Optical Device Technology for Next-generation Computing Using Light

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Abstract

The performance of conventional computers, which have supported the infrastructure of our digital society and developed in accordance with Moore's law, seems to be approaching its limits. To solve many social issues and achieve a safe, secure, and prosperous society, next-generation computers with performance far beyond that of conventional computers, such as quantum computers, are expected. This article outlines the possibilities of next-generation computers that *compute using light* and optical device technologies introduced in the Feature Articles of this issue.

Keywords: next-generation computing, optical computing, optical devices

1. Introduction

Digital technologies used in all aspects of society, including smartphones, consumer electronics, automobiles, the Internet, public infrastructure information systems, finance, and commercial transactions, have become a social infrastructure. In addition, communication technologies that facilitate the coordination of distributed digital information and new digital technologies such as artificial intelligence (AI) and blockchain are having a significant impact on society. Sustainable development of digital technology, which is the foundation of society, is essential for solving many social problems, including energy problems, and for achieving a safe, secure, and prosperous society. Digital technology has continued to develop by increasing the integration of semiconductor integrated circuits that execute calculations, achieving both high performance and low power consumption. Moore's law, which states that the number of transistors in a semiconductor integrated circuit doubles every two years, is widely known as a symbol of this trend. However, the miniaturization of semiconductor integrated circuits is said to be approaching its physical limits, pointing to the limits of Moore's law, which has been maintained for half a century. In addition, the explosive growth of AI, which executes machine learning using more than one trillion parameters, is driving the need for increased computing power beyond Moore's law [1]. For example, a high-performance AI language model called GPT-3, published by OpenAI, consumes 1287 MWh of power when trained on the largest model. This is equivalent to the power consumption of an average Japanese household for approximately 300 years [2].

To overcome these challenges, there is a strong demand for the emergence of next-generation computers that can achieve performance far beyond that of conventional computers with low power consumption, not only by developing semiconductor integrated circuit technology but also using other methods.

The Feature Articles in this issue focus on computing technology using light, which has been attracting attention as a next-generation computing technology, and introduce the optical device technologies used for it. In light-based computing, it is necessary to consider how to represent information in the state of light and how to execute computing using the information represented using light. In the following sections, we review the advantages of representing information as a state of light and computing in such a state as information processing for next-generation computing as well as the optical device technologies required for light-based computing.

2. Information processing using light for next-generation computing

A term similar to information processing is signal processing. Using the analogy of manufacturing at a factory, information corresponds to parts, signals correspond to packages containing parts, signal processing corresponds to transportation such as sorting and transshipment, and information processing corresponds to the manufacturing process by using the contents of the package to make something new.

Just as the upper limit of the production capacity of a factory can be roughly estimated by the upper limit of the flow of goods, we first consider how much light can handle signals and the information they contain, including from the viewpoint of signal processing. Let us consider how information processing can be developed by incorporating light, which has been used in signal processing, in the same manner that manufacturing technology has greatly developed through the line-production system that integrates the manufacturing process and transport of goods.

Optical fiber communication is a typical example of superimposing information on light. In such communication, signal processing is executed to convert information into light intensity, frequency, and phase to transmit information. To provide an optical communication line, optical signals are distributed using an optical splitter, wavelength-multiplexed signals are separated or bundled using an optical multiplexer/demultiplexer filter, or processed in accordance with the frequency of the optical signal using an optical frequency filter. These can be regarded as a type of signal processing using an optical functional device. The signal superimposed on the light is a digital signal, and the information extracted from the light is processed using a digital filter to remove the noise contained in the phase, frequency, and amplitude. Therefore, signal processing and information processing are limited by the processing speed of electronic circuits.

In optical fiber communication, ultrahigh-speed transmission experiments at 100 Gbit/s-class modulation rate frequencies have already been demonstrated. In contrast, more information can be superimposed on light. For example, light with a wavelength of 1.5 μm is an electromagnetic wave with a frequency of about 200 THz, and light with an intensity of 1 mW can be thought of as a stream of about 7.55×10^{15} photons per second, leaving a great many degrees of freedom. However, to process information beyond the processing speed of electronic circuits, it is essential to compute with light because it is necessary to manipulate lightwaves and photons beyond the processing speed of electronic circuits. **Figure 1** shows the relationship between signal processing and information processing with respect to the granularity of information processed using light. When manipulating a digital-signal sequence or a single symbol of a digital signal, light is mainly used as a carrier wave processed using an optical filter as an element for signal processing that is superimposed on light. In information processing using light, however, light is treated as an analog signal wave, or the quantum state of light is used to superimpose information on it and manipulate the state of light to process information. In optical signal processing, optical circuits are used in cooperation with electronic circuits, whereas in optical information processing, optical operations are executed in a closed manner within an optical circuit. Optical operations for information processing are executed by precisely controlling optical interference, homodyne detection, and autocorrelation to obtain amplitude and phase information, then combining them. As described in the Feature Articles in this issue, the basic operations of optical neural networks [3] and optical quantum information processing [4, 5] are beginning to be demonstrated in actual optical circuits. Optical information processing is considered a promising candidate for next-generation computing technology.

3. Optical device technologies for computing using light

By superimposing information on the enormous degrees of freedom of the state of light, we can see the potential of optical computing technology beyond that of conventional computers. In this section, we consider what type of computing is possible with information represented using light and what kind of devices will be needed to achieve this.

Digital technology has mainly used Neumann-type computing, which executes sequential logical operations on data based on programs. High-speed logic operations, including information transmission between processors and peripheral devices, are important for the development of digital technology. Non-Neumann-type computing, on the other hand, uses a method different from conventional sequential logic operations. When using light, as mentioned above, non-Neumann-type operations can be executed instead of sequential logic operations using the enormous amount of light states, enabling large-scale,

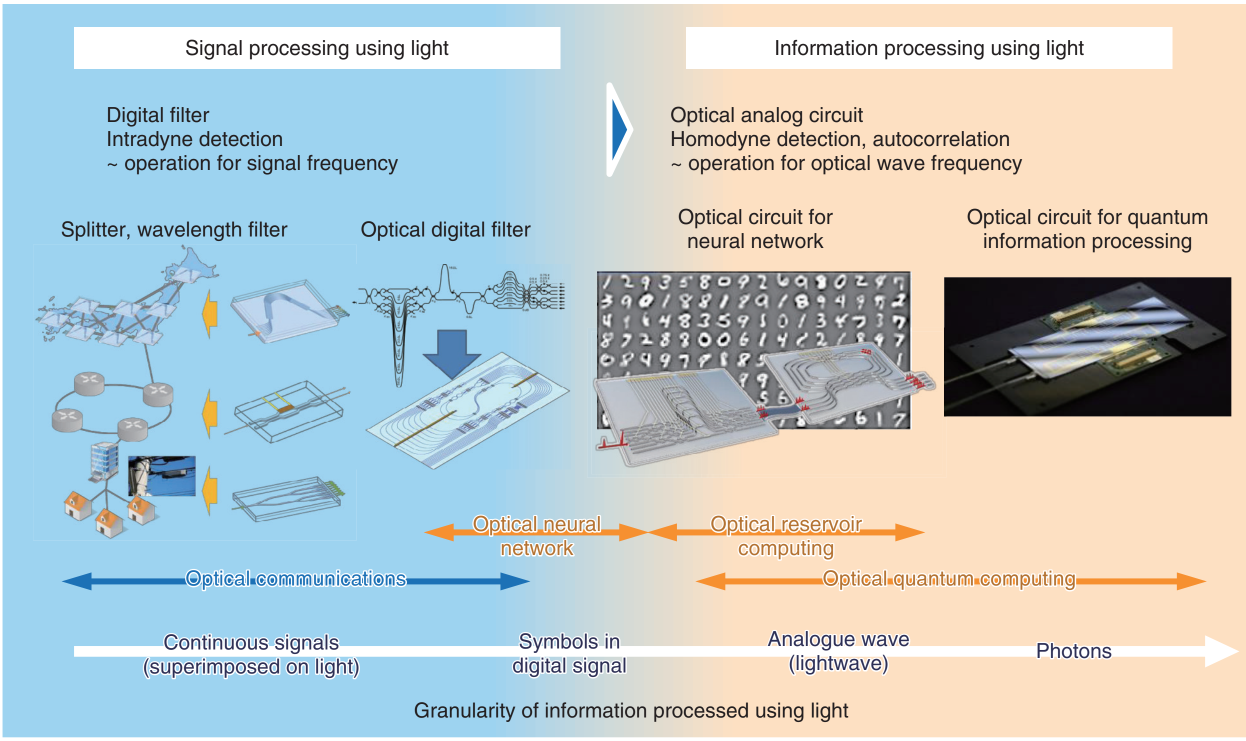

Fig. 1. Relationship between signal processing and information processing with respect to the granularity of information processed using light.

high-speed computing that is not limited by the processing speed of electronic circuits. **Figure 2** shows the correspondence between Neumann-type and non-Neumann-type computing and optical device technologies. For optical devices, lightwaves and photons must be handled well to achieve computing using light, while high-speed and broadband performance is needed to accelerate logic operations in computing. In the direction of high-speed and broadband, opto-electronic convergence technology [6] is expected to contribute to improving the performance of current computing systems, including optical interconnection, in response to high-capacity transmission technology used for optical fiber transmission. When considering wide-area networks, conventional optical devices such as linear optical circuits also support this area of technology.

From the viewpoint of handling lightwaves and photons, nonlinear optical elements for generating correlation of lightwaves superimposed with information, optical circuit technology for generating complicated correlation and operating calculation using light as a system, and systematization technology including electronic control are important. When using photons, a quantum light source, corresponding to a laser light source in optical communications, is required to generate quantum states of light. These devices enable non-Neumann-type computers such as coherent Ising machines [7] and optical reservoir computers/optical neural networks [3]. Quantum light sources and optical circuits for optical quantum information processing are also considered essential devices for implementing optical quantum computers, and their basic operation for optical quantum information processing has been demonstrated [4, 5, 8].

Neumann-type and non-Neumann-type computation technologies are not mutually contradictory, but are combined or complemented in accordance with the computation target and computation purpose, and the equipment-integration technology that integrates them as hardware is important for constructing practical systems [9].

In the following three Feature Articles in this issue, we introduce optical device technologies for optical quantum computers, optical neural networks, and optical reservoir computers, which can be called *computing using light* in the next generation of

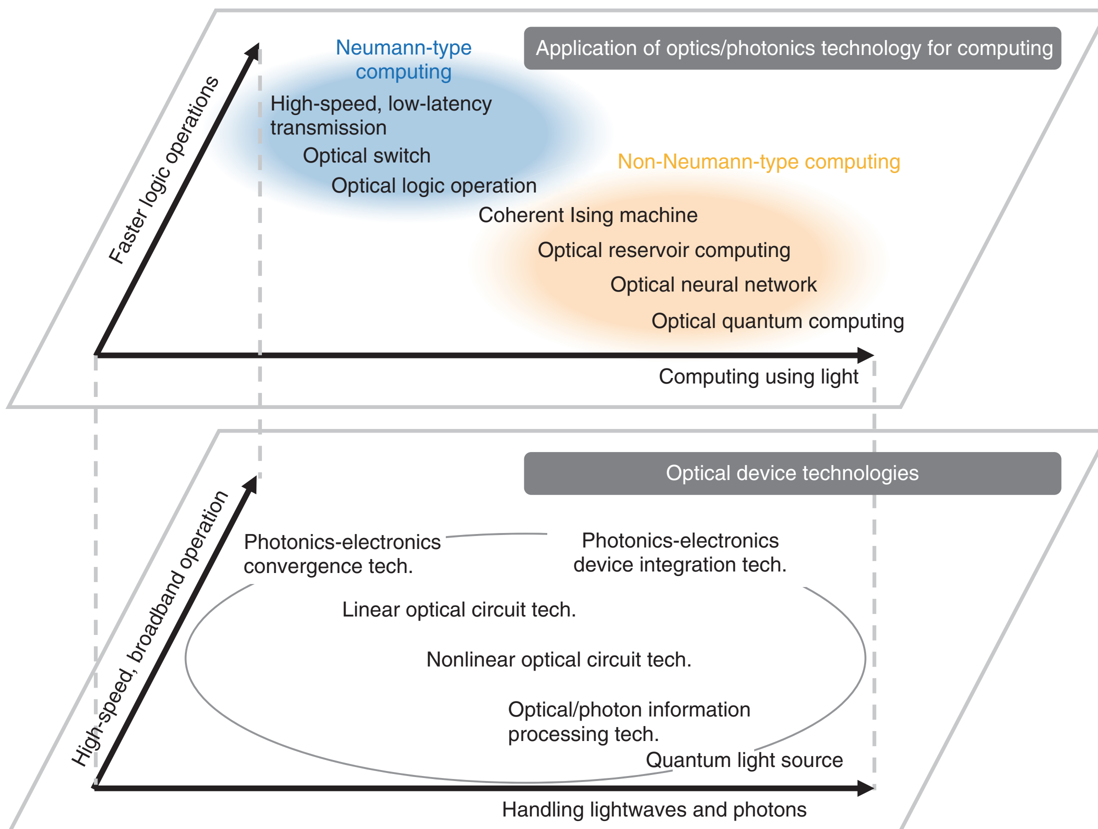

Fig. 2. Correspondence between computing and optical device technologies.

computing. The first article, "Broadband Continuous-wave Optical Quadrature Squeezer for Ultra-fast Optical Quantum Computers" [10], introduces the periodically poled lithium niobate (PPLN) waveguide technology, an optical nonlinear device, and its application to quantum light source technology. In the next article entitled "Optical Circuit Technologies for Next-generation Computing Using Light" [11], linear optical circuits and their applications for optical quantum computing are introduced. In the third article "Photonic Implementation of Reservoir Computing" [12], we introduce optical reservoir computing technology as an optical neural network technology that combines optical device technologies into a system and achieves large-scale sum-of-products operations.

These technologies enable cutting-edge research that incorporates a variety of technologies and are expected to become core technologies for advancing next-generation computing.

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