Ultra-broadband quadrature squeezing with thin-film lithium niobate nanophotonics

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Abstract: We demonstrate squeezed light generation with parametric down-conversion single-pass configuration on thin-film lithium niobate nanophotonics. We measure 0.56 dB quadrature squeezing (∼2.6 dB inferred on-chip) with 7 THz bandwidth. © 2022 The Author(s)

Squeezed light has become one fundamental building block for photonic quantum technology recently. The suppression of measurement variance below shot noise has been widely recognized and implemented for sensing applications [6]. Furthermore, squeezed light also plays a critical role in quantum communications [2]. It provides an important alternative with unique features to the discrete-variable approach using single photons. Quantum information is encoded into the continuous quadrature amplitudes instead of discrete degrees of freedom. This renders the deterministic generation and entanglement operation of quantum states [7].

The further development of continuous-variable quantum technology requires a large number of squeezed light sources and complex photonic circuits [7]. Integrated photonics provides the scalable fabrication of quantum sources with additional advantages including phase stability, near-perfect spatial mode matching, and power efficiency. Currently, squeezed light has been generated using four-wave mixing in microring cavities [1,9]. However, it is challenge to remove the pump without introducing extra loss on squeezed light due to the small wavelength separation. The pump efficiency is low compared with parametric down-conversion (PDC). These platforms also lack electro-optic effect and limit the speed of photonic circuit reconfiguration, preventing essential functions for measurement-based one-way quantum computing such as feedforward measurement [4]. Squeezed light has been generated in bulk lithium niobate waveguide. PDC and fast reconfiguration can be achieved. However, the large cross-sections prevent the scalable integration of large-scale photonic circuits.

In this letter, we report the development of thin-film lithium niobate (TFLN) for squeezed light generation. The strong second-order nonlinearity and sub-wavelength confinement of optical fields facilitate efficient PDC processes in a single-pass configuration. This eliminates the need of photonic cavities for pump recycling. Therefore, squeezed light can escape the device with near-unity efficiency in contrast to the cavity configuration. Quasi-phase matching is realized through periodic poling of TFLN. We have measured 0.56 ± 0.09 dB quadrature squeezing, with inferred ∼2.6 dB on-chip squeezing. Our device further achieves squeezing over 7 THz bandwidth, covering S-, C-, and L-bands for optical communications.

The device is fabricated from a z-cut TFLN wafer with 600 nm device layer. The top width of the ridge waveguide is 1.8 μm with etched depth 400 nm. We use the fundamental transverse-magnetic (TM00) modes for both the squeezed light around wavelength 1550 nm and the pump around wavelength 775 nm to utilize the largest second-order nonlinear component $d_{33} = -25$ pm/V in lithium niobate. To compensate for the wavevector mismatch between the squeezed light $k_s$ and the pump $k_p$, the quasi-phase matching condition is fulfilled when the domain period $\Lambda = 2\pi/(2k_s - k_p) \approx 3$ μm. Figure 1(a) shows the mock-up device after etching in hydrofluoric acid [5]. The total length of the device with domain inversion is 5 mm. Finally, the chip is cleaved to expose the waveguide facets for input and output coupling.

For squeezing measurement, a continuous-wave laser with center wavelength 1554.2 nm is amplified by an erbium-doped fiber amplifier, then the output is collimated and divided into two beams. One beam is injected into a commercial nonlinear crystal for SHG. The second-harmonic beam is used as the pump for the squeezed light generation with TFLN waveguides. The other beam is used as the local oscillator (LO) for homodyne detection. The LO beam passes through a reference waveguide to ensure the optimum spatial mode matching between the LO and squeezed light. The homodyne signal is sent to an electrical spectrum analyzer for noise measurement. A piezo-transducer is used to scan the LO phase with 1 Hz frequency.

Figure 1(b) shows the noise power of the squeezed light, which is detected by zero span measurement at 22 MHz frequency. With 82 mW pump power, the measured squeezing and anti-squeezing levels are $-0.56 \pm 0.09$ dB and 0.83 ± 0.09 dB, respectively. With 12 mW LO power, the shot noise is 9.2 dB higher than the electronic noise of the measurement setup. From linear transmission measurement, we have estimated the optical losses induced by
The on-chip waveguide propagation loss of optical power is 0.5 dB. The power coupling loss due to interface and cutoff of downstream optics is 3.5 dB. The spatial mode mismatch between LO and squeezed light introduces 0.3 dB equivalent power loss. The photodetector has quantum efficiency 87%, equivalent to 0.6 dB power loss. The electric noise of the measurement setup is equivalent to 0.6 dB loss. Therefore, the total power loss is 5.5 dB, corresponding to 28% detection efficiency. If we only consider the 0.5 dB propagation loss, an on-chip squeezing level around 2.6 dB can be inferred.

To estimate the bandwidth of squeezed light, we measure the optical power generated from the PDC process at different wavelengths by replacing the homodyne detection setup with an optical spectrum analyzer. Figure 1(c) shows the optical spectra at different pump powers. The power bandwidth of the squeezed light is estimated to be above 7 THz. The generated squeezed light covers the whole C-, L-bands, and half S-band for optical communications. Such large bandwidth will be beneficial to high-speed quantum systems such as quantum communications with wavelength-domain multiplexing and quantum computation with time-domain photonic cluster states [7].

To further improvement of the measured squeezing level, the on-chip squeezing level can be increased by using a longer device. With a 3 cm device and propagation loss 2.7 dB/m [8], on-chip squeezing above 20 dB can be achieved. Minimizing the detection loss can be realized using photodetectors with near-unity quantum efficiency, optimizing spatial overlap visibility, and lowering electronic noise. The squeezing level will be ultimately limited by the waveguide out-coupling efficiency. Loss below 0.52 dB has been realized between TFLN waveguides and fiber [3]. Therefore, squeezing level above 9.2 dB will be possible.

In summary, we have demonstrated the generation of squeezed light based on PDC using TFLN waveguides. A squeezing level of $0.56 \pm 0.09$ dB has been measured with bandwidth up to 7 THz. This is enabled by the sub-wavelength mode confinement, leading a 10-fold increase in pump efficiency. Our chip-scale platform can enable the integration of squeezed light sources with large-scale photonic circuits for advanced quantum functions. It also enables the realization of second-harmonic generation and fast circuit reconfiguration on the same chip. Therefore, this work will pave the way towards complete on-chip continuous-variable quantum technology.

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