Noise-Robust Quantum LiDAR Using Temporally Long Single Photons and Phase Modulation

國立清華大學 QP LAB

Yen-Cheng Shih[1], Wen-Chia Lo[1], Chih-Sung Chuu[1]

[1]*Department of Physics , National Tsing Hua University*

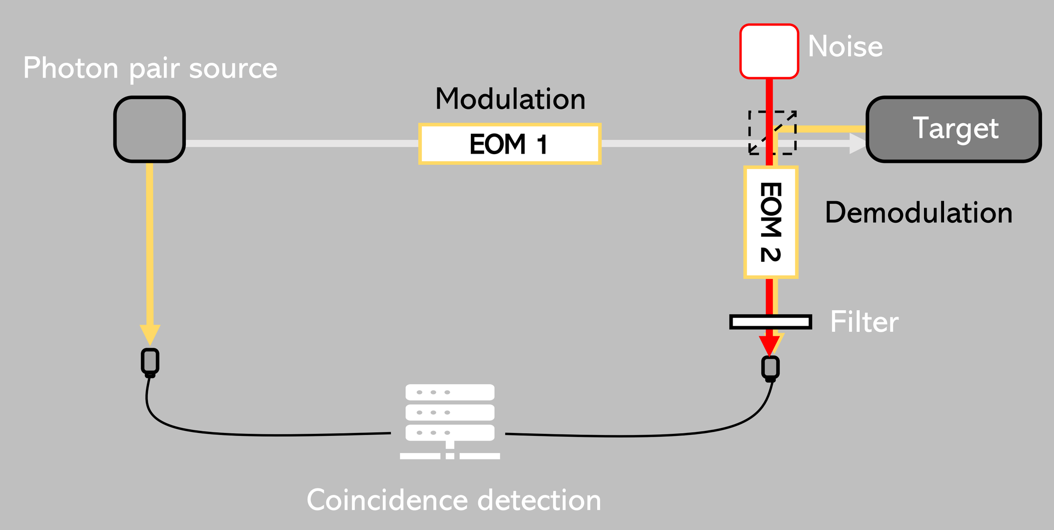
Abstract

Quantum LiDAR is a method that combines quantum light sources with LiDAR techniques, leveraging quantum characteristics for sensing applications. However, in practical scenarios, **immense noise and low reflection rates** often cause quantum light to be overwhelmed by classical light, reducing its efficiency.

Inspired by the spread spectrum technique, we implement **phase modulation** at both the sender and receiver, which serves as an encoding and decoding scheme to effectively filter out unwanted noise. In this poster, we demonstrate the effectiveness of the LiDAR system by achieving **a high signal-to-noise ratio in a noisy environment** and analyze the impact of transmission rate variations on the target, highlighting its advantages and potential applications. We believe this technique has significant potential to improve the practicality of quantum LiDAR and bring it closer to real-world applications.

Introduction

- Quantum illumination- the exponential improvement with entanglement and qubit over classical illumination.
- Challenges: photon number difference in practical situation → enhance signal-to-noise ratio (SNR)
- Modulation and demodulation- encoding and distinguishment



Backwards-wave Cavity-Enhanced SPDC

- Spontaneous Parametric Down-Conversion (SPDC):

A nonlinear optical process that converts a higher energy pump photon into a pair of photons with lower energy, in accordance with the law of **energy** and **momentum conservation** during production (Fig.1).

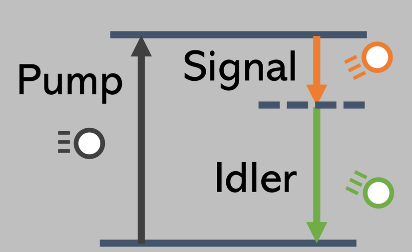
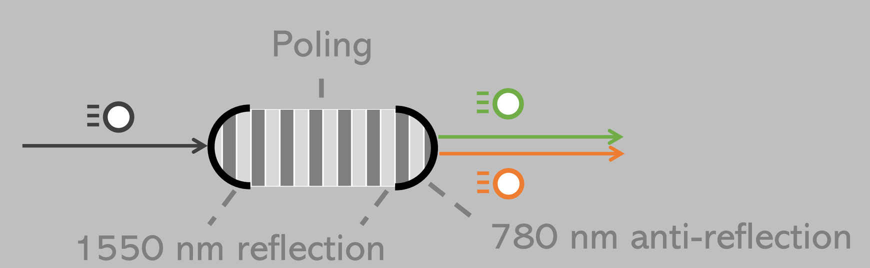
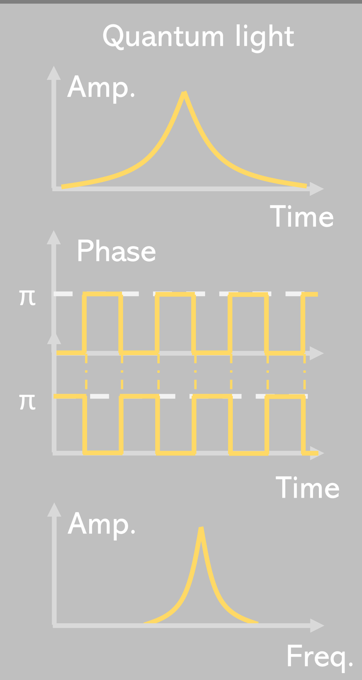


Fig. 1 Schematic of SPDC process



- Ultrabright backwards-wave biphoton source [1]
- Narrow linewidth- less frequency noise
- Optical parametric oscillator (OPO)

Phase modulation technique

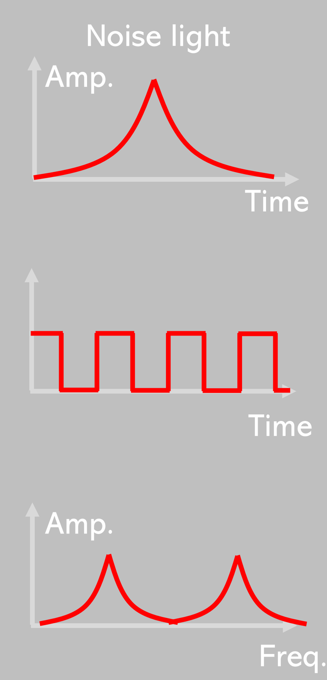


Considering a coherent pulse $f(t)$, after a periodic time phase modulation, the frequency spectrum $F(\omega)$ will be separated to orders of sidebands $F'(\omega)$, which can be seen as:

$$F'(\omega) = \int f(t)e^{-iAS_{\omega_0}(t)}e^{-i\omega t}dt, \quad S_{\omega_0}(t) = \begin{cases} 1, 0 < t < \frac{T}{2} \\ 0, \frac{T}{2} < t < T \end{cases}$$

When $A = \pi$ is allowed, the origin peak will be translated.

Here, we use 500MHz modulation frequency of phase electro-optical modulator (PEOM) to achieve high frequency separation.



Experimental Results

- **Modulation efficiency**

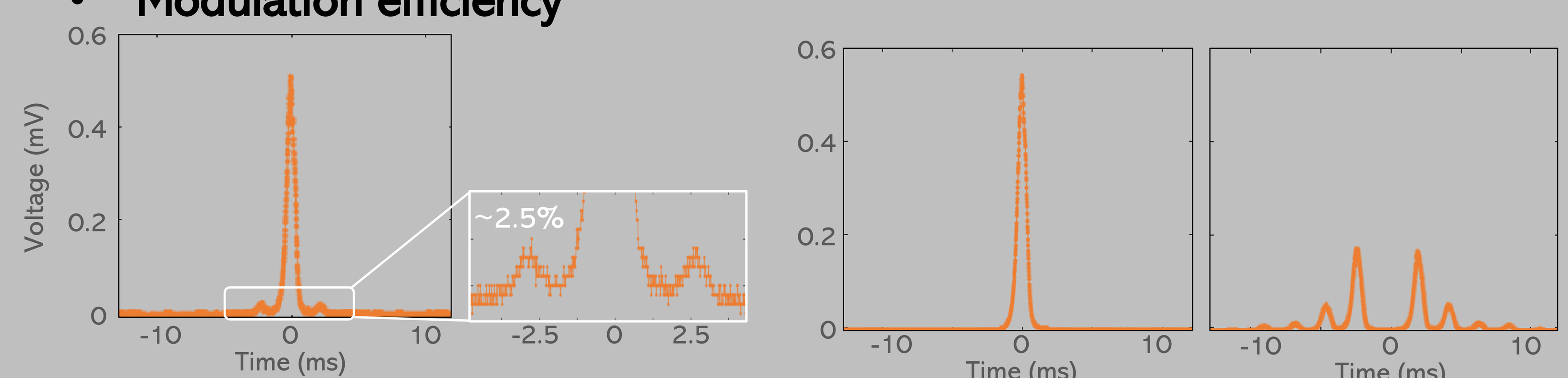


Fig. 2 | Frequency domain representation of double modulation of signal (left) and noise (right) without filtering. The images were obtained using a Fabry-Perot interferometer.

With the adjustment of polarization and bias voltage before EOM, the signal can almost be recovered, and the noise can be separated into two sets of sidebands as shown in figure.2.

- **Quantum signal-to-noise ratio**

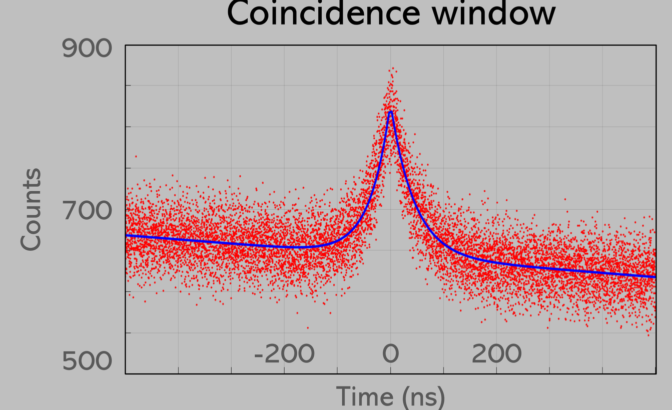


Fig. 3 | Signal-to-noise ratio (SNR) in a high-noise environment (SNR = 0.3)

Here we demonstrate the noise robustness with phase modulation in the coincidence window. Figure.3 represents the situation that noise is much larger than signal.

Signal-to-noise ratio (SNR) is defined using the unnormalized Glauber correlation function, $G^{(2)}(\tau)$. It can be calculated as

$$SNR = \frac{G^{(2)}(\tau)}{(G^{(2)}(\tau))_{bg}}, \quad G^{(2)}(\tau) = E[\mathbb{N}_1\mathbb{N}_2(\tau)].$$

After modulation, the noise will be suppressed and the signal occupied again (Figure.4) The result will approximate a noise-free condition. (Figure.5)

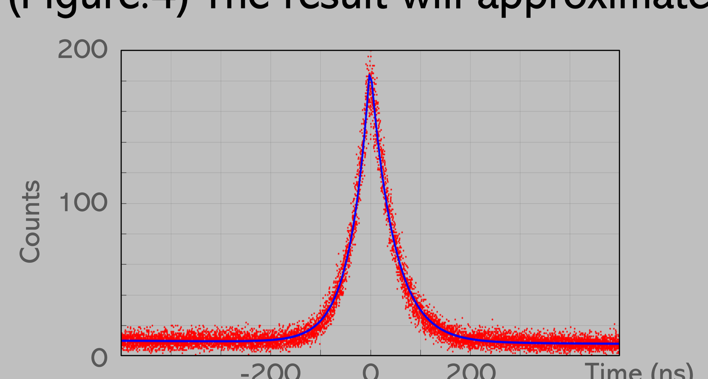


Fig. 4 | SNR improvement after phase modulation (SNR = 22.4).

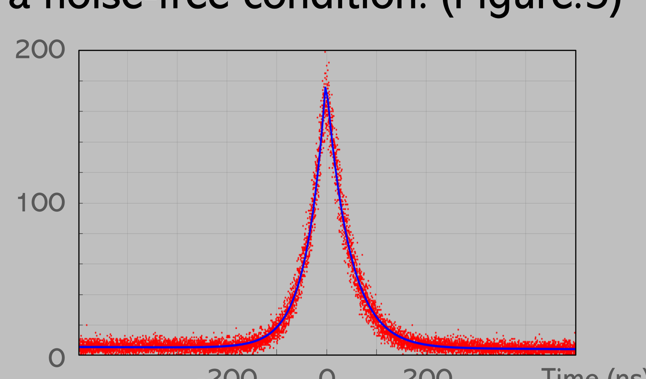
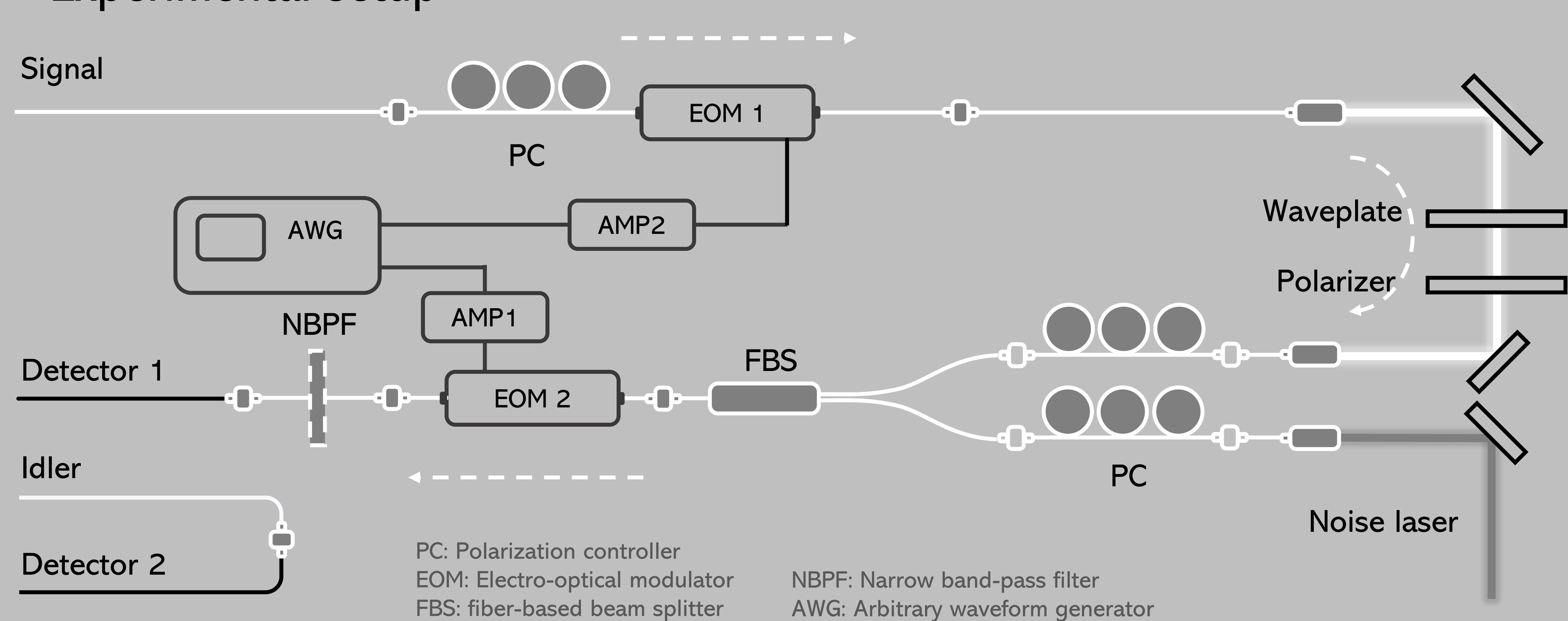


Fig. 5 | Original signal without noise interference (SNR = 41.2).

Experimental setup



Analysis

Signal-to-noise ratio comparison

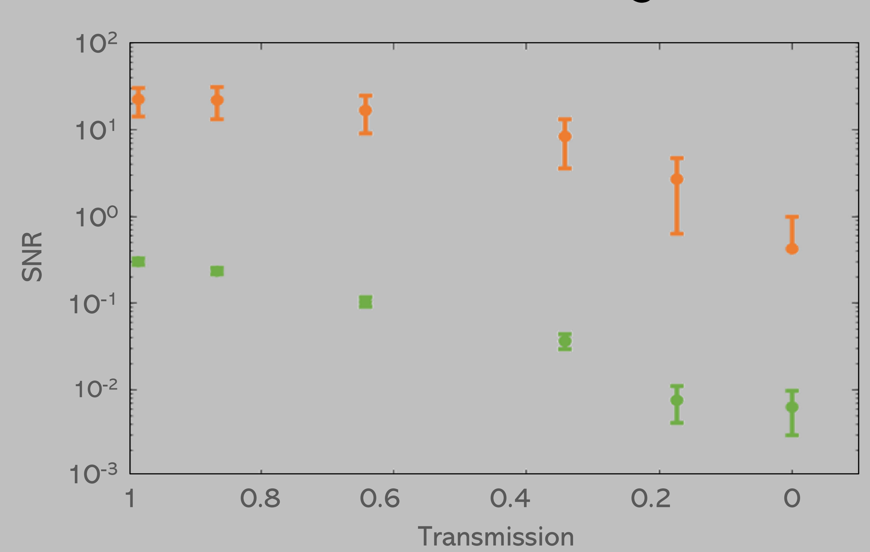


Fig. 6 | SNR comparison for varying transmission rate

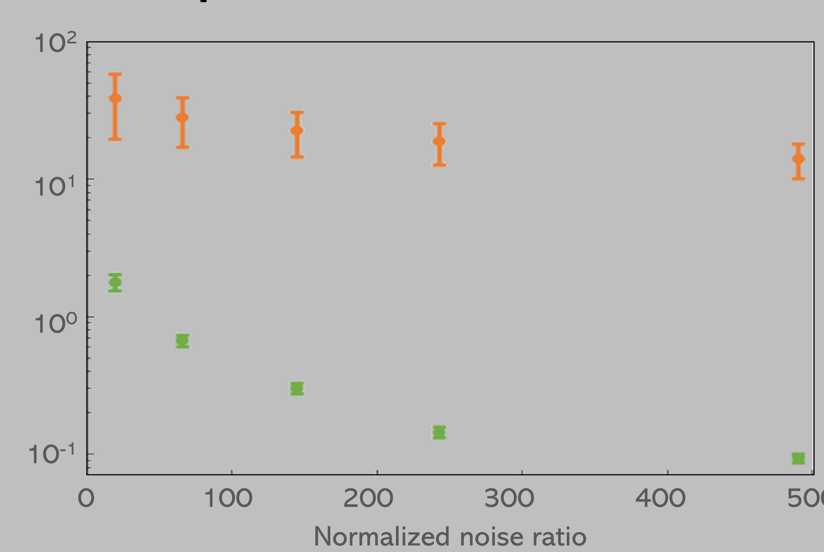


Fig. 7 | SNR for varying noise power

To quantify the effect of modulation technique, we adjusted two parameters (noise and transmission) and maintained all the other parameters. We can directly observe that, the modulated signal has higher SNR compared to the unmodulated case.

	Noise: 11.7 dB Trans: 0.9	Noise: 23 dB Trans: 0.9	Noise: 20 dB Trans: 0.1	Noise: 20 dB Trans: 0.9
Modulated	17.8	12.8	3.4	13.5
Origin	1.4	-7.5	-15.1	-6.3

• Conclusion

This phase-modulation technique demonstrates the efficient method for separating the coherent noise light. We compare and discuss the SNR of the system under varying transmission rates and noise conditions. The temporally long photons provide a suitable platform to match the response frequency of most electric components. We believe that this technique has immense potential at quantum sensing and LiDAR towards practical situation.

• Future work

- Comparison of Classical and Quantum LiDAR
- Quantum secure sensing with random phase encoding
- 2D Sample scanning

• Reference

[1] Chuu, C. S., & Harris, S. E. (2011). Ultrabright backward-wave biphoton source. Physical Review A—Atomic, Molecular, and Optical Physics, 83(6), 061803.

[2] Yin-Huan, Chang. (2024). *Quantum LiDAR with temporal long single photons* (Master's thesis). National Tsing Hua University

[3] Blakey, et al. (2022). Quantum and non-local effects offer over 40 dB noise resilience advantage towards quantum lidar. Nature communications, 13(1), 5633.