Degree of Quantum Coherence of the Light Field from an Optical Mach–Zehnder Interferometer with a NOON State

Kenji Tsujino, Toshio Yamaguchi, Midori Matsumoto, and Junji Kinoshita
Department of Physics, Tokyo Women's Medical University
8-1 Kawada-cho, Shinjuku-ku, Tokyo 162-8666, Japan

Abstract Using the NOON state and a photon-number-resolving detector, the accuracy of phase measurement with a Mach–Zehnder interferometer reached the Heisenberg limit. In an experimental demonstration using the continuous-wave NOON state, the coherence time was much longer than the response time of a photon-number-resolving detector. Therefore, we investigated the time correlation of photon detection events in the light field from the Mach–Zehnder interferometer. As a result, it was found that the photon detection events were anti-bunching. This result suggests that we need a photon-number-resolving detector with a fast response time and a NOON state with a much longer coherence time in order to use a large-photon-number NOON state.

Reducing measurement uncertainty is the most important issue for any scientist. Usually, the uncertainty of a measurement, δx, decreases as the inverse square root of the total number of measurements, $1/\sqrt{n}$. This relationship is called the standard quantum limit.

However, we can beat the standard quantum limit using quantum entangled states as the measurement probe. In this case, the uncertainty of the measurement decreases as the inverse total number of measurements, $1/n$. This relationship is called the Heisenberg limit [1-3].

In optical metrology, various optical interferometers are widely applied in various measurement systems. Therefore, for phase-shift measurement in optical interferometer, if we can reduce measurement uncertainty to below the standard quantum limit, then we might realize some benefits. In gravity wave detection, for example, studies have been carried out to improve phase measurements beyond the standard quantum limit [4,5]. To achieve phase measurement approaching the Heisenberg limit, the uncertainty of phase estimation, $\delta\varphi$, decreases with the inverse photon number $1/N$ of the quantum entangled state as [6,7]:

$$\delta\varphi \propto \frac{1}{N}.$$

In a Mach–Zehnder interferometer, to achieve Heisenberg-limited phase estimation, we use the so-called “NOON” state [8], which is the entangled photon state of the photon number between the two arms of a Mach–Zehnder interferometer,

$$\frac{1}{\sqrt{2}}\left(\left|N,0\right\rangle_{1,2} + \left|0,N\right\rangle_{1,2}\right),$$

where N is the photon number, and the subscripts 1 and 2 represent the two aim modes of the optical interferometer. Ultrashort pulsed lasers have been used in previous experiments for generating NOON states [9-11]. However, the NOON states generated using continuous-wave (CW) lasers are more applicable to particular applications such as gravitational wave detection experiments.

In the NOON state generated using a CW laser source, the coherence time is much longer than the response time of the photon-number-resolving detector that is used for measuring the photon number from the Mach–Zehnder interferometer to estimate the phase shift. That is, multi-photon counting events occur during a NOON state detection. Therefore, we have investigated the time correlation of photon detection events.

We calculated the time correlation for these NOON states with N = 2, 3, and 4. As a result, we found that the photon counting events are anti-bunching. That is, simultaneous multi-photon detection of event is vanishingly small at some initial phases in the interferometer.

This result is important for carrying out the experiment. This is because the photon-number-resolving ability of the novel photon detector is insufficient for detecting huge photon number states. With current technology, the maximum photon number resolution is few dozens of photons [12-14]. Therefore, we must restrict the photon number when generating the NOON state. In the end, we cannot sufficiently improve the accuracy of phase measurement with the interferometer. However, because the result showed that the photon detection events are anti-bunching, we do not require high photon-number-resolving ability in the photon detector, but we do need fast response time. For the anti-bunching condition, we can intuitively estimate detectable the photon number of τ_c/t_r, where τ_c is the coherence time of the NOON state, and t_r is the response time of the photon-number-resolving detector. With current technology, τ_c is more than 100 ns, and t_r is less than 1 ns [14]. Therefore, we might count hundreds of photons.

Moreover, from a physical point of view, it is interesting to investigate the behavior of time correlation as a function of initial phase in the interferometer. The time correlations vary sinusoidally according to the initial phase. Additionally, the period of sinusoidal behavior of the time correlation depends on the photon number of the NOON state. We will investigate the physical interpretations of these behaviors via experiment.

References

[1] V. Giovannetti, S. Lloyd, and L. Maccone, “Quantum-Enhanced Measurements: Beating the Standard Quantum Limit,” SCIENCE, 306, 1330 (2004)

[2] J.J. Bollinger, W. M. Itano, and D. J. Wineland, “Optical frequency measurements with maximally correlated states,” Phys. Rev. A, 54, R4649 (1996).

[3] C. C. Gerry and R. A. Campos, “Generation of maximally entangled photonic states with a quantum-optimal Fredkin gate,” Phys. Rev. A, 64, 063814 (2001).

[4] C. M. Caves, “Quantum-mechanical noise in an interferometer,” Phys. Rev. D, 23, 1693 (1981).

[5] M. Xiao, L.-A. Wu, and H. J. Kimble, “Precision Measurement beyond the Shot-Noise Limit,” Phys. Rev. Lett. 59, 278 (1987).

[6] L. Pezze, and A. Smerzi, “Mach-Zender Interferometry at the Heisenberg Limit with Coherent ant Squeezed-Vacuum Light,” Phys. Rev. Lett., 100, 073601 (2008).

[7] P. Kok, H. Lee and J. P. Dowling, Phys. Rev. “The creation of large photon-number path entanglement conditioned on photodetection,” A 65, 052104 (2002).

[8] K. P. Seshadreesan, P. M. Anisimov, H. Lee, and J. P. Dowling, “Parity detection achieves the Heisenberg limit in interferometry with coherent mixed with squeezed vacuum light,” New Journal of Physics, 13, 083026 (2011).

[9] T. Nagata et. al., “Beating the Standard Quantum Limit with Four-Entangled Photons,” SCIENCE, 316, 726 (2007).

[10] R. Okamoto et. al., “Beating the standard quantum limit: phase super-sensitivity of N-photon interferometers,” New Journal of Physics, 10, 073033 (2008).

[11] I. Afek, O. Ambar, and Y. Silberberg, “High-NOON States by Mixing Quantum and Classical Light,” SCIENCE 328, 879 (2010).

[12] A. E. Lita, A. J. Miller, and S. W. Nam, “Counting near-infrared single-photons with 95% efficiency,” Optics Express, 16, 3032 (2008).

[13] D. Fukuda et. al., “Titanium-based transition-edge photon number resolving detector with 98% detection efficiency with index-matched small-gap fiber coupling,” Optics Express, 19, 870 (2011).

[14] M. Akiba, K. Tsujino, and M. Sasaki, “Multipixel silicon avalanche photodiode with ultralow dark count rate at liquid nitrogen temperature,” Optics Express, 17, 16885 (2009).