Ultra Low Power Coupled Oscillator Arrays for Computer Vision Applications

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Abstract: Coupled oscillators provide an efficient non-Boolean paradigm for solving a variety of computationally intensive problems in computer vision. This motivates the realization of large networks of low-power coupled oscillators. In this work, we experimentally demonstrate: (i) a relaxation oscillator based on the insulator-metal transition (IMT) in vanadium dioxide (VO_2) with record low DC input (peak) power of ~23 µW; (ii) a network of coupled VO_2 oscillators with record number of elements (6 oscillators) which perform image processing functionalities in high dimensional space like color detection and morphological operations such as dilation and erosion). Calibrated simulations show that 10x reduction in power compared to a 32 nm CMOS accelerator at iso-throughput.

Introduction: Quantifying the degree of match or contrast within an image is a ubiquitous operation in computer vision applications for pattern recognition, saliency detection and color interpretation. The conventional Boolean computing platform (Fig. 1) requires a large number of power consuming serial multiply-accumulate (MAC) logic operations to implement such nano-functions [1]. Coupled oscillators, on the contrary, are analog dynamical systems whose synchronization dynamics stemming from the energy minimization (Fig.2) of the system can compute nano-functions in a parallel fashion to find the degree of match. In this work, we demonstrate, for the first time, coupled oscillators with up to 6 synchronized oscillators that allows us to experimentally observe the attractor energy function of the oscillators. The coupled system is shown to perform color detection and morphological operations for an image.

Relaxation Oscillator: The VO_2 relaxation oscillator harnesses negative-differential-resistance (NDR) associated with the abrupt insulator-metal transition (IMT) in VO_2 [2]. Fig. 3 shows the false-colored SEM image of the VO_2 device (in the oscillator configuration) with L_{VO2}~100nm. Spatially-resolved nanoscale XRD characterization performed in operando with electrical bias (Fig. 4) [3] reveals that the electrically induced IMT in in VO_2 is characterized by the formation of a non-homogeneous metallic filament of rutile (R) crystal structure in an insulating matrix (with low-symmetry monoclinic M1 phase). No defect mediated transport mechanisms were responsible for the phase transition, as supported by the high endurance of IMT (>2.5×10^9 cycles [2]). Self-oscillations in the device can be stabilized with negative feedback from a series MOSFET [4]. Fig. 5 shows scaling trends for the oscillator revealing that the input power (and IMT voltage) scales with channel length; we achieve a record low peak input power of 23.75µW for an oscillator operating on the principle of electrically triggered phase transition.

Coupled Oscillators: We investigate the star coupling configuration for the oscillators, as shown in Fig. 6(a), wherein all the oscillator output nodes ($V_{O,i}$) are capacitively coupled to a common output node (V_{out}); Fig. 6(a) shows a set of for 3 coupled oscillators connected in this configuration. Fig. 6(b)(c) show the representative oscillator time domain waveforms before and after coupling, respectively, wherein the oscillators exhibit frequency synchronization after coupling. Fig. 7 shows the amplitude of V_{out} as a function of the input voltages which depends on the relative phase difference amongst the synchronized oscillators [5]. The phase dynamics and, hence, the amplitude of V_{out} are governed by the coupled oscillator system's natural tendency to minimize its collective energy and attain a global minimum in the energy function of the total system. Thus, the surface traced by V_{out} represents the attractor surface and basin of this oscillatory dynamical system. A change in the input vectors alters the phase trajectory along the attractor surface. The simulated attractor surface for the configuration of 3 coupled oscillators is shown in Fig. 8.

Coupled oscillator network with larger number of oscillators: The configuration of three coupled oscillators enables the implementation of image processing functions like color detection. In the past, only pairwise (i.e. 2) coupled oscillators have been demonstrated before. Fig. 9 shows the simulation results for the detection of the color 'brown' using the experimentally measured synchronization dynamics of three coupled oscillators (white color in the output indicates a good match). It can be observed from Fig. 10 that coupling a larger number of oscillators enables more image processing functionalities. We therefore, investigate and experimentally demonstrate the coupling of 6 relaxation oscillators (Fig. 11). Since a minimum of 5 oscillators is required for morphological operations, our results pave the way to implementing this operation as well. Fig. 12 shows the implementation of the dilation and erosion functions using calibrated models of the VO_2 oscillators.

Benchmarking with CMOS: We compare the power-performance metric of a 32 nm node CMOS based custom accelerator, synthesized using Synopsys Design Compiler [6] and the coupled oscillators (Fig. 13). The CMOS accelerator uses ~140,000 gates which consume a power of 1,100 µW (with the ADC consuming an additional 6mW). The coupled oscillators provide an impressive power reduction of ~230× over CMOS. However, in the oscillatory network case, the throughput of the oscillator stage (comprising of 9 oscillators) is constrained by the phase transition time of VO_2 and the coupling capacitance [4], and, hence, is lower than that in CMOS ASIC (~500M Op/s vs. 18.56 M Op/s). This suggests that increased parallelization for oscillatory network is required. Despite this limitation, the oscillators provide a power advantage of 10x under iso-throughput condition of 500M Op/s.

Conclusions: Fig. 14 benchmarks this work against other published reports [7-9] on coupled oscillators and highlights the superior low power oscillator performance and first experimental demonstration of scaled up synchronized network up to 6 oscillators. By implementing a network of 6 coupled oscillators, we are able to realize higher order image processing functions beyond saliency detection to color interpretation and morphological operations. Finally, we show the 10× improvement in the power efficiency of non-Boolean coupled oscillator network as an alternative to CMOS for vision applications.

References: [1] Shibata et al. CNNA, (2012) [2] N. Shukla et al. Sci. Rep, May (2014). [3] Freeman et. al APL December (2013) [4] N. Shukla, IEDM (2014). [5] W.-Y Tsai *et al.* TMSCS (2016) [6] Design Compiler - Synopsys. [7] Kaka et al. Nature, July (2005) [8] A. Sharma et al. JxDC, Sept (2015) [9] A. Sharma et al. VLSI (2015).

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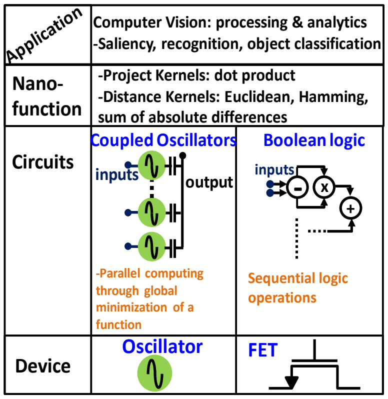
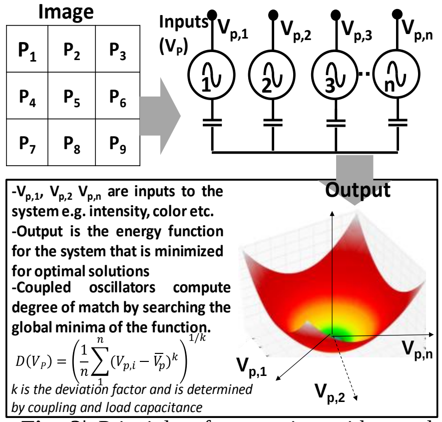


Fig. 1| Motivation. We harness the synchronization dynamics of ultra-low power coupled VO_2-relaxation oscillators for image processing tasks. The system's performance is evaluated and compared with CMOS.



$$D(V_P) = \left(\frac{1}{n}\sum_{1}^{n}(V_{p,i} - \overline{V_p})^k\right)^{1/k}$$

Fig. 2| Principle of computing with coupled oscillators. The oscillators enable finding the degree of match in higher dimensional space (i.e. $V_{p,1}$, $V_{p,2}$, $V_{p,n}$)

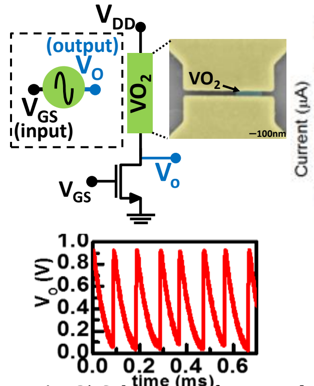


Fig. 3| Schematic of a typical gate tunable VO_2 oscillator. A False colored SEM image of the VO_2 device and the typical waveforms is also shown.

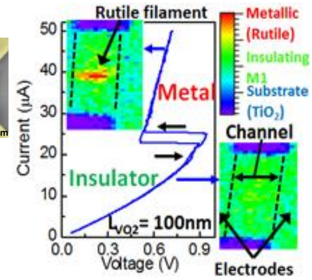


Fig. 4| Current driven IMT showing an NDR which is harnessed in oscillators. Insets show the formation of a metallic rutile filament during IMT; measured using spatially resolved nano-scale XRD.

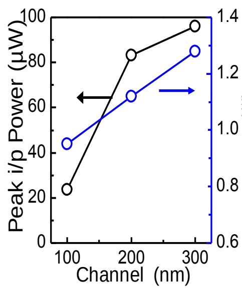


Fig. 5| Evolution of power and IMT trigger voltage (V_{IMT}) as a function of L_{VO2}.

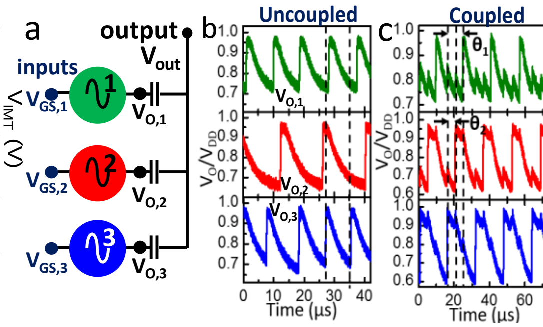


Fig. 6| (a) Coupled oscillator configuration (Star); the coupling of 3 and 6 oscillators is investigated in this work. (b) Before and (c)After capacitive coupling of the oscillators. Post coupling, the oscillators lock phase at a common frequency.

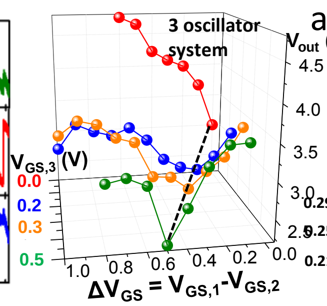


Fig. 7| Output voltage (V_{out}) as a function of inputs $\Delta V_{GS,1}$ and $V_{GS,3}$ ($V_{GS,2}$ is constant) for multiple $V_{GS,3}$ for the 3 oscillator coupled system (experiment). V_{out} is the attractor of the system.

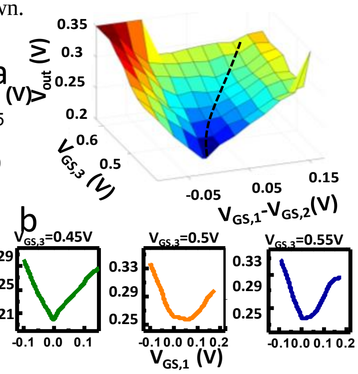


Fig. 8| (a) Simulated V_{out} vs. $V_{GS,1}$ & $V_{GS,2}$ showing the attractor of the coupled 3 oscillator system (b) 2D cross-sections of the 3D attractor for various $V_{GS,2}$

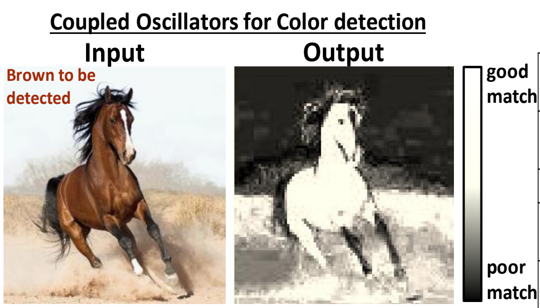


Fig. 9| Color detection using 3 coupled oscillators. White output indicates excellent match to the input color

Image Processing function	Size of Coupled Oscillators
Salience Detection (Pixel-wise) detection	2
Color detection	3
Morphological operation Dilation / Erosion	5
Pattern matching (nearest neighbor)	9

Fig. 10| Designing a larger system of oscillators increases image processing functionality

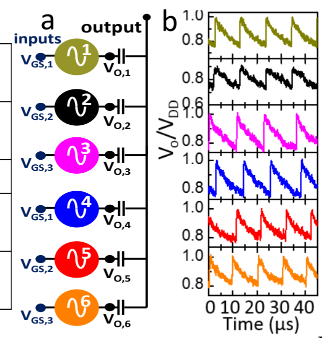


Fig. 11| Experimental coupling of 6 VO_2 oscillators

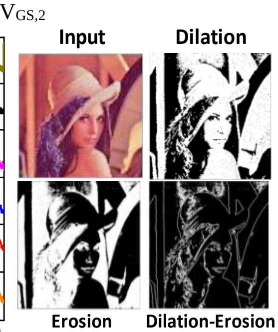


Fig. 12| Dilation & Erosion enabled with 6 oscillators

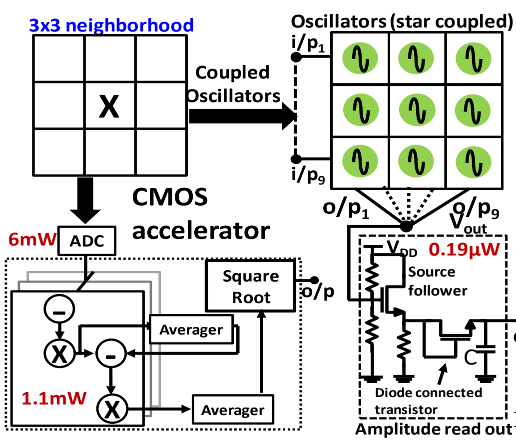


Fig. 13| Schematics of Oscillator-based processing scheme and 32 nm CMOS ASIC for a 3x3 neighborhood.

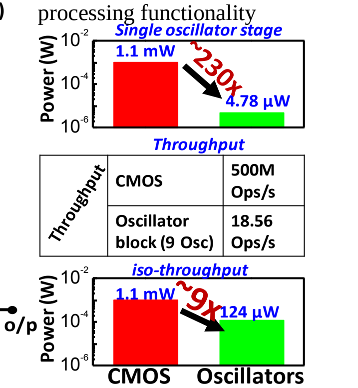


Fig. 14| Power comparison of coupled oscillators with 32 nm CMOS ASIC. At *iso*-throughput, the oscillators enable a 10x reduction in power.

Oscillator characteristics	This work	[7]	[8]
Material	VO_2	$Ta/Cu/Co_{90}Fe_{10}$ $/Cu/Ni_{80}Fe_{20}$ /Cu /Au	TaO_x
Oscillator type	Relaxation	Sinusoidal	Relaxation
No. of coupled oscillators demonstrated	6	2	2
Coupling type	Capacitive (non-dissipative)	Spin current	Capacitive (non-dissipative)
DC input power (peak)	~23.75 µW (~12 µW avg.)	-	≤200 µW [9]
Endurance	>2.5x10^9 cycles [2]	-	-
Coupled Oscillator functionality demonstrated	Color detection & Morphological operation	Microwave Amplification (experiment)	ONN [9]
System level power & CMOS comparison (32 nm node)	~124 µW [~10x reduction vs. CMOS @ iso-throughput]	-	-

Fig. 15| Benchmarking Comparison of oscillators demonstrated in this work with other coupled oscillator systems.