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Optical Technologies and Measurements for Imaging and Sensing Using Quantum Sensors

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ABSTRACT

Quantum optical interferometry has been revived in the last 20 years due to the introduction of powerful sources of correlated photons. While conventional measurement methods are approaching their maximum resolution and sensitivity, quantum-based optical sensing and imaging technologies offer an effective approach to overcome these limitations by exploiting quantum features such as entanglement and superposition. In this work, a quantum-enhanced optical measurement framework is proposed that exceeds the standard quantum limit (SQL) by utilizing orbital angular momentum (OAM)-based interferometry and entangled photon states. To increase sensitivity and resolution, the approach combines interferometric phase estimation with customized quantum state preparation. Compared to traditional quantum sensing methods, the proposed model makes explicit use of OAM entangled photon states to improve noise robustness and phase discrimination. Theoretical analysis and simulation verify the approach's efficacy, demonstrating improved measurement precision in comparison to classical and conventional quantum approaches.

1. INTRODUCTION

Modern technologies profoundly impact everyday life, with sensor-based systems that play a central role in both consumer and industrial applications. There are basic constraints placed by the laws of physics on the quest for increased sensitivity and resolution in sensing and measuring applications [1]. The essential quantum mechanical characteristics of the systems being measured, as well as the equipment used to test them, are crucial for achieving these limits. The extent to which a sensor can achieve this performance is mostly determined by its accuracy and noise characteristics.

In metrology, the examination of accurate measurements is essential for sensor design considerations [2]. As a fundamental concept of nature, quantum mechanics affects the functioning of information-processing-based technologies. Therefore, understanding quantum physics is essential for determining the ultimate limits of these technologies. To investigate the implications of quantum mechanics, the traditional concepts of computation, communication and cryptography have evolved significantly, transforming the modern world over the last five decades [3].

Quantum algorithms for rapid factorization of integers and database searches, super-dense coding and quantum key distribution are some of the fascinating new possibilities that have emerged from quantum mechanics. In addition to the field of imaging, similar super-resolution or super-sensitivity phenomena can also be observed in various measurements and sensing applications and these phenomena are frequently linked to purely quantum-mechanical effects like entanglement [4]. When a unified system with two or more subsystems cannot be divided into separate subsystems, it is said to be in an entangled state, where the system as a whole is described by a single quantum state rather than by the individual subsystems.

In particular, measurements of phase, angular and rotational variables as well as dispersive properties can be performed using non-classical optical states [5]. The application of quantum-based techniques in these situations enables more accurate measurements than those achievable using conventional techniques alone. In many cases, quantum entanglement is regarded as a valuable tool for addressing real-world problems. This perspective is widely accepted within the quantum computing and quantum information communities, although it is less widely recognized in other fields [6]. Quantum Information Science (QIS) has four pillars: quantum sensing, quantum networking, quantum simulations and quantum computing, which are defined for measuring physical quantities [7].

Although quantum sensing and optical metrology have made significant advances, traditional methods are often limited by the inability to fully exploit high-dimensional quantum states and by the challenges associated with implementing entanglement-enhanced measurement techniques in practical settings. Specifically, the use of photon orbital angular momentum (OAM) in interferometric measurements to improve sensitivity and robustness in practical sensing contexts has not been fully investigated. Furthermore, the performance benefits of many traditional quantum interferometric methods are limited because they primarily focus on phase estimation without effectively integrating spatial and angular degrees of freedom.

The paper is further organized as follows. Section 2 reviews related works on quantum sensing techniques. Section 3 presents the proposed quantum-enhanced measurement framework, including OAM-based interferometry, phase estimation and angular measurement. Section 4 discusses the simulation results and performance evaluation. Section 5 concludes the paper and outlines future research directions.

2. RELATED WORKS

Over the past decade, various quantum technologies have been employed for sensing applications, including artificial atoms in wide-bandgap materials, photonic qubits, trapped ions, atomic vapors and superconducting circuits [8]. Quantum approaches have enabled advances in fundamental scientific activities such as imaging, parameter estimation and hypothesis testing. The information obtained from a measurement can be significantly enhanced through the appropriate selection of the quantum probe state or measurement strategy. For example, quantum-based approaches can improve the image resolution beyond the standard Rayleigh limit and reduce measurement noise [9].

Additional advancements include optically enhanced dynamic microscopy and ghost imaging, which extract information from quantum light that is not directly associated with the measured object. Although some of these imaging tasks can also be performed using classical methods, quantum lithography and quantum sensing exploit entangled or correlated light sources to achieve enhanced measurement precision. Quantum approaches can overcome the diffraction limit in situations where source engineering is not feasible, such as in the study of astronomy, by fully revealing the phase and amplitude information contained in the detected light.

The Rayleigh criterion states that the least angular spacing that may be resolved is $\theta_{\min} = \lambda/D$, where the wavelength ($\lambda$) and the lens's diameter (D) have historically been used to limit the resolution of imaging systems. It was demonstrated that even in cases when the origin's angular separation is less than $\theta_{\min}$, there is no reduction in accuracy when determining their separation [10]. In a diffraction-limited system, a point-like object is not represented as an ideal point. Instead, it produces a finite spatial distribution illustrated by the Point Spread Function (PSF). Direct detection of exoplanets is especially a challenging task when two sources overlap in the image, particularly when one source is significantly weaker than the other [11].

Quantum metrology can be used to estimate the angular separation of two sources once their presence has been confirmed with enough confidence. The Quantum Cramér–Rao Bound (QCRB) determines the final precision of this estimation. The highest possible precision for estimating a particular parameter is defined by the Quantum Fisher information (QFI). Nevertheless, not all measurement schemes can reach this limit [12]. The associated Fisher Information (FI), which is the classical equivalent of the QFI, establishes the achievable precision for a certain measurement approach. Spatial-mode Demultiplexing (SPADE) or a similar measuring technique can be used to approach the QCRB when the PSF is roughly Gaussian [13].

When determining the spacing between two sources, conventional methods are not very accurate, especially when the gap is significantly smaller than the PSF width. In certain situations, the estimation precision drastically drops and may even get close to zero. A considerable sub-Rayleigh advantage in quantum-state discrimination between single- and two-source scenarios has been demonstrated by studying the QCRB for estimating the angular separation of two sources with equal intensities [14]. One measuring arrangement can accomplish these goals. This method allows for various measurement jobs within the same experimental setup by employing a simple two-mode interferometer to capture photons at both spatial points [15].

Bismuth is an intriguing material because of its low carrier density and strong spin-orbit coupling. Asymmetric edge currents identical to those observed in HgTe quantum wells are also predicted in single-bilayer bismuth. The presence of these edge currents is indirectly supported by measurements of the conductivity of thin bismuth films. Prior research on HgTe quantum wells used topological energy scales of about 10 meV and required liquid-helium temperatures [16]. Because these edge currents can display macroscopic quantum coherence, similar to the persistent currents seen in Superconducting Quantum Interference Devices (SQUIDs), they may be especially pertinent to quantum information processing. Even in the presence of external noise, these coherent states might maintain their unique characteristics. Furthermore, bismuth and $Bi_{1-x}Sb_x$ systems may provide advantages over SQUID-based methods for quantum information because helical edge currents may be less vulnerable to $1/f$ noise [17].

Polarized light provides a fundamental mechanism for linking optical edge states with visible image information. It is widely known that polarized light can produce spin-polarized currents in Gallium Arsenide (GaAs). It is possible to match the optical frequency with the quantized energy levels linked to particular boundary states by varying the film thickness [18]. Focusing the laser light onto the aperture is an additional method. However, when the aperture is much smaller than the incident light's wavelength, λ, this method may decrease coupling efficiency. The coupling efficiency can be further increased by applying an external electric field. Additionally, this idea could serve as a foundation for creating innovative electro-optical switching devices [19].

A similar principle applies to high-resolution imaging. By designing the source of illumination to create a suitable spatial distribution, it is possible to exceed the Abbe diffraction limit. However, the detection system must be carefully optimized in order to achieve this improvement. Non-imaging quantum sensing applications also use unconventional measurement techniques [20]. Specifically, two-detector coincidence measurements have been frequently utilized to study second-order correlations in quantum systems and to quantify first-order correlations acquired using traditional interferometry [21].

Second-order correlations can reveal quantum mechanical effects that are not accessible through conventional interferometric measurements. Thus, recent advances in quantum sensing have concentrated on both practical technologies, such as interferometric systems and integrated photon sources, and basic measurement concepts. Numerous additional facets of quantum metrology have also been studied [22]. For instance, two-dimensional materials have been used in Van der Waals engineering to create entangled photon pairs. This method creates polarization-entangled photon pairs by the interference of biphoton emissions from two van der Waals thin layers that are positioned perpendicular to one another. The measurement accuracy of the polarization-entangled state is up to 86 ± 0.7% [23]. A comparison of the conventional methods is presented in Table 1.

Table 1. Comparison of conventional methods

Methods	Principles	Advantages	Limitations
Sub-Rayleigh imaging	Exploits quantum measurement strategies to surpass the diffraction limit.	Spatial resolution has improved beyond its classical limits.	Noise sensitivity, ideal conditions and limited for practical deployment.
NOON state	Utilizes photon states that are maximally entangled to estimate phase.	Heisenberg-limited sensitivity is attained.	Poor scalability and extremely fragile under loss and decoherence.
SPADE-based technique	Spatial mode demultiplexing is usually employed for parameter estimation.	Under certain conditions, the optimal estimations are achieved.	Precise optimal alignments are required.
SQUID-based quantum sensing	This provides superconducting interference for highly sensitive interference.	Exceptionally great sensitivity for detecting magnetic fields.	Requires cryogenic conditions and is applicable only in certain domains.

Note: Spatial-mode Demultiplexing (SPADE), Superconducting Quantum Interference Devices (SQUIDs).

The polarization-based scattering technique for characterizing a transition section in a fiber optic communication link has recently been measured using some of the methods discussed here. The measurement uncertainty was approximately 2 attoseconds for the phase delay and 0.1 femtoseconds (fs) for the group delay, representing a substantial improvement over earlier conventional measurement techniques. SQUIDs are widely employed in low-frequency communication systems, aerial magnetometry, biomagnetic measurements, non-destructive testing, magnetic measurement microscopy and other applications [24]. SQUIDs incorporate principles and technologies from several fields, including electromagnetic theory, superconductivity, thin film fabrication, packaging technology, electronic circuits and cryogenics [25]. However, most conventional techniques do not utilize OAM or fully integrate entanglement for phase-based sensing.

To address these limitations, this work proposes a quantum-enhanced optical measurement framework that combines entangled photon states with OAM-based interferometry. The proposed approach is designed to improve phase sensitivity and measurement accuracy by exploiting both quantum entanglement and the high-dimensional characteristics of OAM states. By combining these characteristics, the framework seeks to address the drawbacks of traditional quantum measurement methods and offer a reliable and expandable solution for optical detection and applications involving imaging.

Problem Statement: Conventional optical sensing systems are constrained by the standard quantum limit (SQL), which limits sensitivity and resolution particularly under low light conditions. Existing quantum approaches, including NOON state-based methods, suffer from high sensitivity to photon loss and limited robustness. Moreover, most techniques do not fully exploit high-dimensional spatial properties such as OAM. Therefore, a robust quantum-enhanced sensing framework is required that integrates OAM with entanglement to improve phase-estimation accuracy and noise resilience beyond the capabilities of existing approaches.

3. PROPOSED MODEL: MEASUREMENTS FOR IMAGING AND SENSING

A quantum-enhanced optical measurement framework is proposed that exceeds the SQL by utilizing OAM-based interferometry and entangled photon states. The proposed quantum-enhanced interferometric sensing model combines OAM encoding with entangled photon states for achieving high-resolution phase estimation beyond the SQL limit. To increase sensitivity and resolution, this approach combines interferometric phase estimation with customized quantum state preparation.

The main contributions of this proposed model are as follows:

1. **Integration of OAM and entanglement:** OAM encoding and entangled photon states are combined within a unified interferometric framework.
2. **Enhanced phase estimation:** A phase estimation strategy is developed by using high-dimensional OAM-based quantum states.
3. **Improved robustness:** Compared to conventional NOON state approaches, the proposed approach provides greater robustness to photon loss and measurement noise.
4. **Extended sensing capability:** The proposed framework extends quantum sensing beyond phase-only measurements by incorporating spatial/angular degrees of freedom.

The proposed interferometry approach employs entangled states with a limited number of photons, particularly NOON states. Because these states can offer improved phase sensitivity with comparatively tiny photon quantities, they have garnered significant interest in quantum technologies. Under ideal circumstances, NOON-state interferometry can get close to the Heisenberg limit, where N is the number of photons and the phase uncertainty scales as $1/N$. Super-sensitivity and super-resolution beyond the traditional Rayleigh diffraction limit are made possible by this scaling.

The theoretical basis for evaluating interferometric observations is provided by the analysis of quantum parameter-estimation theory and two-mode quantum interferometry. These ideas are crucial to quantum optical metrology, which uses the characteristics of quantum states to enhance parameter estimation. These improvements are mostly dependent on quantum entanglement and several methods can be used to create entangled states for optical metrology. The suggested interferometric method in this study is intended to take advantage of entanglement in order to obtain phase estimation that is close to the ideal Heisenberg limit.

The generated photons are passed through an interferometric setup consisting of a beam splitter (BS), a phase shifter (PS) which introduces a phase shift 'φ' and spiral phase plates (SPPs) for OAM modulation.

3.1 Standard optical interferometry

Before discussing quantum interferometry, a brief description of the conventional coherent laser light interferometer called cavity geometry, depicted in Figure 1, is provided using standard interferometric principles. Initially, the BS divides the incident laser beam into two beams with equal intensity. As the beams propagate through the interferometer, they acquire an unknown relative phase shift. The two beams are then recombined at the final BS, and the resulting intensity difference between the two output beams is measured.

According to the estimation using standard optics, the intensities at the ports used for output can be expressed as the relative phase φ and the input intensity I_{a0} and it is given in Eqs. (1) and (2).

$$I_{a2} = I_{a0} \sin^2(\varphi/2) \quad (1)$$

$$I_{b2} = I_{a0} \cos^2(\varphi/2) \quad (2)$$

This quadratic error propagation algorithm can be used to establish a decent estimation of the level of accuracy to which one can estimate a mysterious relative phase determined by the measurement of M, with regard to the phase error, or the least identifiable phase, $\Delta\varphi$, given in Eq. (3).

$$\Delta\varphi = \frac{\Delta M}{dM/d\varphi} = \frac{\Delta M}{I_{a0} sin\varphi} \quad (3)$$

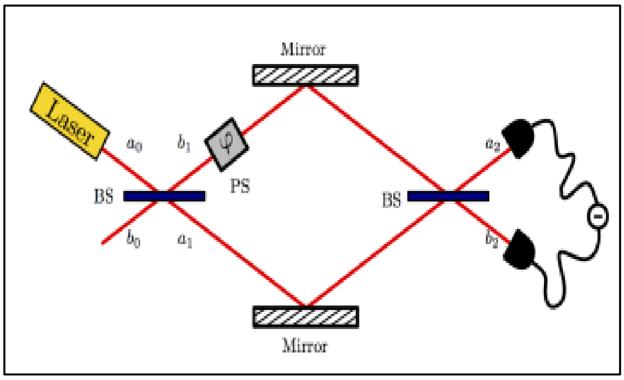

Figure 1. Cavity geometry

The phase determination is capable of being set rationally narrow at a nearby magnitude of phase $\varphi = \pi/2$ by rendering the source of intensity I_a sensibly enormous and by analyzing the intensity differential M with unlimited resolution. However, the prospect of quantifying intensities with unbounded accuracy, that is, having $\Delta M = 0$, is eliminated by quantum physics. This happens because photon detection is essentially a quantum process; instead of detecting a signal with continually changing intensity, the sensor detects discrete, independent units of energy.

3.2 Quantum optical interferometry

In order to provide a totally quantum approach to two-mode optical interferometry, a quantized method of measuring the electromagnetic field is proposed, and all of its phases are explained. The PS and BS transformations are the two most significant continuous optical conversions in interferometry for two distinct photonic modes. The variance dispersion approach is then used to calculate the phase estimation accuracy, using Hermitian operators as the observed values are at the interferometer output.

3.2.1 Electromagnetic field's single mode for quantum states

The creation and annihilation operators of a quantized electromagnetic field mode satisfy specific commutation relations and provide a complete description of the mode. Their effects on the number states of the mode, also known as Fock states, determine the characteristics. The evolution of a pure quantum state within a single-mode field, including its transition from the vacuum state, can be described by the appropriate relations among the creation and annihilation operators.

Any pure state of a single-mode quantum system can be expressed by means of such states. More generally, a density operator, which represents both pure and mixed states as well as statistical ensembles of quantum states, can characterize every single-mode quantum state. The density operator's eigenvalues must be real, non-negative and equal to unity in order to express physically correct probability. Furthermore, the quantum state of a quantized electromagnetic mode can be described using quasi-probability distributions in phase space, such as the distributions connected to the field quadratures 'p' and 'x'.

3.2.2 Dynamics and quantum states using the Mach-Zehnder device

The formation and annihilation operators are associated with the two optical paths in the quantum description of the Mach-Zehnder Interferometer (MZI), where the different mode indices represent the input and output modes of the interferometer. Geometric or polarization phases may be represented by the two phase shifts added within the MZI. The two-mode quantum state at the MZI's output can be obtained in the Fock-state representation by combining the input-mode operators with the matching output-mode operators and adding the entire diffraction matrix.

Phase-space quasi-probability distributions, like the Wigner function, can be used to effectively depict the data transmission through the MZI. As stated in Eq. (4), this representation is produced by connecting the initial field variables to the appropriate interferometer output variables.

$$W_{out}(\alpha_1, \beta_1) = W_{in}[\alpha_0(\alpha_1, \beta_1), \beta_0(\alpha_1, \beta_1)] \quad (4)$$

The two-by-two diffraction matrices provide a similar representation of the interaction across the complex elements, which are expressed in Eq. (5).

$$\begin{pmatrix}\alpha_0\\ \beta_0\end{pmatrix} = M^{-1}\begin{pmatrix}\alpha_1\\ \beta_1\end{pmatrix} \quad (5)$$

The various intensities, such as α_0, β_0, α_1, and β_1, are provided to correspond to the section patterns. By employing Gaussian states with Wigner distributions and Gaussian processes, the phase distributions of the odds technique prove to be especially effective and convenient.

Extracting the thermal state, the unified state and the coherent state are a few examples. This happens since a Gaussian distribution can be fully characterized through its initial and subsequent events, standard deviation and correlations of Gaussian states in a variety of distinctive luminescence methods. This characteristic has the capability of spreading the defined simplistic category based on the mathematical calculations.

3.2.3 Schwinger representation

Schwinger representation provides a different theoretical perspective on quantum states and their behaviour in an MZI, describing the interferometer using angular momentum operators to model the photon modes and their transformations at the BS and PS. In the classical spin $N/2$ region of the Hilbert space's angular momentum, a two-mode N-photon pristine condition is dynamically translated onto an unaltered state according to this connection, as expressed in Eq. (6).

$$|n_a, n_b\rangle |j = \frac{n_a + n_b}{2}, m = \frac{n_a - n_b}{2} \quad (6)$$

3.2.4 Phase estimation and measurement

Following the dual-mode quantum state's evolution through the MZI, an appropriate Hermitian operator is used as a measurement variable for determining the resulting state, which is often a density operator ρ.

In this case, the photon count variation activator is an estimation parameter that correlates to the intensity contrast identified by the standard MZI. Each of the two output methods, namely mode, has been determined to be the most ideal for numerous source states. The photon number parity operator is an intriguing detection approach that can be employed. Moreover, the error dissemination calculation specifies the accuracy that indicates an unidentified phase φ, which can be approximated to a good degree using the selected detection strategy. When an intensity differential becomes apparent, the measuring operator's signal will be generated and it is given in Eq. (7).

$$|\alpha|^2\left(cos^2\left(\frac{\varphi}{2}\right) - sin^2\left(\frac{\varphi}{2}\right)\right) = |\alpha|^2 cos\varphi \quad (7)$$

Eq. (8) describes the variation in the measured intensity, and the second phase of the output state makes it possible to determine the greatest possible phase prediction resolution using coherent interferometric light.

$$\Delta\varphi = \frac{\sqrt{|a|^2 cos^2\varphi + |a|^2 - |a|^4 cos^2\varphi}}{|a|^2\, sin\,\varphi} \quad (8)$$

where, 'a' represents the coherent state's mean photon amount. Let φ be the unidentified phase and θ be the monitoring phase. Then, when θ is an unusual number of $\pi/2$, the accuracy is at its best, reaching the quantum shot noise maximum of $\Delta\varphi = 1/\sqrt{n}$.

3.3 Rotational and angular measurements

Optical wavefronts originate with a twisted structure and it is associated with positive OAM. The Poynting vector (S) rotates every time the wave moves over its z-axis because it needs to be continuously perpendicular to the wavefront, as shown in Figure 2.

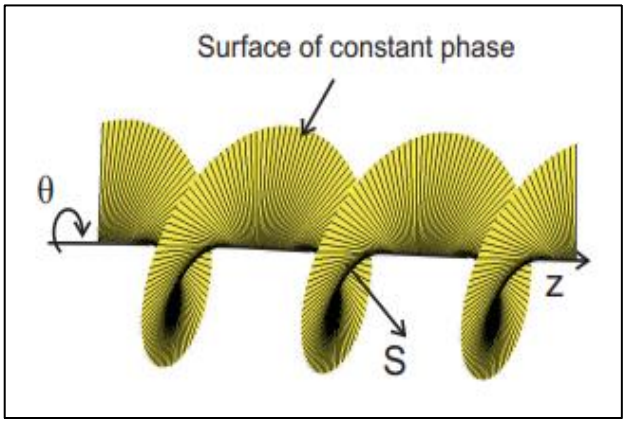

Figure 2. Optical orbital angular momentum (OAM)

3.3.1 Orbital angular momentum

In these events, the super-sensitivity regarding phase results in super-sensitivity leading to alignment axes and angular rotations causing changes in corresponding phase. Optical angular momentum examines its potential uses in the following sections as follows.

Photons possess both spin angular momentum and linear momentum. The spin angular momentum of a photon is associated with its polarization state. Linearly polarized photons can be represented as an equal superposition of right- and left-circularly polarized states. The circular polarization states correspond to spin projections of $s_Z = +1$ and $s_Z = -1$, respectively, along the propagation axis. As a result, a photon's spin state and polarization state can be directly correlated, offering a crucial foundation for examining how polarization and angular momentum interact in quantum optical systems.

A photon's wavefront must have a particular azimuthally shifting phase structure in order for it to carry positive OAM. Several methods can be used to create and impose such spatial phase distributions on the optical field. SPPs, forked diffraction gratings and computer-generated holograms are common methods. These optical components can produce optical modes with well-defined OAM by introducing an azimuthally variable phase that is dependent on the incident light's wavelength (λ).

Using a χ^2 asymmetric crystal, Spontaneous Parametric Down Conversion (SPDC) is the most popular method of generating entangled photons. Through its relationship with the nonlinear crystal, a high-energy photon from the incident beam is transformed into two lower-energy photons during this process. The energy, momentum and polarization of the signal and idler photons produced by this operation may show quantum correlations or entanglement. Thus, depending on the phase-matching circumstances and the features of the nonlinear interaction, the crystal's output can be expressed as a superposition of signal-idler states with various OAM values.

3.3.2 Measurement of angular displacement

A dove prism is considered to demonstrate super-resolution in angular observation. The dove prism, depicted in Figure 3, is designed to have 100% internal reflection on its bottom surface. Due to this reflection, there is no matching horizontal inversion; instead, pictures turn upside down in the vertical direction.

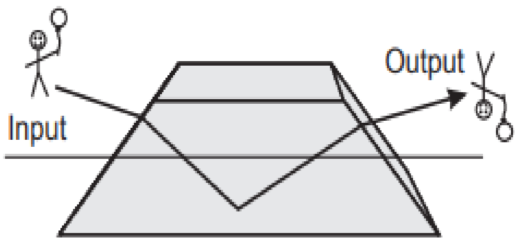

Figure 3. Dove prism

These prisms have a unique characteristic: a dove prism reverses the sign of the incident beam's OAM while maintaining its magnitude and when it is rotated by an angle θ about the propagation axis, the transmitted picture rotates by 2θ. As a result, the matching mode with charge −l is created from an OAM mode with topological charge l. Eq. (9) quantifies the rotation caused by the prism and expresses the consequent angular displacement.

$$\Delta\hat{R} = \sqrt{\langle\hat{R}\rangle^2 - \langle\hat{R}\rangle^2} = cos\left(2/_\theta\right) sin\left(2/_\theta\right) = \frac{1}{2} sin\left(4/_\theta\right) \quad (9)$$

However, some uncertainty occurs in the final estimate. The entangled photons are derived and given using Eq. (10).

$$\Delta\theta = \frac{\Delta\hat{R}}{\left|\frac{\delta\langle\hat{R}\rangle}{\delta\theta}\right|} \quad (10)$$

This process can be extended from two to N entangled photons. It may be demonstrated in the same way, and the phase sensitivity and it is given in Eq. (11).

$$\Delta\theta = 1/_{2Nl} \quad (11)$$

This needs to be contrasted with the scenario in which N independent lights are determined in a collection using the same parameters, which is given in Eq. (12).

$$\Delta\theta_{SQL} = \frac{1}{2\sqrt{Nl}} \quad (12)$$

Entanglement not only permits the sensitivity to be significantly minimized by an extent of *Nl* exceeding the conventional quantum bound in this situation, but it also allows for additional enhancements in the angular sensitivity through the use of states with larger angular momentum. The high degree of precision with which rotations might be measured could eventually be applied in nanotechnology.

3.3.3 Reconstructing images and identifying objects

Only a single photon state can be selected according to the specific requirements of the experiment, as demonstrated by the various OAM-based techniques. Reconstructing the image using a single OAM spectrum is one of this method's primary goals. To accomplish this goal, though, two significant obstacles must be overcome. First, in order to accurately reconstruct the image, it is also necessary to calculate the phase information of the linked coefficients. Consequently, recovering the entire image requires more than just monitoring the intensities of the output OAM components.

The fundamental operation of digital and similar spiral imaging systems does not require entanglement. However, similar to the methods covered in the previous sections, *N*-photon entangled states may allow these techniques to transcend traditional limitations on resolution and sensitivity. Specifically, the angular oscillation frequency can theoretically grow by a factor of *N*, as explained in the preceding subsection. The sensitivity and resolution of fine angular characteristics may be enhanced by this increase. Thus, rather than depending solely on traditional spatial imaging techniques, OAM data may offer a foundation for super-resolved imaging.

3.3.4 Rotational measurements

Rotation ratios can also be determined via optical OAM states. Envision a revolving object's surface reflecting two photons with divergent OAM of ±l. There will be opposite but equal Doppler shifts experienced by the two reflected photons. Thus, if interference between the two mirrored photons is permitted, then the total intensity will show a beat frequency. Even extremely small quantities can be precisely measured if l is large.

3.4 Quantum optical metrology

After introducing the required instruments, quantum optical metrology is discussed by providing an overview of two important non-classical effects: quantum entanglement and squeezing. These effects form the fundamental basis for achieving quantum advantages in optical metrology.

3.4.1 Entanglement

One of the most widely recognized examples of how quantum physics allows correlations between physically isolated systems is quantum entanglement. One essential characteristic of quantum systems is entanglement, which is crucial to quantum information processing. In quantum metrology, it is also regarded as a crucial tool for increasing measurement accuracy.

By expanding the accessible QFI, entanglement can offer an advantage over traditional measurement models. The total QFI is bounded by *N* for *N* separate devices constructed in a separable state without quantum entanglement. As a result, these systems are unable to attain the increased sensitivity linked to entangled states. By using the QCRB, the QFI provides the fundamental lower bound on the uncertainty of parametric estimation.

NOON states can reach the Heisenberg limit in phase estimation because they possess QFI of N^2. The photon-number parity operator has been demonstrated to offer an ideal measuring technique for phase estimation utilizing NOON states. Under suitable measurement conditions, phase information can also be extracted using the photon-number difference operator.

3.4.2 Squeezed light

Squeezed light describes minimal ambiguity states associated with light in which there occurs an increase in oscillations within one orthogonal summation in the space of phases, with the result of a decrease in oscillations in the opposite quadrature. The squeezing operator is used to provide a mathematical description for them. Given a mode a_0, the one-mode squeezing operator acting on it is provided in Eq. (13).

$$\hat{S}(\varepsilon) = exp\left(\frac{1}{2}(\varepsilon a_0^2 - \varepsilon^* a_0^2)\right) \tag{13}$$

The state obtained by applying the squeezing operator to the vacuum state is known as the squeezed vacuum state.

3.4.3 Squeezed vacuum light interferometry coupled with coherent mixing

The Sub Shot Noise (SSN) period estimation was first discovered by interferometry based on blending coherent light with squeezed vacuum light. Hofmann and Ono demonstrated that the condition that emerges across the combination separator is one in which every *N*-photon constituent in the phase possesses a reliability that exceeds 90% when compared to the equivalent NOON state whenever those inputs have been combined in identical concentrations.

3.5 Entangled photons using quantum technologies

A few studies show that entangled photons in interferometry associated with NOON phases can provide increased sensing and imaging features. These studies concentrate especially upon the tiny photon number region, which is important for imaging and sensing devices made of sensitive resources, including atomic combinations, individual molecules, cold classical gases and specimens from life.

3.5.1 Quantum sensing and metrology

Phase approximation has been established exceeding the shot noise restriction and reaching the Heisenberg threshold in a number of studies depending upon the NOON states. The important values projected onto the optical phase during practical photon reduction and various decoding conditions using NOON states were considered. Applications for atomic rotation ensembles include improved quantum atomic interferometry and optical quantum storage.

While atomic spinning groups are subjected to optical observations that include quantum memory storage or presentation, or in atom interferometry that results in spin squeezing, they are naturally affected by scattering-induced excitation distortion. Additionally, photon loss occurs as a result of the optical probes reflecting away the whole thing.

3.5.2 Quantum imaging

Imaging and microscopy represent another crucial field in which optical phase observation is utilized. Divergent illumination difference microscopy is a frequently employed methodology in biology for imaging biological materials. The Signal to Noise Ratio (SNR) of the instrument's reading is correlated with the spatial resolution of the images generated by this method. The shot noise constraint in phase accuracy limits considering an individual light intensity in the context of traditional imaging on laser light. Increasing the intensity of light serves as a technique to improve SNR, although this could have adverse impacts on fragile, photosensitive materials like ice crystals, biological tissues, etc. On the other hand, quantum metrology may improve the SNR without boosting the light power; thus, it could be quite beneficial in this situation. The squeezed light might be utilized to follow diffusive samples of biology in real time by achieving SSN sensitivity on microparticle detection.

3.5.3 Quantum lithography

Lithography uses geometrical disturbance margin generation to detect incredibly small information on an integrated circuit. Nevertheless, the NOON states may exceed this threshold, a phenomenon termed super-resolution. This conclusion had previously been shown by a few separate tests with $N = 2$ NOON states. It was later shown that the technique of NOON state lithography experiences the issue that the effectiveness of sensing *N*-photons with an identical geographic region declines geometrically with *N*.

4. RESULTS AND DISCUSSION

The results are generated using a computational model of a coherent interferometric imaging system to ensure reproducibility and transparency. Poisson-distributed statistics under shot-noise-limited conditions are used to create photon detection events. Unless otherwise noted, each experiment uses $n \approx 68,000$ photons per estimation, with a detection efficiency (ϵ) = 0.54. The results of this study are averaged across several independent examinations, and the angular spacing (θ) is changed in the range of 10^{-5} radians. Table 2 describes the simulation parameters.

Table 2. Simulation parameters

Parameter	Description
Simulation Model	Coherent interferometric system of imaging
Photon Statistics	Poisson distributed with shot noise conditions
Number of Photons (n)	≈ 68000 photons per estimation
Detection Efficiency (ϵ)	0.54
Signal to Noise Ratio (SNR)	Varies under different noise conditions
Angular Spacing (θ)	Varies in the range of 10-5 radians
Wavelength (λ)	Constant
Noise Model	Shot noise (based on photon detection)

4.1 Photon detection

The probability of the photon reaching devices 'a' and 'b' is considered experimentally. The possibility of any one of the devices detecting a photon, depending on the provided phase α, is modified by the air gap's proximity. The possibility of the photon reaching the device is $\epsilon = 0.54$ and angular separations of 1.45×10^{-5} rad and 4.98×10^{-5} rad are shown in Figure 4.

As estimated, the brightness increases with decreasing separations for the range of minimal θ; the light grows increasingly homogeneous as the separation decreases. The level of visibility is supposed to be 100% in concept for a single source of light in the range where $\theta = 0$. The results presented confirm that the proposed framework can reliably represent photon distribution at different spatial separations.

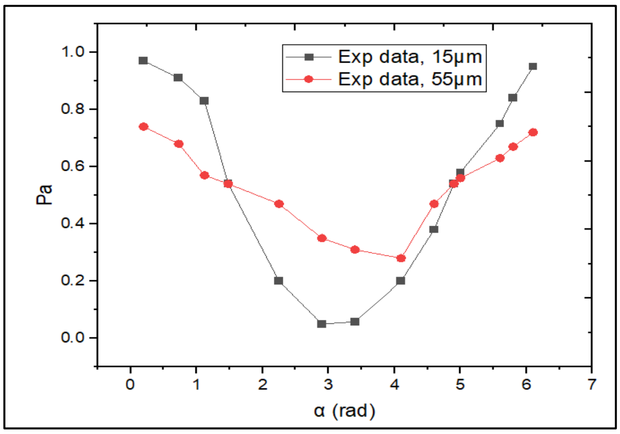

Figure 4. Probability of photon detection

4.2 Relative entropy

The two possibilities of relative entropies are calculated and shown in Figure 5. It displays the points of the experiment's data, the Classical Relative Entropy (CRE) using shot noise constrained Direct Imaging (DI), the Quantum Relative Entropy (QRE) corresponding to the two-mode state and the CRE with the test value optimized across α.

The analysis is performed for an angular separation of 5.74 × 10^{-5} rad, across varying the values of ϵ. The results show that QRE significantly outperforms classical approaches, indicating enhanced distinguishability in the quantum framework. In addition, the relative entropy for imaging directly with a lens that has a diameter equivalent to the 5.3mm fiber's spacing is also shown.

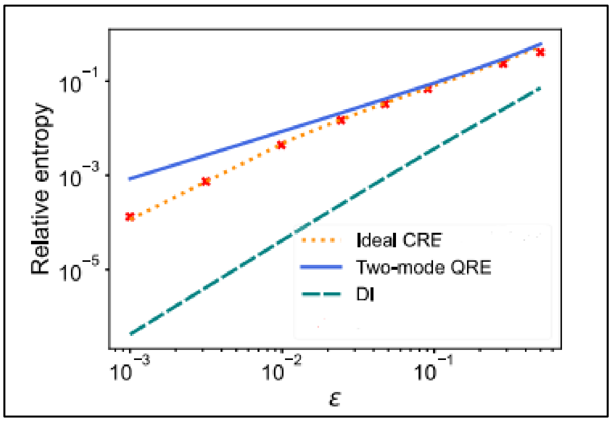

Figure 5. Relative entropy of two theories with various values

The proposed relative entropy has greatly strayed from the optimum quantum situation around $\epsilon \sim 10^{-3}$, because of errors in measurement, yet it still achieves better performance than the existing approach, which suffers from a couple of orders of magnitude under low light conditions.

4.3 Mean squared error

The acquired 30 separate estimations for every parameter that represented the angular separation are identified, each of which received about n = 68,000 photons. Mean squared error (MSE) is increased by $n \times I_\theta$ and it is shown in Figure 6.

The dashed line represents the possible precision with shot-noise-limited DI, while the red lines represent the results obtained for the proposed model. The results demonstrate that the proposed approach achieves significantly lower MSE, particularly for small angular separations. Notably, the method surpasses the Rayleigh resolution limit, which is a fundamental constraint in classical imaging. The basic mean square errors are approximately two to three orders larger and greater than what can be obtained with DI employing an optic of the identical diameter when θ = 1.42× 10^{-5} rad. They are also around 1.63% of the genuine value.

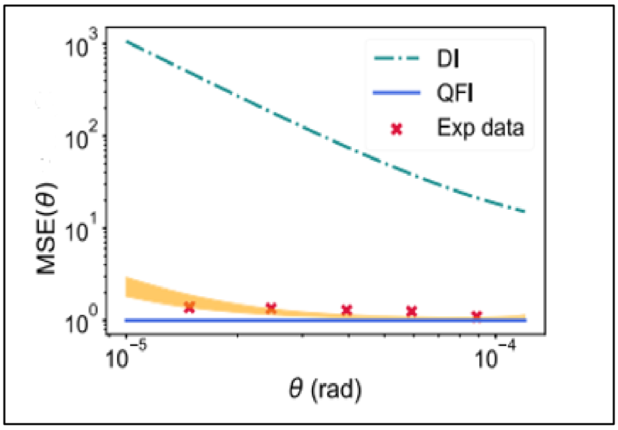

Figure 6. Angular separation with mean squared error (MSE)

4.4 Signal to Noise Ratio

The proportion of the value of R corresponds to direct classical imaging (Rcl) and differential classical imaging (Rdcl) for the SNR. In Figure 7, the mean correlation degree (σ) of each data set is used to depict the proportion R of quantum noise to the conventional SNR. The SSN quantum imaging outperforms conventional imaging for $\sigma < 1$ and has an additional benefit over direct classical imaging when $\sigma <$ 0.5 that vanishes when $\sigma > 0.5$.

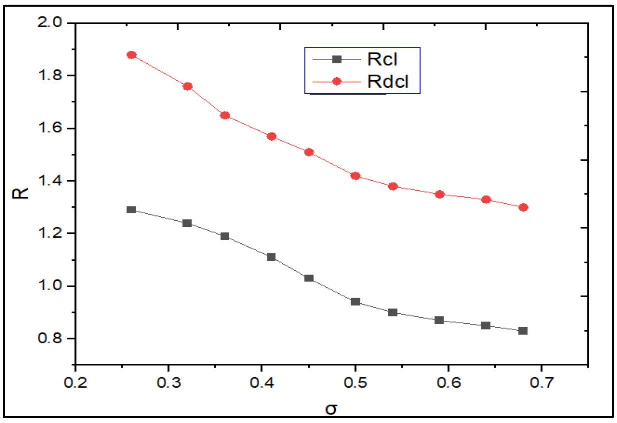

Figure 7. Mean correlation degree (σ) with Signal to Noise Ratio (SNR)

An SNR gain of in excess of 32% is achieved over the most effective classical imaging system and over 70% above the differential classical scheme based on the top attainable values of the correlation degree during the quantum domain. The ratio R is computed based on the σ of each dataset. The results show that the proposed quantum imaging approach achieves a higher SNR compared to classical methods, particularly in low-light regimes.

The obtained results confirm that the proposed model provides superior noise resilience and improved detection capability, making it suitable for high-precision imaging applications. The mean ± standard deviation of 30 separate simulation runs is used to report all performance indicators. Furthermore, 95% confidence intervals are calculated with the assumption that estimates have an approximately normal distribution. This ensures that the specified results are statistically reliable and delivers a strong measure of variability.

5. CONCLUSIONS

Here, a quantum-enhanced optical measurement system is proposed through the integration of OAM-based interferometry with entangled photon states that exceeds the SQL. By utilizing customized interferometric configurations and high-dimensional quantum states, the proposed approach increases the accuracy of phase estimation. The framework outperforms both classical and traditional quantum sensing methods in terms of sensitivity and resolution, according to simulation data. The system is more resistant to measurement uncertainties due to the employment of OAM entangled states, which also improves phase discrimination and noise resistance. Additionally, this proposed model shows that it can function well in low light while retaining high precision. The results confirm that integrating quantum and spatial features offers a major advantage in optical sensing applications. As a result, the framework provides a reliable solution for high-precision imaging applications where traditional methods fail to produce consistent results.

The proposed method demonstrates SSN performance with an MSE < 2 (±0.15) at a photon count of 68,000 and ϵ of 0.54. When compared to DI, there is a notable increase in relative entropy and an average SNR improvement of 32%. The results presented support increased accuracy, robustness and dependability in low light. Overall, the proposed framework provides a robust and high-precision solution for quantum imaging applications, particularly in scenarios where conventional methods fail. Future research will concentrate on testing performance on experimental hardware platforms, enhancing robustness under real-world noise situations and expanding the model to real-time implementations.

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