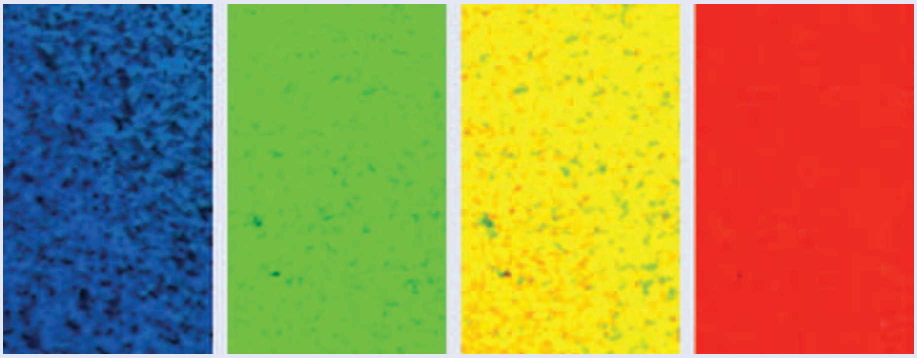
PHOTONIC CRYSTALS

Bridging the visible

Photonic crystals are periodic dielectric structures that can be used to prohibit, confine or control light propagation in a particular wavelength band (known as the photonic bandgap). Consequently, they are an important building block for all-optical integrated circuits. The ability to tune their photonic bandgap dynamically across a wide wavelength range is highly desirable, but it has proved difficult to achieve to date. Now, Tsung-Hsien Lin and co-workers from Taiwan and the USA have demonstrated optical tuning of the bandgap of a liquid-crystal blue-phase (BP) photonic crystal across the entire visible spectrum (*Adv. Mater.* http://dx.doi.org/10.1002/adma.201300798; 2013).

BP photonic crystals are easy to fabricate — a three-dimensional periodic cubic lattice with dimensions of several hundred nanometres can be created through self-organization in a liquid crystal. The researchers found that the photonic bandgap of a compound consisting of chiral azobenzene (1.7%), commercially available nematic liquid crystal E48 (54.3%), chiral dopants S811 (29%) and R811 (15%) could be tuned over a wide wavelength range by irradiating the compound with blue light.



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The compound exists in two phases, BP I and BP II, whose photonic bandgaps lie in different regions of the visible spectrum. A reversible transition between these two phases can be driven by either temperature changes or exposure to blue light (wavelength, 408 nm). The compound initially exhibited Bragg reflection at a wavelength of approximately 470 nm. During irradiation with blue light (intensity, 13 mW cm^{-2}), the reflection band of BP II was observed to shift continuously to longer wavelengths (from 470 nm to 520 nm), until a phase transformation to BP I occurred. On further exposure to blue light, the reflection band of BP I continuously shifted to longer wavelengths (up to 630 nm). After 15 s of irradiation, the reflection band of BP I no longer shifted; rather, it remained constant at 630 nm. Although natural thermal relaxation from BP I to BP II took a few hours, it could be accelerated by irradiation with 532 nm light (intensity, 24 mW cm^{-2}). Increasing the concentration of the light-driven chiral switch in the mixture from 1.7% to 3.5% broadened the optical tuning range of the photonic bandgap from 470–630 nm to 420–710 nm.

NORIAKI HORIUCHI

LASER PHYSICS

Turbulent times

Researchers show that the breakdown of temporal coherence in a fibre laser has strong similarities with the onset of turbulence in fluids. Establishing a conceptual connection between these different systems can offer new perspectives for both fields.

Fatih Ömer Ilday

To observe the transition between laminar and turbulent flow, it is only necessary to go to the kitchen sink and watch how the water flow changes as the tap is increasingly opened. Yet, despite the pervasiveness of turbulence and its long research history (dating back to Reynolds' pioneering work in the 1880s[1]), the seemingly straightforward question of under exactly what conditions turbulence develops has eluded a precise answer. Indeed, the famous and brilliant physicist Richard Feynman described turbulence as "the most important unsolved problem of classical physics" half a century ago[2].

Writing in *Nature Photonics*, Elena Turitsyna and co-workers[3] describe the laminar and turbulent regimes of fibre laser operation, which resemble the equivalent regimes in fluid flow in a pipe, and identify a new mechanism that plays an important role in the transition to turbulence. In particular, they show that during the transition, dark and grey solitons proliferate, form clusters and repeatedly interact with each other, eventually destroying the temporal coherence of the laser. This mechanism appears to be similar to a recently uncovered mechanism in fluid dynamics in which clustering of spatially localized pockets of chaotic flow, known as 'puffs', are thought to be responsible for the onset of fluid turbulence in pipes[4].

The identification of analogous dynamics in lasers and fluids is more than just a scientific curiosity — laser dynamics potentially represents a convenient experimental platform for studying fundamental questions in turbulence. One example of how analogous

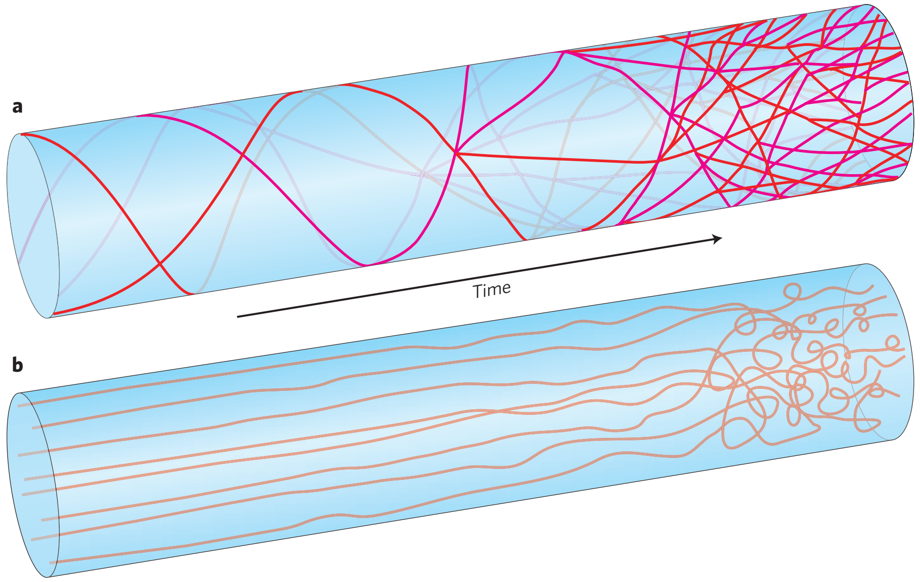

Figure 1 | Depictions of the transition from laminar to turbulent regimes in fluid flow and laser operation. **a**, Temporal behaviour in a fibre laser where dark and grey solitons proliferate, interact and break down the coherence. **b**, Fluid flow in a straight pipe.

systems can provide new insights into related phenomena is the study of rogue waves in optics, which has enhanced our understanding of rogue waves in the oceans[5]. Analogies between different physical systems tend to offer valuable insights because they can help identify the few, critical commonalities that are essential to a process; the numerous differences that exist between the systems are actually superfluous to the process.

In photonics, coherence and the behaviour of noise and fluctuations are extremely important for a broad range of phenomena, including spectroscopy, frequency metrology and the manipulation of matter by light. Fluctuations play a crucial role in the loss of coherence in extremely nonlinear processes, such as filament[6] and supercontinuum[7] generation. They also trigger the onset of mode locking in a laser[8], which is a more coherent state than the high-entropy, multimodal continuous-wave state that precedes it. It is also worth noting that the Reynolds number, a key parameter for characterizing fluid dynamics, is a dimensionless quantity and thus an expression of scale-free (or self-similar) dynamics — an important phenomenon in various areas of photonics[9], including fibre lasers[10].

Fluid flow is laminar when viscous forces far exceed inertial forces. This condition holds in small-diameter channels (as used in microfluidics), because the low mass transport in these channels greatly reduces the inertial forces. Fluid flow becomes turbulent at high flow rates and in wide channels (that is, at high Reynolds numbers).

In their experiments, Turitsyna *et al.* used a continuous-wave Raman fibre laser consisting of a length of normal-dispersion fibre. As the dispersion is normal, increasing the nonlinearity leads to the formation of grey and dark solitons on a continuous-wave background. The use of a normal-dispersion fibre ensures that the dynamics are not subjected to modulation instability, rendering coherent continuous-wave operation stable against small perturbations. Pockets of turbulence develop, but they rapidly decay, resulting in the restoration of laminar flow; this is similar to transient turbulence in fluids. One consequence of this is that linearized stability analysis, which involves writing the solution as the sum of the continuous-wave solution (in the case of a laser) or the laminar solution (for a fluid) and fluctuating perturbations, is not applicable.

At low output powers, Turitsyna and colleagues experimentally observed high-coherence operation of the laser, which had a much narrower spectrum than the spontaneous emission that preceded the onset of lasing. As the output power increased, a transition occurred to a much less coherent (broader spectrum) operation. The researchers regard the high-coherence behaviour as analogous to laminar fluid flow and the low-coherence operation as analogous to turbulent fluid flow. The competition between viscosity and inertia that is a characteristic of fluid flow is replicated in the laser system by the competition between dispersive broadening and soliton-like dynamics arising from the interplay between nonlinear (four-wave mixing) and dispersive effects. In pipe flows, new puffs are created via mitosis (cell division) like behaviour, while previously formed puffs decay. Turbulence becomes sustained when the creation rate of puffs exceeds their decay rate[4]. In a fibre laser, grey solitons are created from fluctuations in the continuous-wave background resulting from nonlinearity, whereas dispersion drives their decay. Thus, in multiple aspects, laser operation and fluid flow are qualitatively remarkably similar.

There are, however, major differences between laser dynamics and fluid flow in a pipe. The evolution of the optical field in a laser can be described as a flow in the two-dimensional space defined by the position in the cavity and time. As the laser cavity imposes periodicity, the corresponding flow is along an infinitely long cylindrical surface. The evolution of a localized structure, such as a grey soliton, roughly corresponds to a helical trajectory whose slope is proportional to its velocity (Fig. 1a). This is important, because helical trajectories with different slopes can, and do, intersect multiple times, transferring energy and apparently amplifying the fluctuations. There is no analogous periodicity associated with fluid flow in a simple pipe (Fig. 1b), as the edges of the pipe are hard boundaries.

Turitsyna *et al.* numerically modelled the laser system, and were able to replicate the transition from laminar to turbulent flow. Their model showed that more solitons are generated as the pump power is increased. Because these solitons have slightly different velocities, they repeatedly intersect each other and undergo wave breaking as they propagate in the cavity. This occurs until one or several solitons become chaotic, causing the entire system to become turbulent. This progression is beautifully illustrated in the Supplementary Movie accompanying the Letter by Turitsyna *et al.* They point out that the spatial breakdown of coherence is the leading effect in this dynamics. Interestingly, this is reminiscent of the observations of the spatial onset of turbulence in fluids[4], and goes against the traditional expectation of temporal complexity leading to turbulence[11]. The solitons can repeatedly interact with each other because of the periodicity of the laser cavity, which has no natural counterpart in conventional fluid flow in a pipe.

However, as the researchers note, Taylor–Couette flow[12] might, in principle, enable repeated interactions between travelling puffs because of its periodic geometry. Taylor–Couette flow occurs between two concentric, infinitely long cylinders, and is driven by the motion of either cylinder. In fact, Taylor developed a beautiful theory that relates the onset of instability to a single non-dimensional parameter known as the Taylor number. Attempting a similar analysis for turbulence in the laser might be the next logical step.

The state of the laser was experimentally monitored using a high-speed oscilloscope with a temporal resolution of ~12 ps. Unfortunately, the temporal width of the solitons is typically shorter than this measurement resolution, precluding direct experimental observation of their evolution. A future task is to find a way to observe the onset with a much higher temporal resolution. In this context, a continuous-wave laser is disadvantageous as its spectrum is too narrow to exhibit significant dispersion, rendering dispersive broadening a nonviable option. A mode-locked laser would be a potential candidate should similar dynamics be identified in such a system. We believe this to be likely, particularly in a cavity that generates soliton rain[13]. We thus recommend re-examining the approach first outlined by Gordon and Fischer[8] in light of the new perspective offered by Turitsyna *et al.*

It remains to be seen whether these interesting, albeit preliminary, connections between the fluctuation dynamics of a fibre laser and fluid flow will pave the way for a fresh look at turbulence in fluid dynamics. But irrespective of this, the insights into laser behaviour are valuable in their own right. One cannot help but wonder how, through analysing and controlling fluctuations in a laser, photonics will contribute to our understanding of fluid dynamics. Conversely, theoretical and experimental techniques used in fluid dynamics may present new opportunities for preventing, controlling and even manipulating turbulence in optical systems. In addition to the motivations from a fundamental perspective, the importance of preserving a narrow linewidth in very high-power fibre lasers for coherent beam combination provides a strong practical motivation for further exploring the correlations between fluid flow and laser dynamics. ❐

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STRETCHABLE LEDS

Light-emitting electronic skin

Flexible electronics and optoelectronics have potential applications in energy generation, biomedicine, robotics and displays. Two recent demonstrations of highly stretchable polymer LEDs suggest that commercial devices may soon become viable.

Michael Vosgueritchian, Jeffrey B.-H. Tok and Zhenan Bao

The development of flexible and stretchable electronics and optoelectronics has been attracting increasing interest in recent years. Electronic devices fabricated on human-skin-like substrates are often referred to as electronic skins. They can offer functions such as chemical and biological sensing, and be fabricated to be biocompatible, biodegradable and self-powered[1–3]. The development of stretchable light-emitting diodes (LEDs) that suit integration with electronic skins is exciting because such LEDs can potentially be used to realize visual readout of sensing data or generate a display directly on artificial skin itself.

In the fabrication of stretchable electronics, it is important for devices to be mechanically compliant and be able to flex and stretch without incurring physical damage. Traditional inorganic electronic materials are normally too brittle to be used in stretchable electronics.

In recent years, John Rogers' research group at the University of Illinois in the USA has produced stretchable devices by transferring very thin inorganic LEDs with an AlInGaP active layer to flexible substrates and then fabricating specially designed interconnects[4]. However, the limited processing area and high cost of lithography makes it difficult to produce inexpensive, large-area devices. In contrast, LEDs composed of organic polymers and molecules are particularly attractive because they can be deposited by low-cost, scalable deposition methods (such as roll-to-roll processing), and intrinsically flexible or stretchable materials can be used[2,5].

Now, in *Nature Photonics,* two independent research groups report important advances in the fabrication of stretchable polymer LEDs (PLEDs) using simple and low-cost processes[6,7]. Because of their relatively simple structures, ease of fabrication and market potential, PLEDs may be the first optoelectronic devices to attain stretchability in commercial applications. Previously, there have been excellent demonstrations of flexible PLEDs, including the fabrication of highly flexible and monolithically integrated active-matrix organic LEDs[8]. However, true stretchability is more demanding than flexibility — flexible devices need to withstand strains of only a few percent, whereas stretchable devices need to be able to accommodate strains of over 10%. The realization of stretchable LEDs will not only permit significantly more durable devices to be fabricated, it will also enable conformal bonding to arbitrary non-planar surfaces and moving parts, which will be useful for applications in robotics, textiles and medical devices and for integration into electronic-skin applications[1,3].

Previously, Sekitani *et al.*[9] realized stretchable PLEDs composed of carbon-nanotube electrodes dispersed in an elastic fluorinated copolymer. They used