

A fully guided-wave squeezing experiment for fiber quantum networks

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Squeezed light is a fundamental resource for quantum communication. In view of its real-world applications, the realization of easy-to-operate experimental systems compatible with existing fiber networks is a crucial step. To comply with these requirements, we demonstrate the feasibility of a squeezing experiment at a telecom wavelength realized, for the first time, in an entirely guided-wave fashion. In our work, the state generation relies on waveguide nonlinear optics technology while squeezing collection and transmission are implemented by using only telecom fiber components. By doing so, we observe up to -1.83 ± 0.05 dB of squeezing emitted at 1542 nm in the CW pumping regime. The compactness and stability of the experiment, compared to free-space configurations, represent a significant advance towards achieving out-of-the-lab continuous variable quantum communications that are fully compatible with long-distance operations in telecom fibers. We believe that this work stands as a promising approach for real applications as well as for “do-it-yourself” experiments. © 2016

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The generation and manipulation of continuous variable (CV) nonclassical states of light have been the objects of intense research due to their importance in both fundamental and applied physics [1,2]. Among others, a valuable feature of CV quantum resources is that they can be generated in a deterministic way at the output of nonlinear optical media [3]. Moreover, CV entanglement is affected but never vanishes completely for any level of external loss [4]. On these bases, CV quantum optics has experienced an increasing interest in its application to quantum key distribution (QKD) [5], with many proposals based on both single-mode [6–8] and two-mode squeezed light [9,10]. Entanglement distillation and entanglement swapping schemes for long-distance quantum communications have been demonstrated [5,11],

and systematic studies have been performed on the robustness of nonclassicality against the communication channel losses [12,13].

A further step towards real-world applications of CV quantum communications has been done by generating squeezed light in the telecom C-band of wavelengths, where low-loss optical fibers and high-performance standard components are available [14–16]. In the perspective of implementing quantum networks that exploit optical fibers to connect distant atomic quantum memories, a quantum interface has recently been developed that converts squeezed light from telecom to visible wavelengths compatible with suitable atomic transitions [17]. In the same spirit, a light–matter interface, coupling light guided in a tapered nanofiber to cold atoms, has been demonstrated [18], as well as the storage of up-converted telecom single photons in a doped crystal [19].

In this framework, and in order to comply with further out-of-the-lab realizations of CV quantum optics, we demonstrate, for the first time, the feasibility of a full guided-wave approach for the generation, distribution, and measurement of squeezed light at a telecom wavelength.

In our scheme, single-mode squeezing at 1542 nm is generated by spontaneous parametric down-conversion (SPDC) in a periodically poled lithium niobate ridge waveguide (PPLN/RW). At the output of the PPLN/RW, the nonclassical beam is measured with a fiber homodyne detector. This configuration allows implementing an extremely easy setup based entirely on commercially available components and fully compatible with existing fiber networks. On one hand, nonlinear optics based on waveguide technology offers, compared to bulk implementations, better compactness and stability [20], as well as the possibility of efficient SPDC in a single-pass arrangement [21–24]. On the other hand, the use of off-the-shelf telecom fiber components permits the realization of a simple and plug-and-play setup that requires no alignment effort for spatial mode matching and that can be straightforwardly modified by connecting additional fiber components [25]. Our approach, by first combining these two technologies and CV quantum optics, paves the way towards the realization of accessible and versatile experiments for CV quantum communication [26].

Eventually, we note that the possibility of miniaturizing CV quantum technologies is at the center of recent investigations, in particular with the demonstration of photonic chips for *in situ* operations on squeezing [27] or for the generation of bright squeezed beams [28]. Compared to these works, our Letter follows a complementary vision by fully exploiting guided-wave optics for networking between remote quantum sources and nodes.

The experimental setup is presented in Fig. 1(a). A telecom continuous-wave (CW) laser at 1542 nm (Toptica, DL Pro, fiber coupled) is amplified using an erbium-doped fiber amplifier (Keopsys, CEFA-C-HG) and directed towards a 70:30 fiber beam splitter. The less intense beam is used as the local oscillator (LO) for the homodyne detector. The brighter beam is frequency doubled to 771 nm via second harmonic generation (SHG) to be subsequently employed as pump field for the SPDC process for the squeezing generation. The SHG stage is implemented employing a commercial periodically poled lithium niobate waveguide (PPLN/W, HC-photonics). At its output, the power at 771 nm, P , scales with the input power at 1542 nm, P_{in} , as $P = P_{in} \cdot \tanh^2(\sqrt{\eta_{SHG} P_{in}})$ [29], with a conversion efficiency of $\eta_{SHG} \sim 2000\%/W$. Frequency-doubled light is directly collected using a standard single-mode fiber at 780 nm that also acts as a near perfect stop filter for residual unconverted light at 1542 nm. The beam at 771 nm then passes through an in-line variable fiber attenuator and is directed towards the SPDC stage. Type-0 SPDC is obtained in a 4 cm-long commercial PPLN/RW working at frequency degeneracy around 1542 nm (NEL, WH-0770-000-F-B-C). The ridge waveguide design offers a strong light confinement owing to a step index profile and guarantees high conversion efficiency over a large bandwidth of operation. Moreover, compared to other PPLN/W structures showing similar efficiencies, these devices show particularly high power handling capabilities, which are required for high parametric gain regimes [30]. We stress that this is, to our knowledge, the first time a PPLN/RW has been employed for a CV experiment. By means of single-photon regime characterization, we estimate an SPDC conversion efficiency of $\sim 1.2 \cdot 10^6$ photon pairs/mW/GHz/s. The SPDC emission covers a continuous spectral bandwidth of 80 nm FWHM [see Fig. 1(b)] corresponding to 10 THz in the frequency

domain. We stress that, as no optical cavity is required to enhance the SPDC process, this value directly represents the squeezing bandwidth [22]. The PPLN/RW input and output facets are connected to polarization-maintaining fibers (PMFs), whose coupling with the ridge waveguide is optimized by the manufacturer thanks to micro-lenses. For the input pump beam at 771 nm, we measured a fiber-to-waveguide transmission of ~ 0.43 . At the output of the ridge waveguide, single-mode squeezed light at 1542 nm is collected with a measured coupling efficiency of $\eta_c \approx 0.80$, and it is directly available at the output of the PMF. To detect it, we send it to a fiber homodyne detector based on a 50:50 fiber beam splitter (50:50 f-BS) followed by two InGaAs photodiodes. In order to minimize the Fresnel reflection losses, the outputs of the 50:50 f-BS are spliced to antireflection-coated fiber optic patch cords. The measured transmission of the signal path from the PMF output to the homodyne optical outputs is $\eta_T \approx 0.95$.

In addition to the compactness and stability of the setup, a major advantage of guided-wave optics lies in the achievement of a high degree of spatial mode matching between the LO and the signal without optical adjustment at the 50:50 f-BS inputs [27]. This huge benefit extremely simplifies the homodyne detector implementation [see Fig. 1(a)]. Moreover, compared to the pulsed regime, CW pumping bypasses the difficulties of obtaining an LO matched with squeezed light in the temporal domain [23]. Polarization matching is simply obtained by inserting a fiber polarization controller into the LO path. A homemade fiber stretcher implements the LO phase scanning [31]. At the 50:50 f-BS outputs, light is directly sent to two InGaAs photodiodes (Thorlabs, FGA10, without cap) each showing $\eta_d \approx 0.88$ quantum efficiency at 1542 nm. The difference photocurrent, obtained by connecting the photodiodes to each other, is amplified by a low-noise homemade trans-impedance amplifier with a bandwidth of ~ 5 MHz. The noise power is measured for each quadrature phase by an electronic spectrum analyzer (HP, ESA-L1500A) set at zero span around the analyzing frequency. As discussed in [22], the observed bandwidth of the squeezed states produced by PPLN/Ws is ultimately limited by that of the homodyne detection. In our experiment, we chose

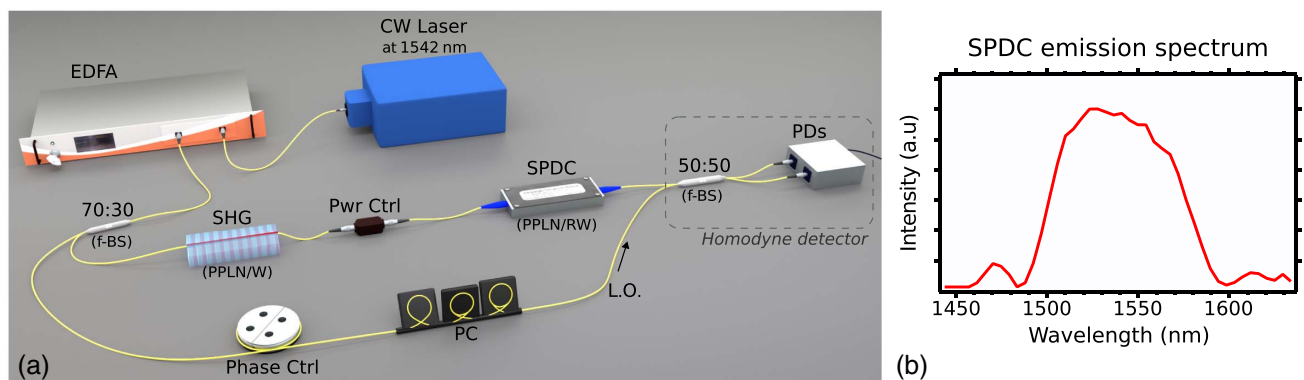


Fig. 1. (a) Schematic of the experimental setup. A fiber-coupled CW telecom laser at 1542 nm is erbium-doped fiber amplified and split into two beams by means of a 70:30 fiber beam splitter. The less intense beam serves as the LO, while the brighter one is frequency doubled via SHG in a PPLN/W and used to pump a ridge waveguide (SPDC, PPLN/RW). The power of the beam at 771 nm is controlled with an in-line fiber attenuator (Pwr Ctrl). At the output of the SPDC stage, the squeezed vacuum state at 1542 nm is sent towards a fiber homodyne detector, where it is optically mixed with the LO based on a balanced fiber beam splitter (50:50) followed by InGaAs photodiodes. The LO phase is scanned thanks to a fiber-stretcher module (Phase Ctrl), while a fiber polarization controller (PC) allows the polarization mode matching at the homodyne detector. (b) SPDC emission spectrum. The spectrum is centered at 1542 nm and shows a bandwidth of 80 nm FWHM, corresponding to 10 THz.

to work at 2 MHz, where for an LO of 6.3 mW, we observe a signal-to-noise ratio (SNR) of 15.6 dB. The residual electronic noise associated with the detectors can be taken into account as an additional loss, $\eta_{el} = (\text{SNR} - 1)/\text{SNR} \approx 0.97$ [32]. Note that squeezing at the telecommunication wavelength of 1550 nm can be detected over bandwidths of more than 2 GHz by means of ultra-fast detectors and electronics [33]. In this context, we recall that the exploitation of broadband squeezing is a key element for quantum channel multiplexing and high-speed quantum communications [33,34].

In the presence of losses, the variance of measured squeezed state quadratures, $\Delta X_m^2(\theta)$, can be written as [35]:

$$\Delta X_m^2(\theta) = \eta[e^{2-r} \cos(\theta) + e^{-2-r} \sin(\theta)] + 1 - \eta, \quad (1)$$

where η is the overall detection efficiency. Here, the values $\theta = 0$ and $\theta = \pi/2$ correspond to anti-squeezing and squeezing, respectively. In Eq. (1), the squeezing parameter r depends on the SPDC pump power as $r = \mu * \sqrt{P}$, where μ is proportional to the crystal length and to the nonlinear interaction strength.

Figure 2 shows detected squeezing and anti-squeezing (both in dB) as functions of the pump power at 771 nm. We adopt a frequency domain approach to measure the quadrature noise [36]. Each point corresponds to an average over several acquisitions with an error of ± 0.05 dB. The data include the effect of imperfect ridge waveguide-to-fiber coupling, propagation losses in the waveguide and in the fiber components, nonunitary detection efficiency, and residual electronics noise. The pump powers reported on the graph are estimated with an error of 5% and refer to inferred values at the PPLN/RW input, taking into account the coupling and propagation losses at 771 nm. Different power levels are obtained with the variable attenuator at the SHG output. As can be seen, the experimental data for both squeezing and anti-squeezing correctly follow the quadratic behavior predicted by the theory. This shows, in particular, the absence of unwanted excess noise on anti-squeezed quadratures. By fitting the entire ensemble of data with Eq. (1), we obtain $\mu_{\text{fit}} = (0.101 \pm 0.002) \cdot \text{mW}^{-1/2}$ and an overall detection efficiency of $\eta_{\text{fit}} = 0.54 \pm 0.01$. A comparison of η_{fit} with our estimated detection efficiency, $\eta_{\text{est}} = \eta_c \cdot \eta_T \cdot \eta_d \cdot \eta_{el} \approx 0.65$, gives for the propagation losses inside the ridge waveguide a value of $\eta_{\text{wg}} \approx 0.4$ dB/cm, which is in agreement with the typical reported values [30]. Figure 3 shows a typical squeezing curve obtained by scanning the phase of the

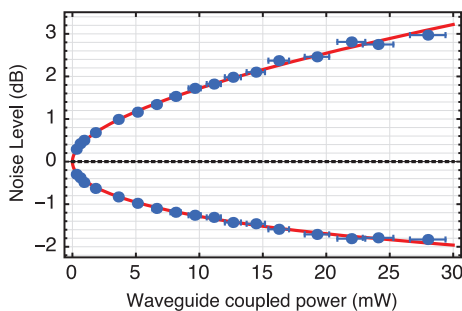


Fig. 2. Squeezing and anti-squeezing levels as functions of the pump power coupled inside the PPLN/RW. Each point corresponds to the mean value of the minima (maxima) of the quadrature noise power (see, as an example, Fig. 3). The error on each point is ± 0.05 dB for the noise levels and 5% on the pump powers. The data fit gives an overall detection efficiency of $\eta_{\text{fit}} = 0.54 \pm 0.01$ and a squeezing parameter of $\mu_{\text{fit}} = (0.101 \pm 0.002) \cdot \text{mW}^{-1/2}$ [see Eq. (1)].

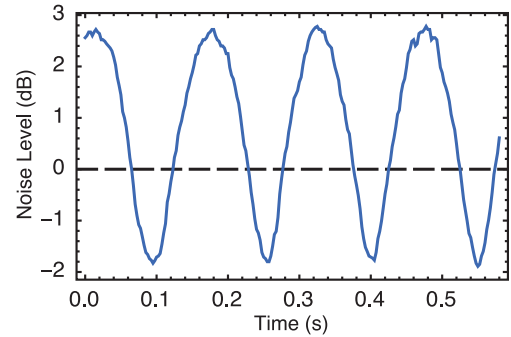


Fig. 3. Normalized noise variances at 2 MHz of the squeezed vacuum state at 28 mW of coupled pump power as a function of the local oscillator phase (proportional to the time). The spectrum analyzer resolution and the video bandwidths are set to 300 kHz and 30 Hz, respectively.

local oscillator over time. It corresponds to the highest pump power (28 mW) coupled inside the PPLN/RW and to a measured squeezing value of -1.83 ± 0.05 dB, with an anti-squeezing of 2.79 ± 0.05 dB. We stress that, by correcting the measured values for η_{est} , we can infer the squeezing at the output of the waveguide to be ~ -3.4 dB, which is among the best values reported to date for CW-pumped squeezing [22]. A further improvement could be obtained by reducing the propagation losses inside the PPLN/RW and by employing detectors with a higher η_d at ~ 1550 nm. The fabrication of low-loss ridge waveguides is at the center of intense investigations, with encouraging results leading to propagation losses lower than 0.2 dB/cm [37]. In parallel, detection efficiencies as high as 0.99 at 1550 nm have already been demonstrated on custom detectors [14]. Eventually, the setup performances could be enhanced by improved pumping conditions. These could be achieved, for example, by implementing another PPLN/RW for the SHG stage. This way, higher SHG pumping regimes can be attained, thus leading to available optical powers at 771 nm up to 1 W [30]. By assuming, as for our system, a coupled input power at 771 nm of 430 mW and by considering lower propagation losses inside the PPLN/RW, we can expect for the squeezing at the output of the SPDC a value as high as -9.9 dB.

Let us emphasize that for any application relying on entanglement as a quantum resource, our setup can be easily modified so as to generate two-mode squeezing. This can be achieved by mixing the output of two identical PPLN/RWs at a 50:50 f-BS plugged just before the homodyne detector. The use of such a fiber component would automatically guarantee the mode-matching conditions for high-visibility quantum interference between the two squeezed states [27] and will only introduce an additional propagation loss typically of 0.05 dB. Experimentally, the relative phase between the two squeezers can be locked by recycling the residual light at 771 nm after the SPDC stage [38]. The LO phase for the double homodyne detection can be locked by implementing a duty-cycled data acquisition scheme [39]. By considering our best measured squeezing level of -1.83 ± 0.05 dB and based on the Duan criterion for CV entanglement [40,41], this configuration would lead to a correlation variance of $0.68 < 1$, which is well below the classical limit and is in line with recent experiments showing the on-chip detection of Einstein–Podolsky–Rosen entanglements [27].

In conclusion, based on advanced waveguide nonlinear optics and telecom technology, we have implemented, for the first time, an entirely guided-wave optical setup allowing both the generation and the detection of single-mode squeezed light at a telecom wavelength. We observe squeezing levels down to -1.83 ± 0.05 dB. Our setup exploits plug-and-play components fully compatible with existing telecom fiber networks and requires no alignment procedures for spatial mode matching. These advantages guarantee extreme reliability and make our approach a valuable candidate for real-world quantum communications based on continuous variable quantum optics.

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