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OPTICAL PHYSICS

One ring to multiplex them all

High-speed communication systems that use optical fibres often require hundreds of lasers. An approach that replaces these lasers with a single, ring-shaped optical device offers many technical advantages. SEE LETTER P.274

VICTOR TORRES-COMPANY

Optical-fibre communication systems form the backbone of the Internet. Current systems rely on a technology called wavelength-division multiplexing to transmit digital information at high speeds. On the transmitter side, this technology combines (multiplexes) many optical channels into a single optical fibre. Each channel uses a laser of a different frequency, and hundreds of lasers are typically needed to occupy the bandwidth available in a fibre-optic link. On page 274, Marin-Palomo *et al.*[1] demonstrate that all of these lasers can be replaced by a single light source known as a microresonator frequency comb — a development that could lead to extremely fast data transmission.

A microresonator frequency comb is an optical device that allows light of many optical frequencies to be generated in a micrometre-scale platform (Fig. 1). Tobias Kippenberg, one of the current paper's co-authors, helped to pioneer this technology about a decade ago[2]. The device essentially consists of a light source, called a pump laser, and a microresonator — a set-up also known as an optical cavity, which is used to trap light at certain 'resonance' frequencies. The frequency of the pump laser is closely tuned to a particular resonance of the cavity, and for microscale low-loss cavities, the light is highly confined. The authors made their cavity from a nonlinear material, which allowed the photons from the pump laser to be converted into photons of different frequencies[2].

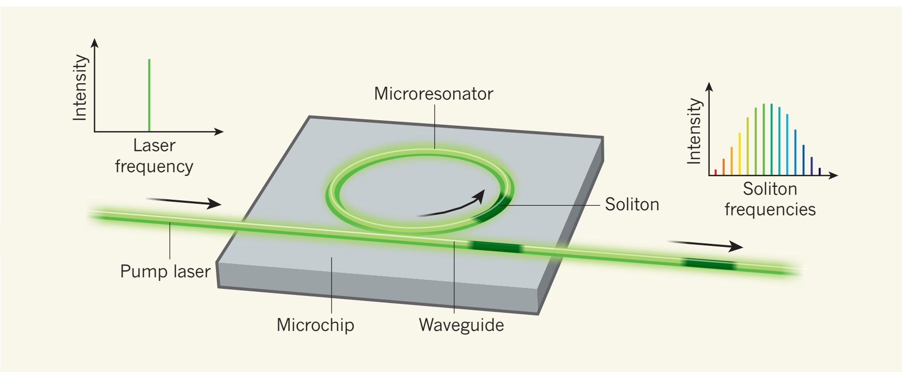

Figure 1 | Optical-fibre communications using a single laser. Marin-Palomo *et al.*[1] report a light source for simplifying data transmission through an optical fibre. Their device consists of a microchip containing a ring-shaped optical system called a microresonator and a waveguide — a structure that directs the propagation of light. The microresonator confines light at certain frequencies known as resonances. By tuning the frequency of a 'pump' laser to one of these resonances, the authors show that a sequence of short optical pulses called solitons can be produced. The optical spectrum of these solitons is a set of evenly spaced frequency lines, each of which can be used for an individual optical channel carrying an independent data stream. The authors control the number of channels by precisely engineering the dimensions of the microresonator, enabling them to generate more than 90 frequency lines from a single device. The quality of these signals is sufficiently high to achieve a data-transmission speed of more than 50 terabits per second (1 terabit is 10^{12} bits). The black arrows indicate the direction of light propagation.

Under the right conditions, the new optical frequencies are phase-locked. This means that at certain times there is constructive interference between all the frequencies (the crests and troughs of the light waves reinforce each other), leading to a substantial build-up of optical power inside the cavity. The resulting waveform consists of a sequence of pulses known as dissipative Kerr solitons. The formation of these solitons in an optical cavity requires a fine balance between the properties of the cavity and the pulses themselves[3].

Although Marin-Palomo *et al.* are not the first to observe dissipative Kerr solitons in optical cavities[4], they are the first to use these light sources for optical communications. The authors manufactured their optical cavity using advanced microlithographic techniques. The cavity consists of a microresonator arranged in a ring-like structure (with a radius of 240 micrometres) that is made of silicon nitride, a widely used thermal insulator in the electronics industry. The authors carefully engineered the cavity's geometry to enable the generation of more than 90 optical frequencies from a single pump laser. These frequencies entirely cover two of the bands used for optical-fibre communications (the C- and L-bands), corresponding to a bandwidth of approximately 10 terahertz (1 THz is 10^{12} Hz). The authors can control the frequency spacing between the channels with a precision of approximately 200 kHz — a feature that, besides its uses in optical-fibre communications, offers prospects for molecular spectroscopy[5].

Marin-Palomo and collaborators report a series of impressive system-level demonstrations, whereby the individual channels are multiplexed to yield a data-transmission rate of more than 50 terabits per second. The current transmission-speed record[6] is 2,150 terabits per second, but involves a special type of optical fibre and a different kind of laser frequency comb. The key aspect of the authors' microresonator comb is that it achieves an astonishing performance in a microscale platform. With recent developments in 3D photonic integrated circuits[7], one can start to dream about combining all of the necessary optoelectronic components of a comb-based wavelength-division-multiplexing system, as required for practical applications.

One concern when generating many frequency components from a single laser is the amount of power that can be obtained per channel. A fundamental drawback with dissipative Kerr solitons is that they have unfavourable power-conversion efficiencies[8]. In the case of Marin-Palomo and colleagues' system, less than 1% of the laser pump's power is transferred to the newly generated frequencies. There are alternative microresonator combs that have much higher power-conversion efficiencies[9], but they have not yet been investigated in the context of optical-fibre communications. Increasing the efficiency of microresonator combs will be essential for future optical-fibre communication systems, which will use a special type of fibre containing multiple spatial channels to achieve unprecedented transmission speeds[6].

Marin-Palomo *et al.* have clearly demonstrated that dissipative Kerr solitons can be used for wavelength-division multiplexing. Using a light source that has phase-locked frequencies represents a fundamental difference from an array of individual lasers because the frequency spacing between channels is fixed. This aspect might be the key to mitigating transmission impairments[10] or drastically simplifying the way signals are received. In this respect, the use of laser frequency combs (be it in the form of dissipative Kerr solitons or something else) constitutes a pivotal change in the design of optical-fibre communication systems. Exploiting their unique properties will require a collaborative effort between the disciplines of photonic integration, fibre optics, ultrafast optics, computer engineering, information theory and signal processing. ■

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NEURODEGENERATIVE DISEASE

RNA repeats put a freeze on cells

Droplet-like assemblies of RNA in cell nuclei are associated with certain neurodegenerative diseases. Experiments reveal that these assemblies become 'frozen' gels in cells, potentially explaining their toxicity. SEE ARTICLE P.243

DAVID W. SANDERS
& CLIFFORD P. BRANGWYNNE

Many inherited neurodegenerative diseases are associated with nucleotide-repeat expansions, in which a normal tract of DNA that has a repetitive nucleotide sequence expands to many times its original size. When this occurs in non-coding regions (introns), it results in the formation of repetitive RNA sequences that are not translated to make proteins. An explanation for the toxicity of these RNA expansions has remained elusive, but a potential clue lies in the observation that such RNAs form spherical clusters called RNA foci in cell nuclei[1]. Jain and Vale[2] report on page 243 that RNA repeats can undergo a phase transition to form either a condensed liquid or a gel-like state. Such 'frozen' RNA foci might contribute to neuronal dysfunction.

RNA and proteins can condense into dynamic organelles, in much the same way that water vapour condenses to form droplets at the dew point. This behaviour is known as liquid–liquid phase separation (LLPS) and forms the basis of an emerging hypothesis of intracellular organization[3,4]. Unlike most organelles, the cellular compartments formed by RNA and proteins lack a phospholipid bilayer, and arise from repetitive, weak interactions between their resident molecules. Many proteins associated with the neurodegenerative disease amyotrophic lateral sclerosis (ALS) are prone to undergo LLPS *in vitro*, and disease-associated mutations in these proteins may trigger further conversion of the resulting dynamic liquid to a gel[5], a process similar to the setting of a gelatin dessert.

Jain and Vale wanted to test whether such phase transitions might also take place with RNA alone. They first performed *in vitro* experiments with purified RNA, focusing on poly-CUG (an RNA consisting of repeats of the CUG nucleotide sequence, which are associated with the disease myotonic dystrophy), poly-CAG (which is associated with Huntington's disease) and poly-G4C2 (which consists of GGGGCC repeats and is implicated in a form of ALS known as C9ORF72-associated ALS). The authors observed that each of these RNAs undergoes LLPS at nanomolar concentrations, resulting in spherical assemblies

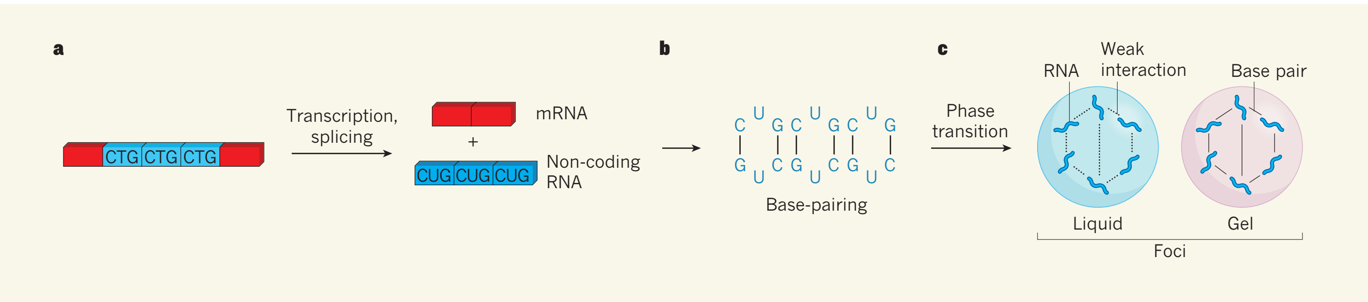

Figure 1 | Foci formation. a, Nucleotide-repeat expansions occur when a section of DNA that has a repetitive nucleotide sequence (here, repeats of CTG) expands to many times its original size. When expansions occur in the non-coding regions (blue) of genes, transcription and processing (splicing) of the nascent transcript generates non-coding RNAs that have repetitive sequences (here, CUG), in addition to messenger RNAs. Coding regions of the gene are shown in red. **b**, **c**, Jain and Vale[2] present evidence suggesting that complementary pairing of bases between non-coding RNA molecules (**b**) might trigger RNA assembly processes, driving an RNA phase transition (**c**) from a diffuse form to a dynamic liquid state, or to a gel in which molecules are 'frozen' into position. These results provide a biophysical foundation for the formation of RNA foci — spherical clusters of RNA molecules in cell nuclei that are characteristic of diseases associated with certain nucleotide-repeat expansions.