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Fiber-coupled EPR-state generation using a single temporally multiplexed squeezed light source

Mikkel V. Larsen, Xueshi Guo, Casper R. Breum, Jonas S. Neergaard-Nielsen and Ulrik L. Andersen

A prerequisite for universal quantum computation and other large-scale quantum information processors is the careful preparation of quantum states in massive numbers or of massive dimension. For continuous variable approaches to quantum information processing (QIP), squeezed states are the natural quantum resources, but most demonstrations have been based on a limited number of squeezed states due to the experimental complexity in up-scaling. The number of physical resources can however be significantly reduced by employing the technique of temporal multiplexing. Here, we demonstrate an application to continuous variable QIP of temporal multiplexing in fiber: Using just a single source of squeezed states in combination with active optical switching and a 200 m fiber delay line, we generate fiber-coupled Einstein-Podolsky-Rosen entangled quantum states. Our demonstration is a critical enabler for the construction of an in-fiber, all-purpose quantum information processor based on a single or few squeezed state quantum resources.

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the squeezed beam into two different fibers at a frequency of 500 kHz; thereby delaying one mode by 1 μs with respect to the other. To compensate for the delay and thus synchronize the two modes in time, the mode ahead propagates through a 200 m fiber spool. The two modes interfere with a relative phase shift of $\pi/2$ in a balanced fiber coupler, thereby forming a two-mode squeezed state.

For state characterization, we sample on an oscilloscope the quadratures of the fiber coupler outputs measured by two homodyne detection stations, Alice and Bob. Typical time traces of such measurements are shown in the inset of Fig. 2. A single dataset consists of 16,000 time traces triggered by the switching signal. Each time trace is affected by a frequency-dependent response of the detector giving rise to the negative slope seen in the inset of Fig. 2, and a noisy oscillatory response of the fiber switch. Besides this, there is a variation in the slope of each time trace due to spurious interferences—both effects occur from the coherent amplitude of the initial bright squeezed state together with limited detection, switching and feedback bandwidths. However, since these effects are systematic, repeatable and synchronized with the switching process, they can be tracked and compensated in the data processing—see Methods.

We have striven to reduce the loss of all components to maintain as much of the non-classicality as possible. We used an anti-reflection coated graded-index lens to couple the squeezed light into the fiber with an efficiency of 97% (by matching counter-propagating light in the OPO cavity), we spliced together all fiber components to minimize fiber-to-fiber coupling losses and by using the wavelength of 1550 nm, fiber propagation loss was negligible: Even through the 200 m fiber delay (standard SMF-28e + fiber), the propagation loss is $\leq 1\%$. The largest loss contribution is caused by the fiber switch (Nanona by Boston Applied Technologies Inc.), where light is coupled into a bulk electro-optic material and back into fiber leading to 17% loss. Including OPO escape efficiency, detection efficiency, and various tapping for phase locks, the total

Fig. 1 Quantum information processing architectures using optical switching and optical delay. a Switching and delay lines applied to a single squeezed state resource in order to generate multiple time-synchronized squeezed state. b Switching between homodyne detection and the more demanding cubic-phase gate-teleportation measurement with $|\chi\rangle$ being an ancillary cubic-phase-state. c Example of switching temporal modes into or out of a cluster state. d Loop-based architecture for fully temporally encoded MBQC utilizing switching and delay.

Fig. 2 Schematics of the experiment. Bright amplitude squeezed states of light are generated using type-0 parametric down-conversion in an optical resonator (OPO) at the wavelength of 1550 nm, seeded with a coherent beam for phase locks. The squeezed states of light are coupled into a single mode fiber network (marked by blue lines) in which the generation of two-mode squeezing takes place: Using a fiber switch, two consecutive temporal modes (marked by green and purple) are guided in different directions. Subsequently, the two modes are synchronized by a fiber delay of 200 m in one of the modes. Finally, the two spatial modes interfere in a 50:50 fiber coupler, thereby forming a two-mode squeezed state in the output as the phase difference of the two input modes are locked to $\pi/2$ (using active feedback to a fiber-stretching device described in Methods). The quadratures of the two-mode squeezed state are measured with two fiber-based homodyne detection stations, Alice and Bob. A typical measurement output in time-domain is shown in the inset together with illustrations of the corresponding states in phase space, alternating between two-mode squeezed states and vacuum states.
transmission from the squeezed state source to the detected signal becomes $\eta \approx 68\%$ (for more details see Methods).

Experimental results
To perform partial tomography of the generated two-mode squeezed states, we measure the quadratures $q_A(\theta) = q_A(\theta_0)$ and $q_B(\theta)$ restricted to $\theta_0 = \theta$ and $\theta_0 = \theta$ with $\theta_0 = \theta$ and $\theta_0 = \theta - \pi/2$ as a function of $\theta$. Here, $q_A(\theta) = x_A \cos \theta + p_A \sin \theta$ and $q_B(\theta) = x_B \cos \theta - p_B \sin \theta$, respectively, where $x_A$ is the amplitude and $p_A$, $p_B$ the phase quadrature at Alice and Bob ($i = A$ and $i = B$). The resulting noise variances at the 3 and 10 MHz side band frequencies are shown in Fig. 3 together with theoretical predictions. We observe that the noise variances at the 3 MHz side band frequencies are significantly lower than at the 10 MHz side band frequencies.

Maximum squeezing and anti-squeezing are measured at $\theta = 45^\circ$ where correlations are strongest, corresponding to the measurements of $q_A(\theta) = q_A(\theta_0)$ and $q_B(\theta)$. At $\theta = 0^\circ$ and $90^\circ$, we expect no correlations and measure the variances ($\langle \Delta q_A^2 \rangle + \langle \Delta q_B^2 \rangle$) for an additional noise added in the delay line—both noise effects are discussed and analyzed below and in supplementary information section 3.

The variances of $q_A(\theta) = q_A(\theta_0)$ and $q_B(\theta)$, respectively, are

$$\langle \Delta q_A(\theta) \rangle = \langle \Delta q_A(\theta_0) \rangle = \langle \Delta q_A(\theta_0) \rangle \cos^2 \theta + \langle \Delta q_A(\theta_0) \rangle \sin^2 \theta,$$

$$\langle \Delta q_B(\theta) \rangle = \langle \Delta q_A(\theta_0) \rangle \cos^2 \theta \sin^2 \theta,$$

associated with the maximally squeezed and anti-squeezed quadratures, respectively, are seen to be constant with $\theta$, indicating symmetric two-mode squeezing. This is expected as the individual single mode squeezed states in the direct ($x_i, p_i$) and delay ($x_i, p_i$) line originate from the same squeezing source, that is $\langle \Delta x_i^2 \rangle = \langle \Delta p_i^2 \rangle$ and $\langle \Delta x_i^2 \rangle = \langle \Delta p_i^2 \rangle$. From the datasets at $\theta = 0^\circ$ and $90^\circ$, entanglement can be verified by the inseparability criterion, which reads

$$\langle \Delta (x_A + x_B)^2 \rangle + \langle \Delta (p_A - p_B)^2 \rangle = 1.72V_0 < 4V_0,$$

at 3 MHz, and $2.42V_0 < 4V_0$ at 10 MHz. Here, $V_0$ is the variance of the vacuum state.

When measuring the variances of $q_A(\theta) = q_A(\theta_0)$, $q_B(\theta) = q_B(\theta_0)$ as a function of $\theta$, we trace out one specific projection that in particular realizes the squeezed and anti-squeezed quadratures.

Here, the entries with ‘--’ were not measured as it would require a more elaborate measurement scheme, but they should in principle be zero due to the symmetry of the states. However, due to uncertainties in the phase control and non-perfect phase-space alignments, the values will in practice be slightly different from zero. This is also clear from the off-diagonal correlation terms ($x_A p_B$) and ($x_B p_A$), which in practice are non-zero as seen in the measured co-variance matrix but in theory should be zero for a perfectly aligned system (see supplementary information section 4). Finally, from the covariance matrix we determine the conditional variances between Alice and Bob’s measurements from which we test the EPR-criterion:

$$\Delta_{\text{rd}}^2 x_{AB} \cdot \Delta_{\text{rd}}^2 p_{AB} = 0.69V_0 < V_0^2,$$

where $\Delta_{\text{rd}}^2 q_{ij} = \min_\theta \langle \Delta (q_i - q_j)^2 \rangle = \langle \Delta q_i^2 \rangle - \langle q_i q_j \rangle^2 / \langle \Delta q_j^2 \rangle$ is the conditional uncertainty in predicting $q_i$ when measuring $q_j$. Since both conditional variance products are below $V_0^2$, the generated states are EPR entangled in both directions.
measurements are shown in Fig. 4. The squeezing spectra are Lorentzian and resemble that of the OPO cavity. Furthermore, the anti-squeezing is seen to be symmetric, while the squeezing has degraded slightly in the direct line due to additional phase noise. To characterize this, we measure the seed spectrum by blocking the pump to the squeezing cavity. The low-frequency noise that can be observed in the direct line results from technical noise of the seed beam. Even more low-frequency noise is apparent in the squeezed state of the delay line. We believe it originates from phase noise generated by the 200 m fiber and amplitude noise from the fiber switch, which is most prominent at 5–6 MHz.

To infer the phase fluctuations, $\sigma_f$, associated with the direct ($t = 1$) and delay ($t = 2$) line, the squeezing spectra including a normal distributed phase with $\sigma$ standard deviation, approximated to $\langle \Delta q_f^2 \rangle \cos^2(\theta + \sigma_f) + \langle \Delta \delta_f^2 \rangle \sin^2(\theta + \sigma_f)$ for $\theta = 0$ and $\pi/2$, is fitted with $\sigma_f$ as the only fitting parameter. Here, following42 with additional seed noise coupled into the OPO and $V_0 = 1/2$,

$$\langle \Delta q_f^2 \rangle = \frac{1}{2} + \frac{2\gamma\eta}{(\gamma \pm \epsilon)^2 + \omega^2} + \frac{K_q}{(\gamma \pm \epsilon)^2 + \omega^2}, \quad q = x, p,$$

(6)

where $\epsilon$ is the pump rate, $\gamma$ is the total OPO decay rate, $\eta$ is the overall efficiency and $\omega$ is the angular frequency, while $K_q = 4\gamma\eta\eta_1(\langle \Delta q_f^2 \rangle - 1/2)$ with $\eta_1$ being the decay rate due to the seed beam coupling mirror and $\langle \Delta q_f^2 \rangle$ is the seed beam quadrature noise before injection into the OPO (for detailed derivation see supplementary information section 3.1). We find a decay rate of $\gamma/2\pi = 8.1$ MHz by measuring the OPO intracavity losses (0.5%), the cavity length (320 mm) and the transmissivity of the coupling mirror (10%), and we estimate the pump rate to $\epsilon/2\pi = 5.2$ MHz for a pump power of 350 mW and a measured OPO threshold power of 833 mW. $K_q$ is estimated as $K_q = (\gamma^2 + \omega^2)(\langle \Delta q_f^2 \rangle - 1/2)$ where $\langle \Delta q_f^2 \rangle$ is the quadrature noise measured with no pump ($\epsilon = 0$, gray points in direct line of Fig. 4). Finally, to include excess noise of the delay line, the seed noise difference of the direct and delay line is added to the fit in the delay line. The fit is shown as hollow points in Fig. 4, and is seen to fit very well with the measured data. The resulting phase fluctuations obtained from the fit are $\sigma_1 = 1.9 \pm 1.2^\circ$ and $\sigma_2 = 4.1 \pm 0.6^\circ$ with uncertainties estimated as the 95% confidence interval. These values are included in the theoretical model used for Fig. 3.

From the theoretical model with fitted phase fluctuations, the solid lines in Fig. 4 indicate the expected squeezing spectra if the seed beam were shot noise limited and no additional noise existed in the delay line. In that case, we can expect more than 4 dB two-mode squeezing. The phase fluctuation in the delay line, $\sigma_2 = 4.1 \pm 0.6^\circ$, is more than double that in the direct line, $\sigma_1 = 1.9 \pm 1.2^\circ$. This is mainly due to limited phase control bandwidth of the fiber delay and low signal-to-noise ratio of the feedback signal. Finally, the dotted line in Fig. 4 shows the squeezing spectrum we would expect if we had perfect phase control, and thus the optimum squeezing we may measure with the given efficiency.

**DISCUSSION**

The fast switching frequency of 500 kHz demonstrated here is suitable for encoding temporal modes of megahertz bandwidth and is thus applicable in the optical schemes in Fig. 1. Similarly, the low loss of the 200 m fiber allows for an efficient delay of almost 1 μs, compatible with the temporal modes defined by the switching. However, the 17% loss of the particular switch used here, as well as the phase fluctuations of 4° standard deviation in the fiber delay, leads to decoherence and results in some limitations when used in quantum settings: For cluster state generation from a temporal multiplexed source, as in Fig. 1a, or when switching modes in and out of a cluster state, as in Fig. 1c, the switching loss and phase fluctuation leads to limited entanglement even when large amount of initial squeezing is available. Yet, it does not accumulate through the cluster state as the loss and phase fluctuation on each mode is local, and so it does not limit the cluster state size. It will be more detrimental in loop-based architectures, as in Fig. 1d, where a temporal mode passes through the same switch and delay line multiple times, and so the switch efficiency and phase fluctuations limit the number of passes possible and thereby the computation depth.

High-efficient fast switching is demonstrated in free-space,43 while one can imagine more compact fiber-coupled switching based on Mach-Zehnder interferometry. However, in either case care must be taken not to compromise the high switching frequency, as this leads to longer delay lines necessary and thereby larger phase fluctuations. In work towards temporal
encoded optical quantum information processing, faster switching is preferable as it minimizes the required delay lengths and increases the computational speed. Thus, the ideal switch, besides being efficient, is as fast as the detection or squeezing source bandwidth.

In conclusion, using a single squeezing source with optical switching and delay, we have successfully generated in-fiber EPR-states with nearly 4 dB of two-mode squeezing, characterized by fiber-coupled homodyne detection. Our set-up has great scalability potentials: Adding an additional delay line, it is possible to extend the set-up to generate one-dimensional cluster states, and by adding a multi-port switch and more delay lines, two-dimensional cluster states can be generated from a single squeezing source. Moreover, by inserting the switch inside a loop, optical transmission efficiency is near unity, as it simply depends on the fiber, which has negligible loss at 1550 nm wavelength. This allows high-efficient in-fiber phase control, and the same design is used for phase control of the local oscillators in the homodyne detection.

In-fiber phase control
For locking the π/2 relative phase difference when interfering the two beams of bright squeezed states in a balanced fiber coupler for EPR-state generation, 1% is tapped off one of the fiber coupler output arms, and fed back to a homemade fiber stretcher in the delay line based on ref. Here, using a piezoelectric actuator, a phase shift is induced by stretching the fiber. For more details, see the supplementary information section 2. The optical transmission efficiency is near unity, as it simply depends on the fiber used.

Fiber-coupled homodyne detection
To detect quadratures of the in-fiber generated EPR-state, we developed a fiber-coupled homodyne detector (HD) where signal and local oscillator (LO) is interfered in a balanced fiber coupler before detection. For schematics and details, see supplementary information section 2. This has the benefit of being mobile, and the visibility between signal and LO is easily optimized to near unity due to the single mode nature of the fiber used.

The fiber coupler is not exactly symmetric, but has a coupling ratio of ~48:52. To compensate for this, the HD is balanced by attenuation in the fiber coupler output arm of stronger LO by inducing bending losses. With an asymmetry of 4% in the fiber coupler, after balancing this leads to 4% loss.

Finally, to couple and focus light from the fiber onto the HD photo diodes of 100 μm diameter (Laser Components Nordic AB), anti-reflective coated graded-index (GRIN) lens are used in front of the diode, leading to a free-space waist diameter of 13 μm at 5 mm from the GRIN lens facet. The quantum efficiency is measured to be 97%, and so together with 4% loss from balancing and 99% visibility, the total HD efficiency achieved is 91%.

Overall efficiency
With the OPO escape efficiency of 95%, and 1% tapping for gain lock, the efficiency in free-space before fiber coupling is 94%. In fiber, including 97% fiber coupling efficiency, 17% loss in the fiber switch and 1% tapping for phase control, the efficiency is 80%. Finally, with 91% detection efficiency,
the overall efficiency becomes
\[ \eta = 0.94 \cdot 0.80 \cdot 0.91 = 68\% . \] 

Temporal data processing
To recover two-mode squeezing from the acquired time traces affected by a frequency-dependent detector response (leading to a negative slope), spurious interference (leading to slope variations) and an oscillating response from the switch, we use the statistic of 16,000 time traces in a dataset synchronized with the switching process. To compensate for the negative and varying slope of each time trace, linear regression lines (as the dashed lines in the inset of Fig. 2) are subtracted from each individual trace of the dataset. The result is shown in Fig. 5 (left). Here, the repeatable oscillating noise is visible, and compensated for by subtracting the average trace of the dataset. The result is shown in Fig. 5 (right) with a constant temporal histogram and a single time trace at Alice and Bob showing anti-correlations as in ref. 29. For detailed discussion on the data processing, see supplementary information section 2.1.

DATA AVAILABILITY
Experimental data and analysis code is available on request.

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AUTHOR CONTRIBUTIONS
U.L.A., J.S.N., and M.V.L. conceived the experiment. J.S.N., X.G., and C.R.B. designed and built the squeezing source. M.V.L. performed the experiment and analyzed the data. All authors contributed to the manuscript.

ADDITIONAL INFORMATION
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