Optical Technologies for Optical Quantum Computing with Continuous Variables

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Abstract

Quantum computers are increasingly seen as a potential solution for computing problems that are difficult to solve with conventional technologies. A photon-based quantum computer is a promising technology that enables the development of large-scale, universal quantum computing at high speeds at room temperature with large-scale quantum entanglement thanks to photons' inherent characteristics. This article explores NTT's efforts to develop optical quantum computers using optical fiber communication technology.

Keywords: continuous-variable quantum state, quantum computer, optical component

1. Introduction

For sustainable development of society, computer technology must also be developed sustainably to address increasingly complex and challenging issues such as the economy, climate change, energy, and exploration of materials and living phenomena beyond our current knowledge. The rapid growth of semiconductor technology, as exemplified by Moore's law, is reaching its limits. Consequently, there are growing expectations for new computing technologies that can solve problems beyond the capabilities of conventional computers in a practical timeframe. Quantum computers that leverage quantum properties to execute calculations are attracting attention as a potential solution. Quantum algorithms use physical states with quantum properties, such as superconductivity, ion traps, cooled atoms, and electrons, as a medium for calculation. Using a quantum of light as a computational medium is emerging as a leading candidate of an enabler for quantum computers. It possesses three key features: (1) it operates at room temperature[*1], (2) can achieve large-scale quantum entanglement, and (3) operates at high speeds. While feature (1) is intrinsic to photons, features (2) and (3) require technology that uses the characteristics of photons. NTT is working toward developing a photon computer by applying optical device technology for optical fiber communications. This article outlines NTT's efforts toward optical quantum computers.

2. Continuous-variable optical-quantum-information processing and large-scale quantum-entanglement generation

In many quantum computers, physical states called qubits are spatially arranged, and quantum information is processed using the superposition of these states or quantum correlations (quantum entanglements). The optical quantum computer introduced in this article, however, processes quantum information on the basis of the quantum state of the amplitude of

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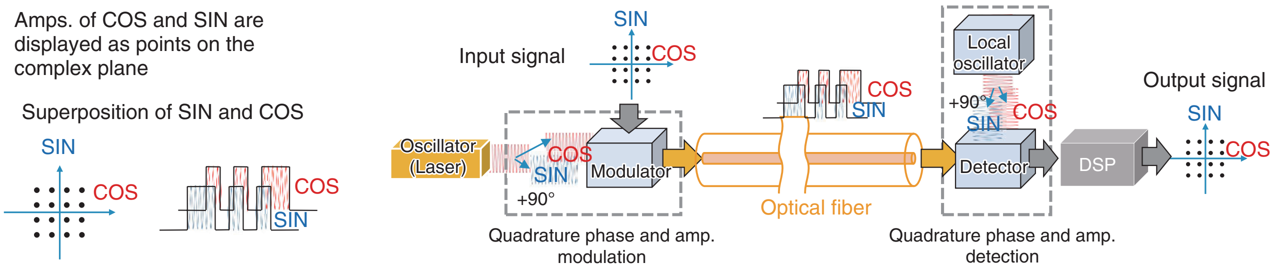
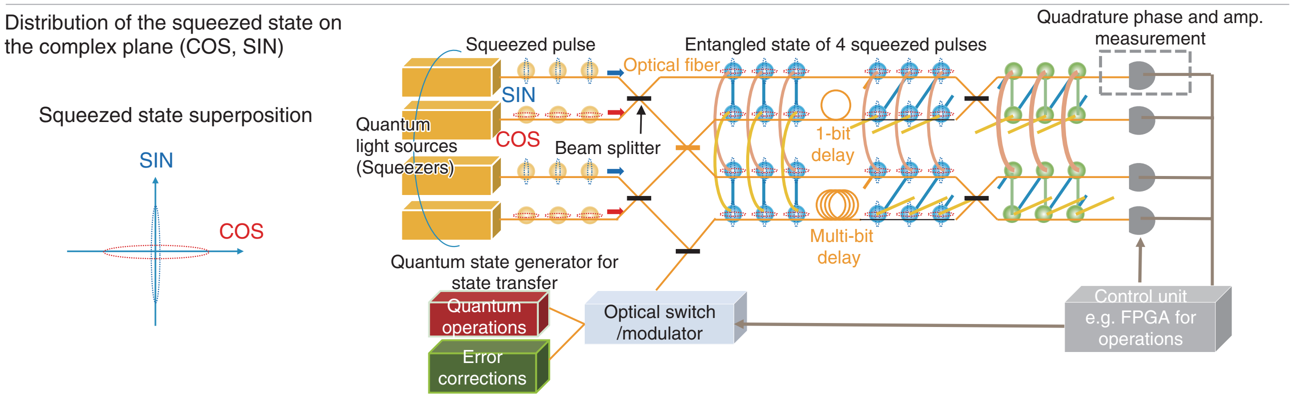
[*1] It operates at room temperature: By converting the photon energy ε to a temperature T using Boltzmann's constant (k_B), $T = \varepsilon/k_B$ is 2.93×10^4 K. This temperature is high enough for the thermal noise generated at room temperature, suggesting that the system can effectively operate at room temperature.



(a) Optical fiber communications (Digital coherent transmission)



(b) Continuous-variable optical quantum computer

DSP: digital signal processor
FPGA: field-programmable gate array

Fig. 1. Configuration of optical fiber communications and continuous-variable optical quantum computer.

light. (The amplitude of light is represented by a continuous complex number. When it is quantized, it becomes what is called a continuous-variable quantum state.) It takes advantage of the fact that wave superposition, interference, and so on are phenomena that correspond directly to quantum operations. Optical quantum computing makes arranging pulse-like photon states in the time domain possible. It thus enables an optical quantum computer to execute large-scale operations without restrictions due to the spatial arrangement of quantum qubits used with other physical quantum computers. Large-scale entanglement states to execute large-scale operations can also be generated relatively easily using simple devices such as beam splitters, thanks to the wave nature of photons. Continuous-variable optical quantum computers use superposition of optical quadrature phase amplitudes, similar to that used in digital-coherent transmission technology for optical fiber communications (**Fig. 1(a)**). The digital coherent transmission superposes modulated quadrature components (cosine and sine components) of laser light (coherent light) for transmitting. Each quadrature is acquired by interfering with the light of a local oscillator reconstructing the original signal by using digital signal processing for receiving. However, simply adding the cosine and sine components does not produce a superposition of quantum states used in continuous-variable optical quantum computers. To obtain quantum effects, we need to use a quantum state of light called squeezed light, which has intentionally distorted distribution. **Figure 1(b)** shows an intentionally biased distribution of squeezed light as a dotted ellipse, superposing two quantum states spread in the cosine and sine directions. A continuous-variable optical quantum computer calculates by executing quantum operations on squeezed light. Pulses of squeezed light (the spheres in Fig. 1(b)) emitted from a squeezed light source (quantum light source) propagate through an optical fiber and are separated by a beam splitter that functions as a half mirror to achieve a state in which different squeezed

Table 1. Correspondence and differences between optical fiber communications and continuous-variable optical quantum computer.

	Optical fiber communications	Continuous-variable optical quantum computer
Operations	Digital coherent transmission (compensates for large dispersion)	Measurement-based quantum computing (computation with large quantum entanglement)
Representation space for signals and information	Coherent light (carrier wave) and quadrature phase and amp.	Squeezed light and quadrature phase and amp.
Generation of carrier waves	Laser light source (coherent light source)	Quantum light source (squeezed light source)
Signal generation and quantum operations	Beam splitter Phase shifter Modulator	Beam splitter Phase shifter Displacement operator (modulator) Squeezing operator Third-order nonlinear operator
Signal demodulation	Quadrature phase and amplitude detection	Quadrature phase and amplitude measurement

Red text indicates differences.

light pulses are superposed simultaneously. These states are entangled quantum-mechanically, and huge entangled states can be created by shifting light pulses in the time domain and repeatedly mixing them with beam splitters [1]. This massively entangled state enables measurement-based quantum calculations, which are known to correspond to gate-type quantum calculations. Measurement-based quantum computing[*2] is a very interesting computational method. However, we focus on the technology required for continuous-variable optical quantum computers and the correspondence of optical fiber communication technology as an optical technology for continuous-variable optical quantum computers.

3. Application of optical fiber communication technology to a continuous-variable optical quantum computer

Table 1 shows the similarities and differences between optical fiber communications and continuous-variable optical quantum computers. To conduct arbitrary continuous-variable quantum calculations, a squeezer, demultiplexer (beam splitter), phase shifter, displacement operation (optical modulator), and third-order nonlinear gate are all necessary [2, 3]. The beam splitter, phase shifter, and optical modulator are elements used in classical optics and components of optical fiber communications. Continuous-variable optical quantum computers also use quadrature amplitude measurements with the same configuration as that used for quadrature amplitude detection in optical fiber transmissions. The squeezers and third-order nonlinear gates require technologies not directly used in optical fiber communications. As a quantum light source corresponding to a laser light source in optical fiber communications, a squeezer is an essential element of an optical quantum computer. However, a squeezer with good characteristics applicable to an optical quantum computer had not been implemented because it requires large optical nonlinearity to generate squeezed light.

To achieve squeezer characteristics suitable for optical quantum computing, NTT has implemented a waveguide-type periodically poled lithium niobate (PPLN), which has been researched and developed for optical fiber communications. For optical fiber communications, phase-sensitive amplification, a state of an optical parametric amplifier, has been considered a preferred technology that does not increase noise. NTT has been developing waveguide-type PPLN technology to provide high-performance optical parametric amplifiers. PPLN is an optical device that enhances nonlinear conversion efficiency by periodically inverting the polarization of lithium niobate, a nonlinear optical crystal. NTT further

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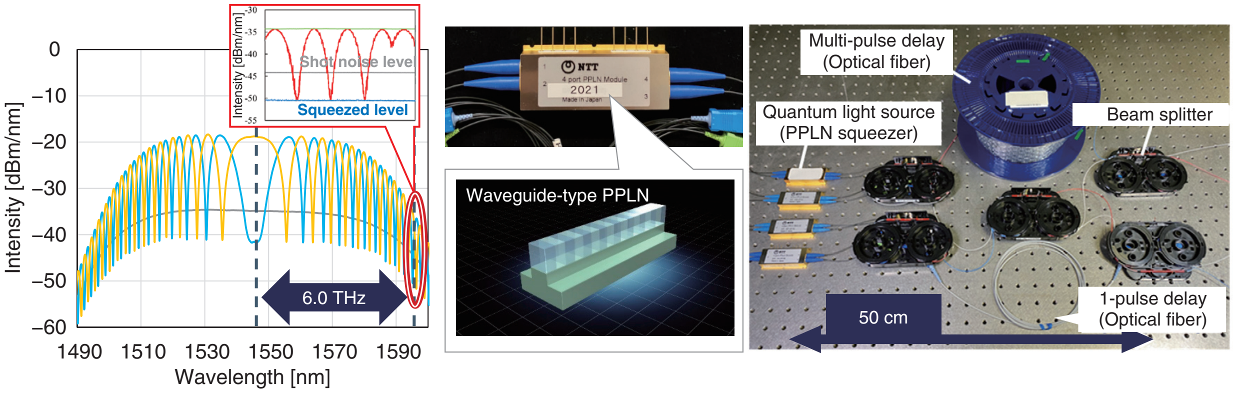
[*2] Measurement-based quantum computing: A method of quantum computation that achieves operations equivalent to quantum operations by repeatedly changing the projection direction of a projection-valued measure for subsequent pulses on the basis of the measurement results. A projection-valued measure obtains a specific state component as output by changing the incident state or reference state in a quadrature phase amplitude measurement. A typical example is a Bell measurement that determines the components of a quantum entangled state called a “Bell state.”



(a) Bandwidth of quantum light source

(b) Quantum-light-source module

(c) Components of a large-scale quantum-entanglement generator

Fig. 2. Quantum-light-source module and fiber-based continuous-variable optical quantum computer (components of a large-scale quantum-entanglement generator).

processed the optical waveguide structure on the PPLN and demonstrated that it is applicable as an amplifier for long-distance transmission, which had been difficult, by confining the light propagating in the optical waveguide in a narrow area and increasing the nonlinearity [4]. We have confirmed that this high-performance waveguide PPLN technology has advantages not only in phase-sensitive amplification but also in quantum light sources, or squeezers, by fabricating quantum light sources. **Figure 2** shows a large-scale quantum-entanglement generator for a continuous-variable optical quantum computer consisting of a quantum-light-source module and fiber-type devices. The quantum-light-source module uses a waveguide-type PPLN to improve nonlinear conversion efficiency, eliminating the need to reciprocate inside the resonator to obtain the optical path length required for conversion, which causes frequency dependence, and expands the bandwidth to 6 THz. It also achieves a squeezing level of 6 dB, an index of the asymmetry of compression in the distribution of the squeezing light. It was the highest squeezing level achieved by a non-resonator type of squeezer [5]. This wide bandwidth can accommodate many quantum pulses and various quantum states corresponding to waveforms in optical fiber communications. We have demonstrated that the module can generate pulses of arbitrary quantum states in time slots [6].

It has been too difficult to achieve third-order nonlinear gates because they require larger optical element nonlinearities than those needed for squeezers. However, an alternative method of generating third-order nonlinearity using quantum teleportation has been proposed [7] and is becoming feasible as technology advances.

4. Summary and future prospects

We have shown that we can provide the components of a continuous-variable optical quantum computer by using optical fiber communication technology. As well as optical communication components acting as components of optical quantum computers, further developments in component technology for optical fiber communications will enable the implementation of important optical quantum computer components such as squeezers and third-order nonlinear gates. For a continuous-variable optical quantum computer to operate as a system, in addition to the optical devices, it is necessary to develop the electronic devices that control optical components and the software that operates them. Measurement-based quantum calculations executed by a continuous-variable optical quantum computer require the high-speed operation of electronic circuits and control systems because the measurement results must reflect instantaneously to update the projection-valued measure system and quantum states. The middleware will also become essential to reflect quantum algorithms in actual devices. By addressing these challenges, NTT aims to develop a continuous-variable optical quantum computer using optical components by 2030 and a chip for an optical quantum computer by 2050, as shown in **Fig. 3**. A challenge is

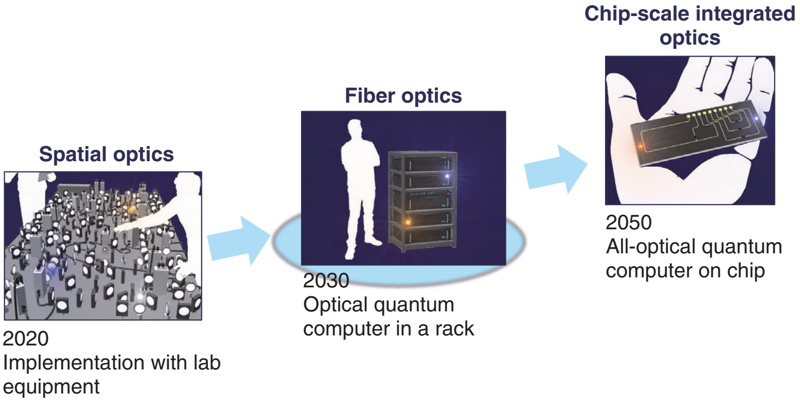


Fig. 3. Roadmap for continuous-variable optical quantum computers.

improving the characteristics of current optical devices. For example, the squeezing level of the squeezer as a quantum light source for fault-tolerant operations, which use GKP codes to error-correct large-scale quantum entangled states, must be several dB higher than the current level of 6 dB [8]. The losses introduced by the constituent optical components also remain a significant noise source that disturbs the quantum state, thus must be reduced. These are challenges that are difficult to overcome even with the high-performance device technology cultivated in optical fiber communications. Through our efforts to achieve a continuous-variable optical quantum computer, we aim to further advance optical technology and bring about explosive developments in quantum computing and optical fiber communications.

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