Overview of Optical Science and Technology at NTT Basic Research Laboratories

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Abstract

Although the progress of electronic devices has followed Moore's law up to now, microelectronics is approaching its fundamental physical limits. The demand for broadband networks is rapidly increasing and this has led to a growing need for an all-optical network. This paper gives an overview of the present status and future expectations of optical science and technology for the photonic network.

1. Introduction

The Optical Science Laboratory (OSL) of NTT Basic Research Laboratories (BRL) is a completely new laboratory dedicated to finding new concepts and phenomena based on quantum optics and optical properties. This basic research is a continuation of many years of research in the old Physical Science Laboratory of NTT-BRL, which produced many of the brilliant successes on the road to establishing today's fiber transmission systems.

We are now beginning to meet the challenges of the new age of the photonic network. As the trend of Internet subscriptions in Japan (**Fig. 1**) [1] shows, the total number of subscribers is gradually saturating, but the percentage of broadband users is increasing rapidly, especially in terms of FTTH (fiber to the home) users. Thus, the total subscriber traffic is growing quickly, as seen by the rapid growth in IP (Internet protocol) exchange traffic transmitted through the backbone network in Japan (**Fig. 2**) [2], [3]. Therefore, we need to increase the traffic-carrying capacity of the network and simultaneously reduce costs.

An all-optical IP network based on wavelength division multiplexing (WDM) transmission and all-optical switching at the network nodes is a promising system for resolving the above problems [4]. To create such a system, we must be able to control the optical signals without optical-to-electrical and electrical-to-optical conversion at the nodes [5]. Such nodes require not only large-scale integrated optical switching devices but also memory devices to keep the optical signal as it is.

This paper outlines recent trends in optical science and technology related to silicon photonics for highly integrated optical circuits using silicon photonic crystal, slow light as an active optical buffer memory, quantum cryptography for a secure photonic network, and other new optical phenomena. It also introduces the other selected papers in this issue, which provide an update to previous selected papers in NTT Technical Review in 2003 and 2004.

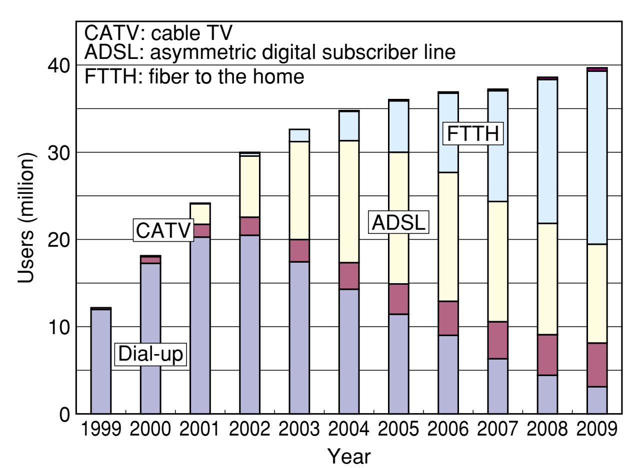

Fig. 1. Estimated number of Internet users in Japan.

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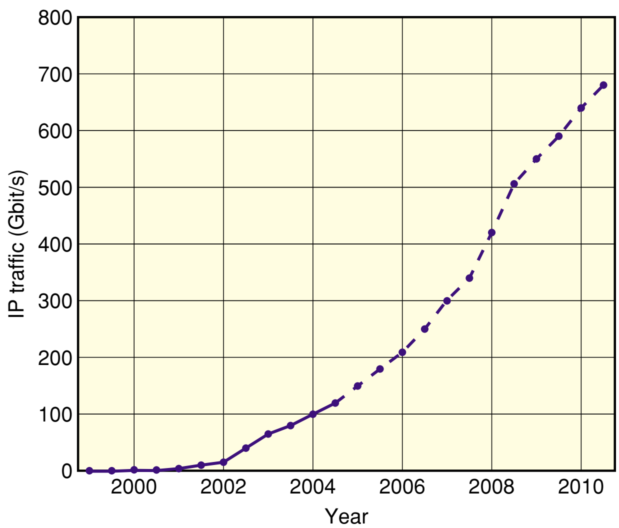

Fig. 2. Trend and estimate of IP traffic on backbone network.

2. Silicon photonics

Silicon is an almost perfect semiconductor for electron devices. Its only drawback as a material is that it cannot emit light easily because of its indirect interband transition. Recently, the monolithic integration of electronics and optics in silicon has attracted considerable attention because it can reduce unwanted electrical parasitics and also make it possible to reduce the overall size. Moreover, silicon computers are nearing the physical limit of their ability to carry information electronically, and they will need something similar to the fiber-optic network if the rate is to continue to improve. The use of optical signals without electrical conversion is a promising technique, and silicon photonics is a key technology for achieving it. We are currently pursuing two parallel approaches to opto-electronic integration in silicon. The first is to achieve a level of photonic integration that is much higher than that of a conventional planar lightwave circuit (PLC). The second is to create functional devices that cannot be achieved electronically.

Optical devices such as add/drop multiplexers, n × n switchers, and n-channel selectors are composed of PLCs, where the light waveguide is fabricated on a silicon wafer such as an LSI (large-scale integrated circuit), and the light signal pulses pass through the circuits by following the waveguide. The basic principle of handling optical signals in a PLC involves confining light in the waveguide using the total reflection phenomenon found in, for example, optical fiber. Light is confined as a result of the small difference between the reflective indices of the waveguide core and cladding. Therefore, the waveguide should not be bent sharply: the usual minimum bending radius is about 5 mm, which prevents us from miniaturizing the PLC.

Photonic crystals are periodic dielectric or metallo-dielectric nanostructures that are designed to affect the propagation of light in the same way that the periodic atomic configuration in a semiconductor crystal affects the electron motion by defining allowed and forbidden electronic energy bands. If we fabricate line or point defects in photonic crystals, we can propagate the light along the defects or confine it in the defects. We can confine the light in a sharply bent line defect because the confinement is achieved by diffraction rather than total reflection. This means that we can design a much smaller lightwave circuit with much greater freedom than when using a PLC. Photonic crystals that are three-dimensionally periodic would be ideal for 3D optical integrated circuits, but they are very difficult to fabricate. Two-dimensionally periodic photonic crystal is practical: the light is confined in the XY-plane by the photonic crystal structure and along the Z-axis by total reflection. We can fabricate a lightwave circuit in a photonic crystal plane in the same way as a PLC. Since the basic physical phenomenon of photonic crystal is based on diffraction, the periodicity of the photonic crystal structure must be on the same scale as the wavelength of the light i.e., about 400 nm for photonic crystals operating in the 1.55-μm region.

We have already developed the components of photonic crystal lightwave circuits, which include single-mode waveguides, a high Q-value resonator, and a spot-size converter to enable connection to an optical fiber. We are aiming to make large-scale integrated photonic circuits that are ultrasmall (**Fig. 3**). Two major results are introduced in other selected papers in this issue [6], [7].

3. Slow light

The speed of light is about 300,000 km/s in a vacuum, and it is very difficult to slow light down. Sometimes we need to delay optical pulse signals, so we use a long optical fiber as a delay line. However, it is impossible to extract a signal on demand or keep it for a long time. Although we can control the speed by changing the refractive index of the medium in which the light propagates, the range of speed is very small. We are currently pursuing two parallel approaches for controlling the speed of light. The first is to use a pho-

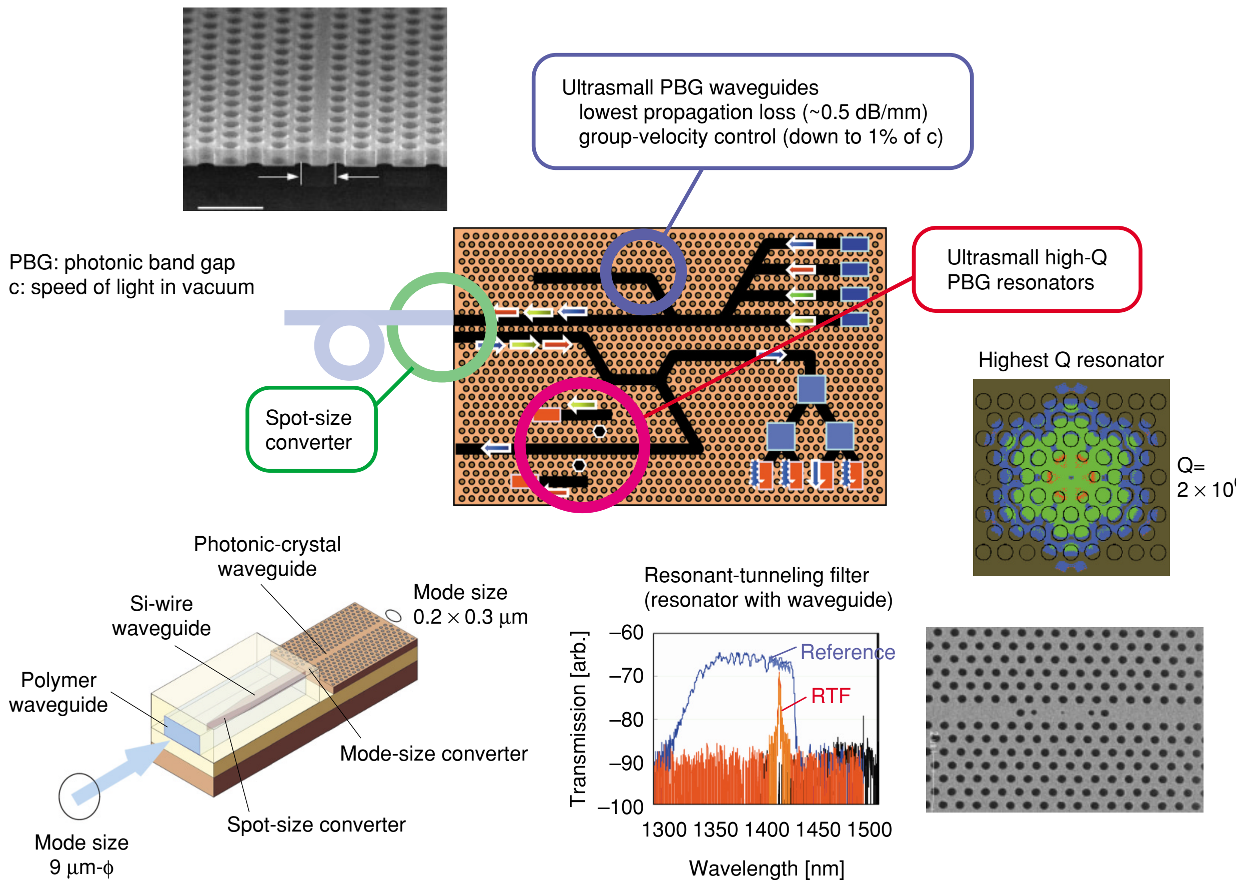

Fig. 3. Schematic of integrated optical circuit using photonic crystal.

tonic crystal structure, which provides us with a very large change in speed. The second is to convert photon information to nuclear spin information and then retrieve that.

A photonic crystal can not only confine the light but also reduce its speed. The group velocity dependence of the dispersion characteristics in photonic crystal is very different from that of a conventional waveguide and can be widely tuned by designing the line defect structures. The group velocity v_g is expressed as the derivative of the dispersion curve, that is, $v_g = (d\omega(k)/dk)$, and the slope of the curve for the line defect waveguide in photonic crystal is gentle near the band edge. This means that the photonic crystal structure enables us to slow down the apparent speed of light. It should be noted that the photonic crystal structure does not change such intrinsic properties of silicon as the refractive index; however, multiple diffraction or scattering leads to a reduction in the propagation of light.

Several line defect waveguides embedded in photonic crystal were fabricated on a silicon wafer, and the group index was measured using Fabry-Pérot interference. As a result, the deduced group index varied approximately from 5 to 90. This means that the speed of light propagating along a defect line was 1/5 to 1/90 the speed in air [8].

Although photons are difficult to localize and store, they are the fastest and most robust carriers of quantum information. On the other hand, nuclear spins can be localized and can retain quantum information for several seconds. If the quantum information held by photons can be mapped to nuclear spins temporarily, this disadvantage of photons could be overcome. Recently, an approach based on the use of electromagnetically induced transparency (EIT) has demonstrated a classical memory for light [9]-[12].

EIT is an effect that allows the effective speed of light through a medium to be slowed by several orders of magnitude or allows normally opaque objects to transmit light. Its mechanism is explained in **Fig. 4**. The ‘probe light’ is absorbed by the transition of the atomic energy level in the medium and this energy is released as fluorescence. This absorption is

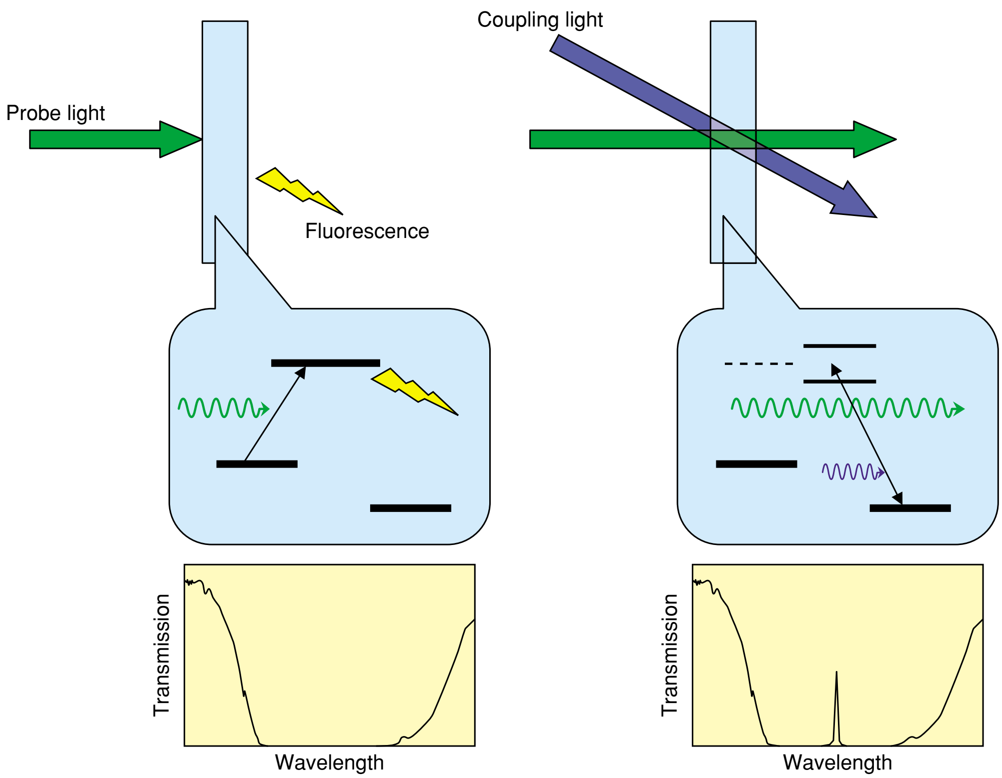

Fig. 4. Schematic of electromagnetically induced transparency.

suppressed by irradiation from the second laser beam, which is referred to as ‘coupling light’. The coupling light splits the upper energy level, so the probe light is not absorbed at the original wavelength. In this situation, the dispersion curve of the probe light exhibits a strong dependence on the frequency. This in turn leads to the light having a very slow group velocity.

We are studying EIT using a quantum dot in a semiconductor. The quantum dot is a suitable place in which to manipulate electrons, holes, and nuclear spins by using light. An exciton is a pair consisting of an electron and a hole generated by irradiating the quantum dot with light. The strong coupling between the exciton and photon generates a polariton, which is confined in the quantum dot and preserves the quantum information of the photon [13], [14].

4. Quantum cryptography

The security of today’s main cryptosystem, known as the public key system, is based on the large number of calculations required to break it. That is, while it is easy to calculate the product of two prime numbers such as 68,737 and 75,367, it takes much longer to extract the factors X and Y of a large number such as:

$$5{,}180{,}501{,}479 = X \times Y \tag{1}$$

Several decades ago, it took a computer several hours to obtain the values of X and Y, but now it takes only a few milliseconds. Personal computers can now resolve the 64-digit number 3789628733 3037522463 4064576462 6869366881 8845178228 6296222614 5991 into factors within 5 minutes. Therefore, the safety of the public key cryptosystem is becoming increasingly fragile.

Quantum cryptography is a system that provides two people with secret keys. (In the field of cryptography, the conventional names for the two communicating parties are Alice and Bob, while Eve is the name given to an eavesdropper.) Since this system does not encode the message itself using quantum mechanics, a more accurate name for this system is quantum key distribution.

The most famous quantum cryptography protocol is BB84, which was proposed by Bennett and Brassard in 1984 [15], [16]. BB84 uses four different bases, namely vertical and horizontal polarizations for table A and clockwise and anti-clockwise polarizations for table B. Alice selects the table randomly and sends a photon whose state is one of the bases on the table, and Bob receives the photon using a randomly selected table. Therefore, half of the signals received by Bob would be discarded if Alice and Bob did not select the same table. Moreover, the so-called plug-and-play scheme is used for fiber transmission because it can cancel out the influence of fiber dispersion by propagating the light in both directions through the fiber. However, there are several disadvantages including an increase in the noise photons as a result of Rayleigh backscattering.

NTT and Stanford University have proposed a new protocol called differential phase shift quantum key distribution (DPS-QKD) to improve the plug-and-play BB84 protocol [17]-[19]. The setup for DPS-QKD is shown in **Fig. 5**. Alice randomly modulates the phase of a coherent pulse train and transmits it with a power level of 0.1 photons per pulse. Bob detects the pulses after they have passed through a one-bit-delay interferometer and records both the received time and which detector clicked. Bob tells Alice the time instance of the photon detection. From this information and her modulation data, Alice knows which detector clicked at Bob's site. Alice and Bob have an identical bit string provided that the D1 click represents "0" and the D2 click represents "1". In the above protocol, Bob only tells Alice the time instance; the bit information is not disclosed to the public.

This system has two main advantages over BB84. One is that DPS-QKD can use all the data Bob receives, which means that the key generation rate is up to double that of BB84. The other is that the transmission is one way, which means that it is free from backscattering noise. The dependence of the raw key generation rate of the reported BB84 and DPS-QKD on transmission distance is shown in **Fig. 6**. Note that the raw key includes some bit errors, so error correction and privacy amplification are needed if the secure key is to be shared. The best key generation rate obtained to date is much slower than the data transmission rate, so this speed must be increased. The main factor limiting the rate is the performance of the detector. The conventional detector for a single photon in the 1.55-µm band is an InAs avalanche photodiode. The quantum efficiency of this detector is about 10%, and several types of noise including the dark count and the after-pulse prevent a higher rate of detection. We are developing a new detection method using parametric up-conversion with periodically poled lithium niobate. This enables us to convert a 1.55-µm photon to a 0.7-µm one, which is much eas-

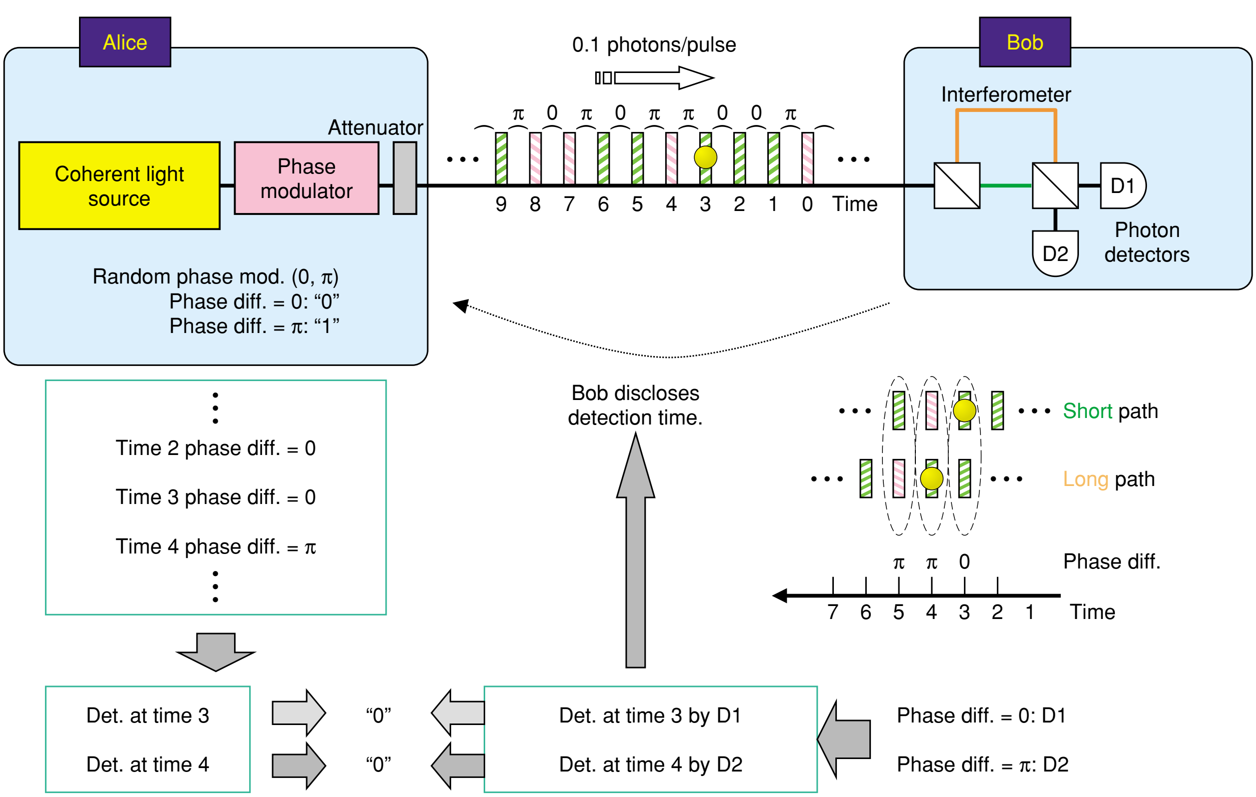

Fig. 5. Setup and protocol of differential phase shift quantum key distribution (DPS-QKD).

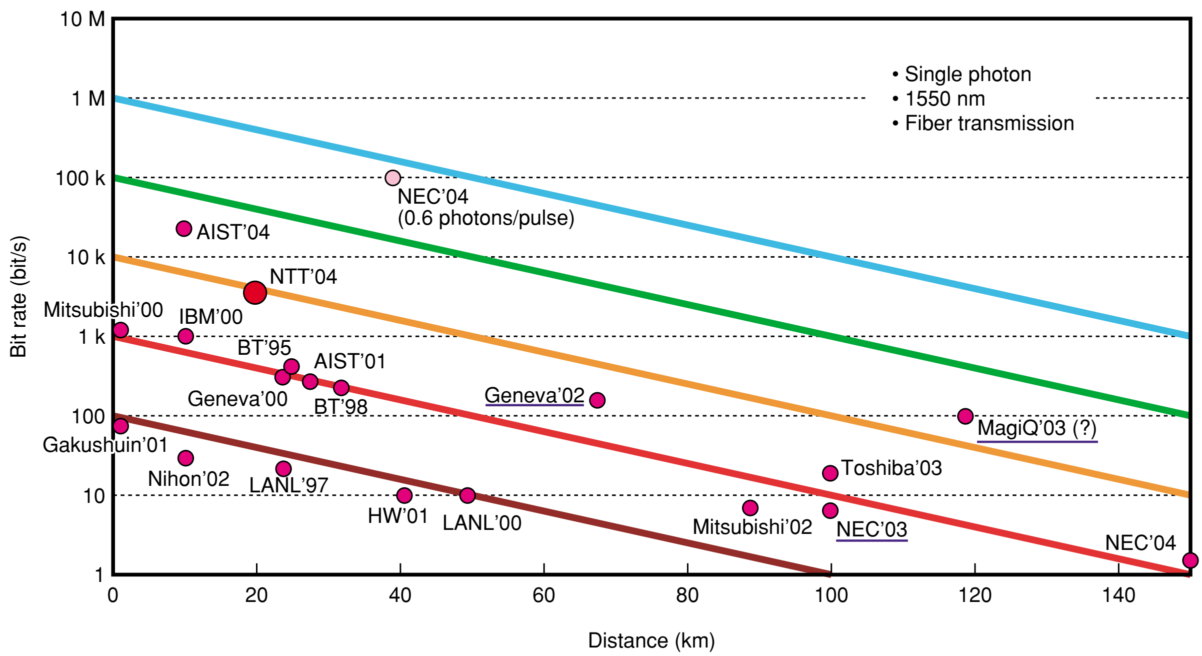

Fig. 6. Comparison of key generation rates and transmission distances of quantum cryptography methods.

ier to detect using a silicon avalanche photodiode.

In order to provide a less expensive and widely accessible cryptosystem, it will be essential to use an ordinary network, such as the Internet. In a public network, the signal photon must be propagated not only through optical fibers but also through an optical switching board to reach the correct receiver. However, it was unclear if such a weak signal as a single photon could be controlled in the same way as a commonly used light signal. We demonstrated the transmission and route control of a single photon through an optical switching board composed of interferometric-type optical switches (PLC-MZ). First, we confirmed that a weak pulse signal at the single-photon level could be input into one port of the switch and detected from one port and that by changing the switch condition we could control the optical path. Next, we sent a weak signal together with a large-bandwidth data transmission. Although the two lights crossed in the matrix switch, we were able to send them simultaneously and independently by using an optical filter at the weak signal receiver port.

Unfortunately, a photon signal used for quantum cryptography cannot be amplified because amplification destroys the quantum state of the photon. Therefore, we need a new method if we are to transmit the signals over a long distance. Quantum entanglement—the curious physical phenomenon in which two or more photons share a single, inseparable quantum state—is one of the candidates for increasing the transmission distance. Entangled photon pairs can be separated into individual photons and sent in different directions, and their quantum correlation is still maintained after separation. The generation of entangled photon pairs is described in the sixth of the selected papers in this issue [20].

5. Ultrashort light pulse

Ultrashort light pulse technology is very important, not only for achieving higher-bit-rate communications, but also for exploring various phenomena in chemistry and physics that will lead us to a new world governed by new concepts. We introduce two main results related to ultrashort light pulses in this issue. One is high irradiance, namely short-pulse soft X-ray generation from femtosecond laser-produced plasma, and its application to the analysis of very fast chemical phenomena, which is described in the fourth paper [21]. The other is the ultimate control of optical pulses including both the carrier envelope and the phase included in the pulse, which is described in the fifth paper [22].

6. Conclusion

The importance of optical science and technology is increasing rapidly, because of the rapid growth in the demand for broadband communication and because electronic devices cannot meet all the requirements of a high-speed network with a large carrying capacity. NTT Basic Research Laboratories is always considering the society of the future, namely our lives and environment ten or twenty years from now, and pursuing ways to create the systems, equipment, devices, and materials that will be needed at that time. An optical buffer memory is one such key device that must be made, but the underlying principle and fundamental physics for it are still unclear. We must find new concepts that can act as the bases for achieving our dreams.

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