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AUTHOR(S):
Takeuchi, Shigeki

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Review

Photonic quantum information: science and technology

By Shigeki TAKEUCHI*1,†

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Abstract: Recent technological progress in the generation, manipulation and detection of individual single photons has opened a new scientific field of photonic quantum information. This progress includes the realization of single photon switches, photonic quantum circuits with specific functions, and the application of novel photonic states to novel optical metrology beyond the limits of standard optics. In this review article, the recent developments and current status of photonic quantum information technology are overviewed based on the author’s past and recent works.

Keywords: quantum optics, quantum information, quantum computation

1. Introduction

The hypothesis of ‘light quanta’ was advocated by Einstein in 1905,1) which was two decades earlier than the formalism of quantum theory by Schrödinger2) and Heisenberg.3) However, the validity of the basic concepts of quantum theory was still controversial. The nonlocality of quantum theory, which was named ‘quantum entanglement’ by Schrödinger,4) was deeply debated by Einstein, Podorsky, Rosen (EPR)5) and Bohr.6) However, these discussions were purely theoretical and only employed ‘Gedankenexperiment (thought experiment)’.

A change in the situation occurred around the time of the invention of laser in 1960.7) The second order intensity correlation first observed by Hanbury-Brown and Twiss (HBT)8) opened the door for experiments in photon statistics. Kimble, Dagenais and Mandel used the HBT method to observe evidence for single photon emission from sodium atoms in 1977.9) On the other hand, the effort for experimental verification of the nonlocality of the quantum theory had been continued by Clauser and his collaborators10) from the late 1960s. Finally, Aspect and his collaborators experimentally confirmed the existence of quantum nonlocality.11)

Another important technological invention is the generation of twin photons using parametric down–conversion in a nonlinear crystal. This phenomenon was first observed by Harris, Oshman and Byer12) when they attempted to realize a color change of laser beams. In 1970, the correlation of these twin photons was clearly demonstrated by Burnham and Weinberg;13) however, the stream of this research entered a resting stage for a decade, until Mandel’s series of experiments in the middle of the 1980s. The famous two photon interference was experimentally demonstrated by Hong, Ou and Mandel in 1987,14) and the first realization of an entangled photon source using parametric down–conversion was demonstrated by Ou and Mandel in 1988.15)

Simultaneous with this progress in physics, a new trend of information science based on quantum physics emerged in the 1970s when Weisner proposed to use the uncertainty principle to prevent the copying of bank notes.16) Later in 1984, Bennett and Brassard proposed ‘quantum cryptography’,17) which would enable two distant parties to share a secret key of random digits. In 1985, computation based on a ‘quantum bit’, which can exist in a superposition of the ‘0’ and ‘1’ states, was proposed by Deutsch.18) and in 1992, Deutsch and Jozsa showed that such a computer can solve a certain problem intrinsically faster than current computers.19) In 1994, Shor proposed an algorithm for quantum computers to efficiently solve factoring.20) The security of public key cryptosystems, which are widely used in daily life, relies on the difficulty of factoring, so that Shor’s algorithm attracted much

*1 Department of Electronic Science and Engineering, Kyoto University, Kyoto, Japan.
† Correspondence should be addressed: S. Takeuchi, Department of Electronic Science and Engineering, Kyoto University, Kyoto Daigaku-Katsura, Nishikyo-ku, Kyoto 615-8510, Japan (e-mail: takeuchi@kuee.kyoto-u.ac.jp).
attention and a new paradigm of quantum information technology was established.

Photons are appealing in quantum information technology due to their low noise, light-speed transmission and ease of manipulation. In this review article, the development and current status of quantum information technology using photons are overviewed based mainly on the author’s past works. In section 2, we discuss the generation of a single photon and entangled photon using parametric down-conversion. Advanced single photon detectors will also be introduced. In section 3, the proposal and experimental demonstration of a quantum computation algorithm using a single photon are discussed. In section 4, the realization of quantum gates between two photons using two photon interference at a beam splitter is explained. In section 5, photonic quantum information technology to metrology and nanofabrication is introduced. The application of photonic quantum circuits combining photonic gates for photons are discussed later. In section 6, photonic quantum information technology using photons are overviewed based mainly on the author’s past works. In section 7, the development and current status of quantum information technology was established.

Figure 1 shows a CCD camera image of photons generated via SPDC. In this case, parametric fluorescence is generated in two small spots with the appropriately selected phase matching condition. The generated twins are concentrated onto the spots, so that a high single count rate and coincidence count rate per pump power was observed. In this case, the ratio of the coincidence count rate to the single count rate was 80%, where the loss at filters and the quantum efficiency of the detectors were compensated. The shape of the image changes from a spot to an empty circle as the phase matching condition changed. A detailed description of SPDC can be found elsewhere.24)

2.2. Entangled photons. Quantum entanglement is used for the superposition of different states of correlated particles, where the state of each particle cannot be described independently. For example, the following state,

$$|\phi\rangle = \frac{1}{\sqrt{2}} (|H\rangle_A \otimes |V\rangle_B - |V\rangle_A \otimes |H\rangle_B),$$

is an entangled state, where $|H\rangle_A$ denotes the photon A is horizontally polarized. Entanglement was proposed by Schrödinger to discuss the philosophical concept of quantum mechanics; however, it has become an important resource for various protocols of information science.

SPDC has been widely used for the generation of entangled photon pairs. Photons entangled in polarization25,26 have been used for various types of
experiments. Recently, the entangled states between the polarization states of two-photon Fock states have attracted attention, which can be regarded as the entanglement between spin 1 systems.\textsuperscript{27,28)\textsuperscript{27,28}}

Note that photons can be entangled in other degrees of freedom or physical properties, such as angular momentum\textsuperscript{29–31)\textsuperscript{29–31) and frequency.\textsuperscript{32,33)\textsuperscript{32,33) These various entangled states are particularly useful for quantum metrology, as will be introduced later.

2.3. Single photon detectors. Single photon detectors generate electric pulses upon the detection of single photons and are a basic tool in photonic quantum information technology.\textsuperscript{34)\textsuperscript{34)} In the early experiments performed in the late 1980s, photomultiplier tubes (PMT) were used. The large open aperture is one of the advantages of PMTs, so that they are still widely used for the sensing of photons, for example, neutrino detectors. The disadvantage is the moderate quantum efficiency (approximately up to 30\%) and dark counts (approximately hundreds to thousands per second), which is caused by false output pulses without photon injection.

Later, silicon avalanche photodiodes (Si-APD) operated in Geiger mode became popular due to their high detection efficiency at visible wavelengths (~70\% for a wavelength of 700 nm) and relatively low dark counts (tens of counts per second). Si-APDs are still widely used in experiments on photonic quantum information and metrology using visible wavelengths. For telecommunication wavelengths, indium gallium arsenic (InGaAs) avalanche photodiodes are used in Geiger mode, where the typical detection efficiency is approximately 20\% with relatively high dark count rates. However, APD detectors operated in Geiger mode have one drawback for some applications, in that they do not distinguish the number of simultaneously incident photons.

With regard to this issue, we developed a photon detection system that has high quantum efficiency (>88\%) and is able to discriminate the number of incident photons.\textsuperscript{35)\textsuperscript{35)} In this system, single-photons were detected using a visible light photon counter (VLPC) operated at 6.9 K. The VLPC is a solid state device that makes use of avalanches across a shallow impurity conduction band in silicon. Threefold tight shielding and viewports that function as infrared blocking filters were used to eliminate the dark count caused by room-temperature radiation. Corrected quantum efficiencies as high as 88.2 ± 5\% (at 694 nm) were observed, which was the highest reported value for a single-photon detector at that time.

The VLPC also featured noise-free avalanche multiplication and narrow pulse height distribution for single photon detection events; therefore, we investigated the simultaneous multi-photon detection capability using twin photons generated by parametric down-conversion.\textsuperscript{36)\textsuperscript{36) The result is shown in Fig. 2, which shows the output electrical signal with the change in the arrival time interval (delay) between the photons in a pair generated by SPDC. The resulting pulse height for the two-photon incidence is twice as high as the single photon incidence. In addition, there is no deadtime for this detector. However, the drawback of this device is the dark count, which was 2.0 × 10\^4 cps at the highest quantum efficiency.

Recently, single photon detectors using superconductors have attracted attention. There are two types of such detectors: superconducting nanowire single photon detectors (SNSPDs)\textsuperscript{37)\textsuperscript{37)} and transition edge sensors (TESs).\textsuperscript{38)\textsuperscript{38)} A typical SNSPD uses a superconductor nanowire with a width of tens of nanometers, which covers a certain region (approximately 10 × 10 µm\(^2\)) with meander-like pattern. When a single photon is absorbed by the nanowire in the superconducting state, the excitation of pseudoparticles causes a phase transition to the normal state, which results in a sudden change in the resistivity of the device. SNSPDs are sensitive over a broad bandwidth from visible to infrared.

Fig. 2. Real-time trace of a photon detection signal recorded with a 5 GS/s digitizing oscilloscope. The time delay between the two beams is changed by modifying the optical path length. The traces are shifted vertically for clarity. (a) Single-photon detection signal, (b) Zero delay, (c) 3 ns delay, (d) 5 ns delay.
Recently, detection efficiencies greater than 90% have been reported using a device with a special cavity structure. Another advantage of SNSPDs is the small dark counts. We have recently observed ultralow dark counts ($1.5 \times 10^{-3}$ cps) with an SNSPD. The drawback of this type of device is the operation temperature (~2 to 3 K), which requires special refrigeration system. TESs have also attracted attention for their higher detection efficiency (>95%) and photon-number distinguishability; however, they have a drawback in their slower detection speed (up to MHz).

3. Quantum computation using a single photon and linear optics

In the following sections, we explain past and recent progress in experiments on photonic quantum information. The first example is the experimental demonstration of quantum algorithms using a single photon and linear optics.

Quantum computation is a new concept that utilizes quantum superposition states for ultrafast parallel processing. There have been several proposals for the realization of quantum computers. Of these, nuclear magnetic resonance quantum computation (NMR-QC) has played the role of a testbed for quantum algorithms. However, NMR-QC has the following restrictions: the input qubits are prepared in ‘hot mixed states’, and the results are always given by an average over a large number of quantum systems. Therefore, there is a class of algorithm that cannot be performed by NMR-QC.

Quantum computation using linear optics is an alternatively important testbed for quantum computing. If a single photon is used for computation, then the result is given not by an average, but by a single quantum computation. In quantum algorithms, appropriate unitary transformations are applied to quantum registers. Reck and Zeilinger found that linear optics can be used to realize any unitary transformation. The theoretical proposal of quantum computation using linear optics was given by Takeuchi, whereby the quantum register was realized by modes and polarization of photons, and the unitary transformation was implemented with linear optics. An example of an optical circuit for the 4-bit Deutsch-Jozsa quantum algorithm was presented, where for each quantum computation, the answer to the Deutsch-Jozsa problem is given by a single-photon detection. This is in striking contrast with the NMR quantum computer, where the results are always given by an average over a large number of quantum systems. A similar idea was suggested independently.

We also reported an experimental demonstration of the Deutsch-Jozsa quantum computation algorithm using linear optics and a single photon. First, let us introduce the problem of the Deutsch-Jozsa algorithm. Suppose we are given $2N$ digits. We call the arrays “even” when they include as many 1’s as 0’s (e.g., 1,0,1,0 for $N = 2$), and “uniform” when they are filled with only 0’s or 1’s (e.g., 1,1,1,1). The problem for the Deutsch-Jozsa algorithm is to find the correct answer between “the given array is not even” and “the given array is not uniform”. When the array satisfies both cases, either of them can be the answer. A classical computer requires $N + 1$ steps in the worst case. However, a quantum computer can find the answer with $O(\log(N))$ steps.

In the experiment (Fig. 3), an incident single photon becomes a superposition of being in four optical paths (Path 1 to Path 4). The polarization of the state at each path is then rotated by electro-optic (E/O) modulators upon the oracle function $f(i)$, of which the value is either 0 or 1. When the photon is detected by the photon detector, the answer is that the given oracle $f(i)$ is not even. If the photon is not detected, then the answer is that the given oracle $f(i)$ is not uniform. For the input single photons, strongly attenuated light from a laser diode (LD) was used, where the average number of photons present in the optical system was $3 \times 10^{-5}$, and the probability of finding two or more photons in the coherent length of 10 cm was less than $3 \times 10^{-4}$. In this sense, the

![Fig. 3. Schematic diagram of the optical system used for the Deutsch-Jozsa algorithm with 4-bit inputs. Reprinted with permission from Shigeki Takeuchi, Physical Review A, Vol. 62, 032301, 2000, Copyright (2000) by the American Physical Society.](image-url)
computation was performed using the quantum phenomenon of single-photon interference. A reference light was used for precise control of the path lengths.

The experimental results are shown in Fig. 4. The vertical axis shows the four-bit digits given to the quantum computer and the horizontal axis shows the probability $P$ of photon detection at the output port. The theoretical values are shown by solid lines and the experimental values are plotted as black dots. This result shows that we can determine whether the statement “the given oracle $f(i)$ is not even” or “the given oracle $f(i)$ is not uniform” is correct with small average error rates of 2.7% and 4.0%, respectively, by the detection of a single photon. Here, the initial state was a pure state and the answer was given by single photon detection. Thus, the key aspect of the Deutsch-Jozsa algorithm to obtain the answer with a single quantum computation was fully demonstrated for the first time. The experiment was equivalent to 3 qubits, which was the largest size of a quantum computer when reported. Our demonstration suggested that quantum computation using linear optics is not only useful as a testbed for quantum algorithms, but also practical for small scale quantum processing, namely for quantum communication.

Although this scheme is useful to implement small scale quantum processing, there is a problem in that the number of required modes increases exponentially as the number of qubits increase. To overcome this difficulty, multiple photons must be used for multiple qubits and realize two-qubit gates between single photon inputs, which is discussed in the next section.

4. Realization of a photon-photon switch—a photonic controlled NOT gate

In one of the earliest proposals to implement quantum computation, each qubit was encoded in a single photon existing in two optical modes. The main advantage of the photonic implementation of qubits is the robustness against decoherence and the availability of one-qubit operations. However, the difficulty of realizing the nonlinear interactions between photons that are required for the implementation of two-qubit operations has been a major obstacle. Knill, Laflamme and Milburn (KLM) have shown that this obstacle can be overcome using linear optics, single photon sources, photon number detectors, and multi-photon interference at a beam splitter.

Here, let us explain the concept of multi-photon interference. 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. 5). Suppose two

![Diagram of Hong-Ou-Mandel two-photon interference](https://example.com/hongoumandel.png)

Fig. 5. 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.
Fig. 6. Schematics of the ‘compact’ CNOT gate. (a) Optical circuit in the original proposals\cite{49,50}, where the polarizing beam splitters (PPBSs) reflect (transmit) photons with vertical (horizontal) polarization. (b) Optical circuit without any path interference using partially polarizing beam splitters. Reprinted with permission from Ryo Okamoto, Holger F. Hofmann, Shigeki Takeuchi, and Keiji Sasaki, Physical Review Letters, Vol. 95, 210506, 2005. Copyright (2005) by the American Physical Society.

‘Indistinguishable’ photons are incident to a beam splitter with a reflectivity of 50% (50 : 50 BS). If the photons behave like classical particles, then 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, and (4) both photons are transmitted. A 50 : 50 BS reflects a photon with a probability of 50%; therefore, it is logical to assume a probability of 50% that a photon is emitted from each output port simultaneously. However, this probability is actually 0 due to quantum interference; the probabilities for cases (3) and (4) have the same amplitude but opposite sign, and thus destructively interfere with each other. Hong, Ou and Mandel experimentally demonstrated this phenomenon using pairs of photons generated via an SPDC process\cite{14}. This phenomenon is also called Hong-Ou-Mandel (HOM) interference.

Following KLM’s proposal, the authors\cite{49} and Ralph et al.\cite{50} have independently shown that a ‘compact’ CNOT gate can be realized by interaction at a single beam splitter with a reflectivity of 1/3 and post-selection of the output (Fig. 6(a)). The beam splitter sitting in the center of the circuit is the essential splitter that realizes the quantum phase gate operation, where the phase of the quantum state of two photons that are horizontally polarized are flipped, or shifted by $\pi$, due to two-photon interference. The other two beam splitters with reflectivity of 1/3 are inserted in each of the interferometer paths to balance the amplitudes between vertically and horizontally polarized components.

The gate operation is successful when both of the photons input to $C_{in}$ and $T_{in}$ are output to each of $C_{out}$ and $T_{out}$. The success probability of this operation is 1/9. This gate requires no ancillary photon inputs or additional detectors; therefore, it should be especially useful for the experimental realization of photonic quantum circuits.

However, there have been two crucial difficulties. In the original scheme\cite{49,50}, the polarization sensitivity of the operation was achieved by separating the paths of the orthogonal polarizations, essentially creating two interacting two-path interferometers. Therefore, experimental realization based on the original proposal may be very sensitive to environmental noise (thermal drifts and vibrations), which would make it necessary to control and stabilize nanometer order path-length differences. In addition to these problems, perfect mode-matching is required in each output of the interferometer. Thus, it is very difficult to construct quantum circuits using devices based on those experimental setups.

These problems were solved in our realization of the ‘compact’ optical CNOT gate\cite{49,50} without any path interference\cite{51} (Fig. 6(b)). It was shown that the CNOT gate can be implemented using three partially polarizing beam splitters (PPBSs) with suitable polarization-dependent transmittance and reflectance, where the essential interaction is realized by a single intrinsic PPBS (PPBS A), while the other two supplemental PPBSs (PPBS B) act as local polarization compensators on the input qubits. The intrinsic PPBS A implements the quantum phase gate operation by completely reflecting vertically polarized light and reflecting (transmitting) 1/3 (2/3) of horizontally polarized light. The two supplemental PPBS Bs are inserted to adjust the amplitudes of the local horizontal and vertical components of the photonic qubits by transmitting (reflecting) 1/3 (2/3) of vertically polarized light and completely transmitting horizontally polarized light. Figure 6(b) shows that the use of PPBSs enable the four optical paths in Fig. 6(a) to be reduced to only two optical paths, and path interferometers are no longer required.

The measurement results for the input-output probabilities of the CNOT gate are shown in Fig. 7. Figure 7(a) shows the measured probabilities where the control and target qubits are set to either $|0\rangle$ or $|1\rangle$ (ZZ basis). For the inputs ‘00’ (‘01’), where the control qubit is $|0\rangle$ and the target qubit is $|0\rangle$ ($|1\rangle$), the output state is the same as the input state with high probability. On the other hand, for the ‘10’
input, the output state is ‘11’, where the target qubit is flipped from |0⟩ to |1⟩ with high probability. The fidelity of the CNOT operation in the ZZ basis was 0.85. Figure 7(b) shows the result for the input/output qubits in the superposition states between |0⟩ and |1⟩ (XX basis). The fidelity of the operation on an XX basis was 0.87, which is in good agreement with that for ideal operation.52)

These results have opened a door to the realization of more complex quantum circuits for quantum computing, as discussed in the next section. Similar work from Germany and Australia has also been independently published.53),54)

5. Photonic quantum circuits

Next, let us introduce photonic quantum circuits, in which two-photon interference is used as the source of required gate operations.

5.1. An entanglement filter. The first example is the photonic quantum circuit for entanglement filter. Filters, which allow passage of the desired and reject the unwanted (material, signal, frequency, polarization, etc.) are one of the most important scientific and technological tools available to us. Quantum information science and technology is concerned with harnessing quantum mechanical effects to gain exponential improvement and new functionalities for particular tasks in communication, computation, measurement, and lithography. Perhaps the most unique of these quantum mechanical features is entanglement. Filters that act on the quantum correlations associated with entanglement must operate non-locally on multiple quantum systems, typically two-level qubits.

Figure 8(a) shows a case where a single photon is incident to a conventional polarization filter. In this example, vertically polarized photons can pass the filter, while horizontally polarized photons are rejected. When diagonally polarized photons are injected, only the horizontal components of the photons are transmitted. Figure 8(b) shows the function of the entanglement filter. The filter transmits photons only when they share the same vertical or horizontal polarization. Suppose that two diagonally polarized photons are injected to the quantum filter (Fig. 8(c)). A diagonally polarized state |D⟩ is a superposition of a vertically polarized state |V⟩ and a horizontally polarized state |H⟩; therefore, the state of the two incident photons is a superposition of four combinations: |HH⟩, |HV⟩, |VH⟩, and |VV⟩. Only |HH⟩ and |VV⟩ are transmitted and the quantum coherence between these two components is preserved during the process, so that the output state is entangled.

We proposed a photonic quantum circuit for such an entanglement filter55) (Fig. 9). Two input photons are injected to modes S1 and S2, and output from S1OUT and S2OUT. The quantum filter operation is successful only when both of the two ancillary photons input from A1 and A2 are detected simultaneously at detectors D1 and D2. Note that although the success probability of the operation is 1/32, the operation is, in principle, always successful when the coincidence detection events between D1 and D2 occur. For a detailed explanation of the mechanism, please refer to the original paper.55)

However, there was a serious technical problem to overcome before this quantum filter could be realized. The proposed optical circuit (Fig. 9) required
two ancillary photons and multiple quantum gates, which require both quantum interference and classical interference in several nested interferometers. Later, the entanglement filter was demonstrated by combining two key recent technological approaches: a displaced-Sagnac architecture and partially polarizing beam splitters (Fig. 10(a)).

We first checked the essential operation of the filter circuit by preparing input signal photons in the four combinations of horizontal (H) and vertical (V) polarizations (which we call the Z-basis states) and observed how these input states were filtered by the circuit (Fig. 10(b)). It is clear from the experimental data that the photon pairs are transmitted through the filter when the two input photons share the same polarization (HH or VV), and most of the pairs are filtered out when the two input photons have different polarization (HV or VH). The observed fidelity of this process was $F_{Z-Z} = 0.80$. The device was also evaluated for input and output states on a different basis and the entangling capability of the filter was verified as distinct from classical filters.

The filter can be used for the generation as well as the purification of entanglement, which will be important in realizing quantum relays and repeaters for long distance quantum communication.

5.2. Knill-Laflamme-Milburn controlled-NOT operation. As discussed in Sec. 4, the lack of highly efficient optical Kerr nonlinearities at single photon level was a major obstacle. In a breakthrough, KLM showed that such an efficient nonlinearity can be achieved using only linear optical elements, auxiliary photons, and measurement. They proposed a...
heralded controlled-NOT (CNOT) gate for scalable quantum computation using a photonic quantum circuit to combine two such nonlinear elements. We have experimentally demonstrated a KLM CNOT gate, where a stable architecture was developed to realize the required four-photon network of nested multiple interferometers based on a displaced-Sagnac interferometer and several PPBSs (Fig. 11). The result confirms the first step in the original KLM ‘recipe’ for all-optical quantum computation, and should be useful for on-demand entanglement generation and purification. Photonic quantum circuits that combine giant optical nonlinearities may find wide applications in quantum information processing, communication and sensing.

6. Quantum metrology

Quantum metrology involves using quantum mechanics to realize more precise measurements than can be achieved classically. The canonical example uses entanglement of \( N \) particles to measure a phase with a precision of \( \Delta \phi = 1/N \), the Heisenberg limit. Such a measurement outperforms the \( \Delta \phi = 1/\sqrt{N} \) precision limit possible with \( N \) unentangled particles, the standard quantum limit (SQL). As for photons, high-precision optical phase measurements have many important applications, including microscopy, gravity wave detection, measurements of material properties, and medical and biological sensing. Although a reduced de Broglie wavelength has been reported for three\(^{60}\) four,\(^{61,62,63}\) and even six\(^{64}\) photons, the SQL has only been beaten with two photons\(^{55,66}\).

We demonstrated an entangled four photon phase measurement with a visibility that exceeds the threshold to beat the SQL.\(^{57}\) An ultrastable displaced-Sagnac implementation of a scheme with high intrinsic efficiency (Fig. 12) is used to achieve a four photon interference visibility of 91\% (Fig. 13). We also demonstrated that measurement of a reduced de Broglie wavelength does not mean beating the SQL, via another experiment, which shows...
high-visibility multi-photon fringes, but cannot beat the SQL.

As a real application of the quantum metrology beating the SQL, we proposed and demonstrated an entanglement-enhanced microscope,67) which is the differential confocal microscope where an entangled photon pair source is used for illumination. We showed that the signal to noise (S/N) ratio of the image obtained by the entanglement microscope is 1.35 times better than that limited by the SQL.

The high-precision multi-photon quantum-interference demonstrated here is key, not only to quantum metrology and quantum lithography,68) but also to other photonic quantum technologies.

7. Quantum lithography

Optical lithography is an indispensable technique for the mass production of microstructures such as semiconductor devices. However, there exists a resolution limit; the minimum period of the interference fringe is $\lambda/2$ for a conventional light source.69) As the design rule for integrated circuits becomes smaller, the diffraction limit becomes a more significant problem. Quantum lithography68) is a method to overcome this limit completely, because the resolution limit for the N-photon entangled state is reduced to $\lambda/2N$. Several experiments have observed a reduced de Broglie wavelength of photons in the time-domain.57),66),70) In the spatial-domain, the reduction of a double-slit interference diffraction pattern by a factor of 2 has been reported using two-photon interference.71),72) However, the direct observation of spatially formed interference-fringe periods smaller than $\lambda/2$ in the spatial-domain, which is an indispensable step for the realization of quantum lithography, had not been reported before we reported the direct observation of interference fringes beating the diffraction limit.73) We used a high-fidelity entangled photon source,74) a stable interferometer without active stabilizer,75) and a specially developed near-field scanning optical microscope (NSOM) probe76) (Fig. 14). The experimental result is shown in Fig. 15. We succeeded in the observation of the two-photon interference fringe with a period of 328.2 nm, which is smaller than the diffraction limit of 351.1 nm. Our result confirmed quantum lithography as a viable technique and opened up new possibilities for the use of quantum-optical phenomena in nanotechnology.

The next step is the fabrication of patterns that beat the diffraction limit using real multi-photon absorbing photoresist materials. In addition to the experimental technologies developed here, ultra-bright sources of entangled photons and multi-photon absorbing photoresist materials with large cross-sections are required for such experiments, which still remain as challenging problems.

8. Conclusions and future prospects

In this review article, we have discussed the current status of photonic quantum information science and technology: single photon and entangled photon generation, photon number discriminating detectors, demonstrations of quantum computation algorithms, photonic quantum gates and photonic quantum circuits, photonic quantum metrology and lithography.

It should be noted that photonic quantum information technology is not only for quantum computers. This technology will certainly be applied to advance quantum key distribution systems, which have already become commercial products; however,
this technology will also lead to innovations in the fields of sensing and metrology. One example is quantum optical tomography (Q-OCT)\cite{77}, by which the monitoring of biomedical tissues such as the retina will become possible with much more improved resolution. It is predicted that photonic quantum information technology will be used in very broad fields of science, spanning from astronomy and particle physics to medicine.

For each of these specific applications, further developments of photonic quantum information technology will be required. For example, an entangled photon source with a very broad spectrum\cite{32} is required to improve the resolution of Q-OCT. Such a source may also be useful for a quantum key distribution multiplexed in a frequency region. Many efforts have been devoted to realize solid state single photon sources that generate indistinguishable single photons. When the visibility of two photon interference using these photons becomes comparable to the best (96\%) of that using heralding single photon sources with parametric down-conversion\cite{78}, the research on photonic quantum technology will be dramatically enhanced.

Another problem to be solved is loss of photons. For example, the enhancement of sensitivity is strongly limited by the loss in optical paths or detectors. Although the effect of loss differs between the applications, the improvement in detection efficiencies of single photon sources, coupling efficiencies of single photon sources to photonic circuits are common key issues. Exploration of loss tolerant schemes for each application is also quite important.

Fig. 14. Schematic of experimental setup. Photon pairs entangled in polarization, $(|VV\rangle_a + |HH\rangle_a)/\sqrt{2}$, were generated from two BBO crystals and passed through an interference filter (IF) and a single mode fiber (SMF). The entangled photons are then spatially separated into paths b and c depending on their polarization in a calcite crystal (Cal). The polarization in path b is rotated by 90° using a half wave plate (WP), which gives a two-photon NOON state $(|2\rangle_a|0\rangle_b + |0\rangle_a|2\rangle_b)/\sqrt{2}$. An aspheric lens (L) is used to focus the photons to a small spot and form an interference fringe in the focal plane (FP). A near-field scanning optical microscope (NSOM) probe with elliptical opening (inset) is scanned with a piezo-actuator along the focal plane. The SMF output of the probe is divided by a 50:50 fiber coupler and detected by SPCMs. Reprinted with permission from Yoshio Kawabe, Hideki Fujiwara, Ryo Okamoto, Keiji Sasaki, and Shigeki Takeuchi. Quantum interference fringes beating the diffraction limit, Opt. Exp., Vol. 15, 14244–14250 (2007).

Fig. 15. (a) Interference fringe of single photons. A polarizer is placed before the SMF to select only horizontally polarized photons. The polarization was then rotated 45°. The effective detection efficiency ($<$1 $\times$ 10$^{-3}$) including the collection efficiency of the probe is so small, so that the generated fringe is the same as that for a single-photon state in two modes: $(|1\rangle_a|0\rangle_b + |0\rangle_a|1\rangle_b)/\sqrt{2}$ when the output of the one of the two detectors is recorded. The black lines are sinusoidal curves weighted with a Gaussian function fitted to the experimental data. (b) Interference fringe of entangled photons beating the diffraction limit. The vertical axes indicate coincidence count rates (red dots, left axis). The fringe period of 328.2 nm is smaller than the diffraction limit of 351.1 nm. Single count rates of one of the two detectors measured simultaneously are shown for reference (blue dots, right axis). For (a) and (b), the NSOM probe was scanned with 25 nm steps. The accumulation time for one data point was 5 s. The error bars are shown assuming Poisson statistics. Reprinted with permission from Yoshio Kawabe, Hideki Fujiwara, Ryo Okamoto, Keiji Sasaki, and Shigeki Takeuchi. Quantum interference fringes beating the diffraction limit, Opt. Exp., Vol. 15, 14244–14250 (2007).
As bulk electric parts such as transistors or registers have disappeared in electric products, such items are now combined in integrated circuit chips. Similarly, all the bulk optics, single photon sources, and detectors will be packaged on a chip. In this sense, progress in optical integrated circuits will have a significant impact on the future of photonic quantum information technology.\(^7\)

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References

1) Einstein, A. (1905) Über einen die Erzeugung und Verwandlung des Lichtes betreffenden heuristischen Gesichtspunkt. Annalen der Physik 17, 132–148.
2) Schrödinger, E. (1926) An undulatory theory of the mechanics of atoms and molecules. Physical Review, second series 28, 1049–1070.
3) Heisenberg, W. (1925) Über quantentheoretische Umdeutung kinematischer und mechanischer Beziehungen. Zeitschrift für Physik 33, 879–893.
4) Schrödinger, E. and Born, M. (1935) Discussion of probability relations between separated systems. Math. Proc. Camb. Philos. Soc. 31, 555–563.
5) Einstein, A., Podolsky, B. and Rosen, N. (1935) Can quantum-mechanical description of physical reality be considered complete? Phys. Rev. 47, 777–780.
6) Bohr, N. (1935) Can quantum-mechanical description of physical reality be considered complete? Phys. Rev. 48, 7696–7702.
7) Maiman, T.H. (1960) Stimulated optical radiation in ruby. Nature 187, 493–494.
8) Hanbury-Brown, R. and Twiss, R.Q. (1956) Correlation between photons in two coherent beams of light. Nature 177, 27–29.
9) Kimble, H.J., Dagenais, M. and Mandel, L. (1977) Photon antibunching in resonance fluorescence. Phys. Rev. Lett. 39, 691–695.
10) Clauser, J.F., Horne, M.A., Shimony, A. and Holt, R.A. (1969) Proposed experiment to test local hidden-variable theories. Phys. Rev. Lett. 23, 880–884.
11) Aspect, A., Dalibard, J. and Roger, G. (1982) Experimental test of Bell’s inequalities using time-varying analyzers. Phys. Rev. Lett. 49, 1804–1807.
12) Harris, S.E., Oshman, M.K. and Byer, R.L. (1967) Observation of tunable optical parametric fluorescence. Phys. Rev. Lett. 18, 732–734.
13) Burnham, D.C. and Weinberg, D.L. (1970) Observation of simultaneity in parametric production of optical photon pairs. Phys. Rev. Lett. 25, 84–87.
14) Hong, C.K., Ou, Z.Y. and Mandel, L. (1987) Measurement of subpicosecond time intervals between two photons by interference. Phys. Rev. Lett. 59, 2044–2047.
15) Ou, Z.Y. and Mandel, L. (1988) Violation of bell-inequality and classical probability in a 2-photon correlation experiment. Phys. Rev. Lett. 61, 50–53.
16) Wiesner, S.J. (1983) Conjugate Coding. SIGACT News 15, 78–88.
17) Bennett, C.H. and Brassard, G. (1984) Quantum Cryptography: Public key distribution and coin tossing. In Proceedings of the IEEE International Conference on Computers, Systems, and Signal Processing, Bangalore, 175–179.
18) Deutsch, D. (1985) Quantum theory, the Church-Turing principle and the universal quantum computer. Proc. R. Soc. Lond. A Math. Phys. Sci. 400, 97–117.
19) Deutsch, D. and Jozsa, R. (1992) Rapid solution of problems by quantum computation. Proc. R. Soc. Lond. A 439, 553–558.
20) Shor, P.W. (1994) Algorithms for quantum computation: discrete logarithms and factoring. In Proceedings of the 35th IEEE Symposium on Foundations of Computer Science. 124–134.
21) Bouwmeester, D., Pan, J.W., Mattle, K., Eibl, M., Weinfurter, H. and Zellinger, A. (1997) Experimental quantum teleportation. Nature 390, 575–579.
22) Jouhaud, A., Nishioka, T., Hasagawa, T., Takeuchi, S., Tsurumaru, T., Sasaki, K. and Matsui, M. (2007) Quantum key distribution at 1550 nm using a pulse heralded single photon source. Opt. Exp. 15, 726–734.
23) Takeuchi, S. (2001) Beamlile photon generation by use of type II parametric downconversion. Opt. Lett. 26, 843–845.
24) Takeuchi, S. (2014) Recent progress in single-photon
and entangled-photon generation and applications Jap. J. Appl. Phys. 53, 030101.
25) Kwiat, P.G., Mattle, K., Weinfurter, H., Zeilinger, A., Sergienko, A.V. and Shih, Y. (1995) New high-intensity source of polarization-entangled photon pairs. Phys. Rev. Lett. 75, 4337–4341.
26) Kwiat, P.G., Waks, E., White, A.G., Appelbaum, I. and Eberhard, P.H. (1999) Ultrabright source of polarization-entangled photons. Phys. Rev. A 60, R773–R776.
27) Howell, J.C., Lamas-Linares, A. and Bouwmeester, D. (2002) Experimental violation of a spin-1 Bell inequality using maximally entangled four-photon states. Phys. Rev. Lett. 88, 030401.
28) Tsujino, K., Hofmann, H.F., Takeuchi, S. and Sasaki, K. (2004) Distinguishing genuine entangled two-photon-polarization states from independently generated pairs of entangled photons. Phys. Rev. Lett. 92, 153602.
29) Mair, A., Vaziri, A., Weihs, G. and Zoller, P. (2001) Entanglement of the orbital angular momentum states of photons. Nature 412, 313–316.
30) Kawase, D., Miyamoto, Y., Takeda, M., Sasaki, K. and Takeuchi, S. (2008) Observing quantum correlation of photons in Laguerre-Gauss modes using the Gouy phase. Phys. Rev. Lett. 101, 050501.
31) Kawase, D., Miyamoto, Y., Takeda, M., Sasaki, K. and Takeuchi, S. (2009) Effect of high-dimensional entanglement of Laguerre-Gaussian modes in parametric downconversion. J. Opt. Soc. Am. B 26, 797–804.
32) Okano, M., Okamoto, R., Tanaka, A., Subashchandran, S. and Takeuchi, S. (2012) Generation of broadband spontaneous parametric fluorescence using multiple bulk nonlinear crystals. Opt. Exp. 20, 13977–13987.
33) Tanaka, A., Okamoto, R., Lim, H.H., Subashchandran, S., Okano, M., Zhang, L., Kang, L., Chen, J., Wu, P., Hirohata, T., Kurimura, S. and Takeuchi, S. (2012) Noncollinear parametric fluorescence by chirped quasi-phase matching for monoycle temporal entanglement. Opt. Exp. 20, 25228–25238.
34) Hadfield, R.H. (2000) Single-photon detectors for optical quantum information applications. Nat. Photon. 3, 696–705.
35) Takeuchi, S., Kim, J., Yamamoto, Y. and Hogue, H.H. (1999) Development of a High-Quantum-Efficiency Single-Photon Counting System. Appl. Phys. Lett. 74, 1063–1065.
36) Kim, J., Takeuchi, S., Yamamoto, Y. and Hogue, H.H. (1999) Multiphoton detection using visible light photon counter. Appl. Phys. Lett. 74, 902–904.
37) Natarajan, C.M., Tanner, M.G. and Hadfield, R.H. (2012) Superconducting nanowire single-photon detectors: physics and applications. Supercond. Sci. Technol. 25, 063001.
38) Fukuda, D., Fujii, G., Numata, T., Yoshizawa, A., Tsuchida, H., Fujino, H., Ishii, H., Itatani, T., Inoue, S. and Zama, T. (2009) Photon number resolving detection with high speed and high quantum efficiency. Metrologia 46, S288–S292.
39) Subashchandran, S., Okamoto, R., Zhang, L., Tanaka, A., Okano, M., Kang, L., Chen, J., Wu, P. and Takeuchi, S. (2013) Investigation of the performance of an ultralow-dark-count superconducting nanowire single-photon detector. Jpn. J. Appl. Phys. 52, 102801.
40) Gershenfeld, N.A. and Chuang, I. (1997) Bulk spin-resonance quantum computation. Science 275, 350–356.
41) Cory, D.G., Price, M.D. and Havel, T.F. (1998) Nuclear magnetic resonance spectroscopy: An experimentally accessible paradigm for quantum computing. Physica D 120, 82–101.
42) Reck, M. and Zeilinger, A. (1994) Experimental realisation of any discrete unitary operator. Phys. Rev. Lett. 73, 58–61.
43) Takeuchi, S. (1996) A simple quantum computer: Experimental realization of the Deutsch-Jozsa algorithm with linear optics. In Proceedings of Fourth Workshop on Physics and Computation: PhysComp96 (ed. Toffoli, T.). New England Complex Systems Institute, Cambridge, pp. 299–302.
44) Cerf, N.J., Adami, C. and Kwiat, P.G. (1998) Optical simulation of quantum logic. Phys. Rev. A 57, R1477–R1480.
45) Takeuchi, S. (2000) Experimental demonstration of a three-qubit quantum computation algorithm using a single photon and linear optics. Phys. Rev. A 62, 032301.
46) Takeuchi, S. (2000) Analysis of errors in linear-optics quantum computation. Phys. Rev. A 61, 052302.
47) Milburn, G.J. (1989) Quantum optical feedkin rate. Phys. Rev. Lett. 62, 2124–2127.
48) Knill, E., Laflamme, R. and Milburn, G.J. (2000) A scheme for efficient quantum computation with linear optics. Nature 409, 46–52.
49) Hofmann, H.F. and Takeuchi, S. (2002) Quantum phase gate for photonic qubits using only beam splitters and postselection. Phys. Rev. A 66, 024308.
50) Ralph, T.C., Langford, N.K., Bell, T.B. and White, A.G. (2002) Linear optical controlled-NOT gate in the coincidence basis. Phys. Rev. A 65, 062324.
51) Okamoto, R., Hofmann, H.F., Takeuchi, S. and Sasaki, K. (2005) Demonstration of an optical quantum controlled-not gate without path interference. Phys. Rev. Lett. 95, 210506.
52) Hofmann, H.F. (2005) Complementary classical fidelities as an efficient criterion for the evaluation of experimentally realized quantum operations. Phys. Rev. Lett. 94, 160504.
53) Langford, N.K., Weinhold, T.J., Prevedel, R., Resch, K.J., Gilchrist, A., O’Brien, J.L., Pryde, G.J. and White, A.G. (2005) Demonstration of a simple entangling optical gate and its use in Bell-state analysis. Phys. Rev. Lett. 95, 210504.
54) Kiesel, N., Schmid, C., Weber, U., Ursin, R. and Weinfurter, H. (2005) Linear optics controlled-phase gate made simple. Phys. Rev. Lett. 95, 200506.
210505.

55) Hofmann, H.F. and Takeuchi, S. (2002) Quantum filter for nonlocal polarization properties of photonic qubits. Phys. Rev. Lett. 88, 147901.

56) Okamoto, R., O’Brien, J.L., Hofmann, H.F., Nagata, T., Sasaki, K. and Takeuchi, S. (2009) An Entanglement Filter. Science 323, 483–485.

57) Nagata, T., Okamoto, R., O’Brien, J.L., Sasaki, K. and Takeuchi, S. (2007) Beating the standard quantum limit with four-entangled photons. Science 316, 726–729.

58) Okamoto, R., O’Brien, J.L., Hofmann, H.F. and Takeuchi, S. (2011) Realization of a Knill-Laflamme-Milburn controlled-NOT photonic quantum circuit combining effective optical non-linearities. Proc. Natl. Acad. Sci. U.S.A. 108, 10067–10071.

59) Giovannetti, V., Lloyd, S. and Maccone, L. (2004) Quantum-enhanced measurements: Beating the standard quantum limit. Science 306, 1330–1336.

60) Jacobson, J., Björk, G., Chuang, I. and Yamamoto, Y. (1995) Photonic de Broglie waves. Phys. Rev. Lett. 74, 4835–4838.

61) Mitchell, M.W., Lundeen, J.S. and Steinberg, A.M. (2004) Super-resolving phase measurements with a multiphoton entangled state. Nature 429, 158–161.

62) Walther, P., Pan, J.W., Aspelmeyer, M., Ursin, R., Gasparoni, S. and Zeilinger, A. (2004) De Broglie wavelength of a non-local four-photon state. Nature 429, 158–161.

63) Sun, F.W., Liu, B.H., Huang, Y.F., Ou, Z.Y. and Guo, G.C. (2006) Observation of the four-photon de Broglie wavelength by state-projection measurement. Phys. Rev. A 74, 033812.

64) Resch, K.J., Peggrew, K.L., Prevedel, R., Gilchrist, A., Pryde, G.J., O’Brien, J.L. and White, A.G. (2007) Time-reversal and super-resolving phase measurements. Phys. Rev. Lett. 98, 223601.

65) Rarity, J.G., Tapster, P.R., Jakeman, E., Larchuk, T., Campos, R.A., Teich, M.C. and Saleh, B.E.A. (1990) 2-photon interference in a mach-zehnder interferometer. Phys. Rev. Lett. 65, 1348–1351.

66) Edamatsu, K., Shimizu, R. and Itoh, T. (2002) Measurement of the photonic de Broglie wavelength of entangled photon pairs generated by spontaneous parametric down-conversion. Phys. Rev. Lett. 89, 213601.

67) Ono, T., Okamoto, R. and Takeuchi, S. (2013) An entanglement-enhanced. Microscope. Nat. Comm. (Received Aug. 10, 2012; revised Sep. 7, 2015; accepted Nov. 18, 2015)
Profile

Shigeki Takeuchi was born in Osaka in 1968. He received his B.Sc., M.Sc., and Ph.D. degrees in Physics from Kyoto University in 1991, 1993 and 2000 respectively. He became a researcher of the Central Research Lab., Mitsubishi Electric Co., Japan in 1993, and a lecturer, associate professor, and professor of Research Institute for Electronic Science, Hokkaido University, Japan, in 1999, 2000, and 2007 respectively. He also served as an Invited Professor (residing) at the Institute of Scientific and Industrial Research, Osaka University, Japan from 2007 to 2014. Since 2014, he has been in the current position, a Professor of the Department of Electronic Science and Engineering, Kyoto University. His interest lies in understanding and controlling the nature of light quanta (photons). One of the directions of his research is to invent new concepts and technologies that use photons for quantum information protocols, i.e., quantum computing and quantum key distribution. He is also interested in nano-photonics, namely, the application of solid state micro-cavities and nano-optical fibers to quantum information science and biology. He has received several awards including the Young Scientist Award from the Minister of Education, Culture, Sports, Science and Technology (2005), The Scientific American 50 award, awarded by Scientific American (2007), the 6th Japan Society for the Promotion of Science (JSPS) Prize (2010), the Daiwa Adrian Prize awarded by the Daiwa Adrian Foundation (2010), the Hokkaido University President’s Award for Research Excellence (2012), and Osaka Science Prize (2015).