## **Spatiotemporal Pattern Recognition with Cascadable Graphene Excitable Lasers**

Bhavin J. Shastri, Alexander N. Tait, Mitchein certain problem domainimus, neuromorphic technology with photonics could potentiallygrant the capacity for complex, ultrafast categorizion and decisionmaking **[2]**. The ideas of biophysical computation algorithms the context of harnessing the high speed, high bandwidth, and low **crosstalk available tophotonicinterconnects [3][4] could provide a wide range of computing and signal processing**  applications (e.g. adaptive control, reatime embedded soctem analois, and cognitive RF processing) Neuromorphic signal processing incorporates sparse coding scheme called spiling. This high id analog and digital **processing technique take advantage of both the bandwidth efficiency of analog computation and the noise**  robustness of digital computation<sub>[5]</sub>, making the spike -based approach attractive forinformation processing We **recently discovered [6] close analogy between the dynamics of lasers and those of spiking biological neurons both of which canexhibit excitability B** blowever, to enable this emerging computation paradigm the following **k**y criteria must be met: logic-level restoration, input ut put isolation, and cascadability [9].

**Here, we demonstrate a photonic spatiotemporal pattern recognition circuit. This simple experiment provides a**  proof-of-concept for cascadability and inputoutput isolation in excitable lasers for spiking neural networks (SNNs) while simultaneously demonstrating polythrony [10] —an important concept in computational neuroscience, defined as an event relationship that is precisely timelocked to firing patterns but not necessarily synchronized to a global **clock reference Polychronization presents a minimal spiking network that consists of cortical spiking neurons with**  axonal delays and spike timing dependent plasticity **STD**) an important learning rule for spike - encoded neurons. As a result of the interplay between the delay and STD, spiling neurons spontane ously self-organize into groups **and generate patterns of stereotypical polychronous activity.**

**The computational primitive in our experiment is a graphene excitable laser. Graphæne, atomic scale** hexagonal cretal lattice of carbon atoms[11] could be an excellent candidate in excitablesser processing devices [12][13] as a conseqence of its nonlinear saturable absorption due to Pauli blocking, which includes ultrafast carrier relaxation, low saturable absorption threshold, large modulation depton, wan elengthindependent absorption(lue **to linear dispersion near the Fermi energy We experimentally demonstrated [12][14] an excitable fiber laser**  incorporating a graphene saturable absorber  $SA$ ) for a variety of complex operations including pulse regation **and reshaping, asynchronous phase locking, interspike time encoding, and coincidence detection.**



Fig. 1. Spatiotemporal pattern recognition circuit with two cascaded graphene excitable lasers.

In our case the objective is to distinguish (i.e. recognize) a specific input pattern: a pair of pulses separated by time interval *t* (equal to the delay between the excitable lasers). These analog inputs are directly modulated with an arbitrary waveform generator and are incident on both the lasers. The outputs from the first laser are fed to the second laser via a single-mode fiber (SMF), which acts as a delay element, and a photodetector (PD) to modulate the laser diode (LD) (allowing wavelength conversion from 1560 to 1480 nm). It has recently been shown [15] that such an excitable laser and PD system can emulate both a leaky integrate-and-fire neuron and a synaptic variable, completing a computational paradigm for scalable optical computing. The dynamics introduced by the PD are analogous to synaptic dynamics governing the concentration of neurotransmitters in between signaling biological neurons. The second laser is biased such that it requires stronger perturbations to fire; it will not fire unless two excitatory pulses (original input and output from the first laser) are temporally close together; that is, when *t* . Synchronous arrival of these two spikes causes enough excitation above the threshold causing the laser to fire a pulse. The system therefore only reacts to a specific spatio-temporal bit pattern. The resulting experimental data output pulse profile as a function of the normalized time interval between the two input pulses—is shown in Fig. 2.



Fig. 1. Measured output pulse peak power, pulse duration, and input and output waveforms as a function of the time interval between the two input pulses. Output pulse energy is the largest when *t* showing the system only reacts to a specific spatiotemporal input pattern.

In conclusion, we have demonstrated a spe  $2()$ -231(p) a-(e)-2(  $2()$   $2(sp)$ -1((a)-20.08(n)-3(c)-2(l)1(ua-3(c)-2(l)2(s)h373(c)-2(l)cn