**QUANTUM OPTICS**

**Enlightened chips**

Using quantum optics to process data could herald a new era of information technology. With the latest semiconductor source of photons, researchers are paving the way towards this enticing goal.

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The ability to integrate electronic circuits into semiconductor microstructures has laid the foundation of modern information and communication technology. Quantum information could bring about a second information revolution, but not until scientists develop the technology needed for microscopic circuits that can be built on a large scale. Researchers from France and Switzerland have now produced an integrated semiconductor source of pairs of single photons\(^1\), which are a crucial ingredient for optical quantum-information processing. Their advance is a promising step towards chip-based quantum-information technologies.

Quantum-information devices are based on storing, processing and retrieving data using physical systems that are dominated by quantum effects. When it comes to factors such as speed, capacity, security and computing power, quantum computers and communication systems have the potential to leave their classical counterparts standing in the dust. During the past decade major strides have been made towards this exciting technology. We have successfully identified several useful carriers of quantum-information 'bits' (qubits) including atoms, ions, superconducting quantum-interference devices (SQUIDs) and photons\(^2\). In addition to the remarkable proof-of-concept demonstrations and field tests of quantum technology that have been performed, a good deal of effort has focused on miniaturizing the technology onto semiconductor chips. This is important both for making large-scale quantum circuits and for enabling future quantum technology to compete with today's silicon-based information market.

Recently scientists have produced chip-based traps for atoms and ions\(^3,4\), quantum-dot-based entangled-photon sources\(^5,6\) and lasers and nonlinear optics fully integrated into silicon\(^7\). The present work by Lanco et al.\(^1\) offers yet another possible route towards integrated quantum information processing (QIP) using light.

Quantum-information processing based on light brings several advantages: photons can be transmitted over long distances (a key ingredient for quantum networks), they can be easily manipulated by linear optical elements (that is, ones that do not alter the number of photons) and they can undergo ultrafast logical operations for computing purposes\(^8\). Optical QIP hinges upon the efficient generation of single photons and pairs of entangled photons, and the standard way to achieve this is through a process known as parametric down-conversion in nonlinear optical materials\(^9\) (Fig. 1). The most prominent down-conversion approach is effectively a quantum analogue of three-wave mixing. In classical three-wave mixing, the amplitudes of three phase-matched beams (pump, signal and idler 'waves') travelling through a medium become correlated as a result of the medium's second-order nonlinear properties. In the quantum world, this process can happen even if the initial signal and idler waves are absent, because vacuum fluctuations of the signal and idler modes are still present. The outcome is that photons...
from a strong input pump beam incident on a nonlinear sample can decay into pairs of photons — signal and idler — of lower energy, whose combined energy and momentum match that of the original pump photon.

The generated photon pairs are tightly correlated in time, which essentially gives us a single-photon source: by measuring one of the photons of a pair we know very accurately that one and only one photon is available for further processing. Admittedly, the down-conversion mechanisms used to date in bulk nonlinear dielectric crystals lead to rather inefficient creation of photon pairs, but more efficient down-conversion routes have been suggested or demonstrated, such as down conversion in photonic-crystal waveguides\(^{10}\) or four-wave mixing in photonic-crystal fibres\(^{11}\).

The work from Lanco and colleagues exploits the basic principle of down conversion to produce time-correlated photon pairs, but does it in an experimental setting that is potentially much more useful for practical quantum technology (Fig. 2). First, the authors’ choice of AlGaAs as the nonlinear medium allows the sample to be grown, micromachined and interfaced with other devices using standard semiconductor fabrication technology. Second, the photons are generated at a useful telecom wavelength (1.5 micrometres) with high efficiency due to the comparatively large nonlinear coefficients of AlGaAs at this pump wavelength. The authors build their AlGaAs structure from periodically alternating layers of different density in the direction of the pump beam, which helps to optimize the phase matching between pump, signal and idler waves and thus boost the down-conversion efficiency. Furthermore, the sample is manufactured so that the generated photon pairs are emitted directly into a waveguide — making it possible to guide the light along the chip for further processing, or else couple it into optical fibres for long-distance transport.

Finally, in contrast to previous studies with semiconductor quantum dots, the experiment works at room temperature.

As the pump beam hits the sample surface at almost 90°, momentum conservation forces the outgoing photons to travel in opposite directions — a useful effect that had been predicted but not shown until now. Time-correlation measurements between the outgoing photons unambiguously show that counter-propagating twin photon pairs are produced. Because the two photons of any given pair are spatially separated both from each other and from the pump beam, the photon-filtering constraints usually applied in pair-generation experiments involving waveguides can be significantly relaxed. Moreover, because the polarizations of the emitted photon pairs are correlated, the system should be capable of generating entangled pairs of photons. A second pump beam could be used to coherently combine two such two-photon emission events and thus generate a polarization-entangled state.

Lanco and co-workers have set important new trends with their latest work. But the actual performance numbers show there is still a way to go before we have chips with optical circuits that contain several tens of quantum logic gates. Luckily, this first demonstration leaves much room for improvement in terms of the noise levels and efficiency of the scheme. An interesting next step might be to replace the external pump laser with an electrically pumped surface-emitting laser that is directly integrated into the structure. Although our most pressing problem — the efficient generation of many photons on a chip — is not yet solved, Lanco and colleagues have certainly brought us closer to this goal.

**References**