Physical Reservoir System with Single-Walled Carbon Nanotube/ Asymmetric Porphyrin-Sandwiched Polyoxometalate Random Network

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[Introduction] Reservoir computing is an emerging tool for prediction or classification task in an energy-efficient way faster way as it requires only training of output weights for better learning. Several physical hardware platforms that reflects inherent reservoir properties of non-linearity, memory effect and high-dimensionality are proving to be an alternative to software based interface[1]. Herein, we introduce a physical reservoir of randomly connected single-walled carbon nanotube (SWNT)/asymmetric porphyrin-sandwiched polyoxometalate (Por-POM) network as previously theoretically modeled [2] and affirm the characteristic reservoir properties of this system experimentally. Finally two benchmark reservoir tasks of waveform generation and non-linear autoregressive moving average (NARMA) [2] time series prediction were performed to prove its credibility as a reservoir computer.

[Method] SWNT/ Por-POM ($SV_2W_{10}O_{40}[H_4TPP]$) in the ratio 1:20 by weight was sonicated in ethanol. It was transferred onto Al sputtered micro electrodes; patterned using photolithography; by vacuum filtrating the dispersion through a micro-cellulose filter paper followed by dissolution of the filter paper via acetone vapors. I-V and a rudimentary reservoir task of waveform generation were performed using a semiconductor analyzer and a custom built probe set up driven by LabVIEW software. All measurements were performed at ambient condition.

[Result and discussion] The pretreated SWNT/Por-POM was subjected to time-varying sine wave inputs and outputs from various electrodes were plotted against the inputs as Lissajous plots (Fig. 1a). Non-linear switching output indicates high interaction of external wave with the reservoir system creating multiple memory states due arising from reversible redox of Por-POM. Different shaped Lissajous plots from linear to elliptical with memory states suggest echo-state property of learning from current and recent past inputs. Such dynamics enable output of even and odd higher harmonic frequency generation (HHG) confirmed by the FFT analysis of in Fig. 1b. Two-time lag NARMA-2 (Fig. 1c) along with square and sawtooth waveform generation using linear regression model were successfully achieved indicating, unison of non-linearity and memory of SWNT/Por-POM is indeed an important factor for fast learning. Improvements in further complex waveforms and higher time series (NARMA-10) prediction are under study in order to develop a full-fledged reservoir system that can help in speech recognition task, for example, in near future.

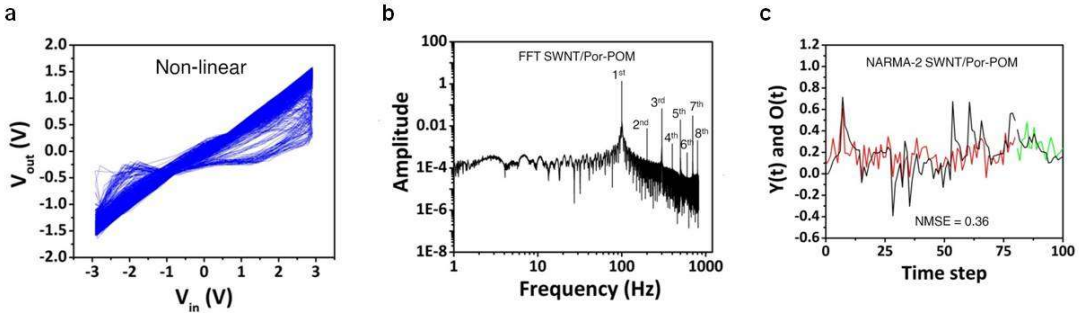

Fig. 1 (a) Non-linear switching Lissajous plot due to redox of Por-POM obtained from one of the electrodes. (b) HHG of odd and even frequencies compared to fundamental 100 Hz. (c) NARMA-2 trained (red) and predicted (green) series compared to target (black). Minimum error value of NMSE indicates the best learning.

Keywords: Reservoir computing, single-walled carbon nanotube, $SV_2W_{10}O_{40}[H_4TPP]$, polyoxometalate.

References: [1] G. Tanaka et al., *Neural Netw.*, **115**, 100-123 (2019). [2] H. Tanaka et al., *Nature. Commun.* **9**, 2693 (2018). [3] E. Torres et al., (2019), doi: 10.1109/ROBOSOFT.2019.8722777.