Quantum Information Science Using Photons

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1. INTRODUCTION

Quantum information science has been attracting significant attention recently. It harnesses the intrinsic nature of quantum mechanics such as quantum superposition, the uncertainty principle, and quantum entanglement to realize novel functions. Its applications include quantum cryptography, whose security is guaranteed by the laws of physics, and quantum computing, which provides computational power fundamentally superior to current computers based on classical physics. Recently, quantum metrology is emerging as another appealing application of quantum information science.

Quantum information is based on so-called "qubits" (quantum bits). There are many possible ways to physically express a qubit, including electron spin, nuclear spin and superconducting coherent devices. However, photons offer some noteworthy advantages. Photons are robust against decoherence and can be transmitted over long distances(~tens of km), making them an indispensable information carrier for communication and an important tool for metrology. In addition, the operations for single photons (single-qubit gates) are easily realized by linear optical elements such as beam splitters (half mirrors) and wave plates (polarization manipulators).

In this article, we present our recent results concerning functional photonic quantum circuits and quantum metrology that exceeds the standard quantum limit (SQL).

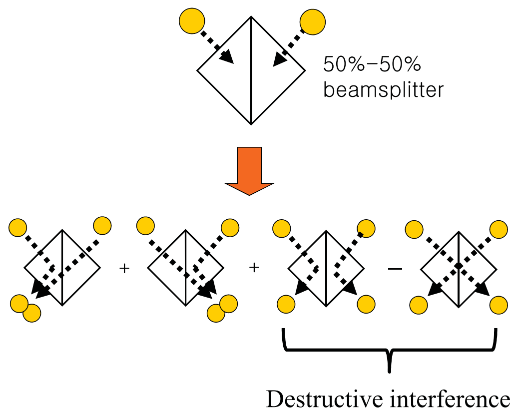

Fig. 1: Hong-Ou-Mandel two-photon interference. When two indistinguishable photons enter a half mirror, the two cases shown on the right side do not occur due to quantum interference.

In section 2, as background, the concept of two-photon interference is explained. In section 3, two photonic quantum circuits, 'an entanglement filter'[1,2] and 'a heralding controlled-NOT gate'[3] are introduced. In section 4 and 5, 'a four-photon interference experiment'[4] and 'an entanglement- enhanced microscope,'[5] both of which surpass the SQL, are explained. In section 6, we summarize this article and discuss future prospects.

2. TWO-PHOTON INTERFERENCE AND PHOTONIC QUANTUM GATES

In quantum mechanics, when physical processes share the same initial and final states, 'interference' occurs. To calculate the probability of observing such a phenomenon, it is necessary to evaluate the probability amplitude of each process, and then calculate the square of the absolute value of their sum. This results in an unusual phenomenon when we consider the case where two photons are incident to a beam splitter (Fig. 1).

Suppose two 'indistinguishable' photons are incident to a beam splitter with a reflectivity of 50% (50:50 BS). If the photons behaved like classical particles, there would be four cases: (1) the left photon is reflected and the right one is transmitted. (2) The opposite case (the right photon is transmitted and the left photon is reflected.) (3) Both photons are reflected. (4) Both photons are transmitted. Since a 50:50 BS reflects a photon with a probability of 50%, it is logical to assume a probability of 50% that a photon is emitted from both output ports simultaneously. However, this probability is actually 0 due to quantum interference; the respective probability amplitudes of case (3) and case (4) have the same amplitude but opposite signs, and thus completely and destructively interfere. Hong, Ou and Mandel experimentally demonstrated this phenomenon using pairs of photons generated via a spontaneous parametric down-conversion (SPDC) process.[6] This phenomenon is also called Hong-Ou-Mandel (HOM) interference.

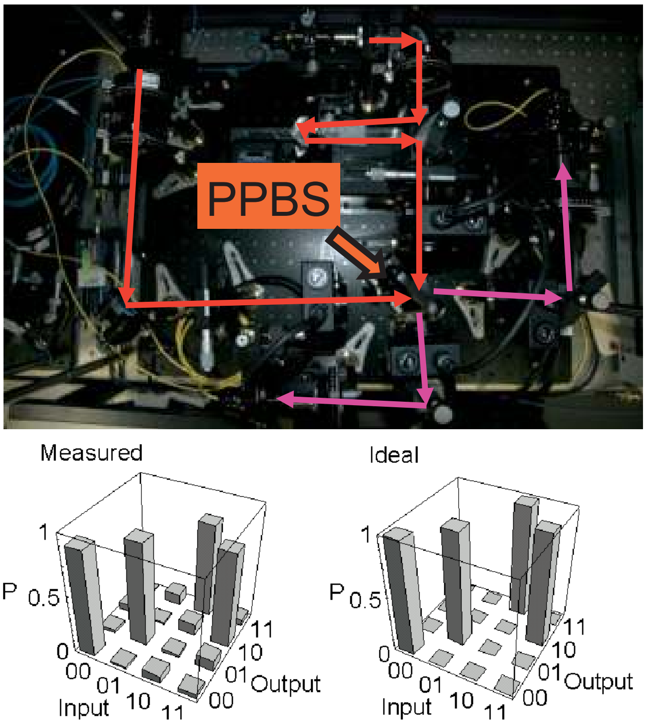

Fig. 2: Experimental demonstration of a photonic quantum gate using a partially polarizing beam splitter (PPBS). (Upper panel) The experimental setup. Red lines (pink lines) represent input (output) photons, whose polarization states are used as qubits. (Lower panel) The measured and ideal truth tables for the controlled-NOT gate operation. 01 in input and output denotes the state where the control qubit is 0 and the target qubit is 1. *P* is the probability.

Two-photon interference has become a general tool for quantum information processing. A photonic quan tum circuit known as an 'entanglement filter'[2] utilizes such two-photon interference at a 50:50 BS to monitor the number of photons passing through specific optical paths. This process can be used to realize quantum logic gates that handle pairs of photonic qubits.[7] By adjusting the reflectivity of the beam splitter, the two-photon interference phenomena can be adapted to the required function. A controlled-NOT (CNOT) gate that handles two photonic qubits was realized using a beam splitter with a reflectivity of 1/3 by both us and Ralph et. al., independently.[8,9] A CNOT gate requires two qubits, the control qubit and the target qubit, as the input and output, respectively. Only when the control qubit is $|1\rangle$ is the target qubit flipped.

Following that, we succeeded in demonstrating a CNOT gate[10] using a partially polarizing beam splitter (PPBS), which had a reflectivity 1/3 for horizontal polarization and 1 for vertical polarization (Fig.2). Similar schemes were reported independently by other groups.[11,12] The operation of this compact CNOT gate is successful only when the input photons are output from each of the output modes. This CNOT gate can be considered a single-photon level all optical switch; only when the control photon is vertically polarized is the polarization of the target photon changed.

3. PHOTONIC QUANTUM CIRCUITS

We tried to combine several of the developed photonic qubit quantum switches to make a quantum circuit with a specific function. Figuratively speaking, our efforts may be compared to making a radio (a functional circuit) by combining transistors (an elementary device). Here we discuss an entanglement filter as an example.

Figure 3 is a schematic illustrating the function of the entanglement filter.[1,2] The filter transmits the input photon pair only when the photon pair shares the same vertical or horizontal polarization, keeping the coherence between these two states. If one of the input photons is

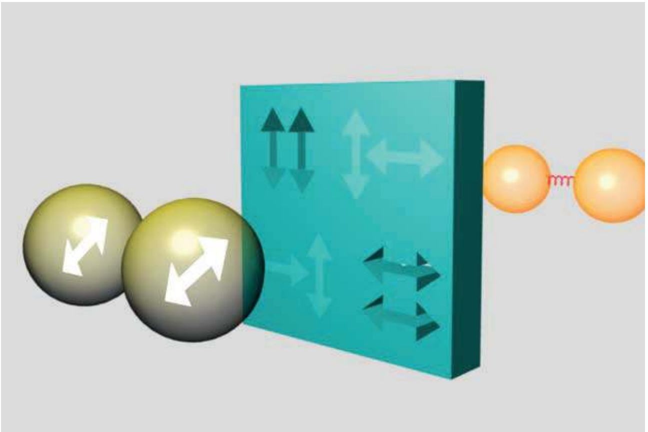

Fig. 3: Schematic image of the entanglement filter.

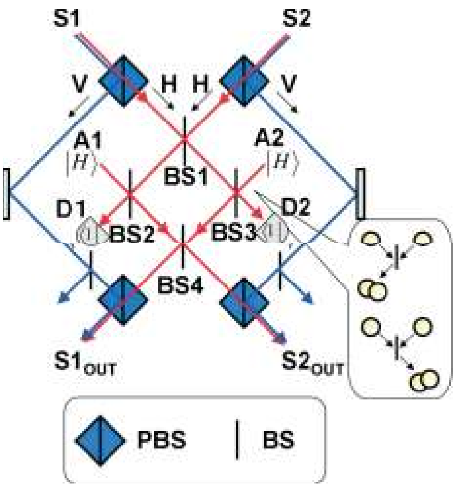

Fig. 4: A photonic quantum circuit for the entanglement filter. S1 and S2 are the input ports, and $S1_{OUT}$ and $S2_{OUT}$ are the output ports. A1 and A2 are ancillary photon inputs. D1 and D2 are the photon detectors. BS is the beam splitter and PBS is the polarization beam splitter.

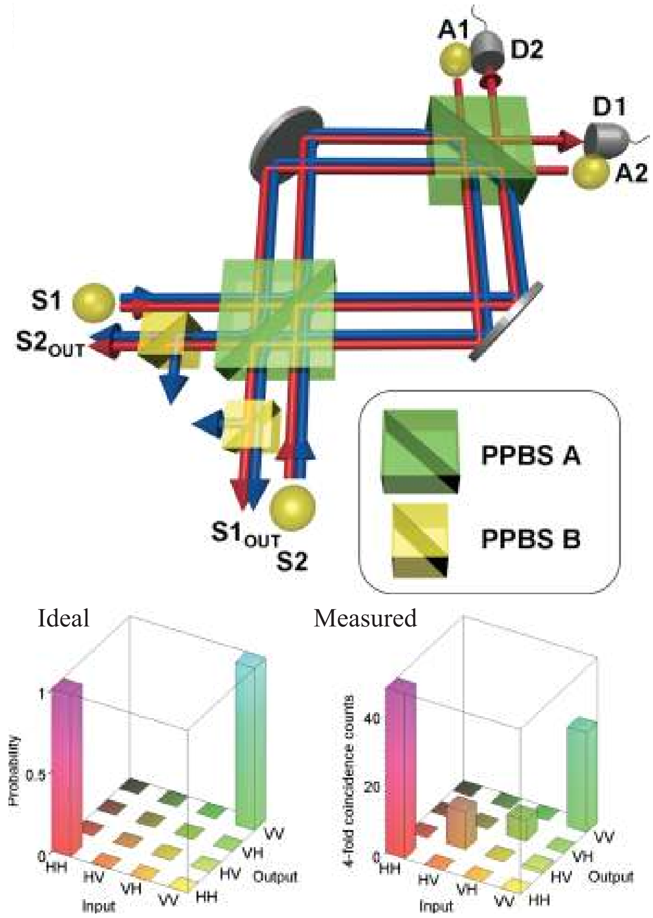

Fig. 5: Physical implementation and experimental results of the entanglement filter. (Upper panel) Photons are input at S1 and S2 and the results are output from $S1_{OUT}$ and $S2_{OUT}$. The ancillary photons are input at A1 and A2 and detected by photon detectors D1 and D2. The detailed characteristics of PPBS A and PPBS B can be found elsewhere.[2] (Bottom panel) The ideal and measured truth tables for the entanglement filter.

vertically polarized and the other is horizontally polarized, the pair is rejected by the filter.

We consider the case when the two input photons have diagonal polarization. Since a photon with diagonal polarization is in a superposition of the horizontal $|H\rangle$ and vertical polarization state $|V\rangle$, the input state is a superposition of the four states as follows.

$$\frac{1}{\sqrt{2}}(|H\rangle_A + |V\rangle_B) \otimes \frac{1}{\sqrt{2}}(|H\rangle_B + |V\rangle_B)$$
$$= \frac{1}{\sqrt{2}}(|H\rangle_A \otimes |H\rangle_B + |H\rangle_A \otimes |V\rangle_B \quad (1)$$
$$+|V\rangle_A \otimes |H\rangle_B + |V\rangle_A \otimes |V\rangle_B)$$

The entanglement filter only transmits the components $|H\rangle_A \otimes |H\rangle_B$ and $|V\rangle_A \otimes |V\rangle_B$, so the output state is

$$\frac{1}{\sqrt{2}}(|H\rangle_A \otimes |H\rangle_B + |V\rangle_A \otimes |V\rangle_B), \quad (2)$$

which is a polarization entangled state.

Figure 4 shows a photonic quantum circuit for such an entanglement filter, as proposed in 2002.[1] In this circuit, four 50:50 beam splitters (BS1~BS4) are used as quantum gates (where two-photon interference occurs).

For example, the two-photon interference at BS3 is used to monitor the number of photons routed to BS3; only when a single photon state is routed to BS3 is the single photon detection event at detector D2 possible (Fig. 4 inset).

It was diffcult to realize this circuit, because it contains not only four two-photon interferences, but also concatenated multi-path (classical) interferences where optical path length differences must be controlled and maintained to an accuracy of a few nanometers.

We realized this entanglement filter[2] (Fig. 5) by adapting the displaced Sagnac architecture with PPBSs, where the concatenated multi-path interferences were passively stabilized. Even when one of the devices (a mirror or beam splitter) was tilted or displaced due to vibration or thermal drift, both optical paths experienced the same change since they pass through the same optical devices. As a result, the path length difference was robust against such disturbances.

The bottom panel of Fig. 5 shows the ideal and measured truth tables of the entanglement filter. In the ideal case, the HH and VV inputs are output with a probability equal to unity but the HV and VH inputs are terminated, i.e., the output probability is zero for all four outputs in these cases. In the measured table, the output for HV and VH inputs are well suppressed while those for HH and VH inputs are maintained. We also checked that our filter works with input photons in a superposition of the H and V polarized states and confirmed that such operation cannot be realized by a classical device.

Recently, we successfully developed a quantum circuit for the 'heralded' CNOT gate operation,[3] whose successful operation can be heralded by the success signal. Therefore, photon number monitoring at the output required for the previous CNOT gate (Fig. 2) is not necessary. This heralded CNOT gate was proposed by Knill, Laflam me and Milburn[7] as a basic element for scalable linear optics quantum computation, but was not realized for 10 years.

4. MULTI-PHOTON INTERFERENCE BEATING THE STANDARD QUANTUM LIMIT

In the previous section, we saw that the manipulation of the quantum states of multiple photons is possible through the use of linear optical circuits and multiphoton interference. In this section, we will discuss the applications of such multi-photon entangled states for quantum metrology.

Phase measurements using optical interferometery are applicable to many fields, for example, astronomy (gravitational wave detection), engineering (optical fiber gyroscopes) and life sciences (differential contrast microscopy). There are two important concepts for such measurements: precision and sensitivity. In principle, precision can be improved by increasing the probe light intensity or the number of measurements made. However, the sensitivity is fundamentally limited by the precision per unit power or the number of photons provided by the probe light. The left panel of Fig. 6 shows a typical

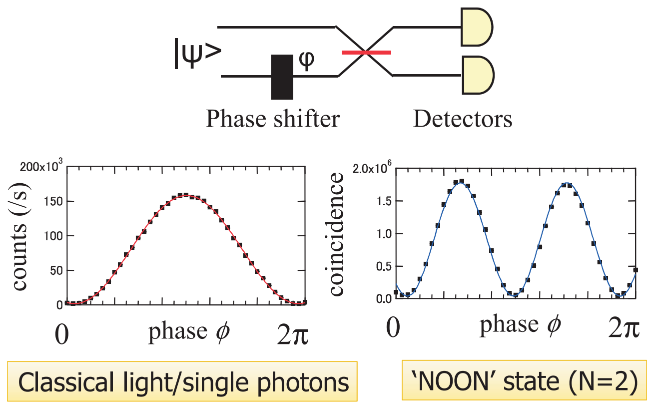

Fig. 6: Single-photon and entangled-photon interference.

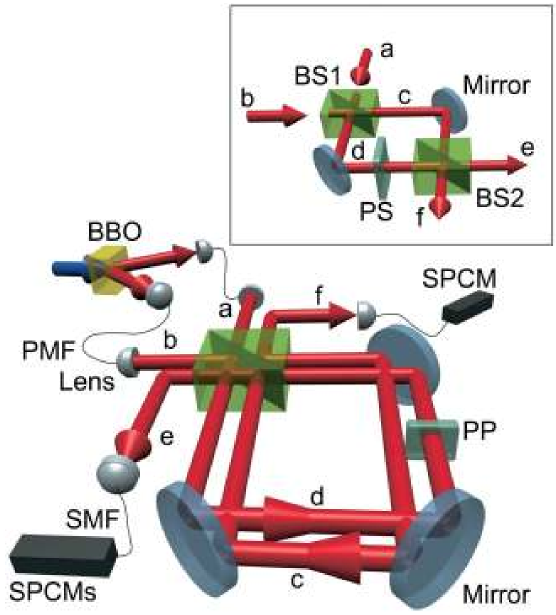

Fig. 7: Experimental setup for the four-photon NOON state interferometer. The displaced Sagnac interferometer in the main panel is, in principle, the same as the Mach-Zender interferometer in the inset. One or two pairs of photons are generated via SPDC in the beta barium borate (BBO) crystal and are then injected into the interferometer. Photons are counted by single photon counting modules (SPCM) at modes e and f. The phase is modified by a rotating phase plate (PP).

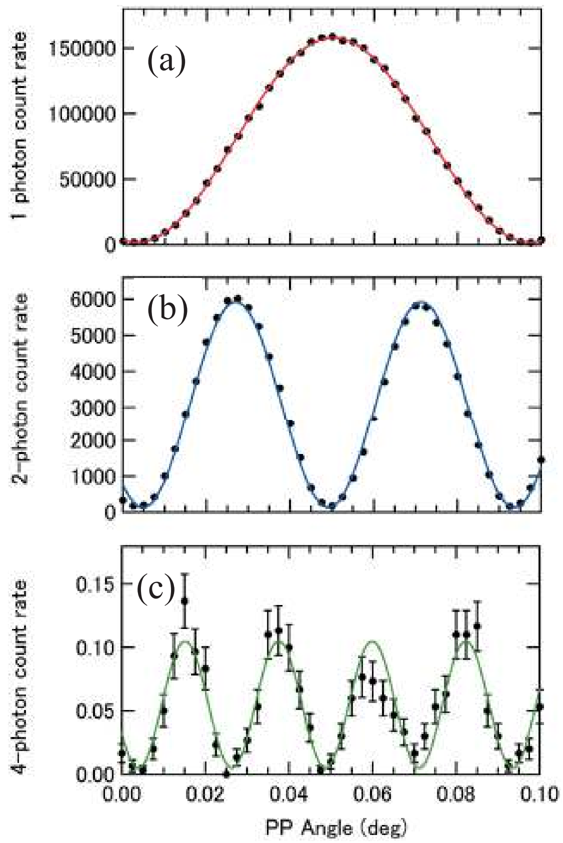

Fig. 8: Experimental results. (a) Single photon count rate in mode e as a function of the phase plate (PP) angle with single-photon input $|10\rangle_{ab}$. (b) Two-photon count rate in modes e and f for input state $|11\rangle_{ab}$. (c) Four-photon count rate with three photons in mode e and one photon in mode f for the input state $|22\rangle_{ab}$. Accumulation times for one data point were (a) 1 s, (b) 300 s, and (c) 300 s.

interference fringe observable using classical light (laser etc.) or single photons. Suppose we are trying to detect a small phase shift from a bias phase. When we set the bias phase to that where the slope of the interference fringe is maximum, the change in the output due to the phase shift is maximized and the highest sensitivity achieved. For single photons (a classical light source), the sensitivity limit (the standard quantum limit (SQL)) is given by $1/\sqrt{N}$ where N is the number of photons in a given state. The right panel of Fig. 6 shows an interference fringe when the input is a superposition of two photon states: (1) a two-photon state is in the upper path and no photons are in the lower path and (2) no photons are in the upper path and a two-photon state is in the lower path:

$$|\phi\rangle = \frac{1}{\sqrt{2}}(|20\rangle + |02\rangle) \tag{3}$$

A generalized state for N photons, $(N0\rangle + |0N\rangle)/\sqrt{2}$, is usually called a 'NOON' state.

Interestingly, the fringe period becomes half of that for the single photon case. As a result, the slope of the interference fringe becomes twice as steep, yielding sensitivity beyond the SQL. The fringe period of an N photon NOON state is 1/N of that of the single photon case. For the multiple photon case, the sensitivity limit (the Heisenberg limit) is given by 1/N.[13)]

Recently, we demonstrated four-photon interference exceeding the SQL.[4)] Using parametric fluorescence and a stably displaced Sagnac interferometer (Fig. 7), we observed one-photon, two-photon and four-photon interference fringes with high visibilities (Fig. 8).[14)] The visibility V is a parameter describing the quality of the interference as follows:

$$\mathrm{V} = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}}, \tag{4}$$

where I_{max} and I_{min} are the maximum and minimum photon counts. The sensitivity degrades when the visibility is lower. The sensitivity also depends on the method used to observe the correlation of the photons at the output. For the scheme we adopted, the threshold visibility required to surpass the SQL was 82%. The visibility of the four-photon interference fringe shown in Fig. 8(c) was $91 \pm 6\%$, clearly exceeding the threshold.

5. AN ENTANGLEMENT-ENHANCED MICROSCOPE

Optical phase measurement is playing an important role in microscopy. Differential interference microscopes (DIM), which detect the optical path-length difference between two adjacent optical paths at the sample, are widely used for the evaluation of opaque materials or the label-free sensing of biological tissues. A laser confocal microscope (LCM) combined with a DIM (LCM-DIM, Fig. 9, left panel) has recently been used to observe the growth of ice crystals with a single molecular step resolution. The depth resolution of such measurements is determined by the signal-to-noise ratio (SNR) of the measurement, and the SNR is in principle restricted by the SQL.

Recently, we proposed and demonstrated an entanglement-enhanced microscope[5)] which is based on an LCM-DIM (Fig. 9, right panel). Instead of laser light and an intensity measurement, entangled photons (in the NOON state) and a coincidence measurement were used. The SNR of the entanglement microscope is $\sqrt{N}$

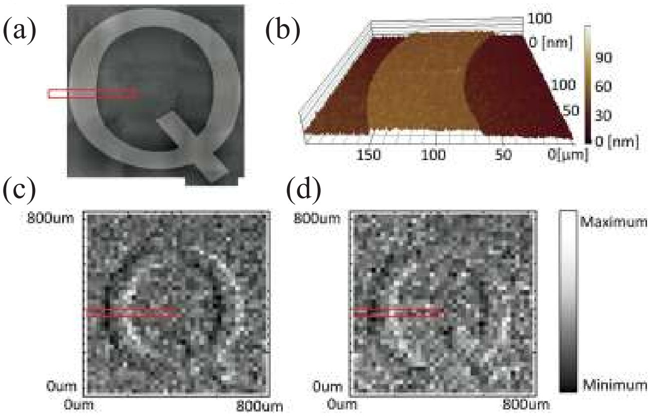

Fig. 9: (Left panel) Illustration of LCM-DIM. (Right panel) illustration of the entanglement-enhanced microscope. The red and blue lines indicate horizontally and vertically polarized light.

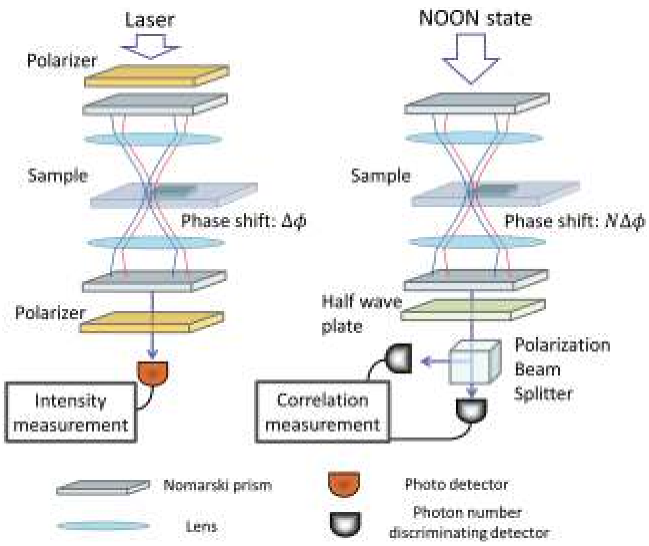

Fig. 10: Experimental results obtained with the entanglement microscope. (a) Atomic force microscope (AFM) image of a glass plate sample (BK7) with a Q shape on its surface carved in relief with an ultra-thin step using optical lithography. (b) Section of the sample outlined in red in (a). The height of the step is estimated to be 17.3 nm from this data. (c) Image of the sample using an entanglement-enhanced microscope where a two-photon entangled state is used to illuminate the sample. (d) Image of the sample using single photons (a classical light source).

times better than the conventional LCM-DIM restricted to the SQL.

In the experiment, we used a two-photon NOON state (N=2) source as the probe. (Fig. 10). The sample was a glass plate with a Q shape on its surface carved in relief with an ultra-thin step of ~17 nm using optical lithography (Figs. 10 a and b). Figures 10 c and d show the two-dimensional scan images of the sample using entangled photons and single photons, respectively. The step of the Q-shaped relief is clearly seen in Fig. 10 c, whereas it is obscure in Fig. 10 d. The average total number of photons contributing to these data is set to 920 per position assuming unity detection effciency. In a detailed analysis, the SNR of Fig. 10 c is 1.35 ± 0.12 times better than 10 d, which, taking the visibility of the single and two-photon interferences into account, agrees well with the theoretical prediction of 1.35

6. SUMMARY

In this article, we introduced our recent developments of quantum circuits and quantum metrology using photons. We showed that two-photon interference can be used as a 'photon-photon' switch, and experimentally demonstrated an entanglement filter. We also showed that the sensitivity and the SNR can be improved to $\sqrt{N}$ times higher than that achieved using a classical light source, and demonstrated an entanglement-enhanced microscope surpassing the SQL.

Increasing the number of photons is of the utmost importance. When we are able to use a ten-photon NOON state (N=10) the SNR will be more than 3 times higher than the SQL. In other words, the same SNR can be achieved with just 10 % of the photon flux. Recently it has been predicted that multi-photon interference calculations for a given photonic network will be problematic for conventional computers, and the task may be beyond the power of state-of-the-art super computers when $N\sim$ 10 to 30.[16] Photonic quantum simulators[17] that evaluate exact solutions of molecular energy levels have been proposed and their application to hydrogen molecules demonstrated (H_2).[18] Effcient single photon sources,[19] effcient photon number detectors, and integrated photonic quantum circuits are important research areas for the continual advancement of this field.

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