Graphene Excitable Laser for Photonic Spike Processing

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Abstract: We demonstrate for the first time an excitable laser using graphene. This technology is a potential candidate for applications in novel all-optical devices for information processing and computing.

Spike processing has evolved in biological (nervous systems) and engineered (neuromorphic analog VLSI) systems where information is encoded as *events* in time. Since the time at which a spike occurs is analog, while its amplitude is digital, this hybrid scheme can exhibit the efficiency of analog computation and the noise robustness of digital computation [1]. A critical property of spiking networks is excitability—a nonlinear dynamical mechanism underlying all-or-none responses to small perturbations [2]. A system is said to be *excitable* if it is at an attracting equilibrium state, but can be triggered by a small perturbation to produce a large amplitude excursion, after which the system settles back to the attractor in what is called the *refractory phase*. Exploiting the high speed, high bandwidth, and low crosstalk available to photonic interconnects, networks of spiking lasers could be used to implement high-performance optical reservoir computing [3]. The potential of excitable lasers to perform temporal logic grants the capacity for complex, ultrafast categorization and decision-making [4,5]. Excitable lasers have recently been demonstrated with a semiconductor saturable absorber (SA) mirrors (SESAMs) [6,7]. However, SESAMs have a narrow tuning range, slow recovery time, low optical damage threshold, and complex and costly fabrication systems, considerably limiting their applications [8].

In this paper, we experimentally demonstrate for the first time an excitable laser based on passively Q-switching with a graphene SA. We recently predicted excitability with graphene via simulations [4]. Graphene is a two-dimensional atomic-scale honeycomb crystal lattice of sp^2-hybridized carbon atoms whose optical properties originate from its linear dispersion near the Fermi energy with massless Dirac fermions. The optical nonlinear saturable absorption of graphene, as a consequence of Pauli blocking, includes the following features: ultrafast operation (recovery time in fs or ps), low saturable absorption threshold (one order of magnitude lower than SESAMs), large modulation depth (>60% for few layered graphene), and wavelength-independent (infrared to visible spectrum) operation with absorption of 2.3% of light per layer [8]. We show that this SA laser—an architecture ubiquitously employed for self-pulsating lasers [2]—exhibits excitability near a saddle-node homoclinic bifurcation.

A graphene film—synthesized by a simple, quick, and cost effective method [9]—forms the SA and is sandwiched between two fiber connectors with a fiber adapter. The graphene-SA is integrated into the laser cavity [Fig. 1(a)] 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 1530 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 are input to the system via a 1480/1550 nm WDM. These analog inputs—from other excitable lasers, for example—are modulated with an arbitrary waveform generator (AWG) that drives a polarization dependent Mach-Zehnder modulator (MZM) [Fig. 1(b)].

Fig. 2 is a demonstration of the system's ability to display excitability, as a series of excitatory spikes are incident upon it. An excitatory pulse increases the carrier concentration within the gain region by an amount proportional to its energy (width)—gain enhancement. Enough excitation results in an excursion from equilibrium causing the laser to fire a pulse [Fig. 2(a) and (b)] due to the saturation of the absorber to transparency. This is followed by a relative *refractory period* during which an excitatory pulse is unable to cause the laser to fire [Fig. 2 (c)] as the pump current settles the system back to the 0-power attractor. Because the phase-space excursion resulting from an excitable response is stereotyped and repeatable, all emitted pulses have identical pulse profiles [Fig 2. (d)], an important property for pulse regeneration, reshaping, and signal integrity for processing. All outputs are asynchronously triggered, as shown by the output phase locking to input perturbations [Fig. 2 (e)]. In addition, our system is capable of emitting spike doublets [Fig. 2 (f)], in which the interspike timing encodes input amplitude. Doublet encoding can play an important role in selective activation of resonant subcircuits [10].
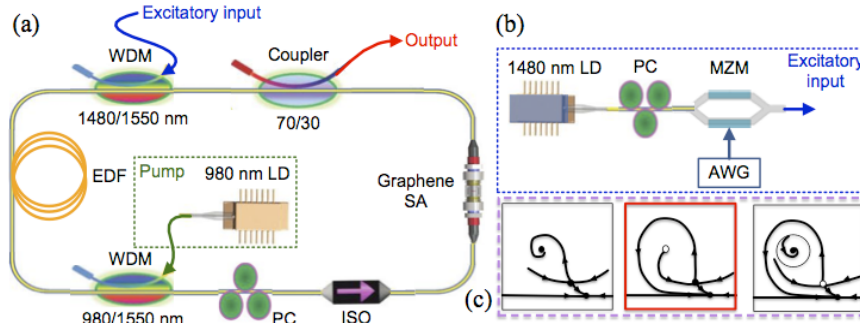
Fig. 1. (a) Graphene excitable laser. (b) Generation of excitatory inputs. (c) Different topologies of phase space that can occur as the physical parameters (pump current, length of cavity, absorption.) are varied. We desire excitability in the second phase portrait (outlined in red).
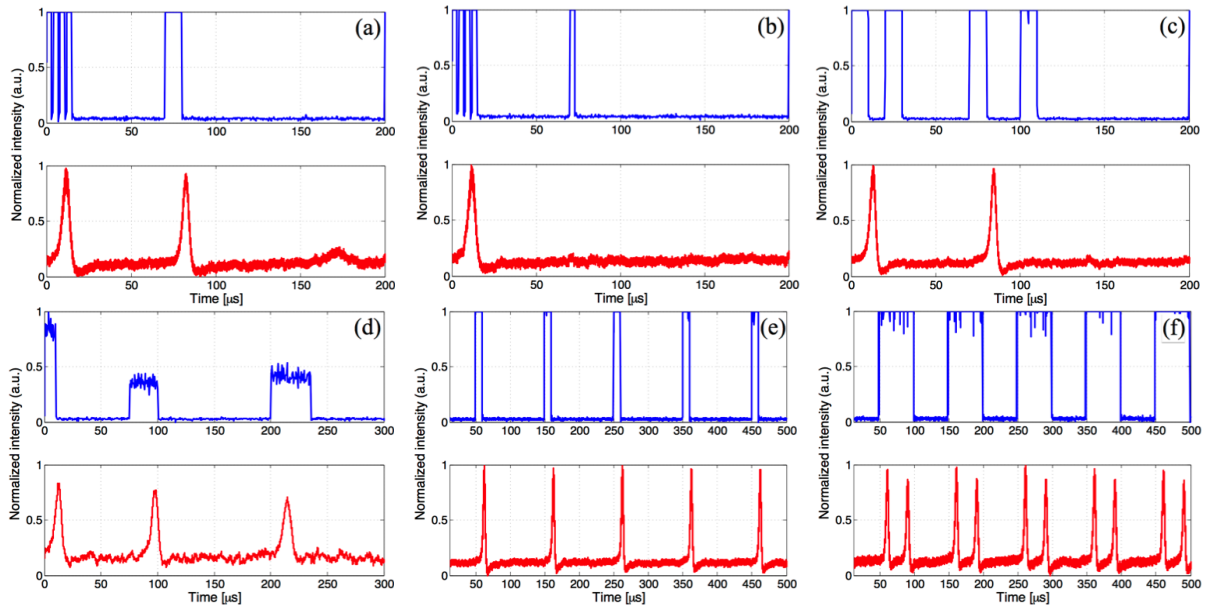

Fig. 2. Experimental results. For each plot, excitatory optical inputs on top (in blue) and response of graphene excitable laser at bottom (in red).

In conclusion, we have demonstrated a novel excitable laser employing passively Q-switching with a graphene-based SA. Such an excitable system has recently been theoretically shown to behave analogously to a spiking neuron [5][11], opening up applications to biologically inspired cortical algorithms for learning and adaptive control. Furthermore, an integrated version of this excitable laser could also be an enabler for applications of optical computing [12].

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