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# Mimicking Biological Sensorimotor Systems by Opto-electronic Artificial Neurobotics

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**Summary:**
Principally new artificial bioinspired optoelectronic sensorimotor system based on inorganic optical synapse (In-doped $TiO_2$) assembled into a liquid metal (galinstan) actuator for the controllable imitation of opto-genetically engineered neurons in the biological motor system is reported. The innovatively fabricated sensorimotor system is characterized by the low-energy consumption and precise modulation of electrical and mechanical outputs.

**Keywords:** Sensorimotor device, liquid metal actuator, galinstan, optical synapse,

## Introduction

Principally new approach consisting of artificial synapse innovatively incorporated into the liquid metal actuator device to imitate sensorimotor functions is proposed and executed in the present research. To imitate the biological motoneurons behavior, a visible light sensitive $TiO_2$ optical synaptic device is integrated into a liquid metal actuator, which acts as artificial muscular component. Schematically this approach is presented below in Fig. 1. In the developed device, the indium (In)-doped $TiO_2$ optical synapse plays the role of visible light sensor, which receives optical signals and then generates informative postsynaptic current and potential pulses. The employed doping technique has broadened the optical sensitivity of ultra-thin high bandgap $TiO_2$ film to visible light region. The transfer of controlled potential pulses to the liquid metal actuator induces the mechanical motion, which in turn, mimics the muscular contraction/relaxation in the artificial neuro-robotic device. The following investigation of mechanisms behind the mechanical motion provides valuable insights towards the motor function of fabricated sensorimotor system. This achievement is fulfilled by precise design and optimization of sensorimotor components.

There are just a few cases which make a substantial step forward to confront the fundamental challenges of the development of biological sensorimotor systems [1]. In bioscience, an integration of the visible light-driven artificial synaptic device with a motor system can trigger several fundamental applications in cutting-edge technologies including optical wireless devices, light-driven robotics, neurological optoelectronic sensorimotors, microfluidic chips and nano-pumps in drug delivery systems.

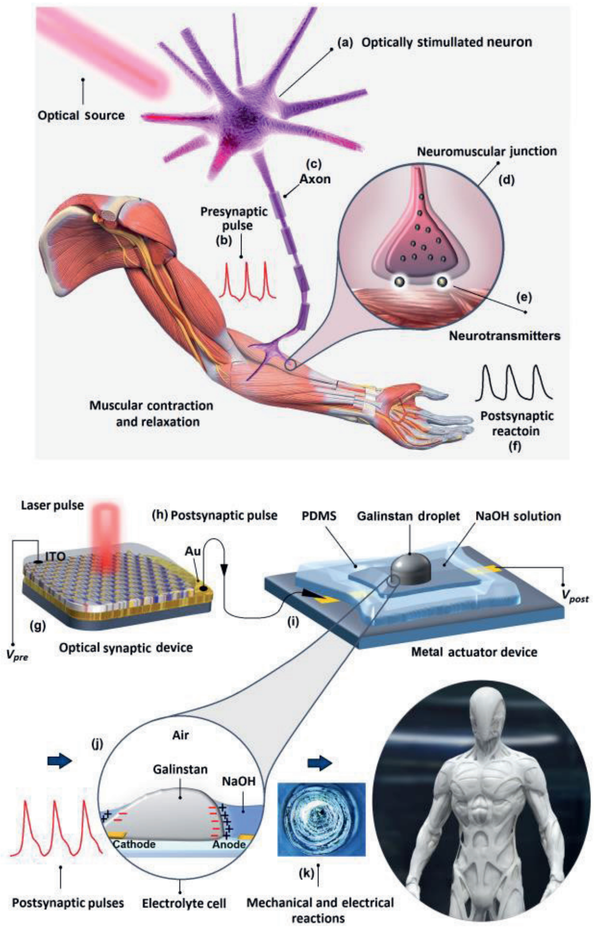


*Fig. 1. The scheme of opto-genetically engineered neuron system (top) and artificial optoelectronic sensorimotor device (bottom).*

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## Results

Artificial sensorimotor system (memristor) was made using In-doped 7.0 nm thick $TiO_2$ film on Au electrodes. The optical synapse was stimulated by successive laser pulses with the same amplitude at the different frequencies to imitate the short-term plasticity (STP) to long-term plasticity (LTP) transition in a biological system. The results demonstrate that the optical stimuli with lower pulse intervals are beneficial for facilitation the LTP capabilities. Observations confirmed that the shorter pulse intervals resulted in the higher gain values, which is consistent with the effect of residual generated carries on the following pulses.

The actuator device was made by using liquid metal (galinstan) (Fig. 2a). The liquid metal droplet in the bath of NaOH solution technically constitutes an electrochemical cell, which receives the postsynaptic pulses (Fig. 2b) from the optical device. The imposition of conductance vibration (Fig. 2c) and postsynaptic pulses (Fig. 2d) leads to the reconfiguration of the charge distribution on the surface of galinstan droplet in NaOH. It facilitates the mechanical oscillation of liquid metal in NaOH bath resembling a neuromuscular electronic system in robotic devices. By applying patterned optical pulses, the weight and rhythm of the potential signals can be designed, and consequently, the motion of galinstan actuator can be accurately controlled.

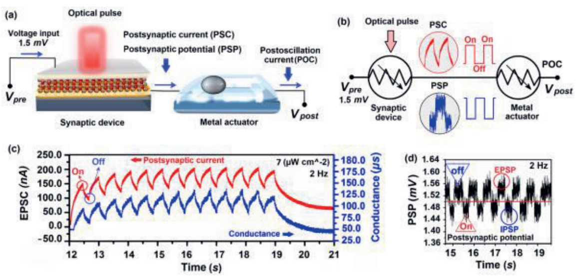


*Fig. 2. Sensorimotor system (a) and its corresponding circuit (b), exitatory postsynaptic potentials (EOSC) and conductance variation on the device illuminated by 7 µWcm$^{-2}$ poulsed light λ=530 nm and (d) corresponding variation of patterned postsynaptic potential (PSP) pulses of the same device.*

Figure 3 shows the scheme of galinstan droplet, its actual top view and the light contrast developed image. By applying a singular external potential, the galinstan/NaOH system acts as an electrolyte cell. The power consumption for a singular heartbeat oscillation caused by 0.1 sec optical pulse was calculated. The difference between EPSC and voltage variation ($V_{Max}$-$V_{Bias}$) were used to calculate the required power consumption for oscillation of galinstan droplet. Regarding the voltage variation, it was found that a singular oscillation, activated by 0.1 sec pulse duration, by average needs 1.2 ~ 0.3 µW power and approximately consumes 30 nJ energy.

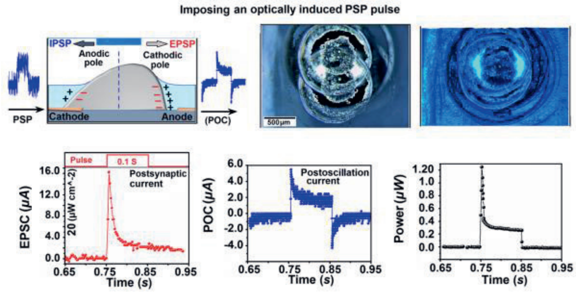


*Fig. 3. The observation and characterization of oscillation behavior of galinstan droplet.*

Figure 4 Illustrates typical mechanical oscillation with different frequencies and measurement of mechanical oscillation. It was discovered that at the shorter pulse intervals and higher light frequencies, the galinstan droplet acts as another synaptic component in the system where the charge transfer through the galinstan/liquid electrolyte interface controls the output current of sensorimotor system.

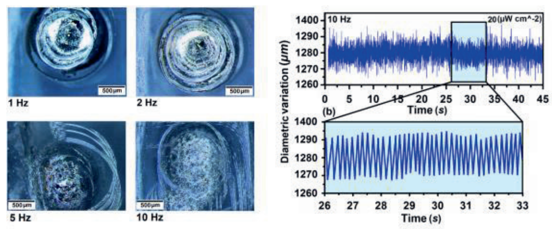


*Fig. 4. The modulation of oscillation of galinstan droplet. Typical transitional motion of a 1280 µm diameter galinstan droplet by applying sequential PSP pulses originated from the optical synapse.*

## Conclusions

The present study demonstrated outstanding capabilities of the artificially developed bioinspired opto-electronically sensorimotor device with optical synaptic and actuating components to modulate the functionalities of optogenetically engineered biological motor systems. In fact, developed optically stimulated synapse is a memristor with visible light-sensitive component, which has facilitated various synaptic dynamics. The characterization studies revealed that the potentially activated electrochemical mechanisms are behind the oscillation of liquid galinstan droplet.

## References

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