Photonic Quantum Information Technologies Explored by Quantum Optics Research

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Abstract

The quantum nature of light provides us with a novel technology for information processing and communication that is based on the principle of quantum mechanics. The Optical Science Laboratory of NTT Basic Research Laboratories has been engaged in investigating photonic quantum information processing, which involves quantum cryptography and quantum computing. These Feature Articles present the current status of our research activities involving quantum optical state control and the underlying light-matter interaction.

Keywords: photonic quantum information processing, quantum computing, quantum communication

1. Quantum nature of light and photonic quantum information processing

The invention of lasers, which radiate light beams with well-defined waveforms, and of optical fibers, which transmit light beams while preserving their waveforms, has resulted in today's Internet communication environment supported by optical networking technologies. Moreover, various physical characteristics of light are utilized for precise measurement and information interface techniques. Of these, we have not yet fully understood or utilized the quantum mechanical nature of light. Matter is composed of atoms, and an atom consists of elementary particles. In a similar way, light consists of photons, which is an elementary particle that is impossible to divide. The intensity of light corresponds directly to the number of photons.

It is easy to code a photon with a bit of information, 0 or 1, by utilizing the difference between the *horizontal* or *vertical* polarization states. Quantum mechanics represents those states as $|0\rangle$ and $|1\rangle$, respectively. Quantum mechanics prescribes that any quantum state of a photon is represented by a superposed state $|\psi\rangle = a|0\rangle + b|1\rangle$ of $|0\rangle$ and $|1\rangle$. Here, coefficients a and b are called probabilistic amplitudes and are determined in such a way that $|a|^2 + |b|^2 = 1$. The coefficients a and b quantify the overlap of $|\psi\rangle$ with $|0\rangle$ and $|1\rangle$, respectively. This means that no state other than $|1\rangle$ can be completely distinguished from state $|0\rangle$. A set of states $\{|0\rangle,|1\rangle\}$ is called a *basis*, and the choice of basis is not unique. For instance, a set of states $|+\rangle = (1/\sqrt{2})(|0\rangle+|1\rangle)$ and $|-\rangle = (1/\sqrt{2})(|0\rangle-|1\rangle)$ is another basis. The superiority of quantum information processing is attributed to the wide variety of chosen bases that are available depending on the purpose of information processing.

Quantum key distribution relies on the fact that the errorless transmission of a key bit is possible only when the sender and receiver choose the same basis accidentally. An eavesdropper, who is ignorant of their basis choices, unavoidably disturbs the quantum state whenever she tries to access the key bits. By contrast, a sufficiently low error rate estimated for a sample of the key bits convinces the legitimate users of the secrecy of the remaining key bits.

Quantum computing utilizes the fact that many different patterns that are input into a computer can be processed simultaneously by changing the choice of basis. For instance, if the states of photons A and B are $|+\rangle_A$ and $|-\rangle_B$, the whole state is represented by $|+\rangle_A|-\rangle_B = (1/2)\, |0\rangle_A|0\rangle_B - (1/2)|0\rangle_A|1\rangle_B + (1/2)$

$|1\rangle_A|0\rangle_B$ − (1/2) $|1\rangle_A|1\rangle_B$. This suggests that parallel processing takes place for the four different inputs (00), (01), (10), and (11). During the computation, the designed interaction between two photons alters each coefficient value. This precisely describes an operation gate in quantum computing.

As a result, the whole state can evolve to $(1/\sqrt{2})$ $|0\rangle_A|0\rangle_B - (1/\sqrt{2})\, |1\rangle_A|1\rangle_B$, which is impossible to factorize. This implies that the states of photons A and B cannot be specified independently and have a certain correlation. Such a state is called an entangled state and is an important resource for quantum information processing. The article "Distribution of Entangled Photon Pairs over 300 km of Optical Fiber" (article 3) [1] describes an example of an entangled state.

2. Four problems in photon manipulation

If we can manipulate a photon in a similar way to an electron, we can easily achieve photonic quantum information processing. However, there are four problematic tasks regarding photon manipulation: (i) generating a photon with certainty whenever necessary, (ii) slowing the photon velocity close to zero, (iii) making two photons interact strongly, and (iv) transmitting a photon without disturbing the quantum state. These problems are difficult to solve with existing technologies.

At first glance, it appears easy to provide a single photon by sufficiently attenuating a laser pulse. However, this inevitably results in a probabilistic distribution as regards the number of photons found in one pulse. Moreover, as the photon has no electric charge, the photon interacts with a material very weakly, and a photon-photon interaction intermediated by the material is not strong enough to alter the photonic quantum state. To cope with the above difficulties, we must gain a deep understanding of light-matter interaction and design and implement an artificial physical process based on it. The articles "Photonic Quantum Information Devices Using Coupled-resonator Optical Waveguides" (article 2) [2] and "Rare-earth Epitaxial Films as a Platform for Quantum Information Manipulation" (article 4) [3] challenge the artificial design of light-matter interaction.

Another approach is to design an information processing scheme that can be achieved with available technologies. The success of quantum key distribution is a typical example of this approach. The unavoidable transmission loss of photons is not crucial for random number distribution. This is because a new random number can be generated even if only the photons that arrive at the receiver's detector are sampled. Hence, we can realize quantum key distribution by using a highly attenuated laser pulse. Thus, designing a new scheme or protocol is very important in addition to studying the physical process. For instance, there are many different possible ways to encode a bit of information in a photon other than using the polarization state.

3. Research trends in photonic quantum information processing

For the past ten years, quantum key distribution has been the main research topic of the Optical Science Laboratory. Our research interest has now shifted to practical considerations regarding actual use. Hence, the main target of our basic research has changed to the study of (i) a quantum repeater system for extending the quantum communication distance and (ii) the photonic implementation of quantum circuits. To progress with these research topics, we must cope with the four problems mentioned in the previous section. The following briefly introduces each topic covered in these Feature Articles.

Article 2 relates to a novel technique for slowing the velocity of light to increase the interaction time of photons in a nonlinear optical medium. This is a solution to the second and third problems. As a result, the photon pair generation rate is greatly improved. This offers a solution to the first problem. This is because we can ensure the certain emission of one photon by detecting another photon. The latter part of the article introduces a technique for adjusting the temporal position of photons, which makes it possible to synchronize many photons launched into a quantum circuit. The above techniques are implemented with a photonic circuit integrated on a small-size silicon chip. This guarantees the temporal stability necessary for quantum computing. Article 3 describes the photonic realization of an entangled quantum state. Quantum correlations between two photons are confirmed even when photons are 300 km apart in optical fibers. The preserved entangled quantum state has convinced us of the technical feasibility of long-distance quantum entanglement distribution.

Article 4 and article 5, "Investigating the Properties of Glasses Using High Resolution Spectroscopy of Er^{3+} Ions" [4], correspond to the second problem, where a photon is stored in a medium and then retrieved. The medium works as a photon memory. The quantum state of the photon is correctly transferred to the electron in the medium and vice versa.

Such a technique has already been demonstrated with laser-cooled atomic gases. However, there is no atomic species available for the 1.5-μm optical communication wavelength. Hence, we employ a solid-state medium doped with erbium (Er^{3+}) ions, which has an optical transition line at a wavelength of 1.5 μm. Article 4 first explains why a crystal doped with erbium ions is expected to be a candidate for a photon memory, and then reports the fabrication and characterization of a novel erbium doped material, Er_2O_3. Article 5 presents an interesting phenomenon peculiar to glasses that we found by observing the quantum state of silica optical glass fiber doped with erbium ions.

The sixth article, "A Bose-Einstein Condensate Achieved on a Persistent-supercurrent Atom Chip" [5], introduces an alternative approach to quantum information processing, where we employ condensed gases of ultra-cold atoms instead of photons. The first step is the realization of a Bose-Einstein condensate of cold atoms, which is confined by a strong and stable magnetic field supported by a persistent superconducting current in a chip-size loop circuit. Fifty-thousand identical atoms occupy the same quantum state, which behaves as a matter wave.

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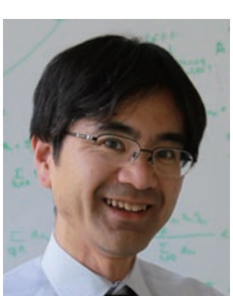

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