Coincidence Detection with Graphene Excitable Laser

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Abstract: We demonstrate a photonic coincidence detection circuit with a graphene excitable laser. This technology is a potential candidate for applications in novel all-optical devices for information processing and computing.
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Neuromorphic engineering [1] exploits the biophysics of neuronal computation algorithms to provide a wide range of computing and signal processing applications, such as adaptive control, perception, sensory processing, and learning. Photonics offer an alternative approach to neuromorphic systems by exploiting the high speed, high bandwidth, and low crosstalk available to photonic interconnects which potentially grants the capacity for complex, ultrafast categorization and decision-making [2]. Photonic neuromorphic signal processing incorporates hybrid analog and digital processing techniques that take advantage of both the bandwidth efficiency of analog computation and the noise robustness of digital computation [3], making the spike-based approach to information processing a perfect fit for the technology. We recently discovered [4][5] a close analogy between the dynamics of lasers and those of biological systems, both of which can exhibit excitability—a nonlinear dynamical mechanism underlying all-or-none responses to small perturbations [6]. This key correlate was experimentally demonstrated with an excitable fiber laser incorporating graphene as a saturable absorber (SA) [7].

Neocortical systems encode information in electrochemical pulse position, not just the mean firing rate. The role of an individual neuron is that of a coincidence detector, which compares pulses from many different inputs and produces an output if enough occur close together. Specifically, the coincidence detection [Fig. 1(a)] of temporally close but spatially distributed input signals is required for encoding and storing associative memories [8]. So called temporal encoding is an extremely expressive technique, closely related to spike timing-dependent plasticity (STDP)—a standard model for learning in networks of spiking neurons [9].

In this paper, we experimentally demonstrate for the first time a photonic coincidence detection circuit enabled by a graphene excitable laser. Graphene is a two-dimensional atomic-scale honeycomb crystal lattice of carbon atoms which could prove to be ideal in such unconventional laser processing devices as a consequence of its optical nonlinear saturable absorption which includes ultrafast carrier relaxation, low saturable absorption threshold, large modulation depth, and wavelength-independent operation with absorption of 2.3% of light per layer [10].

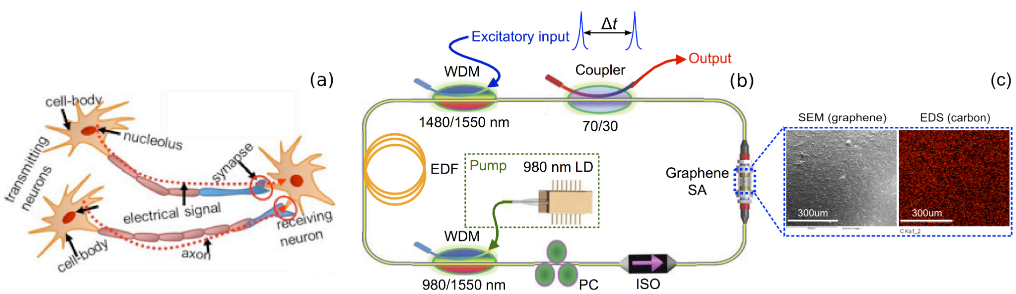

Fig. 1. (a) Neuromorphic coincidence detection. (b) Photonic coincidence detection circuit with graphene excitable laser. (c) Scanning electron microscope (SEM) image of deposited graphene film on fiber and energy dispersive spectrometer (EDS) micro-analysis showing uniform distribution of carbon.

We synthesized a graphene film by a simple, quick, and cost effective method [11] to form a SA and sandwiched it between two fiber connectors with a fiber adapter. The graphene-SA is integrated into the laser cavity [Fig. 1(b)] with a 75-cm long highly doped erbium-doped fiber (EDF) as the gain medium which has peak core absorption coefficients of 60, 50 and 110 dBm^{-1} at 980, 1480, and 1560 nm, respectively. The EDF is pumped with a 980 nm laser diode (LD) via a 980/1550 nm wavelength-division multiplexer (WDM). A polarization controller (PC) maintains a given polarization state after each round trip improving the output pulse stability. An isolator (ISO) in the cavity ensures unidirectional propagation. The 30% port of an optical coupler provides the laser output at ~1560 nm. The rest of the cavity consists of single-mode fiber. To induce perturbations to the gain, 1480 nm excitatory pulses with time interval Δ*t* are incident on the system via a 1480/1550 nm WDM. These analog inputs—from other excitable lasers, for example—are directly modulated with an arbitrary waveform generator (AWG).

Fig. 2(a) shows the excitable laser's output behavior in response to a single input pulse with different energies (amplitude or width) and is typical to that of a spiking primitive. An excitatory pulse increases the carrier concentration within the gain region by an amount proportional to its energy—gain enhancement. Enough excitation results in an excursion from equilibrium causing the laser to emit a pulse due to the saturation of the absorber to transparency. The excitable generation of a new pulse is stereotyped and repeatable, so all emitted pulses have pulse profiles relatively invariant to input pulse characteristics. This is an important property for pulse regeneration, reshaping, and signal integrity for processing. Fig. 2(b) depicts the system's ability to demonstrate coincidence detection, as a series of excitatory pulses are incident upon it with different time intervals. Coincidence detection relies on separate inputs converging on a common target, incorporating the principles of spatial and temporal summation. The excitable laser is biased such that it will not fire unless two excitatory pulses are temporally close together. Synchronous arrival of these two spikes causes enough excitation above the threshold causing the laser to fire a pulse. This phenomenon can reduce temporal jitter by spontaneous activity, and form associations between separate spiking events, thus influencing spike information processing.

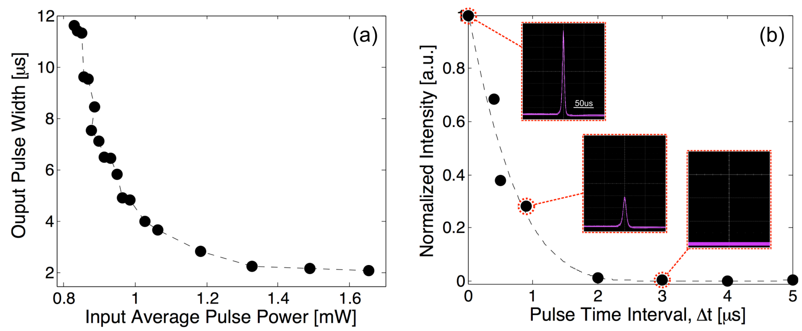

Fig. 2. Experimental results. (a) Pulse width increases asymptotically as the input perturbation approaches threshold. This is a trend commonly observed in excitable systems and *Q*-switched lasers, indicative of hybrid analog-digital decision dynamics (b). Output response is strongly dependent on the temporal correlation of two inputs. Average input power is kept constant with changing pulse interval.

In conclusion, we have demonstrated a novel photonic coincidence detection circuit enabled by a graphene excitable laser. Such an excitable system has been theoretically shown to behave analogously to a spiking neuron [4][12], opening up applications to biologically inspired cortical algorithms for learning and adaptive control. Ongoing research on graphene microfabrication may soon make it a standard technology accessible in integrated laser platforms and could potentially be an enabler for applications of optical computing [13][14] operating on picosecond timescales which is eight order of magnitude faster than the biological counterpart.

References

[1] M. Mahowald and R. Douglas, "A silicon neuron," Nature **354**(19), 515–518 (1991).
[2] A. N. Tait, M. A. Nahmias, Y. Tian, B. J. Shastri, and P. R. Prucnal, "Photonic neuromorphic signal processing and computing," in *Nanophotonic Information Physics*, ser. Nano-Optics and Nanophotonics, M. Naruse, Ed. Springer Berlin Heidelberg, 2014, pp. 183–222. [Online]. Available: http://dx.doi.org/10.1007/978-3-642-40224-1_8.
[3] R. Sarpeshkar, "Analog versus digital: extrapolating from electronics to neurobiology," Neural Comput. **10**(7), 1601–1638 (1998).
[4] M. A. Nahmias, B. J. Shastri, A. N. Tait, and P. R. Prucnal, "A leaky integrate-and-fire laser neuron for ultrafast cognitive computing," IEEE J. Sel. Topics Quantum Electron. **19**(5), 1800212 (2013).
[5] B. J. Shastri, M. A. Nahmias, A. N. Tait, Y. Tian, M. P. Fok, M. P. Chang, B. Wu, and P. R. Prucnal, "Exploring excitability in graphene for spike processing networks," in *Proc. of Numerical Simulation of Optoelectronic Devices (NUSOD)*, Aug. 2013, paper TuC5, pp. 83–84.
[6] B. Krauskopf, K. Schneider, J. Sieber, S. Wieczorek, and M. Wolfrum,"Excitability and self-pulsations near homoclinic bifurcations in semiconductor laser systems," Optics Commun. **215**(46), 367–379 (2003).
[7] B. J. Shastri, M. A. Nahmias, A. N. Tait, Y. Tian, B. Wu, and P. R. Prucnal, "Graphene excitable laser for photonic spike processing," *IEEE Photonics Conf. (IPC)*, Sep. 2013, pp. 1–2. [Online]. Available: http://dx.doi.org/10.1109/IPCon.2013.6656424.
[8] H. Markram, J. Lubke, M. Frotscher, and B. Sakmann, "Regulation of synaptic efficacy by coincidence of postsynaptic APs and EPSPs," Science **275**(5297), 213–215 (1997).
[9] R. C. Froemke and Y. Dan, "Spike-timing-dependent synaptic modification induced by natural spike trains," Nature **416**(6879), 433–438 (2002).
[10] F. Bonaccorso, Z. Sun, T. Hasan, and A. C. Ferrari, "Graphene photonics and optoelectronics," Nature Photon. **4**(9), 611–622 (2010).
[11] X. Zhou, J. Zhang, H. Wu, H. Yang, J. Zhang, and S. Guo, "Reducing graphene oxide via hydroxylamine: a simple and efficient route to graphene," The Journal of Physical Chemistry C **115**(24), 11957–11961 (2011).
[12] M. A. Nahmias, A. N. Tait, B. J. Shastri, and P. R. Prucnal, "An evanescent hybrid silicon laser neuron," in *Proc. IEEE Photonics Conf. (IPC)*, Sep. 2013, paper ME3.4, pp. 93–94.
[13] D. Woods and T. J. Naughton, "Optical computing: photonic neural networks," Nature Physics **8**(4), 257–259 (2012).
[14] H. J. Caulfield and S. Dolev, "Why future supercomputing requires optics," Nature Photon. **4**(5), 261–261 (2010).