Liquid crystals

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Chirality-assembled on-chip lasers

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Optical micro-printing provides a way to directly self-assemble photonic microchips with chiral liquid-crystalline photonic elements.

While the number of transistors in electronic microchips doubles every year, similar miniaturization, low-cost fabrication and biomedical utility of photonic microchips remain a challenge[1,2]. In addition to a plethora of other biomedical uses, electronic microchips nowadays enable emerging developments in brain–computer interfaces, whereas photonic microchip analogues of the brain–computer and brain–machine interfaces are still in the early stages of development[3]. However, in a year or two, the decades-long densification of electronic microchips and the predictions of Moore's law are about to be challenged, as transistors approach dimensions where quantum phenomena can alter the physical underpinnings of the electronic elements.

At the same time, we are projected to enter the yottabyte era soon, with faster processing and transmission of information becoming an urgent necessity. Photonic chips may hold the key to this future development, since nothing can travel faster than light. At the moment, mishaps related to the electronic computer–brain interface are common; nevertheless, photonic microcircuits that use optical signals within the brain may be part of future technological solutions, because nothing can be gentler than light of low intensity that can be used in biocompatible photonic chips within brain–computer interfaces[3]. Unlike their electronic counterparts, photonic microchips require no cooling; moreover, they use less energy, can be integrated with conventional electronic chips[1,2], and have high sustainability and efficiency, making them promising alternatives to modern electronics[1].

Despite the promise, the fabrication of photonic microchips still faces many challenges[1]. While electronic microchips can be based solely on silicon – being fabricated via steps of etching, photolithography and doping to create desired transistors and other elements on the same silicon wafer – photonic microchips rely on different micro-integrated materials and typically require many more complex fabrication steps and hazardous chemicals[1,2]. Despite considerable research and development efforts, cost-effective fabrication of on-chip lasers remains particularly challenging[1,2].

Now, writing in *Nature Photonics*, Mahendran Vellaichamy and colleagues describe an approach for making an on-chip mirror-less laser based on the self-assembly of chiral photonic structures (Fig. 1a–d) integrated into photonic microchips using laser-written micro-confinement and waveguiding structures[4]. The team used a liquid crystal composed of nanometre-sized elongated molecules that locally co-align and twist around a helical axis as a result of molecular chirality while retaining the ability to flow and form one-dimensional self-assembled chiral photonic structures (Fig. 1e).

Nature has taken advantage of self-assembled chiral photonic structures over billions of years, with one familiar example being the vivid coloured reflections caused by chiral helicoidal structures of biopolymers, such as chitin, in the cuticles of beetles[5]. Such photonic structures can play many functional roles that, over the course of evolution, provide various forms of life different advantages over other species, such as being able to adapt to local climates through thermal management using broadband golden- or silver-like selective reflections[5]. The era of utilizing such self-assembled elements in modern photonic chips may be just beginning[4].

Indeed, while various micrometre-sized chiral liquid-crystal-based lasers have been demonstrated previously, including in chiral nematic microdroplets[6], integrating them into microchips by means of simple laser micro-printing is a major new development in soft-matter photonics (Fig. 1a–d) (ref. 4). The study by Vellaichamy and colleagues demonstrates how the chirality-mediated self-assembly of helicoidal photonic structures of chiral liquid crystals replaces many of the tedious fabrication steps that one would need to follow in order to make such lasers by other fabrication means in solid-state photonic microchips[4]. Furthermore, the facile response of the chiral nematic medium makes such on-chip lasers highly tunable and reconfigurable by external stimuli, including light itself. The demonstrated soft-matter photonic chips effectively integrate the chiral liquid-crystalline micro-lasers and laser-written polymer waveguides, and also take advantage of resonant stimulated-emission depletion to switch the light by light (all-optical control)[4]. Their functionality and operating wavelengths can be easily pre-engineered by tuning the helicoidal pitch of chiral liquid crystals and selecting different dyes doped into them[4]. Importantly, such photonic integrated devices can be made biodegradable and biocompatible.

These chirality-assembled (self-assembled) microchips with on-chip nanosecond laser sources may be key to future data communications. Notably, optical fibre technology is already very broadly used in long-distance communications. Scaling such light-enabled technology down to the microchip scale, along with the on-chip sources of light (Fig. 1f), may significantly boost the computing power. Polymer based micro-printed waveguides and chiral liquid-crystal micro-lasers are structurally similar to biopolymers and anisotropic molecular organizations already found in our body and in living animals, which are important for many biological functions. Indeed, the very first chiral liquid crystals with characteristic photonic structures and coloured reflections were observed in substances extracted from animals[7]. Thus, the soft-matter forms of photonic chips are poised to boost the biomedical utility of photonic microchips, with uses ranging from brain–computer interfaces[3] to sensors that measure oxygen and glucose levels, as well as applications in medicine, wearable photonics, logic circuits, and many other fields[4]. Compared with solid-state counterparts, the soft-matter photonic microchips could substantially reduce both production costs and complexity, as well as avoid the use of toxic chemicals needed for manufacturing. The fabrication of on-chip lasers just requires the injection of a dye-doped liquid crystal into the micro-printed confinement – a step that also couples the laser with the waveguides (Fig. 1a–e) – which is considerably simpler than the process used for solid-state on-chip lasers[1,2].

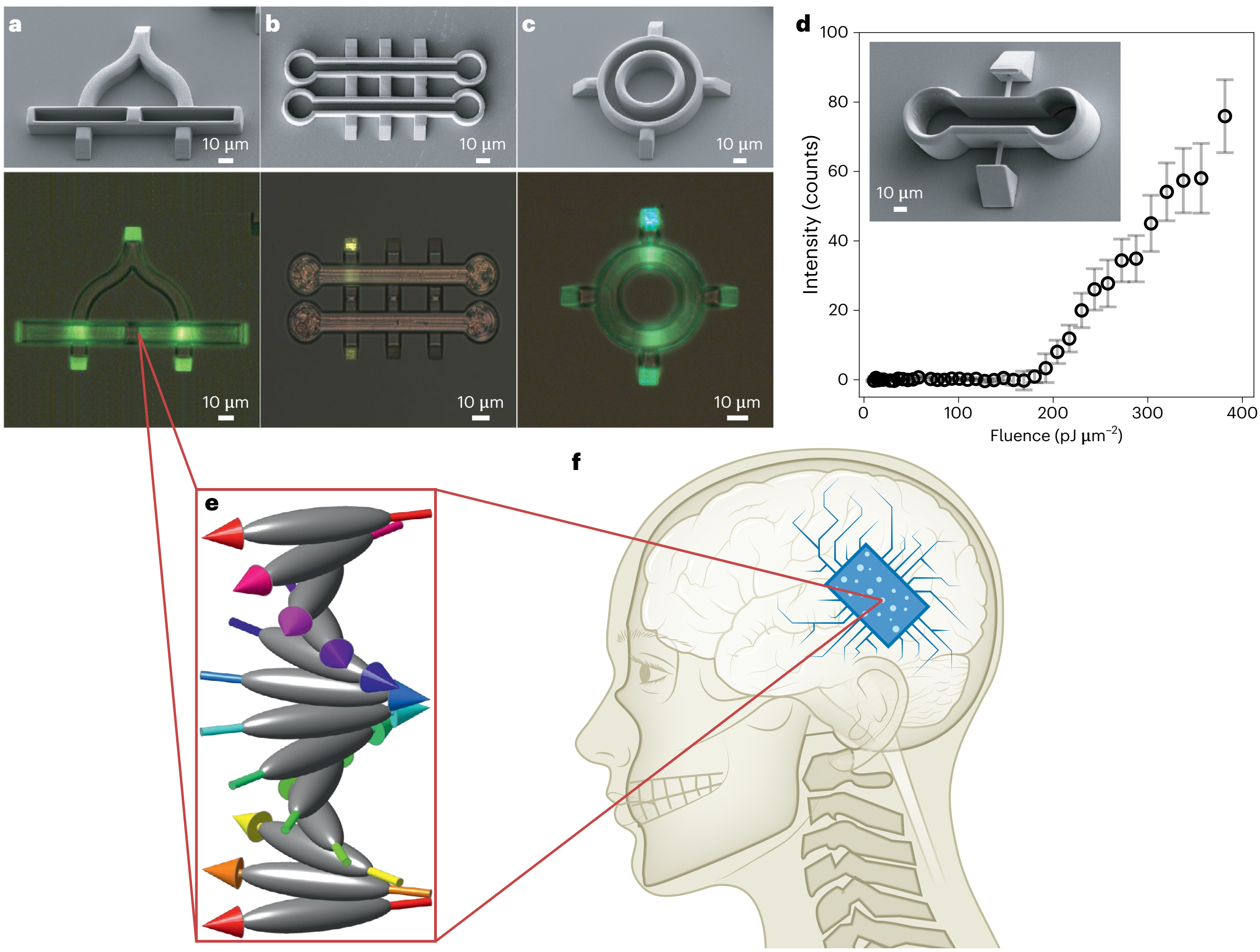

Fig. 1 | Towards chiral photonic microchips and brain–machine interfaces. **a**–**c**, Images of laser cavities for filling chiral liquid crystals (top row) and lasing from them (bottom row). **d**, Lasing threshold from a micro-laser cavity shown in the inset. **e**, Chiral liquid-crystal photonic structure within a micro-laser. **f**, Futuristic depiction of self-assembled chiral photonic microchips and their use as photonic brain–machine interfaces. Panels **a**–**d** reproduced from ref. 4.

The work by Vellaichamy and colleagues[4] elegantly demonstrates the generation and control of nanosecond light pulses by light itself within microscale-confined soft-matter components that are not only self-assembled and micro-printed but also biodegradable and biocompatible. Moreover, these components have the potential to outperform solid-state photonic microchips in many key measures. One such measure is the size of the resonator cavity, which in the on-chip lasers made from chiral liquid crystals was just ~2 µm^2 × 8 µm, pumped at a fluence of ~80–300 pJ µm^{-2} to generate nanosecond pulses in the visible spectral range. Now, since the technique used for micro-printing (namely, two-photon-absorption-based photopolymerization) allows for three-dimensional resolution in defining complex structures[8], waveguides could be shaped to allow multi-layer photonic microchips, thus boosting photonic element density. Other chiral phases, such as cholesteric blue phases, could also be utilized in micro-laser and other photonic element designs[6]. The use of nematic non-polar and ferroelectric liquid crystals could allow for the micro-self-assembling of different types of tunable polarizing optics within microchips. Elastomeric 'soft-solid' liquid crystals could allow photomechanical actuators to be micro-printed, and since photonic microchips do not have to be solely soft-matter based, colloidal inclusions of solid-state particles could allow researchers to realize on-chip, light-powered micro-motors[9] and photon upconverting elements when using specially designed nano- or microparticles[10]. The self-assembled biocompatible elements like micro-lasers could allow photonic microchips to be used to create new types of brain–computer interfaces (Fig. 1f) (ref. 3), which may one day be implanted into our brains so that we can control machines solely by our thoughts, potentially having optical circuits as complex as the ones currently occupying entire optical tables.

From the fundamental research perspective, one can imagine creating microchip-scale characterizations of materials or liquid solutions that only require tiny samples to perform complex characterizations that nowadays require complex optical tabletop set-ups. The study by Vellaichamy and colleagues may facilitate the emergence of new photonic microchip research frontiers, with major impacts on future science and technologies.

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Competing interests

The authors declare no competing interests.