All-Optical Intra and Inter Neuronal Communication Protocol Platform

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Abstract: We demonstrate an all-optical neuromorphic implementation of photonic axons and synapses in laser-written gallium lanthanum sulfide waveguides. Neuronal communication protocols such as excitatory/ inhibitory responses and signal summations are exhibited in our chip.

OCIS codes: (130.2755) Glass waveguides; (160.1245) Artificially engineered materials (160.2750) Glass and other amorphous materials; (160.5335) Photosensitive materials; (200.4700) Optical neural systems

The field of neuromorphic engineering seeks the development of computational devices based on the human brain [1]. Up to now, some software and complex electronic hardware based on biological nervous system architectures have been demonstrated [2]. However one limitation of conventional inorganic computers is that they are extremely power and time inefficient to compute these algorithms. To overcome this inefficiency, the search for novel materials capable of mimicking properties present in biological neural networks is required. Photonic approaches could open a new path towards scalable neuromorphic systems with ultrafast signal transmission speeds, higher bandwidths and improvement in power consumption compared to microelectronics. In the search for new materials, chalcogenide glasses are attractive due to their photosensitivity for sub-bandgap illumination wavelengths and their important role as phase change materials (PCM), whose physical properties may be altered with light, both temporarily or permanently. Among all chalcogenides, gallium lanthanum sulfide (GLS) is a perfect candidate for photonic device applications since it is As and Ge free glass, avoiding the high toxicity that these elements introduce in chalcogenides.

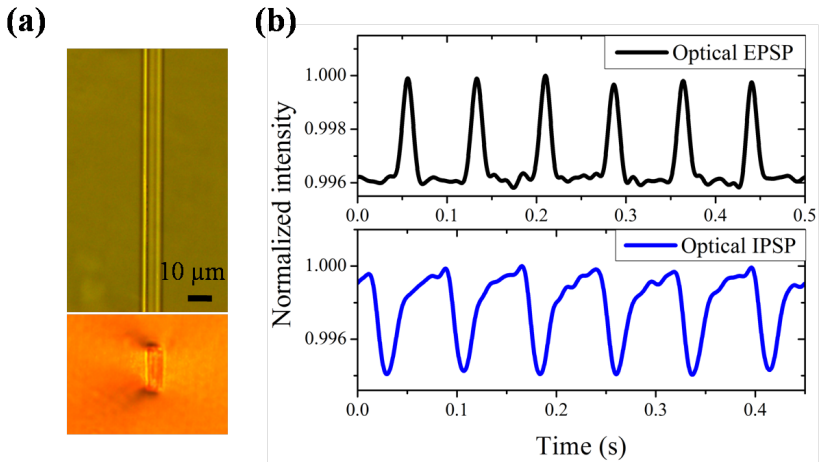

Fig. 1 (a) Microscope images of a femtosecond laser inscribed waveguide in GLS glass from an overhead (top) and transverse (bottom) view. (b) Optical EPSP and IPSP. EPSP obtained by reducing photodarkening (depolarizing) at 532 nm wavelength with a chopping frequency of 13 Hz and duty cycle of 30%. IPSP obtained by inducing photodarkening (hyperpolarizing) at 13 Hz chopping frequency and a duty cycle of 40%.

We present a replica of biological axons and synapses implemented in an integrated photonic waveguide chip. In the biological neural network, axons are the elongated channels of a neuron allowing the propagation of information while synapses are junctions between a pre-synaptic and a post-synaptic cells, where they exchange chemical signals through the release of neurotransmitters [3]. In order to form the photonic neuron, the multiscan femtosecond laser writing technique [4] was applied for waveguide inscription in GLS glass to create optical axons necessary for information propagation, in analogy with a biological neural network (Fig. 1(a)). The waveguides were designed to be single mode at 808 nm. In our experiment, photonic synaptic junctions are emulated by a side flash of illumination at a sub-bandgap wavelength of 532 nm at the exposure point of the optical axon. In order to

check the propagated light along the optical axons, an 808-nm diode laser beam is coupled into the waveguides. By modifying the power of the 532-nm laser beam, the transmission along the optical axon can be modulated via transient photodarkening. This transient photoinduced phenomenon implies nonradiative recombination of photoexcited charge carriers and defects, being time and intensity dependent and resulting in an attenuation of waveguide transmission. Transient changes vanish after the sub-bandgap illumination is removed.

Inducing photodarkening at the photonic synapse, information propagation along a biological cell in the form of electrical action potentials (spikes) is emulated in our photonic circuit. By increasing the power of the pre-synaptic beam (532 nm laser) at the photonic synapse, an increase of photodarkening will induce a depression (*repolarization* in the biological nerve cell) in transmission while lowering the power will induce a potentiation (*depolarization*) in transmission. Applying a pre-synaptic signal formed by a pulse train of depression and potentiation levels at different duty cycles induces a change in the response of the post-synaptic photonic cell, giving various spiking schemes. Excitatory post-synaptic potential (EPSP) and inhibitory post-synaptic potential (IPSP) schemes can be obtained at the output of the optical axons (Fig. 1(b)) similar to the two basic types of response of a post-synaptic biological neuron.

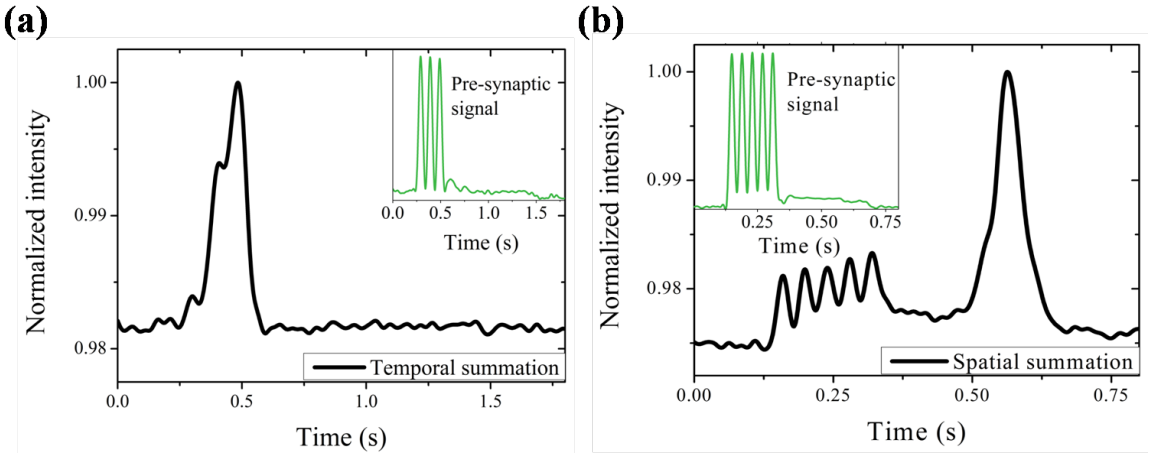

Fig. 2 (a) Temporal summation at the photonic synapse. (b) Spatial summation at the photonic synapse.

In addition to these basic neurobiological features, temporal and spatial summations can be demonstrated by our neuromorphic photonic implementation. Temporal summation is the process that determines whether or not an action potential, coming from repeated inputs of a single pre-synaptic cell, will be triggered. Spatial summation occurs when various inputs from different pre-synaptic cells send signals to a target neuron and a total sum of all of them (or partially) is triggered. In the same way as it occurs in biological neurons, laser inscribed GLS waveguides show an equal principle. When a pulse train carrying sufficient optical power is sent at a single photonic synapse, the optical axon triggers the signal and a summation of all combined individual pulses is generated as a response (Fig. 2(a)). Also, pre-synaptic pulses coming from different junctions of the optical axon can produce a triggered signal that results in a summation of all the inputs (Fig. 2(b)).

In summary, we demonstrate an integrated photonic platform with implementation of artificial neural networks and demonstrate some of the functionalities and principles that underlie learning and cognition in biological systems.

References

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