4 Quantum Node Technology
4-1 Optical Quantum Control Technologies

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In information and communication networks, transmission capacity and security are main technical demands that are required to be continuously and rapidly upgraded.

To use the maximum physical potential of the network, one has to develop “quantum node technology” which enables us to control quantum states of light and matters to achieve the ultimate communication capacity and sensitivity.

In this article, we review our recent progress toward this goal, in particular, the technical progress of the quantum control photonic signals and demonstration of new quantum communication protocols by using these technologies.

1 Introduction

With the ever increasing prevalence of smartphones and the Internet, the pursuit of higher efficiency and accuracy of information propagation have become increasingly urgent. By the same token, it has become a serious concern that the communication capacity of trunk lines, where a tremendous amount of information comes and goes, will sooner or later reach its technological limits. The hitherto terrestrial-bounded communication range is now embracing near outer space surrounding the earth thanks to satellite networks, and the need for interstellar high speed communication—between the moon, Mars, and earth—must be addressed in the near future. In such ultra-long distance space communication, even the optical signal suffers severe diffusion, resulting in extremely weak received intensity and limitations of communication speed due to quantum noise which is intrinsically contained in light. To overcome such challenges, the signal reception technologies must utilize all possibilities to exploit information from optical signals. Recent achievements in quantum information theory have demonstrated that, to realize ultimate transmission capacity limited only by the laws of physics, the receiver must decode the signal with a concurrent performance of inter-signal pulse quantum calculations. Such process can evolve macroscopic superposition of quantum states, often called “Schrödinger’s cat,” within the decoding circuit, as well as quantum entanglement (correlation among the signal pulses in quantum domain). Future technologies must be able to control such phenomena to perform successful measurements. The receiving device capable of such control is called an optimized quantum receiver, or quantum decoder.

As described elsewhere in this special issue, quantum technology can also provide ultimate security in cryptographic technology, i.e. quantum cryptography. However, the feeble laser light (coherent light) approach now under progress toward commercialization has limitations in terms of communication distance and key generation rate. Development of private key relaying method, as well as provision of very many trusted nodes are needed to overcome such limitations. Many attempts toward realization of quantum cryptography networks, now under verification stage worldwide, invariably have opted for this approach. A serious challenge inherent to this approach is its vulnerability to hijacking: if any one node between two remotely separated locations is hijacked by an attacker with malicious intent, the secret key and related information may easily be taken out. A technology, called a quantum repeater, is expected to fill the gap. A quantum repeater makes use of a photon pair with special mutual correlation, called quantum entanglement, instead of feeble laser light to transmit information. Through quantum mechanical handling at each repeater point, the photon pair can be transferred to the next repeater point without its entanglement relation being corrupted through its exposure to measurement. This approach promises to realize much larger communication distance than that enabled using conventional quantum cryptographic technologies.

The common element required to realize the optimized quantum receiver and quantum repeater is the technology for controlling quantum states of photons at will in a highly accurate and precise fashion, which in turn requires novel quantum mechanical tools that are not yet in our inventory. Toward realization of such photon control technologies, we are developing a quantum entanglement source, a basis technology, as well as conducting principle verification experiments of quantum-domain specific communication protocols.

2 Development of a high-speed, high-purity quantum entanglement source

Quantum entanglement represents a correlation among particles that appears only in the quantum mechanical domain and is totally inexplicable in terms only of conventional mechanics and electromagnetism (i.e. classical physics in contradistinction to quantum mechanics). For example, we generate photon pairs whose polarization is quantum mechanically entangled. To explain the basic nature of quantum entanglement, let us first consider classical correlation without resort to quantum mechanical tools. We assume the existence of a light source that, according to a random selection of longitudinal/horizontal polarization, continues to generate two photons at a time with the selected polarization. The two photons thereafter maintain the same polarization, i.e. correlation exists between them. This correlation can be detected, for example, when measurement is made of each photon by passing it through a filter capable of distinguishing longitudinal and horizontal polarization. However, measurement of different polarization base, for example right-hand/left-hand circularly polarized light, cannot give definite correlation because each individual photon rotates in a random manner. This represents an example of classical correlation. In contrast, if photons are entangled, the correlation always appears, which is irrespective of the choice of the measurement, longitudinal/horizontal polarization measurement or circular polarization measurement. The results of measurement are not affected even if the choice of measurement method is made after the entangled state is formed. Preservation of correlation, independent of the choice of measurement technique, is the most quintessential feature of quantum entanglement. Quantum entanglement is acknowledged as being a basic resource in many areas of quantum information technologies.

Up to the present, the research and development on a quantum entanglement source has been largely limited to the near infrared region (around 800 nm). In view of future applications for quantum information communication, we have worked on the development of a quantum entanglement source in telecom wavelengths (around 1.5 μm), and successfully developed a high-purity single photon source and quantum entanglement source[1]–[3].

For practical application of a quantum entanglement source in quantum information processing protocols, creation of high-purity quantum entanglement states, as well as its high-generation and detection rate, is a high hurdle to surmount. Research efforts pursuing higher generation rates are actively underway worldwide. Up to now, these attempts have focused mainly on enhancing the pulse intensity of driver lasers to attain a higher rate in the generation of quantum entangled photon pairs. Higher pulse intensity, however, entails increased noise, giving rise to deterioration of correlation between the entangled pair. Alternative approaches include the method of enhancing

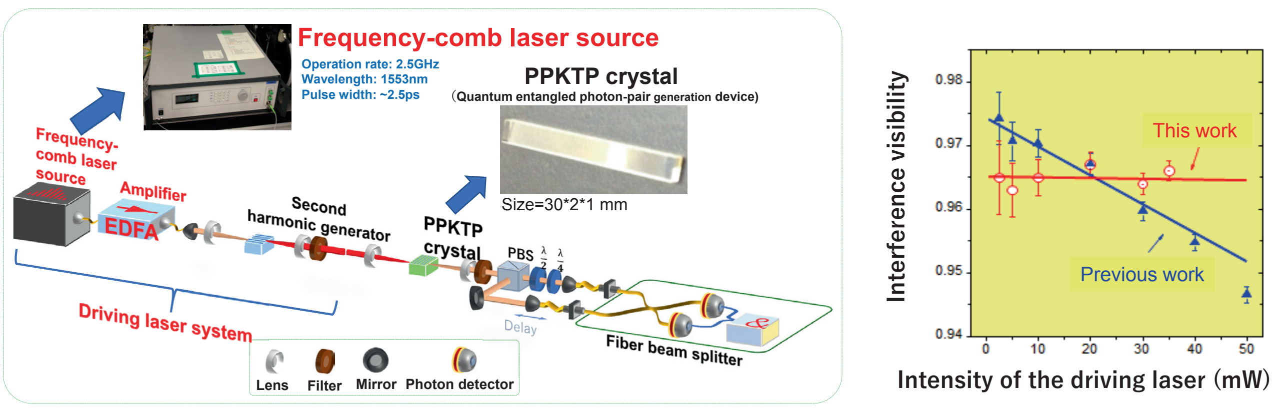

Fig. 1 High-speed, high-purity quantum entanglement source Left: Experimental setup Right: Results from measurements

the repetitive frequency of the driver laser, resulting in higher total intensity. This method does not involve deterioration of correlation as the pulse intensity remains the same, but past research invariably reported that the upper most frequency was around 76 MHz or below. The authors have succeeded in attaining a higher operation rate without involving more noise by combining a new driver laser capable of generating 2.5 GHz repetition frequency with a high-purity quantum entanglement source. Higher frequency was enabled by using a frequency comb source developed independently in NICT[4]. The driver pulse laser must satisfy such requirements as: variable wavelength, variable pulse width, high frequency rate, and operational stability. The frequency comb source developed in NICT can provide all these features. Figure 1 shows the setup overview and the result of the experiment. The experimental result indicates clarity of interference produced by the entangled photon pairs as plotted against the intensity of driver laser output. The higher the interference visibility, the higher the purity of quantum entanglement. The plot clearly indicates the use of the 2.5 GHz frequency comb source has the effect of maintaining high visibility even under higher intensity operation (red line) as compared with the case of a conventional driver laser (blue line). In summary, we achieved a much greater system operation rate, as high as more than 30 times that of conventional systems, by designing an entirely new system based on the frequency comb source.

3 Quantum communication protocol using a quantum entanglement source: a new phenomenon

Among the communication protocols based on a quantum entanglement source, the one called entanglement swapping provides the networking basis for quantum cryptography and quantum computing. Figure 2 shows the two stages that constitute entanglement swapping. First, point A and B, and point B and C respectively share different pairs of entangled photons. At this point of time, the two photon pairs—one shared between A and B, and the other between B and C—have no correlation whatsoever. Next, Bell measurement (a special technique to project two photons onto the quantum entanglement basis) is taken at point B to detect the arrival of the photons. The measurement is figuratively described as trying to capture a photon blindfolded, but it can cause the formation of new quantum entanglement between A and C by intentionally letting the incoming direction (A or C) of photons remain obscured. As illustrated in Fig.3, the experimental setup includes optical elements (e.g. a mirror that exhibits high reflectance only at specific wavelengths), a NICT developed a superconducting single-photon detector, as well as the quantum entanglement source developed in NICT (see description in previous section). Application of these proprietary devices enabled the experiment to generate high-purity entanglement swapping at a much higher rate (the success count of entanglement swapping observation was 1,000 times or higher than reported by previous studies)[5]. The lower right plot of Fig.3 shows the results of correlation measurements on photon polarization arriving at point A and C, indicating good visibility much larger than 33% (the generally accepted threshold value to guarantee the existence of quantum entanglement). These results are significant in paving the way for a new domain of entanglement swapping experiments on optical fiber networks that have been quite impractical due to slow speed.

The high-speed, high-purity quantum entanglement source and detection method also enables the observation of new phenomena in quantum optics. An example is Holland-Burnett interference, a photon-photon quantum coherence well known in quantum optics. Although the observation was limited only to a two-photon system up to the present, availability of a much faster source and detector enabled the observation of multi-photon systems. We conducted interference measurements involving up to 6 photons, and revealed the occurrence of a variety of quantum interference patterns depending on the number of photons[6]. Further, in collaboration with the researchers of U.S. National Institute of Standards and Technology (NIST), we developed a frequency resolving measurement method applied to the photons after the interference. This technique was successfully applied to the frequency resolving measurement of Hong-Ou-Mandel (HOM) interference, a well-known phenomenon as one of the most basic quantum interference phenomena[7]. The HOM interference fringes have been hitherto considered to disappear in certain parameter regions, but the experiment revealed for the first time that strong quantum interference remains to exist even in the regions among the frequency resolved photons. Although these results are not directly linked to information telecommunication, we consider them to be significant scientific contributions in expanding quantum optics—a basic science from which a variety of achievements may be derived. The frequency resolving technology and the novel knowledge concerning quantum coherence

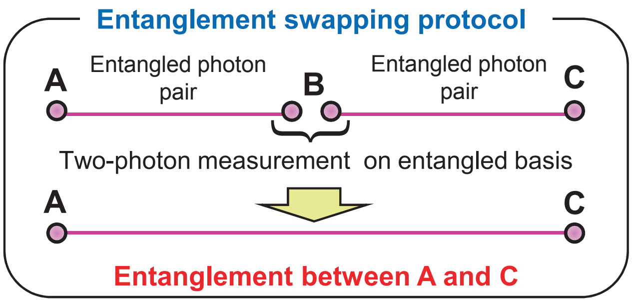

Fig. 2 Steps for swapping quantum entanglement

lead further to new discoveries: the authors succeeded in producing the world's first generation of a high-dimensional entangled photon pair, which is characterized by more than 10 degrees of freedom, and the photon pair's quantum entanglement is distributed in more than ten different frequencies[8]. To evaluate the validity of these experimental results, we constructed a theoretical framework that enables accurate modeling of optical experiments in quantum entanglement research, without the need to resort to large-scale numerical simulations[9][10].

The research described in this report is still in the basic stage, and does not at present indicate a direct link to the upgrading of the performance of telecommunication. However, the combination of this new knowledge in physical science is expected to help accelerate the establishment of underlying technologies for future quantum node applications.

4 Integration of quantum entanglement source

To make the quantum entanglement source a more practical device, a higher degree of integration is necessary using versatile materials as far as possible. We are also tackling the integration of a quantum entanglement source that operates in telecom wavelengths, attempting to put silicon photonics to use. Figure 4(a), (b) shows an example: an integrated circuit consisting of a tiny silicon ring resonator (approx. 10 μm radius) and two silicon waveguides flanking the resonator is constructed on a board, and a four-wave-mixing process (a non-linear optical process) is initiated within the ring resonator by introducing excitation light via the waveguide to generate quantum entangled photon pairs. By introducing a 1551.63 nm pump laser, the generation of a correlated photon pair was observed at two wavelengths, 1539.01 and 1564.43 nm, both falling in the range of telecom wavelengths[11]. From the output, photon pairs with time-bin entanglement—entanglement in terms of positional information along the time axis—can be generated by passing each output photon pair through an asymmetric interferometer (planer light wave circuit: PLC).

The entanglement thus generated showed a high degree of quantum visibility (≧90%), proving it to be a high purity quantum entanglement (Fig.4(c)). We also succeeded in generating "wavelength-multiplexed quantum entangled photon pairs" (simultaneous generation of two photon pairs from four wavelengths) through careful

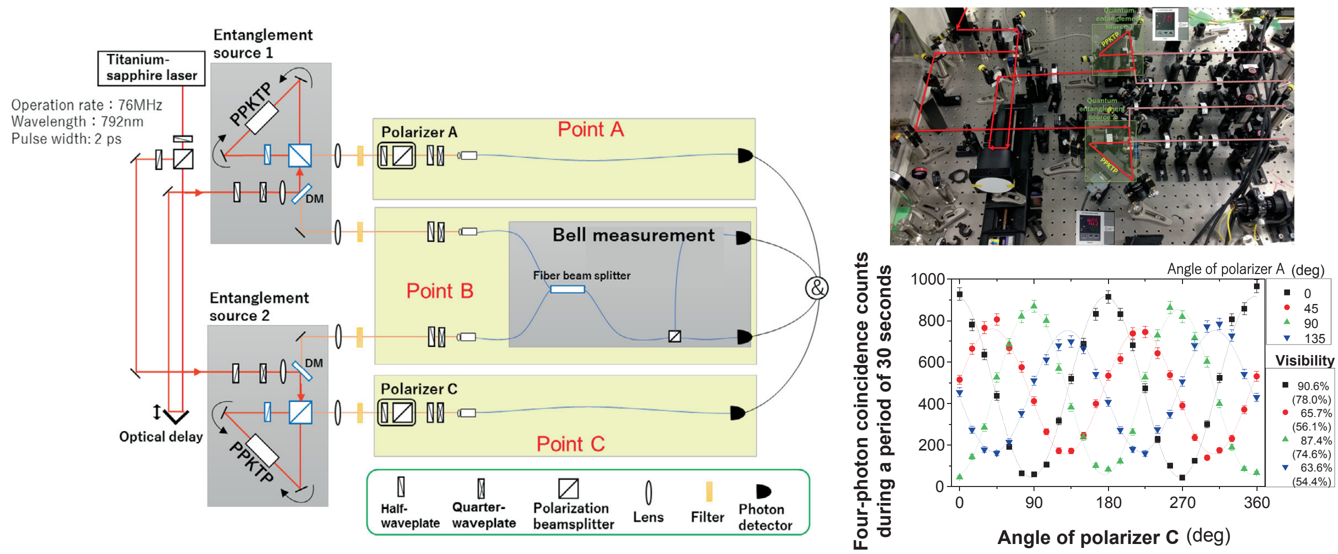

Fig. 3 Entanglement swapping experiment Left: Overview of experimental setup Upper right: Photograph Lower right: Experimental results

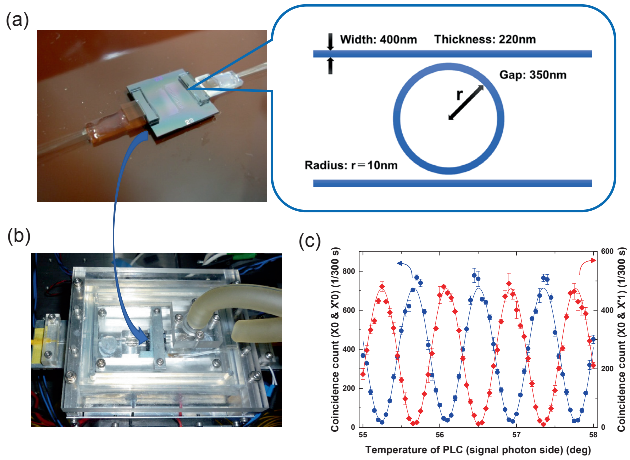

Fig. 4 Experiment on integrated quantum entanglement source. Silicon ring resonator (a) is operated in a temperature controlled environment (b) (c): Visibility of generated quantum entanglement light

control of device temperature and a frequency-selective filter[12]. In addition, the experiment setup has proved the feasibility of its use in a double pump scheme—pump light is incident from both ends of a waveguide, and photon pairs are taken out from both ends of the other waveguide(Fig.5). It is interesting to note that, although it seems a natural consequence that the number of photon pairs generated from bi-direction output mode become, in aggregate, twice as large as those of single direction output mode (pump on one end, and output from the other end), the experimental results clearly show the ratio of production rate was greater than two (Fig. 5, right. Upper and lower plots show respectively the observation results from two operation modes: quantum visibility of an entangled photo pair obtained from single direction output mode, and that of bi-directional output mode (only the photon pairs from one end are shown)). Comparison of the two plots clearly indicates a higher photon detection rate in the lower plot. This phenomenon needs further analysis in order to provide full elucidation of a causal link: a tentative explanation is that reflection and interference of excitation light at the junctions between the waveguide and resonator may have the effect of increasing the effective excitation rate to a value greater than two. In any case one can say this distinctive phenomenon will have a very favorable influence on the future development of quantum integrated devices.

5 Concluding remarks

We describe a certain aspect of R&D in photon control technologies with a main focus on the development of a quantum entanglement source. Realization of an integrated quantum entanglement source with a higher rate and purity would raise high expectations over it becoming a mainstream light source for next generation quantum cryptographic technologies. Free exchange of quantum information between the quantum memory of matter and photons—although this is a highly advanced subject—would bring the realization of quantum repeater technologies much closer.

R&D on receiver technologies in the quantum domain

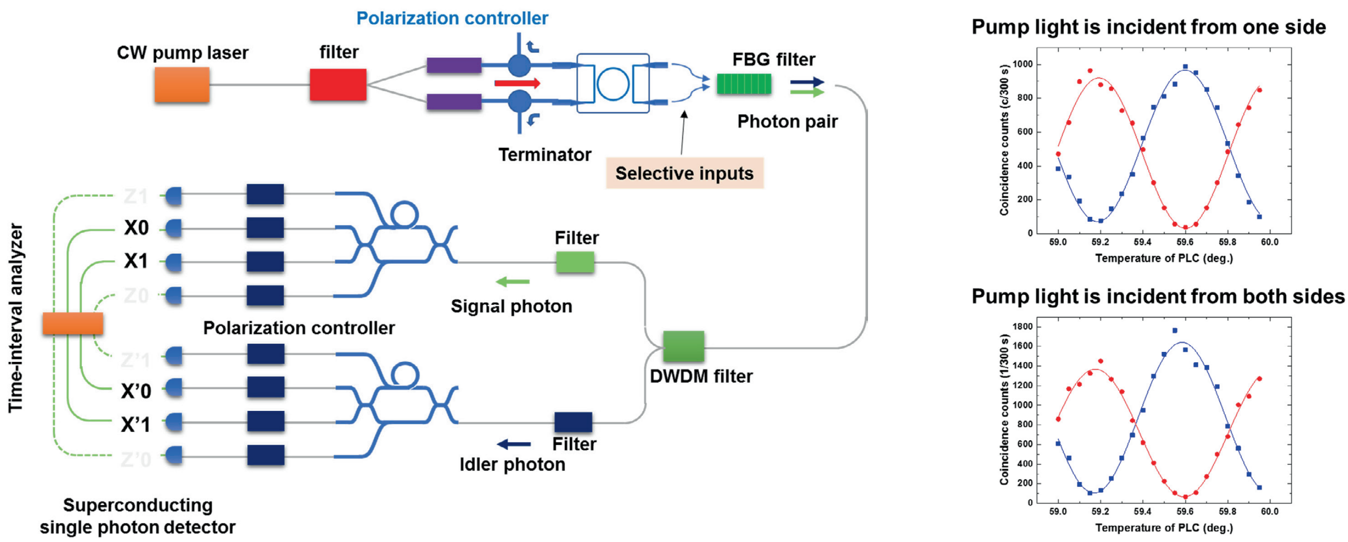

Fig. 5 Silicon ring resonator experiment (bidirectional input)
Left: Schematic representation of experiment setup
Right: Experimental results

are also underway in NICT, aiming at establishing an ultra-high sensitivity method for extracting information from feeble coherent light signals, as described in the introduction[13]–[19]. Quantum noise overpowers modulation signal in the domain where the handling of extremely weak photo-level light is of concern, almost ruining the validity of conventional technologies used in optical communication. The novel approach NICT is undertaking represents the technologies that pursue the ultimate limits of signal identification, where an important role is played by technologies such as photon detection, specialized schemes of phase, and amplitude modulation that can preserve the quantum nature of the signal. In the future, the development of quantum entanglement control technologies as applied to such quantum receivers is expected to make quantum decoding, or signal error correction on quantum levels, feasible in the future. This would further pave the way into the realm of optical communication where communication capacity comes close to the limits allowed by physical laws.

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