Capability of optical code-based MPLS (OC-MPLS)

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Key words: MPLS, optical code, photonic label, IP packet, optical path, flow, optical implementation

Abstract: We will focus on the novel applications of optical code base MPLS, so-called OC-MPLS to demonstrate its versatile capability. The OC-photonic label can be used as an identifier of the data encapsulated in an optical frame. The OC-photonic label is an optical code consisting of a sequence of optical chip pulses, and its recognition is performed based upon ultrafast time-domain optical correlation. The applications include label switched path (LSP) switching, IP packet routing, and packet flow classification. Noet that the IP packet routing using OC-photonic label is not on the main focus but the label applications are not limited within the OC-MPLS but also extended conventional IP packet routing. In the optical implementations, two types of match algorithms of OC-photonic labels such as *exact match* for the LSP and flow classification as well as *longest prefix match* for IP packet routing are presented. Finally, the exact match, longest prefix match, and classification of optical packet flows will be experimentally demonstrated at the bit rate of 10Gb/s.

1. INTRODUCTION

Recent progress of wavelength division multiplexing (WDM) technology has significantly increased the point-to-point link capacity, providing scalable bandwidth for rapidly growing internet traffic demands. However, the capacity increase tends to shift the network capacity bottleneck from the link to the node due to rather slow packet processing capability in electronic layer at the node.

One promising technique to alleviate the bottleneck is via circuit-switched MPL(ambda)S or MPλS (multi-protocol lambda switching) technology [1,2]. The MPLS performs packet forwarding decisions only at the edges by eliminating forwarding task at the core nodes, thus allowing the core nodes to perform only switching. MPλS is an extension of MPLS concept by provisioning wavelength path or optical path to establish a logical topology over WDM link network [3]. MPλS enables traffic engineering by providing optical paths where bandwidths or wavelengths are required. It allows the cut-through of the traffic not to be terminated at the node, and this is powerful to alleviate the load of router at the node. However, MPλS still poses several limitations due to the facts that [4];

1) The unit of path granularity is of wavelength capacity, which may be sometimes too large to accommodate the end-to-end traffic within the MPLS domain.
2) The number of available wavelengths is too small for the label space to accommodate all the paths required (Table 1) as the wavelength resource is not abundant.
3) Aggregation of packet flows having the same wavelength labels may not be feasible. The aggregation may require the label exchange within the network, but it needs the wavelength change at the node.

Table 1 Photonic label space[5]

Code	Number	Label processing	Issues
Wavelength	1,000	Simple Optical filter	Flow control
Subcarrier	100	Simple RF filter	<40Gbit/s
Optical code	Abundant	Analog & relatively simple, Passive waveguide	Impairment due to fiber dispersion

Optical packet switching might be an ultimate solution in the long run to overcome the above problems of MPλS. It has been extensively studied; for example, the European KEOPS project has shown a broadcast-and-select switch [6], where wavelength converters are used to perform space switching and delay selection. Packet contention at the output ports can be resolved by utilizing fiber delay lines, but a large number of semiconductor optical amplifier (SOA) gates are required for the broadcast-and-select stage. Another example is the WASPNET prototype [7] that uses currently available optical devices such as tunable wavelength converters, arrayed waveguide gratings (AWG), and fiber delay lines to resolve contention. However, these optical packet switches still rely on relatively slow electronic header processing and hence can provide the line interface only up to the bit rate of 10Gb/s.

To overcome bothe the problems of circuit-switched MPλS and slow electronic header processing in optical packet switchings, optical code-based photonic label MPLS, so-called OC-MPLS has recently been proposed [4]. Here, OC-MPLS is referred to a special class of Generalized MPLS (GMPLS) which incorporates OC-photonic label as the generic label entry. OC-MPLS is a framework in which circuit-switched routing for stream and burst data as well as optical packet switching can be supported.

In this paper, we will focus on the novel applications of OC-MPLS to demonstrate its versatile capability. The OC-photonic label can be used as an identifier of the data encapsulated in an optical frame. The OC-photonic label is an optical code consisting of a sequence of optical chip pulses, and its recognition is performed based upon ultrafast time-domain optical correlation. The applications include label switched path (LSP) switching, IP packet routing, and packet flow classification. It should be noted that the IP packet routing using OC-photonic label is not on the main focus but the label applications are not limited within the OC-MPLS but also extended conventional IP packet routing. In the optical implementations, two types of match algorithms of OC-photonic labels such as *exact match* for the LSP and flow classification as well as *longest prefix match* for IP packet routing are presented. Finally, the exact match, longest prefix match, and classification of optical packet flows will be experimentally demonstrated at the bit rate of 10Gb/s.

2. APPLICATIONS OF OC-MPLS

2.1 Concept of OC-MPLS

Before going into the applications, we will briefly review the concept of OC-MPLS [4]. The concept of OC-MPLS network is schematically illustrated in Fig.1. The label switching is distinct from conventional IP routing architecture in that MPLS uses just one forwarding algorithm of exact match on the label in the shim header. When the ingress photonic label switching router (PLSR) receives a packet without label from the IP router, the PLSR determines the forward equivalent class (FEC) of this packet and the next hop and attaches the OC-photonic label. The core PLSR carries out the label switching and swaps the label in optical layer. The egress PLSR strips the label from the packet and hands the packet to the IP router.

The PLSR may have functionality of either optical crossconnect switch or packet switch. As shown in Fig.2, a basic idea is to encapsulate into an optical frame the various types of data by attaching the OC-photonic labels as the identifier, and then the identifier can be processed and recognized in optical layer by exploiting ultrafast OC-photonic label recognition, followed by controlling the tasks of either switching or flow classification based upon the information of the header. It should be noted that the IP packet routing using OC-photonic label is not on the main focus but the applications are not limited within the OC-MPLS but also extended conventional IP packet routing.

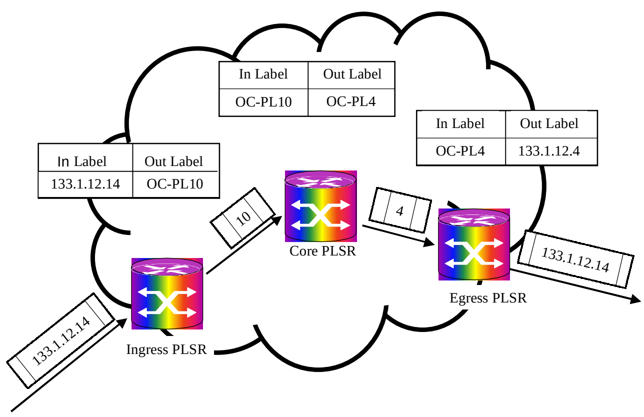

Fig.1 Concept of OC-MPLS

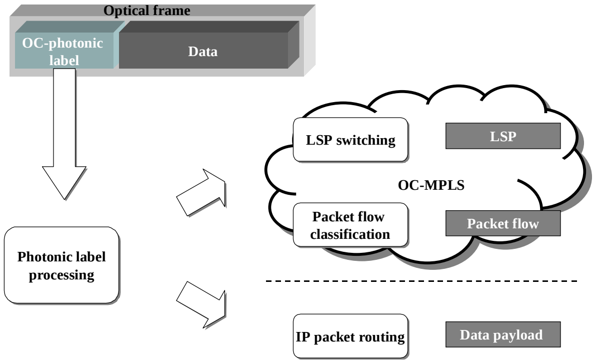

Fig.2 Basic idea using OC-photonic labels as the identifier of LSP, IP packet, and packet flow

2.2 Forwarding algorithms : Longest match and exact match

In the conventional IP routing architecture, different functionality requires different forwarding algorithm. For example, forwarding of unicast packets requires longest match based upon the network layer destination address, forwarding of multicast packets requires longest match on the source network layer address plus the exact match on both source and destination network layer addresses, whereas unicast forwarding with Types of Services requires the longest match on the destination network layer address plus the exact match on the Types of Services bits carried in the network layer header [8]. OC-photonic label enables both the two match algorithms; longest prefix match and exact match, and therefore the applications are not limited within the OC-MPLS but also extended conventional IP packet routing.

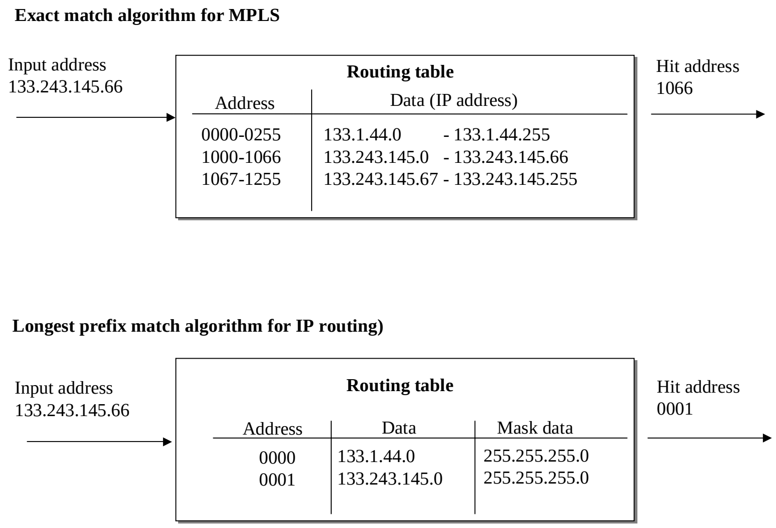

Fig.3 Forwarding algorithms : Longest prefix match and exact match

The architecture of the photonic packet router which performs split of the flows as well as packet forwarding is shown in Fig.4 [9]. First, the variable time gate operates on the incoming label. This determines the match algorithm. It can gate out one of the labels, for example, the destination and/or source labels. It can also gate out a part of the label for the longest match. Then, the photonic processor recognizes the label and generates the control signal to drive the optical switch for forwarding or some other task. The architecture will be varied with the longest match and exact match. The photonic label can be processed based on the optical correlation between the codes. The optical correlation is performed by matched filtering in time domain [9]. This will be elaborated in Ch.3.

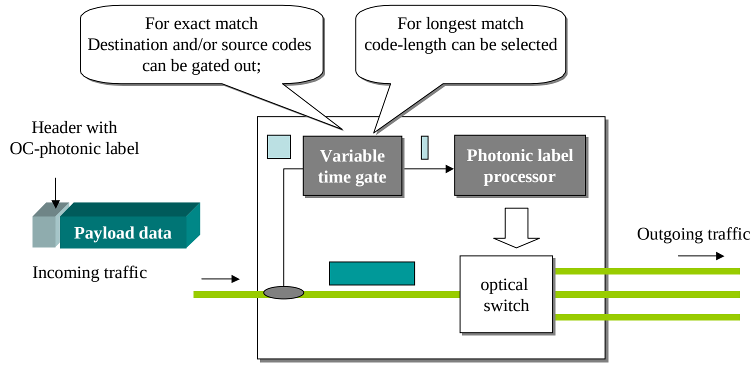

Fig.4 Architecture of OC-photonic label processor for exact match and longest match

2.3 Packet flow classification

The LSR in an electronic MPLS is generally able to perform various operations on packet labels. Those include label swapping, label merging, and label stacking [3]. Perhaps an exception can arise if wavelength conversion is available. Consider merging packet flows in MPλS network in Fig.5 (a). Here, a flow is defined as a set of packets traveling between a pair of hosts with the same destination address but the different source addresses. Obviously, it is difficult for MPλS to merge two flows on a single wavelength unless they are put on two different wavelengths λ_1 and λ_2 (Fig.5 (a)). Otherwise, the next hop at Node C wouldn't be able to correctly reassemble these packets into the original flows. However, a high-speed wavelength conversion is difficult to perform on a packet-by-packet basis by the current technology, and therefore, functionalities of Core LSRs are very limited in MPλS.

In Fig.5 (b) we will propose a novel label merge and split for packet flows. It adopts the exact match algorithm which is performed on the source address labels attached to the packets. The OC-photonic label merge and split will allow merging flows on a single wavelength at the core router and splitting flows at the destination node. This can be realized by attaching identifiers of the source nodes as well as the destination nodes, thus enabling to split packets originated from the different source nodes. Another way is to put the identifier at the end of the flow, and the OC-photonic label could also be used as the identifier.

Hereafter, we will focus on the scheme of attaching the source and destination addresses on each packet in a flow.

The photonic flow merge on a single wavelength is simply carried out by optically interleaving packets of different flows. It will be implemented with optical coupler with electrically controlled time sequencer. However, it should be noted that if the collision occurs between two packets in different flows, the overlap of the header must be avoided by time-shifting one of the packets. The collision between the headers likely to occur at an extremely low probability when we consider the packet length of 400-bit long average size of IP packet, while the header including the source and destination labels only occupies one or two bits. The time-shift required to avoid the header collision is within a few bits, therefore, this small time shift won't cause a serious congestion. Furthermore, this nature would be particularly suitable for variable-length packets, because the time-shift does not depend on how long the payload data are.

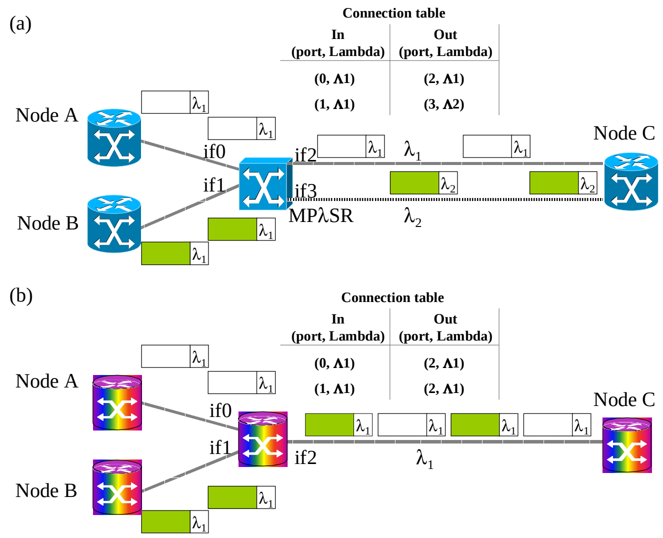

Fig.5 Classification of packet flow in (a) MPλS network and (b) OC-MPLS network

The architecture of the photonic label processor which performs split of the flows as well as packet forwarding is shown in Fig.6. First, photonic processor 1 processes the destination address and generates the control signal to drive the 1x2 optical switch only if the packet is destined to its own node. Thus, the terminated packet is directed to the second 1xN optical switch. Otherwise, the packet is forwarded to the next hop through the 1x2 optical switch. Next, photonic processor 2 processes the source address and controls the 1xN optical switch to split the packets to appropriate output ports. Photonic processor 2 is provided with the lookup table which contains the source address entries. The photonic label can be processed based on the optical correlation between the codes. The optical correlation is performed by matched filtering in time domain. The optical gate switches select one of the two photonic labels in the header in front of the processors.

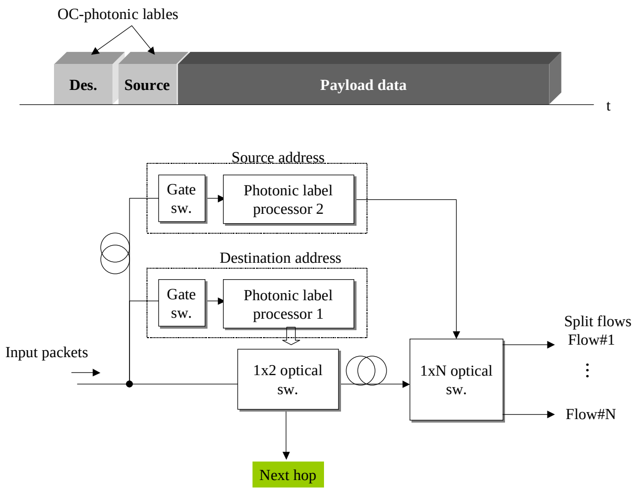

Fig.6 Architecture of photonic label processor which performs split of the flows

3. OPTICAL CODE-BASED PHTONIC LABEL

3.1 OC-photonic labels and their recognition based upon optical correlation

The photonic label is simply a relatively short, fixed-length identifier that bears the information of either the LSP label, the IP address, flow label. Each label is mapped onto an optical code, a sequence of optical pulses, so-called chip pulses [10]. The chip itself is a short pulse, and the time duration of the sequence has to be within a bit time duration. The number of optical code increases as the code length increases, and it could be abundant in practical applications, contrast to the scarcity of wavelength resource for the labels. The photonic label recognition is based upon the optical correlation between the optical codes. The optical correlation is performed by matched filtering in time domain. For example, a family of optical codes of 4-chip long codes and their auto-correlation waveforms are illustrated in Fig.7. The code is bipolar, in which the phase of optical carrier of individual chip pulse takes two states of either 0 or π, representing binary value of 1 or -1, respectively. As increasing the number of nodes, the longer code will be required. Unique to the label selector is that no optical logic operation is involved, and this is a key to the ultrahigh-speed operation of label processings.

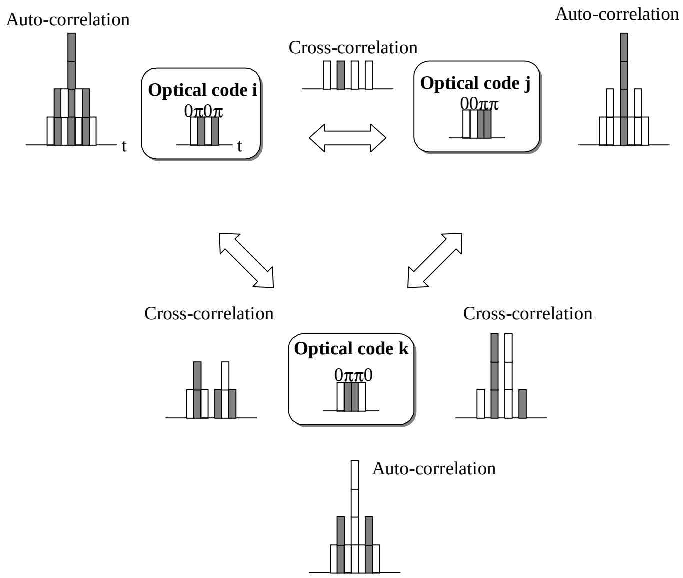

Fig.7 Optical correlation beteen two optical codes

3.2 Optical encoder / correlator

The optical encoder generates an OC-photonic label. Promising devices for the optical encoder are a waveguide type of tapped delay line [10] and a fiber Bragg grating (FBG) [11], shown in Figs.8 (a) and (b), respectively. The tapped delay line is a wave-guide device having an optical phase shifter on each arm, which is monolithically integrated on a silicon substrate. The FBG is a tiny optical fiber device, on which phase-shifted Bragg gratings are imprinted along the fiber axis. Both can generate bipolar optical codes.

The photonic label processor is structured with an optical correlator, a time-gate, optical thresholding, and an optical/electrical (O/E) conversion. The block diagram is schematically illustrated in Fig.9. Note that the identical optical device can be used for both the optical encoder and the optical correlator. The time gate, which follows the optical correlator, allows only the auto-correlation mainlobe to pass by, rejecting the sidelobes. The optical time gate has been achieved in an asynchronous system by using a semiconductor optical amplifier (SOA) based upon four-wave mixing (FWM)[12]. The optical gate is optically driven by the optical clock which is extracted from the incoming packet by using a mode-locked laser diode [13]. The gate width shorter than 10ps has been realized in the experiments [12,13]. Very recently, an ultrafast optical thresholding has been demonstrated with fiber-optic nonlinear loop mirror [14]. Several high-speed off-the-shelf optical space switches have now become available.

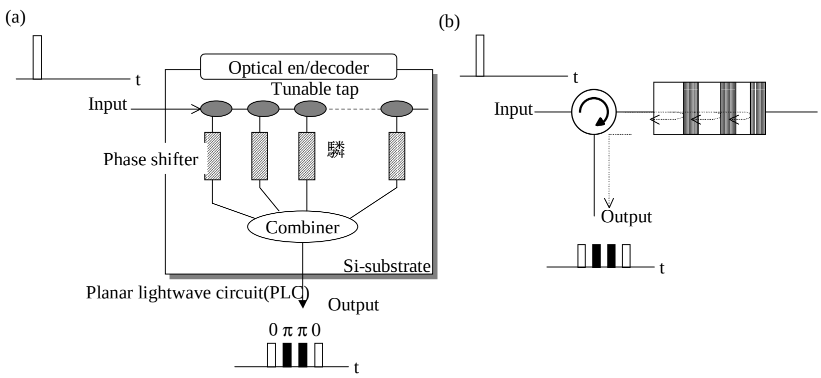

Fig.8 Optical encoder / correlator: (a) Waveguide tapped delay line and (b) FBG

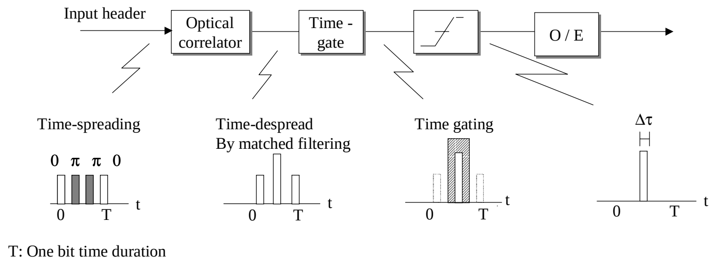

Fig.9 Block diagram of photonic label processor

4. EXPRIMENTS

4.1 Longest prefix match and exact match

In Fig.10 the experimental setup of the longest prefix match is shown [9]. The programmable optical encoders/ decoders consist of tapped delay lines with thermo-controlled optical phase shifters. In variable optical gate a saturable absorber (SA) is used as the optical gate. The time window can be variable by pumping with a desired-length control optical code. An MLLD at λ_1=1550nm with a repetition rate of 10GHz is used as the light source. The optical encoder generates an 8-chip binary phase shift keying (BPSK) optical code with a chip time interval of 5ps. The optical decoders generate correlation outputs. The peaks of the auto-correlation peaks are compared by using a dual-pin PD.

The optical code at 10Gb/s is duplicated and launched into variable optical gates. Time windows of optical gates are set to be 4- and 8-chip long. The same 4- and 8-chip codes are assigned to optical decoders 1 and 2, respectively, and thus the decoder outputs will show the auto-correlation functions of optical codes. The optically-gated control optical codes, the decoder outputs before and after the dual-pin PD are shown in Figs.11 (a), (b), and (c), respectively. The optical signal levels exactly correspond to the autocorrelation peaks, 4 and 8 in Fig.11 (b). The subtraction of 4 minus 8 in electrical domain shows the photocurrent of minus sign in Fig. 11 (c), and this allows us to determine that 8-chip code wins the longest matching.

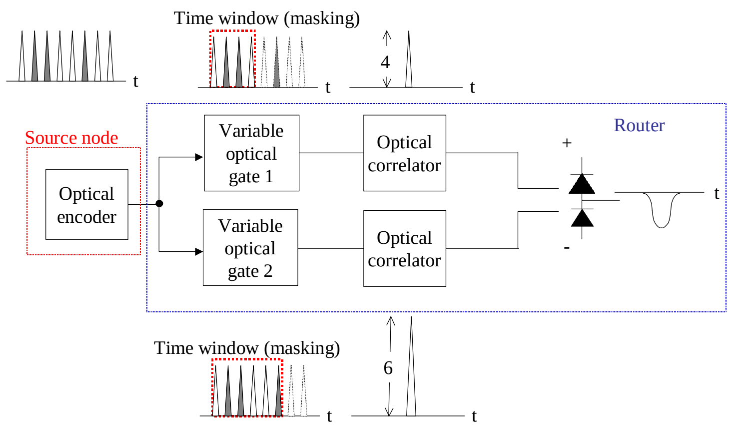

Fig.10 Experimental setup for longest prefix match

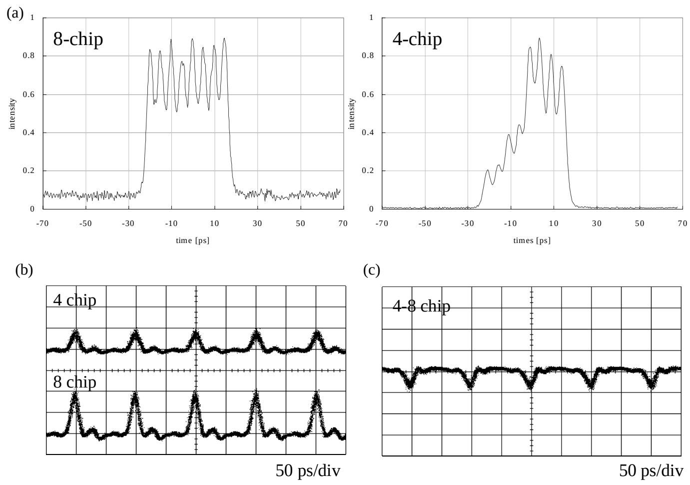

Fig.11 (a) Optically-gated control codes, (b) optical decoder outputs: auto-correlation waveforms, and (c) output of a dual-pin PD

4.2 Packet flow classification

The experimental setup for photonic split of merged flow is shown in Fig.12. In this experiment only the merge and split of packets are performed, and the packet forwarding is omitted for simplicity. It consists of an optical packet transmitter, a photonic label processor, and an 1x2 optical switch. The optical packet transmitter consists of a 1.3ps-10GHz-MLLD, $LiNbO_3$ intensity modulators (LN-IMs), and two optical encoders. At the receiver side, photonic label processor is composed of an optical gate, an optical decoder, a photodiode, and a gate signal generator. The optical encoder/decoder is a programmable tapped delay-lines with thermo-controlled optical phase shifters.

The photonic label processor performs optical correlation between the optical code of arriving packet and the assigned code of Node A at the receiver. If the codes match, the auto-correlation output is obtained, and after the photodetection it generates the gate signal. The gate signal drives the 1x2 optical switch to direct the packet to the upper output port. Otherwise, the cross-correlation output is obtained, but no gate signal is generated to hold the optical switch in the original state, and the packet emerges from the lower output port.

The experiment of the photonic merge and split are conducted for packets at the data bit rate of 10Gbit/s. The measurements are made before and after 50km-long SMF+RDF fiber transmission. The measured waveforms of two generated 64-bit long packets with a pair of photonic labels in the header, generated control signals, and the merged and split packets are shown in Fig.13. It is confirmed that the optical switch, controlled by photonic label processor, splits the packets to the two different output ports. The measured bit error rates (BERs) of the split packets are shown in Fig.14. The BERs less than 10^{-9} are obtained both before and after the transmission, thus guaranteeing the proper operation. The power penalties are presumably due to the ASE noise of the EDFAs used in the transmission.

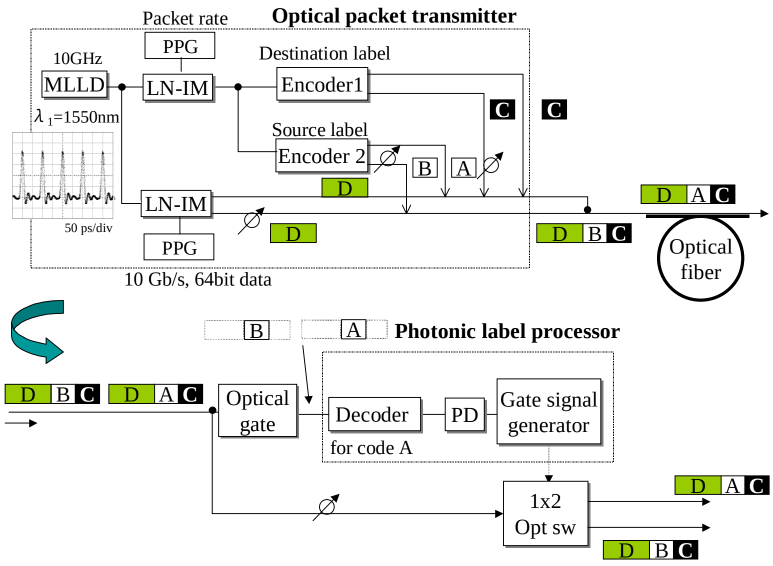

Fig.12 Experimental setup for photonic split of merged flowS

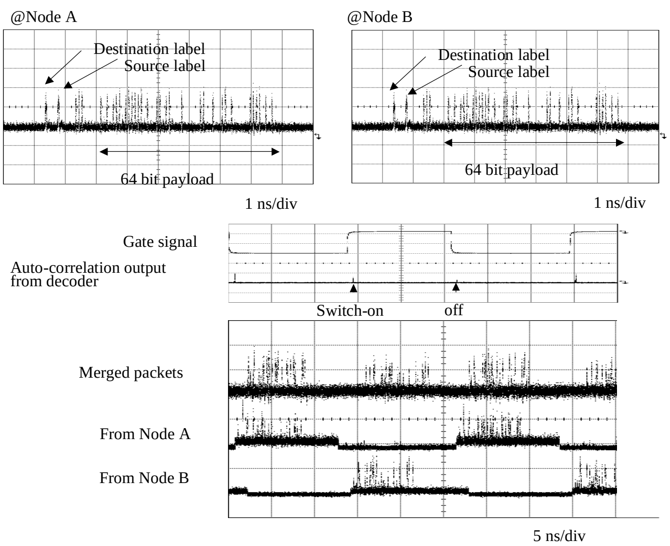

Fig.13 Measured waveforms; generated 64-bit long packets with two photonic labels in the header (on the top), generated control signals (in the middle), and the merged and split packets (on the bottom)

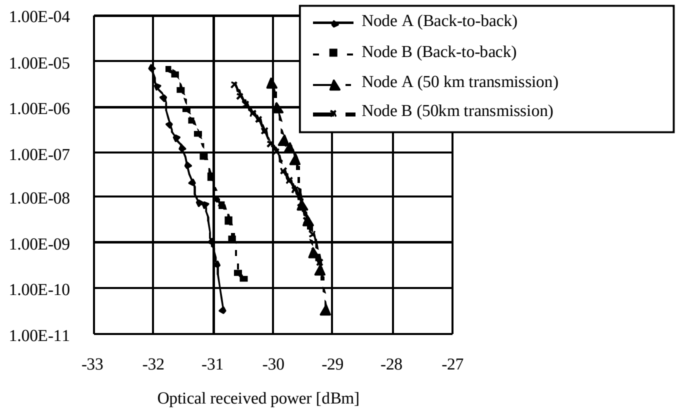

Fig.14 Measured bit error rates (BERs) vs optical received power

5. CONCLUSION

It has been shown that OC-MPLS is a framework in which circuit-switched routing as well as optical packet switching can be supported. We will focus on the novel applications of OC-MPLS to demonstrate its versatile capability. The application such as LSP switching, IP packet routing, and packet flow classification have been investigated. In the optical implementations, two types of match algorithms of OC-photonic labels such as exact match for the LSP and flow classification and longest prefix match for IP packet routing have been presented. Finally, the exact match, longest prefix match, and classification of optical packet flows have been experimentally demonstrated at the bit rate of 10Gb/s.

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