OPTICAL PHYSICS

A larger quantum alphabet

Quantum objects that can hold more information than quantum bits have been generated and manipulated in an integrated photonic platform, paving the way for advanced protocols in quantum information processing. SEE LETTER P.622

ROBERTO OSELLAME

Quantum technologies are expected to introduce revolutionary changes in the ways in which information is processed in the near future. Furthermore, worldwide funding campaigns, such as the Quantum Technologies Flagship of the European Commission, announced last year (see go.nature.com/2mpp4oa), have been set up with the aim of boosting applications that encompass quantum communications, computing and sensing. However, it has yet to be demonstrated experimentally that a quantum technology is appreciably better than its classical counterpart. The main difficulty being faced is the creation and handling of many quantum bits (qubits), which limits the amount of information that can be processed by quantum means. On page 622, Kues *et al.*[1] demonstrate an approach in which photons that have many potential frequencies are generated. This extends the usual two-level encoding capacity of qubits, increasing the amount of information that can be stored in the same number of quantum objects.

In the race to develop a mature quantum technology that has real-world applications, there are many competing platforms, including those that use photons, trapped ions and superconducting circuits[2]. Quantum photonics is eminently suited to applications in communications and sensing, but it has also proved valuable for quantum computing and simulation[3]. The photonic platform has become even more valuable in the past few years with the introduction of devices based on photonic integrated circuits, which can be used to generate and manipulate non-classical states of light on a microchip[4]. This advance has facilitated the impressive miniaturization, cost-effectiveness, scalability and stability of quantum photonic devices.

In Kues and colleagues' approach, pulses of light from a 'pump' laser are converted into pairs of photons using a microresonator — a ring-shaped waveguide, contained in a microchip, that traps light at certain frequencies known as resonances (Fig. 1a). Thanks to a nonlinear optical process called spontaneous four-wave mixing, two photons at the pump frequency are annihilated to create two photons whose frequencies are distributed over the multiple resonance frequencies of the microresonator. The optical spectrum of the resulting photons is a set of evenly spaced frequency lines, known as a frequency comb (Fig. 1b). Crucially, each resonance frequency at which a photon can be generated represents a different letter in an alphabet that extends the 'zero' and 'one' encoding of qubits, enabling multilevel encoding on each photon.

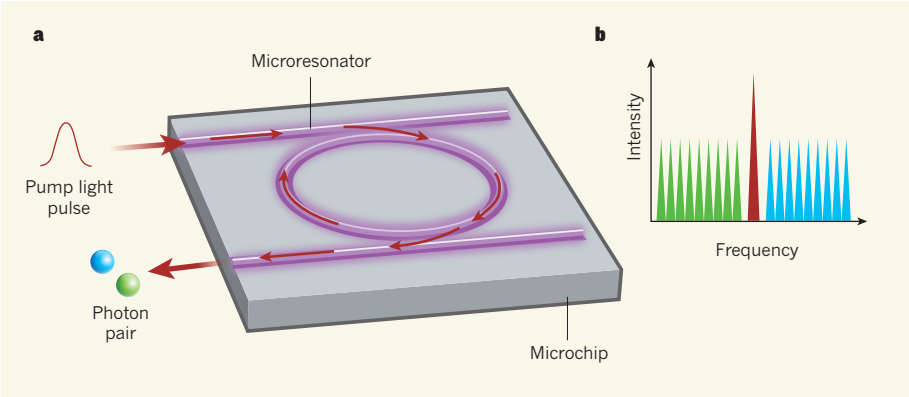

Figure 1 | Generation of entangled photons for the multilevel encoding of information. **a**, Kues *et al.*[1] demonstrate an approach in which pulses of light from a 'pump' laser are converted into pairs of photons using a microresonator — an optical device, contained in a microchip, that traps light at certain frequencies known as resonances. The red arrows indicate the direction of light propagation through the device. **b**, Because the microresonator has multiple resonances, the optical spectrum of the resulting photons is seen as a set of evenly spaced frequency lines (green and blue peaks). The authors demonstrate that each of these frequencies can be used to encode information, extending the usual binary alphabet ('zero' and 'one') of quantum bits. Energy conservation implies that the frequencies of the two photons are entangled (correlated in a non-classical way), which imposes spectral symmetry on the photons with respect to the frequency of the pump laser (red peak). The combination of multilevel encoding and entanglement in such an integrated photonic platform is a key requirement for advanced quantum information processing.

As an added benefit, the authors' approach automatically generates pairs of photons whose frequencies are entangled (correlated in a non-classical way) because of the energy conservation of the nonlinear production process. Entanglement is a key requirement for many quantum protocols — from quantum precision measurements[5] to quantum communications[6] — and was demonstrated by the authors after they propagated their photons through a 24.2-kilometre-long telecommunications fibre.

Previous studies have exploited the paths[7] and timing[8] of photons, rather than their frequency, to generate multilevel entangled states. However, using the resonance-frequency approach allows Kues *et al.* to apply simplified circuits and operations — a key aspect of the authors' work is that manipulation of the multilevel-encoded photons is performed by commercial, off-the-shelf telecommunication components. Although they were not designed for quantum operations, it is surprising to see how well these standard devices can operate on quantum-encoded photons, without perturbing the photons' quantum state. As well as their practicality, the components can be easily reconfigured, enabling the implementation of a range of quantum protocols using the same experimental set-up.

One important limitation of integrated quantum photonic platforms is the presence of photon losses. Such losses limit quantum communication through fibres across long distances (hundreds of kilometres), and are a considerable problem in integrated photonic chips — current technologies produce devices that lose a few per cent of the propagating photons for every centimetre travelled. If each photon represents a qubit, and many

qubits are used to encode some information, the information is preserved only if none of the photons are lost — something that becomes exponentially more unlikely as the number of qubits required increases. In this respect, Kues and colleagues' use of multilevel encoding, rather than the two-level encoding of qubits, is a smart choice because the same information can be transferred using fewer carriers, which reduces the impact of photon losses.

Another limitation of many quantum photonic systems, including that of Kues *et al.*, concerns the use of a spontaneous nonlinear process to produce the photons used as carriers of the quantum information. This intrinsically probabilistic process causes practical difficulties when synchronizing the operations that comprise a quantum protocol. In addition, the limited rate at which photons are generated, and the low probability that different devices will emit single photons at the same time, make the scaling of these systems rather unfavourable. A promising alternative involves the use of structures called quantum dots[9], whose atom-like behaviour enables single photons to be generated on demand and at a relatively high rate. However, the efficiency at which these photons are collected still needs to be improved, and the creation of entanglement between photons is much more complicated than in the nonlinear production processes.

The future success of quantum technologies, in terms of outperforming their classical counterparts, will be crucially dependent on the amount of information that can be processed by a quantum platform. Kues and colleagues estimate that their multilevel encoding of two photons could achieve the equivalent of 13 qubits — still far from the hundreds or more that are required to demonstrate the potential of quantum technologies. This limitation is not specific to quantum photonics, but is common to all such current platforms. The next challenge will be to demonstrate a technical breakthrough in one of these platforms or to combine them in a synergistic way to harness the advantages that each can provide. ■

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INFECTIOUS DISEASES

Predictions of virus spillover across species

Most human infectious diseases are initially transmitted from animals. An analysis of all known mammalian viruses improves our understanding of such cross-species spillover, with potential benefits for public health. SEE LETTER P.646

JAMES O. LLOYD-SMITH

In ancient Rome, priests divined the future by examining animal entrails. Today, scientists attempt to predict the emergence of human pandemics by surveying the pathogens carried by animals. Most infectious human diseases, including newly emerging ones, involve pathogens initially transmitted from other animals (these diseases are called zoonoses). Viral zoonoses, such as HIV, pandemic influenza and Ebola, are particularly concerning, given their track record of devastation. On page 646, Olival *et al.*[1] provide the most comprehensive view yet of past, present and future virus-sharing between humans and other mammals.

Efforts to understand the drivers of zoonotic risk have been dogged by concerns about biases arising from uneven research focus across species and regions, and by challenges in untangling alternative hypotheses. For instance, are we at greater risk of zoonoses from apes, which share our genes, or from rats, which share our cities? Influential studies[2–4] have addressed subsets of these issues or particular host types. Olival *et al.* confront the full challenge head-on, amassing a database of more than 2,800 animal–virus associations that span all known viruses of mammals and all major orders of terrestrial mammals. The authors used statistical models to attempt to assess all hypotheses at once, while controlling for uneven research efforts. Their work paints a far-reaching picture of the factors that govern how many viruses (total and zoonotic) are carried by mammalian hosts.

Pleasingly, this broad canvas consolidates many earlier findings, often adding nuance. For instance, a host's relatedness to humans was known to affect its propensity to carry zoonotic viruses[2], but the authors' analysis shows that the detectable effect arises almost entirely from varying patterns of virus carriage between primates. Bats, primates and rodents carry the highest proportions of zoonotic viruses, but only bats carry significantly more than other species after controlling for confounders, reinforcing an earlier finding[3]. An analysis of the viral traits linked to zoonotic potential (aimed at predicting whether a newly discovered virus can infect humans) confirmed that an ability to replicate in the cell cytoplasm increases such potential[5]. This analysis also solidified the intuitive idea that viral generalists, those capable of infecting a wide range of animals, are most likely to be able to infect humans.

The study's most ambitious aim was to predict where and in which host species we might find 'missing' zoonoses — those that exist, but have not yet been detected. The authors extrapolated their models to predict the number of viruses that would be found per host species if all hosts were subject to elevated research efforts, then subtracted from this the number already known for each host (echoing a strategy used to predict future zoonotic diseases from rodents[4]). This approach yielded enticing predictions of the species and regions that are most likely to harbour missing zoonoses, such as bats in northern South America and carnivores in East Africa. Although caveats apply, and the authors detected biases in their predictions for some regions, these findings could guide future investment in global virological surveys.

Olival and colleagues must be commended for their robust, methodical approach to tackling this immense problem, the unruly complexity of which is arguably matched only by its value for public health. The authors have brought order to our understanding of virus sharing between humans and other mammals. But the potential of these findings to shape policy and research priorities demands a clear-eyed view of the challenges ahead.

The study aimed to predict zoonotic spillover, but each word in this phrase bears careful examination. First, predict. The researchers considered total virus numbers per species, the proportion of viruses that are zoonotic per species and the zoonotic potential of each virus. For each of these outcomes, they produced models to explain observed patterns (taking into account various biological factors, as well as research effort), which can be pared down to models that predict outcomes for unstudied species (considering only biological factors, because research effort has no effect on true outcome). The authors are exemplary in stating the explanatory power of each model, including the lower power of predictive