Resonant Excitable Switching with Graphene

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Abstract: We experimentally demonstrate resonant switching and pulse regeneration using a graphene-based excitable fiber ring laser and simulate an analogous integrated device structure. Such devices could find use in pulse regeneration or optical computing.

1. Introduction

Self-switching is one of the simplest nonlinear operations, outputting a signal only if it is above a critical threshold, T. It is the mechanism underlying digital logic buffering, comparators, digital-to-analog converters, and thresholders. We have investigated a novel implementation to self-switching based on the dynamical phenomenon of excitability. A system is said to be excitable if it remains stable in an attracting equilibrium state, can trigger as a result of a small perturbation to produce a large amplitude excursion, and is followed by a refractory period, in which the signal recovers back to the attractor. Its role in lasers has been investigated for some time now [1], but it has garnered renewed interest as a dynamical analogy to spiking neural networks [2, 3]. Excitable systems possess unique pulse generation properties and strong ties to the underlying physics of the devices.

Here, we show resonant excitable self-switching in a graphene-based fiber laser. We demonstrate experimental results and simulate the physical system integrated into a smaller footprint. Unlike other switching approaches, excitability is both cascadable and regenerative, and may offer a unique direction for photonic signal processing.

2. Graphene Fiber Laser

As a prototype, we built a fiber ring laser that exhibits excitability, modified from the original [4]. A schematic is shown in Figure 1(a). It is fundamentally based on the interaction between a gain section, a saturable absorber section—which provides the nonlinearity via Pauli blocking in graphene—and light within the cavity. A $980\ \mathrm{nm}$ pump brings the gain section, an erbium-doped fiber (EDF) above transparency, but saturable cavity losses from graphene prevent lasing. Our input channel is a $1480\ \mathrm{nm}$ signal, which also pumps the EDF. A strong input pulse will bring the gain above the losses, resulting in saturation and the release of an optical pulse. As shown in Figure 1(c), a pulse below the threshold triggers no output, but pulses of different widths—shown in the insets—trigger the same stereotypical output pulse. Our system can be described by a three-dimensional system with nonlinear dynamical variables (power, gain, and saturable absorption) as described in [5]. The absorber was assumed to be instantaneous (since the relaxation time of graphene is much faster than the gain or intensity $\tau_A << \tau_L, \tau_R$). There was a strong agreement between simulation and experiment.

3. Integrated Excitable Laser Simulation

The phenomenon shown in our experimental prototype can also be realized in a much smaller, integrated cavity with an intra-cavity saturable absorber. It has been shown that graphene can be evanescently coupled to passive waveguides [6]. We investigate how this couples into active waveguides based on an analogous model to the graphene fiber laser above. Our cavity is designed as a distributed feedback laser (DFB) cavity with a graphene layer on top. A conceptual diagram of the 2D transverse profile of the cavity is shown in Figure 1(b). The gain can be modulated selectively either optically ([7]) or electronically ([3]) in an analogous way to the fiber system. Layers of graphene are deposited on top of the waveguide, and couple with the evanescent mode. One advantage of this approach is that the use of compact graphene layers—rather than a separate absorber section—does not interfere with the confinement factor between the gain and the mode, improving performance. The enormous decrease in cavity length between a distributed feedback (DFB) laser and our fiber laser ($\approx$ factor of 1 million) leads to a corresponding increase in speed and decrease in power consumption.

We simulated a DFB laser using realistic parameters in a rate equation model (as in [2]). The results—shown in Figure 1(d)—reveal a sharper threshold boundary between the zero and one levels and lower switching energies.

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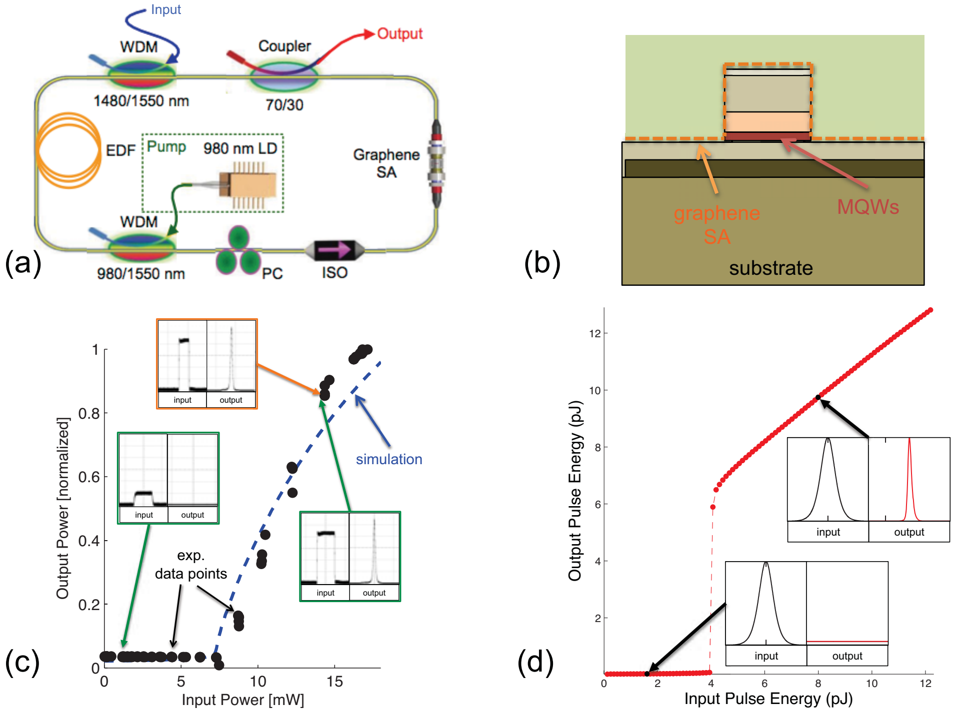

Fig. 1: (a) An experimental diagram of the graphene excitable laser. (b) A conceptual diagram of an active integrated device with graphene. (c),(d): Pulse energy transfer functions, experimentally measured in fiber laser with a graphene absorber (left) and simulated in a distributed feedback laser with an evanescently coupled graphene absorber (right). Shown in insets are various input and output pulse profiles along each transfer function.

4. Conclusion

Excitability emerges directly from laser dynamics, and can perform a variety of complex operations, including thresholding, bistability, pulse regeneration, and computing. More advanced, integrated versions of this technology could have applications in increasingly sophisticated optical processing platforms. The excitable mechanism described here is based on a simple configuration, requiring only an active and passive absorption section within a laser cavity, but utilizes graphene for its unique high absorption-to-volume ratio and wideband operation. The model is generalizable and implementable into more compact, high Q resonators—i.e. micro-pillar lasers [8]—which could lead to ultra-low power, high-bandwidth switching, processing, and logic.

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