3-2 Ultra-fast photonic packet routing technology

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The great proliferation of the Internet has led to massive data exchanges between terminals such as computers and cellular phones. This growth in information exchange has resulted in a need for higher speed, larger capacity, and enhanced functionality of the information communications network that serves as the basis of data exchange. A photonic network, in which information is transmitted by light, is essential if we hope to the implementation of an ultra-fast, ultra-high capacity network that meets consumer demands. This paper reviews photonic routing technology, describes the concept of photonic packet routing technology employing optical orthogonal encoding labels, and then discusses our research into this technology. Also outlined are the concept and results of a proof-of-principle experiment of photonic packet routing technology using a multi-wavelength label, which is an improved system of MP-Lambda-S (Multi-Protocol Wavelength Switching). This paper concludes with an outline of and results from a proof-of-principle experiment of photonic label processing technology using spectral holography.

Photonic packet routing technology is a means of applying optical information technology to optical communications systems, and is expected to further develop in the future.

Keywords
Photonic Network, Photonic Packet Switching, Optical Code Label, All Optical Label Recognition, All Optical Processing

1 Introduction

As a result of the widespread use of the Internet, a massive amount of information has become available to nearly everyone at any time. Individuals who previously received information in one direction from media such as television and newspapers now have the opportunity to disseminate information themselves via the Internet. This change has caused an explosive growth in network data traffic due to the huge amount of data being exchanged between computers. Furthermore, the Internet is now being utilized in a wider range of application fields, including economic activities, medical services, and public services, and is penetrating deeper into daily life.

This rapid growth in data exchange has caused a serious problem with regard to the capacity of the existing communications network. The increase in communications data is expected to continue, and even accelerate, in the years ahead, and therefore the information communications network must be improved as soon as possible in terms of speed, capacity, and functionality. In order to realize an ultra-fast, ultra-high capacity network that will fulfill public needs, a photonic network in which information is exchanged by light wave through optical fibers, as opposed to the existing electrical signal system, is essential. The key technologies for implementing such a photonic network are classified into two components: photonic transmission technology for linking nodes in networks, and photonic transfer technology for routing information to individual lines. In terms of transmission technology, it is now possible to send terabit data via each fiber thanks to the development of WDM technology. On the other hand, the switching capability at network nodes for each input is still in the order of one gigabit per second, and it is this that causes the primary bottleneck in networks. Indeed, there is a gap of two orders of magnitude between the transmission speed and the transfer speed. In order to eliminate this bottleneck, photonic technology must be applied to nodes, because there are limits to present electrical signal processing capabilities (Fig.1).

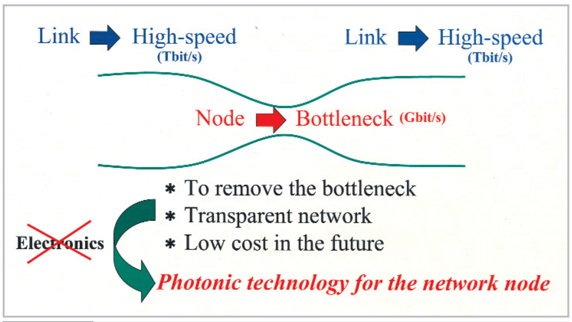

Fig.1 Information transmission speed in network

Major networks are currently shifting configurations from the circuit-switching type, represented by the telephone network, to the packet-switching type, represented by the Internet. As shown in Fig.2, in a circuit-switching type network using point-to-point protocol (PPP), a circuit is occupied by communication between, for example, terminal A and terminal D. Another terminal (for example, terminal B) is not allowed to use this circuit even if there is no traffic on this channel. Thus the communication band channel efficiency is low. Meanwhile, in a packet-switching type network using Internet protocol (IP), other terminals are allowed to use this channel for communication (for example, between terminal B and terminal C) by using vacant time slots, even in the midst of communication between terminal A and terminal B. In this case, however, nodes X and Y are required to be able to send packets after multiplexing them and demultiplexing/routing them, based on their packet address information. This function is known as packet routing. All header processing, including address recognition, is carried out by electrical means in the current network nodes. Thus even when the information has been sent via light signals, it must be converted into electrical signals for routing at nodes. The speed of routing, therefore, is limited by the signal processing capability of the electrical circuit at the node. In order to handle packets beyond the capability of electrical circuits, photonic packet routing technology becomes necessary as it can send optical signals as they are, without converting them into electrical ones.

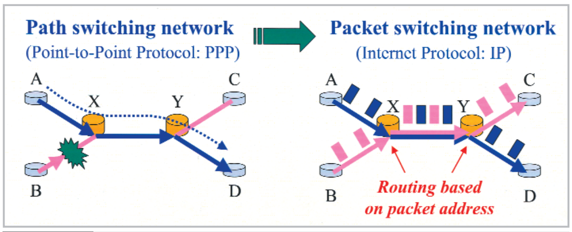

Fig.2 Change in network protocol

Conventional electrical nodes also pose security concerns. Tapping or hacking of the transmission lines is physically possible, but in reality these security breaches rarely occur. More commonly, security problems arise at nodes where light signals are converted into electrical ones and the electrical signals are saved in a buffer until the header processing is completed. Photonic routing sends the packets via light signals thus greatly diminishing such problems and improving network security.

This paper first reviews photonic routing technology and then describes the outline and results of research into photonic packet routing technology employing an optical orthogonal encoding label. Also described are the outline and results of research into a proof-of-principle experiment of photonic packet routing technology using the multi-wavelength label, which is an improved form of the MP-Lambda-S (Multi-Protocol Wavelength Switching). This paper concludes with a description of the outline and results of research into a proof-of-principle experiment of photonic label processing technology using time-space conversion processing and spectral holography.

2 Current Status and Issues

Due to the fast-growing popularity of the Internet and the concomitant increase in data traffic via networks, there has been great interest in WDM (wavelength division multiplexing) technology, which can accommodate in conventional optical fibers more than 100 Gbps of traffic. Networks implementing WDM technology are proliferating in response to growing demands for increased network capacity.

Currently, however, the Internet applications of this technology are limited to links between neighboring routers. When exchanging data between transmission and reception nodes via a number of routers, or transit nodes, the packet handling speed of these transit nodes plays a key role, and the data processing capability of these transit nodes must be upgraded to ease data throughput of the network as a whole. However, if we rely on only electronic technologies to increase packet handling speed, we can expect relatively limited improvements[1]; there is a higher potential for improvement in transmission capacity of optical fibers if we utilize WDM technology. In conventional network configurations, based on a layered structure, the routing capabilities of transit nodes causes bottlenecks.

To solve this problem, a number of methods have been proposed regarding the setting up of a photonic network in lower layers that will reduce IP routing jobs. For example, MPLS (multi-protocol label switching) technology[2][3] and optical path network technology (circuit-switching type WDM network)[4][5] have been proposed. According to these methods, IP packets are capsulated in a wavelength and then run through the photonic network. The transit node employs optical cross-connects (OXC) and optical add-drop multiplexers (OADM) to provide photonic processing that has a speed beyond the limits of electronic methods. These transit methods, however, only branch light signals through predetermined routes wavelength by wavelength. They have no ability to read the information embedded in the input wavelength and route data of the same wavelength into different routes. Packets of a pair of transmission and reception nodes are capsulated in each wavelength. Furthermore, the transmission speed of the optical channel (wavelength) is usually fixed at a certain speed, such as 2.4 Gbps or 10 Gbps, for example, and it is impossible for multiplexing light signals to enter from a number of input ports through a single route. Thus when an edge node of a network uses a bandwidth smaller than the transmission rate limit, the large bandwidth provided by optical technologies is not fully utilized.

In order to efficiently use the bandwidth of an optical layer it is essential to be able to branch light signals sent from a transmission route (for example, wavelength) into two or more routes and combine light signals sent from a number of routes into a single one. It is possible to efficiently use the bandwidth as shown in References[7][8] in IP over WDM[6], because the IP router has this capability. However, as previously mentioned, since the routing process still tends to cause bottlenecks, the signals should be multiplexed in the optical layer. Moreover, when burst traffic is observed on the Internet, the simple time division multiplexing system does not allow efficient use of bandwidth. Instead, packet exchanging should be adopted and the packets routed in the network according to the address information embedded in them.

A number of optical packet exchangers have been proposed[9][10][11]. They read the routing information of packets after converting it into electrical signals and then output the packets to corresponding ports. In other words, the data itself reaches its destination in the form of a light signal, but its address information is not read directly from that signal. The speed of the packet matching process is limited to the same level as that of the IP routers for electrical processing. Optical processing, therefore, is essential for faster signal matching.

Once these issues are resolved, there will be heightened expectations for a large-scale packet exchange network capable of light-based data transmission. Mixed packets with different destination addresses in a transmission route require that the network provide a sufficient number of labels. However, if the MPLS network [3] and optical path network technologies, which take up a wavelength per label, are adopted, it is clear that all wavelengths will be quickly used. Although around 1,000 wavelengths are available[12], they may not be enough to sufficiently expand the network to the scale needed to establish a photonic network.

3 Photonic Label Switching Using Optical Code

Fig.3 demonstrates the configuration of the proposed system. The proposed optical packet consists of an optical code, in which the address information has been mapped, and the payload data. This optical packet is accommodated as the optical path payload in an optical frame that has the wavelength routing information in the optical path header. The photonic label switch consists of a wavelength demultiplexer and a photonic label processor. The photonic label processor consists of a header processor, a *1*×*N* photonic switch, and an optical delay. The header processor conducts parallel label matching and consists of optical amplifiers, optical correlaters, optical pulse reshapers, and address

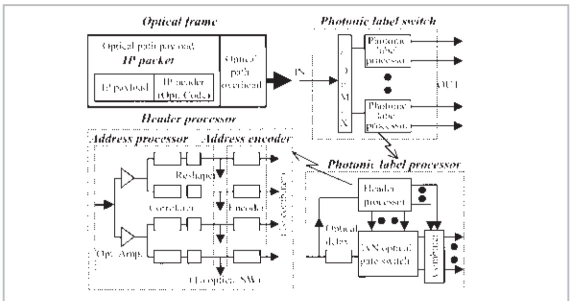

Fig.3 Optical packet and photonic label switching system

encoders. The group of optical correlaters works as an address bank[13] that records codes corresponding to the addresses held in the routing table.

The input packets are divided wavelength by wavelength, and then sent to each photonic label processor corresponding to individual wavelengths. In the photonic label processor, as shown in Fig.4, the header processor simultaneously produces replicas of the input code and conducts label matching, based on the calculation of optical correlation, thus outputting the photonic switch control signal. A control signal of a high peak value can be issued only when the input label matches the intrinsic label information that each correlater holds; when this occurs, the other correlaters do not output a high peak signal. The photonic switch conducts the routing of each packet based on this control signal. This label matching process in the optical domain does not require logic calculation. Label matching can be carried out based on optical correlation calculation in the time domain between the input optical code and the code held in the address bank. This parallel processing leads to faster data handling.

4 Packet Routing Experiment

The experimental setup is shown in Fig.5. This experimental system is comprised of an optical packet transmitter and a photonic label processor[14]. The optical packet transmitter is made up of a semiconductor mode-locked laser diode (MLLD) that generates 2ps-10GHz pulses, $LiNbO_3$ intensity modulators (IM), optical encoders, and an optical delay. The optical encoder is composed of optical taps, 5ps delay lines, phase shifters, and a combiner, all of them being integrated into a chip by PLC technology. In the optical encoder, as shown at the top of Fig.6, a single pulse is separated into eight chip pulses arrayed at intervals of 5 ps. Each pulse is given a phase shift of either 0 or π, and then an 8-chip optical bipolar code (BPSK-code) is generated[15]. The photonic label processor is composed of a

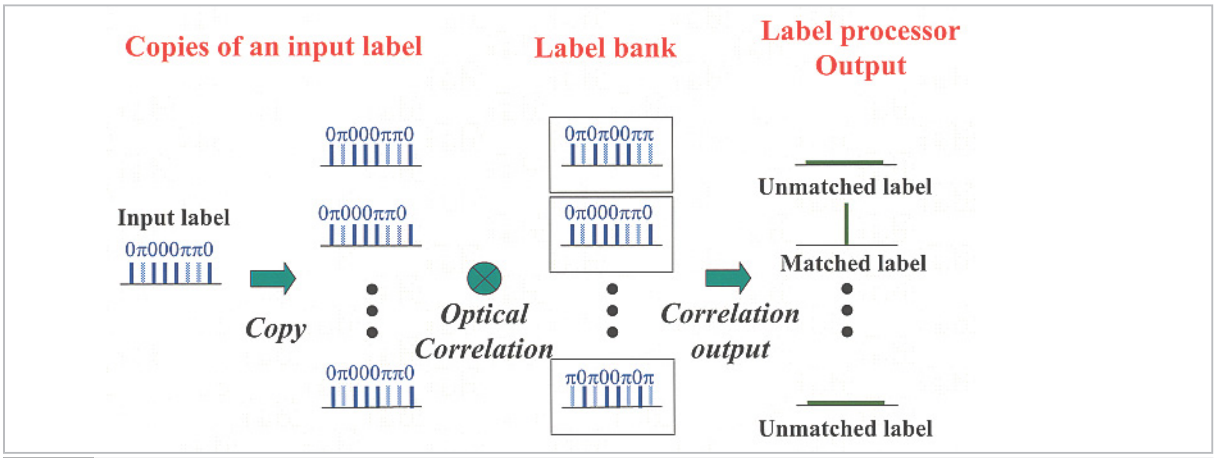

Fig.4 All-optical parallel label processing

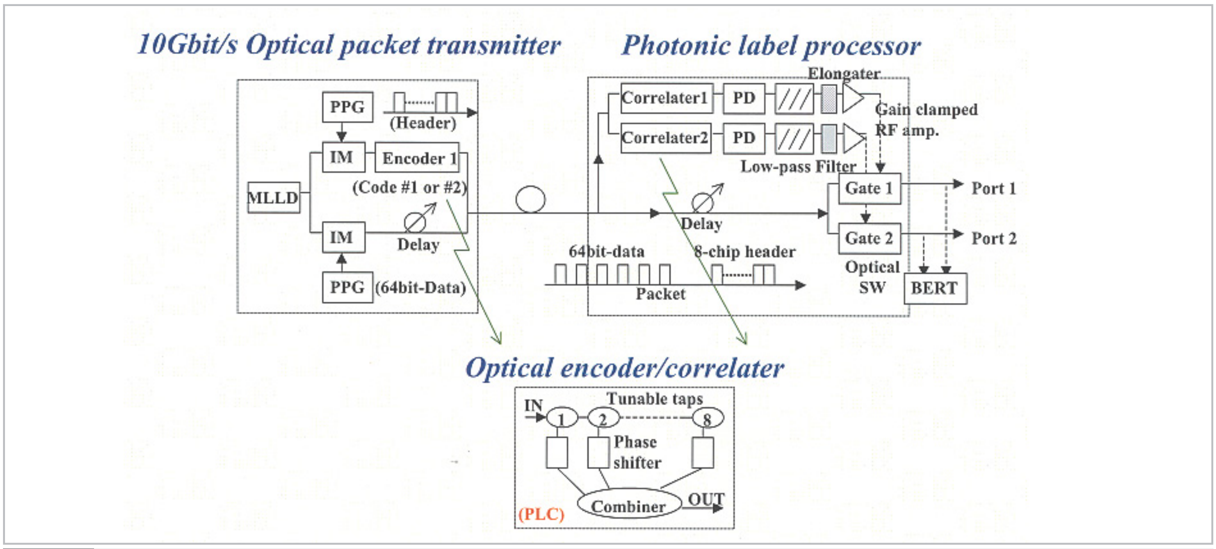

Fig.5 Optical packet routing experiment system

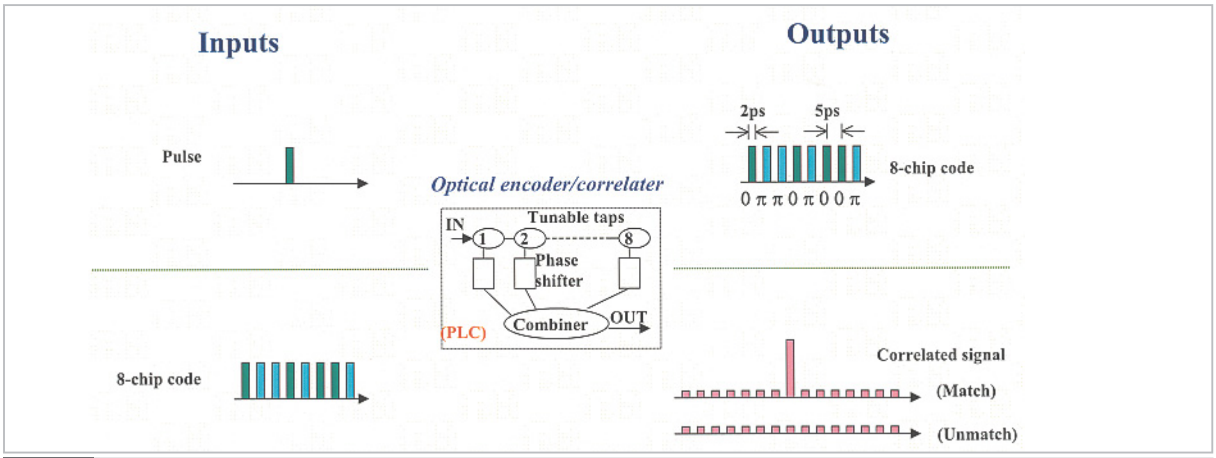

Fig.6 All-optical encoder/correlater

header processor unit and an optical switch unit. The header processor is composed of optical correlaters, photodetector (PD), low-pass filters, and gain-clamped drivers. The 1×2 optical gate switch composes two intensity modulators (IM) having a bandwidth of

40GHz. The optical correlater and the optical encoder have the same structure.

The optical packet transmitter generates burst data at a rate of 64bit@10Gbit/s and 8-chip BPSK optical codes, which are combined and then output as optical packets. As shown at the bottom of Fig.6, the photonic label processor yields an auto-correlated waveform of a high peak from its correlaters when the BPSK code agrees with the code held in the optical correlater. Meanwhile, a cross-correlated waveform is issued that has a low intensity when codes do not match. The output of an auto-correlated waveform obtained from the correlaters in case of code matching is converted into an electrical signal and then extended on the time axis by the low-pass filters and the gain-clamped amplifiers to open the gate switch while the packet passes. On the other hand, when there is no match, the output cannot open or pass the IM gate switch because of its low value. A packet exits only from the gate the label has matched, and then the packet is routed.

Fig.7(a) is a streak camera image of the top of a packet holding an optical code "0ππππππ0" as a label. Figs.8(b) and (c) show the outputs from the optical correlaters in the header processor for the packets having optical codes #1"0ππππππ0" (matched code) and #2 "0π0π0π0π" (unmatched code) as optical labels. An auto-correlated waveform of a high peak value is given to the matched code, while a cross-correlated waveform of a low value is given to the unmatched code. Therefore, the output from the optical correlater for the matched code can be the control signal strong enough to drive the optical switch. The 64bit data following the optical code is diffused when passing the optical correlater and thus does not affect the control signal. Figs.9(a) and (b) demonstrate the outputs from the optical gate switches for the labels of optical code #1 or #2. The figures indicate that the 64bit burst data is successfully branched in accordance with the attached optical codes. The bit error rates in both ports are as low as 10^{-10} or less, indicating that the packets have been successfully branched.

In addition, since the photonic label processor employed in this method is a passive and transparent device, it can be used universally for signals of different wavelengths with no modification. Therefore, the signals of different wavelengths that have been multiplexed by WDM can be separately and simultaneously handled with a single recognition device. As a result, it becomes possible to downsize the system for each packet switching node and provide ultra-high data throughput capability. Fig.10 shows the entire system configuration. The results obtained provide strong support for the feasibility of ultra-high-speed photonic packet routing.

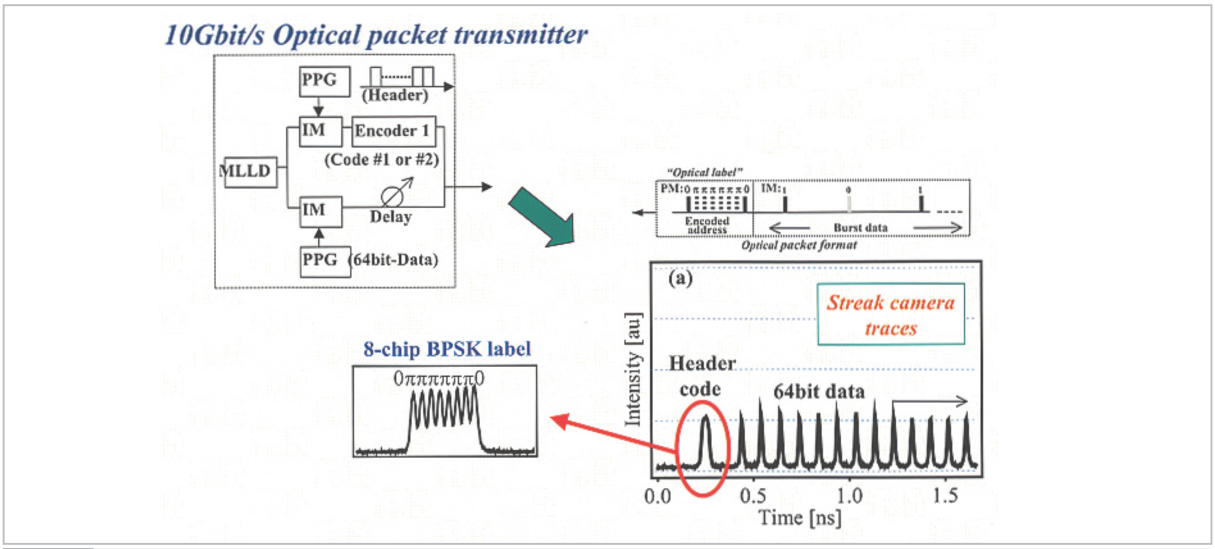

Fig.7 *Generation of an optical packet having an optical code label*

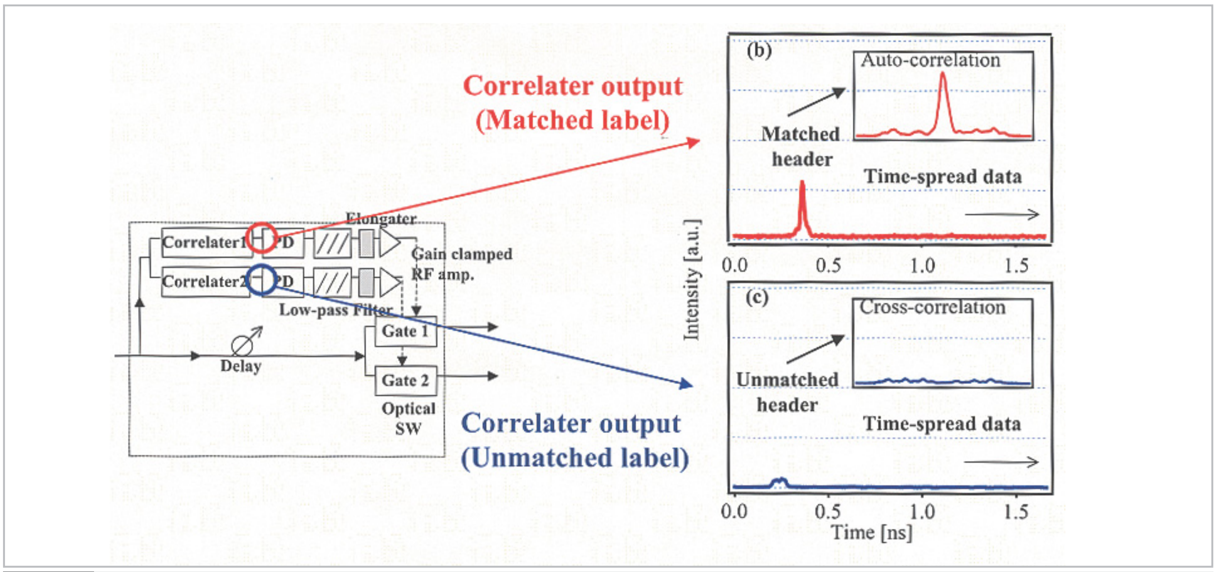

Fig.8 All-optical label matching

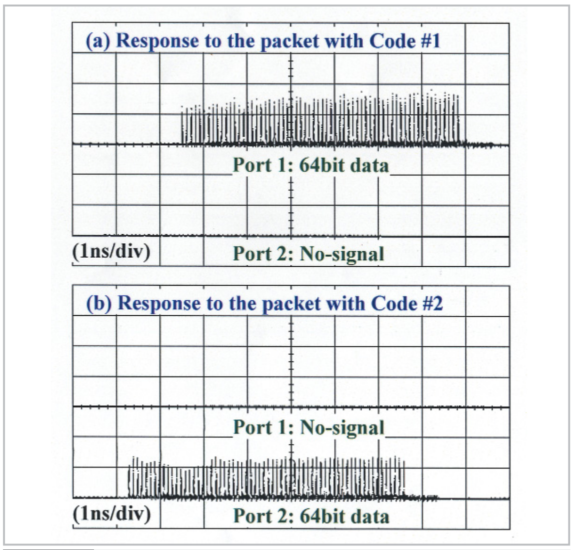

Fig.9 Packet routing test results

5 Photonic Label Switch Using Multi-Wavelength Label

Communications Research Laboratory has successfully proposed a method of using the multi-wavelength label and proof-of-principle experiment in addition to the above-mentioned optical orthogonal coding method[16][17]. Fig.11(a) shows the proposed packet format. The label is made of a series of *K*-chip pulses chosen from as many as *W* wavelengths.

Fig.11(a) shows the case of $K = W = 4$, where λ_{1A}, λ_{1B}, λ_{1C}, λ_{1D} represent wavelengths that are used to generate a multi-wavelength label. The payload data uses a separate wavelength, λ_{1E}. The wavelengths from λ_{1A} to λ_{1E} comprise a wavelength band $\lambda_{1A\text{-}E}$. The same number of independent multi-wavelength labels may be generated in the individual wavelength bands ($\lambda_{1A\text{-}E}$, $\lambda_{2A\text{-}E}$, $\lambda_{3A\text{-}E}$...). The label uses one wavelength for each of the *K*-pulse series and different wavelengths are assigned to the individual pulses (hereafter refered to as label configuration A).

Fig.11(b) shows the structure of a network employing the multi-wavelength label packet (hereafter refered to as multi-wavelength label network). The multi-wavelength label network is comprised of multi-wavelength edge nodes (MλEN), multi-wavelength label switching nodes (MλLSN), and wavelength routers (λOXC).

The multi-wavelength edge node is capable of assembling optical packets by adding the multi-wavelength label to the data that has arrived from an external system and then sending the packets to the network. It also removes the label from the packet and sends the data outside the network when it has received an optical packet. The multi-wavelength label switching node is made up of a multi-wavelength label switch (MλLS) and a multiplexer. The multi-wavelength label switch has the function of reading the multi-wavelength label and sending the optical

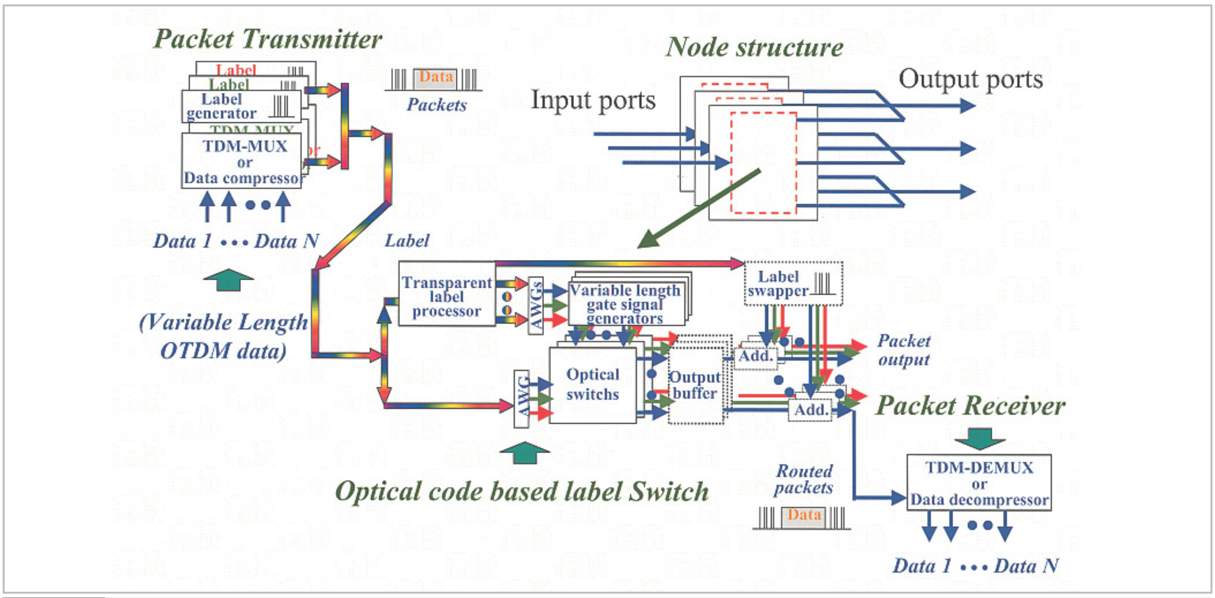

Fig.10 Ultra-high throughput photonic packet switching system

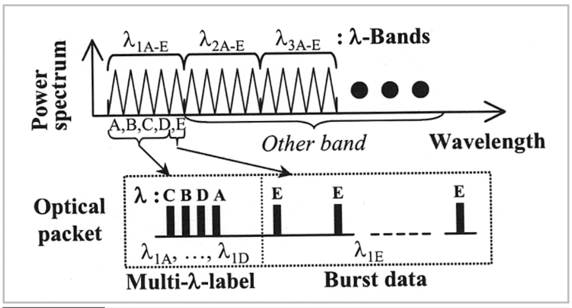

Fig.11 (a).Packet format having a multi-wavelength label

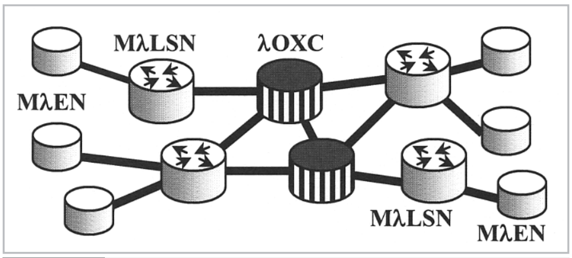

Fig.11 (b).Network configuration

packet to the corresponding port. Generation and readout of the multi-wavelength label is carried out by optical processing using multi-section FBGs. The multiplexer combines the optical packets that have arrived from a number of multi-wavelength label switches. The wavelength router sends all the wavelengths in a band to the same output port. Thus the packet made of wavelengths, which belong to the same bandwidth shown in Fig.11(a), is not discomposed by the wavelength router. According to the above configuration, two different kinds of nodes are allowed to exist within the same network, and a flexible network can thereby be built in the optical layer[18].

The necessary number of wavelengths required for label generation can be reduced in the multi-wavelength label network, compared with other networks or an optical path network where one wavelength is needed to make each label. In label configuration A, as many as $W!/(W-K)!$ different labels $(W \geq K)$ can be generated when as many as W wavelengths and K-pulse series are used in forming a label. The necessary number of wavelengths may be reduced to the least integer W that meets $W!/(W-K) \geq N$ in the network having as many as N edge nodes that conduct routing based on the shortest-path routing method. For example, assume a case in which the label equivalent to the destination address is included in the packet in a backbone network of approximately N=100. If the network uses one wavelength for each label, as many as 100 wavelengths will be needed. About 10,000 wavelengths will be needed in the optical path network. On the other hand, only 11 wavelengths are sufficient in the multi-wavelength label network if a label consisting of two pulses is used. If a label consisting of four pulses is used, five wavelengths are sufficient. Even when regarding the hosts in the Internet as edge nodes that route packets of an address length of 32 bits, 20 wavelengths (eight pulses) at most are sufficient in the multi-wavelength label network.

The number of optical labels may increase. Assume that each of the wavelengths for labeling is used once and assigned to a desired position in the label-space of K-pulse (Label configuration B). To recognize the top of a packet, at least one wavelength has to be assigned to the top position. Then the number of labels becomes $K^{W}-(K-1)^{W}$[18].

Fig.12 illustrates the relationships between the number of wavelengths, label length, and label number for configurations A and B. In either case, more than 10,000 labels can be provided if as few as eight wavelengths are used in labeling. See Reference[19] for a more detailed analysis.

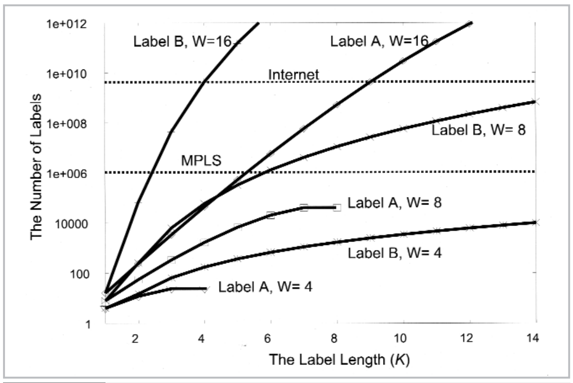

Fig.12 Comparison of label numbers

6 Configuration of Multi-Wavelength Label Switch

Fig.13 shows the block diagram of the system configuration of the multi-wavelength label switch (MλLS). The multi-wavelength label switch comprises a label/data separator, optical delay generator, a multi-wavelength label processor, a $1 \times N$ optical switch, and a label changer. This configuration of the switch is the same as that of the aforementioned photonic switch system using the optical coding label but differing in the label/data separator and label processor unit. Also, the configuration of the label changer is different[20], but is not referred to in this paper.

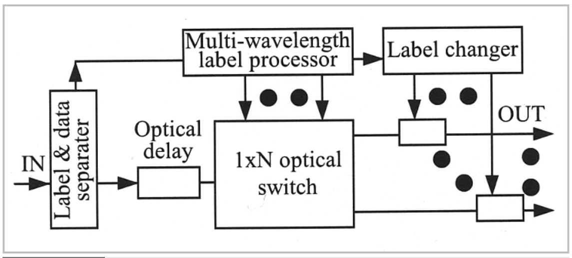

Fig.13 Multi-wavelength label switch

When a packet having the multi-wavelength label enters this system, the label portion is separated by the label/data separator and sent to the label processor. The label processor conducts label recognition and matching with the label banking in parallel on an all-optical basis. Based on the result of this label matching, the label processor controls the optical switch and sends the packet to the correct port. If the label needs to be changed, the label changer provides a new label and sends it out.

7 Multi-Wavelength Label Switching Experiment

Fig.14 shows the configuration of the proof-of-principle experiment. The experimental setup consists of a multi-wavelength label packet transmitter, 33km dispersion shifted fiber (DSF), and a three-output port multi-wavelength label switch. The multi-wavelength label packet transmitter consists of a super continuum (SC) light source[21] (providing multi-wavelength pulses of a bandwidth of 140 nm @ 10 GHz), $LiNbO_3$ intensity modifiers (IM), a multi-wavelength label generator[22] (comprised of a three-section fiber grating (FBG) and an optical circulator, an optical band-pass filter (O-BPF), and a delay. A multi-wavelength light pulse emitted from the SC light source is divided into three pulses by the three-section FBG after its repetition speed is lowered to the packet rate by IM, and then the multi-wavelength labels (λ_{1A}, λ_{1C}, λ_{1B} in Fig.14) is generated. Meanwhile,

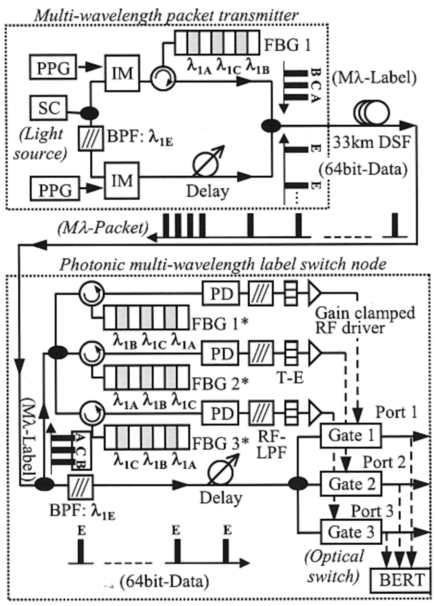

Fig.14 Experimental system

the pulse with a center wavelength of λ_{1E} is extracted from the SC light by BPF, and IM generates 64bit burst data. The generated multi-wavelength label is laid ahead of the burst data in which the time shift has been controlled by the optical delay and then sent out as a packet with a multi-wavelength label.

The three-port output multi-wavelength label switch consists of an O-BPF, optical delay, multi-wavelength label correlater (comprised of three-section FBGs and optical circulators), photodetector (PD), low-pass filters (RF-LPF), RF threshold processor, RF waveform expander, gain-clamped RF amplifier, and 1×3 optical switch. The 1×3 optical gate switch has 40GHz-bandwidth $LiNbO_3$ intensity modulators. The three-section FBG array in the multi-wavelength label switch conducts correlation processing for label recognition and works as a label bank. When the input label matches the combination of corresponding wavelengths of the correlater, the FBG correlater outputs a light pulse of a high peak value. On the other hand, when the wavelength array of the input label does not match the combination of wavelengths of the correlater, a pulse of a low peak value is issued instead of a high peak pulse. The optical output from the correlater is converted into electrical signal by PD; this signal is electrically expanded after a threshold processing to allow the gate switch made of a $LiNbO_3$ intensity modulator to be opened for the period of time needed for the packet to pass. The strong pulse, which has matched the input label and been issued by the correlater, is regarded as “1” by the threshold processing and then converted into the gate signal by electrical processing. Meanwhile, the correlater output that has not matched the input label has no peak in the pulse, and thus it is regarded as “0” by threshold processing. The output after the electrical processing remains at level-zero. Then, only the gate switch connected to the correlater whose wavelength set has matched the input label will open; the other gate switches will stay closed. The input packets are thereby branched to the ports corresponding to individual labels.

Fig.15 shows our experimental results. Figs.15(a) and (b) show results obtained with a sampling oscilloscope of the multi-wavelength label “λ_{1A}, λ_{1C}, λ_{1B}” that was generated by the multi-wavelength label packet transmitter and of the intensity of the packet having such a label as header. Figs.15(c) and (d) demonstrate the waveforms of the outputs from correlater FGB 1*(λ_{1B}, λ_{1C}, λ_{1A}) and correlater FGB 3*(λ_{1C}, λ_{1B}, λ_{1A}). A pulse of a high peak value is provided in Fig. 15(c) where the label matches the wavelength set of the correlater, while a high peak is not seen in Fig.15(d) where the label does not match. These results indicate that all-optic multi-wavelength labeling is viable. Figs.15(e) and (f) show the waveforms of outputs from the three-port switch. Fig.15(e) shows the output of the label switch for the case where a packet having the multi-wavelength label “λ_{1A}, λ_{1C}, λ_{1B}” matching the correlater FBG 1* has entered the label switch, while Fig.15(f) shows the output for the case where a packet having the multi-wavelength label “λ_{1A}, λ_{1B}, λ_{1C}” matching the correlater FBG 3* has entered the label switch. The results indicate that the multi-wavelength label switches successfully switch the outputs according to the

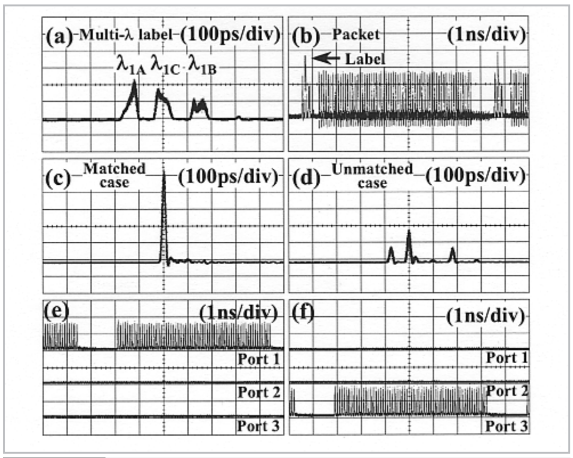

Fig.15 Experimental results (1)

label information of each packet.

Fig.16 shows the bit error rate of packets sent back-to-back on a 33km transmission. Figs.16 (a), (b) and (c) correspond to outputs from ports 1, 2, and 3, respectively. It is evident from the port output results that transmission and routing have been successfully performed. This investigation shows that it is quite possible to create a photonic network using the multi-wavelength label switch.

8 Holographic Label Processor

The above studies describe the optical code label switching method (Fig.5) using a PLC-type correlater and the multi-wavelength label switching method using an FGB-type correlater (Fig.14). Since one correlater corresponds to one address in these methods, a large number of correlaters will be required in the header processor for exact matching of address information.

We have proposed a holographic address processor[23][24] using spectral holography, which is capable of recording a great deal of address information in a single device, as the address bank on behalf of the PLC decoder array.

Fig.17 is a block diagram illustrating the basics of holographic label processing. After a time-space conversion[25][26], the input optical label is Fourier-transformed and entered into an angular-multiplexed spectral hologram (AMSH)[27][28]. The AMSH holds information corresponding to a multitude of input labels. It works as an address bank and outputs pulses in different angular directions according to the kinds of input label. The output pulse runs through a Fourier-transform lens, and it is converted into positional information and then detected by a positional information detector. The final output is thereby obtained in accordance with each kind of input label. Matching for a number of labels can be performed on a real-time basis with a single device.

Fig.18(a) shows the system for performing multiplex writing (holographic label banking)

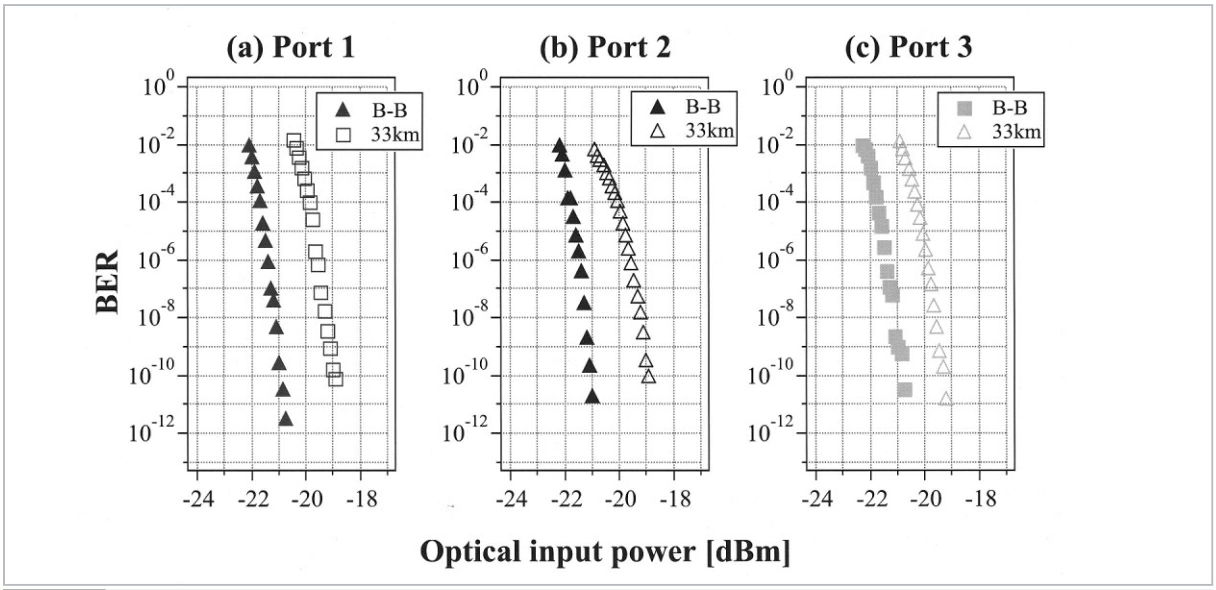

Fig.16 Experimental results (2)

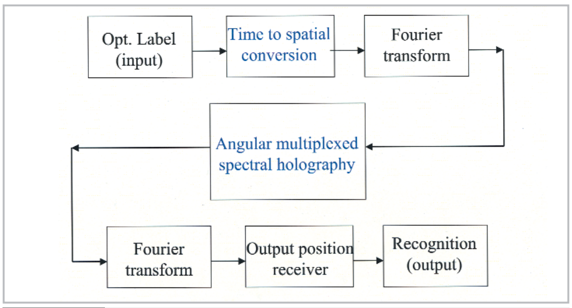

Fig.17 Principles of holographic label processing

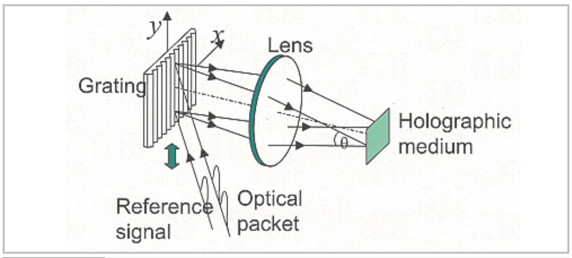

Fig.18 (a).Writing of label information

of label information in an AMSH. This system consists of a time-space conversion grating, Fourier-transform lens, and holographic medium. The optical label and the reference label are time-space converted simultaneously and then recorded onto the holographic medium by interference after passing through the Fourier-transform lens. All optical labels experience this processing for multiplex recording. In this case, the position for inputting optical labels is fixed, while the position for inputting reference pulses is changed for each optical label. The AMSH label bank is thereby prepared.

Fig.18(b) shows the configuration of the holographic label processor. The processor consists of a grating, two Fourier-transform lenses, and an AMSH. The optical label whose address information has been mapped is time-space converted by the grating and entered into the spectral hologram via the Fourier lens. Information about a number of optical labels has been written in the spectral hologram by angular-multiplexing using the system shown in Fig.18(a). The light emitted from the spectral hologram passes through the other Fourier lens and reaches the position corresponding to each label in the incident

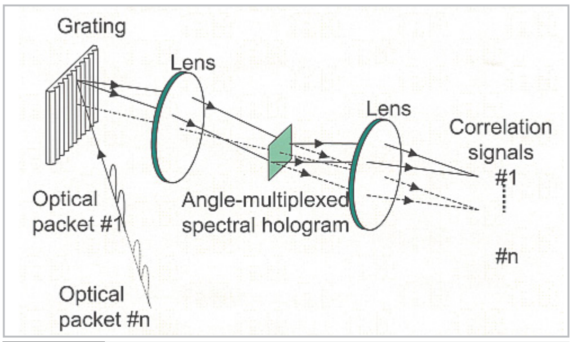

Fig.18 (b).Label matching

light. Unlike conventional spectral holography, there is no need to conduct time-space conversion again so as to convert the signal into a waveform on the time axis.

9 Proof-of-Principle Experiment and Results

Fig.19 shows the experimental system for confirming the mechanism of an all-optical address matching process at 10 Gbit/s. This experimental system comprises a mode-locked semiconductor laser diode (MLLD), optical fiber amplifier (erbium-doped fiber amplifier: EDFA), filter, polarization controller (PC), isolator, PLC-type 8-chip optical encoder, dispersion-shifted fiber, collimator, holographic address processor, optical spectrum analyzer (OSA), and optical power meter (OPM). The pulse (central wavelength 1550 nm, 10 Gbit/s, pulse width 2ps) emitted from the MLLD is converted into an 8-chip optical intensity code with the PLC-type 8-chip optical encoder. The generated optical code enters the holographic address processor, and a pulse signal comes out in the position corresponding to each kind of optical code based on the above mechanism. The output signal is then

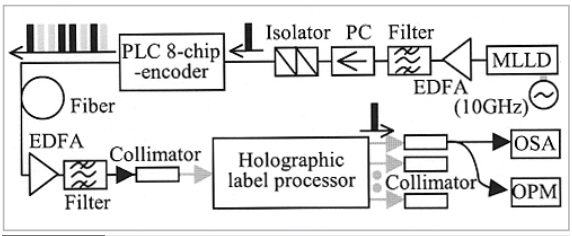

Fig.19 Experimental system for holographic label processing

observed with an optical spectrum analyzer (OSA) and an optical power meter (OPM).

Because a holographic medium for the 1.5 μm-band was not available for the experiment, we prepared a signal pattern that was modified for use in the 1.5 μm band and made a holographic address bank using an He-Ne laser with a central wavelength of 632.8nm. We employed Agfa-Gevaert 8E75, originally prepared for visible light, as the holographic medium. When employing the He-Ne laser to create a quasi hologram for use in the 1.5 μm band, an AMSH for optical phase code label banking cannot be produced because we cannot project the real input beam (signal) onto the holographic medium. Thus we used the optical intensity code as the label in this mechanism confirmation test.

Figs.20 and 21 show the experimental results. Figs.20(a) and (b) show the streak camera traces (waveform along the time axis) of the optical coding labels "10010010" and "10000010", respectively, which were generated by the PLC-type encoder. In the previous photonic routing experiment using the PLC-type correlater, we generated a combined optical phase code made of "0 and π" for creating the address information. Because of the above-mentioned reason, however, in this experiment we used an intensity label of "1 and 0".

Figs.21(a) and (b) show power spectra observed at output ports of the address processor for the cases in which the code of incident light matches or does not match the code that has been assigned to each port in advance. When the address information shows a match, a strong peak appears and address recognition can be made. Fig.22 is a comparison of intensity distributions between the positions of output beams corresponding to optical coding labels "10010010" and "10000101", in the case in which an optical coding label of "10010010" is entered into an AMSH in which the optical coding labels "10010010" and "10000101" have been recorded in advance. These experimental results indicate considerable potential for practical use of a multiplex recording label recognition device relying on an AMSH.

In this experiment we failed to provide output light strength that was adequate to drive the optical switch because the light in the 1.5μm-band showed significant power loss in a holographic medium that had origi-

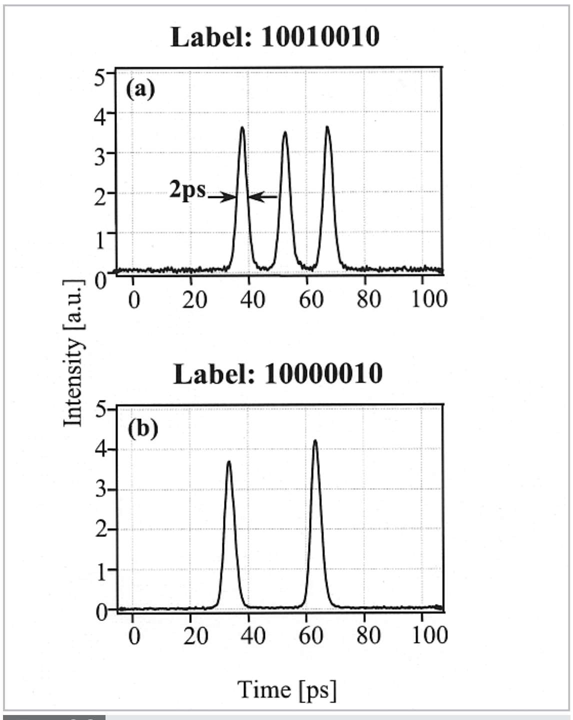

Fig.20 Generated 8-chip OOK label

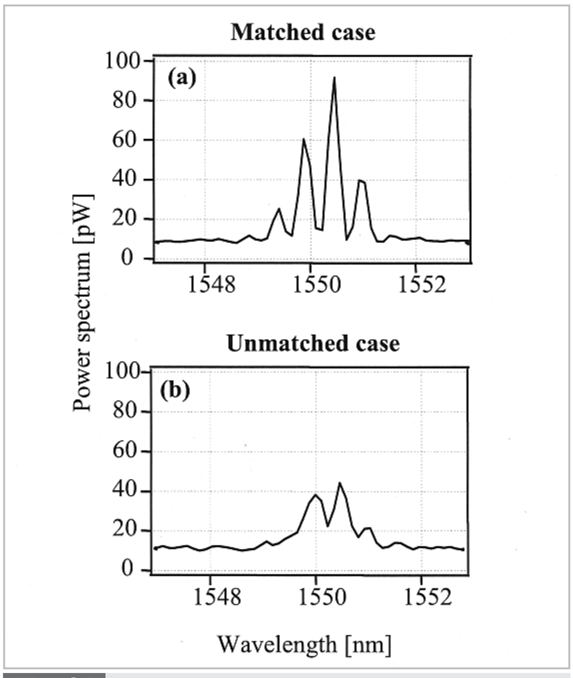

Fig.21 Recognition of 8-chip OOK label (1)

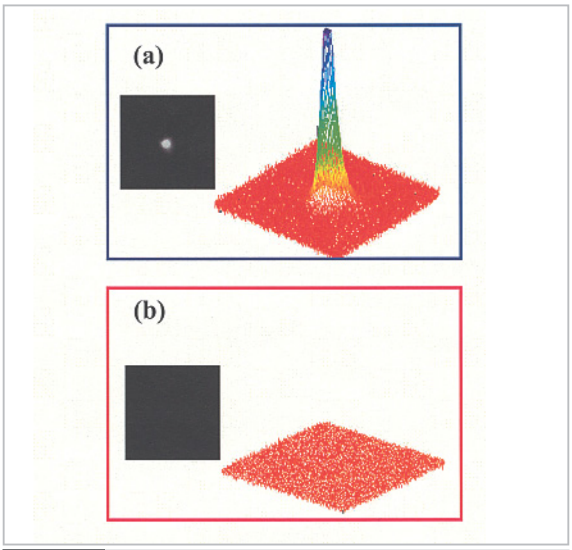

Fig.22 *Recognition of 8-chip OOK label (2)*

nally been prepared for visible light. The development of a low-loss hologram for the 1.5μm band is one of the keys to its successful use in the future.

10 Conclusions

We have reviewed photonic packet routing technology and explained the results of research into this technology with regard to an optical orthogonal coding label. We have also examined the structure of packet switching nodes capable of ultra-high levels of data throughput. The outline and results of a mechanism confirmation test of photonic packet routing technology using the multi-wavelength label, which is an improved form of MPλS, have also been discussed. Finally, we have examined the outline and results of a proof-of-principle experiment of photonic label processing technology using spectral holography. Photonic packet routing technology is a means of applying optical information processing technology to optical communications. To further improve this technology it is important to develop a material suitable for optical information process in the 1.5μm band.

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Photonic Network, Photonic Packet Switching, Photonic Node