matter–light systems — a fundamental problem that is of great interest beyond the study of dissipative solitons.

For driven cavity schemes, dissipative polariton condensate solitons were first predicted for nonlinear media such as dilute atomic gases[5]. Although the theoretical physics of such a system is interesting, practical implementations are difficult to perform because the critical temperature is near absolute zero (less than 1 μK). However, the critical temperature is inversely proportional to the carrier mass, so replacing atoms with excitons, whose effective mass is of the order of the electron mass, increases the critical temperature up to room temperature.

Unfortunately, however, it is not easy to find operating parameters for which stable dissipative solitons exist in a driven semiconductor microcavity. For the experiment of Sich *et al.*, recent work that theoretically investigated the optimum conditions for the existence of two-dimensional bright dissipative polariton solitons[6] was especially important. In fact, the work of Sich *et al.*[1] is the experimental implementation of the main ideas of ref. 6, which have been generalized by taking into account polarization phenomena. To produce a bright soliton, which has a maximum intensity at its centre, Sich *et al.* used a GaAs microcavity driven by a pump laser beam whose wavelength and incidence angle corresponded to a negative polariton effective mass. The pump beam was a transverse-magnetic-polarized continuous-wave beam with a diameter of 70 μm.

As with other investigations into dissipative solitons[4], the solitons in the work of Sich *et al.* were initiated by a transverse-electric-polarized writing laser pulse (pulse duration of 5 ps and diameter of 7–15 μm) focused onto a small area of the scheme's wide aperture. It is in this area that polariton solitons were born (Fig. 1c). Resolution-limited measurements revealed the transverse dimensions of the polaritonic solitons to be around 5 μm. The solitons propagated (Fig. 1b) with a transverse velocity of approximately 1.6 μm ps^{-1}. Comparing the widths of the polaritonic solitons at these two points confirms the absence of beam spreading and proves the nonlinear compensation of light diffraction widening. Finally, the solitons leave the area of the pumping beam (Fig. 1a) and decay.

The work of Sich *et al.* is of fundamental significance because it represents the first demonstration of dissipative matter–light solitons. This proof-of-principle experiment will stimulate investigations into other schemes that have so far been studied only theoretically. The picosecond response time of polariton solitons makes them more useful for ultrafast information processing than the light-only solitons of semiconductor cavity lasers, which exhibit nanosecond response times. Furthermore, because their excitonic component leads to weaker diffraction and therefore stronger interparticle interactions, polaritonic nonlinearities are 2–3 orders of magnitude larger than the nonlinearities found in semiconductor lasers, which suggests lower powers are required to achieve nonlinear functionality.

As for subsequent experiments with such driven microcavities, it would be interesting to determine the energy flow distribution required for dissipative optical structures. Other investigations, such as using different semiconductors to raise the operating temperature from the inconvenient level of 5 K up to room temperature, or studying the quantum features of dissipative solitons, including their Brownian motion under the effect of quantum fluctuations and matter–light quantum squeezed states, will also attract considerable attention. Through careful examination, microcavities exhibiting the strong and fast polaritonic nonlinearities demonstrated by Sich *et al.* might one day be the work-horse of next-generation efficient information-processing devices. ❐

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NANOPHOTONICS

Remote on-chip coupling

Scientists have demonstrated strongly coupled photon states between two distant high-*Q* photonic crystal cavities connected by a photonic crystal waveguide. Remote dynamic control over the coupled states could aid the development of delay lines, optical buffers and qubit operations in both classical and quantum information processing.

Jie Gao, James F. McMillan and Chee Wei Wong

Coupled cavities with two-level systems are predicted to exhibit unique characteristics such as superfluidity and quantum phase transitions[1]. Mode splitting has been previously demonstrated in a system comprising two adjacent coupled optical cavities linked by evanescent coupling over a short distance[2] (Fig. 1a). When the coupling strength between the cavities exceeds that of all other decay channels, a coherent exchange of energy between them leads to mode splitting in the spectrum domain and Rabi-like oscillation in the time domain.

Reporting in *Nature Photonics*, Yoshiya Sato and co-workers have now demonstrated strong coupling between two photonic crystal cavities separated by more than 100 wavelengths[3]. Despite such a large separation distance, the researchers experimentally obtained a spectral splitting of 150 pm and Rabi-like oscillation with a period of 54 ps. They also achieved remote dynamic control of the coupled state for both single- and multiphoton power levels.

The team achieved coherent energy transfer between distant photonic crystal cavities by implementing a novel set-up comprising photonic crystal Fabry–Pérot waveguide modes (Fig. 1b). Appropriate modification of the waveguide's photon density states substantially suppressed photon leakage and allowed the two distant high-*Q* cavities to couple to each other rather than to the waveguide's discrete modes. In this way, the interaction between the two cavities via the waveguide performs the same function as directly coupled resonators (Fig. 1a). Dressed states such as those shown in Fig. 1a are formed, but the physical distance between the two cavities can be large. Rabi-like oscillations with coherent oscillations of more than 400 ps demonstrate that the photon energy is predominately concentrated in the cavity modes ($Q \sim 460,000$) rather than in the Fabry–Pérot waveguide modes ($Q \sim 50,000$). Moreover, in contrast with the optical analogue of electromagnetically induced transparency[4] and the super-radiance effect[5], in which two optical cavities couple to an open waveguide (Fig. 1c), the scheme used in the work of Sato *et al.*[3] makes sure the coupling strength between the cavities is much larger than the individual decay to the waveguide or the outer environment.

Achieving a strongly coupled state on-chip between two sufficiently distant cavities allows precise dynamic control by independently tuning one of the cavities. Sato *et al.* demonstrated this by introducing a short control pulse to shift the resonant wavelength of one cavity during the Rabi-like oscillation. The shift in resonance breaks the coupling between the cavities, thereby changing the photonic density of states and ceasing the Rabi-like oscillation. Breaking the coupling traps the light in its current state. More importantly, remote control of the photon state over long distances can be realized even if the control pulse strikes one of the cavities when the photons are populated only in the other cavity. This is in stark contrast with previous methods of all-optical photon control[6,7], in which the control and signal photons must overlap in space. As well as allowing for remote photon control, this scheme does not suffer from the problems of large free-carrier-induced optical absorption or photon lifetime degradation that are often associated with dynamic control. The above functionalities can be used broadly for stopping/slowing light and in optical buffers/memories, which serve as important components for manipulating photon states in classical photonic circuits.

Strong coupling and Rabi oscillations have been widely investigated throughout the field of quantum optics and cavity quantum electrodynamics[8] for use in quantum computation schemes such as entanglement state preparation and two-qubit quantum gate operation. As a classical analogue to solid-state strongly coupled quantum systems such as the quantum dot–cavity polariton state, integrated strongly coupled cavities can be valuable components in chip-scale quantum photonic circuits[9] even without the quantum nature of nonlinearity in cavity quantum electrodynamics. Dynamic control enables single-qubit operation and two-qubit gate operation (which requires a single quantum dot to mediate the process), thus benefitting future quantum technologies such as information processing, computation, communication and metrology.

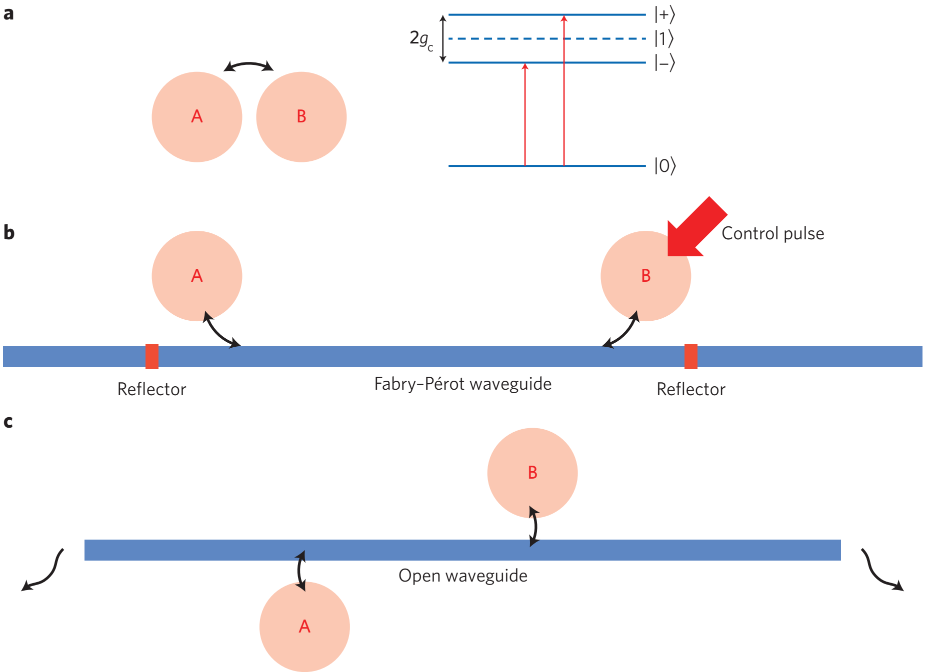

Figure 1 | Operating regimes of coupled cavities in a solid-state implementation. **a,** Two close-by optical cavities coupled directly to each other (left), resulting in a mode splitting of $2g_c$ (right). **b,** Two distant optical cavities coupled via a Fabry–Pérot waveguide with near-perfect reflectors. The black arrows indicate the couplings between cavity and waveguide modes. The control pulse applied to cavity B provides dynamic control. **c,** Two optical cavities coupled to an open waveguide, representing the optical analogue of electromagnetically induced transparency and the super-radiance effect.

The work of Sato *et al.* in the quantum regime follows experimental demonstrations in the classical regime, where the cavities contain many more photons. The researchers demonstrated dynamic control and photon modulation of cavity A, according to the timing of the control pulse on cavity B, at the single-photon power level. The principal limitations in this work were the attenuated laser source and the time resolution of the single-photon detector, whose timing jitter of ~100 ps was larger than the Rabi-like oscillation period. This work is a necessary step towards the experimental expansion of this field into the quantum regime. In the future, quantum operations performed with sub-Poissonian single-photon qubits based on such strongly coupled cavities system will prove the potential application of this principle for use in quantum circuits.

From a technical point of view, Sato *et al.* have presented the beautiful integration of various photonic structures on a chip with high fabrication quality and precise controllability. Experimental realization of this field at the quantum regime will require components and techniques such as multistep heterostructure cavities with Q factors of one million, high-reflectivity (>90%) reflectors in photonic crystal waveguides formed by the mode-gap effect, precise frequency tuning of around 400 pm by laser-assisted oxidation or free-carrier injection, and extremely low photon losses to ensure single-photon power level measurements. These achievements also demonstrate that photonic crystal devices can be a very promising platform for advanced functional photonic circuits in scalable classical and quantum information processing. ❐

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