The phase difference between adjacent pulses is set to either 0 or π, which encodes the key bits. Bob then performs a round-robin measurement. He splits the packet in half with a beam splitter, delays one part with respect to the other by an integer value n ($n \in [1, L - 1]$) of the pulse separation interval Δt and then interferes the two parts at a second beam splitter. The delay is chosen randomly for each packet, and it leads to the random selection of the measured bit, which an eavesdropper is unable to predict in advance. The longer the packet L, the smaller the chance that an eavesdropper gets it right, and so longer packets will more strongly limit the eavesdropper's information.

The key optical element required to experimentally implement the new protocol is a discretely variable delay line integrated inside an interferometer. This poses an interesting challenge for photonic engineering. Not only does the delay line require a constant relative phase between all delay steps, but ideally also the insertion loss should be tolerable and constant for each step, and it should be rapidly switchable. The three research groups find very different solutions to this problem.

Wang *et al.*[4] have employed the following direct approach. They construct a fibre polarization-insensitive Michelson interferometer with both arms having a choice of eight delays. Each delay is formed by a length of fibre with a precision of 10 μm, and switching among them is realized with solid-state optical switches featuring low loss of about 0.6 dB and a switching time of 100 ns. The phase of each delay element is controlled by an individual piezoelectric fibre stretcher. The interferometer allows a differential delay of up to 64 ns with a step-size of 1 ns. The packet size therefore is 65. The low-loss nature of their setup and the relatively large packet allow them to perform RRDPS over a distance of 90 km with a secure key fraction per transmitted pulse of approximately 10^{-6} in the asymptotic limit.

In contrast, Takesue *et al.*[5] circumvent the difficulty of active switching by using passive selection of the optical delay by a beam splitter. The problem of implementing a fast and low-loss optical switch is thereby replaced by the necessity for several additional single-photon detectors. Because the path of the photons is not actively routed, two single-photon detectors have to be connected for each delay step. Using a neat time-multiplexing trick, they halve the number of required detectors to four for their packet size of five. The delays are integrated on silica photonic circuits with temperature stabilization to ensure a fixed phase for each delay step. Takesue *et al.* demonstrate a maximum transmission distance of 30 km with a secure key rate of the order of 10^{-9} per transmitted pulse.

The most inventive solution was proposed earlier in the year by Guan and colleagues[6]. In their variation of the RRDPS protocol, Alice's pulses no longer have to interfere with each other, thereby removing the need for the variable delay lines altogether. Instead, they interfere with a phase reference that Bob generates. In relation to Alice's pulses, this reference must be locked in wavelength to achieve a reasonable packet size, and, more challengingly, locked in phase for ultimate performance. In their implementation, Guan *et al.* simulate perfect wavelength-locking using the same laser to generate both Alice's and Bob's signals, but purposely let their relative phase drift. Despite the high base error (25%) due to the phase drift, they achieve a transmission distance of 53 km with approximately 10^{-7} secure bits per transmitted pulse.

All three implementations have their strengths and weaknesses. The active bulk-fibre implementation from Wang *et al.*[4] has low insertion loss but requires a demanding phase control and is not ideal for long-term operation. The passive implementation by Takesue *et al.*[5] suits higher operational speeds as it is not limited to the switching speed of the active component, and it is intrinsically more stable. It has a scaling problem, however, as the required number of detectors increases linearly with the packet length. The passive variation by Guan *et al.*[6] does not need a variable delay line but requires a non-trivial wavelength/phase-locking scheme.

Overall, the current performance of RRDPS still lags far behind what was achieved with QKD based on Heisenberg's uncertainty principle, which now routinely delivers orders-of-magnitude higher key rates and operates over distances of more than 100 km. More effort is needed to improve the performance of RRDPS QKD systems and to harvest the full benefits of the new protocol. But this pursuit may lead to the development of new photonic components and will continue to further our understanding of quantum cryptography. ❐

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THERMOPHOTONICS

LEDs feed on waste heat

Heating LEDs from room temperature to 615 K is found to increase their emission power fourfold. The finding suggests that thermophotonics could remove the need for heat sinks for high-power devices.

Jani Oksanen and Jukka Tulkki

The next hot topic in LED research could literally turn out to be heat, or more precisely heat-assisted emission. A team of scientists from the University of California at Santa Barbara and Massachusetts Institute of Technology have discovered that externally heating specially designed blue light-emitting diodes (LEDs) can significantly increase emission power, with negligible decrease in device efficiency[1]. The finding is important because it offers not only a route to brighter LEDs but also a means to set them free from the bulky heat sinks that usually accompany high-power devices. It is also a somewhat surprising result, given that high device temperatures are known to contribute to efficiency droop in LEDs.

Writing in *Applied Physics Letters*, Xue *et al.*[1] describe how they managed to tailor a LED's thermodynamics to support high-temperature operation at low bias voltages, thus allowing the thermal energy present in the device's semiconductor lattice to be put to good use in feeding the LED emission (Fig. 1a). In their work, Xue *et al.* were able to increase the optical power of an InGaN LED with a single quantum-well structure, operating at its peak efficiency, by a factor of four by heating the LED from room temperature (293 K) up to 615 K. The unpackaged LEDs that they used do not yet work in the electroluminescent (EL) cooling regime where the LEDs can actively extract heat from their surroundings and truly operate as heat pumps (Fig. 1b). Nevertheless, the work is an important step forward in exploiting the possibilities of thermophotonics for designing more efficient solid-state lighting.

The fundamental role of thermal energy in semiconductor light emission has been understood for over half a century[2,3], but until recently it has not been explored by the LED research community. As originally pointed out by Harder and Green, LEDs can also be used for heat-energy harvesting[4] or as heat pumps[5]. Figure 1 depicts the fundamental mechanisms of the heat exchange in thermophotonic systems. These involve energy transfer between the charge carriers, the semiconductor lattice, the emitted light, and the external heat and light reservoirs. Despite the early recognition of the possibility of EL cooling and the considerable progress in the neighbouring field of laser cooling of solids[6–8], it was only very recently that the EL cooling phenomenon started to gain wider visibility. Following a number of theoretical studies on harnessing EL cooling (for example, ref. 9 and references therein), the first successful experimental demonstrations of the effects were reported by Santhanam *et al.* in 2012 at very low powers[10]. This was soon followed by a similar room-temperature demonstration[11] as well as the first demonstration of laser cooling of semiconductors[12].

Today, the availability of high-efficiency LEDs makes the fundamental principles of EL cooling extremely easy to observe: biasing a high-quality red LED emitting at wavelengths 620–650 nm (photon energy of 1.9–2.0 eV) using a standard 1.5 V battery will result in light emission that is easily observed by the naked eye. The emission of each 2.0 eV photon results from a radiative recombination of an electron and hole. They initially received only 1.5 eV of electrical energy from the battery. Therefore the missing 0.5 eV must be obtained from the lattice heat, as deduced already half a century ago by Keyes and Quist[3]. As the internal quantum efficiency of modern light-emitting materials can reach values in excess of 99% (refs 13,14), there are no fundamental reasons

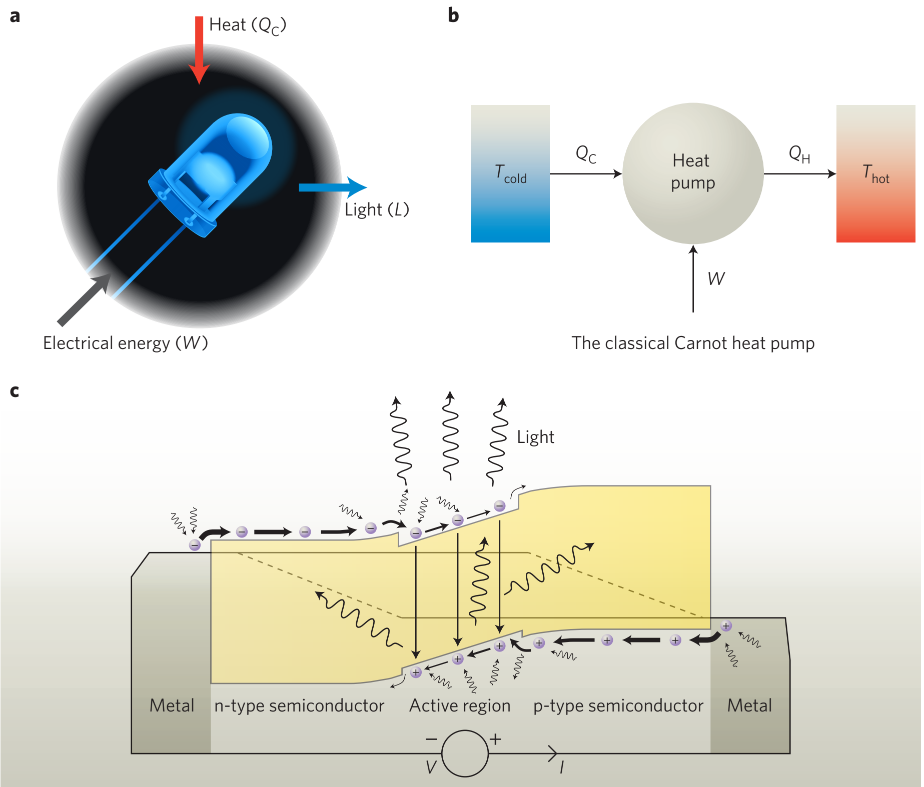

Figure 1 | A thermophotonic LED. **a**,**b**, A thermophotonic LED uses both electricity (W) and heat (Q_C) to emit light (**a**), and its thermodynamics shares many features with heat pumps (**b**). **c**, In a LED chip, biased by a voltage V, heat energy is exchanged between the charge carriers (small purple spheres) and lattice phonons (small wavy arrows) through the thermoelectric effect and Joule heating associated with the inelastic collisions that enable carrier rethermalization as the carriers travel across material interfaces or potential gradients. A net absorption of thermal energy and thus electroluminescent cooling can take place if qV is smaller than the energy of the emitted photons (large wavy arrows) and the external quantum efficiency of the LED is sufficiently high. Adapted from ref. 17, AIP. LED image in panel **a** © sajithsaam/iStock/Thinkstock.

why the EL cooling regime could not be reached and exploited at practical operating powers once the technological challenges in minimizing other losses have been overcome.

The approach of Xue *et al.* makes use of thermophotonic heat absorption and extraction to modify the operating conditions of LEDs. In their experiment, a blue single-quantum-well LED emitting at 450 nm (2.75 eV) is externally heated to temperatures ranging from 295 K to 615 K in steps of 80 K. The authors observed that although heating the LED up to 615 K lowers its peak quantum efficiency (as expected), the optical output power at the peak efficiency increases fourfold. Despite the higher temperature, the overall efficiency of the LED does not change significantly, because of the thermally induced decrease in the operating voltage. The authors analyse the origin of the thermophotonic improvements and the associated thermoelectric heat-capture mechanisms taking place during the thermalization of the electrons and holes on their route to the quantum well. Energy conservation requires that the heat capture associated with each emission event is equal to $\hbar\omega - qV$, where $\hbar$ is the reduced Planck constant, ω the angular frequency of the photon, q the charge of the electron and V the device's bias voltage. In thermoelectric cooling, the requirement that the Peltier cooling and heating along a closed current path must add up to zero introduces severe material optimization challenges[15]. In contrast, the thermophotonic configuration enables heat extraction from the system along with the emitted photons.

The efficiencies of the unpackaged LEDs studied by Xue *et al.* are only of the order of 15%, and their operating voltages near room temperature seem to be higher than in state-of-the-art LEDs. From the engineering point of view, the most important question is therefore what are the conditions for observing similar behaviour in very high-efficiency LEDs. Recent results[16] published by the US company Soraa Inc. seem to suggest that a similar trend is visible in state-of-the-art GaN-on-GaN LEDs emitting at 415 nm (3.0 eV) with a peak efficiency of 84%. In Soraa's results, the efficiency of the LED operating at elevated temperature is higher than at room temperature at a wide range of bias currents, all the way up to the technologically relevant high current densities of 100 A cm^{-2} (in particular, see Fig. 2 in ref 16). We note that in Xue's results, the high-temperature measurements also show an increased efficiency all the way to similar current densities.

It is instructive to speculate on whether the voltage losses in the state-of-the-art LEDs can be substantially decreased. The peak-efficiency operating voltages in Xue's paper are still generally larger than the bandgap near room-temperature. At high temperatures the voltages are substantially reduced, which compensates for the temperature-induced reduction in the quantum efficiency. From the fundamental point of view, however, voltages exceeding the bandgap generally allow population inversion and laser operation in structures where ohmic and other electrical losses are insignificant. In the case of idealized LEDs, this implies that as soon as the bias voltage exceeds the average photon energy, the LED reaches population inversion, enabling laser operation. As the LEDs studied by Xue *et al.* do not seem to show any signs of lasing, this suggests that the electrical losses in the studied LEDs are still large.

Overall, the results of Xue *et al.* constitute the first technologically promising demonstration of thermophotonic exploitation of waste heat in a LED to enhance emission power. The work does not yet provide a quantitative explanation for the observed fourfold increase in the emitted power, and it remains to be seen whether state-of-the-art LEDs whose electrical losses (and thus heat generation) are already very low at room temperature can also benefit from the approach. In any case, the results will undoubtedly provide the industrial motivation for further research into thermophotonics. ❐

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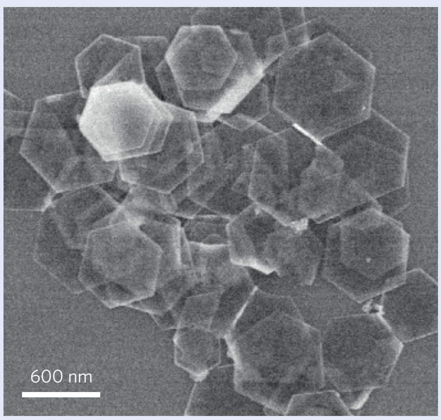
TOPOLOGICAL INSULATORS

Nonlinear opportunities

Topological insulators — fascinating materials whose bulk is insulating but whose surface can be conductive with well-defined spin textures — may turn out to be useful for creating novel nonlinear optical devices. That's the conclusion of a study into their properties, which has revealed that they can exhibit a broadband, ultrafast nonlinear effect called spatial self-phase modulation (SSPM). Bingxin Shi and co-workers from Hunan University and Shenzhen University in China observed and studied SSPM in a topological insulator made from nanosheets of bismuth telluride (Bi_2Te_3) dispersed in alcohol (*Appl. Phys. Lett.* **107,** 151101; 2015). They report that the sample exhibits broadband SSPM from the ultraviolet (400 nm) to the near-infrared (1,070 nm) due to the presence of a large, ultrafast, broadband third-order optical nonlinearity.



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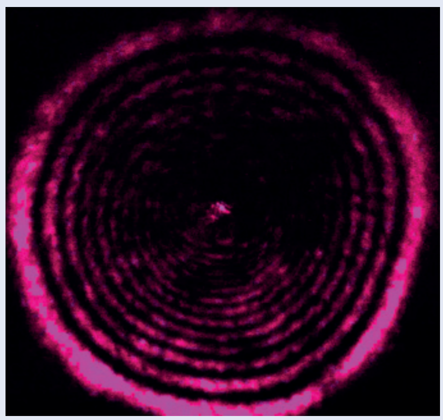

The scientists synthesized ultrathin Bi_2Te_3 nanosheets by a solvothermal method that involved dissolving bismuth chloride ($BiCl_3$) and sodium selenide (Na_2TeO_3) in ethylene glycol and then heating to 200 °C. The result was the creation of hexagonal-based plates of uniform size (400–600 nm across), as determined by field-emission scanning electron microscopy (pictured; left). The nanosheets were dispersed in an alcohol solution, which was then poured into a quartz cuvette for optical characterization.

Femtosecond laser light with a central wavelength of 800 nm, pulse duration of 100 fs and repetition rate of 1 kHz was focused onto the sample and the transmitted light was collected by a CCD (charge-coupled device) camera placed 5 cm behind the sample. The authors observed the generation of diffraction rings due to SSPM (pictured; right).

They report that the formation of the diffraction rings showed complex temporal behaviour; the rings rapidly appear, and then the upper half of the rings begin to collapse, finally the structure becomes stable after about half a second. The distortion in the upper part of the rings is believed to be due to thermal effects and gravity. Tiny gas bubbles moving upward were generated as a result of the absorbed laser energy, causing non-uniform density distribution of the Bi_2Te_3 nanosheets in the solvent and consequently distorting the intensity distribution of the diffraction rings. The SSPM diffraction rings were also observed for laser illumination at wavelengths of 400 nm and 1,070 nm. The study indicates that the nonlinear refractive index $n_{2,single}$ of the Bi_2Te_3 nanosheets is ~10^{-15} m^2 W^{-1}, corresponding to the third-order nonlinear susceptibility of ~10^{-9} esu.

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