Frequency Injection Locking-Controlled Oscillations for Synchronized Operations in VO2 Crossbar Devices

Elisabetta Corti, Corentin Delacour, Aida Todri-Sanial, Siegfried Karg

Frequency Injection Locking-Controlled Oscillations for Synchronized Operations in VO_2 Crossbar Devices

Elisabetta Corti[1*], Corentin Delacour[2*], Aida Todri-Sanial[2] and Siegfried Karg[1]
*contributed equally
[1]*IBM Research Zurich, Säumerstrasse 4, 8803 Rüschlikon, Switzerland*
[2] *LIRMM CNRS, 161, rue Ada, 34095 Montpellier, France*
Email: corentin.delacour@lirmm.fr / Phone: +33 (0) 4 67 14 97 44

Introduction

Compact oscillating devices can be realized by exploiting the insulator-to-metal transition of VO_2 (IMT). Coupled oscillators can be locked in frequency and phase through connections realized with resistors or capacitors. Oscillatory neural networks based on VO_2 devices are researched as neuromorphic computing hardware for image recognition applications [1,2]. Physical demonstrations of large networks of coupled oscillators are yet hindered by the device-to-device variability [3]. In this work, we present a frequency-injection scheme which allows additional tuning and control of the oscillator network comprising non-ideal VO_2 devices.

Results

The VO_2 devices are realized in a crossbar (CB) geometry on a Si/SiO_2 substrate using a CMOS compatible process. Planarized bottom contacts have been fabricated with ebeam-lithography and lift-off. Consequently, a VO_2 film is prepared with atom layer deposition and post-anneal. Finally, with a last lithography step the top contact is defined (Fig.1). Due to the polycrystalline nature of the VO_2 layer, some device-to-device variability occurs. The current-voltage (IV) characteristics of the device is measured with a current source in a temperature-controlled environment and exhibits an IMT transition which a negative differential resistance (NDR) behavior (Fig.2). Relaxation oscillators were formed biasing the VO_2 device in the NDR region using a series transistor as load (Fig.3). It has been shown in literature that the greatest limitation in experimentally achieving large systems of coupled oscillators is indeed the device-to-device mismatch, which causes the natural frequency of the oscillators to diverge and therefore doesn't allow for the devices to lock in frequency [3]. The harmonic injection (HI) approach achieves tuning of the output oscillating frequency through the injection of an AC signal superimposed to the gate voltage of the biasing transistor. The spontaneous oscillations of a VO_2 device measured at the drain of the transistor is shown in Fig. 4 a together with the applied gate voltage (V_{G1} kept at 1.1 V). The VO_2 device presents spontaneous oscillations at 4.7 kHz (Fig. 4 b). When V_{G1} is modulated with a 200 mV peak-to-peak harmonic injection (HI) AC signal at 5 kHz, the VO_2 device locks in frequency with the input AC signal (Fig. 4 c and d). Systematic experiments show that the VO_2 oscillator output frequency locks with the AC input for a wide range of frequencies, down to 3.5 kHz and up to 6 kHz. Outside these values the synchronization is lost (Fig. 5). Therefore, the HI technique enables to tune the oscillation frequency of the single oscillators and to promote coupling of devices which present device-to-device variability. This is demonstrated experimentally in Fig. 6, where two VO_2 oscillators with the same dimensions present different oscillating threshold voltages. Through the coupling with a resistor and the HI in the gate voltages, the oscillators are coupled in frequency and achieve in-phase and out-of-phase synchronization.

We assess the impact of device-to-device variability on oscillator frequency by performing circuit-level simulations of two coupled VO_2 devices. At circuit-level, we emulate the oscillator's frequency mismatch by varying the load capacitor C_p from 0.8 to 1.2 nF to obtain variations with respect to the nominal case at 300 kHz. Then, we simulate two mismatched VO_2-oscillators coupled by a 6 kΩ-resistor, using the VO_2 compact model from [4] to determine the synchronization region (Fig. 7) for two different configurations: 1) without harmonic injection and 2) with harmonic injection where we apply the same 200 mVpp sinusoidal gate voltage at 300 kHz. In the first configuration, up to 5% of frequency deviation is tolerated when one oscillator switches at the nominal frequency, whereas up to 18% frequency mismatch is tolerated using the frequency injection technique. Overall the synchronization region is enlarged, making the frequency injection attractive for oscillatory neural networks design where information is contained in the phase between frequency-locked oscillators.

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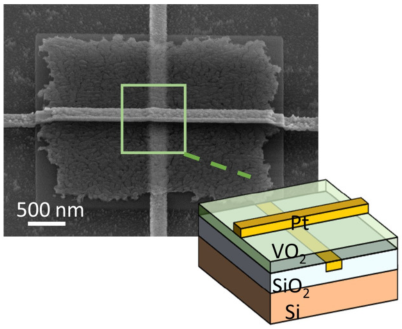

Fig.1: Scanning Electron Microscope picture of a crossbar device and corresponding device schematic.

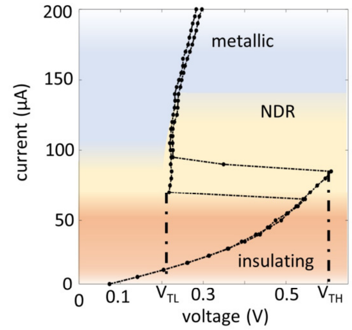

Fig.2: IV characteristic of a VO_2 CB device. The insulating, metallic and NDR regime are highlighted.

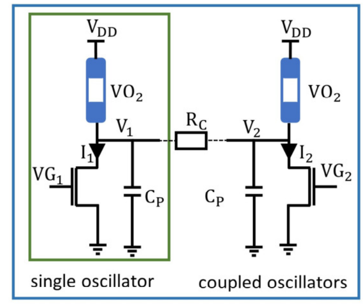

Fig.3: Electrical connections for a single and coupled oscillator experiment.

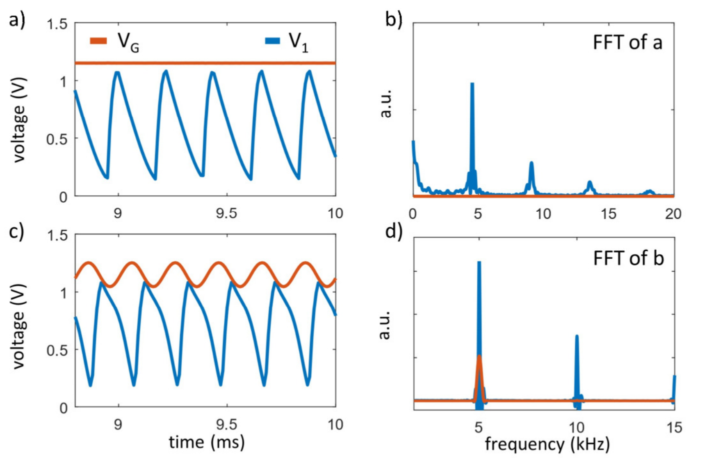

Fig.4: Experimental curves of a single VO_2 oscillator. a) and b) oscillations and corresponding fast Fourier transform (FFT) with a constant gate voltage. c) and d) superimposing an AC signal at the gate voltage, the VO_2 oscillator output signal locks to the AC input frequency, allowing for frequency tuning.

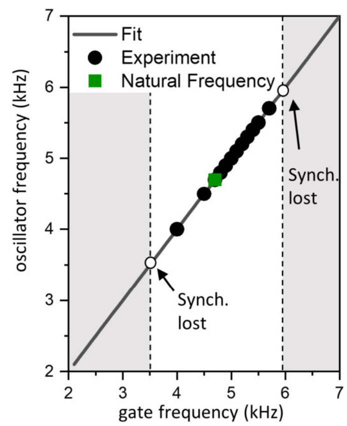

Fig.5: experimental results of frequency injection locking. Changing the frequency of the gate signal, we can tune the oscillator frequency. For $|f_g - f_n| > 25\% \ f_n$, the VO_2 oscillator cannot follow anymore the input gate voltage and synchronization is lost.

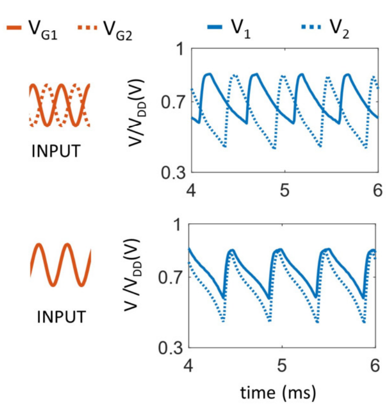

Fig.6: Experimental curves of two oscillator with variable threshold voltage values (V_{TH} and V_{TL}) locked in frequency thanks to the HI synchronization scheme. The relative phase of the oscillators can be controlled through the phase of the AC input.

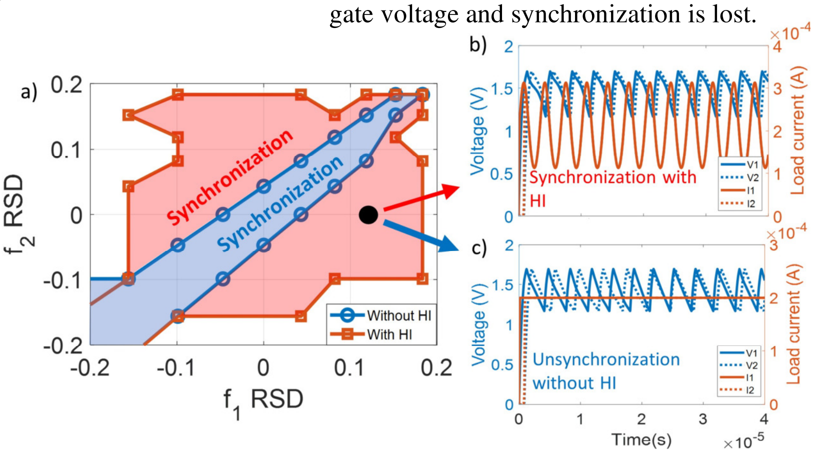

Fig.7: a) Simulations shows the synchronization space of two resistively-coupled VO_2 oscillators with different natural frequencies. Without the HI technique, the synchronization space is limited, with the HI technique synchronization is achieved for diverging natural frequencies up to 18% Relative Standard Deviation (RSD). b) and c) examples of oscillator output with and without HI.