The results reported by Hamel *et al.*[5] provide interesting insights into the behaviour of bifurcations. In particular, it is well known from theoretical studies that the SSB bifurcations feature two generic forms, as shown in Fig. 2. These forms are super- and subcritical ones, alias forward and backward bifurcations (which are tantamount, respectively, to the phase transitions of the second and first kind in statistical physics). The subcritical bifurcation features bistability of the symmetric and asymmetric states in a narrow region of the power, *N*, below the critical point. A supercritical bifurcation may be transformed into a subcritical one by a change of the underlying nonlinearity (for example, by a transition from self-focusing to a combined focusing-defocusing nonlinearity).

However, a more relevant option for the expansion of the studies of the SSB phenomenology is to extend the effectively zero-dimensional dual-cavity setting (with each cavity treated as a single quantum dot) to the one-dimensional geometry, in which the two cavities embedded into the photonic crystal are elongated, in the form of parallel stripes devoid of holes, thus establishing a transverse direction, and adding transverse-diffraction terms to the underlying system of coupled CGLEs[11].

In this new geometry, it is predicted that various species of two-component solitons, coupled by super- and subcritical SSB bifurcations, should exist[11]. The creation and experimental observation of such solitons is the next experimental challenge for research in the area. Beyond the framework of photonics, it would be very interesting to see the SSB experimentally realized in a BEC trapped in a dual-core cigar-shaped configuration, as an extension of the single-cigar set-up where matter-wave solitons have been created[12]. ❐

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NONLINEAR OPTICS

Nonlinear virtues of multimode fibre

The finding that multimode optical fibres support a rich and complex mix of spatial and temporal nonlinear phenomena could yield a plethora of promising applications.

Antonio Picozzi, Guy Millot and Stefan Wabnitz

Supercontinuum generation — the extreme spectral broadening of laser light (a span from the ultraviolet to the mid-infrared is possible) — is a fascinating process that takes place in a dispersive and strongly nonlinear optical medium. For example, a supercontinuum can be created by the propagation of intense ultrashort pulses in a short section of glass, or less powerful pulses in a long optical fibre[1]. High spectral brightness supercontinuum light sources have widespread applications, including use in optical metrology, environmental and biomedical spectroscopy, medical imaging, gas sensing and communications.

This growing list of applications is fuelling intense development of such sources of broadband coherent radiation. Indeed, a resurgence of interest in supercontinuum studies has followed the development of photonic crystal fibres (PCFs)[2]. PCFs are highly beneficial for nonlinear experiments as they can be engineered to have a reduced core size, which substantially increases the beam intensity, and the fibre's dispersion profile can be tailored to match virtually any pump laser source.

Supercontinuua generated in a single-mode optical fibre have superior beam quality with respect to bulk media. However, single-mode fibres have an inherent major drawback, which is the relatively low energy (typically less than 20 μJ) that can be collected at their output due to their micrometre-scale core size. Thus, supercontinuum sources based on single mode fibres are of limited use for applications that require high-energy sources, such as airborne remote sensing.

Now, as they report in *Nature Photonics*, Logan Wright and co-workers[3] provide the first demonstration of an alternative, all-fibre route to the development of high-energy supercontinuum light sources based on spatiotemporal nonlinear effects in a multimode fibre. Indeed, since the advent of fibre amplifiers, the power of fibre lasers has been increasing significantly, up to megawatt peak values for lasers that operate in the pulsed regime. These developments require fibres with larger mode areas that can guide higher injected pump powers. As it is increasingly difficult to meet such requirements with conventional single mode fibres, it is natural to replace them with multimode fibres for high-power applications.

From a fundamental viewpoint, the experiments of Wright *et al.*[3] involve a range of remarkable nonlinear effects whose complexity requires a much deeper understanding of spatiotemporal nonlinear pulse propagation in multimode fibres. A variety of applications will also likely benefit from the development of novel high-energy, short-pulse broadband and versatile fibre sources, inspired by the results described by Wright and colleagues[3].

The findings may also help to improve optical signal processing techniques for spatial division multiplexing, whereby the individual modes of a multimode fibre are exploited to define separate spatial channels for information transmission[4]. In addition, the observations by Wright *et al.*[3] reveal that multimode fibres can easily be used to generate intense mid-infrared radiation in a conceptually simple experimental arrangement — a feature of great interest for many sensing and spectroscopy applications, as most molecules display fundamental vibrational absorptions in this domain.

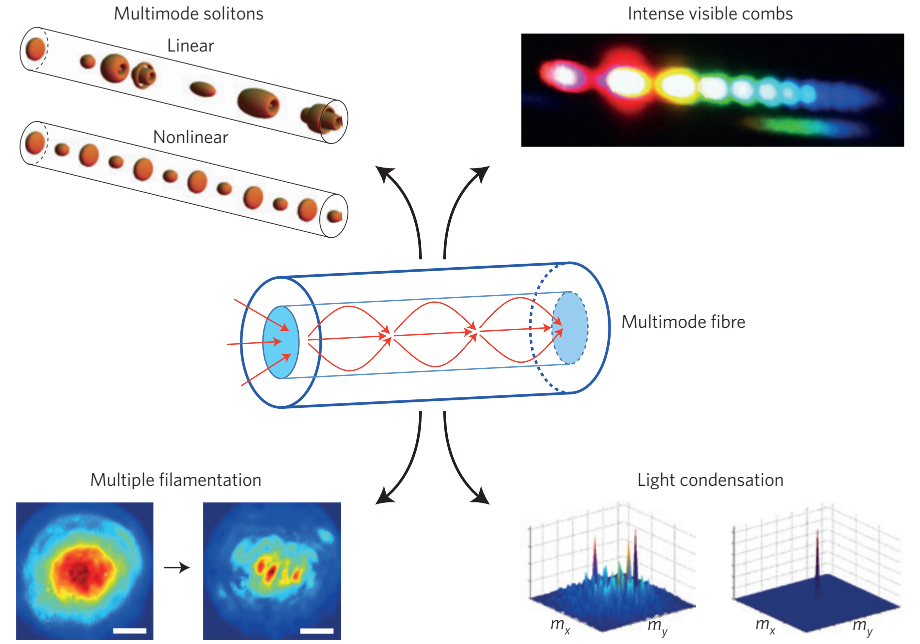

Figure 1 | Conventional multimode optical fibres constitute ideal testbeds for the study of complex spatiotemporal nonlinear optical phenomena. The phenomena that can be tested include multi-octave-spanning supercontinuum generation involving intense visible frequency combs (top right), multiple filamentation processes (bottom left; the scale bars are 17 micrometres), optical pulse propagation in the linear regime where the spatial modes separate and lead to pulse deformation, and in the nonlinear regime where multimode solitons form (top left), and light condensation into the fundamental mode of the fibre resulting from natural optical wave thermalization to equilibrium (bottom right). The top left image is reproduced from ref. 7, NPG; the top right and bottom left images are reproduced from ref. 3, NPG; and the bottom right image is reproduced from ref. 11, Elsevier.

To properly appreciate the physics underlying the numerous nonlinear phenomena reported by Wright *et al.*[3], it is convenient to briefly introduce the important concept of the multimode soliton (MMS). Conventional single-mode optical solitons are known to play a key role in understanding the purely one-dimensional temporal dynamics of pulse propagation in single-mode fibres in applications including, for example, soliton communication, supercontinuum generation or mode-locked lasers[1,5].

Along the same lines, MMSs may provide a natural platform for understanding the three-dimensional spacetime dynamics of pulses in multimode nonlinear optical fibres. In essence, an MMS is a soliton with multiple components, self-consistently coupled together by fibre nonlinearity, so as to maintain its shape during propagation. In this respect, it is important to comment on a main drawback inherent to pulse propagation in multimode fibres, namely the effect of modal dispersion. This effect can be interpreted from a simple optical ray approach: rays that enter with a shallower angle travel by a more direct path and arrive sooner than rays that enter at a steeper angle. As a result of modal dispersion, an optical pulse composed of several modes temporally broadens during propagation — an unwanted characteristic that can be circumvented with an MMS.

To recap, solitons are localized waves that arise from a balance of linear dispersion and nonlinear phase modulation: processes that, each individually in isolation, would lead to a decay of the wave. In a multimode fibre, because of modal dispersion one would expect that each individual single-mode soliton associated with a different mode would propagate with its own group velocity, thus leading to a spreading of a multimode optical signal. However, thanks to the nonlinear spatiotemporal coupling among the modes in the fibre, this isn't actually the case, and an attractive force between the individual solitons binds them together to form a single entity, the MMS (Fig. 1, top left). In this way, multimode fibres constitute an ideal testbed for studying MMSs and, from a broader perspective, spatiotemporal solitons or 'light bullets'[6].

It is surprising to note that, although the concept and potential impact of soliton formation in multimode fibres has been known for a long time[5], experiments aimed at revealing the existence of MMSs have only been reported recently by Frank Wise and his group[3,7]. In their latest work in *Nature Photonics*, Wright *et al.*[3] provide experimental evidence of the multimode spacetime nature of several important phenomena related to those commonly observed in single-mode fibres[5]. For instance, they recognize the fundamental role of the Raman effect, which is shown to cause a continuous redshift of the mean frequency of the MMS as it propagates through the multimode fibre. Another fundamental mechanism that is known to play a key role in supercontinuum generation in single-mode fibres is the process of dispersive wave emission[1,5], which can be interpreted in analogy with Cherenkov radiation in electrodynamics. The experiments by Wright *et al.*[3] indicate the existence of resonant couplings among MMSs and linear dispersive waves induced by higher-order dispersion effects, thus leading to the emission of multimode dispersive waves.

The observations reported by Wright *et al.*[3] also reveal the formation of broad multi-octave supercontinuum spectra, which are characterized by the presence of a series of sharp spectral peaks in both the mid-infrared and visible regions — see the intense visible combs in Fig. 1, top right. Although the mechanism underlying the formation of such 'mystery' spectral peaks is not yet well understood, simulations reveal that they seem to originate at the point where spatiotemporal compression of a multimode optical pulse occurs, right before its fission into a series of MMSs. The multimode nature of the peaks is confirmed by simulations showing they are much reduced when only the fundamental mode is excited, or when higher-order modes are neglected. It is interesting that both in the experiments and in simulations there is an irregular frequency spacing among the spectral peaks, in analogy with the quasi-phase-matched four-wave mixing that occurs in dispersion-oscillating optical fibres[8]. Moreover, simulations reveal that third-order dispersion has a dramatic influence in narrowing both the frequency spacing and the width of the peaks, and simultaneously increasing their number.

The results of Wright *et al.*[3] also reveal phenomena that exhibit a strong resemblance with self-focusing and multiple filamentation processes[9], which are typically reported with powerful optical beams in two- or three-dimensional systems. Such a multimode filamentation is characterized by a narrowing and subsequent fragmentation of the transverse surface section of the multimode pulse as it propagates in the multimode fibre (Fig. 1, bottom left). As suggested by the authors, this phenomenon can be ascribed to a Raman beam clean-up effect[3]. However, a recent work reported a similar scenario, in the absence of the Raman effect, involving the interaction of MMSs in multimode fibres[10]. In this latter study, the authors revealed a remarkable process in which, as a general rule, a transfer of power takes place from the higher-order modes towards the fundamental mode of the fibre.

It is interesting to note that such an irreversible transfer of power from higher-order modes towards the fundamental mode can have a purely thermodynamic origin, in the sense that it is thermodynamically advantageous for the optical beam to transfer its power into the fundamental mode of the system to increase the amount of entropy (disorder) in the system (see Fig. 1, bottom right, where m_x and m_y denote the mode numbers). This phenomenon is known as condensation of classical waves[11]. It originates from the natural thermalization of the multimode beam towards a generalized Rayleigh–Jeans equilibrium distribution, whose divergence entails the macroscopic occupation of the fundamental mode of the fibre, whereas higher-order modes exhibit an energy equipartition. From a broader perspective, multimode fibres can be exploited to study a variety of phenomena in physics such as optical turbulence, whose possible regimes are enriched by the intricate mix of spatial and temporal effects. Besides multimode incoherent solitons, the spatiotemporal dynamics can be described by different formalisms inherited from weak Langmuir turbulence in plasma, or the long-range Vlasov formalism relevant to the description of gravitational effects, such as the dynamics of spontaneous formation and interaction of galaxies in the Universe[11]. ❐

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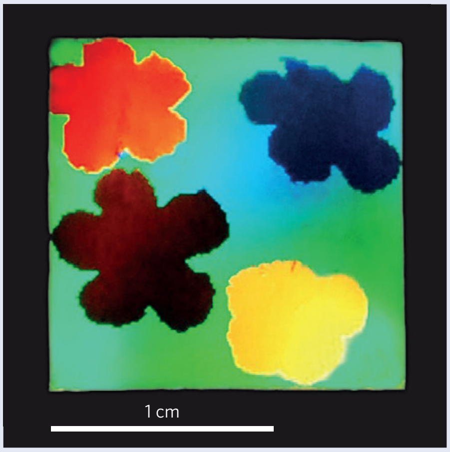
DIFFRACTIVE OPTICS

Tuning colour in flexible silicon

Agile control of the perceived colour of objects is desired for many applications such as sensing and displays. Although it can be achieved by the interference from multiple layers of materials with different refractive indices, a solution that avoids the use of thick structures and different thicknesses for different colours, while having multiple colours tunable on the same flat surface, is highly sought after.

Now, Li Zhu and co-workers from the University of California Berkeley in the USA have experimentally demonstrated brilliant colours tunable from green to orange on a silicon thin film embedded in a flexible membrane (*Optica* **2,** 255–258; 2015). The results are attractive for flexible optics applications.

Their approach was based on the design of high-contrast metastructures (HCMs), which are periodic structures made of a single-layer high-refractive-index material fully surrounded by low-index material, with a periodicity of nearly one wavelength. Their metastructures consist of an array of pixels embedded in a transparent, flexible polydimethylsiloxane membrane. Each pixel is composed of ribbons of silicon thin film, with a thickness of around one to two thousandths the thickness of a dollar bill. Unlike conventional approaches, the team used the same ribbon thickness and only changed the width of ribbon for different colours, making it easy to display a wide range of colours on the same flat surface. They also designed the period for the structure so that it is very close to the wavelength of visible light, and such that only two diffraction orders are allowed (the 0th and –1st) for both reflection and transmission.



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The team explained that due to a large refractive index contrast between the ribbons and their surrounding medium, an interference effect is introduced on the optical wave reflected by the surface. The interference effect is very power-efficient due to the index contrast, leading to vivid colour determined by the spacing and width of the ribbons. Changing the spacing between the ribbons, by means of stretching the membrane, changes the wavelength at which strong constructive interference occurs, hence changing the colour of the surface.

"By carefully designing the structure dimension, it is possible for the interference of the eigenmodes to constructively enhance one particular diffraction order while destructively cancelling out the other orders. Because of the large refractive index contrast, this effect can be very broadband," said Connie Chang-Hasnain.

The researchers achieved 83% diffraction efficiency for the –1st reflection order. The colour of the sample can be tuned from green to orange — a 39 nm change in wavelength from 541 to 580 nm — by stretching the sample with only a 5% deformation, which corresponds to only a 25 nm change of the HCM period. They also demonstrated laser beam steering with more than 36 resolvable beam spots using the same effect, and they showed that the incident laser beam can be steered to more than a 5% deformation without beam width degradation.

"We will improve the design with two-dimensional structures to make it insensitive to diffraction polarization and to mitigate any bending issues in the structures. We also plan to use such mechanically sensitive material for bio-imaging and bio-labelling applications," Chang-Hasnain told *Nature Photonics*.

RACHEL WON