PHOTONICS Research

Chip-based squeezing at a telecom wavelength

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We demonstrate a squeezing experiment exploiting the association of integrated optics and telecom technology as key features for compact, stable, and practical continuous variable quantum optics. In our setup, squeezed light is generated by single-pass spontaneous parametric down conversion on a lithium niobate photonic circuit and detected by a homodyne detector whose interferometric part is directly integrated on the same platform. The remaining parts of the experiment are implemented using commercial plug-and-play devices based on guided-wave technologies. We measure, for a CW pump power of 40 mW, a squeezing level of −2.00 ± 0.05 dB (anti-squeezing 2.80 ± 0.05 dB), thus confirming the validity of our approach and opening the way toward miniaturized and easy-to-handle continuous variable-based quantum systems.

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1. INTRODUCTION

Over the last years, single and multimode squeezed states [1] have played a crucial role in the development of quantum technologies such as quantum computation [2,3], communication [4–6], and sensing [7]. In this context, important experimental and theoretical tools for squeezing generation, manipulation, and analysis have been developed [8,9]. Moreover, it has been proved that squeezed states can be manipulated to generate highly nonclassical states, such as Schrödinger kittens [10] or cats [11] or hybrid entangled states featuring continuous-discrete variable properties [12,13].

So far, most of important squeezing demonstrations have been performed by exploiting bulk optics experiments, where squeezed states are usually generated via resonant systems, such as optical parametric oscillators (OPOs) [14,15], and detected thanks to free-space homodyne detections, for which careful spatial alignment and mode matching are required [16]. As a consequence, in view of practical applications, we have been assisting to the miniaturization of important building blocks of squeezing experiments. Compact and stable squeezing generation has been reported in single-pass waveguides [17,18] and, more recently, in OPO-like devices such as a silicon microring [19] or a waveguide cavity resonator on lithium niobate allowing to measure a squeezing of −2.9 dB for a pump power of ≈23 mW [20]. In parallel, other realizations have reported on-chip homodyne detectors exploiting integrated optics on different substrates [16,21,22]. Eventually, in the last months, a photonic platform for continuous variable quantum information has been demonstrated on lithium niobate [23].

Our work follows this emerging and very exciting research area. It addresses the realization of stable, compact, and telecom-compliant squeezing experiments by merging integrated optics on lithium niobate [24] and mature classical technologies. This association allows satisfying in a simple way the requirements of easy-to-use and scalable experiments in view of out-of-the-laboratory quantum communication in optical fibers [6,25]. The squeezing generation and the optical coupler for the homodyne detector are fully integrated on a single chip with no significant loss between these two stages and no spatial mode-matching concerns [16]. At the same time, with the only exception of homodyne photodiodes, all the other building blocks of our experiment are realized by means of off-the-shelf guided-wave telecom components, fully compatible with existing fiber networks and allowing fast and plug-and-play experiment reconfigurations [26]. More in details squeezed light is generated on-chip via efficient single-pass spontaneous parametric down conversion (SPDC) in a periodically poled waveguide. Squeezing is emitted in the telecom C-band of wavelengths to be compatible with low propagation losses in optical fibers. Its homodyne detection, exploiting on-chip optical mixing with the local oscillator (LO) beam, exhibits low losses, essentially due to Fresnel reflection at the chip end-facet and photodiode quantum efficiency. Thanks to this approach, we measure with the integrated homodyne interferometer a raw single-mode squeezing level of −2.00 ± 0.05 dB (−3.00 ± 0.05 dB corrected by avoidable losses), with a continuous wave (CW) pump power of 40 mW. This value validates our approach and represents, to our knowledge, the best squeezing level obtained in miniaturized systems in single-pass CW pumping regime [17,20,23].

2. EXPERIMENTAL SETUP AND PHOTONIC CHIP

The experimental setup is sketched in Fig. 1. It associates an injection system, exploiting easy-to-assemble guided-wave components, with our home-made lithium-niobate chip.

The setup relies on a master, fiber-coupled laser generating a CW optical beam at 1560.44 nm and amplified up to 0.95 W with an erbium-doped fiber amplifier (EDFA). At the output of the EDFA, the single-mode laser light is split by a high-power 65:35 fiber coupler (f-BS). The less intense output is directed to a home-made fiber stretcher allowing to scan its phase, to be subsequently used as local oscillator for the homodyne interferometer. The brighter output is frequency doubled to 780.22 nm via second-harmonic generation (SHG) and used to pump the squeezer. The single-pass SHG is realized in a commercial periodically poled lithium-niobate ridge waveguide (PPLN/RW [27]) where both input and output ports are fiber-coupled. We note that the ridge output coupling is optimized by the manufacturer to maximize the collection only at 780.22 nm. Residual light at 1560.44 nm at the ridge output is suppressed during its propagation in visible light single-mode fibers and by a fiber-wavelength demultiplexer (WDM 980/1550, not represented in Fig. 1).

The LO at 1560.44 nm and the pump at 780.22 nm are sent to a fiber array and butt-coupled to the home-made photonic chip. A fiber polarization controller (PC) on each arm is introduced to properly adjust the polarization. Typical fiber-to-input guide couplings are of ≈0.60. This value can be increased up to 0.92 by inserting taper structures on the photonic chip input [28]. The entire optical setup upstream from the chip is made using commercial plug-and-play components, exploiting telecom and nonlinear optics technologies and guaranteeing a quick operation with no spatial-alignment procedure [16,26].

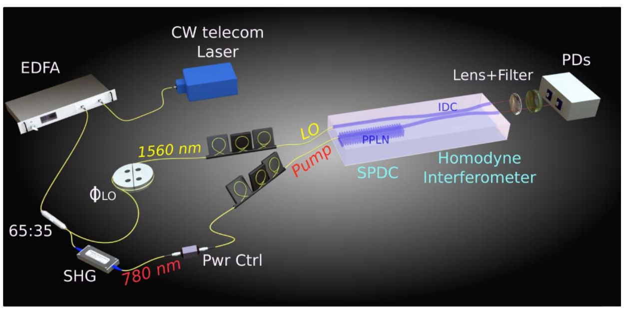

Fig. 1. Experimental setup. A fiber coupled CW telecom laser at 1560.44 nm is amplified (EDFA) and split into two by means of a 65:35 fiber beam splitter (f-BS). The less intense output (upper arm) serves as local oscillator (LO) while the brighter one (lower arm) is frequency doubled via SHG in a PPLN/RW and used to pump an on-chip squeezing generation stage (SPDC). The power of the beam at 780.22 nm is controlled with an in-line fibered attenuator (Pwr Ctrl) and its polarization is adjusted by means of a fiber polarization controller. At the output of the SPDC stage, squeezed light at 1560.44 nm is optically mixed with the LO beam inside the same chip in an integrated directional coupler realizing the interferometric part of the homodyne detector. At the chip output, after passing through a bulk lens followed by an optical filter suppressing residual pump at 780.22 nm, light is sent to two InGaAs photodiodes (PDs). The LO phase is scanned thanks to a home-made fiber-stretcher (ϕ_{LO}).

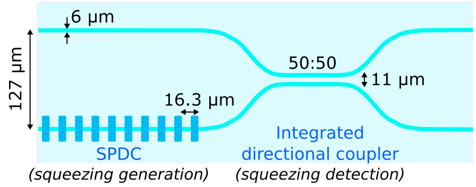

Fig. 2. Schematic of our photonic chip on lithium niobate. The chip includes an SPDC stage, consisting in a periodically poled waveguide (3 cm long with poling period $\Lambda = 16.3$ μm) for squeezing generation at 1560.44 nm, and an integrated directional coupler realizing the interferometric part of the homodyne squeezing detection. The whole chip length is 5 cm. All waveguides are obtained by soft proton exchange [29] and have a width of 6 μm. The 127 μm spacing between the input (output) waveguides is compatible with of-the-shelf fiber-arrays. The homodyne photodiodes are outside the chip and are bulk commercial components.

A schematic of the photonic circuit is presented in Fig. 2. The 5 cm-long chip integrates on a single congruent lithium niobate substrate, the two key components for squeezing experiments, namely the squeezing generation stage and the optical coupler required for the interferometric part of the homodyne detection. Accordingly, it has two input ports, one for the squeezer pump and the other for the homodyne LO, and two output ports that are directly connected to the bulk homodyne photodiodes. The separation between ports on the same facet is 127 μm, i.e., compatible with standard fiber-array coupling systems. The waveguide structures are 6 μm wide, and they are fabricated using soft-proton exchange (SPE) following the technique discussed in Ref. [29]. Propagation losses have been measured to be ≤0.04 dB/cm at 1560 nm and ∼1 dB/cm at 780 nm.

Lithium niobate is particularly suitable to develop integrated squeezers and photonic circuits, featuring high nonlinearity and the possibility of implementing quasiphase-matching to engineer the nonlinear optical response [24]. Our on-chip squeezer is a straight periodically poled waveguide, 3 cm long and designed to have, when pumped at 780.22 nm, a type-0 frequency degenerate SPDC centered at 1560.44 nm. Periodic poling pattern is created by standard electric-field assisted technique with a period $\Lambda = 16.3$ μm [24]. The quasiphase-matching temperature for reaching the desired interaction is 104°C. Such a high temperature has been chosen to mitigate light-induced local modifications of the refractive index in lithium niobate waveguides. Photorefractive effects are, indeed, particularly evident for optical signals at shorter wavelengths and, at high powers, can induce hopping between different spatial modes [30]. At the chosen working temperature, no mode-hopping is observed for red powers up to 40 mW. Moreover, by exploiting on-chip residual cavity effects and evaluating the resonance positions as functions of the input red power, refractive index variations have been measured to be $\leq 4 \times 10^{-5}$. These very small values are consistent with other reported results [31]. The quality of the SPDC stage has been assessed by means of the single-photon counting technique. Typical values for our conversion efficiencies are $\sim 10^5$ photon pairs/(mW·GHz·s) with an FWHM for the spectral emission of 70 nm [32]. We recall that, due to the absence of an optical resonator, this value corresponds directly to the squeezing bandwidth [17,33].

The on-chip homodyne interferometer is based on a balanced integrated directional coupler (IDC), exploiting the evanescent tail coupling [34]. It consists of two waveguides running close to each other over a geometrical length of ~5.5 mm and with a center-to-center separation of 11 μm. The two IDC inputs are fed with the squeezer output (directly on-chip) and with the local oscillator. Its measured splitting ratio is 50∶50 at the SPDC central emission wavelength (i.e., at the LO wavelength). To achieve such a good balancing, the ideal coupling length and BS design have been numerically computed based on our waveguides' typical measured properties. Moreover, to comply with fabrication uncertainties, we have realized on the same sample 17 copies of our photonic circuit, corresponding each to a slightly different IDC length, numerically calculated on the basis of our usual parameter fluctuations. The optimal component has been selected among these copies.

The IDC outputs are directed outside the chip and sent to two bulk photodiodes as required for the homodyne detection. The chip is diced using a semiconductor saw and polished at 0° through chemical mechanical polishing. Due to the absence of anti-reflection coating, light experiences, at its output, a sharp refractive index change at the lithium niobate-air interface and is transmitted with an efficiency $\eta_F = 1 - R_{\text{Fresnel}}$, where $R_{\text{Fresnel}} = (\frac{n_{\text{air}} - n_{\text{chip}}}{n_{\text{air}} + n_{\text{chip}}})^2$. At telecom wavelength, $\eta_F \approx 0.86$ [35]. Thanks to a bulk C-coated lens with 11 mm focal length, the two beams coming out of the photonic circuit are directly imaged on two InGaAs photodiodes (PDs) exhibiting a quantum efficiency $\eta_{\text{PD}} \approx 0.88$ at 1560 nm. By doing so, a nearly perfect chip-to-photodiode coupling is obtained. Residual transmitted light at 780.22 nm is rejected of more than −40 dB with a bulk optical filter, exhibiting a transmission $\eta_f = 0.99$ at 1560 nm. We stress that the lens, the filter, and the homodyne photodiodes are the only bulk optics components in our setup. The difference of the photocurrents from the two photodiodes is amplified by a home-made low-noise transimpedance amplifier with bandwidth of ~5 MHz. Noise power is directly measured with an electronic spectrum analyzer set at zero-span centered at 2 MHz. For 0.5 mW LO power on each photodiode, we obtain an electronic signal-to-noise ratio (SNR) of 12.8 dB. Residual electronic noise effect can be taken into account by introducing an additional loss, through the efficiency $\eta_e = (\text{SNR} - 1)/\text{SNR} \approx 0.95$ [36].

3. EXPERIMENTAL RESULTS

Figure 3 shows a typical squeezing curve obtained by scanning the phase of the local oscillator over time. We measure a raw squeezing value of -2.00 ± 0.05 dB, with an anti-squeezing of 2.80 ± 0.05 dB when 40 mW pump light is coupled in the PPLN arm of the chip. The measured squeezed value is affected by losses at the photonic circuit output, such as Fresnel

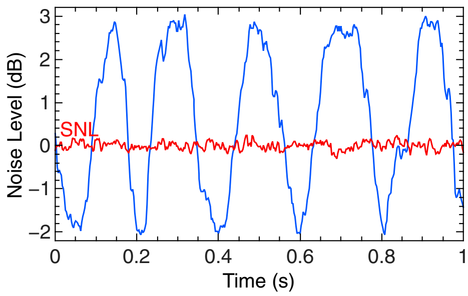

Fig. 3. Normalized noise variances at 2 MHz obtained for a coupled pump power of 40 mW as a function of the LO phase (proportional to the time) and with a sweep time of 1 s. The electrical spectrum analyzer resolution and the video bandwidths are 100 kHz to 30 Hz, respectively.

reflection and detectors' nonunit efficiencies as well as electronic noise. However, we underline that these contributions are not due to unavoidable limitations of our chip and can be easily circumvented by means of anti-reflection coating on the chip output facet, leading to $\eta_F \approx 1$, and by replacing photodiodes and electronics with more performant ones ($\eta_{\text{PD}} \cdot \eta_e \approx 0.99$) [14]. By correcting our measured squeezing for the overall measurement efficiency, $\eta = \eta_F \cdot \eta_f \cdot \eta_{\text{PD}} \cdot \eta_e = 0.71$, we can infer the squeezing at the output of the photonic circuit to be ~ -3.2 dB (anti-squeezing of ~3.6 dB), which is, to our knowledge, the best reported value for CW-pumped squeezing in waveguides without an optical resonator [17,20,23]. We note that the product of squeezing and anti-squeezing net variances is close to the one expected for minimum uncertainty states, thus showing the absence of unwanted excess noise on antisqueezed quadratures. This value provides evidence of the chip quality in terms of both squeezing generation and losses in the interferometric part of the homodyne detector. We underline that our reported squeezing level is compatible with applications in quantum communication protocols like continuous variable entanglement distribution and teleportation [2] as well as with the heralded generation of Schrödinger cat-like states [10] fully compatible with existing quantum networks and with their use for hybrid entangled states [12,13]. At the same time, we note that the optical chip reported here represents a first important building block for more complex optical circuits able to embrace nonlinear and linear operation stages, enabling new perspectives towards quantum enhanced optical processors [2,23]. Eventually, we stress that the squeezing levels can be further improved by increasing the SPDC pump powers. In these regimes, to avoid detrimental photo-refraction in the waveguides, a Mg:O-doped lithium niobate substrate should be used for the photonic chip. Based on our previous results for this kind of support [26], we expect for a Mg:O doped SPE waveguide with the same characteristics as the one reported in this paper, a maximum squeezing from −10 to −9 dB for an SPDC pump power ≈500 mW.

In conclusion, we have demonstrated a compact and easy-to-handle experiment relying on integrated optics on lithium niobate and off-the-shelf telecom and nonlinear components. Our photonic circuit integrates on-chip the squeezing generation and the homodyne interferometer. The squeezed light generated at telecom wavelength exhibits a raw noise compression of −2.00 ± 0.05 dB for a pump power of 40 mW with an anti-squeezing of 2.80 ± 0.05 dB. The whole remaining setup employs plug-and-play components requiring no alignment procedures for spatial mode matching. These advantages guarantee an extreme reliability and make our approach a valuable candidate for real-world applications based on continuous variable quantum systems.

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