Ultrafast all-optical switching in organic photonic devices.

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Abstract—**Using the knowledge gained by studying fundamental light-matter interactions in conjugated polymers, we have developed novel organic photonic devices which are capable of all-optical ultrafast gain switching for applications in data communication networks.**

Keywords-organic photonics; all-optical switching

I. Introduction

Currently, modulation and switching are achieved by a combination of light and electronics: optoelectronics. This limits the speed and density of communications. *All-optical* modulation, on the other hand, performs the whole process with photons providing much higher achievable speeds. All-optical ultrafast switching is currently an open field in terms of materials and mechanisms. Here we demonstrate all-optical gain switching in conjugated polymer-based photonic devices. Organics, and conjugated polymers in particular, are promising candidates for photonic applications as they have large optical cross-sections, are tuneable across a range of wavelengths and are cheap, robust and flexible.

Figure 1 demonstrates a schematic of light-matter interactions in conjugated polymers. (1) Absorption of light ($S_0 \rightarrow S_1$) forms a tightly bound electron-hole pair (exciton). From this excited state (S_1), stimulated emission (2) can occur to produce amplification (gain) or lasing. In addition, charges can be generated through exciton dissociation. The exact mechanisms behind charge generation in these materials is still hotly debated, although it has become clear that (i) it is more likely to occur from higher-lying states (shown by process (3) in Figure 1), and (ii) interactions between chains increase the charge generation yield. Increased charge photo-generation yield, although useful for solar cell applications, is often detrimental for other photonic applications such as lasers and amplifiers, as the charge absorption band overlaps spectrally with the stimulated emission, shown by (4) in Figure 1. Therefore, charge generation acts to quench the stimulated emission, gain and lasing action.

It is therefore critically important to be able to control the charge generation (3) and recombination dynamics (5) in conjugated polymers for optical amplification applications. A step towards this control is to fully understand charge photo-generation. To that end, we study the effect of interchain interactions on charge photo-generation by isolating conjugated polymers in an inert matrix and using a time-resolved technique known as *pump-push-probe* spectroscopy [4].

II. Results

We find that exciton dissociation can occur even in isolated chains, forming *on-chain* charge pairs that recombine rapidly (within 150 fs) owing to the one-dimensional nature of the conjugated polymer chain [3]. Furthermore, intra-chain charge pairs are efficiently photo-generated only through excitation to higher-lying states. Using this knowledge, we can control charge generation using a 'gating' pulse to re-excite polymer chains to higher-lying states. Charges are produced and the stimulated emission is efficiently quenched. Then, fast recombination occurs and the gain recovers.

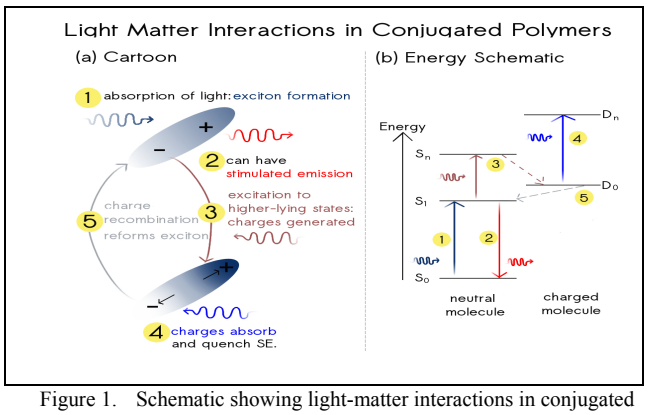

Figure 1. Schematic showing light-matter interactions in conjugated polymers. (a) Cartoon, (b) Energy Level Schematic demonstrating (1) absorption of light ($S_0 \rightarrow S_1$) and formation of exciton, (2) stimulated emission (SE), (3) re-excitation to S_n, to form charges (D_n) (4) absorption by the charges (which overlaps spectrally with SE) and (5) recombination of the charges to form an exciton (S_1) and recovery of the stimulated emission.)

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As an example, Figure 2 shows the stimulated emission (SE) as a function of time in a plastic optical fiber (POF) doped with a fluorene oligomer. The pump arrives at t=0 ps (1) producing SE, (2). The gate arrives at ~2 ps (3) and completely quenches the SE (4). Recovery of SE (5) depends on the photo-generated charge lifetime, which depends on the sample morphology and chemical structure, but is largely independent of polymer length.

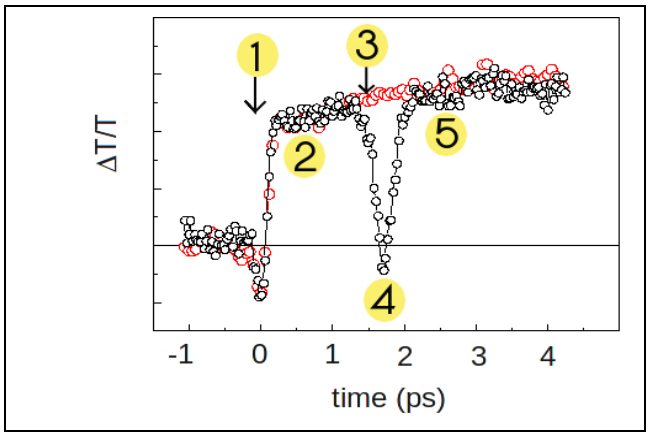

Figure 2. Pump-probe (red) and pump-push-probe (black) dynamics of polyfluorene-doped POF.

III. Applications

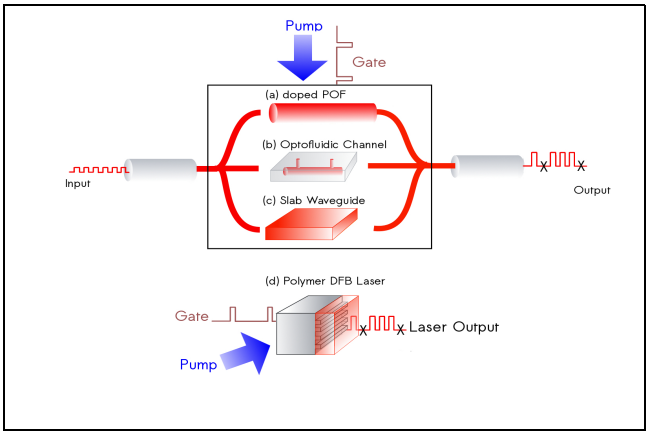

Figure 3. Schematic showing photonic devices using ultrafast switching (a) doped plastic optical fiber (POF), (b) optofluidic channel, (c) slab waveguide and (d) polymer distributed feedback (DFB) laser.

These discoveries have lead to the development of a new generation of organic lasers and amplifiers that can be optically controlled, with a gating pulse acting to switch off the gain. In particular, we have developed four different photonic devices, based on the principle of ultrafast switching (Figure 3): (a) Conjugated polymer/oligomer doped plastic optical fiber amplifiers (POF) for integration in data communication networks [1], (b) Optofluidic channel, capable of lasing, amplification and switching for integration in lab-on-a-chip type applications [4], (c) Conjugated polymer slab waveguides capable of optical amplification and switching, and (d) Conjugated polymer distributed feedback (DFB) lasers capable of being optically controlled [2, 5].

IV. Impact

The work outlined here is a breakthrough in all-optical switching for organic photonics as we demonstrate a *resonant* switching process with high on/off ratios and ultrafast response times. In the future, these findings may increase the data transmission rates in data communications, allow a move towards time-devision multiplexing (TDM) to increase bandwidth and could have implications for all-optical computing.

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