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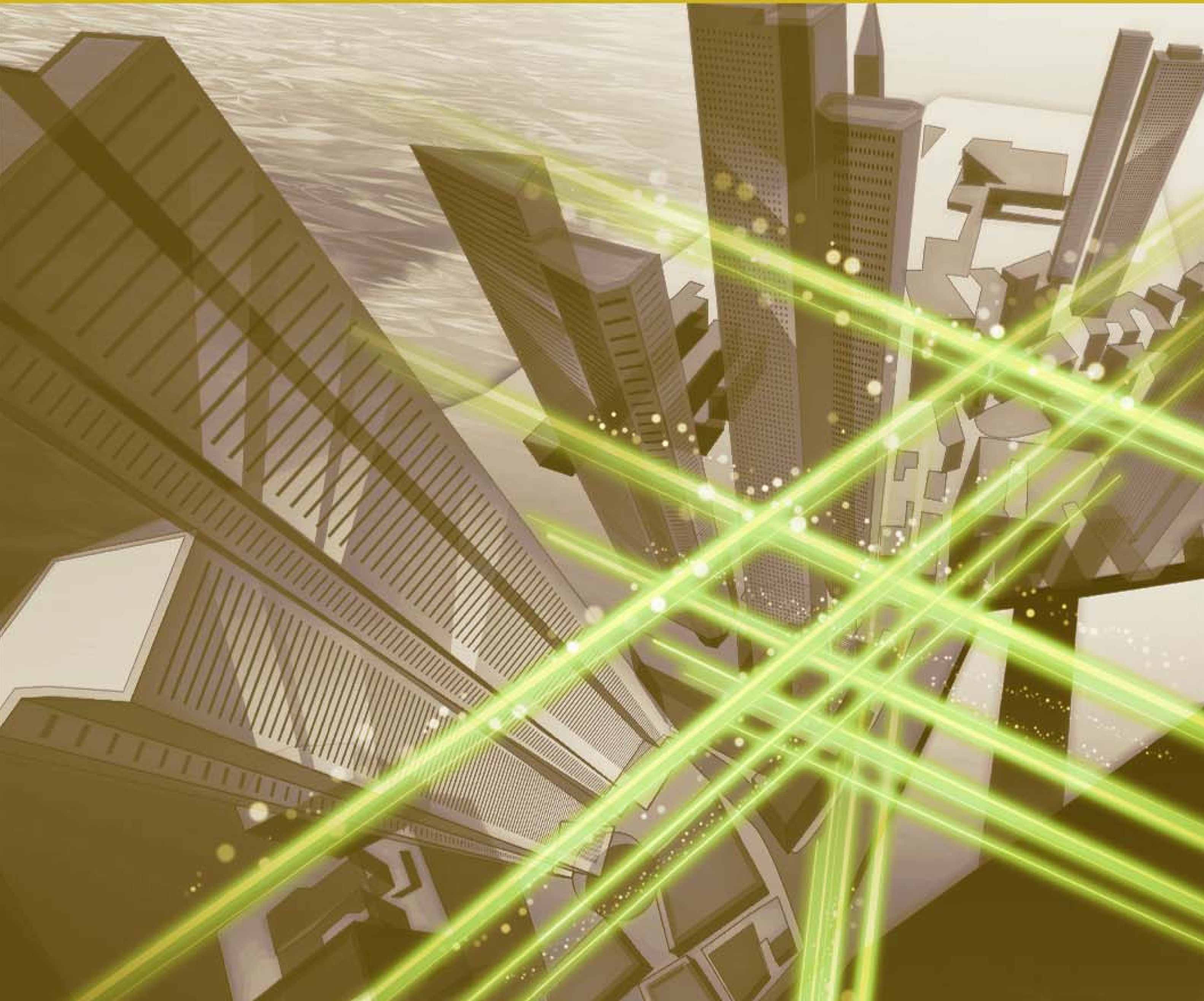

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# Nanophotonic Technologies for On-chip Photonic Integration

*Masaya Notomi and Tetsuomi Sogawa*

**Abstract**

Our research group has been conducting basic research that seeks to introduce optical networking technology in processor chips. Using nanophotonic technology as represented by photonic crystals as the base, we are researching nanophotonic integration technologies to microminiaturize optical devices, drastically reduce energy consumption, and create a variety of new functions. In the Feature Articles in this issue, we introduce our latest achievements in creating nanophotonic devices and our efforts in developing new optical computing technologies using nanophotonics as the base.

*Keywords: integrated nanophotonics, photonic crystal, photonic integrated circuit*

## 1. Introduction

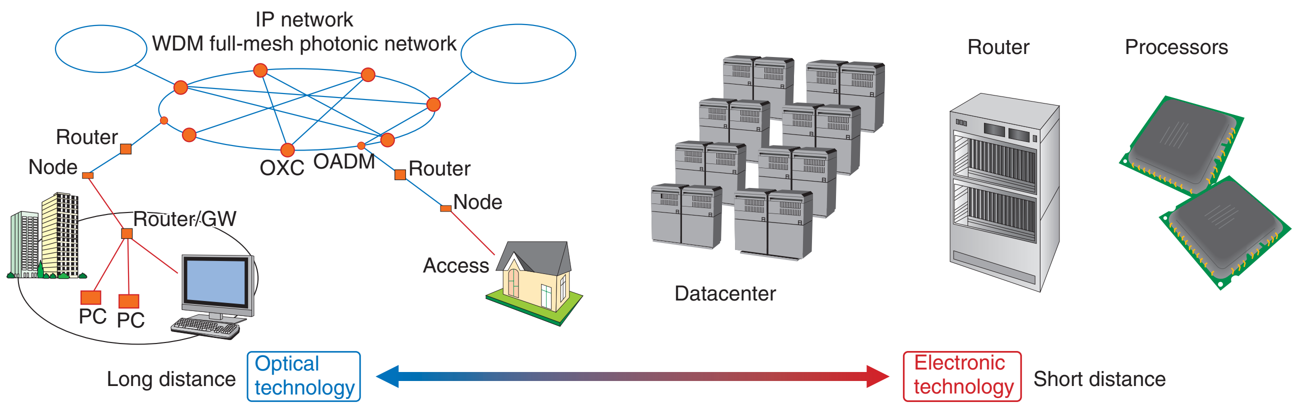
Information technology has become a critical technology for supporting our infrastructure for daily life. The history of information technology is marked by optical signals replacing electrical signals for long-distance communication, and this change is gradually extending to short-distance communication (**Fig. 1**). This trend is taking place due to bandwidth limitation in copper wires, as high bit-rate communication is not possible, and large-capacity signals cannot be sent when transmitting long-distance electrical signals over the wires. Currently, fiber-to-the-home has already become widespread, and the communication system components have become optical-based. In view of this trend, our research group is carrying out research to incorporate optical network technology in processor chips.

Electrical signal processing has been thought to be optimal for short-distance systems such as a processor chip. However, we believe that optical information processing technologies are necessary in future chips for two reasons that we explain below. The reasons are slightly different from the reasons optical fibers replaced copper wires.

Current processor chips face the problem of dramatically increasing power consumption as performance grows. Miniaturized wires and the network between cores consume a large portion of energy in a chip. This heavy consumption occurs due to Joule heating by electrical resistance of wires. In addition, the speed is limited by RC delay (resistance and capacitance of electrical lines). As a result, when the bit rate is high, energy consumption increases.

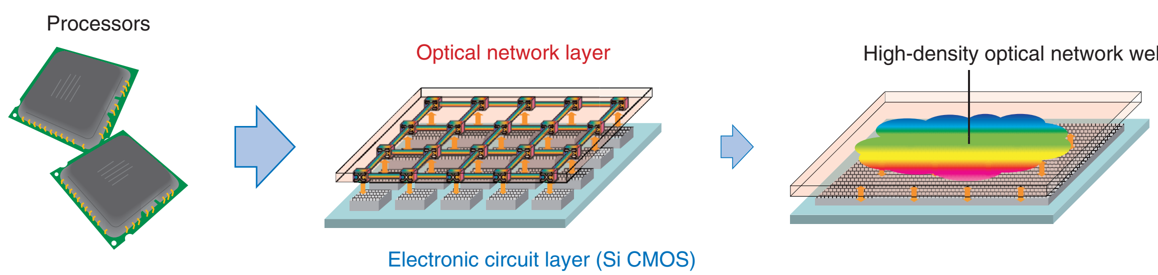
Optical information transfer is not limited by RC delay nor Joule heating, so light does not need more energy than electrical lines at a high bit rate. This is the first reason we seek to deploy optical technology in chips. In the future, it will be necessary to reduce the amount of energy consumed per bit in order to improve processor performance. Electrical information transfer is believed to have a lower limit of several tens of femtojoules per bit due to RC limitations. This is not a serious problem at present, but in 10 to 15 years there will be a need to overcome this barrier. Optical technology is considered a possible means for hurdling past this wall. As shown in **Fig. 2**, we envision that optical technology will be incorporated in future chips and will work in concert with complementary metal-oxide semiconductor (CMOS) electronic circuits [1].

The other reason for incorporating optical technology into chips is related to a processor's computational latency. Although processor performance is improving at present as described by Moore's law, the bandwidth of transistors itself is already saturated,




GW: gateway
IP: Internet protocol
OADM: optical add/drop multiplexers
OXC: optical cross connect
PC: personal computer
WDM: wavelength division multiplexing

Fig. 1. Information communication network at various distance scales.




Si CMOS: silicon complementary metal-oxide semiconductor

Fig. 2. Future concept of processor chips.

leading to high latency; performance improvements are mainly a result of technological developments such as parallelization. However, when true low-latency processing is required, the latency of existing processor chips becomes a problem. In the future, our society will become a cyber-physical system society in which the real world (physical world) and the cyber world will be intimately connected. In such a society, vast amounts of information from the real world serve as input that requires an immediate response from the cyber world, and computational latency will become a critical problem. As discussed below, optical technology has the possibility of dramatically reducing computational latency. This is another reason we seek to develop optical technologies that can be deployed in chips.

Next, we consider what kinds of technologies are necessary to address the issue of high computational latency.

## 2. Necessity of integrated nanophotonics

To introduce optical networking technology and optical computational technology in processor chips, it is necessary to integrate a great number of ultra-small optical devices on a processor chip. However, since it is inherently difficult to confine light in a small space, in general, optical devices are overwhelmingly larger than electronic devices, presenting difficulties for integration.

We show in **Fig. 3** the degree of integration of electronic devices over the years for which Moore's law has been famous, and for comparison, the integration of optical devices. The scale of optical device integration began to take off in around 2000 and has been rising at about the same rate as Moore's law. However,

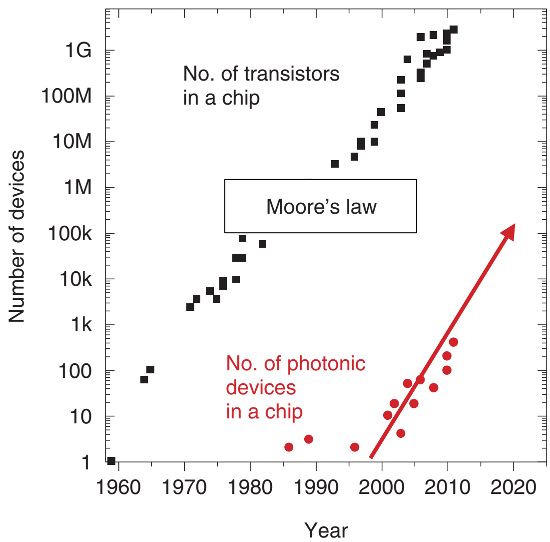



Fig. 3. Change in degree of integration in transistors and optical devices.

this trend will approach a limit in the near future due to the current size of optical devices. Unless optical devices become dramatically smaller, future improvement in the scale of integration cannot be expected.

We are seeking to develop technologies that can integrate about 1 million optical devices on a chip. However, this goal is difficult to achieve with existing technologies. In addition, simply reducing the size of devices is not sufficient. It is also necessary to reduce the energy consumption of each device. Current optical devices consume about 1 to 100 pJ per bit. As noted above, the information transmission cost of light is low. However, no matter how low the transmission cost, it means nothing for the achievement of our goal if optical devices consume energy in the picojoule range. Therefore, there is a need to reduce their energy consumption to 1/1000th of the current level.

As described above, unless there are major breakthroughs in the degree of integration and energy consumption in the future, it will be difficult to integrate a great number of optical devices on a chip. To achieve this goal, we believe that the nanophotonic integrated technologies described in the next section are necessary. We are therefore conducting research on integrated photonics.

Nanophotonics comprises various technologies. We introduce one of them here, the photonic crystal* [2, 3]. A photonic crystal is an artificial structure that modulates the refractive index with a periodicity of about 100 nm. It is known for its ability to realize a variety of new physical properties that cannot be achieved with conventional materials. Especially notable of these features are strong light confinement and light-matter interaction enhancement. As a result, photonic crystals are effective for miniaturizing optical devices and reducing energy consumption. An example of a silicon-based photonic crystal is shown in **Fig. 4**. The creation of this structure was made possible by applying NTT laboratories' cutting-edge semiconductor processing technologies.

## 3. Developments in microminiaturization and low-energy consumption

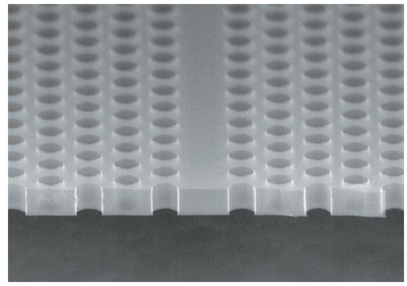
Our research group has developed a variety of optical devices using photonic crystals. The size of all of the devices is about several micrometers, which is 1/100th to 1/1000th the size of conventional optical devices. Energy consumption thus can be dramatically reduced.

The graph in **Fig. 5** compares the energy consumption of various optical switches and their switching energy. For conventional devices, the products of the energy consumed and the switching time lie nearly on a straight line, indicating a trade-off. However, photonic crystal switches [4] are found in an area where the product of energy consumption and switching time is three orders of magnitude smaller. In fact, this product is mostly determined by the device's size. Because a photonic crystal's strong light confinement makes it possible to reduce the device size, ultralow-energy consumption can be achieved without losing switching time.

This principle can also be effectively applied to other types of devices, and we have achieved substantial improvements in low-energy consumption for optical memory devices [5] and laser devices [6]. We have also succeeded in integrating more than 100 bits of optical memory to work together as multi-bit memory, demonstrating the first integration of more than 100 devices in nanophotonics [7].

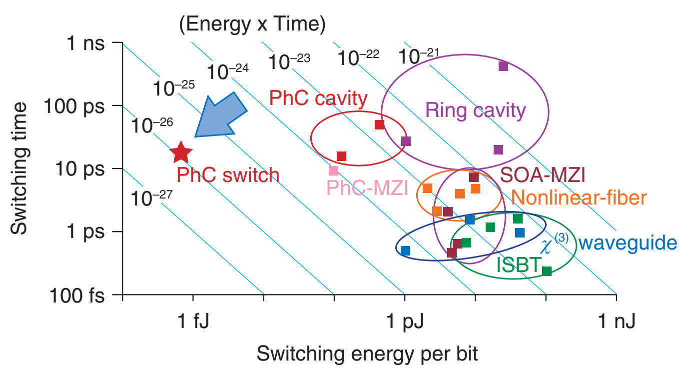
With our recent research, we seek to further reduce device size. One promising technology for this is

* Photonic crystal: A structure in which the refractive index is periodically modulated on the order of the wavelength in the medium. Because optical properties are determined by light's band structures, physical properties not possessed by ordinary substances can be realized. These properties are realized by creating 100-nm-scale periodic structures using semiconductor microfabrication techniques on semiconductors such as silicon with a high refractive index.



The period of holes is about 400 nm and their diameter is about 100 nm. This creates a strong light-confinement effect at the telecom wavelength band (near 1.5 μm).

Fig. 4. Electron microscopy image of photonic crystal fabricated on silicon thin film.




ISBT: intersubband transition
MZI: Mach-Zehnder interferometer
SOA: semiconductor optical amplifier
PhC: photonic crystal

Fig. 5. Comparison of switching time and energy of various optical devices.

plasmonics technology, which is introduced in the article "Toward Application of Plasmonic Waveguides to Optical Devices" [8] in this issue. The technology creates nanoscale structures with metals such as gold, and plasmon modes produced on the metallic surfaces are used to confine light. Use of plasmonics results in some amount of additional loss of light, but light can be confined to a smaller area than with photonic crystals. It has been difficult to couple light from the outside for plasmonic structures. However, we have developed and tested a structure that couples a plasmonic waveguide that confines light to a region that is 1/1000th of the wavelength with a conventional silicon waveguide. Going forward, we seek to further miniaturize devices by using this structure, and we seek to make advances in the high-performance region shown in Fig. 5.

## 4. Impact of ultralow capacitance

We have explained that nanophotonic technology enables the miniaturization of devices and a reduction in energy consumption. However, there is another important aspect when it comes to optical-to-electrical (OE) or electrical-to-optical (EO) conversion devices such as photodetectors (OE) and electro-optic modulators (EO). The most important issue for OE/EO conversion is capacitance. The electrostatic capacitance of conventional optical devices is about several hundred femtofarads. However, as introduced in the article "Ultralow-capacitance Optoelectronic Converters Using a Photonic Crystal" [9], OE/EO conversion devices that have low electrostatic capacitance of 1 fF are being achieved by using photonic crystals. Surprisingly, this electrostatic capacity is

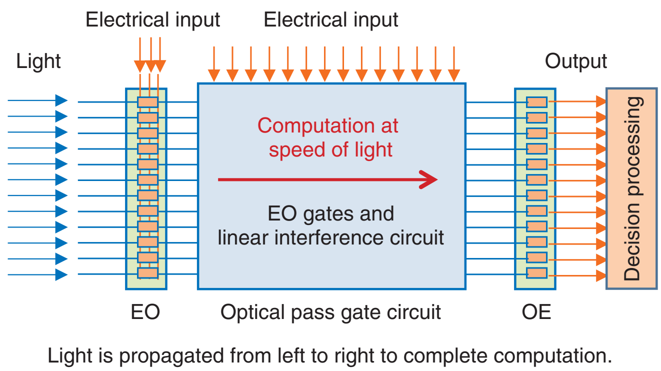



Fig. 6. Optical pass gate-based computation circuit.

already in the same order as CMOS transistors. Conventionally, energy consumption for OE/EO conversion in optical circuits is about several hundred femtojoules. However, our research has shown that by achieving electrostatic capacity of 1 fF for OE/EO conversion devices, it is possible to reduce energy consumption during OE/EO conversion to the 1-fJ range.

OE/EO conversion has traditionally been considered the most energy-consuming part of optical information processing. Thus, it has been considered common sense to reduce as much as possible the number of times OE/EO conversion takes place. However, the above results indicate that there is no substantial difference in the energy consumption of OE/EO conversion in a nanophotonic circuit compared with other processes. As a result, we believe that the way we think about OE/EO conversion in optical processing will greatly change going forward. Another example that is causing this change in thinking is optoelectronic computing technology, introduced in the next section.

## 5. Optical computing revisited

Vigorous research in optical computing took place worldwide in the 1980s and 90s. However, the results failed to surpass those of CMOS processors, and research in the technology waned. However, with the progress made in nanophotonics in recent years, we believe it is a good time to reconsider optical computing. One reason is the ultra-efficiency of OE/EO conversion, as mentioned above. As a result, optoelectronic integrated computing that performs OE/EO conversion in a computer has the possibility of becoming a reality. As described in the Introduction, there is a growing need for low-latency processing, and CMOS transistor latency is approaching saturation at 10 ps or more. Meanwhile, as introduced in the article “Ultralow-latency Optical Circuit Based on Optical Pass Gate Logic” [10], we are investigating a method called optical pass gate logic, which is achieved by connecting electro-optical gates. With this method, computation is performed by light propagation, so shortening the length of optical gates can overwhelmingly reduce the computation time. For example, if the optical gate length can be shortened to 10 µm, the propagation time of light becomes 0.1 ps, and a major reduction in latency compared with CMOS can be expected.

The conceptual system we are researching is shown in **Fig. 6**. Electric input signals enter the electro-optical gate. Computation is performed by propagating the light converted from electricity within a circuit composed of gates and the interference optical system. The light is finally converted to electrical signals by the photodetector to complete the computation process. Using this system, we have succeeded in reaching our goal of implementing a wide range of computing devices such as adders, multipliers, multiply accumulators, pattern matchers, and neural network computers that perform operations at the speed of light propagation. We are continuing to research the design and fabrication of specific circuits.

## 6. Integration of nanomaterials and nanophotonics

Electronic integrated circuits can be made of silicon and silicon-oxide devices. These two materials with dopants are sufficient to realize a variety of functionalities. In contrast, in optical integrated circuits, different materials are required to achieve each function, so determining how to integrate functional materials is critical. In particular, finding a way to combine functional materials having a small volume with nanophotonic structures is key. In recent years, various nanoscale materials showing fascinating properties have been developed. However, because such nanomaterials are much smaller than the wavelength of light, adequate performance cannot be achieved, as these devices cannot confine light. We are therefore seeking to create new platforms by combining a variety of nanomaterials such as nanowires, graphene, and carbon nanotubes with nanophotonic structures. In the article "Compound Semiconductor Nanowire Laser Integrated in Silicon Photonic Crystal" [11], we introduce research on lasers that utilize a resonator formed by such a platform. The resonator is induced by a compound semiconductor nanowire having a diameter of 100 nm joined to a silicon photonic crystal.

## 7. Toward the creation of novel optical properties

Our group is also looking for novel functions and searching for novel optical properties in nanophotonic structures. In the article "Control of Light with Exceptional Points in Coupled Photonic Crystal Lasers" [12], we introduce research findings related to a parity-time (PT)-symmetric optical system in which gain and loss are periodically arranged. In a structure in which gain and loss are arranged in accordance with certain rules, special symmetry (PT symmetry) is satisfied where parity (spatial axis) and the time axis return to their original conditions when inverted simultaneously. However, in recent years it has been discovered that such a system has properties that lead to the breakdown of conventional knowledge of optical properties, and vigorous research is being conducted in this field. We are researching a nanoresonator array with PT symmetry. In this article, we describe strange properties shown by this array.

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# Ultralow-capacitance Optoelectronic Converters Using a Photonic Crystal

*Kengo Nozaki, Shinji Matsuo, Takuro Fujii, Koji Takeda, Eiichi Kuramochi, Akihiko Shinya, and Masaya Notomi*

**Abstract**

The fusion of optical technology and electronic circuitry is the key to increasing capacity in any type of information processing, but optoelectronic integrated processing on a chip requires compact and energy-efficient photodetectors (optical-to-electrical (OE) converters) and optical modulators (electrical-to-optical (EO) converters). This article introduces such OE/EO converters that are implemented using a photonic crystal nanostructure and thus feature low capacitance and an extremely low energy cost.

*Keywords: photonic crystal, photodetector, optical modulator*

## 1. Introduction

Optical technology has played an important role in the optical transmission of information in telecommunication and data communication. Consequently, there is currently a demand for optical technology for communication over ultrashort distances (millimeter order) within computing chips and for the computational processing itself [1]. There is thus a need for combining optical technology with mature complementary metal-oxide semiconductor (CMOS) integration technology, and recent research on the fabrication and integration of small optical elements on silicon substrates has been vigorous. However, conventional optical elements, and particularly optoelectronic converters such as optical transceivers, are large and consume large amounts of energy. Therefore, cost-performance is significantly low when such elements are connected to CMOS circuits for on-chip computation applications, so a fundamental change in the elemental devices such as photodetectors (optical-to-electrical (OE) converters) and optical modulators (electrical-to-optical (EO) converters) is needed.

Since most optoelectronic conversion devices include semiconductor p-i-n (p-type, intrinsic, n-type semiconductors) junctions and metal electrodes, the devices themselves have a certain capacitance component. In the case of a photodetector (PD), absorption of light produces a charge ($Q$) on its capacitance ($C$), and a voltage ($V$) is generated for driving the electronic circuit. Although there are various operating principles for a modulator, one involves modulating light by applying voltage to produce a charge ($Q$) on capacitance ($C$) to create an electric field within the structure. In any case, with the relationship $Q = CV$, the required charge $Q$ can be reduced by lowering the capacitance and operating voltage of the device, thus reducing energy consumption. For that purpose, it is necessary to restrict the light to as small an area as possible to enable a strong interaction of light and material. An effective means of achieving this is to use a nanostructure. At NTT, we have succeeded in developing PDs and modulators that can operate with low latency and extremely low capacitance by combining the nanostructure known as a photonic crystal (PhC) with an indium phosphide (InP) semiconductor, a material that has been important in the manufacture of optical communication devices, for which NTT has excellent fabrication technology.

## 2. Photonic-crystal photodetector (PhC-PD)

Conventional PDs incorporate a transimpedance amplifier (TIA) to generate the voltage required by

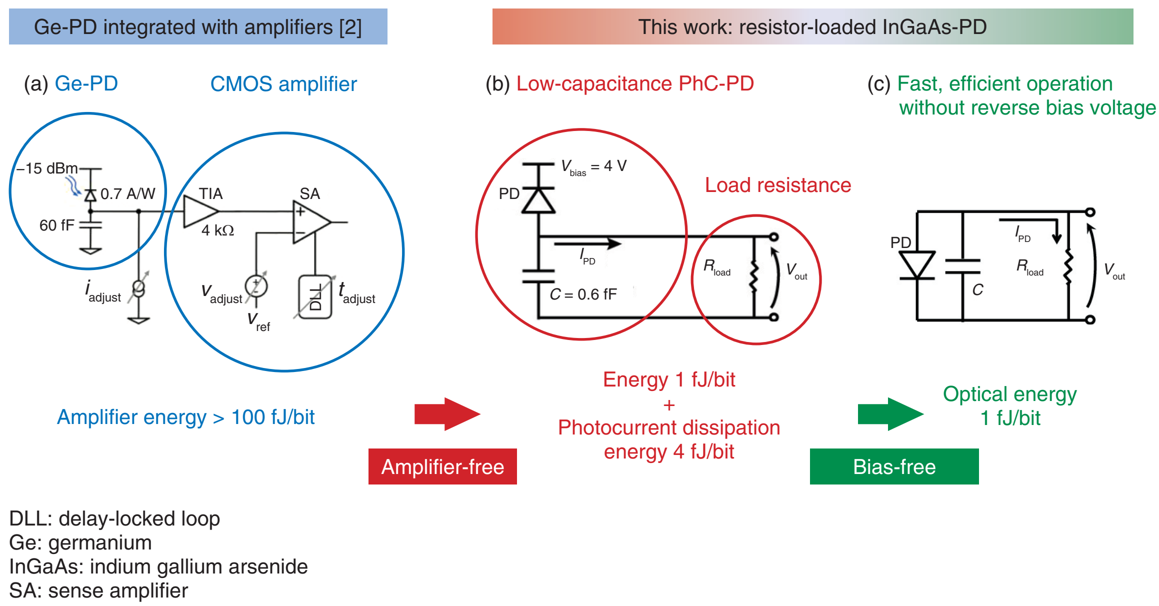
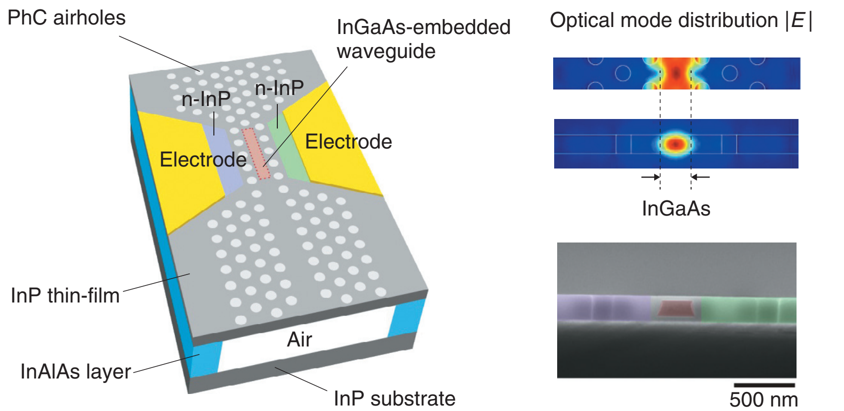



Fig. 1.   Low-energy receiver configuration with low-capacitance photodetector.

the electronic circuit after the photocurrent $I_{pd}$ is produced by light absorption (**Fig. 1(a)**) [2]. However, such devices have major problems when there is dense integration on chips, including high energy consumption on the order of 100 fJ/bit, as well as having a large footprint and delay. Structural simplification can be considered for PDs that are more energy-efficient, and one approach is to connect a high load resistance $R_{load}$ to the PD for a simple configuration that performs light-to-voltage conversion, where the generated voltage is given by $V = I_{pd}R_{load}$ (**Fig. 1(b)**). In this case, there is a trade-off in that the light-to-voltage conversion efficiency is proportional to the load resistance $R_{load}$, but the operating band is inversely proportional to the $RC$ time constant, so this approach is not feasible for conventional devices. To achieve high performance in both aspects at the same time requires reduction of the device capacitance $C$, and if that problem can be solved, an amplifier-free PD may be possible. At NTT, we are working toward developing such a PD by using a PhC nanostructure [3].

The PhC-PD structure is illustrated in **Fig. 2(a)**. The two-dimensional array of airholes that constitute the PhC strongly confine light within the waveguide because of the periodicity of the large refractive index difference, so various kinds of optical devices can be made smaller. The key steps in the fabrication of PDs are the embedding of an indium gallium arsenide (InGaAs) light absorption layer in an InP thin-film (250 nm thick) using highly precise semiconductor embedding heterostructure fabrication technology and the formation of a PhC with high positioning accuracy by electron-beam lithography and plasma etching [4]. As shown by the cross-section photograph in **Fig. 2(b)**, a compact light absorber is formed within a PhC waveguide, and the PD is successfully fabricated by forming lateral p-i-n junctions. The strong light confinement in the PhC waveguide provides sufficient light absorption efficiency to enable an optical responsivity of 1 A/W even in an extremely short PD length (1.7 µm) (**Fig. 3(a)**). This structure of a thin-film and short PD length sandwiched between a low-dielectric-constant material (air) makes it theoretically possible to suppress the capacitance of the p-i-n junctions to 0.6 fF (**Fig. 3(b)**). Also, the dynamic characteristics (frequency response in the 28.5-GHz operating band and the eye diagram for a 40-Gbit/s optical signal) reveal that sufficiently high efficiency and high speed are both achieved, even with such an ultrasmall PD (**Fig. 3(c)**).

The performance of various small PDs is compared in **Table 1**. While our PD has about the same high optical responsivity and operating bandwidth as the germanium PDs that are being actively researched based on a silicon photonics platform [5], it also achieves an ultrasmall absorption layer and ultralow capacitance, features contributed by the nanostructure

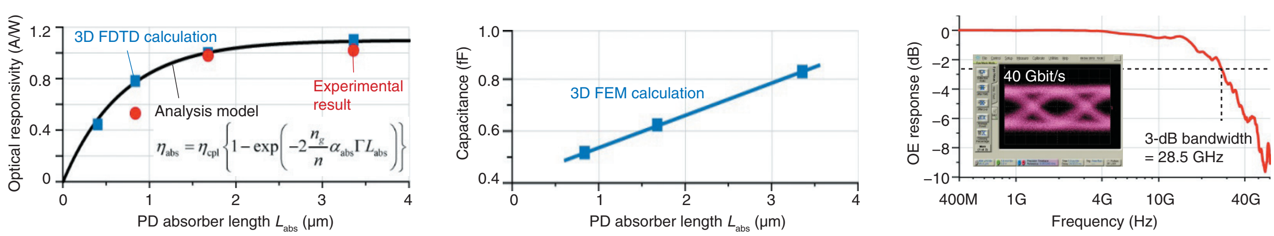



(a) PD structure

(b) Optical mode distribution (upper) and cross-section photograph (lower)

InAlAs: indium aluminium arsenide

Fig. 2. PhC-PD.




(a) Optical responsivity

(b) Simulated capacitance

(c) Frequency response and 40-Gbit/s eye diagram

3D: three-dimensional
FDTD: finite-difference time-domain
FEM: finite element method

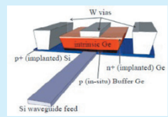
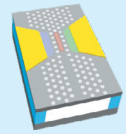
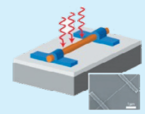
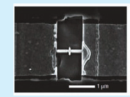
Fig. 3. PD response.

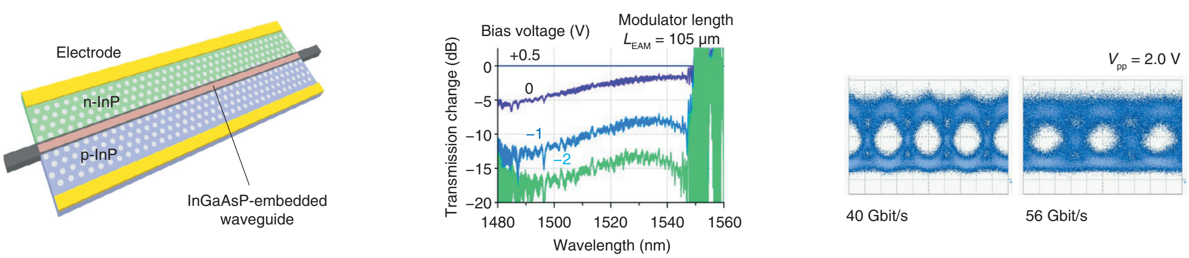
PD. Nanowire [6] and plasmon antenna structures [7] also hold promise for miniaturization, but improvement of light responsivity is currently a problem. We therefore consider the PD described here as the most balanced candidate.

We have investigated light-to-voltage conversion with a circuit in which our PD was connected to a kΩ-order load resistor. Measurements of the voltage generated at the load resistor revealed high conversion efficiency of up to 4 kV/W, which is similar to or higher than that achieved with a PD that integrates an amplifier. Although the operating bandwidth is limited to several gigabits per second because of the parasitic capacitance of the metal wiring, the operation at 40 Gbit/s is possible when considering the theoretical PD capacitance of 0.6 fF. Photodetection while connected to such load resistance can be considered a step towards an amplifier-free photoreceiver.

We have also recently discovered the possibility of achieving a bias-free PD. Conventional PDs apply an external reverse bias voltage to the p-i-n junctions for fast response. In that case, however, the power consumption corresponds to the product of the photocurrent and the bias voltage. Ideally, PD operation without bias is desirable, and if it can be achieved together with the amplifier-free operation described above, an extremely low-power-consumption PD that operates on optical energy alone can be expected (Fig. 1(c)) [8]. The problem is that when a high load resistance connection is considered, a forward voltage that

Table 1. Comparison of small PDs.

| | Ge waveguide [5] | This work (InP PhC) | Nanowire [6] | Plasmon nanoantenna [7] |
|---|---|---|---|---|
| |  |  |  |  |
| Absorber volume | 3.1 μm³ | 0.11 μm³ | 0.05 μm³ | 0.0007 μm³ |
| Capacitance | 2–8 fF | 0.6 fF | <<1 fF | <<1 fF |
| Responsivity | 0.8 A/W | 1 A/W | 0.01 A/W | 0.0001 A/W |
| Bandwidth | 45 GHz | 28 GHz | N/A | N/A |




(a) Modulator structure

(b) Transmission spectral change with bias voltage

(c) Eye diagram for intensity-modulated light

InGaAsP: indium gallium arsenide phosphide

Fig. 4. PhC optical modulator.

corresponds to the generated voltage is applied to the PD. Although that is in the same current-voltage operating region as solar cells, high-speed operation on the gigahertz order is not expected because high-speed carrier transport is difficult.

With our PD, however, high-speed operation can be expected even under forward voltage because of the efficient absorption and carrier extraction in the depletion layer that are enabled by the narrow waveguide cross-section (Fig. 1(b)). Actually, operation at a high speed of 20 Gbit/s and high responsivity has been observed, even with a forward voltage of +0.4 V applied. This feature is not seen with conventional PDs. These results suggest the feasibility of an extremely small, energy-efficient photoreceiver that operates on ultralow optical energy of about 1 fJ/bit.

## 3. PhC optical modulator

Optical modulators, which do the reverse of PDs by converting an electrical signal to an optical signal, must also be made small and energy-efficient for implementation in photonic integrated circuits. For the optical pass-gate logic circuit that we propose, low latency is essential, and hence, a short length is required [9]. NTT has also fabricated a small electro-absorption modulator (EAM) that employs PhC fabrication technology in the same way as the PD described above (**Fig. 4**) [10]. The embedded layer is composed of InGaAsP (indium gallium arsenide phosphide), which has an absorption wavelength of 1.45 μm. Applying a reverse voltage produces the Franz-Keldysh effect*, increasing light absorption to modulate the output light intensity. In the experiment, high-speed optical modulation such as the eye diagram for 40-Gbit/s and 56-Gbit/s signals was obtained.

* Franz-Keldysh effect: An increase in the optical absorption and refractive index of a semiconductor caused by a shift in the absorption spectrum toward longer wavelengths when an electric field is applied.

Research has been done on EAMs that use SiGe (silicon germanium) or other such core material on a silicon substrate for application as on-chip optical modulators [11]. Such devices require a high reverse bias voltage (> 4 V), and the high energy dissipation (7 fJ) due to the photocurrent from absorption and the bias voltage has been a significant bottleneck. Our PhC EAM averts that problem because it operates on a low reverse bias voltage (–0.2 V), significantly reducing energy dissipation (0.2 fJ). At the same time, the low charging energy of 1.6 fJ/bit due to the device capacitance (13 fF) and signal voltage (0.7 V) results in an operating energy of 1.8 fJ, which is much lower than that for conventional devices. In practice, incident light energy is also required for optical transmission, so in the future we will need to conduct an overall evaluation in an optical transmission system that takes the optical energy required on the PD side into account.

## 4. Outlook

We have described optoelectronic conversion at an overwhelmingly lower operating energy than is possible with conventional technology and is achieved with small PDs and EAMs that employ PhC nanostructures. We can expect that future development will go beyond these single devices and achieve multi-functionality through integration. For example, the short-distance optical link for transmitting the signal between the modulator and the receiver is promising for application to high-speed data sharing within many-core chips. The O-E-O optical wavelength converter fabricated by close integration of the PD and modulator for transferring the optical signal to a different wavelength light is also possible. The extremely low operating energy compared to conventional devices enabled by the technology described here is a major differentiating factor, and application to on-chip optical signal routing and optical computing by combining the functions can be expected.

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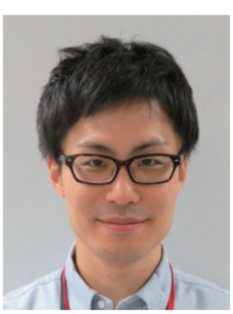

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# Toward Application of Plasmonic Waveguides to Optical Devices

*Masaaki Ono, Hideaki Taniyama, Eiichi Kuramochi, Kengo Nozaki, and Masaya Notomi*

## Abstract

The size of a plasmonic waveguide is not limited by the optical wavelength. This enables plasmonic waveguides on the order of several tens of nanometers in length, which is not possible with dielectric waveguides, and exceptionally strong light confinement and efficient interaction with nanomaterials that have various unique properties become possible. However, such waveguides are not easily introduced in optical integrated circuits, so a three-dimensional plasmonic mode converter is required.

*Keywords: plasmonic waveguide, nanostructure fabrication, photonic integrated circuits*

## 1. Enhancing interaction with plasmonic waveguides and related issues

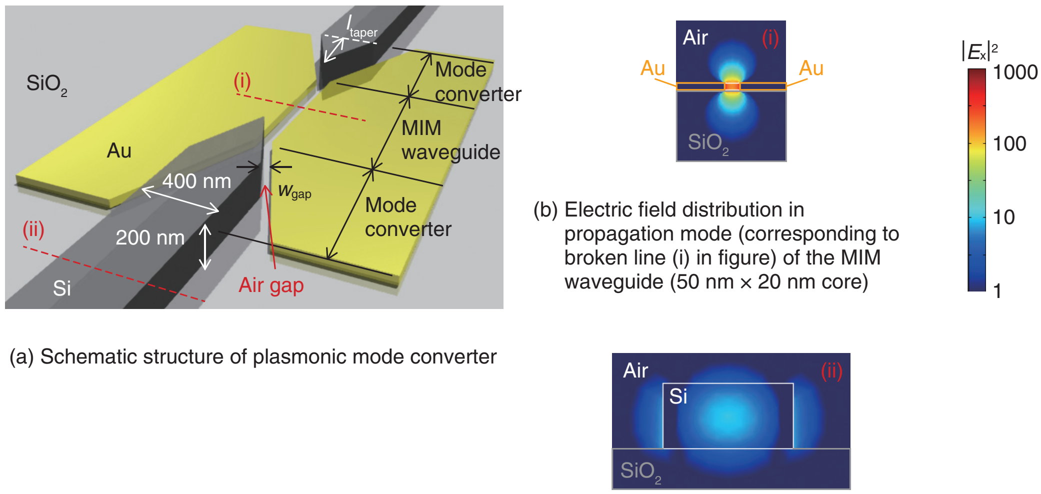
The use of nanomaterials*1 that have unique properties and functions has been increasing recently. The interaction between light and materials strongly affects device characteristics and is thus very important in implementing useful optical devices. However, the size scale of nanomaterials is small compared to optical wavelengths, so efficient interaction between light and nanomaterials is not easily achieved. To address this issue, NTT has been studying coupling systems for nanomaterials and photonic crystal nanostructures that are capable of strong light confinement, and we are developing the nanowire laser described in the article, "Compound Semiconductor Nanowire Laser Integrated in Silicon Photonic Crystal" [1].

However, optical elements that are conventionally used in optical integrated circuits, including photonic crystals, are generally based on dielectric materials. For that reason, the limit on the area of light confinement is determined by the optical wavelength. NTT is taking a different approach to address this issue by investigating optical device applications of plasmonic waveguides, which are not limited in size by the optical wavelength. Plasmonic waveguides can be extremely small, on the order of tens of nanometers. Our objective is to use these features to enhance the interaction of light and nanomaterials and realize the development of unprecedented optical devices.

Plasmonic waveguides consist of metal and dielectric materials (semiconductors or insulators). Light propagates at the interface of the two materials as surface plasmons that accompany an electromagnetic wave. The electromagnetic wave is localized near the interface as near-field light, making it possible to confine the light in a region that is smaller than the light wavelength. Plasmonic waveguides can have various structures as combinations of metal and dielectric materials, but NTT has adopted the metal-insulator-metal (MIM) structure for research. In an MIM waveguide, light is concentrated in the insulator that serves as the core, so smaller cores produce stronger light confinement and a waveguide that has a small propagating mode. The core size of an MIM waveguide can thus extend into the deep-subwavelength regime*2, which is not possible with dielectric waveguides. That enables efficient interaction between light and nanomaterials, which holds promise for achieving optical devices that have unprecedented

*1 Nanomaterials: Two-dimensional materials such as graphene, nanowires, or quantum dots with nanoscale dimensions.

*2 Deep-subwavelength regime: An area that is very small compared to the wavelength; the criterion used here is a waveguide core cross-section area smaller than $(\lambda/n)^2/1000$.




(a) Schematic structure of plasmonic mode converter

(b) Electric field distribution in propagation mode (corresponding to broken line (i) in figure) of the MIM waveguide (50 nm × 20 nm core)

(c) Electric field distribution in propagation mode (corresponding to broken line (ii)) on Si-wire waveguide

Au: gold
$SiO_2$: silicon dioxide

Fig. 1. Schematic structure and propagation mode.

characteristics.

However, deep-subwavelength MIM waveguides are not easily incorporated into optical integrated circuits. All plasmonic waveguides, including MIM waveguides, normally have associated absorption loss due to the metal. That loss becomes prominent when the core is small, and the loss can rise to about 1 dB/μm for cores in the deep-subwavelength regime, making it difficult to construct an optical integrated circuit with MIM waveguides alone. We therefore consider that the ideal configuration is to use MIM waveguides only for functional devices such as the optical detectors and modulators, while using conventional dielectric waveguides such as Si (silicon) waveguides for long-distance signal propagation. Implementing such a configuration requires highly efficient coupling of dielectric waveguides and deep-subwavelength MIM waveguides. However, the shape and size of the propagating modes of the deep-subwavelength MIM waveguide and the dielectric waveguide differ greatly, so a highly efficient plasmonic mode converter is needed.

## 2. Design of plasmonic mode converter

NTT has been working on a highly efficient plasmonic mode converter for conversion between a deep-subwavelength MIM waveguide that uses gold for the metal and air as the insulator, and a Si-wire waveguide (**Fig. 1(a)**) [2]. The propagating modes for the two types of waveguides differ greatly in size and shape (**Fig. 1(b)**, **(c)**), so the mode conversion must involve a size reduction in both the lateral and vertical directions, which means that three-dimensional (3D) mode conversion is necessary. Lateral mode conversion between an MIM waveguide and a Si-wire waveguide has been reported previously [3–5], but those methods involved conversion between waveguides of about the same height and performed only two-dimensional (2D) mode conversion by compression only in the lateral direction with a laterally tapered structure. The use of a structure that is tapered in both the vertical and lateral directions has also been proposed as a means of 3D mode conversion [6], but the complexity of the fabrication process makes that approach impractical for application to optical integrated circuits.

NTT therefore investigated a structure that can achieve highly efficient mode conversion for waveguides of greatly different heights with only a 2D tapered structure. We discovered that efficient mode conversion between a deep-subwavelength MIM waveguide and a Si-wire waveguide can be achieved by introducing a small air gap between the Si and the

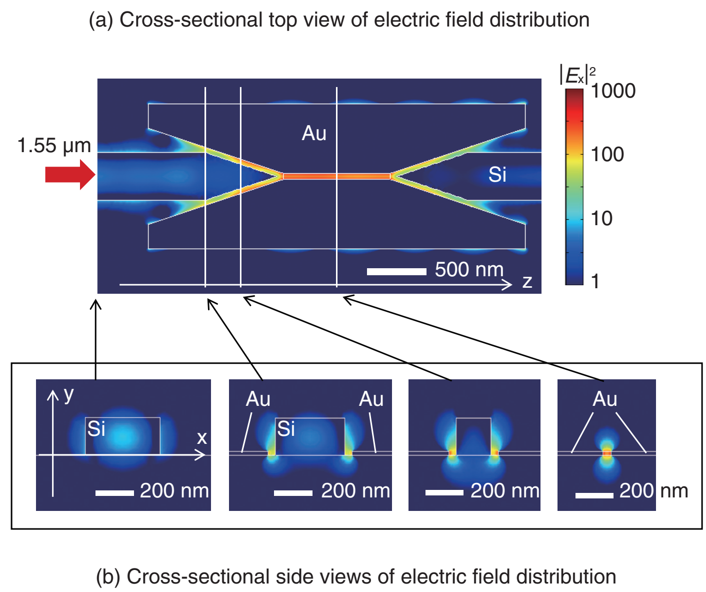



Fig. 2. Calculated electric field distribution in the plasmonic mode converter.

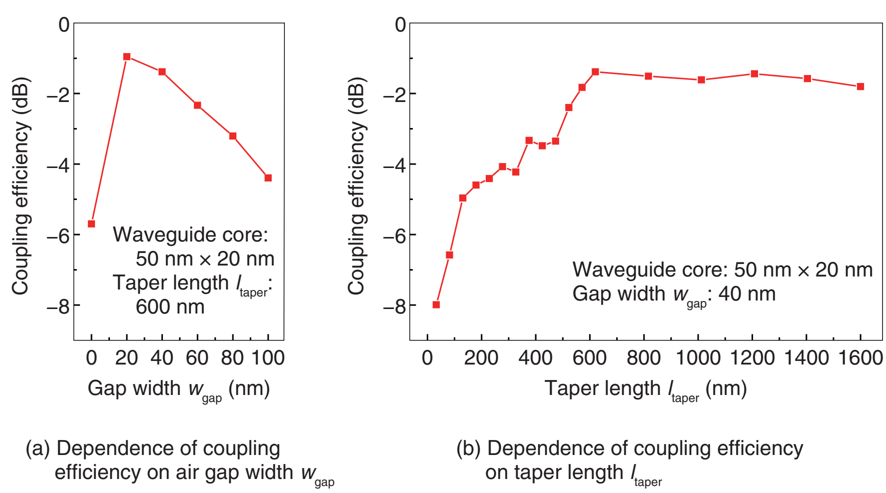



Fig. 3. Calculated coupling efficiency of plasmonic mode converter.

metal.

The calculated propagating mode of 1.55-µm input light in a Si-wire waveguide, mode converter, and MIM waveguide is shown in **Fig. 2**. We can see from the figure that the side lobes of the propagating mode of the Si-wire waveguide are attracted to the metal parts placed near the Si waveguide, and there is coupling with the MIM waveguide that differs greatly in height via the air gap. The coupling efficiency depends on structure parameters such as the taper length $l_{taper}$ and the air gap width $w_{gap}$ (Fig. 1(a)).

The coupling efficiency for various values of the air gap width is shown in **Fig. 3(a)**. We can see from the figure that good coupling efficiency is not obtained without the air gap, but introducing a small air gap of about 20 nm dramatically improves the coupling efficiency. However, the coupling efficiency gradually decreases as the air gap width increases, and for a width of 100 nm, the coupling efficiency is the same as without the air gap. Furthermore, without the air gap, most of the propagating light is absorbed or scattered by the metal part of the mode converter. When the gap is wide, on the other hand, the side lobes of the Si-wire waveguide cannot be sufficiently attracted by the metal, and most of the light is scattered. We can thus see that a very small air gap is important to achieve efficient mode conversion.

The taper length is also an important parameter in determining the coupling efficiency. The coupling efficiency for various taper length values is shown in **Fig. 3(b)**. As the taper length increases, the coupling efficiency increases to reach a maximum in the vicinity of 600 nm and then decreases for longer taper lengths. Although longer taper lengths generally reduce loss in mode conversion, absorption by the metal reduces the coupling efficiency in a plasmonic mode converter because of loss due to absorption by the metal. The result obtained here shows that highly efficient mode conversion (about –1 dB) between a deep-subwavelength MIM waveguide (50 nm × 20 nm core) and a Si-wire waveguide (400 nm × 200 nm core) is possible with a mode converter that has a taper length of 600 nm and an air gap width of 20 nm. These predicted characteristics are very good in terms of coupling efficiency, converter length, and the reduction in waveguide core size compared to previously reported plasmonic converters of the same type.

## 3. Fabrication and evaluation of plasmonic mode converter

The fabricated device comprises a Si-wire waveguide, a plasmonic mode converter, and an MIM waveguide. The Si-wire waveguide and the Si part of the plasmonic mode converter are fabricated on a silicon-on-insulator (SOI) substrate[*3] by electron beam lithography and etching, and then the metal parts are formed by electron beam lithography and evaporation. This series of processes uses conventional nanostructure fabrication techniques and is therefore compatible with the processes used for other Si photonic devices. This enables integration with other optical devices on the same substrate, which is very important for device integration.

A scanning electron microscopy image of the fabricated sample shows that the mode converter was fabricated with precise positioning (**Fig. 4**). We have successfully fabricated a plasmonic mode converter with an air gap width of 40 nm for an MIM waveguide that has a core size of 50 nm × 20 nm. Although the process described here may seem simple, it is not easy because of the positional accuracy required for fabrication at a scale of 20 nm or less. This process is possible with NTT's high-level nanostructure fabrication techniques.

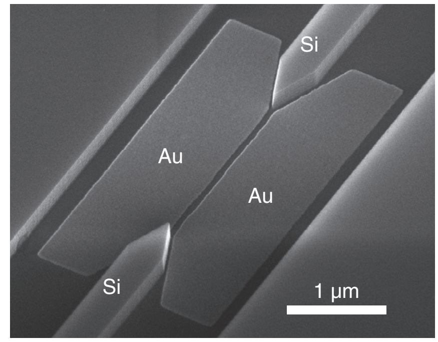


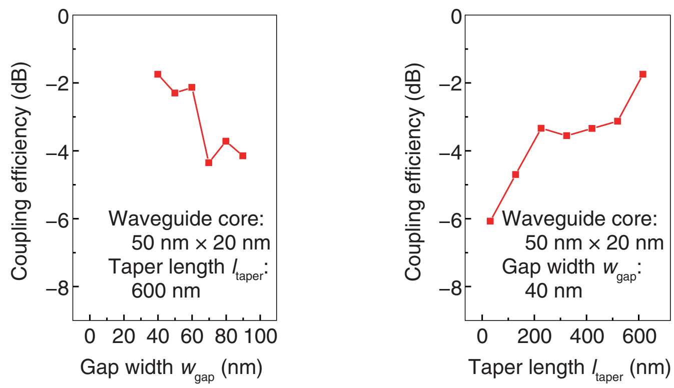

Fig. 4. Scanning electron microscopy image of the fabricated sample.

The coupling efficiency of a fabricated mode converter for an MIM waveguide that has a core size of 50 nm × 20 nm is shown in **Fig. 5**. The coupling efficiency in the fabricated mode converter is as high as –1.7 dB when the air gap width is 40 nm and the taper length is 600 nm, showing good agreement with the calculated value (–1.4 dB). The dependence of coupling efficiency on air gap with and taper length predicted from the calculation results is also exhibited for various air gap width and taper length values. We have achieved highly efficient mode conversion (–1.7 dB) between a deep-subwavelength MIM waveguide (50 nm × 20 nm core) and a Si-wire waveguide (400 nm × 200 nm core) with a mode converter that has a taper length of 600 nm and an air gap width of 40 nm. Furthermore, the core size of the connected MIM waveguide is $(\lambda/n)^2/2000$ ($\lambda$: wavelength; $n$: refractive index). Previously, the smallest core size of the connected lateral MIM waveguide was $(\lambda/n)^2/120$ [3], so these results indicate that we achieved a large reduction in the waveguide core size. Achieving highly efficient mode conversion with a taper length of less than 1 μm is also important for reducing the device footprint.

## 4. Future development

We have described here NTT's efforts to introduce the size advantage of plasmonic waveguides to

*3 SOI substrate: A substrate structure in which a $SiO_2$ (silicon dioxide) layer is sandwiched between Si layers. The thin surface layer of Si is used as a waveguide.




(a) Dependence of coupling efficiency on air gap width $w_{gap}$

(b) Dependence of coupling efficiency on taper length $l_{taper}$

Fig. 5. Coupling efficiency of fabricated plasmonic mode converter.

optical integrated circuits and also touched on the merits and problems of plasmonic waveguides. Development of the first highly efficient 3D mode converter enables introduction of waveguides that have a deep-subwavelength core to optical integrated circuits. In addition to reducing the size of conventional devices, this achievement paves the way for the potential implementation of unprecedented new devices in combination with nanomaterials that have unique properties.

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# Compound Semiconductor Nanowire Laser Integrated in Silicon Photonic Crystal

*Masato Takiguchi, Atsushi Yokoo, Kouta Tateno, Guoqiang Zhang, Eiichi Kuramochi, and Masaya Notomi*

**Abstract**

Compound semiconductor nanowires were integrated in silicon photonic crystals to form nano-cavities in arbitrary places, achieving the first nanowire laser that oscillates continuously at communication wavelengths. High-speed modulation at 10 Gbit/s was demonstrated. This laser is the ultimate heterostructure material hybrid device, having gain material only within the cavity.

*Keywords: photonic crystal, nanowire, nanolaser*

## 1. Fusion of heteromaterials with nanophotonics

The integration of compound semiconductors on silicon is very important for optoelectronic devices for optical interconnection, optical computing, and on-chip devices. Wafer bonding is generally used to bond compound semiconductors and silicon, which are dissimilar materials. Although that method enables the integration of heteromaterials such as compound semiconductors on silicon, it involves problems such as the difficulty of bonding and the difficulty of obtaining the utmost optical function of the optical elements, which themselves are compounds, due to overheating.

In our work, we have adopted a configuration in which high-performance optical elements made of optically low-loss silicon are prepared and compound semiconductor nanowires are placed as gain parts in the necessary locations. This fabrication process does not involve heating, so damage due to overheating does not occur. Moreover, the optical loss is low because the device is based on silicon. Another advantage is that the environmental impact is very low because there is minimal use of the compound semiconductor. Accordingly, this device can be considered an ideal heteromaterial hybrid optical device.

The device described here is a new nanolaser with a hybrid structure comprising silicon photonic crystal and a compound semiconductor. The nanowire is a one-dimensional structure that can be fabricated on a substrate in large numbers at one time. The nanowire can serve various purposes, including a quantum well, quantum dot, and p-i-n (p-type, intrinsic, n-type semiconductors) junction, which can be controlled by switching the gas that is supplied during growth. However, the nanowires themselves are too small to efficiently provide strong light confinement. Silicon photonic crystal, on the other hand, can provide very efficient light confinement without optical loss, but silicon is an indirect transition semiconductor and cannot itself emit light.

In our work, we fabricated a nanolaser by introducing an indium arsenic phosphide and indium phosphide (InAsP/InP) nanowire quantum well into a silicon photonic crystal to form a micro-cavity (**Fig. 1**). This combination can be considered a landmark structure that compensates the weak light confinement of the nanowire and the absence of light emission by the photonic crystal with the light emission of the nanowire and optical confinement of the photonic crystal. This type of structure was used to demonstrate the world's first nanowire laser that operates

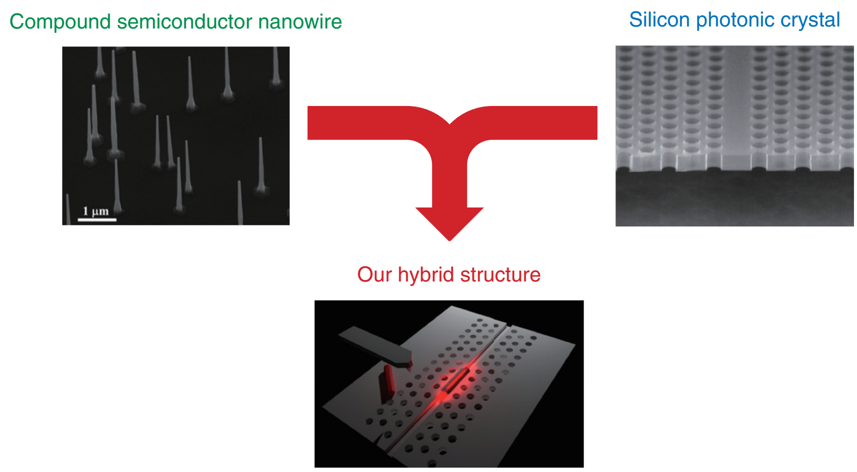


Fig. 1. Conceptual diagram of hybrid structure of nanolaser.

continuously in the communication wavelength band [1].

## 2. Fabrication of hybrid nanowire devices

This device is fabricated by transferring nanowires onto a silicon substrate and then moving them onto the photonic crystal with the probe of an atomic force microscope (AFM)*1 [2]. This method makes it possible to place any nanomaterial freely on a photonic crystal or other optical circuit.

The nanowires used here were fabricated by the VLS (vapor-liquid-solid) method using metal-organic vapor phase deposition [3]. The InP nanowires are grown from gold particles 40 nm in diameter that are dispersed on an InP (111) B substrate. One hundred InAsP layers are formed internally by supplying arsenic for a short time during the nanowire growth.

The light emission characteristic of the nanowire quantum well has a spectrum peak in the 1.3-µm band, and the polarization direction of the emitted light is controlled to be perpendicular to the nanowires. The nanowires are 2.4-µm long and have an average diameter of 114 nm (82 nm minimum and 144 maximum). The silicon photonic crystal has a diameter of 200 nm, a lattice constant of 370 nm, a trench width of 150 nm, and a depth of 115 nm. The nanowires are placed in grooves in the prefabricated photonic crystal. The photonic band at the location where the nanowires are placed is shifted towards shorter wavelengths, and the optical characteristics are changed only at those locations. Because light of particular wavelengths is confined in those locations, cavities are formed. Such photonic crystal cavities are called mode gap cavities (**Fig. 2(a)**).

The polarization of the cavity mode is consistent with the polarization of the nanowire itself, so light can be extracted efficiently. From simulations of the light intensity when nanowires are placed in the photonic crystal (**Fig. 2(b)** and **(c)**), we can see clearly that oscillators are formed, and light is strongly confined at the nanowire locations. Because cavities are formed in the optical waveguide by simple placement of nanowires, this is a very convenient structure.

## 3. Nanowire laser

Next, we investigated the oscillation of the laser produced by the nanowires. A conceptual diagram of the measurement and the measured spectra before and after oscillation produced by placement of the nanowires on a photonic crystal are presented in **Fig. 3(a)** and **(b)**. Light emission was measured using the microscopic photoluminescence method. The device was illuminated with light to excite the nanowires, and the light emitted by the nanowires was measured with a detector. The specimen was cooled to a temperature of 4K. The emission spectrum is steep, as seen in Fig. 3(b). That is the spectrum of the nano-oscillator induced in the photonic crystal by the nanowire. Furthermore, when the

*1 AFM: An instrument that can visualize the surface of a specimen by using a sharp probe attached to the tip of a cantilever to scan the surface and measure the inter-atomic force acting between the probe and the specimen surface. In the process reported here, the scanning function of the probe is used to position nanowires.

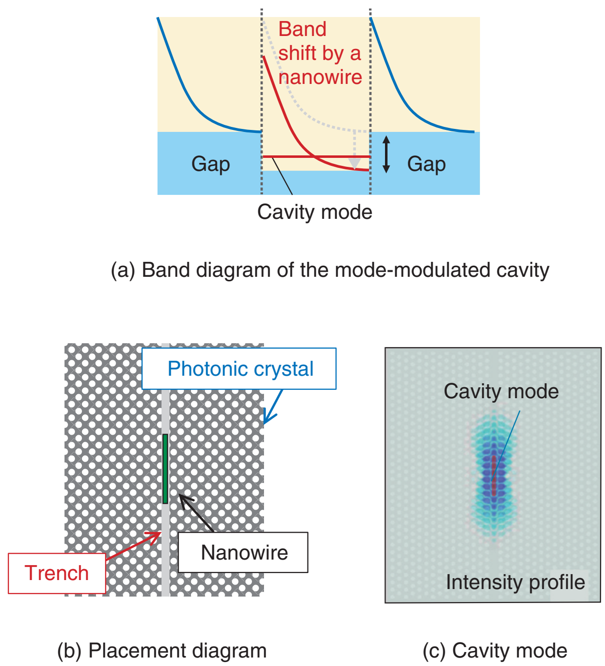


Fig. 2. Nanowire induced photonic crystal cavity.

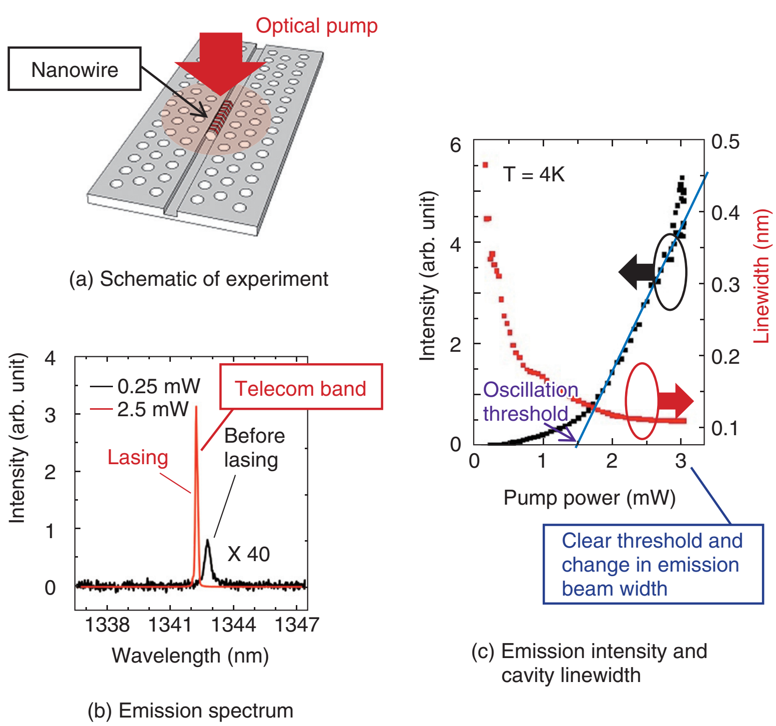


Fig. 3. Measurement of nanowire laser.

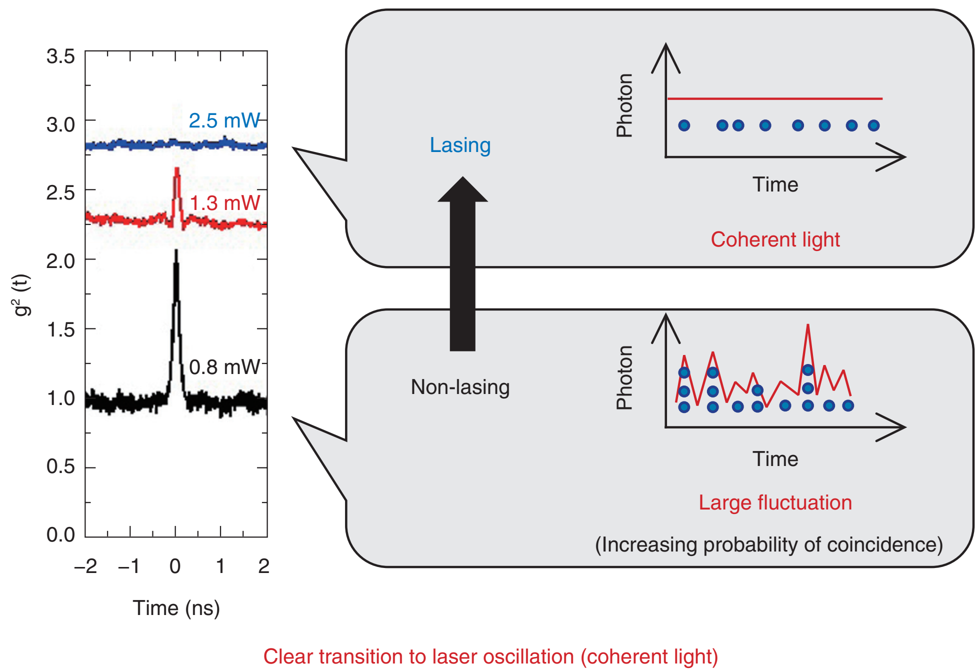


Fig. 4. Photon correlation measurement of nanowire laser.

excitation power is high, the laser oscillates with sharp increases in emission intensity. We investigated this effect in detail by measuring the nanowire emission while varying the excitation power (**Fig. 3(c)**) (light-in, light-out (L-L) measurement). The dependence of the emission and the spectral linewidth of the cavity on the excitation strength is shown in the figure. Generally, the emission sharply increases, and the cavity spectrum width becomes narrow when the laser oscillates, and the result presented here exhibits that behavior. The emission becomes strong at the excitation power of 0.15 mW (the oscillation threshold of the laser), confirming laser oscillation with certainty.

Oscillation of the laser can also be confirmed by investigating photon statistics. Correlation measurements can be used to investigate the time intervals between photons. The light prior to laser oscillation is called spontaneous emission light and is characterized by a large variance in intensity with short time intervals between photons (referred to as *bunching* because the photons are close together). The light after laser oscillation, on the other hand, is called coherent light, because the intensity is stable and there is a uniform distribution of the intervals between photons. The measurements require detection of a photon-level signal, so we used a highly sensitive superconducting single-photon detector[*2] to determine the correlation function ($g^2(t)$). Prior to oscillation, the correlation for this function is at t = 0, and bunching is observed ($g^2(0) > 1$). However, that bunching signal is eliminated once the laser oscillation begins. The effect of change in the excitation power on $g^2(t)$ is that the bunching signal is eliminated and the laser transition occurs (**Fig. 4**). Laser oscillation is confirmed to continue after that point.

Next, we conducted communication experiments with bit signals produced by this laser. The conceptual diagram for the experiment and the input signal, output signal, and eye diagram are presented in **Fig. 5**. The input signal was a 10-Gbit/s pseudorandom pattern produced by a pulse pattern generator. The input light was modulated by an electro-optic modulator, and the signal output from the nanolaser was integrated by the superconducting single-photon detector for measurement. Normally, a sampling oscilloscope and photodetector are used for measurement,

*2 Superconducting single-photon detector: A system that detects photons by using a superconductor with a current bias that is just below the critical current as an optical detector. A photon is detected when the heat of a single photon breaks the superconducting state, increasing the resistance and producing a voltage pulse that is measured. High-speed photons can thus be measured at very high temperatures.

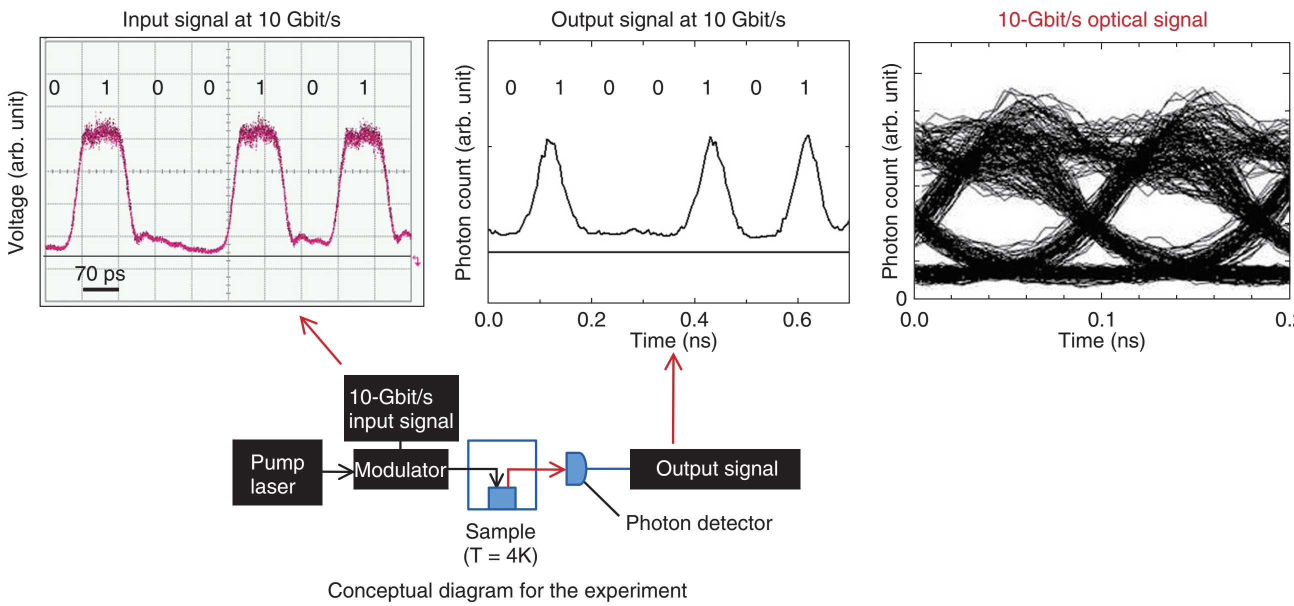


Fig. 5. Modulation measurement of nanowire laser.

but the extremely weak light emitted by the nanolaser is measured in free space, so a highly sensitive detector is used. The light used for excitation has sufficient power to produce laser oscillation. We can see that the obtained waveform is the same as the waveform of the input signal. We analyzed the signal to obtain an eye diagram. The open center of the eye pattern indicates that correct communication of the bit signal is possible.

## 4. Future development

We achieved continuous-wave laser oscillation at communication wavelengths by introducing compound semiconductor nanowires into silicon photonic crystals. We also confirmed that laser oscillation can be evaluated with photon statistics as well as with L-L characteristics. We further confirmed that the laser can be modulated directly at about 10 Gbit/s by modulating the excitation light with a pseudorandom signal. This demonstration of a communication-band nanowire laser and confirmation of modulated operation of a single nanowire laser are world-first achievements.

While the demonstration described here was performed at low temperature, we are aiming for room-temperature operation in the future. The current nanowires and optical confinement are insufficient. Improvement will require thicker nanowires and control of non-emissive re-coupling at the nanowire surface. The structure of the photonic crystal should also be considered. We also plan to fabricate a current injection structure by using nanowires that have a p-i-n structure. In the future, we plan to develop new on-chip devices through on-chip integration of current-injected nanowire lasers, nanowire optical detectors, and nanowire optical modulators.

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# Control of Light with Exceptional Points in Coupled Photonic Crystal Lasers

*Kenta Takata and Masaya Notomi*

**Abstract**

Controlling light in a miniature optical circuit is challenging due to constraints that do not apply to free space or fiber-optic elements. Studies are underway to find ways to overcome such constraints by applying fundamental optical responses of amplification and absorption, which produce exceptional points that cause novel phenomena. These studies form a new and rapidly growing field called parity-time (PT)-symmetric optics and have been attracting a lot of attention. In this article, we describe the research background and the basic concept of PT-symmetric optics. We then introduce NTT's efforts to achieve the ability to control light by using PT symmetry in photonic crystal devices.

*Keywords: integrated photonic circuits, photonic crystals, parity-time symmetry*

## 1. Constraints of optical control in on-chip optical devices

Optical communication is currently at the stage where it is possible to transmit data at speeds on the order of 10 Tbit/s through an optical fiber. It may seem that light can be controlled freely; however, there are limits to the varieties of optical control that are possible in on-chip optical circuits, and there are still problems to be solved for many of the practical applications of these circuits.

The difficulty of optical control arises from the fact that photons have no mass or charge. In other words, it is not possible to control the movements of photons based on conservative forces such as gravity or electromagnetism arising from the energy potential. Therefore, in the range that we normally see, light mainly manifests as electromagnetic (EM) waves. From the Maxwell equation describing the behavior of light, we can derive the property called Lorentz reciprocity (**Fig. 1**). In systems that are stationary in time and exhibit a linear response to EM waves, this means that scattering matrices showing their EM input-output relationship will have a symmetrical form. In other words, the system's optical path has exactly the same transmittance (or mode conversion rate) in one direction as that in the opposite direction, and there is no anisotropy. In photonics, therefore, it is not even straightforward to create transistors and diodes (optical isolators), which are common in electronics.

Currently, purely on-chip photonic components, for which technologies have been well established, include waveguides, lasers, intensity and phase modulators, detectors, and interference switches. These components can generally achieve most basic functions such as the generation and detection of coherent light, the control of intensity and phase (modulation), and the switching of optical paths. As long as they are in static operations, they will not significantly violate the abovementioned Lorentz reciprocity. To perform optical control beyond these constraints, the use of other well-known phenomena such as magneto-optic effects and nonlinear optical effects can be considered. However, particularly in microphotonics and nanophotonics, such effects are generally restricted due to the small device sizes and low-intensity input light available. Moreover, there are severe requirements of integration and processing techniques for heterogeneous materials. As a result, efforts to develop

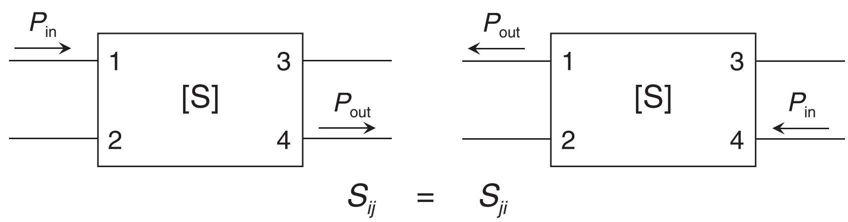



Fig. 1. Lorentz reciprocity for propagating modes. [S] = [$S_{ij}$]: the scattering matrix, which relates the input EM waves to the output EM waves, in terms of their amplitudes and phases; $i$, $j$: channel indices. In the case of single-channel input power $P_{i,\text{in}}$ at the $i$th channel, the output power $P_{j,\text{out}}$ at the $j$th channel is $P_{j,\text{out}} = |S_{ji}|^2 P_{i,\text{in}}$.

devices of this sort are still at the research stage.

In contrast, the field of parity-time (PT)-symmetric optics or exceptional point optics has been rapidly developing, partly because it is based on the prospect of achieving new optical functions by making use of existing technologies.

## 2. Novel optical phenomena based on PT symmetry (exceptional points)

The concept of PT symmetry was first proposed in 1998 by Carl Bender of Washington University (Missouri, USA) and Stefan Boettcher, who is currently at Emory University (Georgia, USA) [1]. This work was originally aimed at expanding the theoretical framework of quantum mechanics.

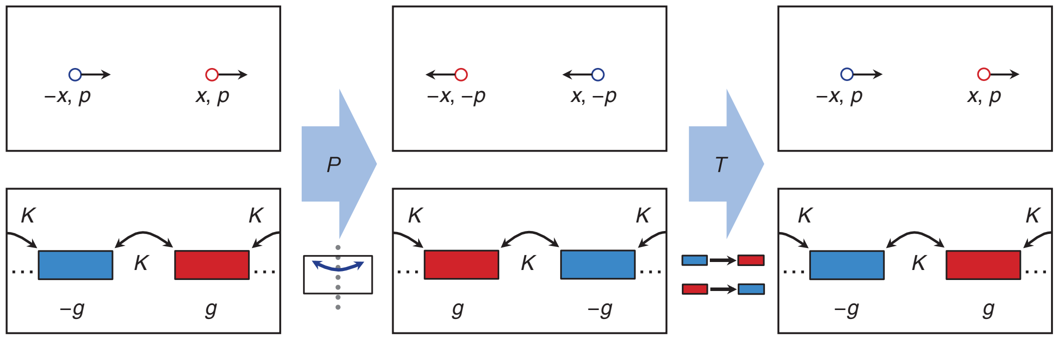
The P in PT symmetry represents space inversion, which is the operation of reversing coordinates around a certain origin in the physical system under consideration. Thus, this operation changes an object's coordinate (position operator) from $x$ to $-x$ and its momentum (momentum operator) from $p$ to $-p$ (**Fig. 2(a)**).

The T in PT represents time inversion, which is the operation of reversing the direction in which time flows. Thus, it also inverts the sign of an object's momentum. In addition, for systems interacting with the external environment (reservoir), an increase in the number of particles (signed rate $+g$) changes to a decrease ($-g$), and vice versa. In PT symmetry, when these two operations are performed simultaneously, the system behaves in the same way as before the operation. In other words, it is a symmetry that represents invariance in the energy operator (Hamiltonian).

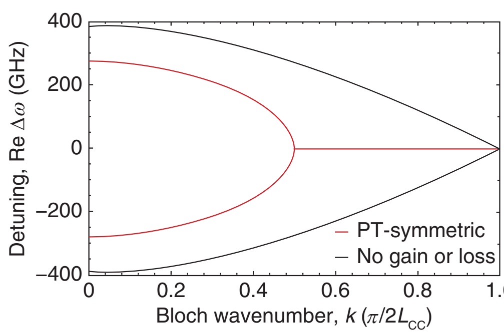
In standard quantum mechanics, closed systems are primarily handled using Hermitian Hamiltonian matrices and the Schrödinger equation. Meanwhile, if we introduce an increase or decrease in the number of particles because of the external environment (non-Hermitian term), then imaginary components arise in energy eigenvalues. In other words, this leads to the inconsistent result in quantum theory, where the energy is not an observable quantity. However, under PT symmetry, this sort of local change in the number of particles can be balanced in the entire system, so the energy eigenvalues can be maintained as observable real quantities.

It is not easy to verify this concept experimentally in quantum systems that rely on the precise manipulation of small numbers of particles. However, the observation in 2008 that an analogy to PT symmetry is possible in optical systems based on classical electromagnetism [2] resulted in an explosion of research on PT-symmetric optics. This is because it was originally recognized in optics studies that gain by stimulated emission and loss in absorption media are natural effects. Furthermore, we can approximate the behavior of light propagating in a material with a thickness on the order of one wavelength (paraxial beam) using the Schrödinger equation. Thus, we can argue that EM waves can also exhibit properties analogous to PT symmetry, which was originally considered in the context of the quantum mechanical wavefunction.

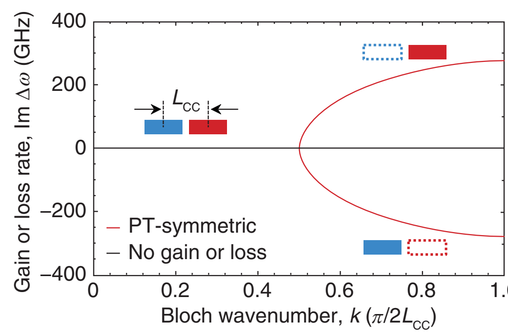
As a result of this groundbreaking work, it was recognized that a PT-symmetric optical system can be implemented as a periodic optical system consisting of amplifying (gain) and absorbing (loss) media with balanced rates ($\pm g$) such that the system's complex refractive index distribution corresponds to $n(r) = n^*(-r)$; that is, the real and imaginary parts of the refractive index are respectively given by even and odd functions with respect to a certain origin. Potential examples of such systems include coupled resonators, coupled waveguides, modulating waveguides with vapor-deposited metal on part of a single waveguide, and fiber ring resonator systems. It has been




(a) PT symmetry. Top: schematic of a particle system. Bottom: coupled resonator system.
Red: amplification. Blue: absorption.




(b) Real part of band structure in a PT-symmetric coupled-resonator array




(c) Imaginary part of the same band structure

Fig. 2. PT symmetry and exceptional points.

shown that these systems exhibit a number of novel phenomena originating from the exceptional point (PT phase transition point) as described below.

Examples are shown in **Fig. 2(b)** and **(c)** of bulk band structures*1 for the real and imaginary parts of the eigenfrequency detuning $\Delta\omega$ of a PT-symmetric coupled-resonator system (taking the identical resonant frequency of each resonator as the reference frequency, i.e., $\Delta\omega = 0$). Here, the system's positive imaginary part $\mathrm{Im}(\Delta\omega) > 0$ is regarded as a net gain, and $\mathrm{Im}(\Delta\omega) < 0$ means a net loss of the eigenstates for each Bloch wavenumber, $k$, in the unit of $\pi/(2L_{CC})$, where $L_{CC}$ is the spatial interval between the cavities. As shown in the lower part of Fig. 2(a), this system has two resonators as periodic units (unit cells). In the absence of gain and loss, the real bands are in the form of halved cosine curves (black lines in Fig. 2(b)), and the imaginary band is zero for all possible $k$ (black lines overlapped in Fig. 2(c)).

In contrast, in the band structure of the PT-symmetric system with gain and loss (red lines in Fig. 2(b)), the upper and lower real bands merge at a certain point inside the first Brillouin zone to form a flat region. In the imaginary band structure (red lines, Fig. 2(c)), a new branch is generated from the wavenumber corresponding to the merge point in Fig. 2(b), and it extends to the edge of the band, $k = \pi/(2L_{CC})$. This merge point is called an exceptional point*2 in complex function theory.

What happens at an exceptional point? In the two states before the real bands merge, light of equal intensity is distributed to both resonators in the unit cell, but in the two states after merging, the light is

*1 Band structure: For the eigenstates (eigenmodes) of EM fields that can exist in an infinite periodic system, the band structure indicates the relationship between the Bloch wavenumber $k$, representing the wave number term in the phase envelope component and the corresponding eigenfrequency.

*2 Exceptional point: A point in a parameter space where its complex function becomes indifferentiable. At the PT phase transition point, the eigenfrequency detuning and eigenstate become undifferentiable, resulting in divergence of differential characteristics such as the group velocity.

localized to either the cavity with the amplifying medium or that with the absorption medium. The imaginary band shows the net gains and losses of the state, and in the state before branching occurs, the light spreads evenly to both resonators, indicating that the overall gains and losses cancel each other out.

In the state after branching, on the other hand, light is biased toward one resonator, so there is either a gain or a loss depending on which side the light becomes localized. In other words, a discontinuous qualitative change from an extensive stable state to an unstable localized state occurs at the exceptional point. In the parlance of physics, this is called a phase transition. Therefore, this point is also called the PT phase transition point. However, it is known that this phase transition and its accompanying phenomena can occur without the gains and losses being perfectly balanced.

Various phenomena occur before and after the phase transition [3]. These can be broadly categorized as two types. The first type consists of directional responses resulting from the breaking of spatial inversion symmetry by gains and losses—for example, unidirectional reflectionless resonances—and double refraction in a single direction. In fact, although it is known that Lorentz reciprocity cannot be destroyed in a standard linear PT-symmetric optical system, it has been proved that if the system is combined with nonlinearity in the laser oscillation, it can achieve the optical isolation at weak input intensities [4, 5].

The second type consists of a phenomenon in which the net gain and loss caused by the phase transition are related. A typical example is single-mode lasing. In addition, lasing caused by an increase in loss of the partial system, accompanied by the phase transition, has also been observed (loss-induced lasing).

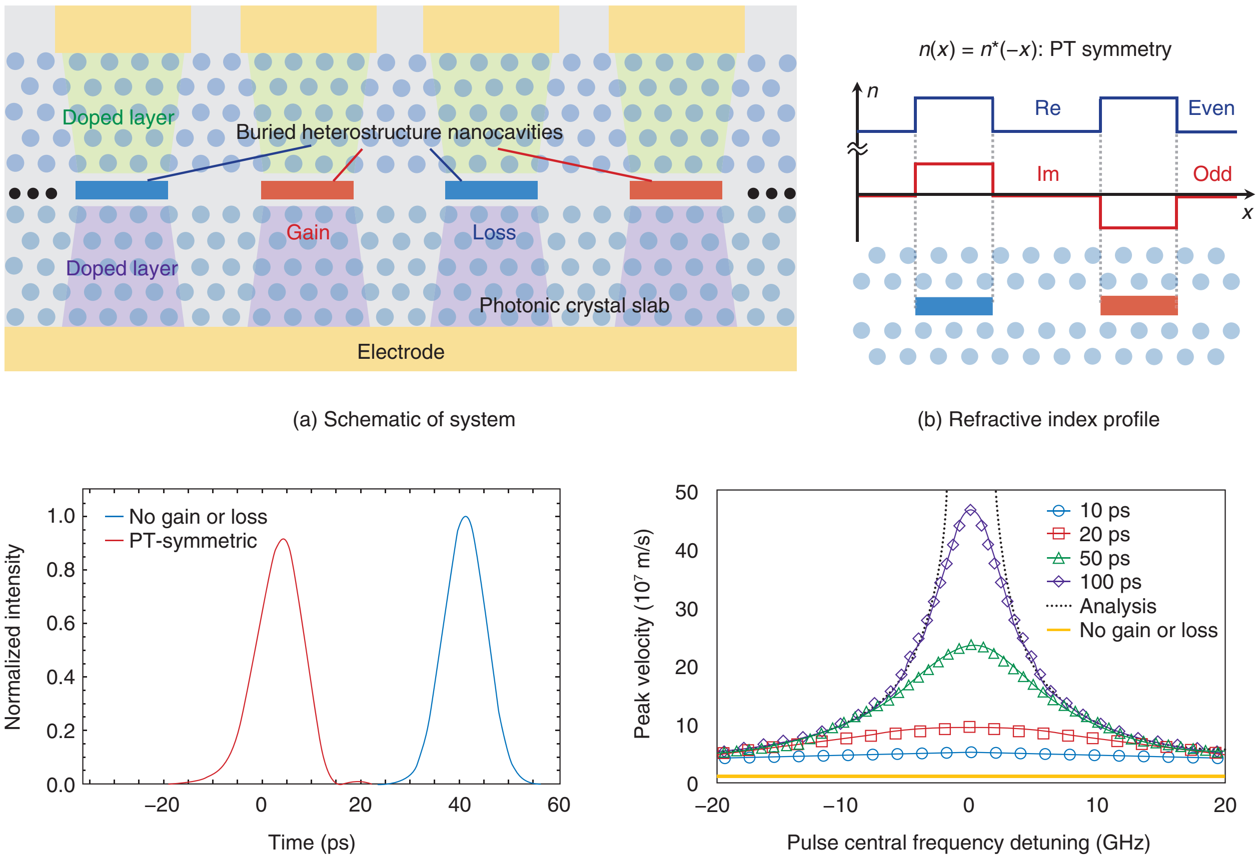
## 3. Control of light group velocity by an exceptional point using a coupled photonic crystal laser array

To introduce these sorts of optical responses and mode control methods into nanophotonics, we proposed a PT-symmetric coupled-resonator optical waveguide based on arrays of buried-heterostructure photonic crystal lasers, and we conducted a theoretical analysis of the system [6] (**Fig. 3(a)**, **(b)**). NTT has developed a fabrication technique for a nanolaser that oscillates with the world's smallest threshold current [7] and has been researching a large-scale Si (silicon) photonic crystal coupled-resonator optical waveguide [8]. By combining these technologies, we hope to achieve devices with new functions like those described above. In particular, we expect it will be necessary to increase the scale of the entire device (the number of cycles of gain and loss media) to control the device's transmission and reflection well and to increase its achievable output power. However, there are few platforms that support both the scalability and fine control of the amplification and absorption. We will therefore explore the possibility of performing optical control with the merits of scale, based on the use of ultra-miniature lasers with gain and loss tuning by current injection or optical pumping.

As an example, we focused on controlling the group velocity in this coupled-resonator optical waveguide. Group velocity is a measure of the propagation speed of optical communication pulses. It is defined as the gradient of the real band ($d\Delta\omega/dk$) in Fig. 2(c) and diverges to infinity at the frequency corresponding to the exceptional point. In this study, we carried out an analysis using the tight-binding approximation*3 and the Schrödinger equation to show that despite the group velocity divergence at the exceptional point, the group velocity dispersion, which quantifies the pulse broadening, converges at a finite value there. This suggests that optical pulses may propagate without collapsing even under the extreme condition with a high group velocity.

Next, we conducted a numerical experiment where optical pulses were excited in a PT-symmetric coupled-resonator optical waveguide and propagated through 100 resonators. Here, their central frequencies were close to the exceptional point, that is, $\Delta\omega = 0$. We used the same parameters assumed for the photonic crystal device discussed above. An example of pulse propagation in this experiment is shown in **Fig. 3(c)**. The horizontal axis here is the time from when the center of the excitation pulse passes through the starting point until the signal is detected after passing through 100 resonators. This figure shows the results for a 10-ps pulse. The pulse peak propagates about ten times faster in a PT-symmetric system than in the system without any gain or loss introduced. However, to obtain such a response, we must selectively excite a pulse with a single direction of travel (excitation wavenumber selectivity).

*3 Tight-binding approximation: An approximation whereby the localization of a wavefunction is strong towards each element of a coupled system (in this case, resonator), and coupling is effective only between adjacent elements.




(a) Schematic of system

(b) Refractive index profile

(c) Example of pulse propagation in photonic crystal device

(d) Pulse peak velocity for different pulse durations

Fig. 3. Photonic crystal PT-symmetric coupled-resonator optical waveguide.

The pulse peak propagation speed increases as the temporal pulse duration increases. This is because a longer temporal width results in a narrower spectral width, which is less susceptible to slow group velocity components and higher order dispersion. The dependence of the peak velocity on the pulse central frequency is shown in **Fig. 3(d)** for several different pulse durations. The data suggest that a pulse with a temporal width of about 100 ps can in principle accelerate beyond the speed of light in the vacuum. Here, it is reckoned that this acceleration of pulses originating from increases and reductions in intensity does not conflict with the theory of relativity.

Finally, we calculated the band structure by conducting an EM wave simulation assuming a realistic three-dimensional photonic crystal slab structure and embedding medium. The results are shown in **Fig. 4**. With suitable gain and loss, the bands exhibit an exceptional point where the principal eigenfrequency detuning component changes from real (black symbols) to imaginary (red symbols) values (respectively represented in the figure as the wavelength and net gain or loss rates). In this case, the signed gain and loss components of the media are about ±300 $cm^{-1}$, which are realistic for semiconductor optical devices. A closer look at the data indicates that the wavelengths of the two band curves (black lines) do not perfectly coincide near the exceptional point, and the maximum possible group velocity is about nine times as high as that of a system without any gain or loss introduced. This is thought to be due to radiation loss perpendicular to the slab surface, which implies that it is important to design devices with strong optical confinement.

## 4. Future prospects

In this article, we described the background of the

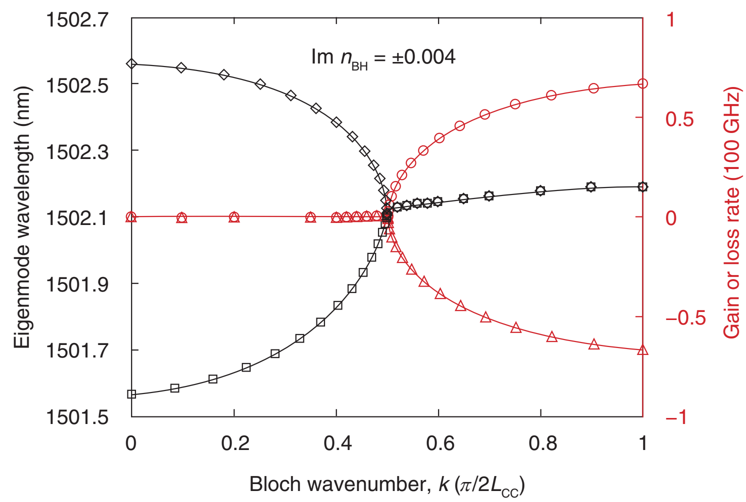



Fig. 4. Band structure of photonic crystal PT-symmetric coupled-resonator optical waveguide.

area of research focused on controlling light by using exceptional points based on PT-symmetric optics. In addition, we theoretically showed the drastic changes in the group velocity in the PT-symmetric photonic crystal laser arrays. We are currently carrying out an experimental demonstration of PT phase transition in a photonic crystal system with two nanolasers and studying advanced theoretical topics including control of photonic topology in coupled laser systems. We are also pursuing a way of implementing large-scale PT-symmetric systems, which we hope to demonstrate in the future.

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# Ultralow-latency Optical Circuit Based on Optical Pass Gate Logic

*Akihiko Shinya, Tohru Ishihara, Koji Inoue, Kengo Nozaki, and Masaya Notomi*

## Abstract

A novel light speed computing technology has been developed by NTT, Kyoto University, and Kyushu University that employs nanophotonic technology in critical paths and thus overcomes the problem of operational latency that is the chief limiting factor in conventional electronic circuits. The ultimate objective of this work is to develop an ultrahigh-speed optoelectronic arithmetic processor. This article provides an overview of our recent work and describes the successful implementation of this novel optical computing technology.

*Keywords: photonic integration, ultralow latency, nanophotonics*

## 1. Importance of ultralow latency operations

Improvements are still being achieved in the processing capacity of processors by increasing the number of cores and enhancing parallelization. However, the frequency response has leveled off, as one can see in **Fig. 1(a)** [1]. In other words, basic throughput continues to improve through integration and parallelization, but reductions in latency or delay have reached a plateau. Particularly in situations requiring spinal reflexive speed response, this calls for a significant technological breakthrough in the development of arithmetic processors capable of responding at super high speed.

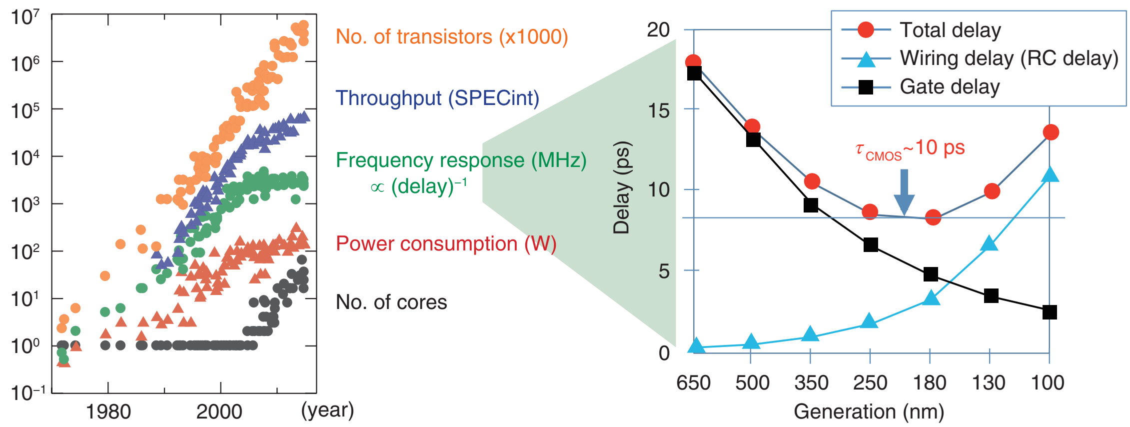
## 2. Introduction of optical technology in arithmetic chips

Research and development in optical computing focused on achieving ultrahigh-speed calculations exploiting the immense broadband of light continued throughout the 1980s. The problem with this approach is that optical transistors are quite large and vastly inferior to complementary metal oxide semiconductor (CMOS) transistors in density, power consumption, cascadability, and other factors. It is not surprising that research in this area fell off sharply in the 1990s. At the same time, however, optical communications has proven vastly superior not only for long-haul communications but also in ongoing research to exploit the vast bandwidth of light in developing optical interconnects within and between chips. Today we see a marriage between light and electronics—optoelectronics—that exploits light for information transport and electronic circuitry for information processing.

More recently we have seen remarkable progress in nanophotonic technology as new solutions have been found dealing with problematic issues that plagued optical and optoelectronic computing research in the past. In photonic crystal technology, for example, optical elements have been significantly downscaled to a mere 1/1000th the size they were a decade ago with corresponding decreases in power consumption, which brings optical elements into close competition with CMOS circuits. It is time that we reconsider the prevailing division between optical and electronic, with optical used primarily for transport and electronic for information processing.

## 3. Arithmetic chip delay factor

The frequency response rate-limiting issue mentioned earlier can be attributed to resistance (R) and

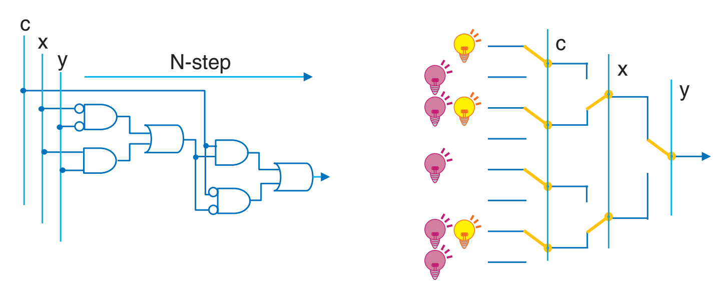



(a) Processor trends

(b) Transistor-generated delay

SPECint: Standard Performance Evaluation Corporation integer benchmark

Fig. 1. Processor trends and transistor-generated delay.




(a) AND/OR logic circuit

(b) Optical pass gate logic circuit

Fig. 2. Circuit configuration comparison.

capacitance (C) in the wiring path of CMOS circuits. The gate switching time of CMOS transistors has been sharply reduced by advances in semiconductor micro-fabrication technology, but the total delay of CMOS gates levels off at around 10 ps due to R and C in the transistor interconnects, as shown in **Fig. 1(b)** [2]. Moreover, R and C in the wiring only increases as transistors become more compactly integrated and wiring is stretched thinner and longer, which further increases the latency of actual circuits.

Electronic circuits also inevitably exhibit a certain amount of latency due to their structure. One of the most widely used circuit configurations is the AND/OR logic circuit shown in **Fig. 2(a)**. The output signal from one logic gate drives the following logic gate, so obviously, the latter gate cannot do anything until the output signal from the previous gate arrives. The wait time involved in these gate operations is proportional to the number of gates, which makes for substantial arithmetic delay.

## 4. Arithmetic chip with optical and electronic elements integrated at transistor level

One solution to wiring-induced latency is on-chip optical communications. This is essentially a photonic technology for conveying information between cores, but here we extend this approach to the transistor level as a solution to the architecture-induced latency problem. In trying to come up with the ideal circuit configuration, we can find a valuable clue in the field of electronics. A schematic pyramid-shaped

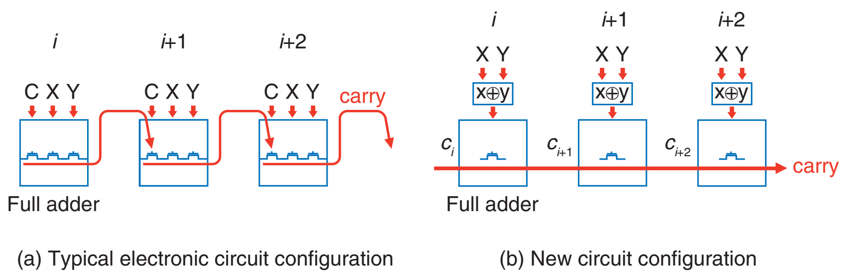



Fig. 3. Schematic diagrams of digital adder circuits.

tree circuit based on a *binary decision diagram* (BDD) [3] is shown in **Fig. 2(b)**. We assume a configuration in which "1" is output from the signal source located in the leaf part of the tree at the base of the pyramid, and Boolean operations are performed by selecting either signal source "1" or no signal source "0" depending on the combination of external inputs ($x_1$, $x_2$…). Various methods for simplifying BDDs have been proposed, and if these methods can be applied to the BDD-based circuit, the number of switches could be greatly reduced.

This type of circuit configuration is called a *pass transistor logic circuit*. The signal passing through the circuit is called a *carry*, and an operation is performed by steering the carry flow with 2 × 1 switches.

Here, we refer to the optical version of this structure as an *optical pass gate logic circuit*, and we replace the electronic switches with 2 × 1 and 2 × 2 optical gates. In this architecture, light is used as the carry signal.

The optical pass gate logic circuit has a number of significant advantages:

- All switches making up the critical path operate collectively—We saw earlier that the gate operation wait time is proportional to the number of gates in an AND/OR logic circuit since subsequent gates cannot act until they receive the carry signal from the previous gate. Since optical pass gate logic circuits operate all gates collectively, though, they support critical paths requiring only a few picoseconds at most.
- Light speed operations—Since the optical carry does not sense R or C in the optical path, circuits are not slowed by R and C limitations in paths. Although optical gate operations do incur some RC delay, the operation time is affected very little since all gates operate collectively.
- Logic operation without optical transistor—Operations that require an optical transistor that controls the optical carry by another light signal are very difficult to implement since with today's technology they consume enormous amounts of energy, generate practically the same amount of latency as CMOS gates, and have a host of other issues. However, our optical pass gate logic circuit performs logic operations without an optical transistor simply by passing the optical carry through electrically controlled optical gates.

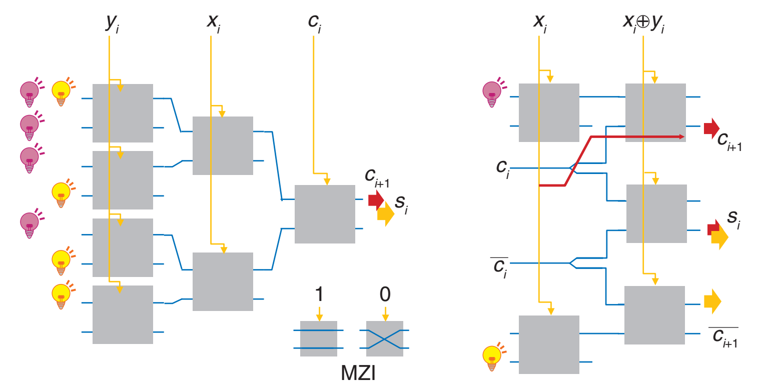
One might assume that this configuration could be just as easily implemented with electronic circuitry, but the carry signal passes right through the series resistance of multiple transistors, which would drive up R and make it virtually impossible to fabricate a high-speed response circuit.

In contrast, our optical carry scheme is independent of R and C, so the carry propagation time is dramatically reduced by exploiting nanophotonic technology. For example, the propagation time for an optical gate length of 100 μm is on the order of ~1 ps. This is just a fraction of the latency generated by a CMOS gate.

## 5. Ultralow-latency optical parallel adder

Let us consider a specific circuit configuration as an example of a digital adder. A typical electronic circuit configuration is illustrated in **Fig. 3(a)**. The carry signal ($c_i$) operates the gate in the $i$ + 1th logic block, and the result generates the next carry signal ($c_i$ + 1). One will note that a certain amount of wait time is generated for the gate operations in the various logic blocks by this step. The new circuit configuration we propose is shown in **Fig. 3(b)**. In this scheme, all gates in the logic blocks are operated collectively, and this fundamentally changes the structure of carry signal propagation.

Let us first configure a BDD-based full adder (FA) as the $i$ + 1th logic block.




(a) Optical FA requiring gate operations by input signal $c_i$

(b) Optical FA not requiring gate operations by input signal $c_i$

Fig. 4. Schematic diagram of optical FA.

An FA takes two 1-bit inputs (x and y) representing the two significant bits to be added. In the circuit shown in **Fig. 4(a)**, a Mach-Zehnder interferometer (MZI) is incorporated as a 2 × 1 switch. The switch is configured to select the upper (lower) input port when the input signal ($x_i$, $y_i$, $c_i$) is "1" ("0"). The circuit selects the light source located in the leaf part of the tree structure according to the truth table in **Table 1**. Note that $x_i$, $y_i$, and $c_i$ are all input at the same time, and consequently, all the MZIs are driven at the same time. This allows the carry operation [$c_{i+1}$ = CARRY ($x_i$, $y_i$, $c_i$)] and $i$th digit addition [$s_i$ = SUM ($x_i$, $y_i$, $c_i$)] to be completed just by propagation of light from the light source.

Note, however, that this circuit only adds two 1-bit inputs, x + y. In order to add multi-bit inputs, the optical carry signal ($c_i$ + 1) output from the $i$th FA circuit must be capable of operating the $i$ + 1th FA circuit gate. For example, this could be achieved using an optoelectronic (OE) converter. Although there is a way of converting $c_{i+1}$ to electronic signals, this involves latency, which again raises the issue of delayed operation time.

This led us to implement the block diagram shown in **Fig. 4(b)** [4]. This circuit operates according to the truth table in **Table 2**, which redefines the truth table in Table 1. Instead of the light source in Fig. 4(a), here we employ optical $c_i$ and $x_i$ signals. Light $c_i$ uses output from the $i$th FA circuit, while the optical $x_i$ signal is produced by combining light from the light source and from the MZI in the upper left. As is apparent from Table 2, the CARRY and SUM operations respectively select $c_i$ ($x_i$) and $\overline{c_i}$ ($c_i$) when exclusive or (XOR) ($x_i$, $y_i$) = 1 (0). This operation drives the three MZIs shown on the right side of Fig. 4(b). For example, the SUM operation is executed when $c_i$ ($\overline{c_i}$) is input to the port in the upper left (lower left) of the MZI in the middle of the right side, and by selecting the port in the lower left (upper left) when XOR

Table 1. FA truth table.

| Input $c_i$ | Input $x_i$ | Input $y_i$ | Output $c_{i+1}$ | Output $s_i$ |
|---|---|---|---|---|
| 1 | 1 | 1 | 1 | 1 |
| 1 | 1 | 0 | 1 | 0 |
| 1 | 0 | 1 | 1 | 0 |
| 1 | 0 | 0 | 0 | 1 |
| 0 | 1 | 1 | 1 | 0 |
| 0 | 1 | 0 | 0 | 1 |
| 0 | 0 | 1 | 0 | 1 |
| 0 | 0 | 0 | 0 | 0 |

Light source

Table 2. FA truth table in which light source is replaced by input signals $C_i$, $X_i$.

| Input $x_i$ | Input $y_i$ | Output $c_{i+1}$ | Output $s_i$ |
|---|---|---|---|
| 1 | 1 | $x_i$ | $c_i$ |
| 1 | 0 | $c_i$ | $\overline{c_i}$ |
| 0 | 1 | $c_i$ | $\overline{c_i}$ |
| 0 | 0 | $x_i$ | $c_i$ |

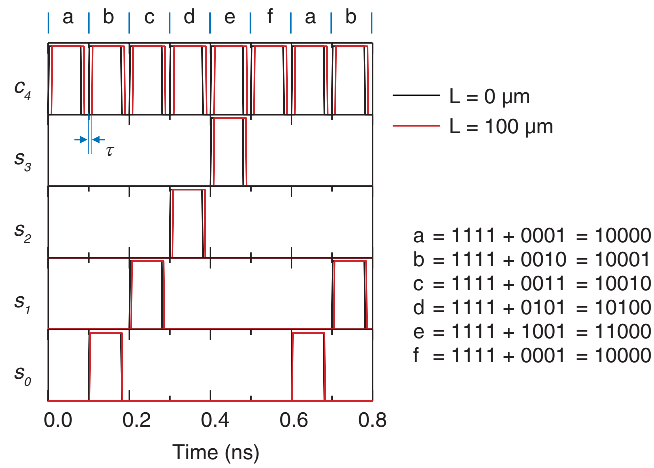



Fig. 5. Simulation results for 4-bit digital adder.

$(x_i, y_i)1 = (0)$. In this architecture, only one MZI is in the path where $c_i$ is input and $c_i + 1$ is output. This is the critical path that limits addition operations.

The simulation results for 4-bit addition are presented in **Fig. 5**. The leading edge of each digit's signal reveals the response speed of XOR operations. Note that arithmetic latency of XOR does not accumulate as the number of digits increases. However, τ in the figure reveals a cumulative arithmetic delay of four digits, which generates a delay of about 1 ps per digit using a 100-μm-long MZI. The bottom line is that this ultralow latency figure is far smaller than the 22-ps-per-digit latency of current state-of-the-art circuits implemented in CMOS.

## 6. Future prospects

This article introduced ultralow-latency optical pass gate logic circuits using a digital adder as an example. We plan to build on this new architecture as we pursue operational trials on ultrasmall-feature devices that we are now developing as a concurrent project.

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# Cloud Native SDx Control Technology

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**Abstract**

As various services are introduced in the cloud environment, service provision can be simplified and accelerated through end-to-end automatic control of network services and the cloud environment that includes applications for providing services. This article provides an overview of cloud native SDx (software-defined anything) control technology and describes a technical verification of automatic control technology.

*Keywords: cloud, automatic control, SDx*

## 1. Carrier network issues

Existing business and social infrastructures will be shifted to mechanisms that assume digitization. Additionally, with the migration to a 5G (fifth-generation) mobile network and the further penetration of cloud services, we can expect the service provision format to be increasingly diversified and an even greater variety of services to be launched, for example, real-time processing for self-driving systems or the utilization of data from various types of sensors. Many of these services will be provided in a cloud environment, so we can envision the need not only for leveraging of cloud features to provide services rapidly but also the need for continuous adding and modification of services. Regarding networks for using services that are provided in a cloud environment, we can foresee that network connection points, quality level, and other factors will have to be changed in an on-demand manner depending on the service.

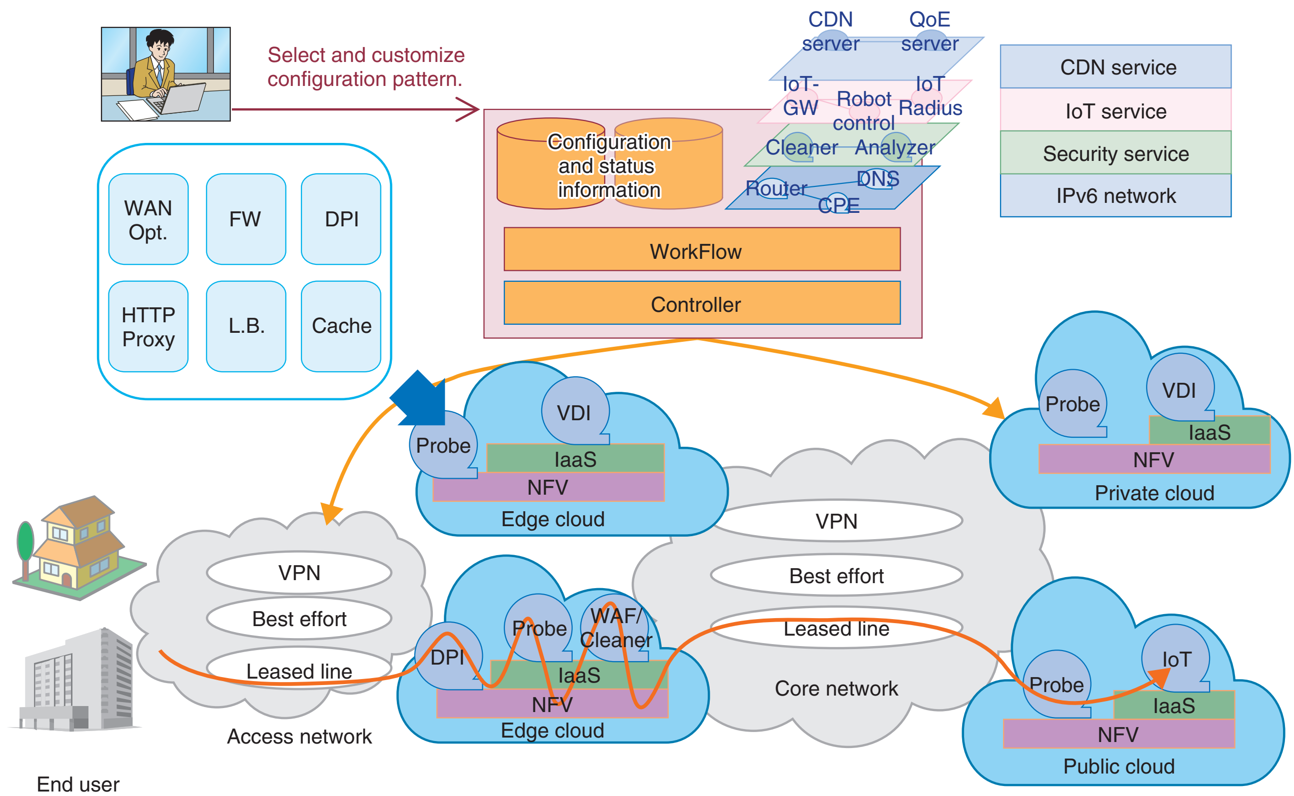
However, network services provided to date have only had a function for connecting the user and service provider, and the inability of the network and the service provision infrastructure on the cloud to sufficiently work together has hindered the rapid provision of services. Additionally, while the quality and reliability of carrier networks themselves have traditionally been high, the ability to control the network from outside the carrier has proved difficult due to various problems including a low degree of freedom, a relatively long time for providing a service or changing settings, and the difficulty of making on-demand changes.

NTT Network Technology Laboratories has been studying cloud native software-defined anything (SDx)* control technology to resolve the above issues. This technology will enable service providers to use diverse functions provided by the network from the outside and to provide more attractive network services than ever. It will also simplify and accelerate the provision of services by enabling the cloud environment and applications for providing services to be collectively and automatically controlled.

## 2. Cloud native SDx control technology

The cloud native SDx control technology enables service providers to subjectively and uniformly control a network that connects end users to services and the cloud environment that is the infrastructure for providing services and service applications (**Fig. 1**).

* SDx: Generic term for technology that enables software-based control of information technology infrastructure resources (servers, storage, networks, etc.).




CDN: content delivery network
CPE: customer premises equipment
DNS: domain name system
DPI: deep packet inspection
FW: firewall
GW: gateway
HTTP: Hypertext Transfer Protocol
IaaS: infrastructure as a service
IoT: Internet of Things
IPv6: Internet protocol version 6
L.B.: load balancer
NFV: network functions virtualization
QoE: quality of experience
VDI: virtual desktop infrastructure
VPN: virtual private network
WAN Opt.: wide area network optimization
WAF: web application firewall

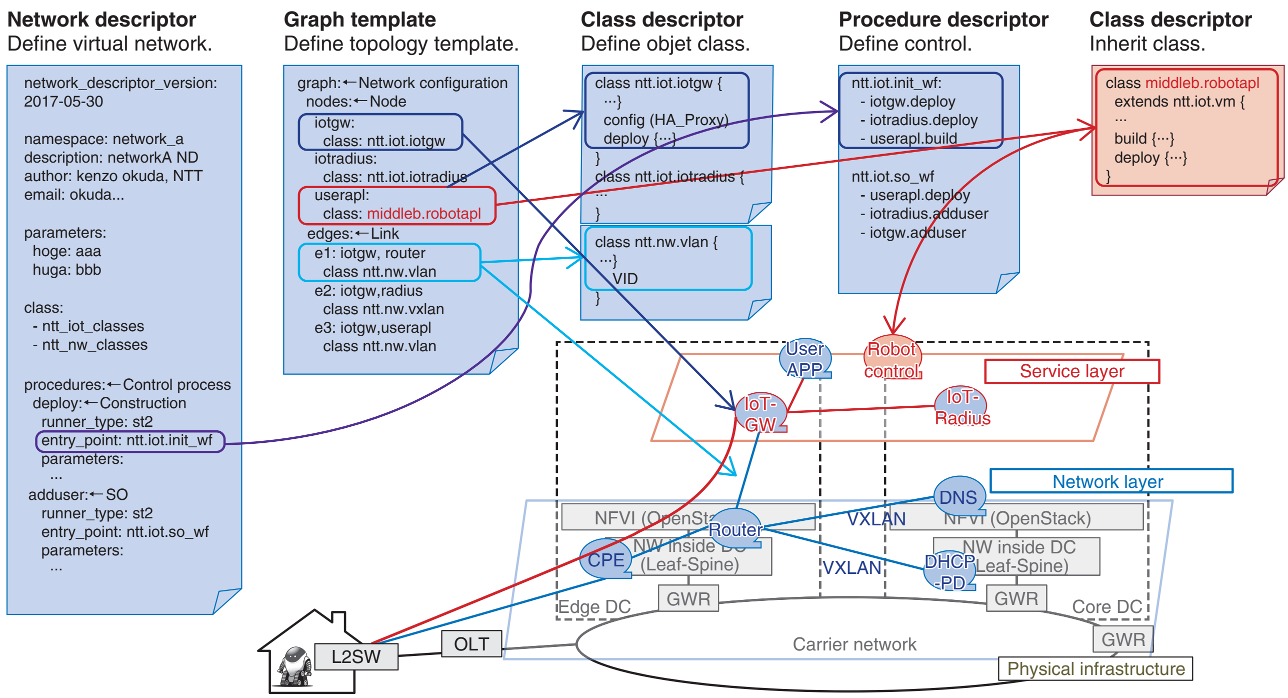
Fig. 1. Cloud native SDx control.

The equipment used in providing network services has generally consisted of dedicated devices, but with the progress being made in softwarization of hardware functions, it is becoming possible to replace those devices with a combination of general-purpose hardware and software. This makes it easier to control the network itself with software. With this change in the environment, and in view of the increasing number of services provided from a cloud, it will be impossible to provide more flexible and prompt services unless a means of integrating control from the network to the application is devised. Cloud native SDx control technology is targeted for all sorts of operators that provide services from a cloud environment, and it is aimed at providing network services that link a common infrastructure with the cloud while automating the immediate provision and maintenance of services.

## 3. Technical elements for SDx control

Achieving integrated control of a variety of targeted services requires (1) a mechanism for automatically controlling the resources (networks, resources on the cloud, etc.) needed for service provision and (2) a method for appropriately managing the information describing the resources targeted for control.

First, with regard to (1), various technologies already exist for implementing a mechanism for automatic control in a cloud environment. Service providers are already using such technologies, so we can use such cloud-based technologies as a basis for including the network as a target of control. Specifically, we are combining technologies such as network functions virtualization (NFV) and software-defined networking (SDN) and studying a mechanism for handling the network and cloud environment as well as




APP: application
DC: datacenter
DHCP-PD: Dynamic Host Configuration Protocol prefix delegation
GWR: gateway router
L2SW: layer 2 switch
NFVI: network functions virtualization infrastructure
NW: network
OLT: optical line terminal
VXLAN: Virtual eXtensible Local Area Network

Fig. 2. Modeling of controlled objects.

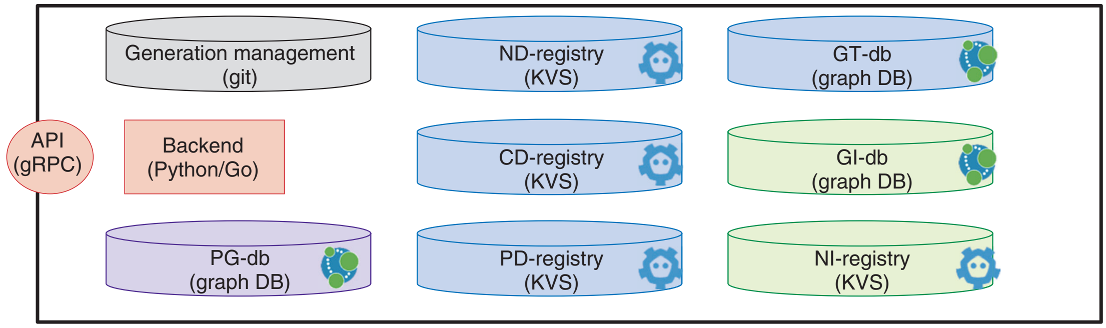
the applications corresponding to different types of services through a series of operations. However, various resources are necessary to provide services, including physical resources (computer, network equipment, etc.) and virtual resources (virtual computers, SDN functions, etc.), and some form of control is needed to link and coordinate them. The controlled objects differ for each service, so creating an automatic-control mechanism for each service would require a great deal of labor.

Consequently, to provide flexible support for diverse services by modeling controlled objects and handling them in a generalized manner, a management method that can uniformly handle resource information as described by requirement (2) above is needed (**Fig. 2**). To build a model, the first step would be to clarify the type of service targeted for control as a network descriptor, and to define what elements (network nodes, computer resources in the cloud environment, etc.) make up the service and the state of each element as a class descriptor. The next step would be to define a graph template that shows how each of those elements are connected, and the order they should be placed in is defined as a procedure descriptor. Because data characteristics differ for each type of information defined, we are also investigating the use of graph databases and key-value store schemes as methods for appropriately managing that information in forms that are easy to handle from the outside (**Fig. 3**).

## 4. Technical verification

We conducted a technical verification to assess the feasibility of achieving automatic control by combining a variety of technologies used on the cloud. For this verification, we created a scenario assuming specific service-provision scenes. The scenario was based on a service provider configuring a service that provides an application for controlling a robot installed in the user's home and that remotely provides robot control functions.

We assumed the following three processes would be carried out in the provision of this service: (1) infrastructure construction, (2) service configuration and provision based on user request, and (3) detection




API: application programming interface
CD: class descriptor
DB: database
GI: graph instance
git: A version control system.
gRPC: An open source remote procedure call (RPC) system.
GT: graph template
KVS: key-value store
NI: network instance
ND: network descriptor
PD: procedure descriptor
PG: physical graph

Fig. 3. Management of configuration information.

and handling of any unauthorized access occurring during the service. For each of these, we constructed an environment using actual equipment to assess operation.

(1) Infrastructure construction

In constructing an infrastructure for providing this service, we succeeded in automatically deploying on the cloud infrastructure gateways for making connections, an authentication function, and an application for robot control.

(2) Service configuration and provision based on user request

We made it possible to automatically launch the application for robot control, set user information to the authentication function, and enable the user to use the application.

(3) Detection and handling of unauthorized access

We made it possible when detecting anomaly traffic to automatically launch a function for checking the content of that traffic and to determine whether unauthorized access has occurred.

If unauthorized access is detected, we made it possible to use that detection as a trigger for automatically launching a function for removing the unauthorized access and recovering the system to a normal state. The configuration for technical verification of unauthorized access detection is shown in **Fig. 4**. In the past, infrastructure construction and service provision based on demand would require the service provider to establish various settings and install the application manually. Furthermore, the only way for the person in charge of system monitoring to discover an anomaly would be to notice indications that an unauthorized access was taking place and then collect and analyze various types of information. Responding to such an anomaly would also be centered around manual operations. Such tasks not only require a lot of work but also increase the possibility of human error in operations.

In this technical verification, we confirmed that many tasks from network settings to application installation and anomaly detection and response could be automated by combining various existing mechanisms (most implemented as open source software). Going forward, we aim to achieve efficient automation of diverse types of service provision by incorporating the modeling and configuration management methods that we are currently studying based on those mechanisms.

## 5. Future outlook

We plan to establish the technologies behind the modeling and configuration management methods now being studied and incorporate them in an automatic control mechanism. In this way, we aim to establish a control infrastructure that can uniformly manage and automatically control all of the resources needed for providing a service.

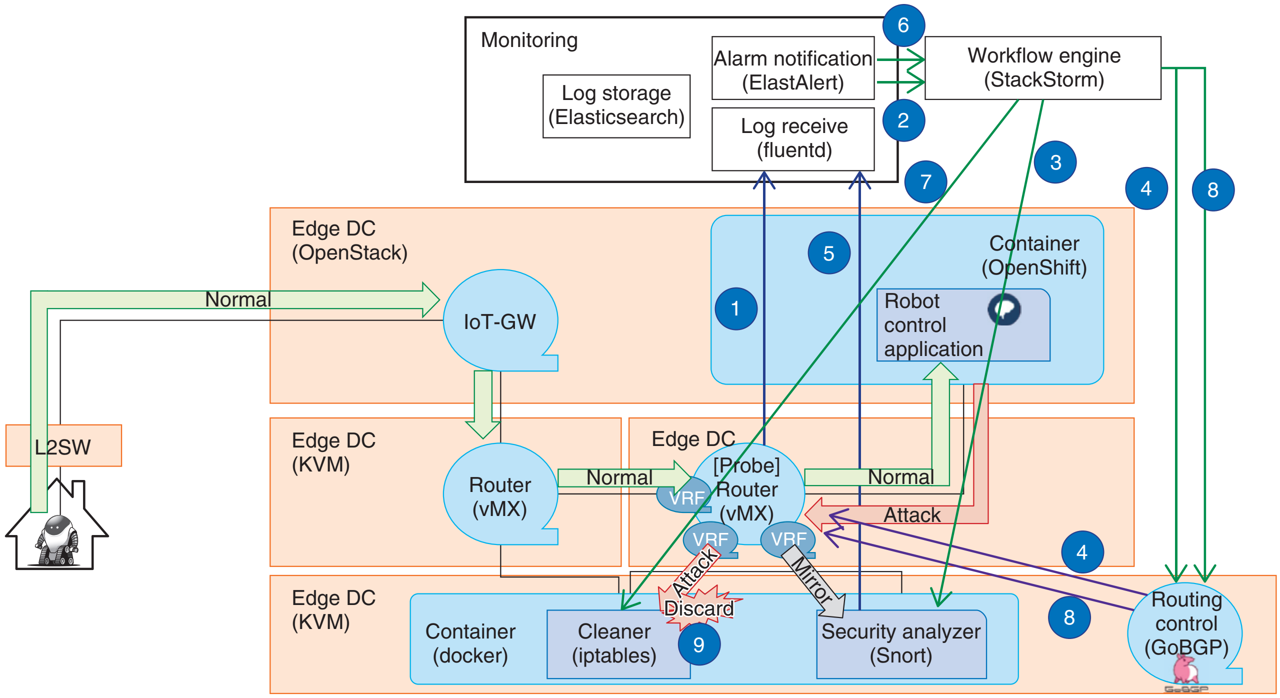



Fig. 4. Technical verification configuration (unauthorized access detection).

## Trademark notes

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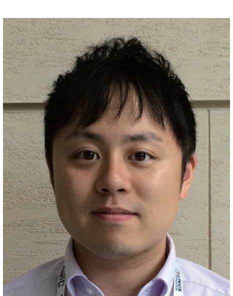

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# Standardization Trends of Virtualized Access Systems by the Broadband Forum

*Kota Asaka and Hirotaka Ujikawa*

**Abstract**

Various organizations are studying the introduction of virtualization technologies to access systems in order to achieve flexible, agile, and cost-effective adaptation of access networks to a diverse range of services. This article reports on the standardization trends of virtualized access systems by the Broadband Forum (BBF) and explains related activities happening at the NTT laboratories.

*Keywords: BBF, optical access, virtualization*

## 1. Requirements of future access systems

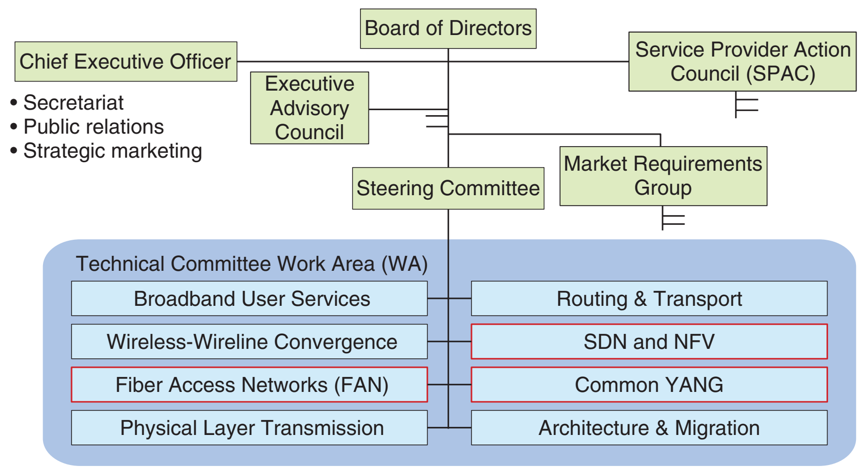
Standardization of the 10-Gbit/s-capable passive optical network (PON) was carried out in order to meet the large demand for high capacity transmission in future optical access systems [1, 2]. In addition, 40-Gbit/s-capable PON, known as Next-Generation Passive Optical Network Stage 2 (NG-PON2), has also been standardized and can support up to 80 Gbit/s [3]. With conventional optical access systems, focus was placed on enhancing transmission capacity to accommodate the rapidly growing traffic. However, NG-PON2 was specified in order to accommodate various services (e.g., enterprise and mobile services) in addition to the fiber-to-the-home (FTTH) service. In light of this background, future access networks are expected to flexibly address further diverse emerging services such as those related to the Internet of Things and edge computing. Future access systems should therefore be flexibly and quickly provided at a low cost to meet various service requirements (bandwidth, latency, reliability, etc.), which might be different for each service.

The use of virtualization technology rather than conventional purpose-built access equipment to achieve such a future access system is attracting a lot of attention from the broadband access industry. Such technology would enable access functions by using commodity hardware (servers and switches) and software components [4, 5]. To establish a virtualized access system, it is important that consolidated access functions inside the equipment are disaggregated to each functional module based on the standardized architecture and interfaces in order to achieve practical future deployment and assured interoperability.

## 2. Broadband Forum (BBF)

BBF is a nonprofit industry consortium established in the United States in 1994. It was formerly known as the ADSL (Asymmetric Digital Subscriber Line) Forum. In 2008, the organization widened its scope to include optical access networks and changed its name to Broadband Forum accordingly [6]. Since then, BBF has contributed to broadband access industries and earned a high reputation for its efforts, especially in developing control/management specifications and interoperability test specifications of access systems, which have been published in more than 200 Technical Reports (TRs).

BBF is composed of more than 150 companies/organizations, which include telecom carriers, multiple service operators, system vendors, ASIC (application specific integrated circuit) vendors, interoperability test labs, and others from around the world. The organization chart of BBF is shown in **Fig. 1**. The




Note: Virtualization technologies in access systems are being discussed in WAs indicated with red borders.

Source: https://www.broadband-forum.org/about-the-broadband-forum/about-the-forum/bbf-working-structure

NFV: Network Functions Virtualization
SDN: Software Defined Networking
YANG: Yet Another Next Generation

Fig. 1. Organization chart of BBF.

Service Provider Action Council discusses various technical topics and directions that are driving BBF. Each Work Area (WA) in the Technical Committee discusses corresponding technical specifications based on the topics and provides TRs as their deliverables, which are disclosed on the BBF homepage [7]. As shown in the figure, three WAs focusing on Common YANG (Yet Another Next Generation), SDN and NFV (Software Defined Networking and Network Functions Virtualization), and Fiber Access Networks (FAN) are working intensively on the development of specifications related to virtualized access systems.

## 3. Standardization trends of virtualized access systems by BBF

The deliverables and documents being developed by BBF that are related to virtualized access systems are summarized in **Table 1**. In the leftmost column (document number) in Table 1, WT stands for Working Text, which is a draft for a future TR that is disclosed only to BBF members. As indicated in the table, BBF is actively developing various documents such as those concerning NETCONF (Network Configuration Protocol), YANG models (modules), and Cloud CO (Central Office) specifications. These are explained in more detail in the following subsections.

### 3.1 Standardization of NETCONF/YANG model (module)

NETCONF is a configuration protocol of network equipment and was developed to remotely conduct configuration and management functions in distributed equipment from a centralized SDN controller. The YANG model is a common data-modeling language that abstracts a structure and the configuration values of each piece of network equipment. Using NETCONF and a YANG model makes it possible to achieve interoperability between network equipment and a controller from various system vendors. In July 2016, BBF launched the first specifications of a YANG module for a fiber-to-the-distribution point (FTTdp)*1 system as TR-355 (Table 1). Since then, BBF has been developing several YANG models (Note: each model consists of several modules) for PON systems, optical network units, access nodes, and home networks, as indicated in Table 1.

### 3.2 Cloud CO

Cloud CO is a project that was proposed and agreed to at the BBF meeting in July 2016. The objective of

*1 FTTdp: A way to provide a broadband Internet service to customer premises with the hybrid use of optical fiber and metal cable. The fiber is installed between a CO and a distribution point close to the customer premises, while the cable is used to connect the distribution point and customer premises.

Table 1. Examples of deliverables and documents under development at BBF.

| Doc. number | Document title | WA |
|---|---|---|
| TR-355 | YANG Modules for FTTdp Management | Common YANG |
| WT-383 | Common YANG modules | |
| WT-374 | YANG Models for Management of G.hn Systems in FTTdp Architecture | |
| WT-358 | Support for SDN in Access Network Nodes | SDN and NFV |
| WT-368 | YANG Models for ANs in SDN | |
| TR-384 | Cloud Central Office Reference Architectural Framework | |
| WT-411 | Definition of interfaces between Cloud CO Functional Modules | |
| WT-412 | Test Cases for Cloud CO Applications | |
| WT-413 | Migration to SDN-Enabled Management and Control | |
| WT-385 | YANG model for management of ITU-T PON | FAN |
| WT-394 | YANG model for management of ONU | |
| WT-395 | NETCONF Management of PON ONUs Architecture Specification | |
| WT-402 | Functional model for PON abstraction interface | |
| WT-403 | PON abstraction interface specifications | |
| WT-414 | PON NETCONF and YANG Data Model Interoperability Test Plan | |

Sources: https://www.broadband-forum.org/standards-and-software/technical-specifications/technical-reports
https://www.broadband-forum.org/standards-and-software/scope/technical-work-in-progress

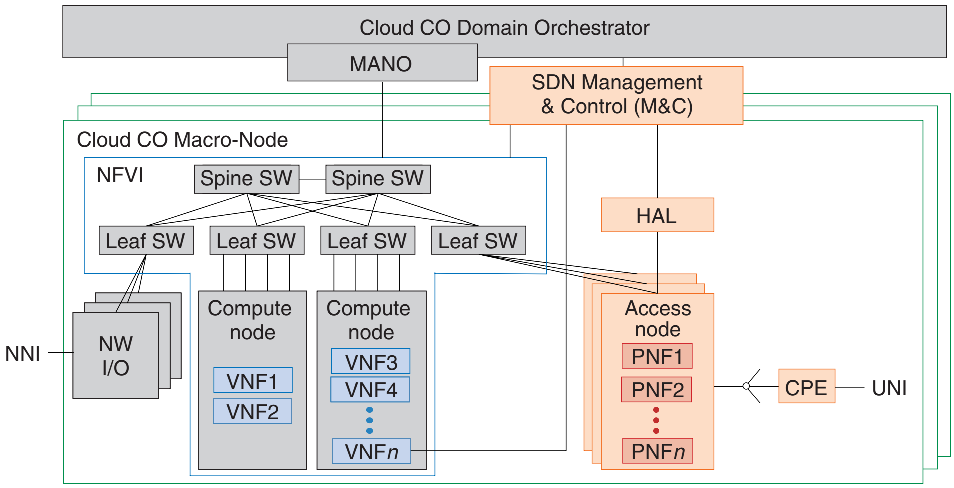
ANs: Access Nodes
Cloud CO: Cloud Central Office
FTTdp: fiber-to-the-distribution point
ITU-T: International Telecommunication Union - Telecommunication Standardization Sector
NETCONF: Network Configuration Protocol
ONU: optical network unit
WT: Working Text

the project is to develop specifications for next-generation COs (telecom carrier central offices that contain network equipment) that use SDN/NFV and cloud technologies. Similarly to Central Office Re-architected as a Datacenter (CORD)*2 developed at the Open Networking Foundation (ONF), Cloud CO will lead to the re-architecting of COs through the use of commodity hardware, softwarized CO functions, and controllers. Furthermore, inter-CO configuration and management can be achieved by using an orchestrator located in a cloud layer. This innovative architecture is expected to lead not only to a reduction in capital expenditures and operating expenses (CAPEX/OPEX) but also to flexibly and agilely provide emerging services.

A reference architecture of Cloud CO is shown in **Fig. 2**. This architecture was created based on the authors' understanding of some figures and corresponding content of BBF TR-384 (Table 1). In Fig. 2, the CO and the network between the CO and the customer's premises are called the Cloud CO Macro-Node. They are composed of network input/output (NW I/O), (network functions virtualization infrastructure (NFVI), access nodes (e.g., optical line terminal (OLT) hardware), CPE (customer premises equipment), and a hardware abstraction layer (HAL). The NW I/O is an interface between Cloud CO Macro-Node and a metro network. Similarly to CORD, the NFVI consists of white box switch (SW) fabric (leaf/spine SWs in Fig. 2) and compute nodes based on commodity servers where virtual network functions (VNFs) are implemented. Using the NFVI approach makes it possible to simplify network equipment by operating some network functions as VNFs on commodity servers. HAL is an abstraction layer that enables vendor-agnostic interoperability between SDN Management & Control (M&C) and the access node. SDN M&C controls flow and FCAPS (fault, configuration, accounting, performance, and security) functions located in physical network functions (PNFs) in the access node and in VNFs in the NFVI. Furthermore, it controls the SW fabric in NFVI.

In Fig. 2, SDN M&C is depicted above Cloud CO Macro-Node for the sake of simplicity, although TR-384 does not specify its location. In the upper layer, the Cloud CO architecture has MANO

*2 CORD: One of the use cases of the Open Network Operating System (ONOS), which is an operating system designed for carriers. CO functions are disaggregated and re-architected with an ONOS controller, commodity hardware, and open source software [4].




Note: This figure is depicted based on the authors' comprehension of Figs. 10, 13, and 15 in BBF TR-384.

CPE: customer premises equipment
HAL: hardware abstraction layer
I/O: input/output
MANO: management and orchestration
NFVI: network functions virtualization infrastructure
NNI: network to network interface
NW: network
PNF: physical network functions
SW: switch
UNI: user to network interface
VNF: virtual network functions

Fig. 2. Reference architecture of Cloud CO.

(management and orchestration), which manages NFVIs, and Cloud CO Domain Orchestrator, which achieves inter-CO orchestration. As indicated in Table 1, the Cloud CO project will release several deliverables related to TR-384 as an umbrella document. These deliverables include interface specifications of functional modules (WT-411), test cases for Cloud CO applications (WT-412), and migration to SDN-enabled management and control (WT-413). In addition, the project is drawing considerable attention from the broadband access industry and will cover reference software/hardware implementation documents.

## 4. NTT's activities in BBF

In February 2016, the NTT laboratories introduced the Flexible Access System Architecture (FASA) concept for technology development on future access networks in order to enable a more diverse range of services provided quickly and at low cost [8]. Rather than using conventional purpose-built access equipment, FASA will modularize the various individual functions of access equipment as much as possible to enable the free combination of these individual software components on commodity hardware. This will allow for software-based functions to be built into the commodity hardware flexibly and quickly as required for services, while still maintaining the same service quality. To achieve FASA, it is necessary to introduce an application programming interface (API) between each software component and the commodity hardware. Since APIs should be commonly usable by various players (system vendors, carriers, etc.), the NTT laboratories released an API set in a FASA White Paper [9].

In addition to flexible control & management functions for future access systems as in CORD and Cloud CO, FASA is intended to achieve the modularization (disaggregation) of time-critical functions in order to achieve updates and/or replacement of those functions. In October 2016, at the meeting of FAN WA of BBF, members of the NTT laboratories proposed a new project called "PON abstraction interface for time-critical applications (TC Apps)" and agreed to start it with support from several carriers and vendors. The disaggregation policy of time-critical PON functions discussed in the project is shown in **Fig. 3**. As shown in the figure, TC Apps will disaggregate time-critical functions (e.g., dynamic bandwidth allocation (DBA)), which remain as PNFs in Cloud CO (TR-384). According to the policy depicted in Fig. 3, the time-critical function will be disaggregated to a *differentiation* part, which leads to software replacement based on service requirements, and a *common behavior* part as an engine. Furthermore,

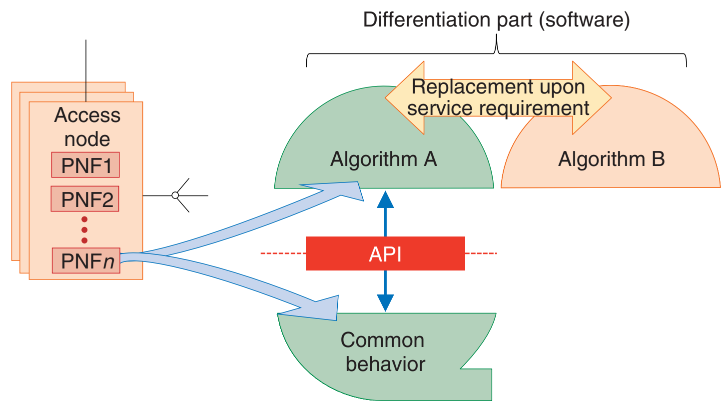



Fig. 3. Disaggregation policy for time-critical PON functions.

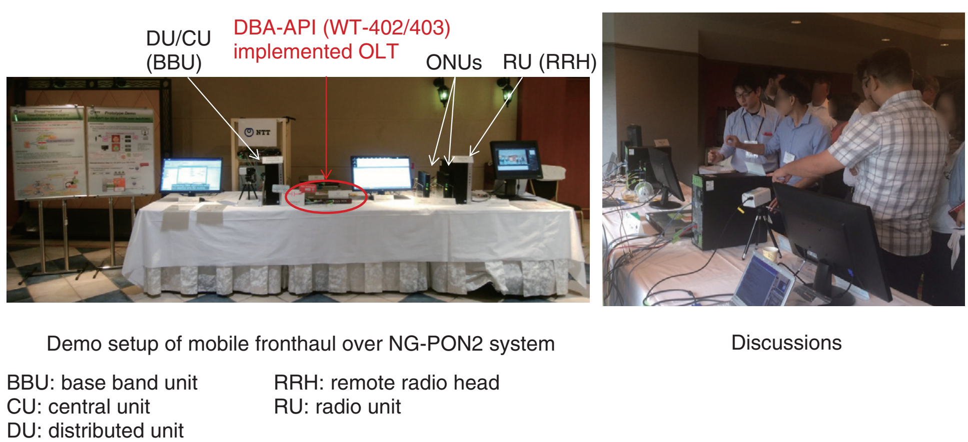



Fig. 4. Photographs of NTT's demonstration at BBF meeting in Osaka (June 14–15, 2018).

APIs between the two parts are under discussion to be specified as standards. The relevant documents of TC Apps are WT-402 and WT-403 in Table 1.

Using the modularization technology even in time-critical functions that require wire-rate processing will make it possible to achieve a flexible and agile adaptation to emerging services on access networks by replacing software components according to service requirements. An attractive use case of TC Apps is mobile fronthaul (MFH) for fifth-generation (5G) or beyond 5G mobile service over a time-division multiplexing (TDM)-PON system. In future mobile systems, dense small cells could be accommodated by the use of the PON architecture, which has an advantage in terms of low CAPEX of physical infrastructure [10]. In this case, by replacing the DBA software from FTTH-DBA to low-latency DBA in the OLT, TDM-PON-based MFH can be achieved without rebuilding the OLT from scratch. This would result in flexible and agile adaptation of an optical access system to mobile services by replacing softwarized time-critical PON functions. At the BBF meeting in Osaka held in June 2018 as shown in **Fig. 4**, members of the NTT laboratories successfully demonstrated their prototype mobile PON system, which implements DBA-API specifications being developed in WT-402 and 403 [11].

## 5. Future prospects

This article reviewed the standardization trends of virtualized access systems by BBF. As a result of the active technical discussions that have taken place, BBF will publish several specifications as TRs in the near future. In line with the progress of virtualization technology, open source software (OSS) is also being intensively developed for VNFs that are necessary in virtualized access systems. The NTT laboratories will continue to contribute to international standardization efforts by leading our project at BBF, and to OSS development at ONF as well.

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# Development and Trial of Low-latency Optical Access Technology that Operates in Coordination with a 5G Mobile System—Achieving Efficient Accommodation and Operation of Base Stations

## 1. Introduction

NTT has developed low-latency optical access technology that helps to reduce the number of optical fibers needed to accommodate base stations, especially during the period when the fifth and subsequent generation mobile systems are being introduced. NTT has also conducted a feasibility trial in which the optical access system operated in coordination with a mobile system.

This technology reduces data transmission latency, which is an issue when applying optical access systems to a mobile system. It is achieved by making optical line terminals (OLTs) and base station aggregation units that are deployed in telecommunications carriers' central offices operate in coordination with the signal control.

Applying optical access systems with this technology to a mobile system makes it possible to efficiently use optical fibers between a central office and the base stations. This reduces both the number of optical fibers required and the ports of the base station aggregation unit, enabling efficient operation of base stations. Detailed discussions on this technology have been initiated by ITU-T (International Telecommunication Union - Telecommunication Standardization Sector), a standardization organization.

NTT is committed to ongoing research and development (R&D) to assist mobile operators with efficient construction of their networks.

## 2. Background

The fifth generation (5G) mobile system is being developed to achieve a high-speed, high-capacity, and low-latency mobile service. In the existing mobile system, optical fibers are used to connect the base station aggregation unit installed in a central office to base stations installed on towers or on top of buildings.

To achieve high-speed, high-capacity wireless communication, the 5G mobile system uses new radio frequency bands. This will require installation of more base stations than before, resulting in an increase in the number of optical fibers used to connect the base stations to the base station aggregation unit and in the number of ports for the base station aggregation unit. These increases are expected to complicate network operations, including fault recovery and maintenance. Therefore, it is essential that base stations can be connected and operated efficiently, especially during the period when the 5G system is expanding, which will require the installation of numerous base stations.

## 3. Research results

An optical access system is employed to connect optical network units (ONUs), which set up connections to user terminals, to OLTs in a central office in an FTTH (fiber-to-the-home) service. NTT has developed low-latency optical access technology to enable

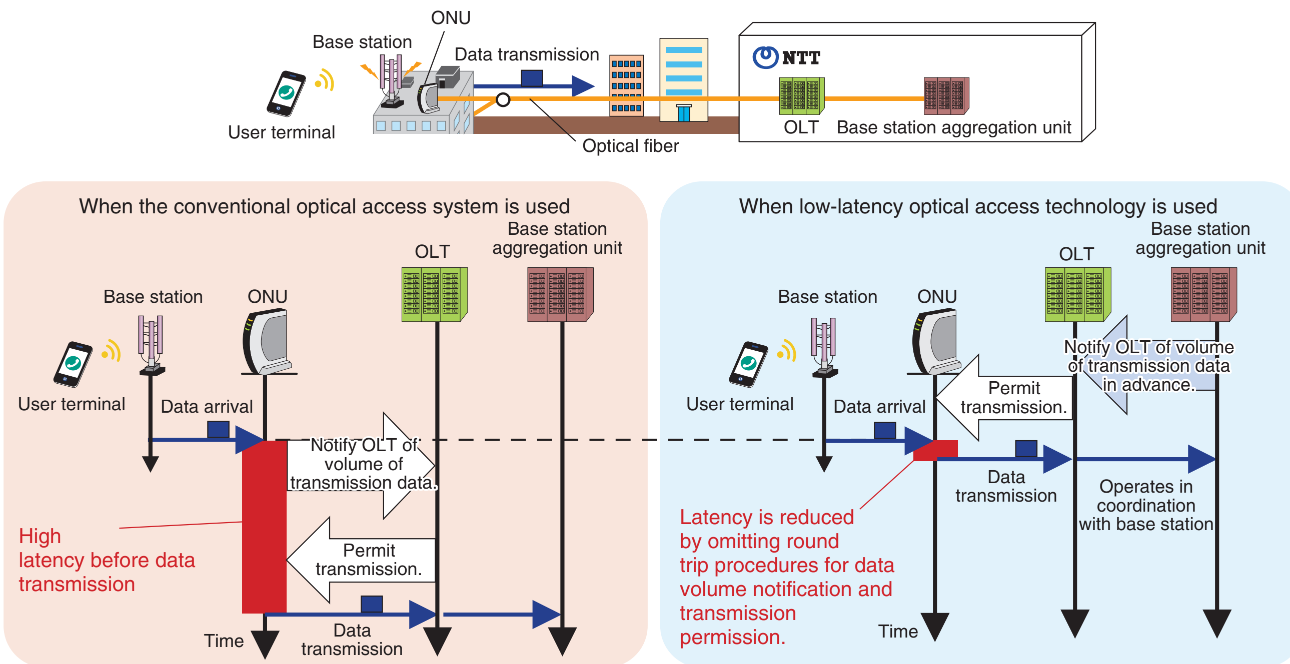


Fig. 1. Low-latency optical access technology.

use of the optical access system in a mobile system.

The conventional optical access system cannot satisfy the low latency requirement demanded by the mobile system. The new optical access technology reduces this latency by making OLTs in the optical access system operate in coordination with the signal control by the base station aggregation unit.

In cases where the conventional optical access system is used, when an ONU receives data from a user terminal, it notifies the OLT of the volume of data that it will transmit. It sends data to the OLT only after it has received permission to transmit data. This causes high latency before the ONU transmits data, which is why the conventional access system cannot satisfy the mobile system's requirement for low latency.

In contrast, when the new low-latency optical access technology is applied, the base station aggregation unit provides advance notification to the OLT of the volume of data that will be sent by the user terminal. This is possible because the base station aggregation unit has been notified by the user terminal in advance of the volume of data that will be sent by the user terminal. Making the optical access system operate in coordination with the mobile system in this way makes it possible to omit the round trip procedures used in the conventional optical access system for notification of the amount of transmission data and for transmission permission, thereby achieving low-latency optical access (**Fig. 1**).

## 4. Future plan

NTT will continue pursuing R&D to assist mobile operators with efficient construction of their networks. It will also promote standardization by conducting global discussions with telecommunications carriers and vendors and studies on coordinated operation of the mobile system and the optical access system.

**For Inquiries**

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# NTT Develops World's First Real-time 4K High Frame Rate HEVC Codec—Enabling Live Transmission of High Frame Rate Video, Resulting in Smoother and Sharper Video Quality

## 1. Introduction

NTT has developed a real-time 4K*1 high frame rate (HFR) High Efficiency Video Coding (HEVC)*2 codec that enables live transmission of HFR video. HFR enhances video smoothness and sharpness by doubling the frame rate*3 of the standard video frame rate (SFR) from 50/60 p to 100/120 p. HFR video is especially effective for fast-moving video content such as sports.

By developing this codec, NTT will contribute to enhancing the quality of broadcasts and public viewing of sporting events. NTT will also develop opportunities to use HFR transmission in virtual reality and surveillance applications.

## 2. Background

Ultra-high-definition (UHD) services have been launched recently by many satellite operators and OTT (over-the-top) platforms throughout the world. In March 2015, NTT announced a real-time 4K/60 p HEVC video encoder LSI (large-scale integrated circuit) called NARA (Next-generation Encoder Architecture for Real-time HEVC Applications) [1], which has contributed to the rapid acceptance of UHD services.

Live sports programs are the main drivers of UHD services, so HFR video technology, which is especially beneficial for sports content, has attracted strong interest from UHD service providers. NTT's real-time 4K HFR HEVC codec enables UHD service operators to conduct live broadcasts of HFR sports content.

## 3. Technical overview

Both the 4K HFR HEVC encoder appliance and the 4K HFR HEVC decoder appliance, key components of the real-time 4K HFR HEVC codec, are a compact 1U (1 rack unit: 44.45 mm height) size (**Fig. 1**). The 4K HFR HEVC encoder appliance provides backward compatibility by supporting temporal scalable coding*4, meaning the output stream can be decoded by a conventional SFR decoder to yield 4K SFR video.

*1 4K video: A video format that has approximately 4000 horizontal lines and 2000 vertical lines. There are some variations. The television industry uses 3840 × 2160 (UHD-4K) resolution, while the cinema industry uses 4096 × 2160 (DCI-4K) as the standard format.

*2 HEVC: The latest video compression standard developed through the joint collaboration of international standardization bodies, ITU-T (International Telecommunication Union - Telecommunication Standardization Sector) and the International Organization for Standardization/International Electrotechnical Commission (ISO/IEC).

*3 Frame rate: The number of frames per second. 60 p indicates that the video comprises 60 frames per second in progressive scanning.

*4 Temporal scalable coding: An output stream of temporal scalable coding contains one or more subset streams. Different frame rate video can be decoded from one video stream by the combined use of subset streams in decoding.

4K HFR HEVC encoder

4K HFR HEVC decoder

Fig. 1. Real-time 4K HFR HEVC codec.

Moreover, our codec supports the MPEG Media Transport (MMT) protocol*5 which enables hierarchical transmission. Two independent transmission routes can be used to transfer the base-layer data, which is used for decoding 4K SFR video, and the enhancement-layer data, which is used together with base-layer data for decoding 4K HFR video.

## 4. Technical features

(1) Multichip encoding

The encoder uses two NARA chips in parallel to achieve the high-speed processing demanded by HFR encoding, while maintaining visual quality by carrying out mutual data transfers between the chips.

(2) Hierarchical transmission by MMT protocol

The MMT protocol enables the base-layer data and enhancement-layer data to be transmitted over different IP (Internet protocol) streams. Using two different transmission routes creates a timing offset in the arrival of the data streams. MMT can reconfigure the order of data by using timestamps based on UTC (coordinated universal time).

## Reference

[1] Y. Omori, T. Onishi, H. Iwasaki, and A. Shimizu, "A 120 fps High Frame Rate Real-time Video Encoder," NTT Technical Review, Vol. 15, No. 12, 2017.
https://www.ntt-review.jp/archive/ntttechnical.php?contents=ntr201712fa3.html

## For Inquiries

NTT Service Innovation Laboratory Group
http://www.ntt.co.jp/news2018/1804e/180405a.html

*5 MMT protocol: MMT (MPEG Media Transport) is the digital container standard developed by MPEG (Moving Picture Experts Group), a working group of international standardization organization ISO/IEC. MMT is designed to distribute media via various transmission routes such as broadcasting and IP networks.

# External Awards

**Young Scientist Presentation Award**
**Winner:** Shengnan Wang, Alice Dearle, Hiroki Hibino, and Kazuhide Kumakura, NTT Basic Research Laboratories
**Date:** March 17, 2018
**Organization:** The Japan Society of Applied Physics (JSAP)

For "Growth of Uniform Hexagonal Boron Nitride Film Using Chemical Vapor Deposition."
**Published as:** S. Wang, A. Dearle, H. Hibino, and K. Kumakura, "Growth of Uniform Hexagonal Boron Nitride Film Using Chemical Vapor Deposition," The 78th JSAP Autumn Meeting, Fukuoka, Japan, Sept. 2017.

**TELECOM System Technology Award**
**Winner:** Yoji Yamato, NTT Network Service Systems Laboratories
**Date:** March 22, 2018
**Organization:** The Telecommunications Advancement Foundation

For "Automatic Verification Technology of Software Patches for User Virtual Environments on IaaS Cloud."
**Published as:** Y. Yamato, "Automatic Verification Technology of Software Patches for User Virtual Environments on IaaS Cloud," J. Cloud. Comp., Vol. 4, 2015.

**The Young Scientists' Prize, the Commendation for Science and Technology by the Minister of Education, Culture, Sports, Science and Technology**
**Winner:** Masayuki Hashisaka, NTT Basic Research Laboratories
**Date:** April 17, 2018
**Organization:** Ministry of Education, Culture, Sports, Science and Technology

For his research on electron dynamics in quantum Hall systems.
This prize is given for experimental studies on fractional-quasiparticle excitations and Tomonaga-Luttinger behaviors in quantum Hall systems.

**The Young Scientists' Prize, the Commendation for Science and Technology by the Minister of Education, Culture, Sports, Science and Technology**
**Winner:** Hiroki Mashiko, NTT Basic Research Laboratories
**Date:** April 17, 2018
**Organization:** Ministry of Education, Culture, Sports, Science and Technology

For his research on a petahertz optical drive with wide-bandgap semiconductor characterized by an isolated attosecond pulse.
This prize is given for experimental studies on observation of petahertz (quadrillion of a hertz) electron oscillation in a gallium nitride semiconductor using an isolated attosecond pulse.

**Achievement Award**
**Winner:** Yoshihide Tonomura, NTT Service Evolution Laboratories
**Date:** June 19, 2018
**Organization:** The Telecommunication Technology Committee

For his contribution to the standardization of immersive live experience technology.

# Papers Published in Technical Journals and Conference Proceedings

**15 × 200 Gbit/s 16-QAM SDM Transmission over an Integrated 7-core Cladding-pumped Repeatered Multicore Link in a Recirculating Loop**

C. Castro, S. Jain, E. De Man, Y. Jung, J. Hayes, S. Calabrò, K. Pulverer, M. Bohn, S. Alam, D. J. Richardson, K. Takenaga, T. Mizuno, Y. Miyamoto, T. Morioka, and W. Rosenkranz

IEEE Journal of Lightwave Technology, Vol. 36, No. 2, pp. 349–354, January 2018.

We investigate a realistic integrated multicore system consisting of directly spliced components: homogeneous trench-assisted seven-core fiber with a length of 60 km, cladding-pumped seven-core amplifiers, integrated seven-core isolators, and fiberized fan-in/fan-out couplers. We analyze the performance of an in-line repeatered multicore transmission system in a recirculating loop by transmitting a 200 Gbit/s 16-QAM test channel and 14×100 Gbit/s QPSK neighboring channels between the wavelengths of 1558.58 and 1564.27 nm in a 50-GHz grid. For every position of the test channel within the considered band we demonstrate transmission distances over 720 km.

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**Ultrahigh-spectral-efficiency WDM/SDM Transmission Using PDM-1024-QAM Probabilistic Shaping with Adaptive Rate**

H. Hu, M. P. Yankov, F. Da Ros, Y. Amma, Y. Sasaki, T. Mizuno, Y. Miyamoto, M. Galili, S. Forchhammer, L. K. Oxenløwe, and T.

Morioka

IEEE Journal of Lightwave Technology, Vol. 36, No. 6, pp. 1304–1308, March 2018.

We demonstrate wavelength-division-multiplexed (WDM) and space-division-multiplexed (SDM) transmission of probabilistically shaped polarization-division-multiplexed (PDM) 1024-state quadrature amplitude modulation (QAM) channels over a 9.7-km single-mode 30-core fiber, achieving aggregated spectral efficiency of 297.82 bit/s/Hz on a 12.5-GHz grid and 7.01-Tbit/s spatial-superchannel on a 25-GHz grid without multiple-input multiple-output (MIMO) processing. Actual soft-decision forward error correction (SD-FEC) decoding was employed to obtain error-free performance, and adaptive rates and spectral efficiencies for individual WDM/SDM channels have been applied according to their channel conditions by adjusting the SD-FEC overhead without changing the modulation format. Probabilistically shaped PDM-1024-QAM has been used to further increase the aggregated achievable rate due to the added performance improvement through shaping gain.

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### Hybrid Cladding-pumped Multicore EDFA/Raman Amplification for Space Division Multiplexing Transmission Systems

T. Mizuno, A. Isoda, K. Shibahara, H. Ono, M. Fukutoku, and Y. Miyamoto

Optics Express, Vol. 26, No. 10, pp. 13639–13646, May 2018.

We propose and demonstrate a hybrid cladding-pumped multicore erbium-doped fiber amplifier (EDFA) and distributed Raman amplification for space division multiplexing transmission systems. The cladding-pumped multicore EDFA is used to efficiently amplify signals in multiple cores simultaneously, while Raman pumping is used to control loss in each core individually. We construct an in-line amplified 7-core transmission line, and show that distributed Raman amplification can compensate loss variation between cores. Furthermore, we transmit 46 WDM PDM-16QAM signals over a long distance of greater than 1000 km and demonstrate good transmission performance.

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### Temporary Optical Coupler for Optical Cable Re-routing without Service Interruption

T. Uematsu, T. Kiyokura, H. Hirota, H. Iida, T. Kawano, and T. Manabe

IEEE Photonics Journal, Vol. 10, No. 3, June 2018.

We design a temporary optical coupler to obtain high injection and extraction efficiencies while keeping the bending loss low with the aim of realizing optical cable re-routing without service interruption. The temporary optical coupler injects/extracts signal lights into/from a fiber by using fiber bending. The extraction efficiency is improved by using a double-clad fiber or a graded-index fiber for light injection and extraction, while the injection efficiency is maintained compared with that of a conventional temporary optical coupler that uses a single-mode fiber. This improvement enables us to realize an optical cable re-routing operation support system that requires no service interruption.

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### Label Propagation with Ensemble of Pairwise Geometric Relations

X. Wu, K. Hiramatsu, and K. Kashino

International Journal of Computer Vision, Vol. 126, No. 7, pp. 689–713, July 2018.

Spatial verification methods permit geometrically stable image matching, but still involve a difficult trade-off between robustness as regards incorrect rejection of true correspondences and discriminative power in terms of mismatches. To address this issue, we ask whether an ensemble of weak geometric constraints that correlates with visual similarity only slightly better than a bag-of-visual-words model performs better than a single strong constraint. We consider a family of spatial verification methods and decompose them into fundamental constraints imposed on pairs of feature correspondences. Encompassing such constraints leads us to propose a new method, which takes the best of existing techniques and functions as a unified Ensemble of pAirwise GEometric Relations (EAGER), in terms of both spatial contexts and between-image transformations. We also introduce a novel and robust reranking method, in which the object instances localized by EAGER in high-ranked database images are reissued as new queries. EAGER is extended to develop a smoothness constraint where the similarity between the optimized ranking scores of two instances should be maximally consistent with their geometrically constrained similarity.

Reranking is newly formulated as two label propagation problems: one is to assess the confidence of new queries and the other to aggregate new independently executed retrievals. Extensive experiments conducted on four datasets show that EAGER and our reranking method outperform most of their state-of-the-art counterparts, especially when large-scale visual vocabularies are used.

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