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# A technology friendly photon condensate

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Two independent demonstrations of room-temperature Bose–Einstein condensation of light in semiconductor optical microcavities with embedded quantum wells may pave the way for harnessing the effect for practical applications, such as high-power, single-mode emission from large-aperture devices.

Particles with integer spin, known as bosons, follow the statistics first described by the famous Indian physicist Satyendra Nath Bose and importantly can occupy the same quantum state[1]. Around 1925, Albert Einstein[2] applied Bose's quantum statistical theory to particles with mass and predicted that above a certain density and below a critical temperature, these bosons would effectively coalesce into a common state, with most occupying the system's ground state — a phenomenon known as Bose–Einstein Condensation (BEC).

It wasn't until 1995 that this quantum phenomenon was first observed experimentally by Eric Cornell and Carl Wieman at the University of Colorado, Boulder[3], a discovery later recognized with the Nobel Prize in Physics in 2001. They achieved BEC using dilute clouds of rubidium atoms, cooling the system to temperatures just a few nanokelvin above absolute zero. The critical temperature for condensation is inversely proportional to the mass of the boson, meaning that heavier particle gases need to be extremely cold to reach the transition point.

Photons were long excluded from this picture because they are massless and have a linear energy dispersion. However, a small effective mass for photons can be induced using microcavities. In this setup, the lowest mode of the cavity introduces a cut-off frequency, leading to a parabolic energy dispersion with a large curvature or, equivalently, a small effective mass — typically around $10^{-5}$ times the mass of an electron. This not only allows for the possibility of photon condensation, but the small mass also allows for much higher critical temperatures, potentially even room temperature. The challenge, however, is that photons interact weakly, only indirectly through matter, making them hard to thermalize. Forced thermalization through strong absorption, as seen in black-body radiation, negates the effects of the cavity.

About ten years ago, a system that satisfied all the conditions for achieving an equilibrium photon BEC was finally realized using a microcavity filled with a dye solution[4]. Dyes, such as rhodamine, are exceptionally efficient absorbers and emitters in the near-infrared and visible spectral ranges, which is why they are often used as the gain material in tunable lasers.

In this system, photons are emitted into the cavity mode and then absorbed by the dye molecules. While absorbed, the interactions among rhodamine molecules in the liquid promote thermalization before the photons are re-emitted into the cavity mode. Owing to the high reflectance of the mirrors, this process repeats multiple times until photons eventually escape and are detected outside the cavity. Remarkably, this system exhibits many classic features of a non-interacting boson condensate. However, dye-based photon BECs are constrained by their weak and slow thermo-optical nonlinearity. These pioneering observations have spurred efforts to achieve BEC conditions in other laser systems, aiming to enable practical technological applications beyond the laboratory. A material system with significant and fast nonlinearities would not only facilitate new physics but also open up various applications.

Now, two independent research collaborations have simultaneously reported the achievement of a BEC of photons operating at room temperature in similar, widely studied, semiconductor devices, bringing the realm of BEC a step closer to potential everyday technological applications. M. Pieczarka and collaborators from Poland and Germany[5] demonstrated a photon BEC in a large-aperture, electrically driven, GaAs-based vertical-cavity surface-emitting laser diode featuring quantum wells (QWs) as emitters. Meanwhile, R. C. Schofield and colleagues in the UK, India, and Germany[6] also reported photon condensation in a microcavity based on the same materials. Their approach utilized optical excitation, and the tunability of an open design, where the cavity length could be finely adjusted through the precise positioning of a movable top mirror. One half is a GaAs/AlAs heterostructure distributed Bragg reflector (DBR) with an InGaAs QW, while the other half is a commercially manufactured DBR on a concave glass substrate (see the scheme in Fig. 1a).

This tunability is particularly important because achieving the balance between thermalization and cavity feedback necessary for BEC hinges on a parameter $\gamma = \alpha/\kappa$, where $\alpha$ is the round-trip QW absorption and $\kappa$ is the cavity photon decay rate[7]. The photon absorption in the QWs is primarily determined by the direct transitions between the valence and conduction bands. In a simplified 2D material model, photon absorption is zero for energies below the band gap and constant above it. However, factors such as defects, interactions with phonons, and electron–hole interactions lead to a more complex dependence, characterized by an exponentially decaying contribution within the gap, the so-called Urbach tail[8], and an exciton-related peak at the gap (Fig. 1b). Both groups identified that the optimal conditions for BEC behaviour lie in this below-gap region, tuning the energy of the cavity mode to achieve the desired $\gamma$ values, specifically between 0.1 and 10. Here, $\gamma$ must be large enough to facilitate thermalization but not so large as to increase the critical intensity, which would result in standard lasing instead of condensation.

By testing devices with different energy detunings between the cavity fundamental mode $\varepsilon_0$ and the QW fundamental transition $\varepsilon_{QW}$, defined as $\Delta = \varepsilon_0 - \varepsilon_{QW}$, the two groups observed a homogeneous BEC of photons with a thermalized spectrum. At low pump intensity, a Maxwell–Boltzmann distribution was observed, indicating thermalized photons. As the occupation increased, emission near the cut-off frequency grew faster than the thermal tail until the threshold intensity was reached. At this point, the ground state population became dominant, resulting in high coherence due to the massive occupation of the system's ground state. This BEC is characterized by both saturation of occupation in the excited states and by condensation in the

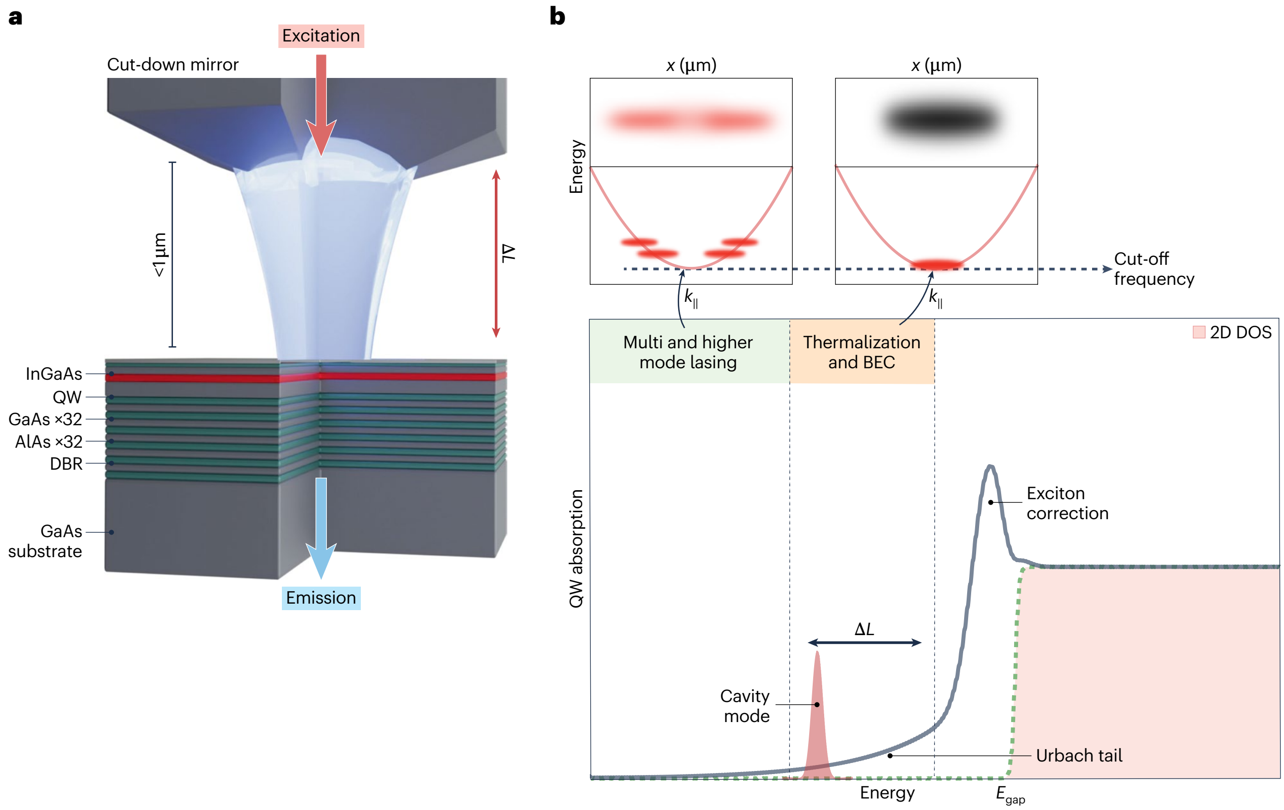


**Fig. 1 | Cavity tuning from standard lasing to thermalized photon Bose–Einstein condensation. a**, Scheme of a photon cavity where the top mirror can be adjusted to change the effective cavity length by $\Delta L$ in order to tune the frequency of the cavity mode. **b**, Bottom panel: Schematic representation of the QW absorption. The different regimes of the photon field are achieved when the cavity mode lies inside the Urbach tail. Top panel: Parabolic energy dispersion of the cavity modes. The lasing and the BEC regimes present a different emission spectrum, the former being usually multi-mode. This leads to a difference in the spatially resolved emission, as schematically illustrated. Figure 1a adapted from[6], Springer Nature Ltd.

ground energy state of the system. By contrast, in structures where the cavity mode energy $\varepsilon_0$ was set deeper into the transparency region of the semiconductor QWs, thermalization was not achieved. Instead, standard lasing occurred, identified by single or multiple higher mode stimulated emissions.

Unlike the condensation of exciton-cavity polaritons (boson quasiparticles formed from a strong coupling between an exciton and a photon)[9], condensates of pure light do not rely on bound excitons and are only weakly coupled to their surroundings.This allows them to bypass the low temperatures and limited excitation conditions required in the polariton strong-coupling regime of the same materials.

Moreover, Bose–Einstein condensation is closely related to superfluidity in $^4$He, which arises from the boson statistics of interacting particles. In these latest demonstrations[5,6], photon interactions in BEC are expected to be mediated by semiconductor nonlinearities, to be significantly enhanced by the cavity, and, unlike dye-based designs, to exhibit a fast subpicosecond response time. Consequently, photon condensation in semiconductor resonators offers the potential to observe the superfluidity of a weakly interacting Bose gas. Furthermore, photon BECs have lower threshold behaviour compared to lasers and hold promise for enabling single-mode, high-power emission from large-aperture devices.

Although the reported experiments do not yet actually demonstrate the superfluidity of condensed photons, it is not difficult to imagine the steps towards directly probing it by perturbing them from the steady state. Additionally, the dissipative nature of the photon condensate encourages further exploration of non-Hermitian effects in low dimensions, for example, a study of exceptional points in the presence of non-linearities. These developments could also be extended to complex lattice geometries to study topological effects and ultra-fast, time-modulated (Floquet) physics, such as those based on cavity optomechanics[10], at room temperature.

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## Competing interests

The authors declare no competing interests.