Interferometric Quantum Stroboscope

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Abstract

Quantum illumination (QI) has traditionally been used to detect low-reflectivity objects in noisy environments using entangled photon pairs. In this note, we explore a hybrid setup that combines the phase sensitivity of classical interference with the robustness of quantum illumination. We analyze how the interference at the point of object reflection can be integrated with QI to detect displacements and motion, particularly periodic motion, with enhanced sensitivity. This leads naturally to the concept of a quantum stroboscope, enabling high-frequency motion detection via quantum protocols.

1 Introduction

Quantum illumination, pioneered by Seth Lloyd [1], exploits entanglement to improve target detection in lossy and noisy environments. Typically, QI does not require the retention of entanglement through the channel. Instead, it uses joint measurements on the signal and idler photons to statistically distinguish between target presence and absence.

Here, we consider a setup in which the signal photon undergoes classical interference at a reflective object, while the idler is stored locally. This differs from conventional QI by combining phase-sensitive interference at the target with quantum-enhanced detection at the receiver. We further extend the idea to moving targets, using the quantum stroboscope paradigm introduced in [2].

2 Classical Setup and Interference

Consider a classical electromagnetic wave

$$y(x,t) = A(x,t)\sin(\omega t + x) \tag{1}$$

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sent towards a double-slit at $x = -10$ meters. An interference pattern forms at $x = -30$ meters. Placing a reflecting object in the central bright fringe and detecting the reflected light at a detector D, located off-axis, allows for classical interference-based displacement sensing. The intensity at the screen is

$$I(y) = I_0 \cos^2 \left(\frac{kyd}{2L} \right), \tag{2}$$

where k is the wave number, d is slit separation, and L is the distance to the screen.

3 Quantum Illumination Framework

A typical QI protocol uses signal-idler photon pairs in the entangled state

$$|\psi\rangle_{SI} = \sum_n c_n |n\rangle_S |n\rangle_I. \tag{3}$$

The signal is sent to probe the target region, and the idler is retained. Despite entanglement being broken by noise and loss, joint measurements allow superior detection capabilities compared to classical light.

4 Hybrid Scheme: Interference at Object + Quantum Detection

In our hybrid approach:

- The signal photon undergoes path interference at a double-slit and reflects off an object placed at the interference maximum.
- The interference pattern modulates the signal photon probability amplitude.
- The idler photon is stored and jointly measured with the returned signal.

Let the fields from the two slits interfere at the object location, leading to a total field

$$E_S^{(\mathrm{obj})}(t, y) = \frac{1}{\sqrt{2}} \left[\psi_1(t, y) + \psi_2(t, y) \right]. \tag{4}$$

The object reflects this coherent sum, and the detector D performs a coincidence measurement with the idler photon.

5 Application: Displacement and Motion Detection

A small displacement δ of the object from the interference maximum changes the phase difference between the two paths, modifying the interference amplitude. This results in a phase-sensitive signal return:

$$E_{\text{ref}}(\delta) \propto \cos\left(\frac{k\delta d}{2L}\right), \tag{5}$$

and the joint detection probability is modulated accordingly. This allows quantum-enhanced sensitivity to nanometer-scale displacements.

6 Quantum Stroboscope Extension

Building on [2], suppose the object is periodically moving. Let the orbital period be T, and the time t required for detection (i.e., the time to collect sufficient signal-idler coincidences) be known. If $t \ll T$, we can capture stroboscopic "snapshots" of the object at consistent positions in its orbit. Since t is smaller with entanglement [1], the system supports detection at higher motion frequencies, enabling quantum stroboscopy:

$$f_{\text{max}}^{(\text{QI})} > f_{\text{max}}^{(\text{classical})}. \tag{6}$$

7 Conclusion

By integrating interference at the object with quantum illumination protocols, we can achieve enhanced sensitivity in detecting displacements and motion. This hybrid strategy leverages classical coherence and quantum correlations to enable novel sensing capabilities, including quantum stroboscopy for tracking high frequency periodic motion.

References

[1] Seth Lloyd, "Enhanced sensitivity of photodetection via quantum illumination," *Science*, vol. 321, no. 5895, pp. 1463–1465, 2008. 1, 6

[2] Aman Chawla, "Quantum Stroboscope: A Note on Quantum Illumination of Moving Targets," 2024. Unpublished manuscript. 1, 6