# 3 Photonic Networks

## 3-1 Optical Code Division Multiplexing and Its Application to Peta-bit/s Photonic Network

Hideyuki SOTOBAYASHI, Wataru CHUJO, and Ken-ichi KITAYAMA

Future ultrafast photonic networks will perform transferring signals in the optical layer. The target of the photonic networks is to provide services at data rates much higher than electronic network can. Ultrafast photonic processing is expected to play a key role in future peta-bit/s photonic networks. Because ultrafast photonic processing could advantageously remove the speed limit that electronics imposes severe technology and economic constraints. Applications of optical code division multiplexing (OCDM) to multi-tera bit/s photonic network based on ultrafast photonic processing are reported. A high spectrum efficiency OCDM/WDM transmission as a link technology, and a transparent virtual optical code/wavelength path (VOCP/VWP) network as a node technology are experimentally demonstrated.

***Keywords***
**Photonic Network, Node, Link, Photonic processing, Peta-bit/s, Optical code division multiplexing**

## 1 Introduction

The rapidly increase in demand for bandwidth from end-users forces network infrastructure to be peta-bit/s capacity. The efficient utilization of the bandwidth of an optical fiber is a major issue in the design of ultra-high-speed photonic networks. The two primary techniques for multiplexing data signals onto the channel of a single fiber are currently time division multiplexing (TDM) and wavelength division multiplexing (WDM). Optical code division multiplexing (OCDM) is an alternative method. A proper choice of optical codes allows signals from all connected network nodes to be carried without interference between signals. Simultaneous multiple access can thus be achieved without a complex network protocol to coordinate data transfer among the communicating nodes[1]. Therefore, OCDM can provide certain real advantages when applied to photonic networks, due to its unique combination of qualities: such as asynchronous transmission, a potential of communication security, soft capacity on demand, and high degree of scalability[2][3]. As a result, the applications of OCDM range from point-to-point transmission[2][3], multiple access[4], an optical path network[5][6], and label switching routing[7][8].

In this paper, we review the applications of OCDM to photonic networks based on ultrafast photonic processing in order to pursuit for developing peta-bit/s capacity networks. In section **2**, the basic concept of ultrafast Photonic processing and its application is explained. In section **3**, we report high spectrum efficiency, multi-tera-bit/s OCDM/WDM transmission as a link technology[3]. In section **4**, we report demonstration of ultra-wideband and transparent virtual optical code/wavelength path network as a node technology[8].

## 2 Ultrafast photonic processing

Ultrafast photonic processing techniques are expected to play a major role in future photonic networks. At data rates near and above 40 Gbit/s, electronics imposes severe technology and economic constraints, which ultrafast photonic processing could advantageously remove. The quasi-instantaneous response of Kerr nonlinearity in fibers makes it an attractive effect to overcome bandwidth limitations. Consider two optical beams of different wavelength copropagating in the same fiber, as shown in Fig.1, the intensity dependence of the refractive index leads to a large number of interesting nonlinear effects; self-phase modulation (SPM), cross-phase modulation (XPM), and four-wave mixing (FWM).

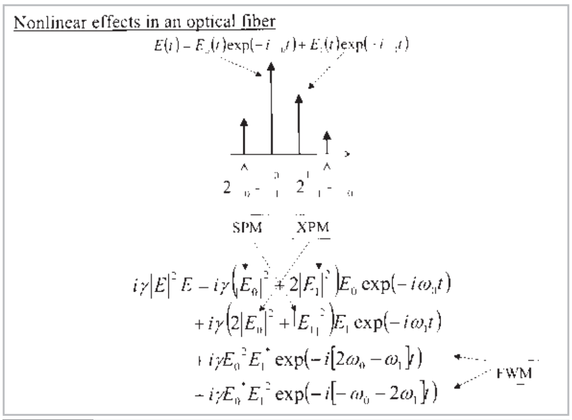


**Fig.1** *Nonlinear effects in an optical fiber*

Photonic processing using optical fiber nonlinearity is categorized into three functions as shown in Fig.2. One is multiplexing in the optical domain, which are used as optical switches, multiplexers, and demultiplexers[9][10]. Another is wavelength conversion, which widely applies to WDM systems. The other is the phase-conjugation generation that applies to the midway optical phase conjugation (OPC) system[11][12].

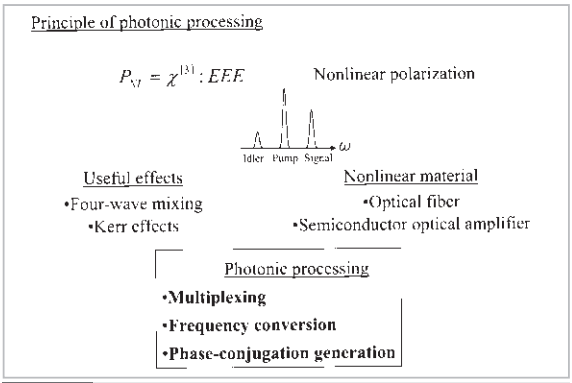


**Fig.2** *Ultrafast photonic processing*

One of the applications of photonic processing using optical fiber nonlinearity is supercontinuum (SC) generation[13][14][15]. SC is the promising technique to generate multi-wavelength optical source used mainly for WDM networks. The techniques to generate SC in optical fibers are divided into two categories. One is spectrum broadening by the pulse compression using soliton effects in anomalous dispersion regime[13]. Another is the spectrum broadening by the accumulation of frequency chirping caused by optical Kerr effects in the normal dispersion regime[14][15]. As shown in Fig.3, in the latter case, the output pulse after propagation in normal dispersion regime is always single pulse. Its shape in the time domain is rectangular and its frequency chirping is almost linear up-chirping. Fig.3 shows the operational principle of multi-wavelength optical signal generation by use of SC[15][16][17]. By spectrum slicing SC using a multiple wavelength filter like an arrayed

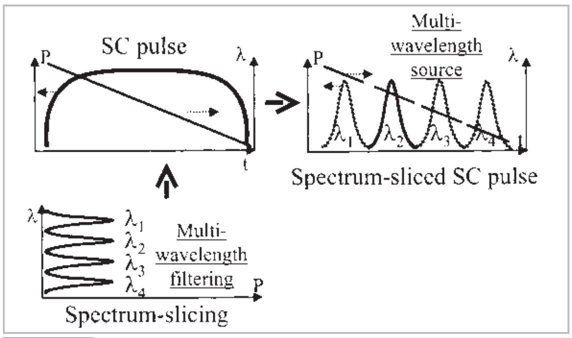


**Fig.3** *Operational principle of multi-wavelength signal generation by spectrum-slicing SC*

waveguide grating (AWG), the multi-wavelength spectrum-sliced SC pulse can be generated. The output pulse by filtering out from SC is always single pulse. The normal dispersion is also useful to generate less intensity fluctuation spectrum. Increasing the input peak power can generate the wider spectrum. These characteristics are attractive for the application of WDM source[18][19].

## 3 1.6 bit/s/Hz, 6.4 Tbit/s QPSK-OCDM/WDM (4 OCDM× 40 WDM×40 Gbit/s) transmission experiment using optical hard thresholding

To meet the peta-bit/s capacity, the spectrum efficiency is becoming a key issue for the full utilization of limited wavelength resources. OCDM is one of the promising multiplexing techniques for the ultimate spectrum efficiency. A record of 1.6 bit/s/Hz spectrum efficiency OCDM/WDM transmission experiment by applying the quaternary phase shift keying (QPSK) optical encoding/decoding accompanied by ultrafast optical time-gating and optical hard thresholding for interference noise suppression. As a result, 6.4 Tbit/s OCDM/WDM (4 OCDM×40 WDM×40 Gbit/s) transmission using only C-band wavelength region is experimentally demonstrated.

### 3.1 Key technologies

QPSK coding is applied to upgrade the spectrum efficiency in OCDM/WDM link[3]. Compared to binary phase shift keying (BPSK) optical coding[2], QPSK optical coding is known to provide the large number of codes with more desirable cross-correlation characteristics. As shown in Fig.4, time spread QPSK pulse codes are used as the optical codes and optical transversal filters are used as optical encoders and decoders. The QPSK-encoded signal is time-despread by the decoder. As a result, QPSK-decoded output shows the correlation waveform, that is, the matched filtering response in the time domain. When the receiver's optical code is matched with the transmitter's optical code, the auto-correlation waveform having a sharp peak at the center is observed. On the other hand, in the case of unmatched codes, the cross-correlation waveform is formed. The transversal filter consists of tunable taps, 5 ps delay lines, programmable quaternary optical phase shifters, and a combiner, all of which are monolithically integrated as a planar lightwave circuit[1]~[8]. An optical code of 3-chip QPSK pulse code sequence with a chip interval of 5 ps is generated. The impulse response of the optical encoding has a frequency periodicity of 200 GHz, because the chip interval of optical encoder is 5 ps[20]. As a result, simultaneous multi-wavelength encoding having the WDM channel spacing of 200 GHz can be achieved using a single optical encoder when a broadband coherent optical pulse such as a SC pulse are used as a chip pulse[2][3].

Besides QPSK optical encoding/decoding, as shown in Fig.4, ultrafast optical hard thresholding along with optical time-gating is applied for the high spectrum efficiency. In order to achieve the strict sense of high process gain, optical time-gating must be introduced to extract only the mainlobe of auto-correlation. As a result, the interference noises arising from interference codes existing outside the time-frame of mainlobe are rejected[1][2]. In addition, by the introduction of hard thresholding in the optical domain, the interference noise existing inside the time-frame of mainlobe also greatly reduces. As shown in Fig.5(a), optical time-gating was performed at 10 GHz repetition rate by using a 100 m high nonlinear dispersion-shifted fiber (HNLF) based nonlinear optical loop mirror (NOLM)[10]. Optical time-gating performs rejecting the interference noise outside the mainlobe of the auto-correlation. For the ultrafast operation, a short length of HNLF was used[2][3][10]. The control pulse used for 10 GHz optical time-gating was 1.5 ps pulse trains and the optical time-gating window ranged from 1.5 ps to 1.8 ps for all WDM channels. As shown in Fig.5(b), optical hard thresholding was achieved by the utilization of the nonlinear transmission response of the second NOLM. The NOLM acts as a pulse shaper by setting the proper threshold level, in the sense that it reflects lower intensity signals but only transmits the higher intensity signal by limiting its intensity to an appropriate level. By adjusting the input signal power, interference noise inside the auto-correlation mainlobe after optical time-gating was suppressed and both signal “0” and “1” level power variations were greatly reduced. For the ultra-high speed operation, the device length and group delay must be shortened. By use of a short length of 50 m HNLF as a hard thresholding NOLM, the group delay in all WDM channels wavelength range (15533–1564 nm) was less than 200 fs, resulting in ultrahigh speed operation.

### 3.2 Experiments and discussions

Fig.6 shows the experimental setup of 6.4 Tbit/s OCDM/WDM (4 OCDM×40 WDM×40 Gbit/s) transmission. A 10 GHz, 1.5 ps pulse trains of the mode-locked laser diode (MLLD) at 1532 nm was 10 Gbit/s modulated and optically multiplexed to 40 Gbit/s. After amplified to the average power of 0.48 W, it was launched into a SC fiber (SCF)[15]. The generated 40 Gbit/s SC signal was linearly polarized and split into eight, and each serves as the light source for simultaneous multi-wavelength optical encoding using QPSK optical encoder. Two groups of four different optical encoded signals were generated. One group of which is changed to orthogonal polarized and both groups of 4 OCDM signals were multiplexed to orthogonal polarized multi-wavelength 2×4 OCDM×40 Gbit/s signals. Each group had the WDM channel spacing of 200 GHz, which corresponds to 1.6 bit/s/Hz spectrum efficiency. The transmission line was composed of two spans of reversed dispersion fiber (RDF) and single mode dispersion fiber (SMF) pair. Each span was 40 km and the total length was 80 km. The average zero dispersion wavelength was 1546.59 nm and the dispersion slope was 0.0087 ps/nm/km/nm. After 80 km transmis-

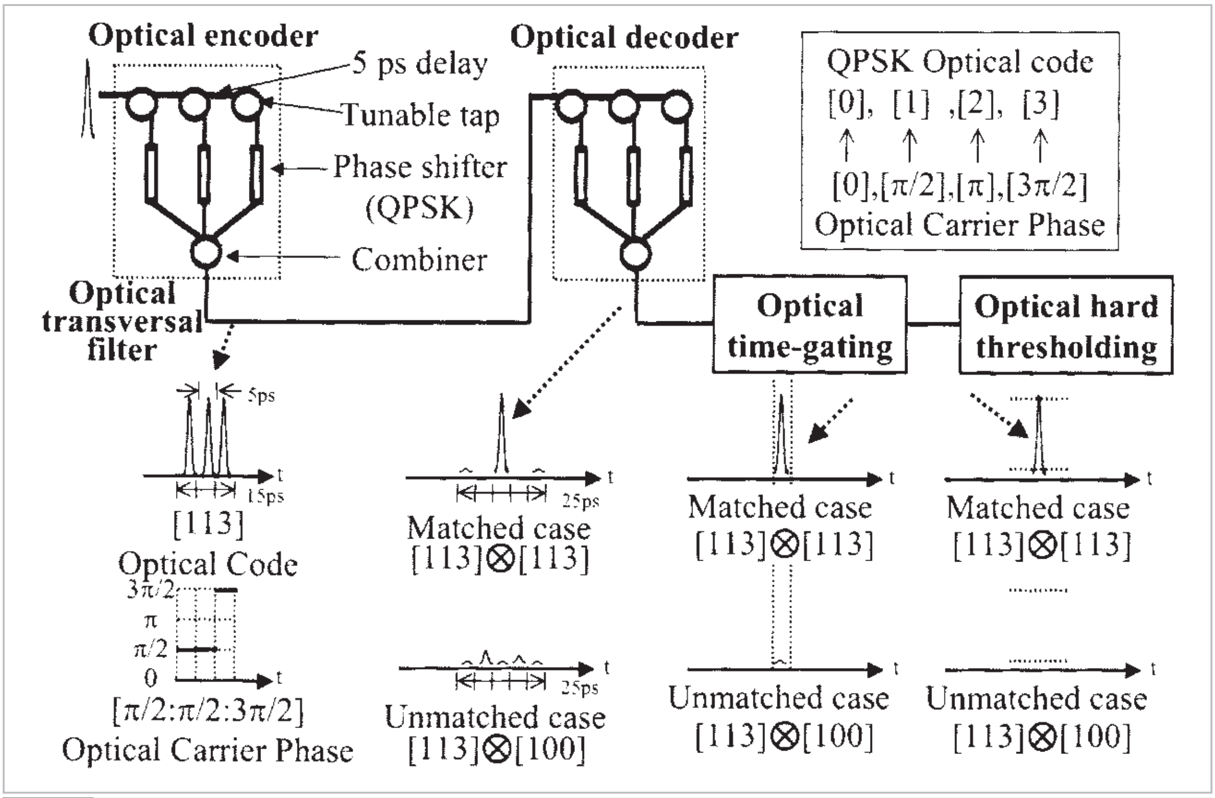


**Fig.4** *Principle operation of QPSK code-OCDM with optical time-gating and optical hard thresholding*

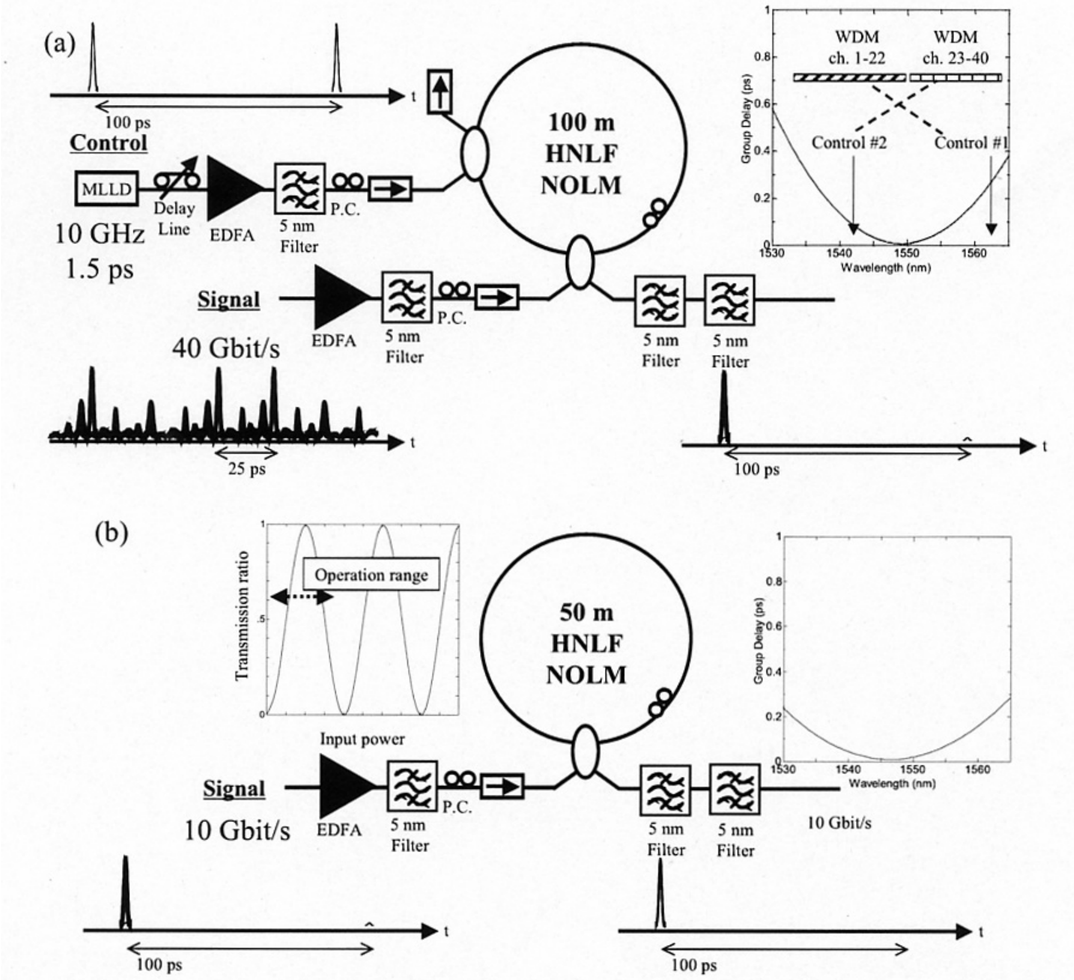


**Fig.5** Operational principle and experimental setup of ultrafast (a) optical time-gating and (b) optical hard thresholding

sion, it was split into two and each was WDM DEMUX by 20 channels arrayed wavelength grating (AWG) having the channel spacing of 200 GHz. The pass band wavelengths of two AWGs were separated by 100 GHz (WDM ch. 1: 1532.68 nm – ch. 40: 1563.86 nm). After WDM DEMUX, frequency chirping is compensated and polarization was demultiplexed. Then, it was decoded by optical decoder and optical time-gated at 10 GHz repetition rate by using a NOLM to suppress the interference noise along with 40 Gbit/s-to-10 Gbit/s demultiplexing. Optical hard thresholding was achieved by the second NOLM.

Fig.7(a)-7(e) respectively show the optical spectrum of (a) SC at the output of SCF, (b) multi-wavelength 2×4 OCDM signals before transmission, (c) after transmission, and (d) odd WDM channels, (e) even WDM channels after WDM and polarization DEMUX. The power difference in all WDM channels was about 8 dB. Fig.8(a) shows the eye diagrams of WDM ch. 40 after optical decoding. The interference noise of other three unmatched codes severely distorted signal to noise ratio. As shown in Fig.8(b), by optical time-gating of the mainlobe of the matched correlation waveforms, interference noise outside the time-gate window was greatly reduced. In addition to this, as shown in Fig.8(c), by introducing optical hard thresholding, interference noise inside the time-gate window was greatly reduced in both signal “0” and “1” level, resulting in clear eye opening. Fig.9 shows the measured BERs of decoded 4 OCDM×40 WDM data signals. For all measured 160 ch. ×40 Gbit/s signals, the BERs were less than 1 $\times 10^{-9}$.

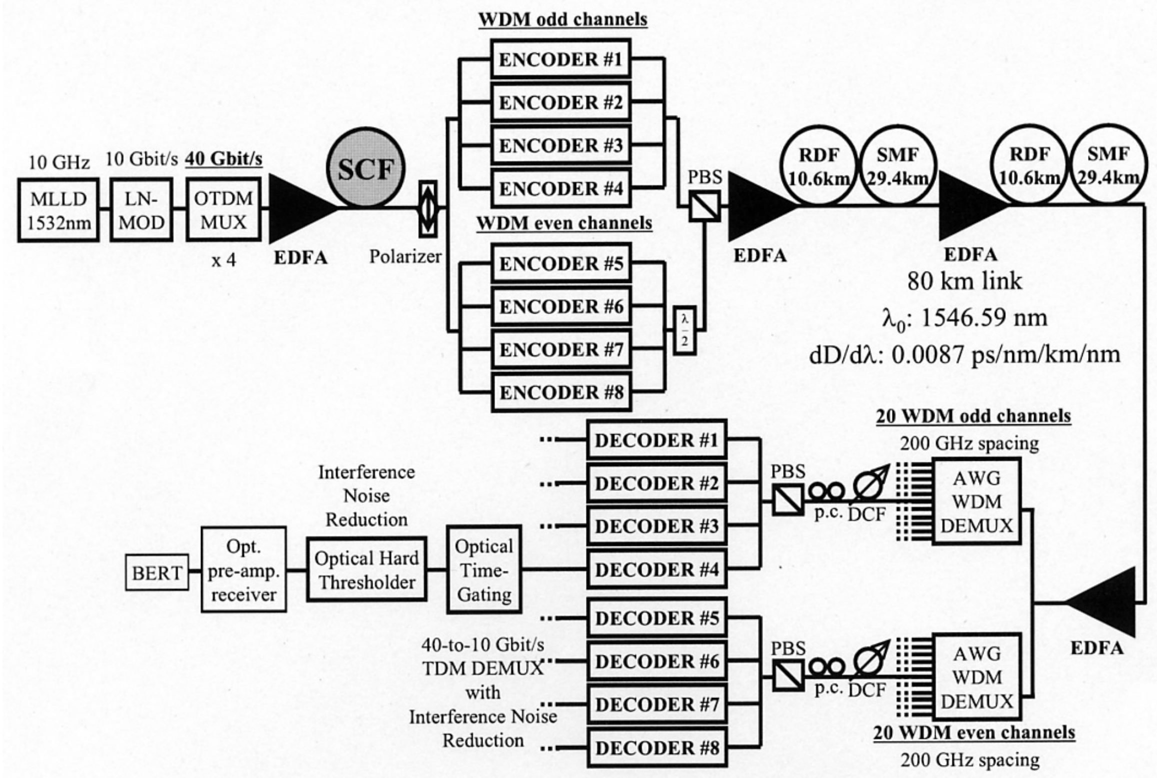


**Fig.6** *Experimental setup*

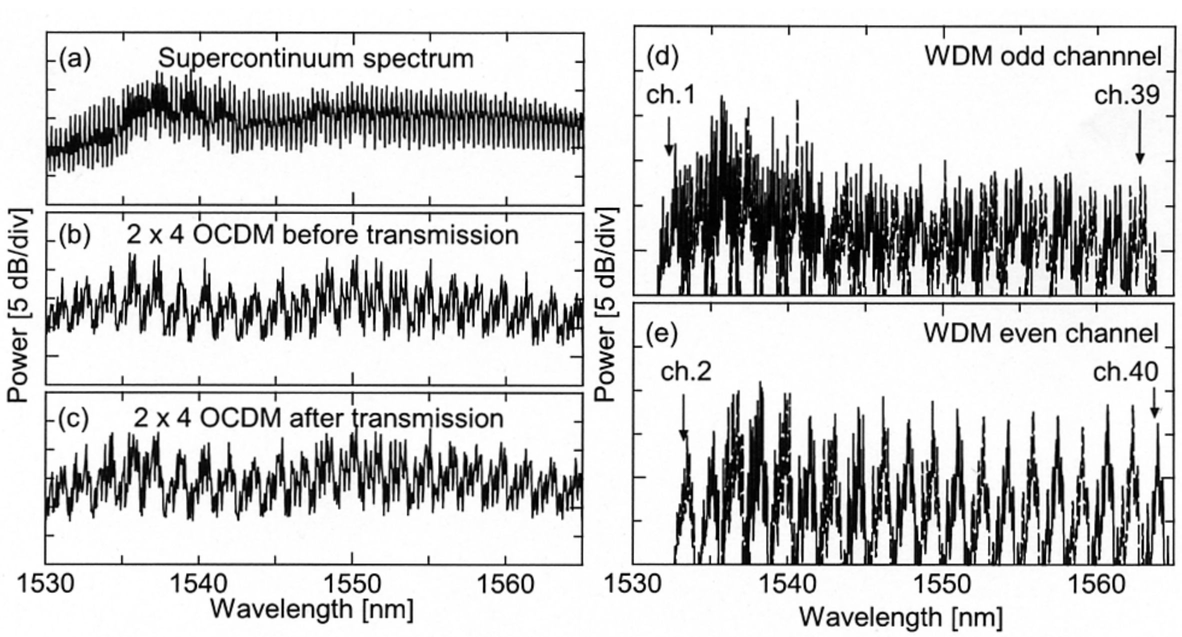


**Fig.7** *(a) 40 Gbit/s SC spectrum. Spectra of 2 x 4 OCDM (b) before transmission, and (c) after transmission. Spectra of (d) odd WDM channels, and (e) even WDM channels after WDM and polarization DEMUX.*

### 3.3 Summary of Section 3

We have experimentally demonstrated a spectrum efficiency of 1.6 bit/s/Hz in OCDM/WDM systems by employing QPSK optical encoding/decoding accompanied by optical time-gating and optical hard thresholding along with polarization multiplexing. As a result, 6.4 Tbit/s OCDM/WDM (4 OCDM×

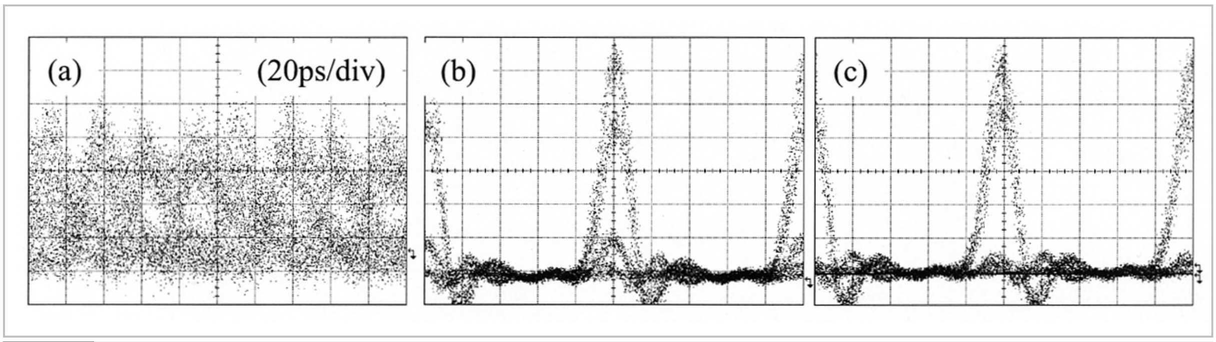


**Fig.8** *Eye diagrams of WDM ch. 40, Optical Code #5 (a) after optical decoding, (b) after optical time-gating, and (c) after optical hard thresholding*

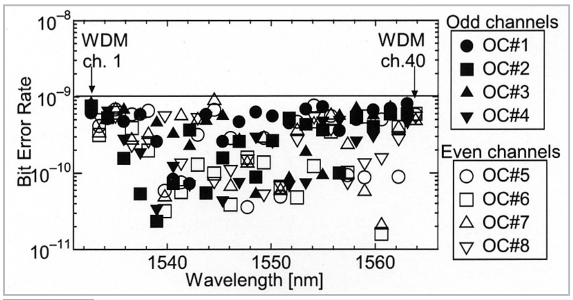


**Fig.9** *Measured BER performances*

40 WDM × 40 Gbit/s) link has been successfully demonstrated only within C-band wavelength region. By increasing the number of optical codes and by expansion the wavelength region such as using the S-, C-, and L-wavelength regions, over 40 Tbit/s OCDM/WDM capacity would be feasible.

## 4 8.05 THz ultra-wideband and transparent virtual optical code/wavelength path (VOCP/VWP) network

OCDM would be favorably applied not only to multiple access networks but also to path networks. The optical code path (OCP), defined as the logical path determined by the optical code (OC), has been proposed within a concept of OCDM networks[5] as shown in Fig.10(a). OCDM can be effectively overlaid onto the existing WDM path networks. The introduction of OCs provides soft capacity of networks and saves the network resources. In the future hybrid OCDM/WDM networks, the flexible OC and wavelength conversion will be a key technology to establish the optical path as shown in Fig.10(b)[6][21].

A simultaneous OC and wavelength convertible node with optical 3R is experimentally demonstrated by SC generation in the operational bandwidth of 8.05 THz. OC and wavelength convertible virtual optical code/wavelength path (VOCP/VWP) network of a total link length of 180 km with four network nodes is also experimentally demonstrated[6].

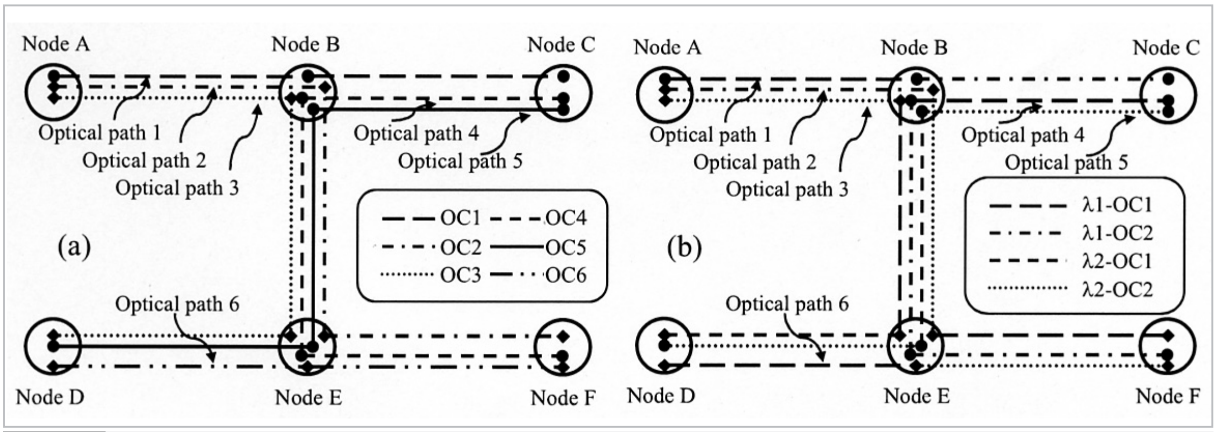


**Fig.10** *Optical paths in (a) OCP network and (b) VOCP/VWP network*

### 4.1 Virtual optical code / wavelength path (VOCP/VWP) network

In OCDM/WDM path networks there are two approaches to OC and wavelength path assignment: without and with the OC and wavelength conversions. Without OC and wavelength conversions, an OC and a wavelength are assigned along the entire optical path, i.e., the optical path is identified by OCP and wavelength path (WP). On the contrary, an optical path provisioning based upon OC and wavelength conversion is referred to as a VOCP/VWP. In the latter case, as shown in Fig.10, the OC and wavelength are allocated link by link. For example, to establish Optical path 3, OC2 at λ2 should be converted to OC1 at λ1 in Node B. To maintain the scalability and reconfigurability of OCDM/WDM path networks, simultaneous OC and wavelength conversion is the key technology which is analogous to the role of wavelength conversion for VWP networks[5]. The introduction of VOCP/VWP potentially solves the OC and wavelength path assignment problems, which may limit the network and optical path expansion.

### 4.2 Experiments and discussions

Fig.11(a) shows the experimental setup of VOCP/VWP path network. For simplicity, data transports of Node A to Node C in Optical path 1 and of Node A to Node E in Optical path 2 and 3 in Fig 10(b) were demonstrated. Three types of OC and wavelength conversions must be done at Node B: i.e., λ1-OC1 to λ1-OC2 (OC conversion), λ1-OC2 to λ2-OC2 (wavelength conversion), and λ2-OC2 to λ1-OC1 (OC and wavelength conversions) in Optical paths 1, 2, and 3, respectively. Each network node was linked by non-zero dispersion-shifted fiber with dispersion compensation fiber. The total lengths were 180 km: i.e. Node A to Node B of 80 km, Node B to Node C of 50 km, and Node B to Node E of 50 km. The average zero dispersion wavelength was 1550.1 nm and dispersion slope was 0.017 ps/nm/km/nm.

At Node A, λ1-OC1, λ1-OC2, and λ2-OC2 were generated and multiplexed. 10 GHz, 1.5 ps pulse trains from the mode-locked laser diodes (MLLDs) at 1549.7 nm (λ1) and 1552.5 nm (λ2) were 10 Gbit/s modulated. Optical transversal filters are used as optical encoders/decoders, each of which consists of 8 variable tapped delay lines with phase shifters. The taps were tuned so that they split into an equi-amplitude eight-pulse sequence. Each delay line had a 5 ps delay. The carrier phase of each tapped pulse was binary changed by 0 or π. Consequently, an optical code of 8-chip BPSK pulse sequence with a chip interval of 5 ps was generated. In this experiment OC1 of[00000000] and OC2 of[0π0ππ0π0] were used.

As shown in Fig.11(b), at Node B, received signals were decoded, 3R regenerated, wavelength converted by SC generation and OC converted. Firstly, they were wavelength demultiplexed using an arrayed-waveguide grating (AWG) having channel spacing of 350 GHz, the FWHM channel width of 284 GHz, and channel number of 24. And they were decoded by optical decoders. Decoded signals were divided into two. One of which lead to injection locked MLLD for 10 GHz clock recovery. The notable feature of the clock recovery was that waveform distortion and noise accumulation are reset (retiming and reshaping) during this process. By clock recovery, high SNR, negligible excess timing jitter, and coherent optical pulses were generated at λc of 1555 nm[22][23]. Recovered clock pulses were divided and one of which are used for pump pulses of semiconductor saturable absorber (SA) time-gate. The time-window opened while the pump pulse saturated the absorber and its duration was 10 ps when a bias voltage was set to –1.7 V[22][23]. By optical time-gating of decoded signal, side-lobe of autocorrelation were rejected and interference noise was greatly reduced[1]. After time-gating, decoded signals were, in turn, used for pump pulses of the second SA time-gate to gate the clock pulse train. By controlling the optical time gate ON/OFF using decoded signals, the data coding could be transferred to newly generated clear optical pulses (regeneration). Thus, all-optical 3R was obtained. For wavelength conversion, SC was produced with pumping by 3R regenerated signals at λc. SCF was a dispersion flattened normal dispersion fiber[15]. After spectrum-slicing using AWG at the wavelength to be converted, they were optical encoded with the OC to be converted. Consequently, simultaneous OC and wavelength conversion with optical 3R was obtained. As shown in Fig.11(c), after subsequent 50 km transmission, OC and wavelength converted signals were detected at Node C or Node E. As was done in Node B, after wavelength demultiplexed and decoded, optical time-gating was done with recovered 10 GHz optical clock to reduce interference noise. The bit error rate was measured after detecting by using an optical pre-amplified receiver.

Measured eye diagram of decoded λ1-OC2 after 80 km transmission at Node B is shown in Fig.12(a). Measured eye diagram of recovered clock induced optical time-gated signals are shown in Fig.12(b). Compared to Fig.12(a), sidelobe and interference noise were greatly reduced. Fig.12(c) shows the optical 3R regenerated decoded signal at λc. As is obviously shown by comparison with Fig.12(b), SNR was increased and timing jitter was reduced by optical 3R. Fig.12(d) shows the optical spectrum of 24 ch. WDM spectrum-sliced SC pumped by optical 3R decoded signal, which ranged from 1524.9 nm to 1590.0 nm that corresponds to 8.05 THz bandwidth. Received power at the BER of $10^{-9}$ for

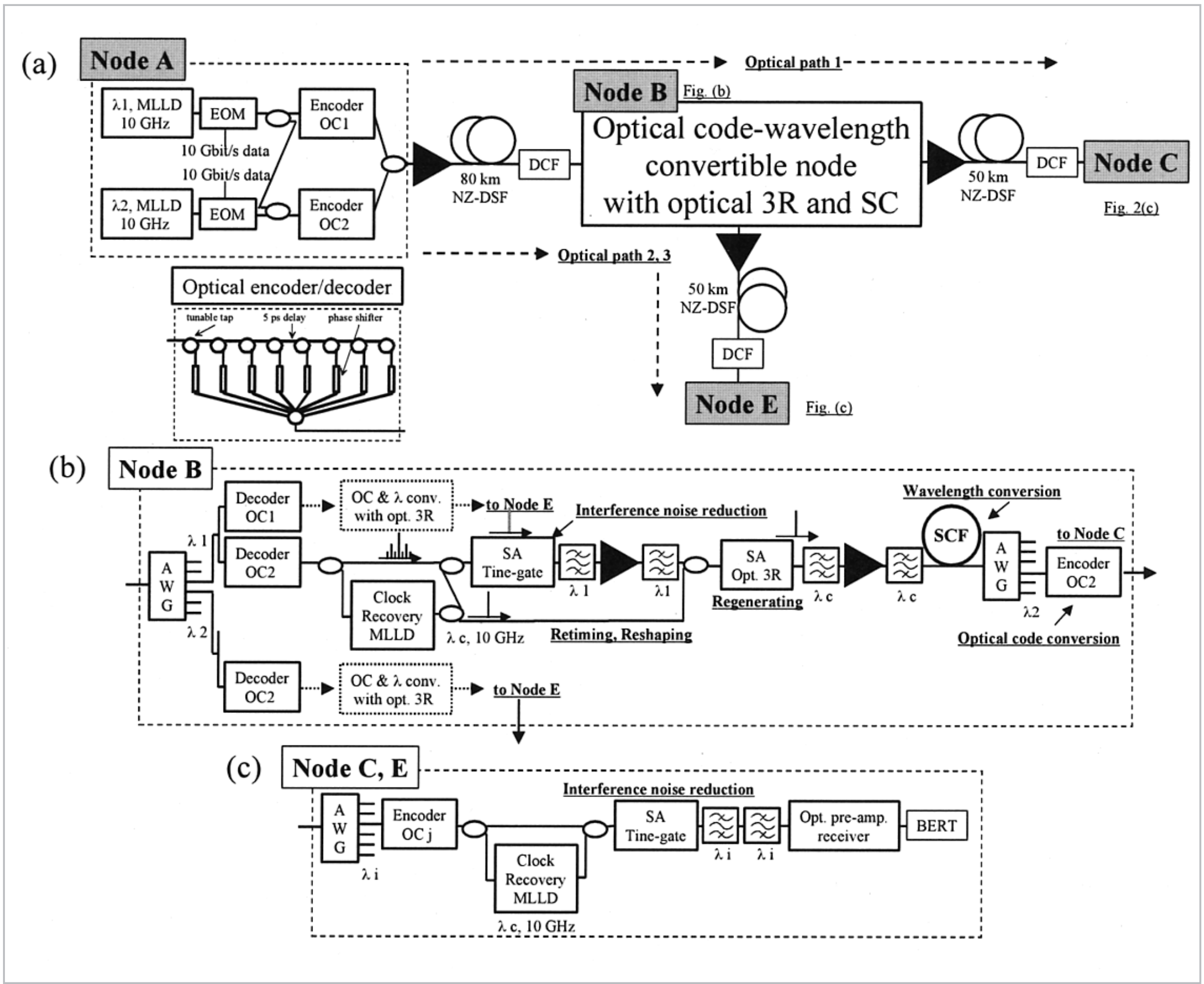


**Fig.11** *Experimental setup of (a) VOCP/VWP network by optical code and wavelength conversion with total link lengths of 180 km, (b) ultra-wideband OC and wavelength conversion by SC generation with optical 3R at Node B, and (c) optical time-gating detection for interference noise reduction at Node C and Node E*

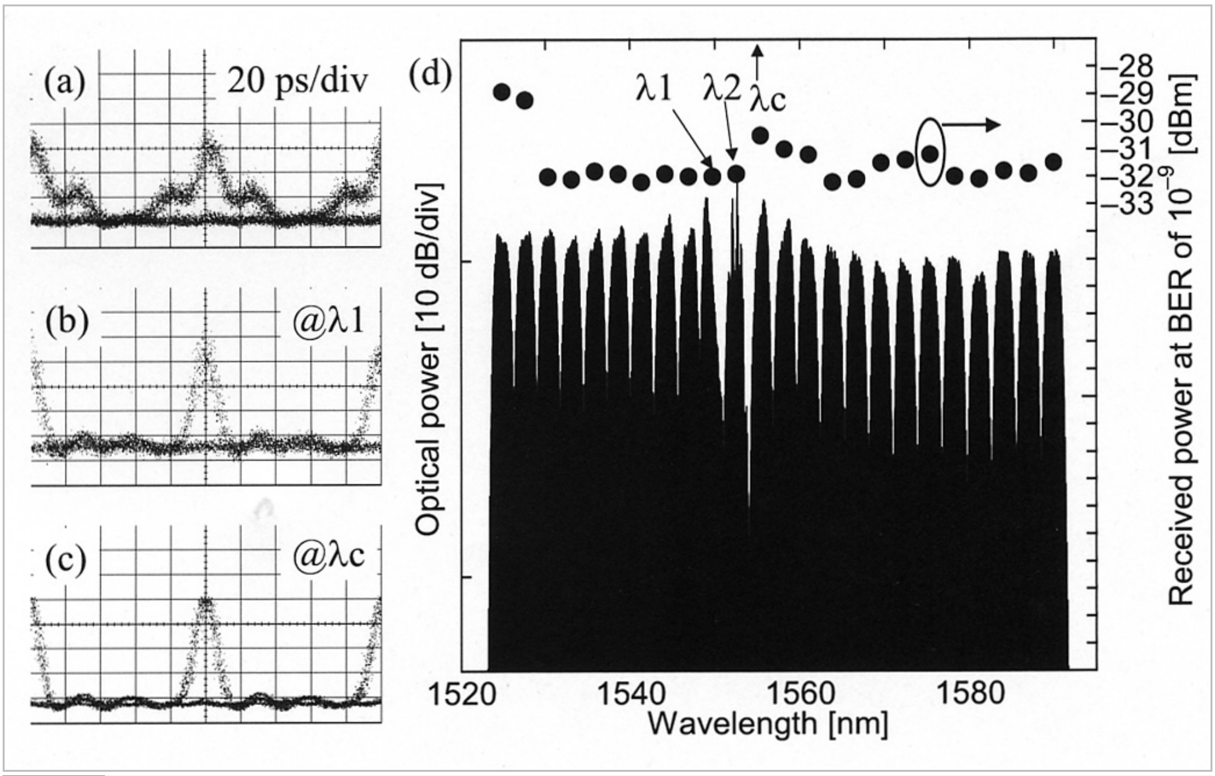


**Fig.12** (a) Eye diagram of decoded **λ**1-OC2 at Node B, (b) eye diagram after optical time-gating for interference noise reduction at **λ**1, (c) eye diagram of decoded signal at **λ**c after optical 3R and (d) optical spectrum after spectrum-sliced SC pumped by optical 3R decoded signal and received power at BER of $10^{-9}$ for each wavelength

each 24 WDM channels were also shown in Fig.12(d). These results show that error-free 24 ch. having the total bandwidth of 8.05THz wavelength and OC conversions were successfully demonstrated using this method.

Fig.13 shows the measured BERs of back-to-back, after 80 km transmission, after OC and wavelength conversion with optical 3R at Node B, and after subsequent 50 km transmission at Node C or Node E. The comparison of BERs after 80 km transmission and BERs after OC and wavelength conversions, almost power penalty-free OC and wavelength conversions were successfully demonstrated by introducing optical time-gating detection followed by optical 3R. In a viewpoint of VOCP/VWP path network, OC and wavelength convertible signal transport in the total link length of 180 km with 4 network nodes were also successfully demonstrated.

### 4.3 Summary of Section 4

We have experimentally demonstrated 8.05 THz ultra wideband OC and wavelength convertible VOCP/VWP network of the total link lengths of 180 km by using SC generation with optical 3R at a channel data rate of 10 Gbit/s. This scheme would be promising for the future hybrid OCDM/WDM path networks.

## 5 Conclusion

We have reviewed the experimental demonstrations of OCDM application in photonic networks. As a link technology, we have experimentally demonstrated 1.6 bit/s/Hz, 6.4 Tbit/s OCDM/WDM transmission. And as a node technology, we have experimentally demonstrated 8.05 THz ultra wideband OC and wavelength convertible VOCP/VWP network. Considering its unique attributes, OCDM would be promising technique to enhance the flexibility in the future peta-bit/s photonic networks.

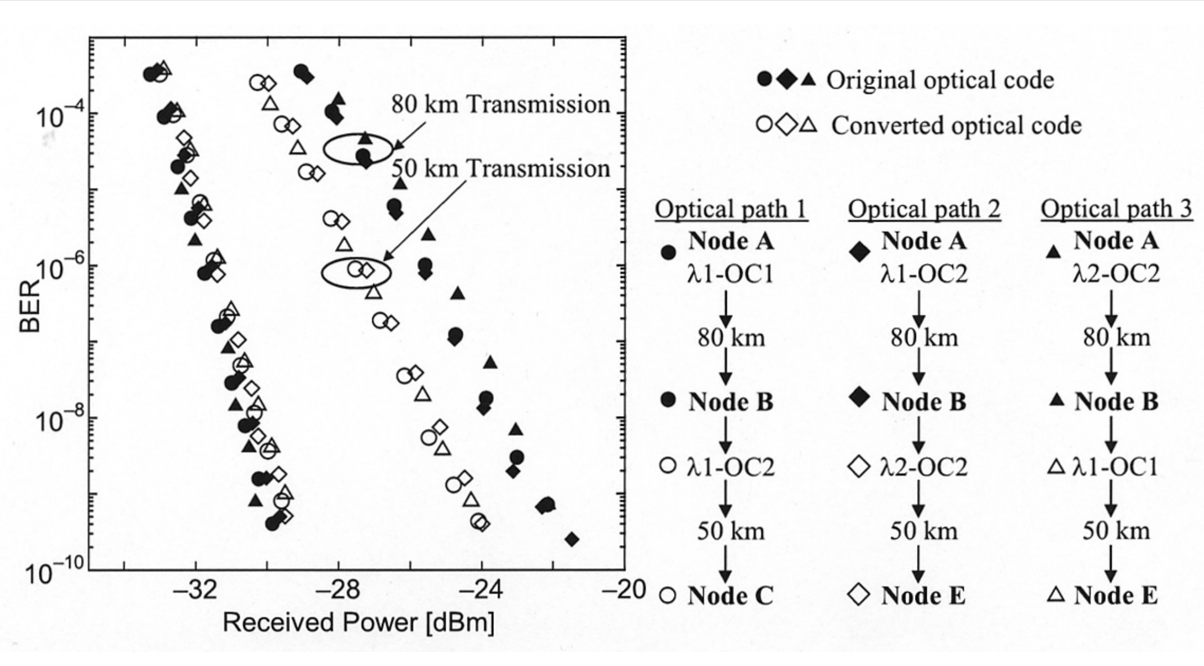


**Fig.13** *Measured BERs: back-to-back, after 80 km transmission, after OC and wavelength conversion with optical 3R, and after subsequent 50 km transmission*

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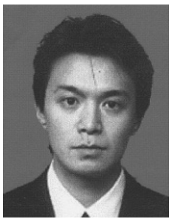
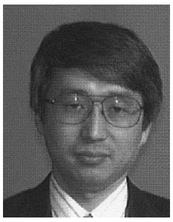


***Hideyuki SOTOBAYASHI**, Dr. Eng.*

*Senior Researcher, Ultrafast Photonic Network Group, Basic and Advanced Research Division*

*Photonic network*



***Wataru CHUJO**, Dr. Eng.*

*Leader, Ultrafast Photonic Network Group, Basic and Advanced Research Division*

*Photonic network*

***Ken-ichi KITAYAMA**, Dr. Eng.*

*Professor, Department of Electronic and Information Systems, Osaka University*

*Photonic network*