limit the sensitivity of the technique. It might be possible to compensate for this by using a pulsed diode laser for the pump, as this could further improve the conversion efficiency while still maintaining a compact experimental design.

One potential application of this technique is in chemical imaging, where the upconverted light could be spectrally dispersed to provide chemical information. This would be particularly useful in the mid-infrared region, where the vibrational spectrum is used to interpret the presence of chemical species. Dispersing the photons in this way lowers the signal-to-noise ratio, however, meaning that this application will be possible only when the efficiency is raised to a much higher level. This technique could be used, for example, to differentiate between wet and dry samples, as light reflected from a wet surface is expected not to contain wavelengths of 3,000–3,800 cm\(^{-1}\) (whereas light reflected from a dry surface should still contain such ‘colours’). In addition, if a polymer sample contains several components that can only be distinguished by their infrared spectrum, then this process of upconverting to different colours could help to visualize the sample’s chemical composition. The possibilities in microscopy — or more likely in telescope, owing to the ease with which photons can be collected — are exciting. Dam et al. have demonstrated some ingenious methods in the development of their upconversion imaging system. Improvements to the sensitivity and spectral range of this upconversion technique will truly give us a new view of nature.

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References

**Optical black-hole analogues**

Optical analogues of gravity let scientists interrogate astronomical phenomena that are otherwise difficult or impossible to study.

**Dentcho A. Genov**

Half a decade after the modern prediction of black holes, remnants of stars that absorb matter and light, Steven Hawking provided a striking new perspective on these stellar objects. According to his interpretation, a black hole is not entirely ‘black’ but can emit virtual particles or photons emergent from the vacuum, thus decreasing the black hole’s mass\(^1\). Although Hawking’s idea suggested a means to detect a black hole optically, no experimental apparatus has been constructed that can successfully measure its footprint. The reason for this is that the thermal radiation emitted by a black hole has a temperature that is much lower than the cosmic background; thus, the signal is hidden in a maze of noise. However, creating tabletop optical analogues of black holes is a new and promising approach that may hold the key to the elucidation of phenomena that are extremely difficult to study through direct astronomical observations (Fig. 1). For example, metamaterials, artificial optical materials made by nanofabrication techniques, have recently been proposed as a means of investigating the scattering of light and matter in close proximity to a black hole\(^2,3\).

Now, writing in *Physical Review Letters*, Franco Belgiorno and colleagues\(^4\) describe the creation of an optical analogue of the event horizon — the illusory boundary beyond which nothing, not even light, can escape the gravitational pull of a black hole. The idea is that ultrashort laser pulse filaments travelling within a transparent optical medium create moving refractive index perturbations that optically mimic the conditions at the black hole’s event horizon. The approach’s validity is supported by the observation and measurement of spontaneous emission of light with characteristics analogous to Hawking radiation.

In 1783, the Reverend John Mitchell speculated in a letter to Henry Cavendish about the existence of massive stars that may prevent matter and light from escaping their influence\(^5\). He named them ‘dark stars’ and even suggested a method of detecting one through the gravitational perturbations of a companion star if both are part of a binary system. This fascinating idea was far beyond its time and was forgotten until, at the beginning of the twentieth century, Albert Einstein published his famous work on the general theory of relativity, which provided a new, geometrical description of gravity\(^6\). Einstein’s theory has significant ramifications for the understanding of cosmological phenomena. In particular, it puts on solid ground Mitchell’s idea of a dark star, or a black hole as we would call it today. Any sufficiently massive collapsing star is fated to form a black hole, wrapping space and time in such a way that both matter and light are sucked within its powerful gravitational domain.

The basic idea of creating analogues of Hawking radiation was described by William Unruh\(^7\), who argued that at the event horizon spacetime can be visualized as a river moving towards a waterfall. The crest and troughs of a surface water wave with a velocity slower than the speed of the river, Unruh argues, can no longer travel upstream. The water waves are thus trapped within the ‘event horizon’ created by the moving river. An optical analogue of this phenomenon was recently proposed and demonstrated in microstructured optical fibers by Thomas Philbin and co-workers\(^8\). The authors argue that such a system can be used to probe the quantum effects of horizons, in particular Hawking radiation.

In the experiment of Belgiorno et al.\(^4\), the river flow is a moving refractive index perturbation in a nonlinear Kerr medium. The use of a high-intensity laser pulse travelling through the medium creates
an optical environment analogous to that encountered by light in close proximity to the event horizon, thus providing a means of measuring a radiation signature closely resembling Hawking radiation. The unique approach taken by the Italian group, which sets theirs apart from related work based on optical fibres, was to use a Bessel- or Gaussian-shaped probe beam that creates sharp, high-intensity laser pulse filaments inside fused silica. Each filament can propagate without diffraction over long distances and its group and phase velocities can be controlled, setting the frequency range where the Hawking radiation is to be expected.

Laser pulses were provided by a regeneratively amplified Nd:glass laser with a repetition rate of 10 Hz. The pulse duration was 1 ps and the energy incident onto the fused silica varied in the range 100–1,200 μJ. In the experimental set-up, the radiation spectra from the light filament is collected at 90° with respect to the direction of the incident light, which allows elimination of parasitic radiation due to a number of optical processes. The interaction of the high-intensity beam with the Kerr medium results in distinctive spectral shifts associated with processes of four-wave mixing and self-phase modulation. These processes, however, do not contribute to the measured spectra at 90° owing to phase-matching constraints.

Furthermore, Belgiorno et al. were able to eliminate spurious background radiation due to broadband Cerenkov-type emission and especially fluorescence. The fluorescence signal has well-defined peaks that can be subtracted from the total spectrum, revealing a new radiation signature centred at 850 nm. The authors have performed polarization studies of this signal, showing unambiguously that it is unpolarized and hence corresponds to a spontaneous emission process that can be interpreted as analogue Hawking radiation. The results obtained closely match the theoretical predictions, both in terms of the radiation frequency and the bandwidth's linear dependence on the input energy.

Although the demonstrated results are the best evidence so far of spontaneous emission of quanta from an event horizon analogue at optical frequencies, they cannot be used to address one of the main characteristics of Hawking radiation — its thermal nature. The curved spacetime of a black hole generates Hawking radiation across a broad spectral range and cannot be simulated completely with dispersive optical materials, such as the fused silica used in the experiment of Belgiorno et al., where the effects can be reproduced only for a finite frequency range. However, the observed radiation has its origin in the same physical phenomena that underlie Hawking radiation, and under the specific material settings of the experiment its generation can be considered a new type of nonlinear optical process. This process should be a common optical occurrence, as pointed out by Belgiorno et al., and must be considered whenever spontaneous emission processes are studied in systems with varying group and phase velocities.

A second, but highly important, feature of Hawking radiation is that photons emerge from the vacuum in entangled pairs. Photons are said to be entangled whenever a quantum measurement of one of them directly affects the state of the other, allowing them to be viewed as a single quantum entity. In the case of a black hole, one of the photons originates within the event horizon and the other forms outside and can be detected as Hawking radiation.

Pair wave creation has recently been demonstrated, by Weinfurtner et al., using Unruh’s moving-water analogue of a white hole. A white hole is the time-reversal of a black hole: matter and light can escape from it, but nothing can enter into it from the outside. Weinfurtner et al. model a white hole using a deep-water flume with a spatially varying fluid velocity generated by a streamlined obstruction placed inside the flume. The obstruction creates a region of high flow velocity that acts as an event horizon for ‘shallow gravity waves’ (conventional water waves) propagating on the water surface. The surface waves within the flume were analysed with high precision using laser-induced fluorescence from rhodamine water-tracing dye dissolved in the water. In a nonlinear process that occurs at the obstruction, three distinctive wave patterns are observed, one corresponding to the incident ‘shallow water wave’ and two to converted ‘deep water waves’ respectively propagating with opposite phase velocities up- and downstream. By measuring the amplitudes of the two converted waves, Weinfurtner et al. unambiguously demonstrate a Boltzmann distribution, indicating a thermal emission process with temperature of $5 \times 10^{12}$ K. In contrast to the findings of Belgiorno et al., the fluid pair wave generation at the analogue white-hole event horizon is due to a process of stimulated emission.

These results reveal that Hawking radiation, which was originally thought to be inherent only to gravitational black holes, is a common phenomenon. As pointed out by Weinfurtner et al., they also show that a complete description of quanta generation in curved spacetimes may not require the development of a theory of quantum gravity, which has been the focus of theoretical physics for the better part of the past century.

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Ultrafast buffering by molecular gas

A simple molecular gas sample can be used to achieve ultrafast optical buffering in two-dimensional optical imaging, thus serving as a promising extension of the well-developed liquid-crystal display technology.

Edouard Hertz, Bruno Lavorel and Olivier Faucher

In the technologies surrounding us today, liquid crystals can be most commonly found in the display of text, images and videos. The principle of liquid-crystal display (LCD) technology is based on the electro-optical Kerr effect in liquid crystals, which is responsible for the orientation of dipole moments when they are exposed to an external electric field. The birefringence induced by the orientation of dipole moments is used to control the intensity of the light passing through the LCD, and the switching time of the LCD is therefore limited by the reorientation of the macromolecules, which occurs on the millisecond timescale. However, the quest for larger bandwidth, in response to a growing demand for high-speed data storage and communications networks, demands faster, ‘all-optical’ device solutions. Their relatively high response time makes LCD devices inappropriate for ultrafast switching, gating and imaging applications in the gigahertz-to-terahertz frequency range.

Writing in Applied Physics Letters, Jian Wu and colleagues1, from East China Normal University in Shanghai, propose the use of gas-phase molecules in place of liquid crystals to overcome the high switching time of LCDs. They have successfully demonstrated ultrafast optical imaging involving optical image storage followed by periodic read-out and display. In analogy with LCD technology, the team orientate the molecules using a transient electric field with a duration of the order of a few tens of femtoseconds, which is much less than the rotational period of the molecules. This is achieved by using a linearly polarized, 35 fs laser pulse as the external field. In this approach, molecules can be seen as ‘quantum buffer memories’ with a writing time limited by the pulse duration of the laser field. A second polarized, femtosecond pulse accomplishes the reading process in a characteristic time also defined by its duration. The team use this ultrafast read–write molecule-based memory to achieve ultrafast imaging.

The idea proposed by Wu et al.1 relies on the basic process of laser-induced molecular alignment that has been investigated by researchers of strong laser fields over the past twenty years2. A laser field (the writing pulse) applied to a molecule induces a torque on its axis, leading to its alignment along the direction of field, as shown in Fig. 1b. In the short-pulse regime, where the pulse duration must be shorter than the rotational period of the molecule, the alignment is produced not only just after the field reaches its maximum, but also after the laser is turned off.

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