Continuous-variable entanglement on a chip

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Encoding quantum information in continuous variables, as the quadrature of electromagnetic fields, is a powerful approach to quantum information science and technology. Continuous-variable entanglement (light beams in Einstein-Podolsky-Rosen, or EPR, states) is a key resource for quantum information protocols and enables hybridization between continuous-variable and single-photon discrete-variable qubit systems. However, continuous-variable systems are currently limited by their implementation in free-space optical networks, and the demand for increased complexity, low loss, high-precision alignment and stability, as well as hybridization, require an alternative approach. Here we present an integrated photonic implementation of the key capabilities for continuous-variable quantum technologies—the generation and characterization of EPR beams in a photonic chip. When combined with integrated squeezing and non-Gaussian operations, these results will open the way to universal quantum information processing with light.

The use of quantum-mechanical systems to encode, transmit and manipulate information promises the development of revolutionary technologies in the fields of sensing, computing and communications. There are two natural ways to encode information in the quantum domain: (1) make use of two (or more) discrete levels of a quantum system (for example, the spin of an electron or the polarization of a photon) or (2) use a continuum of states (for example, a quantized harmonic oscillator) that can be described by continuous variables such as the position and momentum of a particle. Light is particularly suited to the encoding of information in the quantum domain and has been successfully used to demonstrate quantum protocols both with discrete variables (DVs) using the degrees of freedom of single photons and continuous variables (CVs) using the quadratures of beams of light.

DV systems benefit from high-fidelity operations, but are currently limited by the imperfect generation and detection of single photons, as well as the absence of deterministic interactions of photons. In contrast, CV schemes can achieve deterministic, unconditional operation, but demonstrate lower fidelities for the majority of quantum protocols. A new hybrid approach overcomes these problems by combining the benefits of DVs and CVs in a single system. Entanglement between DV and CV systems and teleportation of a DV state using CV protocols have already been demonstrated. However, practical applications of this hybrid approach will require an integrated system in which light is guided, manipulated and made to interfere in a waveguide architecture. Integrated waveguide circuits have been successfully developed for DV applications and have demonstrated high-fidelity and reliable operation. A benefit of this optical integration, in addition to the miniaturization of quantum circuits, is attainment of a high degree of spatial mode matching, which is essential for classical and quantum interference, without any optical adjustment.

Transferring CV systems to such integrated circuits presents considerable technical challenges, including achieving high-efficiency coupling, low-loss operation and a high degree of mode matching, all in an architecture that is compatible with DV operation.

Here, we demonstrate an integrated circuit that can be reconfigured to implement the fundamental operations required for DV quantum optics, and which is compatible with high-fidelity DV operation. We characterize a device composed of directional couplers that can interfere two squeezed states of light, perform phase stabilization, and mix strong local oscillator (LO) beams to perform homodyne detection. We further configure the integrated optical circuit to generate and characterize Einstein–Podolsky–Rosen (EPR) entangled beams of light, obtaining a correlation variance of $\Delta^2 = 0.71$ that demonstrates inseparability. This shows all the components required to achieve quantum teleportation, a Gaussian operation and the most fundamental quantum information protocol, on a single integrated chip.

We first demonstrate that photonic circuits can be used in CV quantum optics and provide the required suppression of coupling between different waveguide modes. Unwanted cross-coupling typically results from stray light arising from insufficient coupling from fibre inputs, waveguide bending losses and cladding guiding. Such cross-coupling is a major limitation in quantum optical networks, reducing the fidelities of quantum operations. It is particularly troublesome for balanced homodyne measurements, because quantum information is encoded on weak optical signals and the presence of light scattered from intense coherent beams such as the LO can degrade the signal and destroy non-classical effects. Here, we avoid the harmful consequences of stray light by using the side bands of the optical field and almost perfect mode matching between squeezed light and LO within a chip, as shown below.

Figure 1 presents the experimental set-up, where the optical network consists of a silica-on-silicon chip that includes four waveguide interferometers (see Supplementary Section I for details). The interferometers are composed of a pair of directional couplers and a phase shifter implemented by a resistive heater lithographically defined on top of one waveguide arm. By tuning the drive current of each resistive heater, it is possible to control the optical phase difference between the two arms. Each interferometer is therefore equivalent to a tunable beamsplitter (BS). As shown in Fig. 1a, the squeezed light $S_L$ and local oscillator $LO_1$ are coupled into the chip and superimposed at beamsplitter $BS_2$. Output beams are collected by optical fibres and measured by a balanced homodyne detector outside the chip. The experiment was performed at a 1.5 MHz sideband of the laser frequency.

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Figure 1 | Experimental set-up. Four variable-reflectivity beamsplitters are implemented in a photonic chip. Each variable beamsplitter is composed of two directional couplers and a variable phase shifter. Beamsplitters BS₁, BS₂ and BS₄ are tuned at a splitting ratio of 50/50 and BS₃ at 99/1. A pair of fibre arrays are used for both entrance and exit facets of the chip to inject and eject beams efficiently. To guide the output from one beamsplitter to another, two fibres are connected mechanically. Continuous-wave squeezed lights SL₁ and SL₂ (at 860 nm) are generated by sub-threshold optical parametric oscillators (OPOs)²⁵,²⁶ outside the chip. A pump beam at 430 nm for the OPOs is generated by an optical frequency doubler²⁷. Weak coherent beams are introduced between squeezed lights SL₁ and SL₂ at 90° using a servo-amplifier and piezo actuator. Output beam EPR₁ (EPR₂) is combined with local oscillator LO₁ (LO₂) at BS₁ (BS₂) and then detected by balanced homodyne detector HD₁ (HD₂).

Figure 2a presents typical results for homodyne measurement of squeezed light SL₁, which was generated by using a sub-threshold optical parametric oscillator (OPO) with a pump power of 100 mW. As the LO phase is varied using a piezo-electric controller, the observed signal oscillates between a saturation of the squeezing level at about 4.02 ± 0.13 dB and an anti-squeezing level of 11.85 ± 0.15 dB. The measurement was repeated for different pump powers. Figure 2b shows the squeezing and anti-squeezing levels as the pump power is varied. The solid curves show calculation results (Supplementary Section II) with almost perfect visibility (0.995) and show good agreement with the experimental values. Saturation of the squeezing level at about −4 dB at a higher pump power is predominantly due to an insufficient overall coupling efficiency (0.72), consistent with the −8.4 dB of squeezing level expected for a perfect coupling efficiency. These results and their agreement with calculations demonstrate the high performances of our integrated device for CV operation. In particular, a high degree of mode matching (interference between two coherent beams shows visibilities of 0.995) and low levels of stray light noise (as a result of the side band measurement) enable the transmission and detection of high levels of squeezing.

We now describe the central result of this work: the generation and characterization of EPR beams within the chip. To characterize the amount of entanglement obtained with our system we use an inseparability criterion. If we introduce the quadrature phase amplitude operators \( \hat{x} \) and \( \hat{p} \) which correspond to cosine and sine components of the optical field, we can write the complex amplitude, \( \hat{a}_1 = \hat{x}_1 + i\hat{p}_1 \) and \( \hat{a}_2 = \hat{x}_2 + i\hat{p}_2 \), respectively. To evaluate the entanglement between two output beams, we define the correlation variance \( \Delta_{1,2}^2 \) as

\[
\Delta_{1,2}^2 = \langle (\Delta \hat{x}_1 - \Delta \hat{x}_2)^2 \rangle + \langle (\Delta \hat{p}_1 - \Delta \hat{p}_2)^2 \rangle.
\]  

It has been proven by Duan and colleagues²⁷ and Simon²⁸ that two beams are inseparable when \( \Delta_{1,2}^2 < 1 \), demonstrating entanglement. It is also possible to re-write \( \Delta_{1,2}^2 \) as a function of the squeezing parameter \( r \) of the input beams, and in this case we have \( \Delta_{1,2}^2 = e^{-2r} \). It can easily be seen that \( \Delta_{1,2}^2 \) goes to zero in the ideal case with an infinite amount of squeezing, achieving perfect correlation.

Experimentally, we generate the EPR beams by combining two squeezed lights SL₁ and SL₂ at beamsplitter BS₁ and locking the relative phase between them, \( \theta_{1,2} \), at 90° (Fig. 1b)²⁹. Quantum
entanglement is verified with a homodyne measurement, using beamsplitters BS1 and BS2 to combine the two EPR beams with two LO beams. In this case the experiment is also performed at the 1.5 MHz side band of the laser frequency. Figure 3a and b show the noise levels of output beams EPR1 and EPR2, respectively, as the phase of the LO is varied. Trace (i) represents the noise of one of the output beams as $\theta_{1,2}$ is varied while simultaneously scanning the LO phase on a faster timescale. The outputs continuously tune from EPR beams to two independent squeezed light beams as $\theta_{1,2}$ changes from 90° to 0° (ref. 19). Traces (ii) and (iii) represent the noise levels of the $x$ and $p$ quadratures when $\theta_{1,2}$ is locked at 90°. We observed noise levels of $\langle \Delta \hat{x}^2 \rangle = +4.91 \pm 0.13 \text{ dB}$ and $\langle \Delta \hat{p}^2 \rangle = +4.85 \pm 0.15 \text{ dB}$ for output EPR1 at HD1, and $\langle \Delta \hat{x}^2 \rangle = +4.10 \pm 0.12 \text{ dB}$ and $\langle \Delta \hat{p}^2 \rangle = +4.18 \pm 0.13 \text{ dB}$ for output EPR2 beam at HD2, above the shot noise level represented by trace (iv). This phase-insensitive behaviour is one of the essential properties of EPR beams: entangled states show strong correlations with each other, but the individual properties are not well defined (tracing out either beam of a maximally entangled state leaves the other beam in a maximally mixed state).

Finally, we measured $\langle |\Delta \hat{x}_1 - \hat{x}_2|\rangle^2$ and $\langle |\Delta \hat{p}_1 + \hat{p}_2|\rangle^2$ to check the inseparability criterion. Trace (i) in Fig. 3c shows the variance of the difference signal between $\hat{x}_1$ from HD1 and $\hat{x}_2$ from HD2, which are taken using a hybrid junction. Trace (ii) represents the variance of the sum signal between $\hat{p}_1$ and $\hat{p}_2$ obtained in the same way. We achieve $\langle (\Delta \hat{x}_1 - \hat{x}_2)^2 \rangle = -1.44 \pm 0.12 \text{ dB}$ and $\langle (\Delta \hat{p}_1 + \hat{p}_2)^2 \rangle = -1.49 \pm 0.12 \text{ dB}$ below the noise level without quantum correlation, as shown by trace (iii). These results yield a correlation variance of $\Delta_1^2 = 0.71$ and satisfy the inseparability criterion, proving the generation of EPR beams and characterization of quantum entanglement within our photonic chip.

Our demonstration of all the key components for Gaussian operations within a photonic chip, including the generation and characterization of EPR beams and the verification of entanglement, points the way to full optical integration of CV and hybrid quantum information processing. The use of side bands of the optical field (to circumvent noise caused by stray light), combined with high-quality interference due to perfect mode-matching in directional couplers, enables simultaneous operation on non-classical light and intense coherent beams in a single photonic chip. Coupling in and out of the device is the major contributor to loss, which limits entanglement. This can be dramatically reduced by concatenating circuits.
in a single integrated network. Further performance gains will be achieved by the integration of photodetectors on the photonic chip, as has been achieved with waveguide-coupled single-photon detectors\textsuperscript{20,21}, further removing the requirement for coupling out from the chip to fibres. Universal quantum information processing will require non-Gaussian operations like photon counting\textsuperscript{22}. Integrated semiconductor\textsuperscript{23} or superconducting\textsuperscript{24} detectors are promising, and will enable the use of side-band techniques using the recently developed optical high-pass filter\textsuperscript{25}, thereby eliminating the influence of stray light that would affect the detection of dark counts.

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Author contributions

A.F. and J.L.O. planned the project. A.F. supervised the project. G.M. and K.M. conducted the experiment and data analysis. J.L.O. and A.F. developed the waveguide chip. T.H. provided experimental information. G.M., A.P. and J.L.O. wrote the manuscript with assistance from T.H. and K.M.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to A.F.

Competing financial interests

The authors declare no competing financial interests.