Valtcheva *et al.* went on to inject viral tracers into the PVN oxytocin neurons of maternal mice; these viruses move through upstream neurons in neural circuits, thereby allowing the authors to label the brain areas that send auditory information to the oxytocin neurons. Intriguingly, areas that process conscious responses to auditory information, such as the AuCX and the inferior colliculus (IC), are not directly connected to PVN oxytocin neurons. Instead, the AuCX and IC send pup-call information through the posterior thalamus, a brain area in which sensory information is organized and redirected towards other regions (Fig. 1).

Specifically, the authors found dense projections from the posterior intralaminar (PIL) nucleus of the thalamus to the PVN. The PIL belongs to the non-lemniscal auditory pathway, which has been suggested to mediate unconscious perception of sounds, such as attention, emotional responses and reflexive reactions[6]. Recent studies have also highlighted the role of the PIL and its projections to hypothalamic areas in the processing of other social cues in mice[7] and in the recognition of social signals in evolutionarily conserved circuits in zebrafish[8].

Valtcheva and colleagues propose a new role of the PIL in the oxytocin PVN circuit that mediates the perception of pup distress calls, and which could therefore influence the quality of maternal care. Indeed, when the authors silenced signalling of the PIL to the oxytocin PVN neurons, using a technique known as chemogenetic suppression, they observed reduced willingness of freely behaving mothers to make sustained efforts to protect their pups from potential dangers.

The PIL neurons responded to pup calls with sustained activity, sometimes firing for several seconds after the pup calls had ended. But although the projections to PVN oxytocin neurons were dense, direct and functional, the synaptic connections from the PIL to the PVN were not strong enough to induce direct firing of oxytocin neurons. Instead, the authors report an intriguing mechanism in which strong inhibition of oxytocin-neuron activation is overcome by the sustained activity of PIL neurons, thereby aiding the response of oxytocin neurons to pup calls (see Fig. 3i of ref. 1).

Finally, the authors hypothesized that the activated PVN neurons cause oxytocin to be released in downstream brain areas, thereby promoting maternal behaviour. To test this, they used a genetically encoded sensor[9,10] that enabled the labelling of oxytocin molecules bound to their receptor protein in selected brain areas when mothers were listening to the pup distress calls. This approach revealed that oxytocin is indeed released after pup calls, in a region called the ventral tegmental area (VTA). The VTA is one of the core nodes of the brain's reward system, and is known to produce motivated behaviour and process reward information. Interestingly, when signalling from the PIL to the oxytocin PVN neurons was silenced, oxytocin release in the VTA after pup calls was negligible.

One of the strongest points of this work could be also seen as its main limitation. The highly controlled experimental setup, in which head-fixed mice listened to pre-recorded pup calls, allowed the authors to obtain unprecedented mechanistic knowledge of how oxytocin neurons in this circuit process information that is highly relevant to natural animal behaviour. However, the dynamics of these neurons' activity during actual natural behaviour are still unknown. For example, do these cells fire differently in response to pup calls from a mother's own progeny compared with the recorded calls?

Overall, Valtcheva *et al.* provide a mechanistic understanding of how sensory cues from offspring are integrated at the level of neural circuits to activate the release of neuromodulators such as oxytocin and promote maternal care. The demonstration that the activation of the pathway from the PIL to the oxytocin PVN neurons is necessary to induce maternal care raises questions for future research. For example, is the activation of this pathway sufficient to drive maternal behaviour in virgin mice?

It is also tempting to think that this circuit is altered in some postnatal conditions that affect many women, such as postpartum depression. If so, then this work might eventually help to elucidate the biological mechanisms of these conditions and potentially open up strategies for drug discovery.

Flavia Ricciardi and **Cristina Márquez** are at the Center for Neuroscience and Cell Biology, University of Coimbra, Coimbra 3060-197, Portugal.
e-mail: cmarquez@cnc.uc.pt

1. Valtcheva, S. *et al. Nature* **621**, 788–795 (2023).
2. Marlin, B. J., Mitre, M., D'amour, J. A., Chao, M. V. & Froemke, R. C. *Nature* **520**, 499–504 (2015).
3. Schiavo, J. K. *et al. Nature* **587**, 426–431 (2020).
4. Carcea, I. *et al. Nature* **596**, 553–557 (2021).
5. Hasan, M. T. *et al. Neuron* **103**, 133–146.E8 (2019).
6. Lee, C. C. *Front. Neural Circuits* **9**, 69 (2015).
7. Keller, D. *et al. Curr. Biol.* **32**, 4593–4606.E8 (2022).
8. Kappel, J. M. *et al. Nature* **608**, 146–152 (2022).
9. Mignocchi, N., Krüssel, S., Jung, K., Lee, D. & Kwon, H.-B. Preprint at bioRxiv https://doi.org/10.1101/2020.07.14.202598 (2020).
10. Lee, D. *et al. Nature Methods* **14**, 495–503 (2017).

The authors declare no competing interests.
This article was published online on 20 September 2023.

Optics

Organic lasers go electric

Stéphane Kéna-Cohen

An organic light-emitting diode has been integrated with an optically driven organic laser to produce laser light from electricity. The design bypasses many of the challenges posed by direct electrical input in such devices. **See p. 746**

Thin layers of organic molecules can be fabricated over large areas at low cost, and their electrical and optical properties can be chemically tuned with ease. These characteristics make organic molecules ideal materials for thin-film lasers. The first such lasers[1,2] were developed in the late 1990s, but these devices needed to be driven optically by a second laser, which limited their usefulness. On page 746, Yoshida *et al.*[3] demonstrate an organic laser that can be driven electrically when integrated with a very bright organic light-emitting diode (OLED) — creating an all-organic package that is both powerful and versatile.

A key component of every laser is a material called the gain medium, which uses energy to amplify the intensity of light in the laser. The use of organic molecules as a gain medium dates back to the invention of the dye laser[4,5], in which a jet of organic dye solution provided the amplification (gain) that is essential to laser operation. In that case, the excess energy came from exciting the dye with a second laser, which prompts the question: why use a laser to make another laser? One reason is that there are many molecules to choose from, so the wavelength of the outgoing light could be easily tailored by using the right molecule. Organic molecules also tend to amplify light over a broader range of wavelengths than inorganic media do — a property that enabled dye lasers to be readily tuned and capable of generating ultrafast light pulses.

But using organic gain media poses some challenges. The absorption of light by a molecule raises the energy of one of the molecule's electrons, while leaving a second, identical, electron behind, unexcited. Importantly,

the total intrinsic angular momentum — or spin — of these two electrons is unchanged after absorbing light. In nearly all cases, this corresponds to zero spin, and the electron spin configuration is known as a singlet. However, there is a small chance that the total spin will flip to a value of one, in which case the system is known as a triplet.

Electrons in a triplet configuration are optically dark, meaning that they cannot emit light. As a result, they stay excited for a long time (milliseconds, compared with nanoseconds for singlets) and this leads to a large build-up of triplets when an organic laser is driven continuously. Triplets contribute to optical loss — unwanted light absorption — in organic lasers. This negates the gain provided by the dye, to the point at which laser operation is prevented completely. Triplets are also often involved in processes that can irreversibly damage the molecules. It was to avoid a build-up of triplets that liquid solutions had to be circulated continuously in dye lasers. Even with such precautions, eventual damage to the molecules required that the dye be replaced regularly — an extremely messy process.

Although dye molecules were incorporated in solid films as early as 1967 (ref. 6), it would be three decades before organic lasers would show potential for rivalling inorganic semiconductor devices. Advances in organic electronics promised to transition bulky table-top dye lasers to a compact package — with dimensions no bigger than a few millimetres — that could be fabricated on flexible substrates (Fig. 1a). The first demonstrations of thin-film devices included light-driven lasers made of polymer films[1] and small molecules[2]. Because dye circulation is not possible in a thin film, organic solid-state lasers need to be driven with short laser pulses, spaced several milliseconds apart, to avoid the build-up of triplets.

Realizing an organic 'laser diode' — an electrically driven organic laser — has since been a long-term goal in organic electronics research, but this feat involves overcoming many new challenges. First, a high electrical current must be injected to achieve sufficient gain for lasing. However, at high current densities, several processes reduce the efficiency with which singlets can be formed in organic layers[7]. Second, when current is injected in organic thin films, the spins of the injected charge carriers (electrons and their positive counterparts, holes) are randomly oriented. This means that three out of four excited molecules will be in the unwanted triplet state, because there are three possible triplet states and only one singlet state. By contrast, just a few per cent of the molecules are in a triplet state under optical excitation[8].

This further increases the required gain, as does optical loss resulting from the charge carriers absorbing light themselves. These processes combine to make the required driving current so high that devices are destroyed by heat before they can lase. Organic laser research has also been fraught with controversy — owing, in part, to some difficulties in correctly identifying lasing[9] and to a now-retracted claim[10].

The first credible claim of laser-diode operation came a few years ago[11], but the devices in question could be operated only for a few pulses before being irreversibly damaged, and the results have been difficult to reproduce. Other groups bypassed many of the difficulties associated with electrical driving by building organic lasers that are driven by inorganic laser diodes[12–14] or light-emitting diodes[15]. In effect, these attempts combined electrical and optical driving in a single package. However, integration with inorganic components can negate some of the advantages of using organic lasers by adding to the cost and size of the devices, and by limiting the substrates on which they can be integrated.

"Inorganic components can negate some of the advantages of using organic lasers by adding to the cost and size of the devices."

Yoshida *et al.* have succeeded in powering a green-emitting organic laser structure with a very bright blue OLED, allowing for electrically driven laser operation in a single chip (Fig. 1b). To achieve this, the team removed the OLED from its original substrate and laminated it onto the laser structure in an exquisite feat of engineering. One advantage of this architecture, aside from being practical from an integration standpoint, is that it enables much more efficient coupling of the OLED light to the laser than would otherwise be achievable. This is crucial, because it more than halves the current needed for laser operation.

Yoshida and colleagues' device could be fabricated on plastic substrates, or in large-area arrays, which could enable applications in spectroscopy, imaging and sensing that are difficult to imagine for conventional lasers. Although the device still requires a pulsed current to reduce heat and triplet build-up, advances in materials development might be able to mitigate this problem in the future.

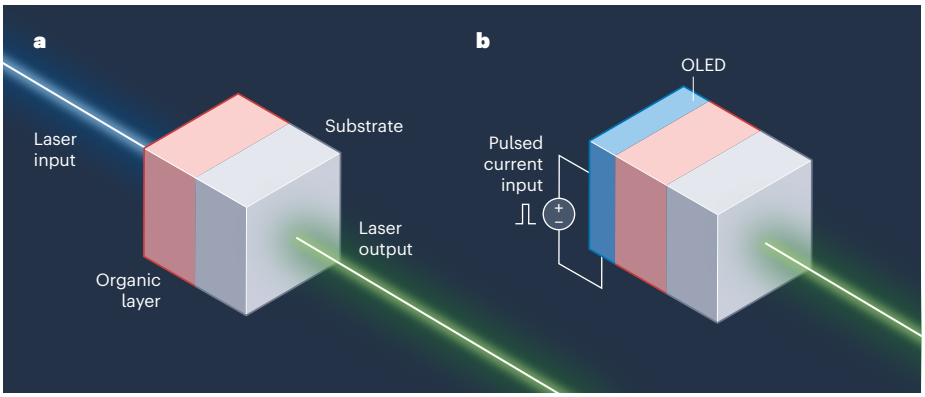

Figure 1 | Organic lasers. Organic materials are attractive for building lasers, but existing devices need to be driven by another light source. **a**, Early organic lasers used a second laser to drive the organic material so that it could amplify light[1,2]. Light from the external laser is absorbed by an organic material that is mounted on a substrate, and provides the required energy. The high currents required for direct electrical driving would destroy the organic material before lasing occurs. **b**, Yoshida *et al.*[3] built an organic laser in which an input current excites an organic light-emitting diode (OLED). The optical power of the OLED is then absorbed by the organic laser, allowing it to produce laser light. Similar ideas have been attempted before[8–11], but never with all-organic components — an impressive feat that is highly promising for future lasing applications.

Stéphane Kéna-Cohen is in the Department of Engineering Physics, Montreal Polytechnic, Montreal, Quebec H3C 3A7, Canada.
e-mail: s.kena-cohen@polymtl.ca

1. Kozlov, V. G., Bulović, V., Burrows, P. E. & Forrest, S. R. *Nature* **389**, 362–364 (1997).
2. Tessler, N., Denton, G. J. & Friend, R. H. *Nature* **382**, 695–697 (1996).
3. Yoshida, K. *et al. Nature* **621**, 746–752 (2023).
4. Schäfer, F. P., Schmidt, W. & Volze, J. *Appl. Phys. Lett.* **9**, 306–309 (1966).
5. Sorokin, P. P. & Lankard, J. R. *IBM J. Res. Dev.* **10**, 162–163 (1966).
6. Soffer, B. H. & McFarland, B. B. *Appl. Phys. Lett.* **10**, 266–267 (1967).
7. Gärtner, C., Karnutsch, C., Lemmer, U. & Pflumm, C. *J. Appl. Phys.* **101**, 023107 (2007).
8. Giebink, N. C. & Forrest, S. R. *Phys. Rev. B* **79**, 073302 (2009).
9. Samuel, I. D. W., Namdas, E. B. & Turnbull G. A. *Nature Photon.* **3**, 546–549 (2009).
10. Schön, J. H., Kloc, C., Dodabalapur, A. & Batlogg, B. *Science* **289**, 599–601 (2000).
11. Sandanayaka, A. S. D. *et al. Appl. Phys. Express* **12**, 061010 (2019).
12. Karnutsch, C. *et al.* in *Conference on Lasers and Electro-Optics/Quantum Electronics and Laser Science Conference and Photonic Applications Systems Technologies*. CFJ3 (Optica Publishing Group, 2006).
13. Riedl, T. *et al. Appl. Phys. Lett.* **88**, 241116 (2006).
14. Vasdekis, A. E. *et al. Opt. Express* **14**, 9211–9216 (2006).
15. Yang, Y., Turnbull, G. A. & Samuel, I. D. W. *Appl. Phys. Lett.* **92**, 163306 (2008).

The author declares no competing interests.