A sub-femtojoule electrical spin switch based on liquid light

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A miniature field-effect spin switch built on polariton condensates is demonstrated at a record-breaking operational energy.

Light travels fast, which is why nowadays all of our communications involve optical fibers. But our computations are based on matter, specifically, electrons that move inside wires and transistors. The problem is that electrons interact with matter, thus causing heat. To minimize heat and to squeeze more transistors onto chips, we have made them smaller and smaller to keep up with Moore’s law (the observation that the number of transistors in CPUs—central processing units—doubles every two years). It seems, however, that we are about to hit a hard wall. When we make the wires very thin and our transistors very small, quantum mechanical interference ruins the signals. Consequently, large technology companies like Intel and IBM are trying new ways of using optical interconnects between separate chips or even integrated inside chips. The idea here is that light does not produce as much heat as electronics do, and it can be 100 times faster. The bottleneck is the conversion between electronics and optics.

The Holy Grail for optical computing is a switch that can convert electrical signals to optical signals quickly and efficiently and can be integrated inside chips. Our group has recently demonstrated an ultra-low-energy spin switch based on a ‘liquid-light’ exciton-polariton condensate. These condensates are half-matter, half-light. Using their matter properties, we can electronically control them and take advantage of their fast dynamics (because they are half-light). It turns out that, similar to field-effect transistors (FETs), we can switch the polarization of liquid lights with minuscule amounts of energy and, because they are micrometer size, they can be integrated into chips as well.

Exciton-polaritons (polaritons) are a superposition of photons in a Fabry-Pérot microcavity and confined excitons (typically in 2D quantum wells). They are very light (100,000 times lighter than electrons) and very fast (>100GHz) thanks to their photonic component, but they can also strongly interact with each other due to their excitonic part. The microcavity is usually composed of two high-quality distributed Bragg reflectors (DBRs, 32 layers), fabricated using molecular beam epitaxy, that form a cavity a few micrometers wide. The quantum wells (in multiple sets) are direct-band-gap semiconductors such as gallium arsenide with nanometer-size thickness.

Because both excitons and photons are bosons, polaritons are bosons, too. Consequently, they can condense in the ground state by stimulated bosonic amplification and form macroscopic coherent states similar to atomic Bose-Einstein condensates. But since their mass is eight orders of magnitude smaller than their atomic counterparts, they can condense even at room temperature. Because the lifetime of polaritons is short (tens of picoseconds), they need to be continuously pumped. The pump, which is optical in most cases, creates hot polaritons as well as dark and bright excitons. These excitons repel the polaritons from the pumping spot and create a blueshifted potential due to the repulsive exciton-exciton interaction. In other words, the pump acts like gain as well as providing a potential. This blueshift induced by the pump allows us to trap and manipulate the escaping polaritons, which behave like liquid: see Figure 1(b). Here, four pump spots create polaritons that roll...
down the potential created by the pump spots and accumulate in the center. Once the density in the center of the trap exceeds a threshold, a confined macroscopically coherent state appears in the middle of the optical trap that emits coherent light (hence the term ‘liquid light’).

Polaritons can spin up or down because of their excitonic component. Once polaritons in the condensate decay, their photonic component leaves the cavity and carries the phase, momentum, and spin information of the condensate with it. Thus, by studying the emission, we can probe the state of the condensate. For example, the spin of the condensate directly corresponds to the circular polarization of the emission. Since the excitation is non-resonant, the phase and spin information from the pump is lost. With linearly polarized light, we expect to excite equal amounts of spin-up and spin-down polaritons and therefore observe a linearly polarized emission. However, the behavior we have actually observed is completely different. Just above the condensation threshold power, the condensate is linearly polarized.

Remarkably, once a particular spin becomes predominant, the condensate stays in that spin state for many seconds, 10 orders of magnitude longer than the response time of the condensate. It turns out that we can also switch the spin of the condensate by applying resonant probe lasers that are 100 times weaker than the pump. Thus, the condensate acts like a fast, long-lived optical spin memory. A small splitting of energy ($\Delta E$) between horizontally and vertically polarized polaritons is crucial in explaining the spin bifurcation phenomenon. We realized that if we can somehow tune the energy splitting, we can tune the polarization of the condensate.

In work recently published in Nature Materials,\(^1\) instead of applying a weak probe, we apply electric fields to the condensate. This allows us to tune the polarization of the emission and use the device as an electrical spin switch. The electric field induces a small energy splitting between horizontally and vertically polarized polaritons in two ways: to the photonic part of polaritons by birefringence due to the Pockels effect; and to the excitonic part by mixing the heavy- and light-hole excitons and removing the degeneracy of the exciton ground state. Both effects are linearly proportional to the applied field and tune $\Delta E$.

Gold contacts are deposited on an etched annular recess and below the bottom reflector to apply fields perpendicular to the quantum-well plane. We create trapped condensates on the mesa, as shown in Figure 1(a), and analyze the polarization of the emission as we change the bias voltage. We observe that at zero bias the condensate is bistable and randomly chooses a circular polarization (right or left). But as we increase the bias, circular polarization first transforms to highly elliptical and then quenches into linear polarization (see Figure 2). To our knowledge, this is the first demonstration of the electrical tuning of the polarization of coherent light.

More interestingly, if we introduce a small imbalance in the pumping rate of spin-up and spin-down condensates (for example, by slightly elliptically polarizing the pump), we observe that the system shows hysteresis as we change the bias voltage: see Figure 3(a). The appearance of hysteresis now means that the system can act like a directional spin switch. By applying a few volts, we can switch to a spin-up or spin-down state. For instance, a +3V pulse will only switch the spin of a condensate initialized in the right-circularly polarized state, whereas the
opposite holds for a ~3V pulse. Moreover, the condensate state persists after the voltage pulse ends, demonstrating the bistable nature of the system. Figure 3(b) shows that, when we apply a 3.3ns electrical pulse with an amplitude of 3V, the condensate spin switches from spin up to spin down in 2.2ns. We are currently limited by the resolution of our apparatus, but calculations show that the switching time can be at least an order of magnitude faster, reaching >1GHz speeds. Since the electrical bias draws minuscule current, the switching energy is also minuscule and is estimated to be ~0.5fJ.

In conclusion, we demonstrated a fast electro-optical spin switch device with a record breaking 0.5fJ operating energy. The device, which is based on exciton-polariton technology, converts electric signals to the polarization of light, and can be used for telecommunications and improving future CPU performance. An electric spin switch based on polariton condensates seems to have ticked all of the right boxes for these applications but for its operation temperature. We have to cool these switches for the device to work. The next step is therefore to achieve switch operation at room temperatures. We know how to achieve this, however, and certain semiconductor materials, such as gallium nitride and transition metal dichalcogenide monolayers, could work at high temperatures. Commercialization will depend on how long it takes us to develop our device with these new materials.

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References