Aside from the technological importance of making progress towards electrically pumped devices, the results are also a step forwards in understanding the physics of organic-based microcavities. The high excitation density regime of polariton bosonic stimulation is a prerequisite for all phenomena related to polariton condensation in which weak polariton–polariton interactions due to their matter side may also manifest. A promising future strategy is the combination of organic and inorganic materials in the same cavity[8]. In this way, both Frenkel and Wannier excitons may be coupled through the photon cavity mode to realize hybrid organic–inorganic cavity polaritons[11,12]. Such strongly coupled hybrid microcavities may well harness the best of three worlds: confined photons, Wannier excitons and Frenkel excitons. In particular, the inorganic subsystem offers good charge injection and transport properties, the organic component offers strong oscillator strengths and high quantum yields, and the strong coupling with the cavity photons coherently mixes Wannier and Frenkel excitons into hybrid polaritons. ❒

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NONLINEAR OPTICS

Towards polaritonic logic circuits

The demonstration of a microcavity polariton switch and logic gate that can be controlled by the polarization state of light suggests that a new class of integrated optical devices with highly efficient, ultrafast operation and small footprints may soon be within reach.

Vinod M. Menon, Lev I. Deych and Alexander A. Lisyansky

In the future, high performance optical signals processors and data routing technologies that support more efficient and faster processing of information will undoubtedly be required. In an attempt to address this need, several all-optical switching architectures based on intensity modulation using both optical fibre and planar chip architectures have been realized. However, most of these switches are energy gluttons because they rely on nonlinear optical effects that have a relatively high threshold for their switching operation. Optical switches that operate at lower energies have been developed using microring architectures[1], but these have a large footprint, which is a major drawback from the point of view of integrated photonic circuits. Another approach is to utilize the polarization state of light for optical switching. Switches based on this approach, however, rely on external optics for their operation, and thus cannot be easily integrated[2]. There has also been considerable progress recently on electronic switches based on interacting excitons (bound electron–hole pairs), and these can be easily integrated and have a smaller footprint than other switches[3]. However, they have much lower operational speeds than their optical counterparts, as they rely on slow exciton diffusion.

Writing in *Nature Photonics*, Amo *et al.* report a new form of compact energy-efficient optical switch that relies on a spin-dependent polariton–polariton interaction within semiconductor quantum wells in a microcavity[5]. The cavity consists of $In_{0.04}Ga_{0.96}As$ quantum wells sandwiched between two distributed Bragg reflectors (each made of a GaAs/AlGaAs stack). Light emission from the structure is experimentally optically switched at low power thresholds over a large (60 μm diameter) illuminated area. Although the experiments were performed with continuous-wave light, the team predicts that in pulsed operation the switches should have very low power thresholds (~ 1 fJ μm^{-2}) and fast switching speeds (~1–5 ps).

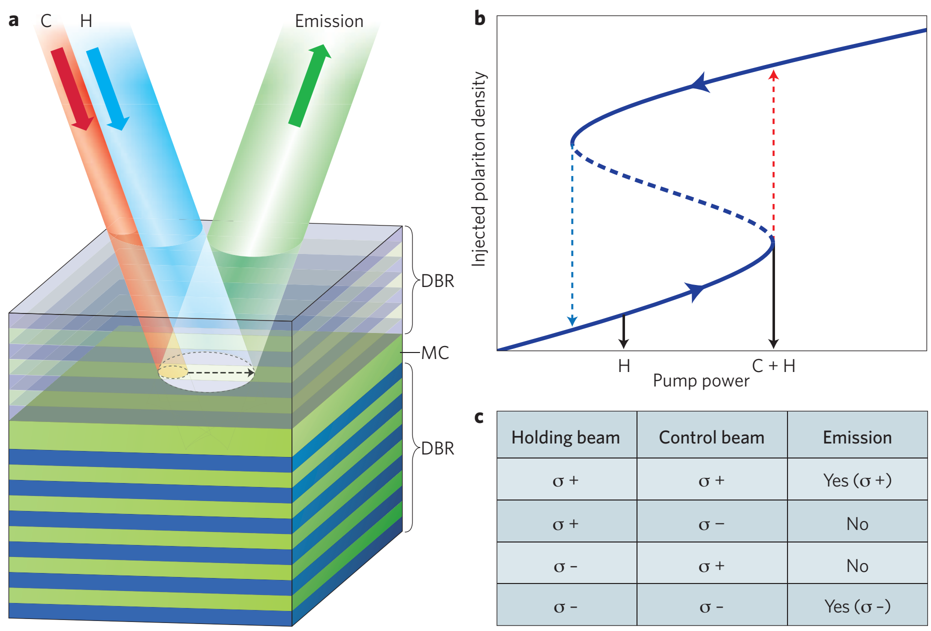
The switching mechanism relies on microcavity polaritons — light–matter quasiparticles formed by the strong interaction between the excitons and photons in a microcavity[4]. They potentially allow the construction of ultrafast, low-energy switches with a small footprint, and are hence the topic of intense research. The attributes of these quasiparticles combine the best of both their constituents: their photonic component gives them a small mass (~10^{-4} times that of an electron) and so opens the door to ultrafast switching, whereas their excitonic component results in a strong carrier–carrier interaction, which is highly nonlinear and thus leads to efficient switching.

The spin degeneracy of polaritons is another factor that makes them attractive for switching applications. This is because the two optically active exciton states, characterized by opposite values of their spin projections ($S_z = \pm 1$), couple only with photon states of the appropriate circular polarization (σ^+ or σ^-). The highly selective spin-dependent polariton–polariton interaction allows the creation of switching devices that have a spin output state controllable by the polarization of input light beams.

The switch demonstrated by Amo *et al.* works as follows. The system is cooled to a temperature of 5 K and is illuminated by a low-power continuous-wave holding beam (pump, denoted 'H' in Fig. 1a) over a large area of the sample at a specific angle. The energy of the holding beam (corresponding to $\lambda = 836.95$ nm) is slightly blue-shifted from that of the lower polariton branch. This represents the off state of the switch, in which the population of the generated polaritons is very small. When illuminated with a localized control beam (probe, denoted 'C' in Fig. 1a) with the same wavelength and at the same angle as the holding beam but at much higher intensity, the polariton–polariton interaction commences. The lower polariton branch is blue-shifted into resonance with the holding beam, resulting in strong nonlinear emission. This process is illustrated in Fig. 1b, which shows the shift of polariton population to the upper branch of the hysteresis curve by the control beam. The system is predicted to stay in the upper branch when the control beam is removed, and to take on a lower threshold value in the reverse mode[6]. However, the present demonstration does not show the reverse mode operation. If indeed such a bistable system is realized using the present structure, it could be used to demonstrate flip-flop operation.

An interesting aspect of the microcavity switch is the polarization of the nonlinear polariton emission, and the authors demonstrate two scenarios. The first is a circular polarization switch that shows AND logic operation based on the circular polarization states of the holding and control beams. The truth table for this process is shown in Fig. 1c. Put simply, the polarization of the nonlinear polariton emission depends on the polarization of the holding and control beams. In a second demonstration, the authors show on/off control of the nonlinear polariton emission using the polarization. This is demonstrated through the use of a circularly polarized control beam and linearly polarized holding beam. The circularly polarized control beam turns the system to the on state only for polaritons with the same polarization (Fig. 1c); polariton emission then has the same polarization as that of the control beam.

Another important and distinguishing aspect of the switching scheme demonstrated by Amo *et al.* is 'non-locality'. The non-local property of the switching scheme stems from the polariton motion in the plane of the microcavity. The localized control beam turns the switch to the on state only in the excitation area; the polaritons created in this localized spot rapidly move out, inducing the neighbouring regions to be switched on when they are illuminated by the holding beam. This eventually causes nonlinear polariton emission from the entire area pumped by the holding beam. The direction and speed of the polariton propagation is related to the in-plane wavevector of the control and holding beams. This switching mechanism is non-local in the sense that a highly localized control beam has an effect at a location determined by the spot size of the holding beam. This non-local behaviour allows for the integration of such devices into planar polariton circuits, which are thought to be possible[6].



c

Holding beam	Control beam	Emission
σ +	σ +	Yes (σ +)
σ +	σ −	No
σ −	σ +	No
σ −	σ −	Yes (σ −)

Figure 1 | Microcavity-polariton-based spin switch, transmission and AND logic operation. **a**, Schematic of the microcavity structure, along with the experimental set-up showing the control beam (C), holding beam (H) and nonlinear polariton emission. The direction of polariton propagation is indicated by the dashed arrow. MC, microcavity; DBR, distributed Bragg reflector. **b**, Dependence of injected polariton density on the incident pump power. The presence of the control signal abruptly shifts the polariton density to the upper branch of the hysteresis curve, as indicated by the bright red dashed arrow. **c**, The truth table corresponding to the circular polarization experiments carried out by Amo *et al.*[5], indicating AND operation. The circular polarization state of the control and holding beams determines the output state of the switch.

The basic switching operation demonstrated by Amo *et al.* depends on the fact that the Gross–Pitaevskii equation (a formalism used to describe the behaviour of weakly interacting bosons such as polaritons) allows for bistable solutions of the polariton density. Although hysteresis was not observed experimentally, the demonstrated quasi-threshold behaviour is a signature of bistability. Studies into the lack of hysteresis for this system would be a promising direction for future research.

Although the present work provides the proof-of-principle demonstration for a microcavity polariton-based non-local switching scheme, further investigations into the dynamics of switching, materials and microfabrication techniques must be carried out to realize practical chip-scale polaritonics. Furthermore, room-temperature operation will be essential for a switch based on this scheme to be practical, and this could potentially be achieved using an alternative semiconductor such as GaN or ZnO, or an organic system.

The results of Amo *et al.* open new possibilities for all-optical spin switching and logic based on microcavity polaritons. One of the most appealing aspects of the present demonstration is the non-local switching capability, which may provide a method for creating planar integrated polariton circuits[6]. The results could also lead to ultrafast integrated planar logic gates and switching elements with a low power threshold, provided polariton channel waveguides can be realized and the temperature of operation is raised. ❐

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