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# 40 km Fiber Transmission of Squeezed Light Measured with a Real Local Oscillator

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**Abstract:** We demonstrate the generation, 40 km fiber transmission, and homodyne detection of single-mode squeezed states of light at 1550 nm using real-time phase control of a locally generated local oscillator, often called a “real local oscillator” or “local local oscillator”. The system was able to stably measure up to around 3.7 dB of noise suppression with a phase noise uncertainty of around  $2.5^\circ$ , using only standard telecom-compatible components and a field-programmable gate array (FPGA). The compactness, low degree of complexity and efficacy of the implemented scheme makes it a relevant candidate for long distance quantum communication in future photonic quantum networks.

## 1. Introduction

Squeezed states of light have by now been generated for more than three decades [1] and have become a ubiquitous resource in optical quantum information science. Unlike coherent states of light, squeezed light has the outstanding property of exhibiting lower noise uncertainty than the fundamental shot noise in some of its quadratures – known as squeezing – while conjugated quadratures exhibit uncertainties above the shot noise limit – known as anti-squeezing [2,3]. This fundamental quantum property of squeezed states has been the engine of numerous quantum sensing experiments, such as the quantum-enhanced measurements of gravitational waves [4] and vibrational modes of molecules [5, 6], and recent quantum computing models including Gaussian boson sampling [7, 8] and measurement-based quantum computing [9–11]. Furthermore, the use of squeezed states (compared to coherent states) improves the performance of continuous variable quantum key distribution systems by increasing the tolerance to optical loss, excess noise and imperfect error correction [12–14], effectively allowing longer transmission distances or improved security.

The most common technique employed to measure squeezed states of light is homodyne detection, which implements the ideal measurement of one quadrature of the electromagnetic field by using a strong reference beam, called the local oscillator, in conjunction with a (balanced) detection system [2, 15]. Because of its versatility, simplicity and high efficiency, it is a widely employed measurement technique in quantum information protocols including the recent demonstrations of Heisenberg limited quantum sensing [16], measurement-induced quantum computing gates [11], long-distance quantum key distribution [17] and high-speed quantum random number generation [18].

In most quantum optical proof-of-concept experiments, the homodyne detection process is carried out with a local oscillator that originates from the same laser as the one that produces the signal, e.g. the squeezed state. The advantage in doing so is that the local oscillator is naturally frequency-synchronized with the signal, and the remaining slow phase fluctuations can be easily stabilized using simple control systems. However, in real-life applications on quantum communication, distributed quantum sensing and networked quantum computing where the information-carrying optical signal, e.g. the squeezed state, needs to be transmitted through optical fibers to remote locations, a centrally distributed local oscillator is problematic for several reasons. Firstly, the optical power of the local oscillator decreases exponentially with propa-

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5 47 gation distance, and therefore, to provide sufficient optical power at the various nodes in the  
6 48 network for enabling low-noise homodyne detection, a significant amount of power must be dis-  
7 49 tributed through the fiber network. In addition to this direct power wastage, the massive power  
8 50 distribution might also lead to deteriorating non-linear optical effects (such as Brillouin scatter-  
9 51 ring) and to distortion of the quantum state of the signal [19, 20]. Secondly, transmitting the  
10 52 local oscillator along with the signal is also fundamentally problematic for continuous-variable  
11 53 quantum key distribution (CVQKD), as there are several eavesdropping strategies that explic-  
12 54 itly make use of the transmitted local oscillator to corrupt the coherent detection at the trusted  
13 55 receiver, therefore breaching the security of the QKD protocol [21–24].

14 56 Hence, it is preferable to generate the local oscillator locally at the receiving nodes. Obviously,  
15 57 real-time control of the phase difference between the signal and the local oscillator becomes  
16 58 more challenging as the two laser sources are in general not frequency-locked; partly for this  
17 59 reason, many current proof-of-concept CVQKD systems, while using an real local oscillator,  
18 60 use heterodyne reception and do not stabilize the phase in real-time, but rather rely on phase  
19 61 estimation and compensation in post-processing, possibly invoking elaborate phase estimation  
20 62 techniques [25]. Moreover, due to the complications associated with an real local oscillator, all  
21 63 previous experiments on quantum communication with squeezed light have employed a local  
22 64 oscillator derived from the same laser as they used for squeezed light generation.

23 65 In this article, we report on the generation, transmission and homodyne detection of single-  
24 66 mode squeezed states of light at the wavelength of 1550 nm using an real local oscillator with  
25 67 real-time phase control. By exploiting a real-time feedback system, we controlled the frequency  
26 68 and phase of an locally-generated local oscillator to such an extent that it enabled homodyne  
27 69 detection with a phase uncertainty of  $2.51^\circ$  of a squeezed state that had propagated up to 40 km  
28 70 in a telecom fiber. Our demonstration constitutes a critical milestone in the construction of a  
29 71 quantum information network based on continuous variable quantum systems.

## 30 31 72 2. Methods

32 73 Balanced homodyne detection works by interfering the mode to be detected, here named the *sig-*  
33 74 *nal*, with a much more intense optical mode, known as the *local oscillator* (LO), on a balanced  
34 75 beam splitter. The outputs of the beam splitter are simultaneously detected with two photodi-  
35 76 odes, and the resulting photocurrents are electronically subtracted to produce a signal which is  
36 77 proportional to a specific quadrature of the signal. The quadrature being measured is governed  
37 78 by the phase difference of the signal and the local oscillator, so in order to enable a long-term  
38 79 measurement of a specific quadrature – as required for most applications – the phase relation be-  
39 80 tween the two input modes must be kept constant. This is often realized with an active feedback  
40 81 control system. A conceptual schematic of homodyne detection is shown in figure 1.

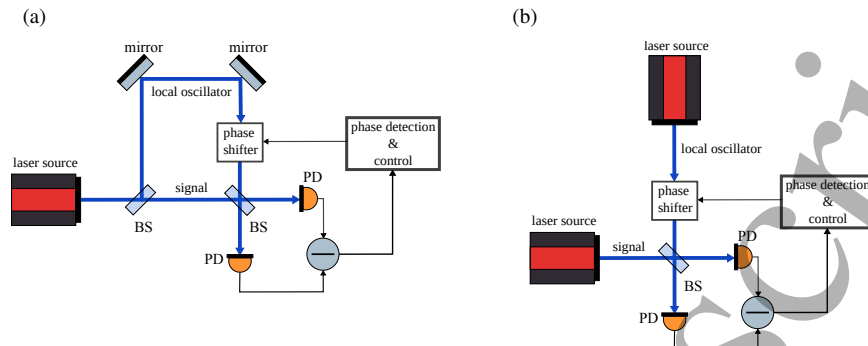


Fig. 1. Conceptual schematic of a typical homodyne detection system. The signal is interfered with the local oscillator onto a balanced beam splitter (BS). The modes output from the BS are input to two photodetectors (PD) and the resulting photocurrents are electronically subtracted, yielding a photocurrent that is proportional to the phase difference between the signal and the local oscillator modes. The latter is used to estimate and control the phase difference, by shifting the phase of the local oscillator relative to the signal (phase shifter). The local oscillator can be (a) generated from the same laser source that produces the signal, or (b) generated from an independent laser source. Blue lines represent optical modes, black lines represent electrical signals.

For the detection of squeezed light, it is common to use the same laser for delivering power to the local oscillator and for generating the squeezed state which means that the central frequency component of the squeezed light is naturally synchronized with the local oscillator frequency. Such frequency synchronization is indeed required as the detection of squeezed light corresponds to the precise detection of adjacent, quantum correlated, frequency side bands located symmetrically around the reference frequency. This in-built frequency synchronization also means that small frequency drifts of the laser play no role in the performance of the measurement.

To achieve homodyne detection of squeezed light at a fixed phase angle with an *independent* local oscillator where frequency synchronization is not inherent, synchronization must be established in real time to counteract the relative frequency drifts. This must be done with a precision that allows for the simultaneous detection of symmetrically correlated sidebands such that the squeezing is revealed. Towards this end, we employ a pilot tone technique as illustrated in Fig. 2a: A pilot tone is a coherent excitation which is extracted from the central laser (which is used for squeezed light generation) and frequency shifted with respect to the squeezed light carrier by  $\Omega_p \approx 2\pi f_p$ . The pilot tone is combined with the squeezed light mode, residing as a single frequency sideband, thereby providing a frequency and phase reference for the local oscillator upon reception at the homodyne detection station. We note that pilot tones are an essential part of the coherent control scheme commonly used to actively control squeezed light sources [4, 26, 27] and, thus, they are readily available in many squeezed light experiments. At the receiver station, the frequency offset and phase difference relative to the real local oscillator are measured through interference at a beam splitter as shown in the figure, and the resulting signals are subsequently used to control the frequency and phase of the real local oscillator mode to compensate for any phase and frequency drifts. The feedback signal is divided into a slow port for frequency control of the LO laser and a fast port for phase control via an electro-optics modulator.

The output signal of a balanced homodyne receiver measuring the pilot tone with an independent laser as LO is proportional to

$$\sqrt{P_p P_{LO}} \cos((\Omega_p + \Delta\Omega(t))t + \Delta\phi(t) - \phi_{\text{set}}), \quad (1)$$

where  $P_p$  and  $P_{LO}$  are the optical powers of the pilot and local oscillator at the input to the

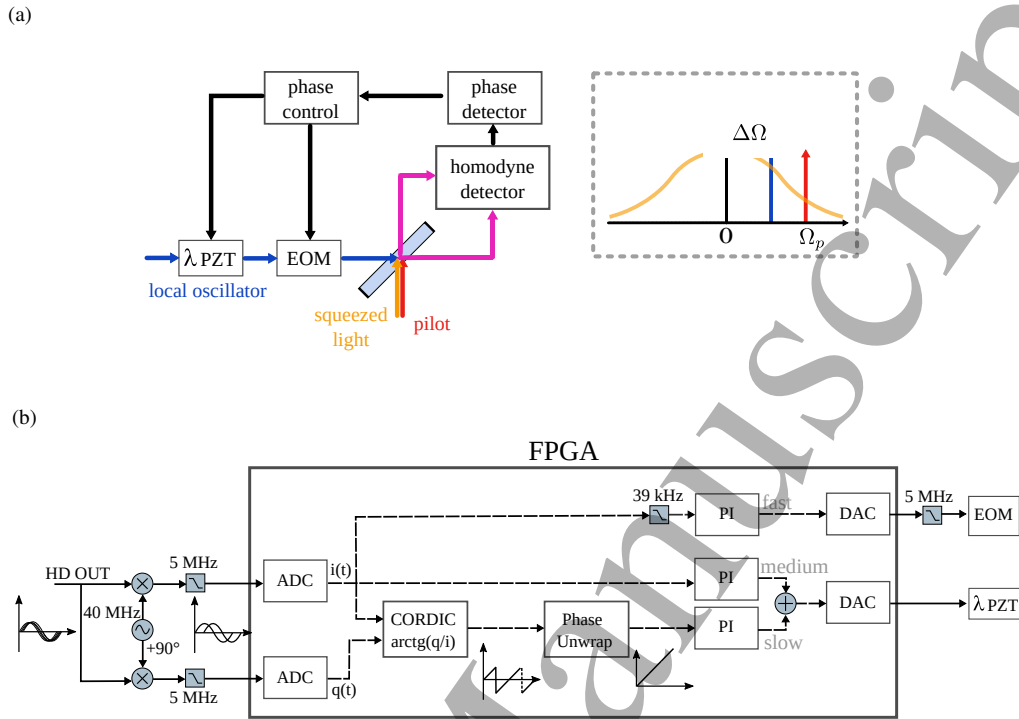


Fig. 2. (a) Conceptual schematic of homodyne detection using a real local oscillator. The frequency-shifted pilot interferes with the real local oscillator on a balanced beam splitter. A phase detector delivers suitable error signals to control the frequency of the local oscillator, via a piezoelectric wavelength modulator ( $\lambda$  PZT), and its phase relative to the pilot, through an electro-optic phase modulator (EOM). Wavelength control aims at shifting the local oscillator by  $f_p = \Omega_p/2\pi = 40$  MHz from the pilot to perform homodyne detection of the squeezed mode. The diagram on the right illustrates the situation in the frequency domain, with the local oscillator, pilot and squeezed fields indicated by the same colors as on the left.

(b) Conceptual schematic of the phase control system for the real local oscillator. The unwrapped instantaneous phase is generated from the pilot/local oscillator interference contained in the signal "HD OUT" inside a field gate-programmable gate array (FPGA), via CORDIC algorithm and phase unwrapping, and is used for a coarse control on the frequency of the local oscillator. Finer frequency control is performed using the demodulated interference  $i(t)$  at the pilot offset frequency  $f_p$ . The same error signal is then used for fast phase correction by the electro-optic phase modulator. ADC: analog-to-digital converter. PI: proportional-integral controller. DAC: digital-to-analog converter.

110 homodyne detector,  $\Delta\Omega(t)$  is the time dependent angular frequency offset of the two lasers, and  
 111  $\Delta\phi(t)$  is the time dependent phase difference between LO and pilot (modulo their frequency  
 112 offset). The goal of our active feedback scheme is to achieve  $\Delta\Omega(t) = \Delta\phi(t) = 0$  and to thereby  
 113 perform homodyne detection at the phase angle  $\phi_{\text{set}}$ .

The laser we employed as LO laser in the experiment was an NKT Photonics E15 which allows for frequency tuning via a piezo-electric transducer (PZT). We complemented this slow frequency actuator with a fast electro-optical phase modulator (EOM), cf. Fig. 2a. The feedback loop, consisting of phase detection and control, was implemented in a field-programmable-gate array (FPGA) as shown in Fig. 2b. To limit the required sampling rate of the analog-to-digital converters (ADCs) connected to the FPGA we first electrically down-mixed the output of the homodyne detector, see Eq. 1, with two orthogonal sinusoidal signals with amplitude  $A_r$ , frequency  $\Omega_p$  and phase  $\phi_{\text{set}}$ . After down-mixing we low-pass filtered the signal with 5 MHz cutoff fre-

quency. The electrical sinusoidal signals have to be synchronized with the generation of the pilot tone at the squeezed light source which can either be achieved by transmitting a clock signal using a wavelength multiplexed channel or a dedicated servicing fiber, which is a standard technique in quantum communication, or potentially by more sophisticated digital-signal-processing [28]. After down-mixing and low-pass filtering, the two signals are given by

$$i(t) \propto \sqrt{P_p P_{LO}} A_r \cos(\Delta\Omega(t)t + \Delta\phi(t)) , \quad (2)$$

$$q(t) \propto \sqrt{P_p P_{LO}} A_r \sin(\Delta\Omega(t)t + \Delta\phi(t)) . \quad (3)$$

114 These were sampled by two ADCs with sampling period  $T_s$ , resulting in a discretization of time  
115 as  $t = nT_s$  with sample index  $n$ .

116 In the FPGA, we established two signal paths corresponding to the two actuators: A fast path  
117 using the EOM as actuator, and a slow path actuating with the PZT. For the PZT actuation path  
118 we estimated the instantaneous phase error by calculating the arctan between  $q(t)$  and  $i(t)$  using  
119 a coordinate rotation digital computer (CORDIC) algorithm [29] which yields

$$\Phi_e(nT_s) \simeq \Delta\Omega(nT_s)nT_s + \Delta\phi(nT_s) \pmod{[-\pi, \pi]} . \quad (4)$$

120 If the phase error exceeds  $[-\pi, \pi]$ ,  $\Phi_e$  undergoes an abrupt transition, often called *phase wrap*.  
121 This can be avoided by accumulating phase increments between consecutive samples, namely  
122  $\Phi_e(nT_s) - \Phi_e((n-1)T_s)$  and detecting a phase wrap event by comparing the last two bits of  
123 the binary representation of the current phase increment, and compensating for it by adding or  
124 subtracting  $2\pi$  [30]. Phase unwrapping allows to detect a wider range of phase fluctuations, at  
125 the cost of decreased signal resolution due to a fixed number of bits used in the implementation.

126 To generate the actuator signal for the PZT, the output of the phase unwrapping algorithm  
127 was injected into a proportional-integral (PI) controller whose output was added to the output  
128 of another PI controller taking directly  $i(t)$  as error signal. The latter allowed to control the  
129 medium frequency range which was not possible with the instantaneous phase error signal due  
130 to latency.

131 The fast path used  $i(t)$  as error signal. This was low-pass filtered at 39 kHz, since at higher  
132 frequencies the measured phase fluctuations hit the noise floor of the detection system. After  
133 PI control, the signal was converted to the electrical domain and low-pass filtered at 5 MHz to  
134 eliminate high frequency electronic noise.

135 The lock was acquired by first tuning the frequency of the LO laser into the capture range  
136 of our controller via the laser's temperature. The capture range was determined by the 5 MHz  
137 lowpass filter before analog-to-digital conversion. The lock was then engaged by first disabling  
138 the fast path as well as the medium frequency part of the slow path which allowed us to achieve a  
139 frequency lock first. Afterwards the two additional paths were enabled to lock the phase without  
140 cycle slips. We note that the homodyne angle can be adjusted by changing the phase  $\phi_{\text{set}}$  of the  
141 electrical LO used for downmixing the homodyne detector output.

142 The described phase locking scheme was experimentally tested with the experimental setup  
143 in Fig. 3 showing a schematic for squeezing generation, fiber transmission and detection.

144 The laser that generates the squeezed and the pilot modes is an NKT Koheras ADJUSTIK  
145 E15, at 1550.12 nm wavelength. Squeezed vacuum at 1550 nm was generated through para-  
146 metric downconversion using a periodically poled potassium titanyl phosphate (KTP) crystal  
147 placed inside an optical cavity resonant for the squeezed field and the pump field at 775 nm. The  
148 pump was generated by a commercial second harmonic generation module (NTT Electronics  
149 WH-0775-000-F-8-C), consisting in a lithium niobate (LN) crystal with waveguide. While the  
150 pump field was used to lock the squeezed light source's cavity on resonance, we used the coher-  
151 ent control scheme for the phase. An acousto-optic modulator (AOM) frequency-shifted a small  
152 fraction of the fundamental laser beam at 1550 nm by  $f_p = 40$  MHz which was then injected

153 into the cavity and its phase was locked with respect to the pump field. This constituted the pilot  
 154 signal used at the detection stage. It had a power of about  $5 \mu\text{W}$  leaving the cavity and it coprop-  
 155 agated with the squeezed light. More details about the squeezed light source can be found in  
 156 Ref. [27]. In principle, lower pilot frequencies can be chosen, with the caution that antisqueez-  
 157 ing noise has higher impact at lower frequencies, thereby resulting in lower signal-to-noise ratio  
 158 for phase locks involving the pilot tone. In Ref. [27],  $f_p = 40 \text{ MHz}$  was set to lie mostly out-  
 159 side the squeezer spectral response and allow for a clean spectral measurement of the squeezed  
 160 light quadratures. Reflected off a dichroic beam splitter (DBS), the squeezed and pilot modes  
 161 were coupled from free space into a standard single-mode optical fiber (SMF-28) and propagated  
 162 towards the free space receiver station, where homodyne detection of the squeezed mode took  
 163 place using a separate laser source at  $1550.12 \text{ nm}$  wavelength (NKT Koheras MIKRO E15) as  
 164 local oscillator. To match the polarization of the squeezed light after transmission through the  
 165 fiber to the local oscillator we used a quarter waveplate and a half waveplate.

### 166 3. Results

167 All our measurements compare the performance of the real LO with a *regular* LO drawn from  
 168 the squeezed light's laser source and transmitted through a separate short optical fiber - 2 m  
 169 length. Using the same length of regular LO fiber as for the signal channel would have been  
 170 more realistic, but we chose a short fiber to benchmark the real LO against the best possible  
 171 regular LO scenario.

172 The experimental results are shown in Fig. 4. First, we transmitted the squeezed light through a  
 173 10 m fiber and compared the performance of the phase locked loop to a measurement for which  
 174 we used a regular LO transmitted along with the squeezed light, through a separate short optical  
 175 fiber. This is shown in Fig. 4a where we plot the variance of the squeezed ( $V_-$ ) and anti-squeezed  
 176 ( $V_+$ ) quadratures for varying pump power of the squeezed light source. To the experimental data  
 177 points we fitted a model given by [31, 32]

$$V_{\pm} = V_{\pm}^0 \frac{1 + e^{-2\sigma^2}}{2} + V_{\mp}^0 \frac{1 - e^{-2\sigma^2}}{2}, \quad (5)$$

178 with

$$V_{\pm}^0 = 1 \pm \frac{4\eta F_g}{(1 \mp F_g)^2 + (f/f_{\text{sqz}})^2}. \quad (6)$$

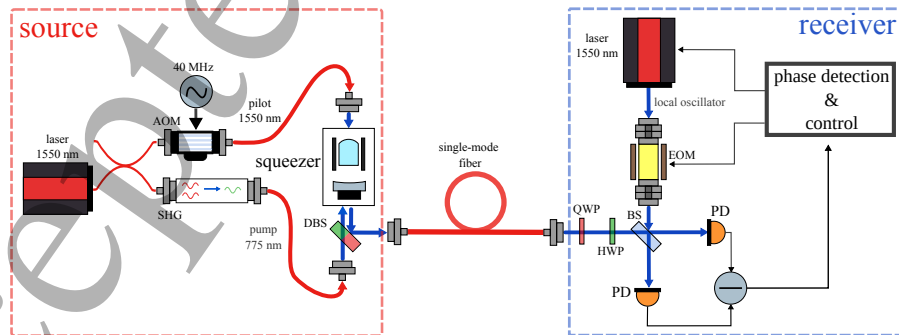


Fig. 3. Basic scheme of the experimental system. Red lines represent light propagating in optical fiber. Blue lines represent light propagating in free space. Black lines represent electrical signals. AOM: acousto-optic modulator. SHG: second-harmonic generation module. DBS: dichroic beam splitter. EOM: electro-optic modulator. HWP: half-wave plate. QWP: quarter-wave plate. BS: beam splitter. PD: photodiode. The figure does not include any employed control system.



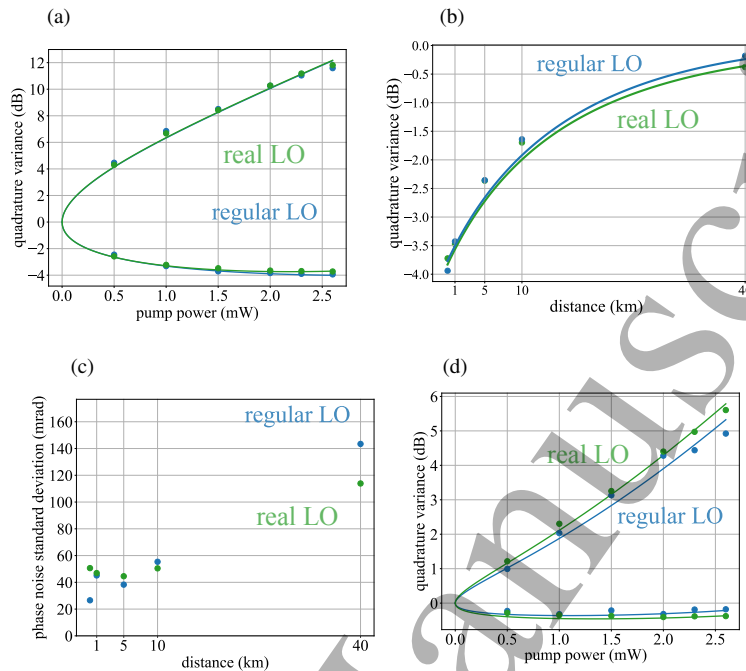


Fig. 4. Experimental results. (a) and (d) present the measured squeezed (below zero) and antisqueezed (above zero) quadrature variance with the two types of local oscillator, for different pump field optical powers coupled into the squeezer, and fiber lengths of 10 m (figure (a)) and 40 km (figure (d)). Figures (b) and (c) represent the squeezed quadrature variance and estimated phase noise standard deviation, respectively, for 2.6 mW pump field optical power and different fiber lengths. real local oscillator: green. Regular local oscillator: blue. Dots represent experimental data, solid lines represent fitting curves. If not visible, the error bars are smaller than the dot sizes.

Here,  $\eta$  is the overall efficiency,  $F_g = \sqrt{P_{\text{pump}}/P_{\text{threshold}}}$  with  $P_{\text{pump}}$  being the optical power of the pump field coupled into the squeezed light source and  $P_{\text{threshold}} \approx 5.12$  mW [27] the pump power where the lasing threshold is reached,  $f = 12.2$  MHz is the measurement frequency,  $f_{\text{sqz}} \approx 66$  MHz [27] is the half-width-half-maximum of the squeezed light source's frequency response and  $\sigma$  is the standard deviation of the phase noise.  $V_{\pm}^0$  are the variances with zero phase noise.

As can be seen from the figure, the measured squeezing with the phase-locked real LO laser is almost the same as with the regular LO stemming from the transmitter. For the highest pump power we measured 3.7 dB and 3.9 dB, respectively. The difference can be explained by phase noise which we determined by the fit to be 56 mrad for the real LO and 29 mrad for the regular one. The total efficiency of the setup was 68 % which limited the measured squeezing to about 3.7 dB.

We then added a 1, 5, 10 and 40 km fiber between the squeezed light source and the receiver and measured squeezing with both the real LO from the receiver laser and the regular LO from the transmitter laser. The power of the pump field of the squeezed light source was 2.6 mW. The results can be seen in Fig. 4b. We note that for fair comparison we did not transmit the regular LO from the transmitter laser through the same fiber but instead used another fiber of constant length. This however led to the accumulation of phase drifts caused by the long fibers the squeezed light travelled through. While the coherence length of the lasers by far exceeds 40 km, the phase fluctuations in the fiber made it necessary to use a fast EOM for phase locking.

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198 From the fit of the theoretical model, shown in the figure, we obtained an effective value for the  
199 fiber attenuation of 0.25 dB/km which is slightly higher than the manufacturer's specification of  
200 0.18 dB/km. The reason is partly due to changing coupling losses when attaching the different  
201 fibers.

202 The residual phase noise standard deviations at the given distances are shown in Fig. 4c.  
203 Clearly, the phase noise increases with transmission distance which can be explained by two  
204 effects: Firstly, the signal-to-noise ratio of the pilot beam drops with transmission distance,  
205 thereby reducing the quality of the error signals at the input of the PI-controllers. Secondly, the  
206 phase fluctuations become stronger while the light travels through the fiber. Since the loop gain  
207 stays constant, the deviations from the lock point increase. Notably the phase noise at 40 km is  
208 higher for the regular LO than for the real LO.

209 This effect can also be seen in Fig. 4d where we investigated the squeezed light transmitted  
210 through 40 km of fiber in more detail. Here we varied again the pump power of the squeezed  
211 light source and measured the noise variances of the squeezed and anti-squeezed quadratures  
212 using both LOs. The overall optical transmission was determined from the fit of the theoretical  
213 model of Eq. 5 to 13% for the real LO and 11 % for the regular one. The deviation may come  
214 from a change of fiber in-coupling or polarization drifts. For the phase noise standard deviation  
215 we obtained 147 mrad and 115 mrad for the real and regular LO, respectively. At 40 km distance  
216 the phase drifts seem to be better compensated by the phase lock of the real LO than the regular  
217 one.

218 At a distance of 5 km we investigated the quadrature noise spectrum and phase noise in more  
219 detail. Figure 5a shows the quadrature noise power spectrum of the squeezed light in the range  
220 0 to 20 MHz measured with the real local oscillator. The noise power has been normalized to  
221 the noise power of the vacuum state. The pump power was 2.6 mW. The fit of the theoretical  
222 model from Eq. 5 reveals an optical transmission of 50.0 %, corresponding to about 1.3 dB fiber  
223 attenuation, and a phase noise standard deviation of 65 mrad. The inset shows histograms of  
224 the noise for the squeezed state in the 0 to 20 MHz frequency range in the squeezed and anti-  
225 squeezed quadrature and the vacuum state as comparison.

226 By acquiring the 40 MHz pilot signal with a data acquisition system digitizing the coherent re-  
227 ceiver output we extracted the residual phase noise power spectral density. The phase estimation  
228 procedure, which is explained in detail in the supplementary material, has been performed for  
229 the regular and the phase-locked real local oscillator. Figure 5b shows the phase noise spectrum  
230 for the squeezed quadrature while Fig. 5c shows it for the antisqueezed quadrature and the cor-  
231 responding phase histograms are shown in Fig. 5d and e, respectively. When phase locked, the  
232 signal-to-noise ratio of the pilot is different in the two cases due to the antisqueezing which low-  
233 ers it by around 5 dB, however, the performance of the phase lock seems to be similar. Although  
234 not directly visible in the figure, between the cases of squeezed quadrature and antisqueezed  
235 quadrature measurement, the noise floor at the pilot frequency (40 MHz) differs by 5 dB, i.e.,  
236 approximately -2 dB in the squeezed case and +3 dB in the antisqueezed case. Thus, since the  
237 pilot mode is noisier when measuring antisqueezing, the signal-to-noise ratio for the control sys-  
238 tem is lower in this condition, provided the pilot mode has the same optical power all the time.  
239 Even so, the performance of the phase lock seems to be similar for squeezed and antisqueezed  
240 quadrature measurements. At low frequencies the phase noise of the real LO is slightly larger  
241 than the phase noise of the regular LO. The phase histograms are taken over the entire frequency  
242 range. Here the peak around 80 kHz in the spectra for the regular LO seems to compensate the  
243 better phase noise behaviour at low frequencies.

#### 244 4. Discussion

245 The developed system allowed homodyne detection of up to 3.7 dB squeezed states of light over  
246 optical fiber spools of up to 40 km length. The control system exhibited a minimum phase noise

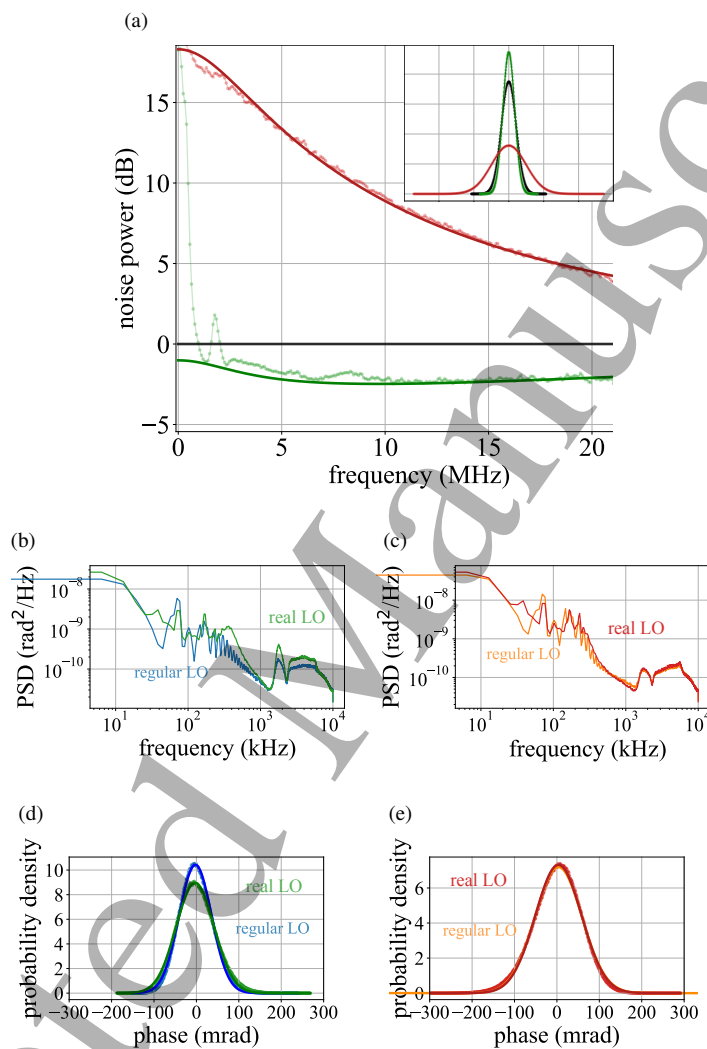


Fig. 5. (a) presents the quadrature measurements performed with the real local oscillator, for 5 km fiber length and 2.6 mW pump field optical power. The largest plot represents the statistical power of the squeezed (below zero) and antisqueezed (above zero) quadratures of the signal, relative to vacuum quadrature noise. As an insert, we include the calculated histogram-based quadrature probability density functions. Figures (b) and (c) represent the power spectral densities (PSD) of the estimated phase noise in the same measurements. Figures (d) and (e) show the histogram-based probability density functions of the phase noise together with Gaussian fits (solid lines). real local oscillator: squeezed quadrature in green, anti-squeezed quadrature in red. Regular local oscillator: squeezed quadrature in blue, anti-squeezed quadrature in orange. Black color represents the vacuum quadrature.

standard deviation of  $(43.78 \pm 0.07)$  mrad, corresponding to  $(2.508 \pm 0.004)^\circ$ , under phase control. In particular, it enables the measurement of squeezed states and other quantum states of light spatially separated from the source without the distribution of high-power local oscillators through the fiber network (thereby avoiding detrimental effects such as non-linear Brillouin scattering in optical fibers [20]). The maximum measured amount of squeezing was not primarily limited by phase noise, but rather by the optical transmission efficiency of the squeezed mode through the experimental setup, which can be improved by accurate single-mode fiber coupling and by optimizing the detection efficiency in future implementations. The phase noise performance of the phase control system could be improved by reducing the electronic amplification noise at the output of the homodyne detector and at the input of the control actuators, and by performing the downmixing and low-pass filtering that yield the signals  $i(t)$  and  $q(t)$  inside the FPGA rather than at its input, thereby avoiding the use of potentially noisy analog mixers and low-pass filters. Furthermore, the three employed PI control systems should be carefully designed, to ensure that phase noise is effectively compensated for over its full Fourier spectrum support, and to avoid detrimental interference between the different control systems in action.

## 5. Conclusions

This work has demonstrated the possibility of transmission and homodyne detection of generalized quadratures of squeezed states of light at 1550 nm wavelength over at least 40 km single-mode optical fiber (compatible with large metropolitan networks), using a phase-locked real local oscillator. Our system makes use of standard telecom components, such as piezoelectric fiber stretchers and electro-optic modulators, and widely used general-purpose digital signal processing devices, such as FPGAs. It is a general homodyne detection technique that allows for the characterization of arbitrary states over long distances in a network, as needed for a variety of quantum information tasks. For quantum key distribution, using a true local oscillator disables eavesdropping attacks that target the transmitted local oscillator [24], and using a real-time phase control avoids the need for accurate and computationally heavy phase estimation techniques, often performed in post-processing within current proof-of-concept CVQKD experiments [25]. The system becomes particularly interesting if applied to the quadrature detection of non-Gaussian and entangled states of light in distributed photonic quantum computing based on measurement-induced quantum computing modules [11], in distributed quantum sensing systems [33, 34] and in quantum communication networks [22, 35]. The quadrature detection of non-classical light with real local oscillators therefore constitute an important technique in future quantum photonics networks for quantum computing, quantum sensing and quantum communication.

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## 7. Data availability

Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

## 8. Disclosures

The authors declare no conflicts of interest.

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