# Optical Squeezing
# SK2903 - Quantum Technology

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## Abstract

The purpose of this experiment was to investigate the generation of optically squeezed light using periodically poled Lithium Niobate (ppLN) waveguides. The focus was on achieving high efficiency in Second Harmonic Generation (SHG) and squeezing through spontaneous parametric down-conversion (SPDC). This work demonstrates the feasibility of single-pass, cavity-free optical parametric amplifiers for precision metrology applications. Key measurements included optimal phase-matching conditions for SHG and the characterization of squeezing levels. Results reveal efficient SHG and significant squeezing levels, corroborating theoretical predictions.


## 1 Introduction

Optical squeezing, a phenomenon where the uncertainty in a quantum variable (amplitude or phase) is reduced below the standard quantum limit, represents a cornerstone of modern quantum optics. Squeezed states are pivotal for advancing precision metrology, quantum communication, and quantum computing. Typically, achieving such states involves intricate setups, including optical cavities. However, this lab explores the simpler and potentially scalable approach of single-pass, $\chi(2)$-based waveguides for generating squeezed light.

This experiment investigates the SHG and SPDC processes in periodically poled Lithium Niobate (ppLN) waveguides. SHG involves the conversion of photons at a fundamental frequency into a higher harmonic, while SPDC facilitates the generation of squeezed states. By tuning critical parameters such as temperature and coupling efficiencies, the experiment measures both SHG performance and the resulting squeezing levels. Notably, the generated squeezing is analyzed using balanced homodyne detection to validate the experimental outcomes.

The significance of this work lies in its potential applications, such as enhancing gravitational wave detection via quantum noise reduction. Our results demonstrate efficient SHG and substantial squeezing, offering practical insights into single-pass optical parametric amplifiers.

## 2 Measurements

The schematic diagram of the setup can be seen in the fig. 1. The first task was to measure the fundamental optical power entering the SHG waveguide and assess its stability over time. We used an integrating sphere to ensure accurate power readings by capturing scattered light. We observed the power level for 5 minutes and noted any fluctuations. A stable fundamental power is crucial because variations can affect the efficiency and stability of the SHG and squeezing processes.

The dependence of SHG output on waveguide temperature was studied using a temperature controller. The 1550 nm light from the VOA was directed into the SHG waveguide, and the 775 nm output was monitored with an integrating sphere. Temperature was increased in small increments, and output power was recorded at each step, covering the full "sinc" curve of quasi-phase matching. This data identified the optimal phase-matching temperature and SHG efficiency. The collected data for power is shown in the 4. Due to inconsistency in the setup we observed unusually low power output. Therefore our data in the figure shows the maximum power of approximately 19.1 mW. This amount of power was not good enough to generate the squeezing so we did not go further with these results. In the second iteration of the

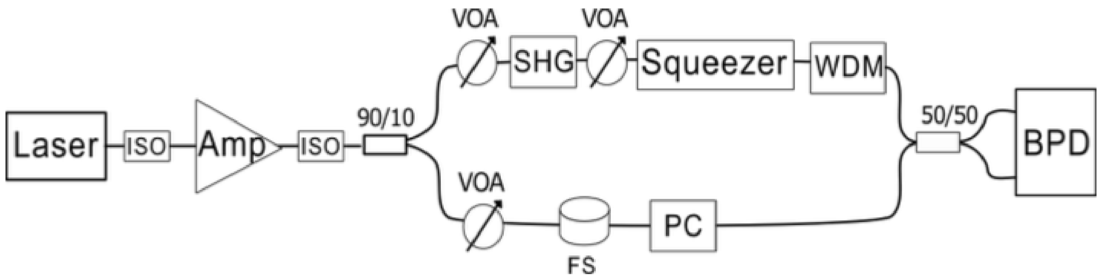


Figure 1: **Schematic diagram of the setup used to observe optical squeezing**.[1]

experiment after the setup was fixed, we got the maximum output power about 80 mW, which was good enough to proceed with the other tasks.

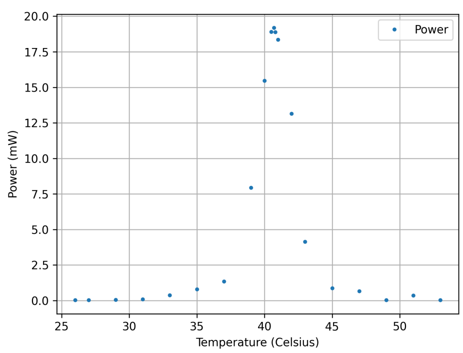


Figure 2: **Power-Temperature dependence data.**

Noise levels were characterized by measuring the dark noise and shot noise of the photodetector. With no optical input, dark noise was recorded. The local oscillator (LO) arm was then connected, and the amplified noise due to the LO was measured as shot noise. These baseline measurements established reference points for evaluating squeezing levels.

| **Measurement** | **Value (dB)** |
|---|---|
| Shot Noise | -97.18 |
| Dark Noise | -98.39 |

Table 1: Shot Noise and Dark Noise Measurements

Squeezing measurements used a balanced homodyne detection setup. After attenuating the 775 nm light, the OPA output was directed to a beam splitter to interfere with the LO. A spectrum analyzer was used to observe squeezing and anti-squeezing arches by varying the LO phase.

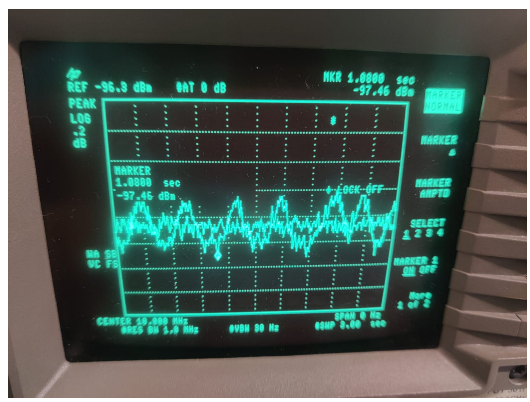

Figure 3: **Spectral analyzer.** The figure shows the measurement of squeezing.

| **Anti-Squeezing (dB)** | **Squeezing (dB)** |
|---|---|
| -96.93 | -97.44 |
| -97.00 | -97.39 |
| -96.97 | -97.41 |
| -96.95 | -97.44 |
| -96.90 | -97.44 |
| -96.95 | -97.46 |

Table 2: Measured Anti-Squeezing and Squeezing Levels (in dB)

The table 2 shows the experimental data collected for measurement of anti-squeezing and squeezing.

# 3 Analysis

## 3.1 Task 1: SHG Power Stability

The measured optical power entering the SHG waveguide was evaluated using an integrating sphere. Over the 5-minute observation period, the power output was found to be $588 \pm 4$ mW. This consistency indicates reliable input conditions, crucial for ensuring stable SHG performance. The use of an integrating sphere minimized beam divergence effects, providing accurate power measurements. Any minor fluctuations observed could be attributed to environmental factors such as temperature or mechanical vibrations.

## 3.2 Task 2: SHG Temperature Dependence

The SHG output power demonstrated a clear dependence on temperature, with the power increasing as the waveguide approached the optimal phase-matching temperature. At the peak output, the optimal temperature was determined to be $40.7°C$. The corresponding maximum SHG efficiency was calculated as 13.6%. Beyond this temperature, the output power decreased symmetrically, following the $sinc^2$ dependence predicted by quasi-phase matching theory. We fit eq.1 to the collected data using python package scipy [2].

$$P_{\text{SHG}} \propto P_{\text{in}} A \, \text{sinc}^2\big(b(T - T_0)\big) \tag{1}$$

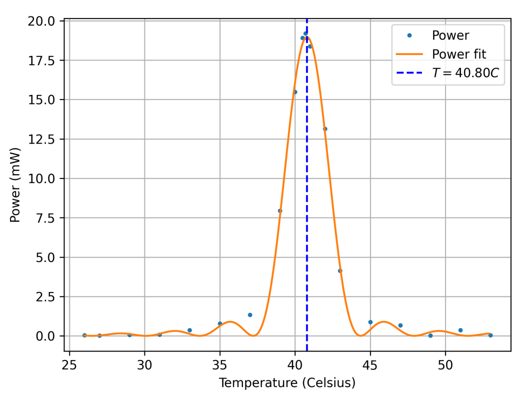


Figure 4: **Power-Temperature dependence curve.** $sinc^2$ curve fit over the experimental data of power vs temperature. Curve reaches its maximum at $40.8°C$ as shown in the figure.

The experimental results closely matches the theoretical model.

## 3.3 Task 3a: Dark Noise and Shot Noise Measurements

As mentioned in the Table 1, the dark noise of the photodiode was measured to be $-98.39dB$, representing the baseline noise of the detector in the absence of light. In contrast, the shot noise level of the local oscillator (LO) was observed at $97.18dB$. The clear separation of approximately $1.21dB$ between the dark noise and the shot noise indicates a sensitive detection system. This separation highlights that the LO shot noise is sufficiently above the detector's electronic noise floor, allowing reliable detection of quantum noise.

## 3.4 Task 3b: Squeezing Arches

Using the spectrum analyzer referenced to the LO shot noise level, the squeezing and anti-squeezing levels were measured. The maximum squeezing level recorded was 0.23dB below the shot noise , while the anti-squeezing level peaked at 0.33dB above the shot noise. These levels demonstrated the characteristic quantum noise suppression (squeezing) and amplification (anti-squeezing).

| **Anti-Squeezing (dB)** | **Squeezing (dB)** |
|---|---|
| 0.30 | 0.21 |
| 0.23 | 0.16 |
| 0.26 | 0.18 |
| 0.28 | 0.21 |
| 0.33 | 0.21 |
| 0.28 | 0.23 |

Table 3: Measured Anti-Squeezing and Squeezing Levels (in dB) relative to shot noise.

Experimental results in dB for anti-squeezing and squeezing is obtained from the above data as $V_{-} = 0.2$ dB and $V_{+} = 0.28$ dB. We can use the eq. 2 [1] to convert the values from dB to W,

$$P[W] = 10^{-\mathbf{P}_{\text{dB}}[\mathbf{dB}]/\mathbf{10}} \tag{2}$$

Final results for experimental anti-squeezing and squeezing are given as $V_{-} = 0.95$ W and $V_{+} = 1.06$ W To calculate theoretical values of anti-squeezing and squeezing we use eqs. 3 7 & 8,

$$R = \sqrt{\alpha_{\text{OPA}} P_{\text{SHG}}} \tag{3}$$

where $\alpha_{\text{OPA}} = 0.764W^{-\mathbf{1}}$ & $P_{\text{SHG}} = \eta_{\text{OPA,in}} \times P_{\text{out}} = 0.04W$. This gives squeezing parameter value as,

$$R = 0.1748 \tag{4}$$

Accordingly, we get squeezing and anti-squeezing values, without considering optical losses as follows,

$$V_{-} = exp(-2R) = 0.7 \tag{5}$$

$$V_{+} = exp(2R) = 1.41 \tag{6}$$

These values are a little far off the experimentally obtained results. Lets consider the optical losses[3], with the net efficiency of the setup to be defined as

$$\eta_i = \eta_{\text{OPA,out}} \eta_{\text{OPA,prop}} \eta_{\text{WDM}} \eta_{\text{cables}} \eta_{\text{BS}} \eta_{\text{PD}}$$

$$\eta_i = 0.26$$

Using these values in eq. 7 and 8 we get better values.

$$V_{-} = \eta_{\text{i}} exp(-2R) + 1 - \eta_{\text{i}} = 0.92 \tag{7}$$

$$V_{+} = \eta_{\text{i}} exp(2R) + 1 - \eta_{\text{i}} = 1.12 \tag{8}$$

When compared to the experimental results, theoretical values turns out to be comparable. Fine-tuning the LO phase and polarization further improved the precision of the measurements.

# 4 Application

Quantum key distribution (QKD) is a technology that uses quantum mechanics to create secure communication channels. Squeezed light has the potential to significantly enhance QKD systems by improving security, speed, and distance. Squeezed light reduces noise in one quadrature, allowing more information to be encoded per measurement, thus increasing the key generation rate. Unlike other QKD techniques where optical losses limit distance and key rate, the bandwidth of squeezing remains largely unaffected, enabling secure communication over longer distances. The use of squeezed light in QKD offers several advantages, including increased tolerance to excess noise (which is inherent in real-world communication channels), reduced need for error correction algorithms, and enhanced security against certain types of attacks.

# 5 Conclusion

In this lab, we explored key principles of quantum optics, including second-harmonic generation (SHG), quantum noise characterization, and squeezing. In Task 1, we successfully demonstrated SHG, verifying the proportional relationship between input and second-harmonic power and highlighting the importance of phase-matching via thermal tuning of the nonlinear crystal. Task 2 involved measuring the dark noise and shot noise. In Task 3, we measured squeezing and anti-squeezing relative to the LO shot noise, consistent with theoretical predictions. While experimental losses impacted the results, our findings aligned well with theoretical models after accounting for these factors.

# 6 Methods

The python code used to analyse the data and perform curve fitting can be found in the jupyter notebook present here.

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# References


[1] Squeezing Lab Manual. Vaishali Adya, Hilma Karlsson, Erik Svanberg. (2024)

[2] https://docs.scipy.org/doc/scipy/reference/tutorial/curve_fit.html

[3] Derivations of formulas. Vaishali Adya, Hilma Karlsson, Erik Svanberg. (2024)