A new twist to tuning lasers

Self-organizing liquid crystals could spawn a new breed of extremely useful and cheap tunable lasers. Such lasers may ultimately prove to be useful for creating flat-screen displays with better colours, enhanced sensors and compact medical instruments. *Duncan Graham-Rowe* takes a closer look.

The term 'self-assembly' has in recent years become synonymous with the field of nanotechnology. But now, thanks to the naturally occurring, self-organizing behaviour of liquid crystals, we could soon see lasers being self-assembled too. According to the scientists developing them, such liquid crystal lasers would be tiny and highly tunable, and ultimately so cheap that they could be made disposable.

These new lasers work by combining the properties of a laser dye with those of the natural photonic bandgap created by the periodic structures of liquid crystals, particularly cholesteric liquid crystals which have a periodic helical structure and are regarded as a one-dimensional photonic crystal. By controlling the degree to which these crystals twist, and therefore their periodicity, it is possible to tune the output wavelength of the lasers.

The potential benefits of these lasers are huge, says Stephen Morris who works as part of a research team led by Harry Coles at the Centre for Molecular Materials for Photonics and Electronics at Cambridge University, UK. This is because liquid crystal lasers combine the best features of dye, gas and solid-state lasers, leaving their respective drawbacks behind, says Morris.

Although dye lasers offer highly wavelength-tunable output, they tend to be rather large. Similarly, gas lasers are also bulky and have fixed wavelengths. On the other hand, semiconductor lasers, such as those used in DVD players, may be small but their wavelengths are fixed or have only a narrow tuning range. In contrast, liquid crystal lasers can be made very small and highly tunable. "Their wavelengths can be tuned from deep ultraviolet to near-infrared," says Morris.

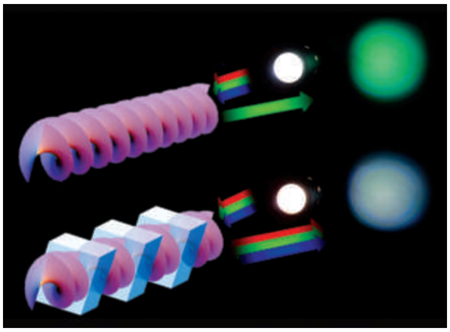

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Figure 1 | Image of red–green–blue reflection by a hybrid dye liquid crystal structure.

Because of these benefits, there is a real potential for these lasers to become a truly disruptive technology, dislodging existing lasers and creating new applications, spanning from laser projectors and sensors to new forms of flat-screen displays and multi-purpose medical scanners.

"In their simplest form, lasers have two mirrors and light bounces back and forth between them," explains Peter Palffy-Muhoray, associate director at the Liquid Crystals Institute at Kent State University in Ohio, USA. The distance between these reflectors defines the optical cavity that ultimately determines the wavelength of light emitted by the laser. As can be imagined, operation of the laser is very sensitive to the positioning of the mirrors.

In the case of liquid crystal lasers, the optical cavity is defined by the pitch — the length of one complete twist — of the crystals, and no mirror is needed, says Palffy-Muhoray. "Normally we have to make lasers very precisely but here the biggest advantage is the liquid crystals do it for us. All we have to do is to pump the liquid and we're ready to go," he says.

Moreover, it is easy to control the length, or the pitch, of the crystals chemically, mechanically or electrically, says Morris. "It's like a spring," he adds. The length can be made longer or shorter and by doing so the wavelength of the laser light emitted can be easily controlled.

Unusual as this approach may sound, the idea is in fact far from new, with some of the earliest patents in the area dating back as far as 1973. Later theoretical forays were made by the likes of Eli Yablonovitch at the University of California in Los Angeles, and Sajeev John at the University of Toronto in Canada, both of whom independently predicted in 1987 that lasing was possible from these kinds of materials. Both realized that spontaneous emission could be inhibited within the photonic bandgap of liquid crystals.

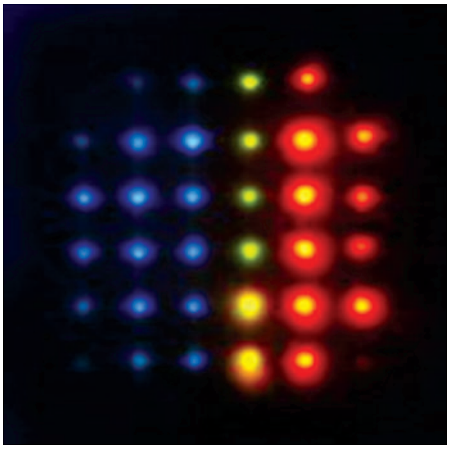

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Figure 2 | Image of laser emission from the gradient-pitch liquid crystal laser cell illustrating simultaneously occurring polychromatic laser emission. The cell is filled with two different liquid crystal and dye mixtures from opposite sides.

Early experiments also showed that under certain circumstances liquid crystals could show extraordinary gain. "However, they couldn't show that it was lasing," says Palffy-Muhoray. It took another 12 years before Azriel Genack and Victor Kopp at Queen's College of the City University of New York, USA, were able to give the first unequivocal evidence for band-edge lasing.

The remarkable property that makes liquid crystals attractive for lasing materials is their capability of self-organizing themselves into photonic bandgap structures, according to both Morris and Palffy-Muhoray. "You could literally paint walls with something that could emit laser radiation perpendicular to the wall," says Palffy-Muhoray.

Indeed, for one of the potential applications this is precisely the plan—to create self-organizing thin films for flat-panel displays. "The potential for display applications is large," says Hideo Takezoe, another pioneer in the field from the Tokyo Institute of Technology in Japan. Using this approach, he says, laser displays with multi-cholesteric liquid crystals in hybrid structures containing dyes (see Fig. 1) could be produced at very low cost. The use of liquid crystal lasers could potentially improve the colour quality of displays because the

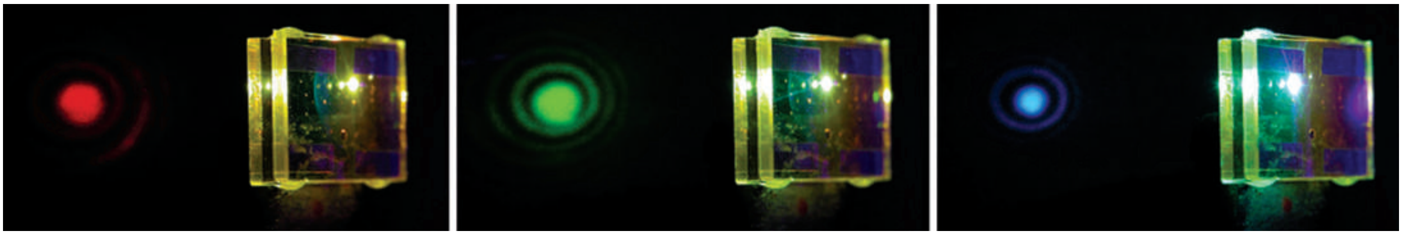

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Figure 3 | Tunable laser action. Laser action tunable in the whole visible region can be achieved by laterally moving the cholesteric liquid crystal cell with respect to the position of a pumping beam. These figures show red–green–blue lasing by the excitation of three laterally shifted positions.

pitch of these liquid crystals, and thus their light-emitting wavelengths, can be very precisely controlled.

In fact, both the Cambridge group and Takezoe's team have shown that it is possible to create a cell of liquid crystals whose pitch follows a gradient depending on where they are, as shown in Figs 2 and 3. In particular, Takezoe's demonstration shows that under the excitation of blue light pulses (420 nm, pumping energy of 1.9 mJ per pulse) the various dye formulations throughout the cell will simultaneously emit monochromatic red, green and blue (RGB) light at wavelengths of 620, 550 and 475 nm, as can be seen from Fig. 3. This capability would provide more natural and continuous colours in displays, says Takezoe.

Besides displays, the potential for medical applications is also vast, says Morris. Generally, in such applications many different types of laser are needed because different treatments require different wavelengths. "The advantage offered by liquid crystal lasers is its capability of creating multi-purpose lasers that can be used for many treatments ranged from dermatology to cancer and diabetes detection," says Morris. Also, given their compact size, they could even be used for lab-on-a-chip applications, hints Morris.

Liquid crystal lasers can also be extremely useful as a form of sensor, says Palffy-Muhoray. "They are very responsive to almost any kind of stimuli, such as temperature changes and even slight mechanical stress," he says. The particular factor that makes liquid crystal lasers attractive as sensors is that the environmental changes are represented as a change in frequency of the light emitted rather than signal strength, he explains. "It's much easier to detect changes in frequency than changes in amplitude," he emphasizes. Although commercial applications of liquid crystals are still a way off, Palffy-Muhoray holds the opinion that the first applications are likely to be sensors of this kind.

Another peculiar property of these materials is that they can be elastomerized to make themselves sensitive to mechanical stresses. Palffy-Muhoray and his co-workers demonstrated this rather spectacularly by showing how a dye-doped cholesteric liquid single-crystal elastomer can be reversibly stretched to produce direct changes in the wavelength of light emitted, as shown in Fig. 4. More specifically, his team showed that a pump beam with 35 ps pulses at a wavelength of 532 nm generated from a frequency-doubled mode-locked Nd:YAG laser could produce lasing from the liquid crystals over the range of 544–630 nm with linewidths of ~3.5 Å. The reported pump threshold for non-deformed samples with a thickness of 0.25 mm was ~280 μJ.

Despite their potential benefits, there is a consensus that these lasers still have some way to go before they will become commercially available. "It's not at the practical stage yet," says Takezoe. "Nobody has created a continuous-wave laser yet."

Morris confirms that the demonstration of a continuous-wave liquid-crystal laser is now one of the next challenges. Only picosecond pulsing of up to 20 pulses a second has been demonstrated, he says. Typical output energies range from hundreds of nanojoules per pulse up to 10 μJ per pulse, and slope efficiencies are in the range of 1–30%. "The main limiting factor for continuous–wave lasing is related to the light emitter that is doped into the liquid crystal," he says. "These are typically laser dyes which are not suitable for continuous-wave operation owing to photobleaching and other effects." In conventional dye lasers, this is circumvented by keeping the dye flowing and effectively 'flushing' out the energy.

Another challenge that needs to be overcome is to find a way to lower the excitation threshold for lasing, says Palffy-Muhoray. "Theoretically you could make it as low as you want, but achieving this in practice is a whole different ball game and requires a deeper level of understanding of the lasing mechanisms," he adds.

"The goal is to remove the need for an additional excitation source," says Morris. However, this can only be done if the threshold is made low enough whereby the additional source can be replaced with something like a flash lamp or, even better, a light-emitting polymer, he says.

Ironically, the company that was established to try to commercialize this research, Chiral Photonics, set up by Genack and Kopp in 1999, became sidetracked over the following decade. Despite having a head start in this field, the aim of the firm became distracted by another idea, say Genack. "It morphed into something else," he says. "We tried to pursue it for a while, and hope to eventually return to it."

If so, they may not want to leave it too long. Although there are still no commercial products in the market, the field is gathering momentum and it seems that it is only a matter of time before ultra-cheap liquid crystal lasers are being assembled *en masse* for displays, medical diagnostics and new types of sensor. ❐

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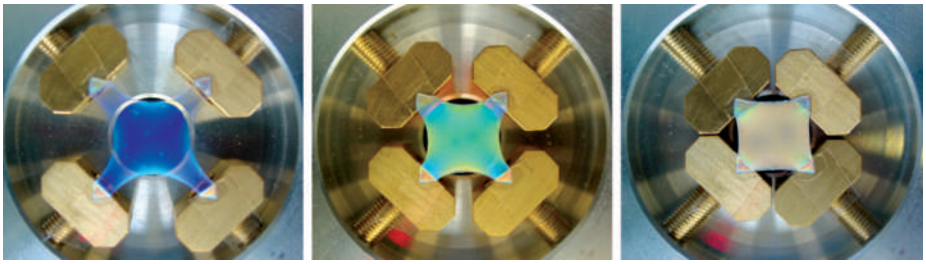

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Figure 4 | Changing appearance of a sample of cholesteric liquid single-crystal elastomer under white-light illumination as a function of mechanical strain.