RANDOM LASERS

An incoherent fibre laser

The demonstration of a 'mirrorless' ultralong Raman fibre laser that provides stable, spatially incoherent continuous-wave lasing may prove to be an important new light source for applications in nonlinear optics, sensing and telecommunications.

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Conventional lasers consist of a resonant cavity containing an amplifying optical medium such as a gas, dye or doped crystal (Fig. 1a). In such lasers, stimulated emission is spatially coherent, and the frequencies of operation — commonly called longitudinal modes — are determined by the resonator's eigenmodes. In 1966, Ambartsumyan *et al.* proposed a new laser, now known to be a type of random laser, in which non-resonant feedback occurs by reflecting photons from a phase-scrambling medium instead of a rear laser mirror[1]. In such a laser the amplified photons scatter multiple times and do not return to their initial location periodically, making it impossible to form a spatial resonance (Fig. 1b). The feedback in the laser is therefore used only to return part of the energy back to the active laser medium, without any selection of the resonant waves (modes). In principle, the emission of such a laser has no spatial coherence and is undefined in phase. The absence of resonant feedback means that the spectrum of the generated laser emission should be continuous; that is, without discrete modes at certain resonant frequencies. In practice, however, such random lasers commonly generate narrow stochastic spikes on top of the laser emission spectrum. It is thought that such behaviour results from residual resonances that occur due to incomplete cavity mode mixing and particular inhomogeneous effects in the random-laser materials[2].

Now, writing in *Nature Photonics*[3], Sergei Turitsyn *et al.* report an important breakthrough in this research area — the demonstration of stable continuous-wave (CW) lasing in a standard telecommunications fibre using only Raman amplification and Rayleigh distributed feedback, without any additional reflectors (Fig. 1c). The laser has strongly suppressed self-pulsations and is free from random optical spectrum switching.

The use of a long (~83 km) length of fibre and the complete absence of end mirrors makes this laser very different from any previously considered systems. The only resonant element in the laser is the Raman amplification line provided by the pumped optical fibre. As the pump power increases, the oscillation narrows continuously towards two pronounced peaks in the Raman amplification line, yielding efficient lasing that is both spectrally and temporally uniform.

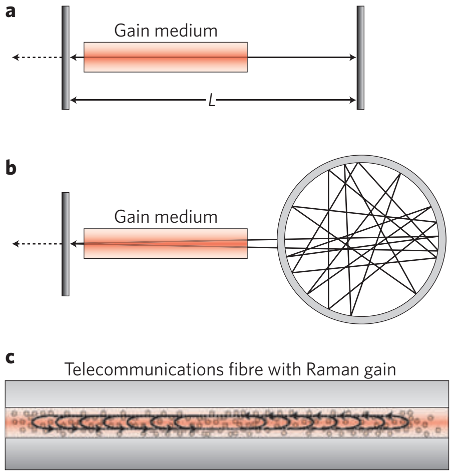

Figure 1 | Examples of laser cavities. **a**, Conventional Fabry–Pérot cavity with two end mirrors, providing laser operation with well-defined equally spaced longitudinal modes. **b**, Non-resonance feedback[1]. **c**, The ultralong Raman–Rayleigh[3] cavity of Turitsyn *et al.*

The work disproves the widely accepted opinion that fibre lasers with distributed Rayleigh mirrors must exhibit highly irregular stochastic behaviour resulting from uncontrollable nonlinear effects[4,5]. This is confirmed by the observation of laser pulsations at low powers — the near-threshold (unstable) operation regime — which makes an important connection between the work of Turitsyn *et al.* and previous studies into fibre lasers with distributed Rayleigh feedback that have explored similar pulsed regimes[4–8].

The physical mechanisms behind the ultralong Raman laser concept can be illustrated in terms of the cavity modes[1], while also taking into consideration some of the fundamental nonlinear properties of telecommunications fibres. First, note that the use of a high-quality telecommunications fibre in the laser cavity ensures uniform distribution of the refractive index irregularities ('frozen' Rayleigh reflectors) along the whole fibre. Second, the use of stimulated Raman scattering as a method of light amplification provides much better conditions for spectrally uniform lasing in an open laser cavity than in traditional solid-state laser media[2], as there is no gain heterogeneity and no spectral hole-burning. Because the Raman amplification itself does not introduce frequency changes to the amplified laser modes (Fig. 2a), in the first approximation the ultralong Raman laser can be considered as a linear coupling of many pumped Fabry–Pérot cavities. The loss of the laser resonance properties can be thought of as resulting from superimposing a large number of resonance curves for different modes that lie close to each other. However, for a linear system the resonant properties never disappear, and the resulting spectrum is always left with residual resonances that increase in magnitude and decrease in linewidth as a greater number of elementary cavities are superimposed (Fig. 2b, inset). Physically this means that among the photons with complex 'trajectories' captured in the cavity, there are some that return back to their initial locations more often than others. Therefore, when the Raman amplification starts to cancel out the fibre loss, these resonant photons reach lasing conditions first, leading to the generation of narrow stochastic components in the emission spectrum.

In turn, the generation of narrowband spectral components in the pumped laser cavity causes avalanche-like Brillouin instabilities. These were observed in the experiments of Turitsyn *et al.* at lower laser powers (the unstable regime) as multiple spikes in the spectral and temporal domain.

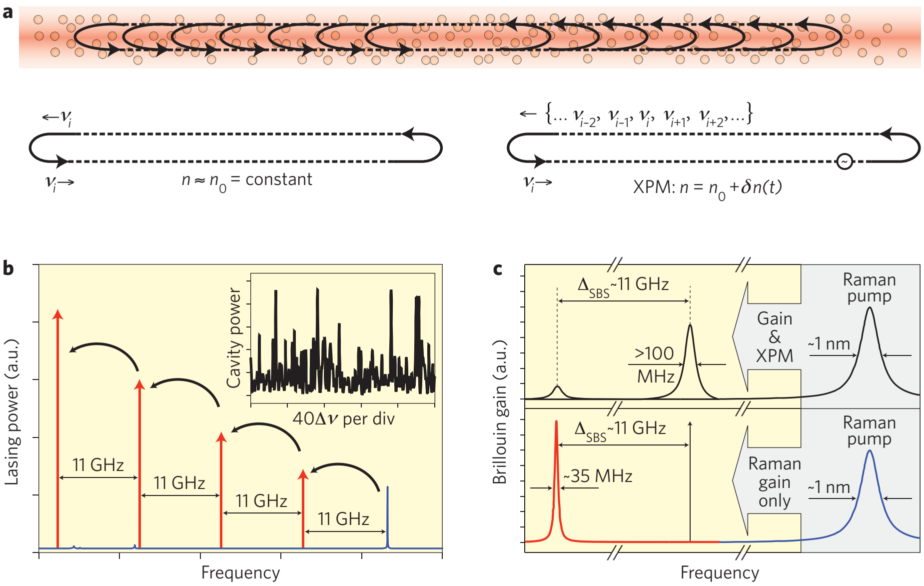

Figure 2 | Illustration of various laser operation mechanisms. **a**, Linear (left) and nonlinear (right) cavity mode mixing. Here, $\{\nu_i\}$ denote discrete resonance frequencies of the laser cavity with an unperturbed refractive index n_0. **b**, Brillouin instability. Inset, discrete resonance frequencies $\{\nu_i\}$. **c**, Suppression of the Brillouin instability by XPM. The temporal index perturbations $\delta n(t)$ are induced by the pump diode power through XPM[10].

Stimulated Brillouin scattering through the resonant interaction of light photons with acoustic phonons is similar to the Raman amplification process, with the difference being in their amplification abilities. For a monochromatic pump at 1,550 nm, the Brillouin gain factor is almost three orders of magnitude higher than the Raman gain, providing amplification with a bandwidth of ~35 MHz and a frequency down-shift of ~11 GHz from the pump frequency. The Brillouin instability is caused by a cascaded Brillouin process, as shown in Fig. 2b. Occasional lasing of a narrowband spectral component due to residual cavity resonance provokes additional Brillouin gain for down-shifted modes, which leads to their fast (exponential) growth[9]. During this cascade process, power from high-frequency components is transmitted to lower-frequency ones, providing a higher growth rate (and higher peak power) for the new frequency components, until the generation of short pulses by the final cascades exhausts the accrued cavity power. This process is typical for all fibre lasers that exploit distributed Rayleigh feedback[3–8].

As the pump power increases, the residual cavity coherence disappears and laser operation commences in a perfect CW mode. It is possible that some optical fibre nonlinearities arise in the fibre at moderate powers and provide deeper mode mixing, which affects the phases of the cavity modes. Indeed, if the frequency of a photon captured in the cavity can change due to certain nonlinear interactions inside the fibre exceeding the interval between modes, then the light field does not belong to any individual mode. This condition guarantees the complete absence of any small residual cavity resonances. Cross-phase modulation (XPM), in which one wavelength of light can change the phase of another through the optical Kerr effect, may be a reason for such a frequency perturbation in the laser cavity, owing to the interaction of the amplified photons with the intense laser diode radiation[10]. Furthermore, XPM is able to suppress the Brillouin instability as soon as the frequency broadening exceeds the Brillouin gain bandwidth (Fig. 2c). During the XPM process in a Raman amplifier, instantaneous intensity fluctuations of the pump diode (a result of its optical linewidth, which is typically ~1 nm) induces a modulation of the fibre refractive index, leading to phase fluctuation and spectral broadening of the co-propagating amplified field. The XPM process arising in an ultralong Raman laser cavity could switch the laser operation from an unstable to a stable regime. These regimes can therefore be interpreted as exploiting linear (without XPM) and nonlinear (with XPM) cavity mode mixing, respectively.

This work allows the design of robust all-fibre designs that can produce spatially incoherent CW radiation tunable throughout the entire transparency window of an optical fibre. However, many specific features of the ultralong fibre laser operation are still yet to be explored. The reported results and proposed concept may have a significant future impact in fibre-optics, including for nonlinear fibre optics, special fibre design, and Rayleigh and Brillouin fibre mirrors, and in the applications of fibre-optics, such as in fibre lasers, distributed fibre sensors and telecommunications. The impact may be particularly strong in applications where highly coherent laser emission is undesirable.

In both the temporal and spectral domains, the behaviour of the laser realized by Turitsyn *et al.* is similar to that of CW single-frequency lasers (but with much larger spectral width), which makes the nonlinear threshold in optical fibres much higher for this laser than for single-frequency sources. This may offer new opportunities — and probably new features — for nonlinear frequency conversion processes based on the Raman effect, four-wave mixing or supercontinuum generation in fibres. For example, powerful laser sources with a low relative intensity noise are in great demand for long-haul optical networks, where they serve as pumps with distributed Raman amplifiers. In summary, the work of Turitsyn *et al.* makes an excellent contribution to the fundamentals of laser science, offering a new platform for the exploration of new research directions in laser physics, nonlinear optics and the practical applications of lasers. ❐

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