POLARITONS

The rise of the bosonic laser

Two independent groups have concurrently reported the first bosonic lasers driven by electrical injection. Although the devices operate only at low temperatures and in a strong magnetic field, they represent an important step forward in the evolution of polariton-based optoelectronics.

Alexey Kavokin

As any photonics researcher should be well aware, the acronym LASER stands for "light amplification by stimulated emission of radiation." Put simply, this means that amplification of light occurs in electronic systems in which stimulated emission exceeds optical absorption[1]. This condition requires an inversion of the electronic population, and gain is achieved by externally pumping the system with an energy that exceeds a critical value, referred to as the 'lasing threshold'. However, in recent years, the use of the term 'laser' has been relaxed, and it is now commonly used to describe any device that produces coherent, monochromatic and unidirectional light[2].

Interestingly, it turns out that stimulated emission of radiation is not the only way to generate 'laser' light. In so-called bosonic lasers, coherent light is emitted spontaneously by a condensate of particles accumulated in a single quantum state[3]. Importantly, although bosonic lasers still need to be pumped, they do not require a population inversion and in principle can exhibit 'zero-threshold' lasing characteristics.

What particles are good for forming condensates that emit light? Although bosonic condensates of atoms have been realised at extremely low temperatures[4], the condensed atoms are usually in their ground state and are thus incapable of emitting light (as there is no lower energy state to which they can drop). This makes atomic condensates impractical for light generation. In contrast, condensates of mixed light–matter quasiparticles, exciton polaritons, emit light very well[3]. These condensates have the potential to be realised in semiconductor microcavities at relatively high temperatures — even as high as room temperature. This is why exciton–polariton lasers (also known as polariton lasers) are most likely to become the first practical bosonic lasers. Until recently, however, polariton lasers driven only by optical pumping had been reported[5]. A laser that needs to be pumped by another laser to operate has a limited area of application. Hence, an important milestone to the large-scale practical use of polariton lasers is the demonstration of an electrically pumped device. Two independent groups working concurrently now claim to have achieved this feat.

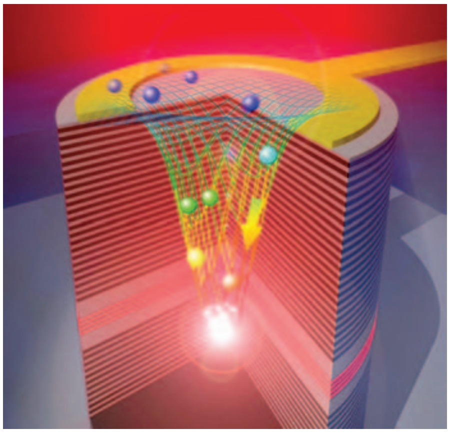

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Figure 1 | Diagram of electrically driven polariton laser. Electrically injected electrons and holes attract each other, resulting in the formation of excitons — hydrogen-like quasiparticles, which emit and reabsorb light inside the microcavity. This leads to the formation of exciton polaritons, which are quasiparticles that alternate between existing as photons and as excitons. The exciton polaritons accumulate in a single quantum state called a condensate, which spontaneously emits light that then tunnels through the mirrors.

The papers by Schneider *et al.*[6] and Bhattacharya *et al.*[7] appeared within 24 hours of each other in *Nature* and *Physical Review Letters*, respectively. Both groups studied high-*Q*-factor p–i–n GaAs/AlGaAs microcavities with semiconductor Bragg mirrors and multiple embedded InGaAs quantum wells (Fig. 1). They both reported two lasing thresholds, which they interpreted as being the thresholds for polariton lasing (condensate-based transition) and conventional photon lasing (stimulated emission); however, they observed the polariton lasing threshold only when a magnetic field of several teslas was applied. The ratio of the polariton lasing threshold to the photon lasing threshold can be considered a key figure of merit for polariton lasers as it indicates the extent to which the bosonic condensate helps to generate coherent light. The threshold of polariton lasing was about 2–5 times lower than that of photon lasing in the Schneider sample, whereas Bhattacharya *et al.* reported the ratio of the thresholds to be of the order of 10^{-3}. The origin of this large difference is currently unclear. In the regime of polariton lasing, the Bhattacharya group reported a build up of spatial coherence and narrowing of the emission linewidth.

Both the Schneider *et al.* and Bhattacharya *et al.* experiments were performed at low temperatures (around 10 K and 30 K, respectively). This leaves significant room for improvement, as room-temperature operation is preferable. Both results raise an important fundamental question — why is a threshold for polariton lasing observed only in the presence of an external magnetic field? Both groups argue that the magnetic field stabilises the excitons (weakly bound electron–hole pairs, which couple to photons to form polaritons), but the specific dependence of the polariton lasing threshold on the magnetic field has yet to be theoretically determined. Schneider *et al.* reported quenching of Zeeman splitting (splitting of spin-up and spin-down polariton energy levels induced by the magnetic field) in the polariton lasing regime; this might be a manifestation of the spin Meissner effect, which has been theoretically predicted for exciton–polariton condensates[8]. The results will undoubtedly stimulate more experimental and theoretical work on bosonic lasers, paving the way to the development of a new generation of optoelectronic devices based on exciton–polaritons.

In terms of practical applications, polariton lasers still need to find their niche. Their chief advantage over conventional lasers is their significantly lower threshold power, as Schneider *et al.*[6] and Bhattacharya *et al.*[7] have convincingly demonstrated. On the other hand, polariton condensates are fragile; they decouple and are destroyed as the pump power is increased. As a result, polariton lasers are unlikely to be suitable for high-power operation.

One benefit is that bosonic condensates of exciton polaritons may be manipulated by applying external electric and magnetic fields and external laser beams. Consequently, the polarisation and intensity of light emitted by polariton lasers can be switched from one value to another within several tens of picoseconds[9]. This controllability and fast response make polariton lasers promising for applications in optical integrated circuits at the interface between electronics and optical communication devices. Another application area that remains to be explored is terahertz frequency generation by polariton condensates[10]. Given the high demand for compact and reliable sources of coherent terahertz radiation, bosonic cascade lasers based on excitons or exciton polaritons offer a valuable alternative to quantum cascade lasers based on electronic transitions in semiconductor superlattices. Potentially, they could operate at room temperature, emit terahertz light in the vertical direction (that is, normal to the plane of the structure) and be as small as any vertical-cavity surface-emitting laser.

The next milestone on the path to developing a truly practical polariton laser will be the demonstration of room-temperature operation under electrical injection. Until recently, GaN-based microcavities had been considered as most the promising means to meet this objective given that excitons in GaN are stable at room temperature[6]. However, one should not forget GaAs-based microcavities, which are worthy of further investigation. The strong coupling to microcavity modes stabilizes excitons in GaAs, which is why they might survive up to room temperature in carefully designed structures. I expect very significant further advances in the area of polaritonics in the coming years, if not months. ❐

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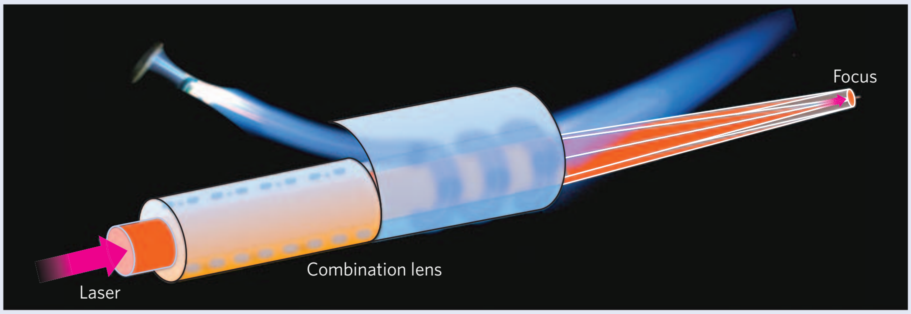
OPTICS

The flame lens

Scientists in South Africa have developed a hot-gas lens that possesses improved optical capabilities and a damage threshold that is estimated to be vastly superior to that of conventional glass optics. Once optimized, such lenses may be useful for focusing ultra-intense laser beams such as those used in X-ray lasers, laser-driven accelerators and laser fusion experiments.

The 'flame lens' is the inspiration of Max Michaelis, Andrew Forbes and co-workers at the University of KwaZulu-Natal and the National Laser Centre in South Africa (*Nat. Commun.* **4,** 1869; 2013). "Our lens can transmit beams whose intensities are two orders of magnitude higher than the maximum intensity that solid-state lenses can transmit without sustaining damage," commented Forbes. "Even if breakdown were to occur, the lens repairs instantaneously, unlike solid-state optics, which are either permanently impaired or must be left to cool for hours."

The idea of using a hot metal tube to create a temperature gradient and thus a lens-like refractive index profile in a gas has been around for some time. Bell Laboratories in the USA investigated the idea in the 1960s not long after the development of the first lasers. Michaelis has been doggedly pursuing the concept and trying to make it practical for the past 25 years.



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Early designs were plagued by severe limitations in terms of their large size, high complexity and weak focusing. "These early tube gas-lens designs suffered from three fundamental problems — their apertures were small (of the order of 7 mm), their focal lengths were very long (2.5 m to 10 m) and they required complicated ancillary apparatus," explained Forbes. "These early lenses were usually of the order of a metre in length, and were thus long and bulky."

To address these issues, the South African team designed a composite gas lens that consists of two parts. The first stage is a 50-mm-long metal-tube gas lens with a 10-mm-diameter aperture that is heated from below and refracts the outer rays of a light beam. The second stage is a shorter tube, 25 mm in length; it contains a spiral flame that mainly acts on the inner rays. The stainless-steel tubes of both lenses are heated to around 400 °C so that they become red hot. The result is a flame lens, which brings light to a sharp focus and is more compact and has a focusing power that is four times stronger per unit length than earlier gas-lens designs.

The team has used a prototype flame lens with a focal length of about 2 m in proof-of-principle experiments that include focusing of high-intensity light, imaging of highly chromatic sources and drilling plastic with high-energy pulses. The team is now using aerodynamic theory to optimize the lens structure and further improve its performance. "We predict that this will remove all the aberrations bar astigmatism, bringing the flame lens into a similar quality realm as conventional lenses," said Forbes. "One could also consider operating the lens at higher pressures or with different gases to decrease the focal length."

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