Quantum integration

On-chip quantum interference between integrated photon sources has now become a reality. Mark Thompson spoke to *Nature Photonics* about the realization of and future outlook for integrated quantum optics.

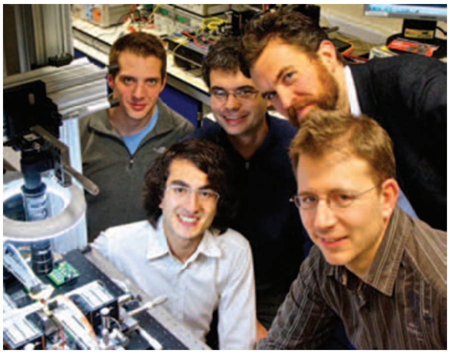
What did you achieve?

We investigated the performance of two identical photon sources integrated on a silicon chip. The on-chip generation of photon states was realized by the process of spontaneous four-wave mixing, and the two identical sources were formed from silicon nanowire waveguides, which spiralled inwards to conserve space. The high Kerr nonlinearity of silicon combined with the strong confinement of the nanowire waveguides leads to strong optical nonlinear effects, enabling efficient photon-pair generation in a short length of waveguide. To achieve quantum interference between the separate sources, the photon states produced must be indistinguishable (that is, identical) and hence the photon sources need to be identical. We fabricated a device containing two such sources, and found a quality of quantum interference far beyond what we expected — with near-perfect quantum interference. What's more, these devices were fabricated using industrial-standard CMOS-compatible techniques by Toshiba in Kawasaki, Japan.

What did you do with the new sources?

We integrated our sources with a simple waveguide circuit so that we could dynamically manipulate the on-chip quantum states generated and perform a number of on- and off-chip interference experiments. We separated the different energy photons from the main pump beam and treated them as pairs of single photons, which can be used for quantum optics experiments.

On our chip, we fabricated two sources side-by-side and pumped them simultaneously, exploiting the inherent phase stability of integrated optics. As we pumped the two sources weakly, only one pair was created and this occurred in only one of the two source waveguides. However, because this pumping was phase stable, an entangled quantum state resulted, which was revealed after we erased the 'which-source' information using an on-chip beamsplitter. We manipulated the phase between the sources using a thermo-optic phase shifter, and observed a two-photon interference pattern — the signature of two-photon path entanglement. All this — the generation, manipulation and quantum interference — happened on the chip. Next, we looked at the well-known Hong–Ou–Mandel-type interference experiment using an external beamsplitter, which allowed us to explore the strong frequency entanglement in our system, and to show how the photons from our device can be used in subsequent quantum circuits.



PETER TURNER

Graham Marshall, Damien Bonneau, Jeremy O'Brien (top row, left to right), Josh Silverstone and Mark Thompson (bottom row, left to right) with their experimental set-up (bottom left).

Will integrated quantum optics yield results or effects not possible with free-space quantum optics alone?

For the moment, the complexity of the problems we have tackled is low enough that experiments can be performed on an optical table — if only barely. Soon, however, we are confident that integrated quantum photonics will produce a step change in the complexity and application of quantum technologies; the high functionality and multi-source integration we've shown is a key step towards this. Integrated quantum circuits have already been used for experiments that are not possible (or at least impractical) with free-space quantum optics — an early success for integrated quantum photonics was the investigation of quantum walks, requiring extremely high phase stability. Besides miniaturization (which has already resulted in a six orders of magnitude reduction in the size of quantum experiments), doing quantum optics on a chip has a number of other benefits: phase stability is guaranteed, single-mode operation is straightforward to achieve, interface losses are eliminated, precise nanoscale control over fabrication tolerances is possible and clear routes exist to realizing very complex circuits containing many thousands of individual components.

Our work has focused on the development of a new quantum photonic technology, demonstrating the most functional integrated quantum photonic circuit and using it to reproduce previously obtained results in a novel way and with a very high fidelity. These developments were based on the existing classical silicon photonics technology platform, which is becoming increasingly accessible through commercial foundry services. Silicon photonics is not without its shortcomings, but we believe that the quality, flexibility and availability of silicon photonic devices will greatly accelerate the advancement of quantum photonics technology to a point where it will trounce even the most sophisticated free-space implementations.

When will we see a truly on-chip quantum optics experiments in which all the components are integrated on the chip?

All the required components have been demonstrated in various materials, but bringing them all together on a single chip remains a challenge. Single-photon detectors, sources and circuits have been reported separately in silicon, but an integrated device is more than just the sum of its parts. Interfacing these elements, and operating them at a common temperature will be a challenge, but it is one for quantum engineering to solve rather than quantum science. For this reason, we hope to see a fully integrated device in the not-so-distant future.

INTERVIEW BY DAVID PILE

Mark Thompson and co-workers have a Letter about on-chip quantum interference between silicon photon-pair sources on page 104 of this issue.