Entanglement enhanced quantum sensing

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ABSTRACT

Entanglement between quantum objects can be used to enhance the sensitivity of measurements. We demonstrate this effect by using entangled multi-photon states to go beyond the shot noise limit when observing polarization rotations.

Keywords: Quantum Optics, Metrology, Entanglement

1. INTRODUCTION

Quantum entanglement is the most important resource for the many new applications of quantum information science, such as secure communcation[1], teleportation of a complete quantum state[2,3] but also plays a vital role in precision improvements in quantum-enhanced measurement schemes[4,5,6]. Its power lies in creating exceptionally strong correlations between constituents in composite systems that cannot be reproduced by classical technologies and that enable sensing and measurement beyond what is possible using classical resources.

Optical systems play a prominent role in metrology, most notably since the advent of the laser, which became the core of a dramatic change in measurement and sensing technologies. With this new tool amazing precision has been reached in conventional measurement systems. For example, gravitational wave interferometers detect path length changes on subatomic scales and high-precision spectroscopy determines optical frequencies to 16 digits. But there are limits, also to these methods. The power circulating in the interferometers can cause back action on the mirrors distorting the results and systematic errors determine the achievable precision in spectroscopy. Even if one could control all such effects, any conventional method would face a severe limit. At present, measurements are typically being done by either measuring an ensemble of objects, like atoms in an atomic clock, or by frequently repeating the same measurement (Fig. 1a). Evaluating the result, one finds that the error (noise) of the measurement of N independent objects or repetitions scales at best like $1/\sqrt{N}$. This limit is universal to all measurements on independent systems and is called the shot noise limit (SNL). Laser-interferometric gravitational-wave detectors, e.g. LIGO[7], or GEO600[8] have confronted the quantum limit[9], and in next generation detectors, optimization of classical parameters will reach the limits of novel technology[10]. Similarly for atomic clocks, where the best perform at the standard quantum limit set by the projection and measurement noise of uncorrelated individual two-level atoms[11].

Quantum metrology can break the standard quantum limit by employing entanglement. Using maximally entangled N-particle Greenberger-Horne-Zeilinger-type states[12] enables an error scaling of $1/N$ [4,13]. This scaling is the so-called Heisenberg limit, and it is a striking manifestation of the potential of entanglement in metrology and sensing, as the precision improvement can be traced to the presence of highly-nonclassical correlations between the measurement results. Contrary to the case of individual evolutions and measurements, here a highly correlated, entangled state between N photons is prepared (Fig. 1b). Then, read out of the correlated evolution of the N quantum systems enables one to determine the parameter defining the evolution with unprecedented precision for the limited number of photons. From the fundamental perspective, it changes dramatically the balance between achievable performance and required resources. However, in real-world scenarios, where losses and decoherence are present, entangled quantum states can become extremely fragile.

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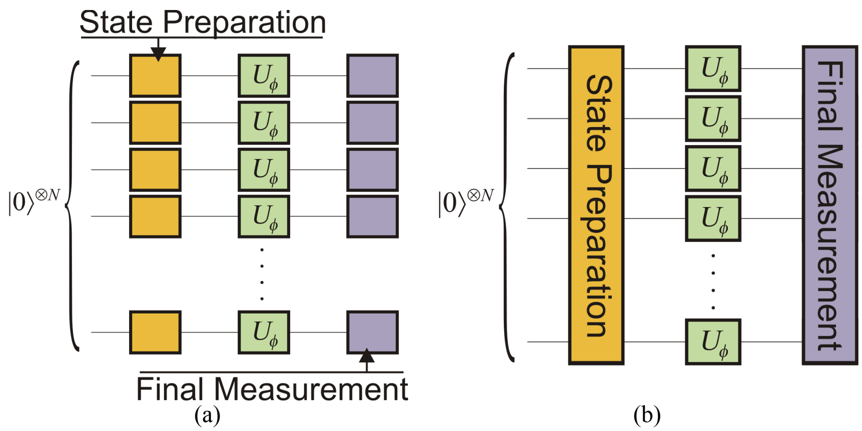

Figure 1. Evolution of quantum metrology: the conventional single particle prepare-and-measure scheme (a) is replaced by collective state preparation and state detection schemes to enable entanglement enhanced metrology for breaking the standard quantum limit (b).

Here we demonstrate how entangled photons can be employed for quantum enhanced measurements. We show how to generate entangled multiphoton states in a flexible way by spontaneous parametric down conversion (SPDC)[14] and how to use them to measure phase shifts with increased resolution. Usually GHZ and NOON-type states are considered to be optimal for measurement purposes. Only recently, alternatives are investigated, which are preferential either due to higher noise tolerance or simpler, more efficient preparation. The flexible set-up enables easy switching between many of these states and thus to optimize the state to the given requirements.

2. PREPARATION OF ENTANGLED STATES

The experimental set-up that allows us a flexible observation of a whole family of states is depicted in figure 2. Four photons originate from the second order emission of a spontaneous parametric down conversion (SPDC) process \cite{Kwi95} in a 2 mm thick β-Barium borate (BBO) crystal arranged in non-collinear type-II configuration. The crystal is pumped by UV pulses with a central wavelength of 390 nm and an average power of 600 mW obtained from a frequency-doubled Ti:Sapphire oscillator (pulse length 130 fs). The four photons are emitted into two spatial modes, denoted by a and b, where a HWP and a 1 mm thick BBO crystal compensate walk-off effects. The spatial modes a and b are defined by coupling the photons into single mode (SM) fibres. Spectral selection is achieved by interference filters (IF) centered around the degenerate wavelength of 780 nm with 3 nm full width at half maximum transmission. A HWP in mode a transforms the polarization of the photons. The orientation of the optical axis, γ, of this HWP is the tuning parameter of the family, and thereby determines the desired state used for the sensitivity measurement. Subsequently, the modes a and b are overlapped at a polarizing beam splitter (PBS) with its output modes denoted by a' and b'. A HWP oriented at $\pi/4$ behind the PBS transforms the polarization of the photons in mode a' from $H(V)$ into $V(H)$. Subsequently, the modes a' and b' are split into the output modes 1,2 and 3,4, respectively, via polarization-independent beam splitters (BS). Birefringence of the beam splitters is compensated by a pair of perpendicularly oriented birefringent Yttrium-Vanadate (YVO_4) crystals. Finally, the polarization state of each photon is analyzed with a HWP, a quarter-wave plate (QWP) and a PBS. The photons are detected by fiber-coupled single photon detectors and registered by a multichannel coincidence unit.

Under the condition of detecting one photon of the second order SPDC emission in each spatial mode the family of states $|\Psi(\gamma)\rangle = \alpha(\gamma)|\Psi^+\rangle \otimes |\Psi^+\rangle + \sqrt{1-\alpha^2(\gamma)}\,|GHZ\rangle$ is observed, with $|\Psi^+\rangle = \left(|H\rangle|V\rangle + |V\rangle|H\rangle\right)/\sqrt{2}$, and where the amplitude $\alpha(\gamma)$ depends on the HWP angle γ via $\alpha(\gamma) = \left(2\cos(4\gamma)/\sqrt{48p(\gamma)}\right)$ [14]. Due to the probabilistic nature of distributing four photons into the four outputs this occurs with a probability $p(\gamma) = (5 - 4\cos(4\gamma) + 3\cos(8\gamma))/48$.

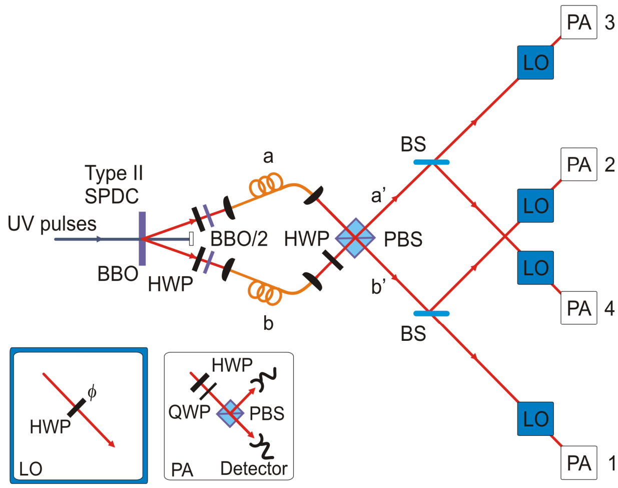

Figure 2. Scheme of the flexible setup for observing a whole family of polarization entangled four photon states. For equal local operations (LO) the phase angle ϕ can be determined by correlated polarization analysis (PA).

This family of states contains the well-known four-qubit GHZ state, the symmetric Dicke state with two excitations, the four-qubit singlet state and the product of two-qubit singlet states. While for these states a dedicated setup exists, for the remaining ones (infinitely many) no setup is known. For the aforementioned cases the respective state can be observed in the dedicated setups with equal or higher probability. Here, however, we profit from the flexibility to choose various entangled states using the same setup.

3. ENTANGLEMENT ENHANCED MEASUREMENT

Let us first consider the case of four independent, polarized photons. A birefringent phase shift ϕ will change the polarization accordingly and thus can be determined by analysis of the polarization, e.g., along the initial direction of polarization, in our case the x-direction, corresponding to the state $\left(|H\rangle+|V\rangle\right)/\sqrt{2}$. In the experiment we observe the different detection probabilities in the two detectors behind a polarizing beam splitter (PBS). The rotated polarization, and thus the measurement signal will vary when changing ϕ and will reach the start value again for $\phi=2\pi$. (Fig. 3, dashed line). Repeating this experiment N times will give a result for determining ϕ, which fluctuates proportional to $1/\sqrt{N}$.

Yet, secondly, with the setup described above we can now apply this phase on the four photons of a polarization entangled GHZ state. In this case one analyzes the correlated rotation of the four photons, i.e. the product of the four polarization measurements. We will now observe an oscillation with fourfold frequency, or with a period of $\pi/2$, respectively. The measurements shown in figure 3 (blue solid line) clearly demonstrate this fact. Consequently, such measurements should allow one to observe the phase shift with increased (twofold) resolution (for an experiment with four photons).

Care has to be used at this point. Due to imperfect state preparation also caused by higher order emissions in the SPDC, the oscillation now exhibits an amplitude smaller than 1, in our case we observe $V=0.683 \pm 0.011$. This in turn reduces the slope and thus the possible resolution. The scatter to be expected therefore scales with $1/N\cdot V$, which however still results in a scaling of 1/2.73, clearly beyond the SNL scaling of 1/2 for measurements on four independent evolutions.

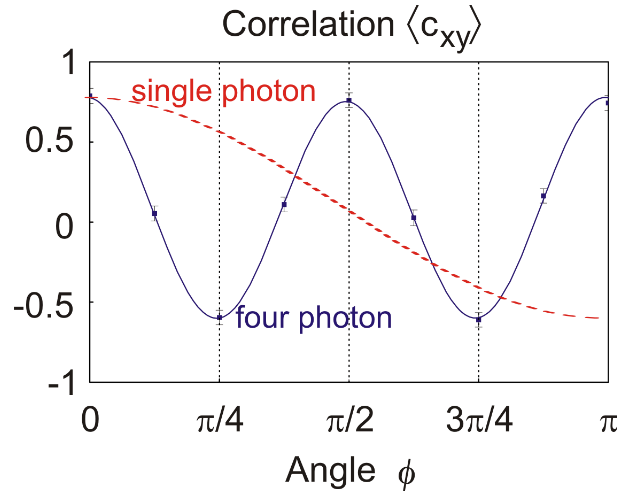

Figure 3. Fourfold increase of the oscillation frequency for correlated polarization measurements when using a four photon GHZ state (blue, solid). For comparison, the polarization correlation when measuring individual photons is shown (red, dashed).

4. OUTLOOK

Correlated measurements on entangled multi photon states give increased phase resolution and thus sensitivity to the physical effect causing the phase shift. So far, mainly GHZ-type states, where the phase shift is applied to each of the photons individually, or so called NOON-states, which are states of the light field propagating in a Mach-Zehnder-interferometer have been discussed and analyzed for their performance. A definite advantage of these states is the possibility to reach the Heisenberg limit, i.e., scaling of the variance as $1/N$. Yet, a particular disadvantage of these states is their sensitivity to loss. All the gain is gone immediately if only one of the N photons is lost in the optical path. It is thus of utmost importance to develop new measurement schemes and find quantum states which still enable one to beat the SNL, but which are more resistive to loss and noise. So called Dicke states seem to be one candidate, which can be observed in the presented setup (N=4) [14] , in its extension to the 6 photon case[15] or with dedicated linear optical setups (up to N=6)[16,17,18]. Another option seems to be the reduction of the entanglement of GHZ states. As the entanglement is decreased, the gain is reduced, too, however, with better resistance to noise[19,20]. With the many well developed methods from quantum information at hand, new approaches for quantum metrology are devised to increase its capability and applicability, and to make it ready for beating the shot noise limit also in real world environments.

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