QUANTUM INTERFEROMETRY

Final Report

JPL Task 1035

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A. OBJECTIVES

In recent years, it has been theoretically demonstrated that quantum photon entanglement has the potential to revolutionize the entire field of optical interferometry by providing many orders of magnitude improvement in interferometer sensitivity [1]. The quantum-entangled photon interferometer approach is very general and applies to many types of interferometers. In particular, without non-local entanglement, a generic classical interferometer has a statistical-sampling shot-noise limited sensitivity that scales like 1/Sqrt[N] (one over square root of N), where N is the number of particles (photons, electrons, atoms, neutrons) passing through the interferometer per unit time. However, if carefully prepared quantum correlations are engineered between the particles, then the interferometer sensitivity improves by a factor of Sqrt[N] to scale like 1/N, which is the limit imposed by the Heisenberg Uncertainty Principle. In addition to these developments, we have also recently shown that optical quantum entanglement effects can be used in interferometric photolithography [2]. This application brings about a breakthrough in lithographic resolution by overcoming the diffraction limit, allowing features to be etched that are several factors smaller than the optical wavelength. Of course, how to prepare the desired quantum correlation is the key issue in quantum interferometry, which is the goal of this proposal.

B. PROGRESS AND RESULTS

1. Science Data

During this period of time, we have designed optical devices that are useful in quantum interferometry. We developed a method to generate maximal path-entanglement with a definite photon number, which is the desired quantum correlation for enhanced resolution in interferometric photolithography and Heisenberg-limited interferometry, as well as applications to quantum networks. The breakdown is shown below:

(1) In our recent work, it has been shown that the Rayleigh diffraction limit in optical lithography can be circumvented by the use of path-entangled photon number states [2]. Subsequently, a proof-of-principle experiment was demonstrated by using two-photon entanglement [3]. However, for more than three photons, optical generation of such a quantum correlation was not known except by using unrealistically large optical nonlinearity. We developed a method of making such quantum states by using so-called

projective measurements. Projective measurement is a process of determining the quantum state of a system by measuring some part of the system, which turned out to be an essential tool in quantum information processing [4]. Our method is unique in that only simple linear optical devices are required, and provides the first experimentally realizable scheme for this purpose. Our result has been recently published in *Physical Review A Rapid Communications.* We further developed a generalization of this scheme for an arbitrarily large photon-number, for which our result has been published in *Physical Review A.* These papers have also been selected for the *Virtual Journal of Quantum Information,* and also the *Virtual Journal of Nanoscale Science and Technology.*

(2) Heisenberg-limited measurement protocols can be useful in measurement precision over classical protocols. While the sensitivity of the conventional interferometers is limited by 1/Sqrt[N] (shot-noise limit) where N is the involved particle flux, the Heisenberg-limited interferometry provides that the sensitivity of the device scales as 1/N, yielding a huge increase of the sensitivity of the phase measurement. Such measurements can be implemented using optical Mach-Zehnder interferometers [1], atomic clocks [5], as well as quantum logic gates [6]. We characterized the common features of quantum enhancement in various kinds of interferometers, and established the concept of quantum Rosetta stone based on the equivalence between them. We have also shown that a particular quantum correlation between the two input ports of the interferometer can be made efficiently with the technique of projective measurements, and the Heisenberg limit can be achieved without using sophisticated final detection schemes previously reported. The result has been accepted for publication in a special issue of *Journal of Modern Optics.* We are currently pursuing application of our method to entanglement of massive particles for atom interferometers.

2. Other Results

a. The results of the work motivated exciting new ideas in various research fields that deal with creating nonlinearity by projective measurement technique. In particular, we have developed a special kind of single-photon quantum nondemolition (QND) device that signals the presence of a single photon with no absorption [7]. Furthermore, we designed an expanded protocol to perform polarization-preserving QND detections of a single photon. This result was filed for NASA New Technology Reports [NPO 30551 (2002)], and submitted for publication in *Physical Review Letters.*

b. In collaboration with Prof. Gerald J. Milburn at the University of Queensland, Australia, we presented an invited paper to Philosophical Transaction of the Royal Society on perspectives of the 21st century quantum technologies based on quantum interferometry.

c. We have also analyzed quantum optical networks for quantum cryptography and distributed quantum computing.

C. SIGNIFICANCE OF RESULTS

This task developed a new method of preparing desired quantum correlations for quantum interferometry and interferometric lithography. The effect of quantum interferometry can translate into a tremendous science pay-off for NASA-JPL missions. For example, one application of this new effect is to fiber optical gyroscopes for deep-space inertial guidance and tests of General Relativity (Gravity Probe B). Another application is to ground and orbiting optical interferometers for gravity wave detection: Laser Interferometer Gravity Observatory (LIGO) and the European Laser Interferometer Space Antenna (LISA), respectively. Other applications are to Satellite-to-Satellite laser Interferometry (SSI), proposed for the next generation Gravity Recovery And Climate Experiment (GRACE II). In particular, quantum correlations employed in SSI could improve the orbital sensitivity to gravity enough to give unprecedented accuracy in measuring Earth gravitational anomalies from space with a resolution of 1 km or less. Such sensitivity could be used for orbital oil prospecting or measuring water content of aquifers.

The application of quantum interferometry in photolithography has tremendous commercial potential in the computer chip and semiconductor industries by allowing sub-100 nm fabrication resolution at low cost. In addition to writing features much smaller than the wavelength, it is also possible to read that information with this resolution. In both lithography and microscopy, the conventional classical road to finer resolution is to actually reduce the wavelength. But it is very hard and expensive to make imaging elements at UV and X-ray scales. In addition, such high-frequency photons pack quite a punch and damage the object to be imaged or written on. Employing quantum entanglement may completely overcome such a bottleneck.

D. FINANCIAL STATUS

The total funding for this task was $100,000, all of which has been expended.

E. PERSONNEL

Dr. Deborah Jackson, Section 367
Dr. Pieter Kok, Resident Research Associate at JPL under National Research Council Associateship Program.
Dr. Hwang Lee, Resident Research Associate at JPL under National Research Council Associateship Program.

F. PUBLICATIONS

[1] Hwang Lee, Pieter Kok, Nicolas Cerf, and Jonathan P. Dowling, "Linear Optics and Projective Measurements Alone Suffice to Create Large-Photon-Number Path Entanglement," *Phys. Rev. A* 65, 030101(R) (2002).

[2] Pieter Kok, Hwang Lee, and Jonathan P. Dowling, “Creation of Large Photon-Number Path Entanglement Conditioned on Photo-Detection,” *Phys. Rev. A* 65, 052104 (2002).

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[4] Pieter Kok, Hwang Lee, and Jonathan P. Dowling, “Single-Photon Quantum Nondemolition Devices Constructed with Linear Optics and Projective Measurements,” (submitted to) *Physical Review Letters* (2002), quant-ph/0202046.

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G. REFERENCES

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[7] G. Nogues, A. Rauschenbeutel, S. Osnaghi, M. Brune, J.M. Raimond, and S. Haroche, “Seeing a Single Photon Without Destroying It,” *Nature* 400, 239 (1999).