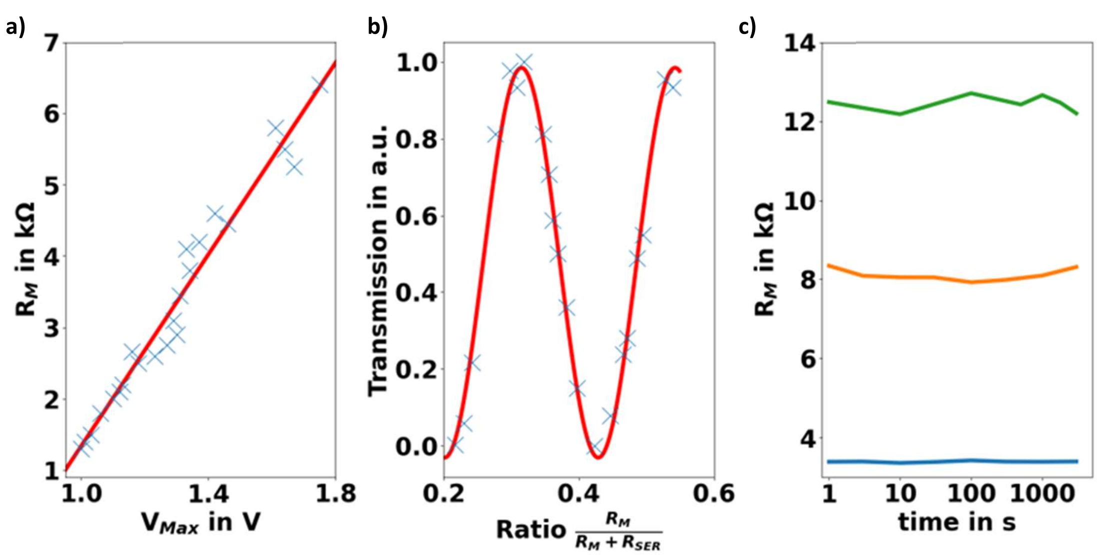

Fig. 2 a) *The resistive state of the memristor R_M as a function of the maximum voltage V_{Max}. The resistive values are represented by blue crosses, a linear regression is plotted by a solid red line.* ***b)*** *MZI-Output plotted against the divider's resistance ratio.* ***c)*** *Memristor retention for three resistance values.*

RESULTS & DISCUSSION

Fig. 2a depicts the relation between the memristive state and the maximum applied voltage V_{max}. By tuning V_{max}, up to 23 resistive states are demonstrated in this example. Thereby, R_M can be adjusted between 1.3 and 6.4 $k\Omega$, an On/Off ratio of 4.9. With a serial resistance of 4.7 kΩ, the voltage divider delivers an output signal between 0.16 and 0.32 V, which is then amplified to 1.6 - 3.2 V on the phase shifter. The output range can be adapted by changing the serial resistance as well as the amplification. Fig. 2b shows the corresponding optical transmission of the MZI The resistance-phase shift relation is computed using the sinusoidal fit of the transmission data using Eq. 1. With an applied signal of only 0.4V at the voltage divider, a 3π optical phase shift is achieved. For the use as non-volatile optical phase shifter, retention is an important figure of merit. In fig. 2c, typical retention of three states of memristive devices measured for up to 3000s are shown.

By increasing the memristor resistivity, as demonstrated in [8], 10x lower power consumption of the voltage divider can be achieved. The here shown combination of the memristor-based voltage divider and the amplifier allows for 23 optical phase states distributed across a range from 3π. Using voltage pulses for programming the memristor, as in [8], is a power-efficient way to set the desired state. This concept of realizing non-volatile optical phase shifters is compatible with back-end of the line processes and can be integrated on most photonic platforms.

CONCLUSION

In this work, we presented a multi-level, non-volatile, photonic phase shifter, utilizing a memristor element in combination with an integrated photonic MZI. We have demonstrated up to 23 reconfigurable states with measured retention up to 3000s. Filamentary memristors are a promising technology for electrically tunable, non-volatile, large scale integration voltage dividers. The application is not limited to MZIs and phase shifters, but can also be used to control other photonic integrated components such as laser sources, amplifiers or electro-absorption elements. This basic building block enables fast and reliable operation of next generation programmable PICs, hardware accelerators for optical neural networks, inference deep neural networks as well as integrated photonic quantum computing [10-13].

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