Squeezed vacuum states from PPLN waveguide chips

Hsin-Hung Wu[1], Jui-Yuan Hou[2], Li-An Chu[1], Rui-Cheng Hong[2], Te-Hwei Suen[1], Chien-Ming Wu[1], Yen-Hung Chen[2,*], and Ray-Kuang Lee[1,*]

[1] *Institute of Photonics Technologies, National Tsinghua University, Hsinchu, Taiwan*
[2] *Department of Optics and Photonics, National Central University, Taoyuan, Taiwan*
* *yhchen@dop.ncu.edu.tw; rklee@ee.nthu.edu.tw*

Abstract: We report the experimental generation and measurement of quantum squeezed light source from a PPMgO:LN ridge waveguide at 1550 nm, up to a maximum squeezing level of -3.1 dB directly recorded, which provides an important platform for the development of quantum integrated optical circuits.

1. Introduction

The development of efficient quantum photon sources, as well as powerful quantum devices and circuits, has been in great demand. On-chip solution for quantum light sources provides the critical step toward integration with optical circuits. As classical counterparts utilizing both digit and analog information processing, we will also provide quantum qubits in continuous variables (CV), which is a complementary family to the fragile discrete variables that only have single photons and photon pairs. In this work, we use the periodically poled lithium niobate (PPLN) waveguide chip, acting as an optical parametric amplifier (OPA), to generate squeezed states with a quantum noise reduction.

As illustrated in Fig. 1, our PPLN waveguide chip consists of multiple waveguide networks on a monolithic PPMgO:LN ridge waveguide chip. A CW light from a main fiber laser at a wavelength of 1550 nm is injected into the first periodically poled waveguide "SHG" to perform a frequency up-conversion for generating a 775 nm pump beam. After the 775 nm pump source is input, the OPA generates squeezed light according to the optical parametric process. The squeezed light is then separated from the beam and interferences with a local oscillator (LO) beam (split from the main laser) by a directional coupler (DC). Electrodes patterned on top of the waveguides are used to control the splitting ratio of the directional coupler and the phase of the LO. The output interference signals were detected by our homemade balanced homodyne detector (BHD), and finally we used the spectrum analyzer to obtain the squeezing levels under different pump power [1,2].

2. Estimation on squeezing levels

Theoretically, we estimate the squeezing level from the chip, by measuring the nonlinear gain of the chip. With known input and output pump power, we have the model of nonlinear gain as

$$P_{out} = \eta_o \exp(\pm 2r)\, P_{in} + (1-\eta_o)P_{in}, \tag{1}$$

where η_o is the overlap coefficient between the pump and signal light, $r = \sqrt{aP_{pump}}$ is the squeezed parameter, a is the conversion efficiency of SHG, and then $G_{\pm} = \exp(\pm 2r)$ is called intrinsic parametric gain.

After we obtain the SHG conversion efficiency a and the parameters of intrinsic parametric gain, we can roughly estimate the squeezing level that the experimental structure and the chip can produce,

$$R_{\pm} = \eta \exp(\pm 2r) + (1-\eta), \tag{2}$$

where η is the effective detection efficiency. During the OPA process, amplification and de-amplification phenomena occur relative to the phase change. The squeezing level R_+ is the orthogonal term of amplification (anti-squeezing), and in opposite, R_- is the orthogonal term of de-amplification (squeezing) [3,4].

3. Experimental results

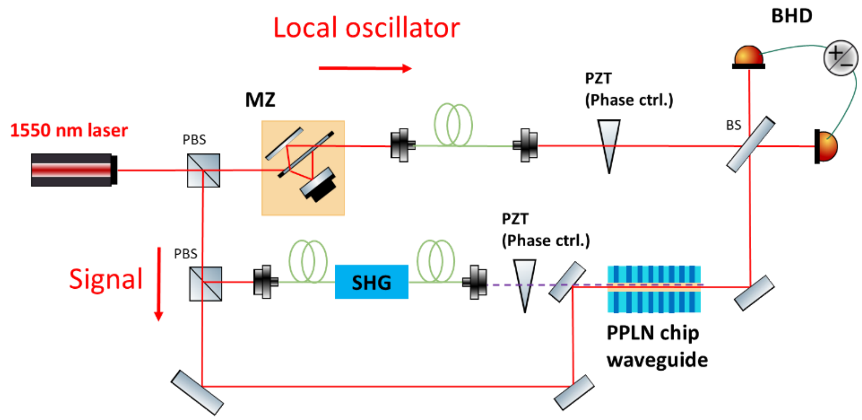

Fig. 1: Schematic of our experimental setup to perform quantum noise measurement [5]. BS: beam splitter; PBS: polarizing beam splitter; MZ: Mach–Zehnder interferometer; SHG: second harmonic generator; PPLN: periodically poled lithium niobate; PZT: Piezo devices made of lead zirconate titanate; BHD: balanced homodyne detector.

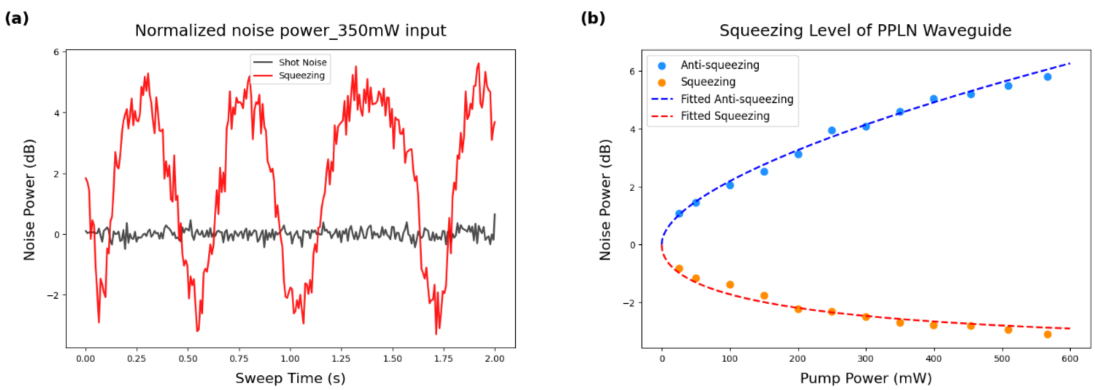

Fig. 2: Squeezed light measurement. (a) The normalized noise power as a function of time with the phase of LO sweeping when the incident pump power is 350mW. (b) The squeezing and anti-squeezing levels at different pump power.

In Fig. 2, we demonstrate the measured resulting quantum noise reduction, illustrated with squeezing and anti-squeezing levels. Figure 2(a) shows the noise power of the squeezed light generated within the PPLN waveguide with phase sweeping of LO light. As Figure 2(b) indicates, with the help of the OPA process, we can reach a maximum squeezing level up to -3.1 dB, while the anti-squeezing state is 5.487 dB at about 570 mW input pump power.

In summary, we successfully used the PPLN waveguide chip to fabricated and measured a quantum noise reduction over -3.0 dB. Compared to the theoretical estimation, our experimental results agree with the parameters measured. In future, to enhance the squeezing level in the measurement setup, we may shorten the distance of the experimental optical path and/or improve the stability of the holder stage.

4. References

[1] R. Domeneguetti, M. Stefszky, H. Herrmann, C. Silberhorn, U. L. Andersen, J. S. Neergaard-Nielsen, and T. Gehring, "Fully guided and phase locked Ti:PPLN waveguide squeezing for applications in quantum sensing," Opt. Lett. 48(11), 2999-3002 (2023).

[2] Y. Taguchi, K. Oguchi, Z. Xu, D. Cheon, S. Takahashi, Y. Sano, F. Harashima, and Y. Ozeki, "Phase locking of squeezed vacuum generated by a single-pass optical parametric amplifier," Opt. Express 30(5), 8002-8014 (2022).

[3] N. Takanashi, T. Kashiwazaki, T. Kazama, K. Enbutsu, R. Kasahara, T. Umeki, and A. Furusawa, "4-dB Quadrature Squeezing With Fiber-Coupled PPLN Ridge Waveguide Module," IEEE J. Quantum Electron. 56(3), 6000100 (2020).

[4] Pao-Kang Chen, Ian Briggs, Songyan Hou, and Linran Fan, "Ultra-broadband quadrature squeezing with thin-film lithium niobate nanophotonics," Opt. Lett. 47(6), 1506-1509 (2022)

[5] Li-An Chu, "Experimental preparation of a quantum wafer to generate a squeezed light field," (Master Thesis). National Tsing Hua University, Hsinchu. (2024).