3-3 Reconfigurable Optical Packet ADM Experiment using JGNⅡ Network Test-bed

WADA Naoya, KATAOKA Nobuyuki, SONE Kyousuke, AOKI Yasuhiko, MIYATA Hideyuki, ONAKA Hiroshi, KUBOTA Fumito, and KITAYAMA Kenichi

Reconfigurable optical add/drop multiplexer (ROADM), which enables dynamic and flexible node-to-node connection via wavelength path, is a key building block in metro ring network nodes. We have proposed and demonstrated a data-granularity-flexible ROADM node that combines a wavelength-tunable filter and an optical packet ADM (PADM). In this report, we demonstrate the first field trial of the data-granularity-flexible ROADM network with wavelength and packet-selective switch at JGN2 test-bed. In this demonstration, PADM based on a novel concurrent generation technique of address-reconfigurable optical code (OC) label and payload is proposed and used. Bit error rate (BER) of less than 10^{-12} for all 16-wavelength channels are obtained over 90 km transmission at 10 Gbps.

Keywords
SONET, Wavelength division multiplexing, Optical-code label, Optical correlation, Optical processing, Optical add/drop multiplexer, Optical packet transmission

1 Introduction

In recent years, many ISPs have been providing a wide range of services that have resulted in a rapid increase in data-traffic volume. We can therefore predict that network demands in the near future will include a variety of traffic-related requirements. For example, granularity of data varies according to the type of service, from content distribution to utility computing to storage. New networks will be expected to provide services with variable data granularities.

An optical add/drop multiplexer (OADM) is an important component of optical ring networks[1]. One such reconfigurable OADM (ROADM) recently developed uses a high-speed acousto-optic tunable filter (AOTF)[2] to enable variable and dynamic node-to-node connection via wavelength paths; however, this system does not support add/drop multiplexing of fine-grained data packets. A recently proposed[3] and tested[4] optical packet ADM (PADM) is add/drop enabled and allows passage of packets on an individual basis by attaching an optical code (OC) label to the header and trailer of each packet. Node address and routing information can be mapped onto these labels. More recently, a variable-data-granularity ROADM node[5] consisting of an AOTF and a PADM offers improved efficiency in wavelength use relative to existing ROADM devices.

In this paper, we will report on a field trial of a variable-data-granularity ROADM network we recently carried out on the JGNⅡ fiber-optic test-bed. Using sixteen wavelength channels, we completed the world's first successful transmission at 10 Gbps over a distance of 90 km. The new technique we adopted in this trial makes it possible to generate address-reconfigurable OC labels as well as to perform continuous concurrent modulation of optical codes and payloads. This technique of generating OC labels is expected to increase network scalability through the ability to generate optical codes of any length. We achieved error-free transmission and addition of packets (bit error rates of 10^{-12} or less) on all of the sixteen wavelength channels over a distance of 90 km.

2 Configuration of variable-data-granularity ROADM node

Figure 1 shows the configuration of a variable-data-granularity ROADM node. This node has two functions: the AOTF function, for add/drop multiplexing of wavelength channels, and the PADM function, for add/drop multiplexing of packets on an individual basis. A ROADM node consists of several AOTFs, PADMs, optical couplers, and one wavelength rejection filter. These AOTFs control wavelength paths[6]. The AOTF has an optical waveguide formed on a $LiNbO_3$ substrate. Key features of the AOTF include fast switching (within 10 μs), wideband wavelength tuning (>100 nm), small size, and low cost.

The PADM mechanism is based on optical code correlation[7][8]. Figure 1 shows the basic PADM configuration employed[4]. The PADM consists of an OC label selector and an optical switch. Each OC label is assigned to only one node and is mapped by an optical code. The input/output port is connected to a single WDM link. Figure 1 also shows the format of an optical packet. A packet consists of header and trailer OC labels and a payload. These OC labels carry destination address information. PADM's basic functions include OC label selection and optical switching. An OC label is selected based on optical correlation between an optical code assigned to the node and the optical bipolar code of the received packet. The OC label selector obtains control information for a received packet through optical processing of the packet's header OC label and determines whether to pass or to drop this packet (via the optical switch) based on the control information. If the packet is dropped, its trailer OC label is used to reset the switch state from "cross" to "bar." Thus, this PADM can perform add/drop multiplexing of optical packets regardless of their lengths.

Optical decoding is a function unique to OC label processing. Optical decoding allows ultra-fast label processing with low power consumption relative to other methods, because the processing speed is limited only by the speed of propagation of light in passive optical devices[9][10]. At a variable-data-granularity ROADM node, some wavelength channels are dropped by the AOTF and guided to the PADM, while others are allowed to pass through this filter. The rejection filter is set to block passage of signals featuring the same wavelengths as those dropped by the AOTF. The PADM adds and drops optical packets to and from the selected wavelengths. Output from the AOTF, the PADM, and the rejection filter are combined and sent to the transmission line.

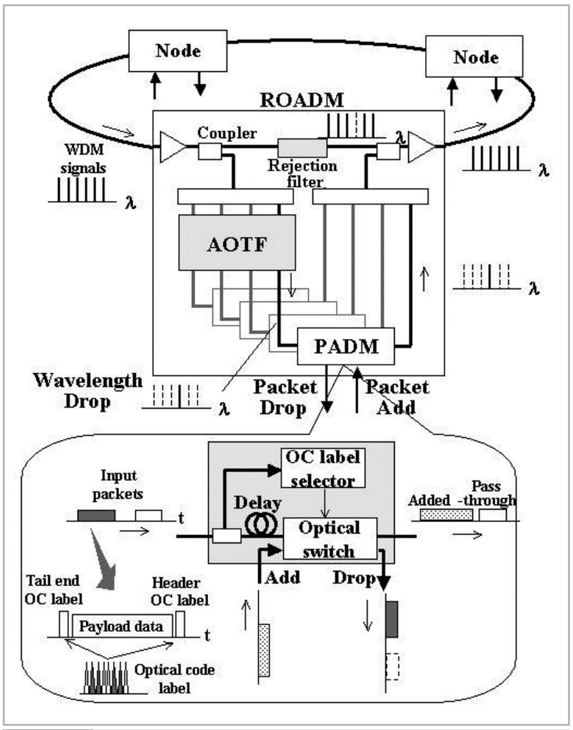

Fig. 1

3 Technique for concurrent generation of optical code labels and payloads

(1) Operational mechanism

To achieve ultra-fast packet selection, payload transmission and header processing must be performed in the optical domain. In this case, header processing includes identification of optical labels and generation of new optical labels. A major strength of the optical label generation lies in its reconfigurability; i.e., in its ability to change optical labels flexibly and in real time based on routing table information at intermediate nodes. In relation to the mapping of routing information on optical labels, recent research has focused on wavelengths, sub-carriers, and optical codes[11]-[15]. At the intermediate node, the PADM identifies OC labels that match any of the labels in the routing table.

OC label encoding/decoding methods have recently been proposed that use passive optical devices such as an optical transversal filter[16][17], fiber Bragg grating (FBG)[18], and a spatial light modulator[19]. Figure 2 shows an illustration of OC label processing that can be performed based on optical correlation. Autocorrelation peaks appear only when the two codes match; in other cases, the graph shows cross-correlation waveforms. These methods allow ultra-fast label processing because the speed of OC label processing is limited only by the delay in propagation in the passive optical devices of the optical decoder. However, an encoder/decoder that uses an optical transversal filter can only support code lengths of up to 32 bits[20], and is not compact. The FBG encoder/decoder, on the other hand, is highly scalable and compact, and has a track record of success in the generation and identification of 511-chip optical codes[21]. However, FBG provides limited code reconfigurability[22]. When using the node system described herein, which provides limited network scalability, it will be necessary to prepare an optical encoder/decoder for each of the optical labels at the node.

As shown in Fig.3(a), we developed and tested the effectiveness of a technique for concurrent generation of OC labels and payloads through serial connection of light intensity and optical phase modulators. This encoding technique uses phase modulation to generate reconfigurable OC labels of any desired length and with any payload at the same time, without the need for a special optical encoder. This technique is simpler than others and provides a higher maximum number of addresses.

(2) Experiment on generation and identification of OC labels

Figure 3(b) shows the configuration of an optical transversal filter used as the optical decoder in this experiment. The generator con-

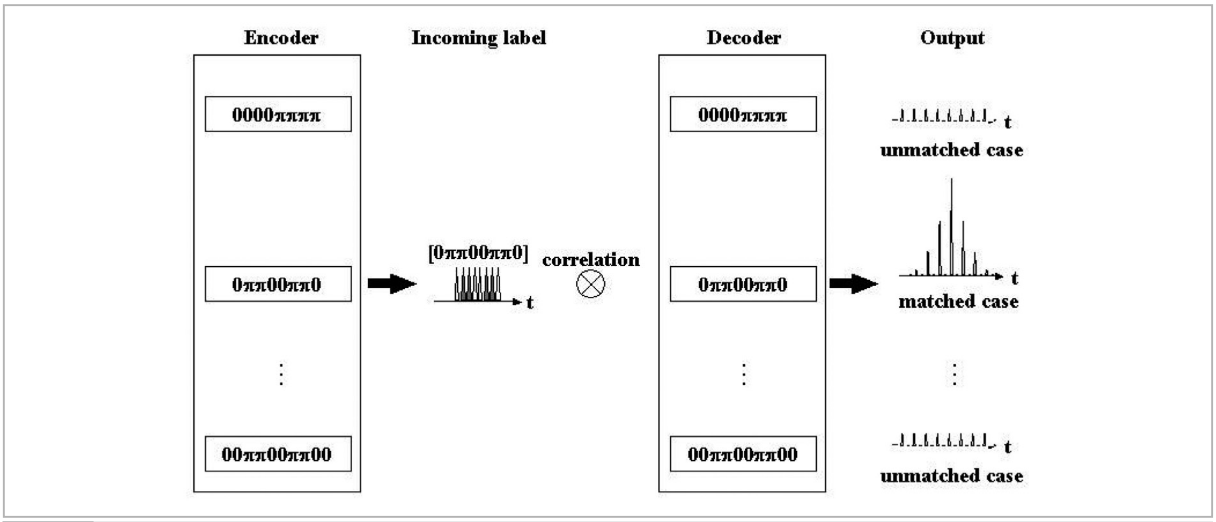

Fig.2

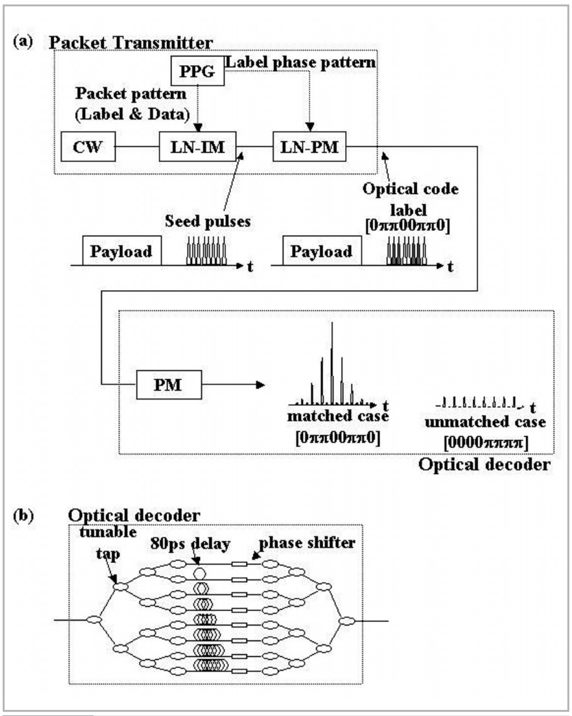

Fig.3

sists of a continuous wave (CW) light source, a $LiNbO_3$ intensity modulator (LN-IM), an LN phase modulator (PM), and a pulse pattern generator (PPG). Since this was a preliminary experiment, data generation was not performed and payloads were added after the generation of seed pulse trains, to simplify the experiment.

The LN-IM generates 8 chips of a seed pulse (full-width at half-maximum of 40 picoseconds) train with a length of 640 picoseconds at 12.5 GHz. The LN-PM modulated this pulse train to generate an 8-chip bipolar phase shift keying (BPSK) OC label. In this experiment, the chip speed of the optical code was 12.5 Gchip/s. It is worth noting here that this chip speed and the payload bit rate can be set independently. The LN-PM bias voltage must be set accurately so that the phase shift will become π. An optical transversal filter is used as the optical decoder to assess the correlation characteristics of generated OC labels. This optical transversal filter consists of taps to divide an input signal into eight branches, numerous 80-ps delay lines, a programmable binary optical phase shifter, and a coupler. These components are integrated as a monolithic planar lightwave circuit (PLC)[23]. Each OC label chip pulse is delayed and divided into eight branches, each with the same amplitude. Each tap undergoes an optical phase shift of 0 degrees or π. The divided chip pulses are coupled and output as a coherent pulse. If a received OC label matches the optical decoder's label (assessed through the combination of phases inside the decoder), the decoder will output an autocorrelation waveform. If not, the decoder will generate a cross-correlation waveform.

Figure 4(a) shows an output waveform from the label data generator. Each optical label chip pulse has a period of 80 picoseconds. Figure 4(b)(i) shows the calculated autocorrelation waveform (upper) and the measured waveform (lower) for Code 0 [00000000]. In this case, the seed pulse is not modulated by LN-PM. There is an 80-ps interval between the peaks of this temporal autocorrelation waveform, corresponding to the period of phase coding in the time domain. The theoretical power distribution in the Code 0 autocorrelation waveform is 12, 22, 32, 42, 52, 62, 72, 82, 72, 62, 52, 42, 32, 22, 12. As shown in Fig.4(b)(i), the measurement results in the time domain are in good agreement with the theoretically predicted values. Figure 4(b)(ii) shows the calculated autocorrelation waveform and the measured waveform for Code 1 [0ππ00ππ0]; and Fig.4(b)(iii) shows a cross-correlation waveform (Code 2 [0000ππππ] at the encoder, and Code 1 [0ππ00ππ0] at the decoder). As shown in these figures, the measurement results in the time domain are in good agreement with the theoretically predicted values. These results prove that our proposed encoding/decoding technique can be effectively applied in optical label identification.

4 Field trial

(1) Test system

Figure 5 shows the experimental set-up used in the field trial. Node 1 uses distributed

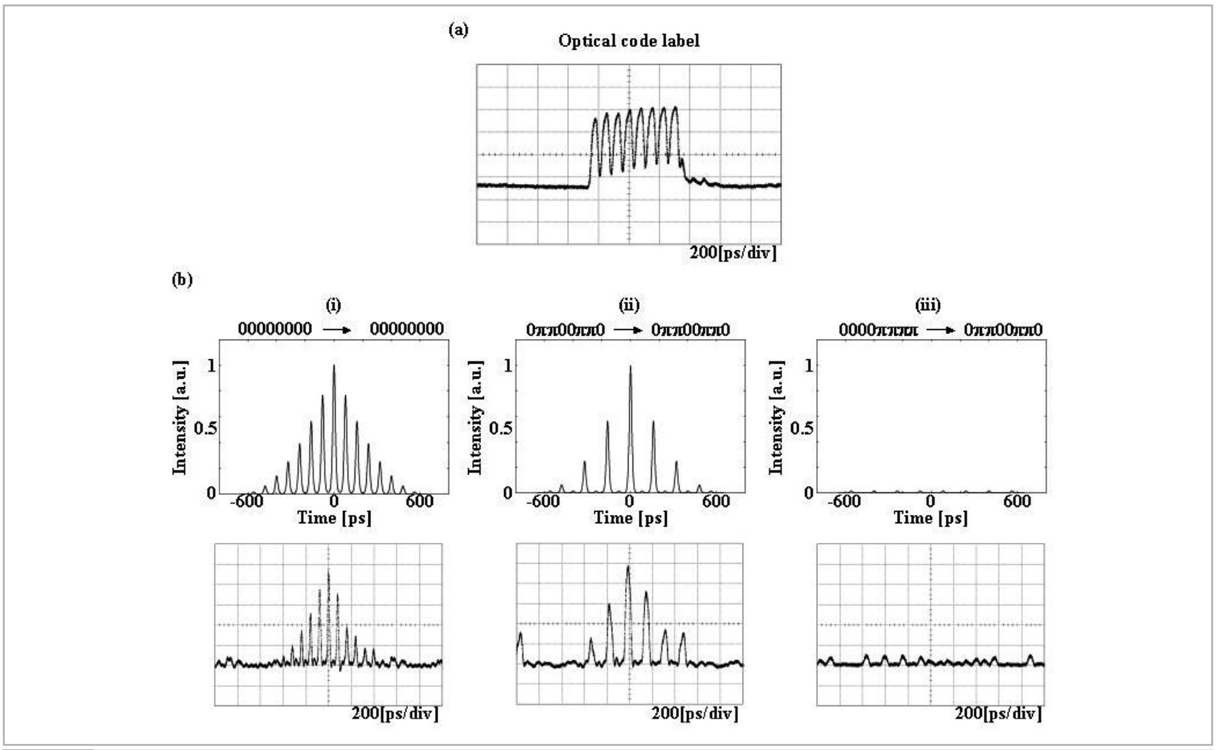

Fig.4

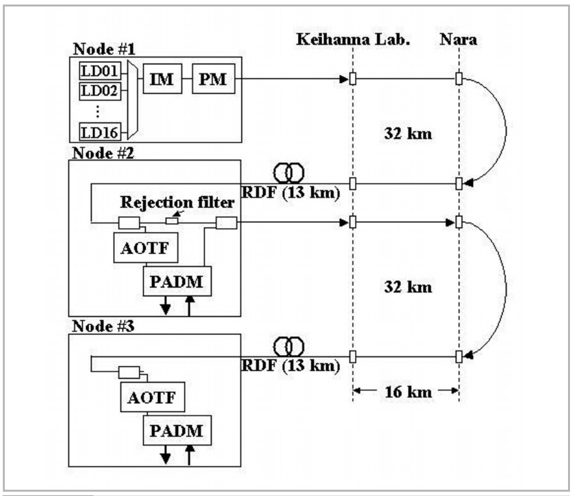

Fig.5

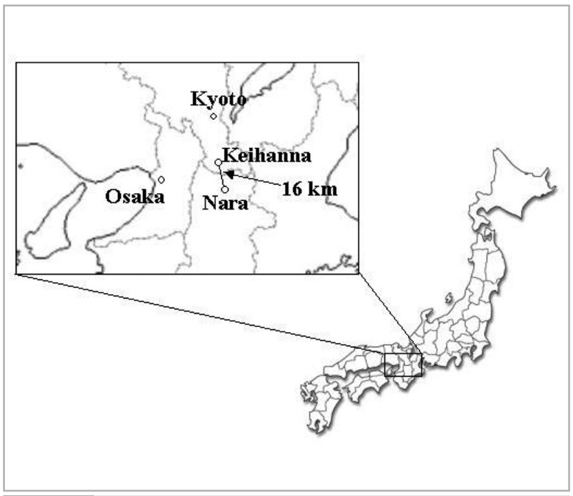

Fig.6

feedback laser diodes (DFB-LDs) to generate sixteen wavelengths with 200-GHz spacing (Channel 1: 1,533.47 nm, to Channel 16: 1,557.36 nm). Two optical packets, Packet 1 and Packet 2, are generated for each wavelength channel. Based on our proposed optical label encoding technique, each packet is made up of 8-chip OC labels (12.5 Gchip/s) and an RZ-format payload consisting of a 2,048-bit-long pseudorandom bit sequence (PRBS) at 10 Gb/s. The destination addresses of OC Label 1 [0πππ00ππ0] and 2 [0000ππππ] are assigned to Nodes 2 and 3, respectively. We tested the transfer of the above-mentioned packets among the three nodes through a single mode fiber (SMF) line. In this case we used a JGNⅡ line (Optical Test-Bed A) laid between NICT's Keihanna Human Info-Communication Research Center and Daianji in Nara[24]. As shown in Fig.6, this transmission line is 32 km in length and features a loop-back configuration. This loop-back line causes a loss of 8 dB, including losses due to the optical jumper cables and connectors used in the laboratory. Since we used a 13-km reverse dispersion fiber (RDF) line to compensate for dispersion at each node, the total transmission distance was 45 km.

There are sixteen wavelength channels. At Node 2, some of these channels are dropped by the AOTF and guided to the PADM, and the others are allowed to pass through this filter. The rejection filter blocks the passage of signals featuring the same wavelengths as those dropped by the AOTF. The PADM can add or drop the desired optical packets to and from selected wavelengths. Outputs from the AOTF, the PADM, and the rejection filter are combined and sent to the transmission line. For Node 3, we selected certain wavelength channels to drop the desired optical packets in the same manner.

(2) Test results

Figure 7 shows optical spectra and optical packet waveforms. Figure 7(i) shows optical spectra of the sixteen wavelengths generated at Node 1. Figures 7(b) and 7(c) show a generated optical packet and 8-chip OC label, respectively.

Figure 8 shows optical spectra and waveforms of packets added or dropped on Channel 08. Figure 8(i) shows input signals at Node 2. The AOTF sorts the input signals and the rejection filter blocks the passage of signals featuring the same wavelengths as those dropped by the AOTF [see Fig.8(ii) and 8(iii)]. As indicated by these spectra, the system enables full operation of variable wavelength paths. The PADM adds or drops Packet 1 depending on whether the packet's included address is assigned to Node 2 [see Fig.8(a) and 8(b)]. Figure 8(c) shows autocorrelation and cross-correlation waveforms output from the optical decoder. These results prove that our proposed encoding/decoding technique can be used to selectively add or drop the desired optical packets for any WDM signal wavelength.

At Nodes 2 and 3, we evaluated the transmission characteristics of packet payloads dropped from each wavelength. We measured bit error rates (BERs) at points (1) to (4) shown in Fig.9. Measuring points (3) and (4) are closely situated: (3) represents the point at which packets from Node 1 pass through the PADM of Node 2 and are dropped at Node 3, and (4) represents the point at which packets added at Node 2 are dropped at Node 3.

Figure 10(a) shows optical signal-to-noise ratios (OSNRs) measured on each channel with a resolution of 0.1 nm. Numbers in the figure correspond to the measuring points in Fig.9. Packet BERs were 10^{-12} or less on all wavelength channels.

Figures 10(b), 10(c), and 10(d) show the relationship between the BERs and OSNRs on Channels 01, 08, and 16, respectively. Penalties between Nodes 2 and 3 are caused by interference noise produced when packets are passed or added at the PADM optical packet

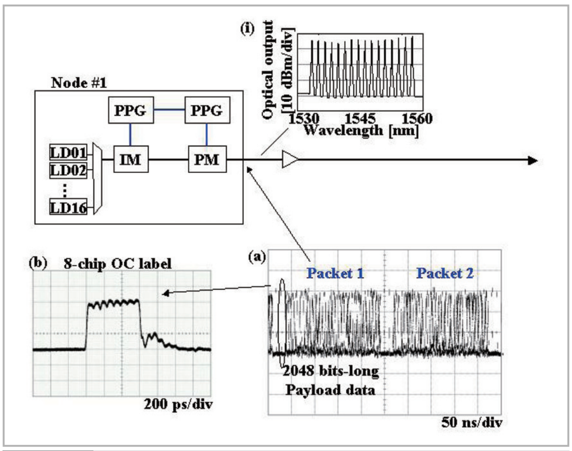

Fig.7

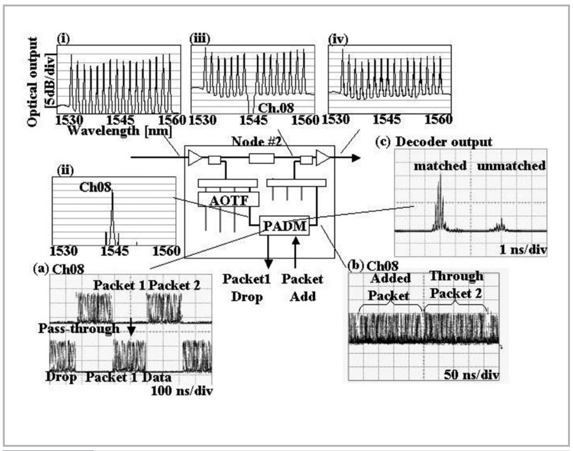

Fig.8

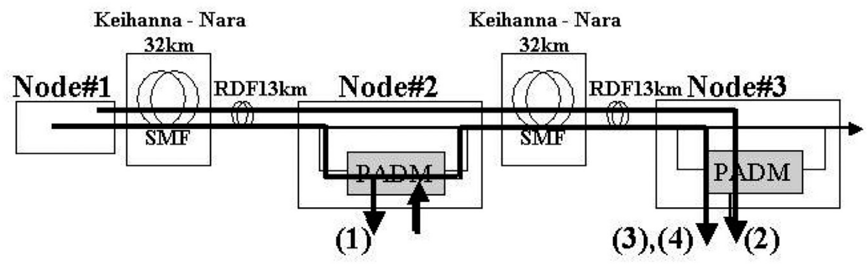

Fig.9

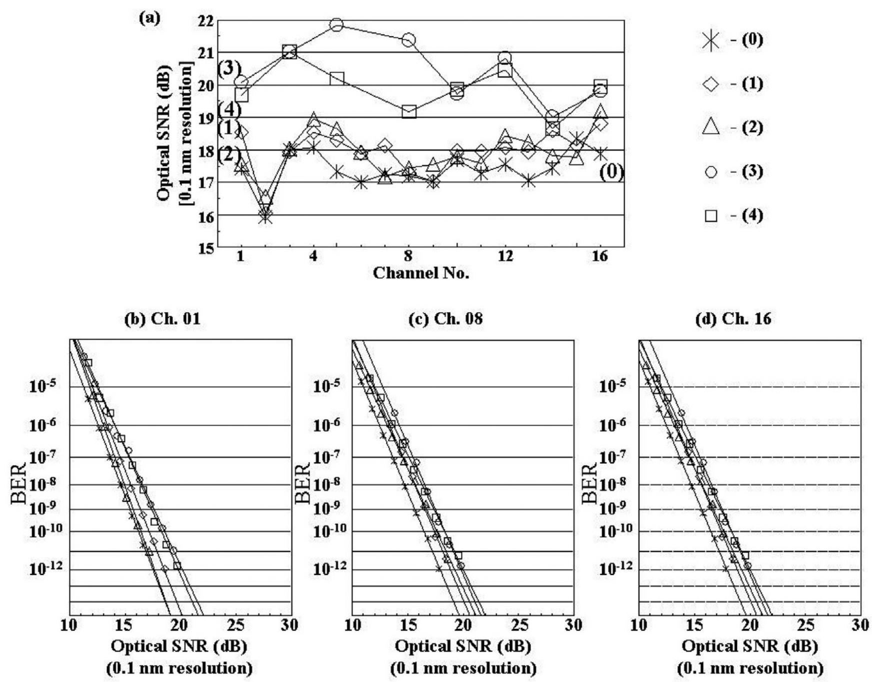

Fig.10

switch. BERs of 10^{-12} or less indicate successful system operation.

5 Conclusions

We performed the first successful field trial of a variable-data-granularity ROADM network. Using a high-speed wavelength selection filter and an optical packet switch based on OC label processing, we performed transmission on sixteen wavelength channels at 10 Gbps over a distance of 90 km. With the adoption of a new technique of OC label generation for continuous concurrent modulation of OC labels and payloads, we can now generate optical codes of any length. This technique is expected to increase network transparency and scalability to a significant extent. We hope this variable-data-granularity ROADM will find immediate and promising use in fields such as high-speed metro ring networks and LAN applications.

We performed the field trial of a leading-edge photonic network technology described in this report using a fiber-optic line that can provide a near-actual environment. This type of field trial allows us to verify the effectiveness of leading-edge technologies and to identify problems or challenges at an early stage, which in turn helps to accelerate overall development.

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***WADA Naoya**, Ph.D.*

Senior Researcher, Ultra-fast Photonic Network Group, Information and Network Systems Department

Photonic Network

KATAOKA Nobuyuki

Department of Electrical, Electronic and Information Engineering, Osaka University

Photonic Network System

SONE Kyousuke

Fujitsu Laboratories LTD.

Photonic Network System

***AOKI Yasuhiko**, Ph.D.*

Fujitsu Laboratories LTD.

Photonic Network System

MIYATA Hideyuki

Fujitsu Limited

Photonic Network System

ONAKA Hiroshi

Fujitsu Limited

Photonic Network System

***KUBOTA Fumito**, Ph.D.*

Reseach Supervisor, Information and Network Systems Department

Photonic Network

***KITAYAMA Kenichi**, Dr. Eng.*

Professor, Department of Electrical, Electronic and Information Engineering, Osaka University

Photonic Network, Radio-on-fiber Communications, Optical Signal Processings