Simultaneous Label Swapping and Wavelength Conversion of Multiple Independent WDM Channels in an All-Optical MPLS Network Using PPLN Waveguides as Wavelength Converters

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***Abstract*—This paper presents the demonstration of all-optical simultaneous label swapping and wavelength conversion of multiple independent wavelength-division multiplexed (WDM) channels using periodically poled lithium niobate (PPLN) waveguides as wavelength converters. Label swapping is one of the required functions in the physical layer for efficient data flow control in the proposed multiprotocol label switching (MPLS) networks. The technique operates directly on the optical signal without optoelectronic (O/E) conversion; therefore, it is bit-rate, label length, and protocol/format independent. Experimental results are presented for the label swapping of distinct 8-b-long labels in a system with 2 WDM data channels at 10 Gb/s. There is a guard time of 400 ps between the payload and the label. The power penalty introduced by the method is less than 3 dB. This method can potentially accommodate 10 WDM channels simultaneously over the PPLN waveguide's ~ 40 nm λ-shifting bandwidth.**

***Index Terms*—Flow control, label swapping, multiprotocol label switching (MPLS), periodically poled lithium niobate (PPLN) waveguide, wavelength conversion, wavelength routing.**

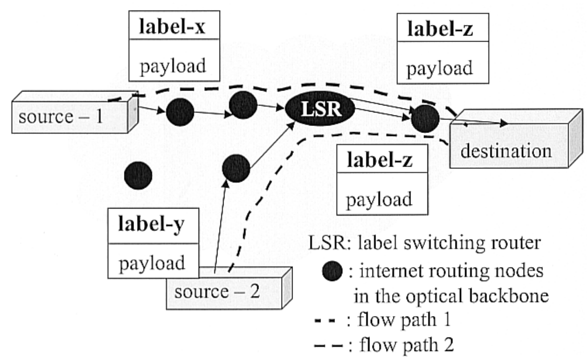

Fig. 1. In MPLS, flow paths are labeled according to the assigned path from the source to the destination. The packets are labeled accordingly at the entrance to the core. Label swapping is a required function at a label switching router (LSR), to connect different flow paths. The LSR will do the label swapping to replace the original labels with the new one (label-y to label-z and label-x to label-z).

I. Introduction

NEXT-GENERATION all-optical networks may require protocol, bit-rate, and format transparency to achieve efficient routing of data packets to their appropriate destination. This transparency of the physical layer operations can better focus the routing process to the determination of the *flow path toward the destination* rather than the potentially costly and time-consuming data processing such as electronic header recognition of data packets. The header of a packet provides more information than needed to find the routing output port for that particular router in the backbone. However, the common flow paths of various packets can be combined and labeled together to form forwarding sets (forwarding equivalence classes, or FECs) so that different packets in the same set will be indistinguishable (Fig. 1). In order to efficiently and transparently route packets to an appropriate destination, future high-speed all-optical networks may require the use of labels, as proposed in multiprotocol label switching (MPLS) [1], [2].

In MPLS networks, the label is assigned to a particular packet once the packet enters the network. There is no further need for the header recognition of the packet in the consecutive label switching routers (LSRs). Instead, the label is used as an index to a look-up table specifying the routing output port and the new label. The switches that are incapable of header recognition at the adequate transmission speed (> 10 Gb/s) can do label look-up and replacement, that is, *label swapping* to achieve MPLS forwarding [2].

The all-optical label swapping techniques will enable the tasks of network provisioning limited to the entrance points of the backbone. This will in turn remove the electronic processing (potentially slower and more costly) from the intermediate nodes to achieve higher speed networks [3]. The

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TABLE I
SAMPLE COLLECTION OF THE CALCULATED/DEMONSTRATED LATENCY OF DIFFERENT OPTICAL NETWORK ARCHITECTURES

Architecture	Data-vortex architecture to eliminate processing delays and internal buffering [4]	OTDM channel selector for wavelength switching [5]	Header logic-circuit implemented in one field programmable gate array (FPGA) and a lithium niobate switch [6]	All-optical routing using multiple WDM channel label swapping in MPLS networks
Latency	10 ns / hop	Max. 320 ps / wavelength switching	105 ns / switch node latency	Potentially instantaneous

approach of processing at the entrance will drastically improve the throughput of the network by reducing the latency. The routing latency of different network architectures is presented in Table I.

The labels can be located in the digital baseband data stream as a separate field at the head or the tail of the packet [7]. They also can be transmitted in a frequency-multiplexed format such as on an ancillary subcarrier [8], [9]. Using a label for routing should remove the burden of high-speed data processing at the intermediate nodes. The advantages then will be fast routing decisions and a rapid and on-the-fly recognition, erasure, and replacement of the label. Various all-optical techniques for rapid label recognition have been presented [10], [11]. A truly flexible and reconfigurable optical MPLS network necessitates the ability for the label to be rapidly "swapped."

Previous reports of all-optical techniques for label swapping include: i) employment of XOR logic in an integrated interferometric wavelength converter [7]; ii) incorporation of fiber Bragg grating filters to separate and replace the subcarrier labels using dispersion-induced fading [12]; and iii) use of a Fabry–Pérot filter for erasure and replacement of subcarrier labels [13], [6]. In addition, replacement of multiple labels by a single label was demonstrated in [14]. However, no reported method to date has shown the functionality of independent label swapping of *multiple WDM channels simultaneously* in a single subsystem. This paper is on the demonstration of the simultaneous label swapping of multiple independent WDM channels using periodically poled lithium niobate (PPLN) waveguides as λ-shifters. The WDM channels are also wavelength converted with this method.

The unique property of the PPLN waveguide for this application is that it can accommodate multiple independent input WDM data packets. Through the PPLN waveguide, all input wavelengths are mapped to their mirror images with respect to a pump signal, i.e., difference frequency generation (DFG) [15]. The PPLN waveguide: i) adds negligible spontaneous emission noise; ii) operates with negligible chirp; iii) has similar up- and down-conversion efficiency; iv) induces negligible crosstalk and high extinction ratio at the output; and v) has $> \text{THz}$ bandwidth enabled by its almost instantaneous nonlinear operation of DFG.

In this experiment, the pump signal is time-gated so that only the payloads of the WDM packets are λ-shifted through the first PPLN waveguide [16]. As a result, the original labels are removed. An additional identical PPLN-waveguide λ-shifts the new labels to the same wavelength as the λ-shifted payloads. These two signals are optically combined, forming the label-swapped packet. Successful label swapping and λ-shifting of two WDM channels at 10-Gb/s is experimentally demonstrated by replacing the labels of individual channels independently. It is consistent with the initial design constraint of MPLS; this label swapping method is bit-rate, label length, and format independent, i.e., the packets with a common label are indistinguishable. Furthermore, this method can potentially accommodate up to 10 WDM channels using the $\sim$ 40-nm λ-shifting bandwidth of the PPLN waveguide in the same module [17]. Label swapping with this technique introduces less than 2.5 dB power penalty.

II. CONCEPT

There are two stages of the implementation (Fig. 2): The first stage consists of the removal of the original label from the incoming packets of the two WDM channels. The second stage is the insertion of a new label. During both of these stages, the input data signals are assumed to have perfect alignment of the starting time of labels and payloads. In addition, the label swapping module is presumed to have the timing information of the incoming packets, i.e., the packets and the new labels are synchronized manually to the λ-shifting pump signals. The synchronization signal can be generated using another optical module [18].

During the first stage, the DFG process selectively λ-shifts the payload parts of the packets simultaneously to output wavelengths [Fig. 2(a)]. The multiple input wavelength channels are *λ-shifted simultaneously* to output wavelengths. The enabling technology is the DFG in the PPLN waveguide. The pump signal is time-gated to λ-shift only the payload parts of the packets. Specifically, this "payload-selector pump signal" is ON only during the payload parts of the packets. Therefore, the wavelength converted output signals have zero power level at the place of the original labels.

The second stage consists of the wavelength conversion and the insertion of the new labels [Fig. 2(b)]. The inputs to this stage are the λ-shifted original payloads and the new labels. In this experiment, there is one single pattern generating equipment, therefore, the new labels are coded into the packet payloads.

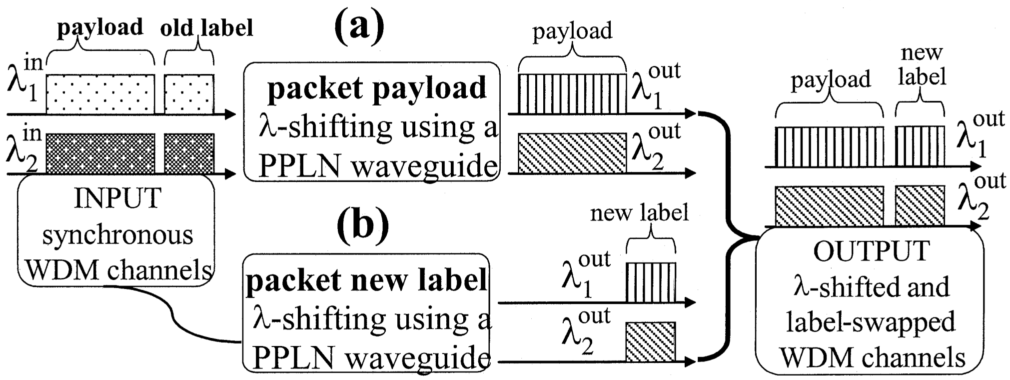

Fig. 2. Original labels are removed in (a) and the payload and new labels (b) are mapped onto new wavelengths. The new label is inserted into the place of the original one to generate the wavelength-shifted and label-swapped output signal.

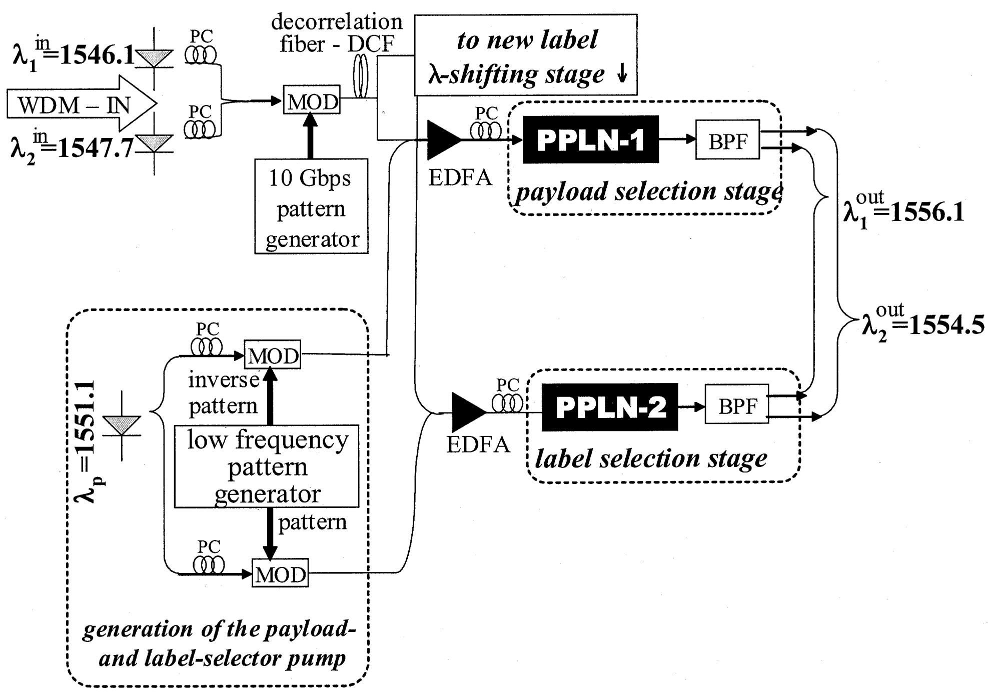

Fig. 3. Experimental setup. The payloads and new labels are wavelength converted by individual identical PPLN waveguides. The outputs are band-pass filtered and combined to form the label-swapped WDM channels.

Similar to the first stage, this time the new labels are wavelength converted using the inverse of the time-gated pump signal. In order to λ-shift only the coded new label parts of the packets, this "label-selector pump signal" is ON only for the duration of the label. The wavelength conversion of the new labels is achieved using a second identical PPLN waveguide.

Consequently, the wavelength-converted original payloads and new labels are synchronously combined. These signals are band-pass filtered at the output of each PPLN waveguide and manually synchronized to each other. During this synchronization, the new labels are positioned to take the place of the original labels. The resulting signal is label-swapped and λ-shifted packet streams of the two WDM data channels.

III. Experimental Setup

Our experimental setup is shown in Fig. 3. There are two WDM input channels at 10 Gb/s with 8-b labels in 60-b-long packets with a 4-b guard time (400 ps) between each label and the payload. The guard time is needed to prevent any potential distortion from the rise (or fall) times of the low frequency payload- and label-selector pump signals. It is assumed that the first bits of each packet of the WDM channels arrive at the label-swapping module at the same time and that their labels are aligned with each other.

For this demonstration, two identical PPLN waveguides (i.e., designed to have the same pump wavelengths, ~ 1551.1 nm,

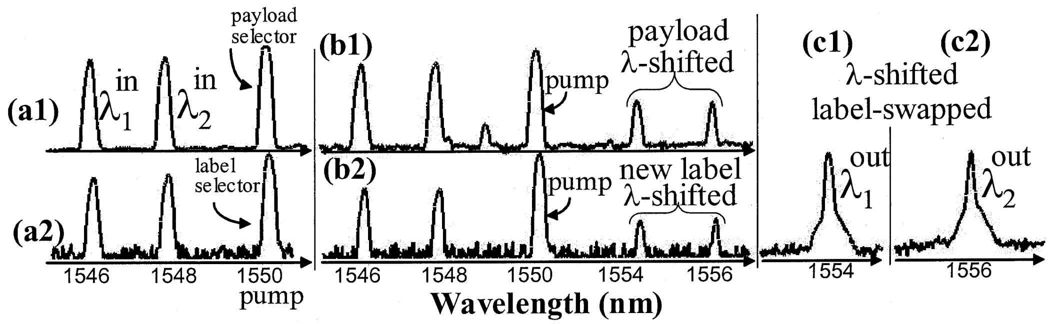

Fig. 4. The spectrum of the label swapping subsystem. (a1), (a2) are the input spectra to the PPLN waveguides, payload and label-selection spectra, respectively. (b1), (b2) are the DFG spectra at the output of the PPLN waveguides. (c1), (c2) are the label swapped and λ-shifted outputs.

and phase matching temperature, $\sim 97°\mathrm{C}$) are manufactured and pigtailed on the same substrate. The PPLN waveguides have a cascaded $\chi^{(2)} : \chi^{(2)}$ process that produces difference frequency generation (DFG), which is much more efficient than four-wave mixing. The minimum required pump power can be as low as 50 mW as revealed by new advances [19]. Since the only source of noise is the pump and input signal amplifier noise, the signal-to-noise ratio (SNR) can easily be increased by ASE filtering at the PPLN waveguide input and output.

The data channels are generated using one modulator and a single pattern generator. The WDM input channels are at 1546.1 and 1547.7 nm. Since there was not an additional signal generator to generate the new label patterns, the new label bits are coded within the payload of the input packets. In order to obtain two different transmission data, WDM wavelength channels are subsequently decorrelated by 1-b time (100 ps), using the dispersion of a spool of DCF fiber (~ 1 km of DCF spool with -90 ps/nm $\cdot$ km dispersion).

The payload-selector pump is a square wave with a duty cycle at the payload rate. Therefore, it is modulated with “1” bits for the duration of the payload and “0” bits for the duration of the label. In order to remove the original labels, only the payloads of the packets of both channels are wavelength converted using the PPLN-1, as shown in Fig. 3 (payload selection stage). In the first PPLN waveguide, the wavelength conversion applies only on the original payloads where the pump input is active/ON. For this reason, the wavelength converted signals have zero power level at the place of the original labels.

The new-label-selector pump is modulated by the inverse pattern of the payload-selector pump. Fiber delays are used to manually align the new labels with the label-selector pump at the input to the PPLN-2 (new label selection stage). This second PPLN waveguide λ-shifts the new labels to the same wavelengths as the wavelength converted payloads. The pump wavelengths for both of these PPLN waveguides are the same, ~ 1551.1 nm, the incoming wavelengths for both the payload and the new labels are the same WDM data wavelengths, 1546.1 and 1547.7 nm, and as a result, the output wavelengths of the PPLN waveguides are the same, 1556.1 and 1554.5 nm, respectively.

The DFG outputs of both waveguides are then band-pass filtered to pass only 1554.5 and 1556.1 nm, and then amplified using EDFAs. The λ-shifted payloads and the new labels are then combined such that the new labels are located in the same position as the original labels.

IV. Spectra of the Wavelength Conversion

The input and output PPLN spectra are shown in Fig. 4. The payload-selection spectra are shown in Fig. 4(a1) and (b1). Similarly, Fig. 4(a2) and (b2) shows the label-selection spectra. The output spectrum of the label-swapping operation for each of the WDM channels is shown in Fig. 4(c1) and 4(c2).

The input spectra to the PPLN waveguides, which is comprised of the 2 WDM input channels and the pump, are shown in Fig. 4(a1) and (a2). The input wavelength channels are marked as λ_1 and λ_2. The pump signal is responsible for selecting the payload part of the packets in Fig. 4(a1). Similarly, the label-selector pump will wavelength convert only the new labels coded inside the packets. The input to this second PPLN waveguide is shown in Fig. 4(a2).

At the output of the PPLNs, the spectra include the wavelength converted payloads, Fig. 4(b1), and labels, Fig. 4(b2). The converted signals are mirror images of the input wavelengths with respect to the pump. In this experiment, the conversion loss is ~ 18 dB through the PPLN waveguides. The conversion loss can potentially be eliminated by advanced integrated manufacturing and pig-tailing techniques for these waveguides. The conversion loss does not change with the increase in the number of input channels.

The spectra of the two λ-shifted WDM channels containing their new labels are shown in Fig. 4(c1) and (c2). These output spectra are obtained after combining the wavelength converted payloads with the new labels. The new labels are aligned to take the position of the original labels.

V. Label Swapping Results and Discussion

Fig. 5 shows time domain waveforms at each stage of the experiment. The waveforms in Fig. 5(a) and (b) are the input WDM channels. There are 4 packets included in these traces. The new-label-selector waveform, Fig. 5(c), is aligned with the new labels that are coded in the packet payloads. Due to its low duty cycle this signal contributes to some distortion. In addition

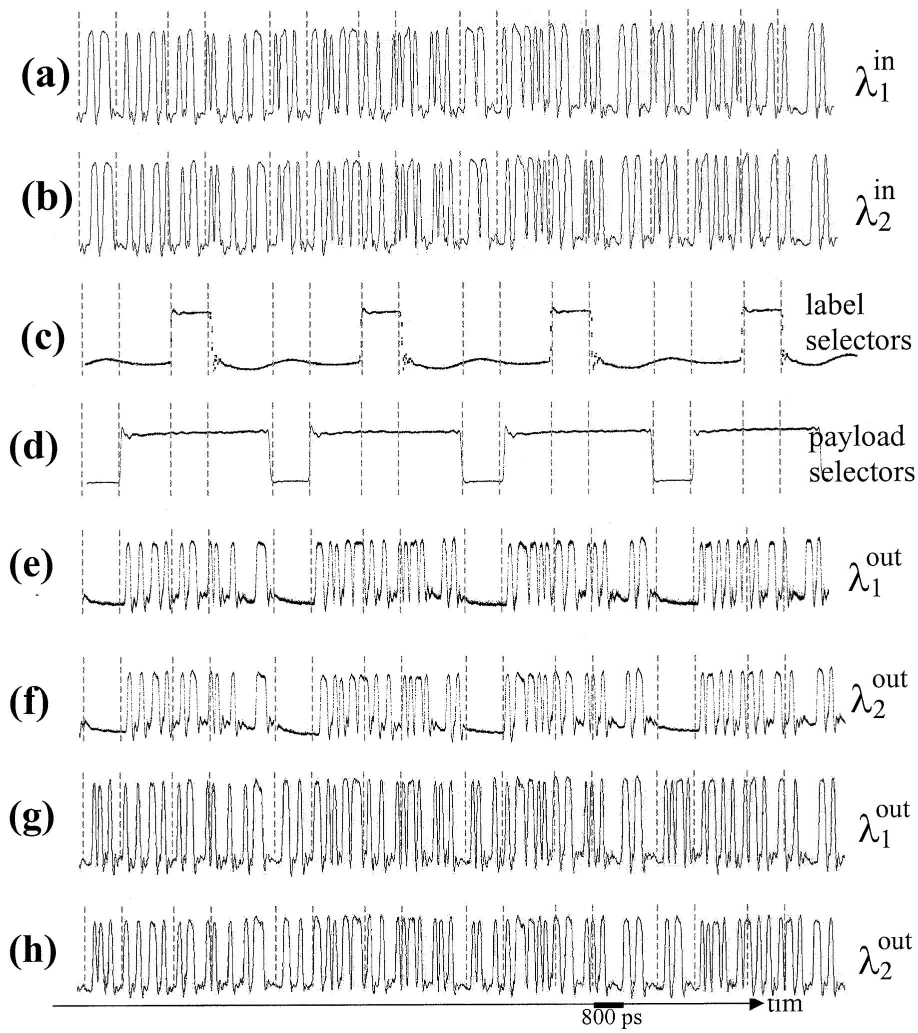

Fig. 5. (a) and (b) Four sample input packets of the two WDM channels. (c) The new-label-selector waveform used as the wavelength-converter pump in the PPLN-1. (d) The payload-selector waveform wavelength-converting the payload of the packets. (e) and (f) λ-shifted payloads for each channel. (g) and (h) Label-swapped output waveforms for each channel.

to rise (or fall) time constraints, the lack of perfect zero power level limits the ability to selectively λ-shift only the new label bits. This causes some power leakage from the payload of the packets to the wavelength converted new labels.

The payload-selector, Fig. 5(d), is ON only during the payload portion of the packet. The wavelength-shifted payloads of the packets are shown in Fig. 5(e) and (f). Wavelength converting only the payloads removes the original labels. The higher duty cycle of this payload-selector signal works better with selective wavelength conversion. However, the ON period of the selector signal is not perfectly flat. Therefore, the amplification of the wavelength-converted signals is not uniform.

Fig. 5(g) and (h) shows the label swapped packets at the output wavelengths. This is the result of the insertion of the λ-shifted new labels to the λ-shifted original payloads.

A magnified view of the input and label-swapped packets of the 2 WDM channels is shown in Fig. 6. The packet patterns for λ_1 with the original label and the new label are shown in Fig. 6(a). The original label pattern of “01 100 111” is label swapped with the new label pattern “00 101 001”. Fig. 6(b) shows similar waveforms for λ_2. For this WDM channel, the original label is “11 101 100” and the wavelength converted and label-swapped output has the new label pattern of “01 010 001”. The wavelength-converted and label-swapped packets do not have any significantly visible added noise or distortion.

Fig. 7 shows the power penalty introduced by this module. The wavelength conversion using the PPLN waveguide introduces a penalty of about 2 dB for this system. The wavelength shifting of the payloads introduced a power penalty of about 1.5 dB for λ_1 and about 2 dB for λ_2. The insertion of the wavelength-converted new labels contributed about 1 dB for λ_2 and about 2.5 dB for λ_1. The additional penalty from insertion of the labels is due to a misalignment of the band-pass filters with the output signals and is not inherent to this method.

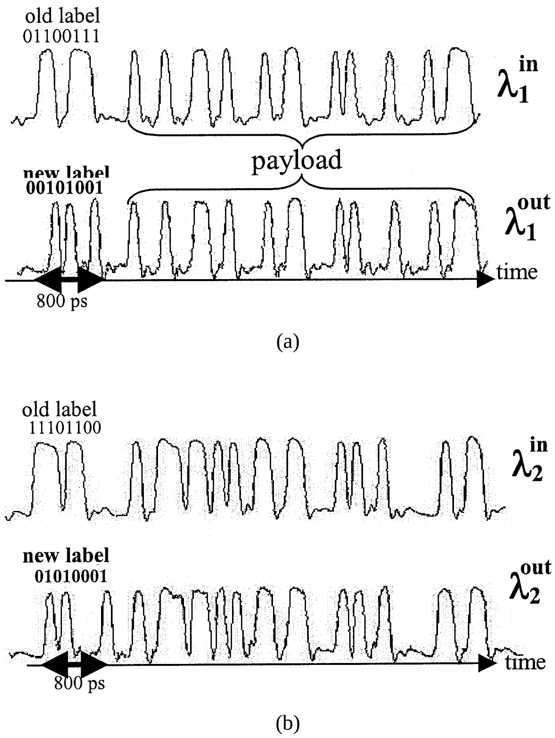

Fig. 6. Waveforms of a single packet from WDM channels λ_1 and λ_2 before and after label swapping. (a) The original label on λ_1, 01100111, is swapped with new label, 00 101 001. (b) The original label on λ_2, 11101100, is swapped with new label, 01 010 001.

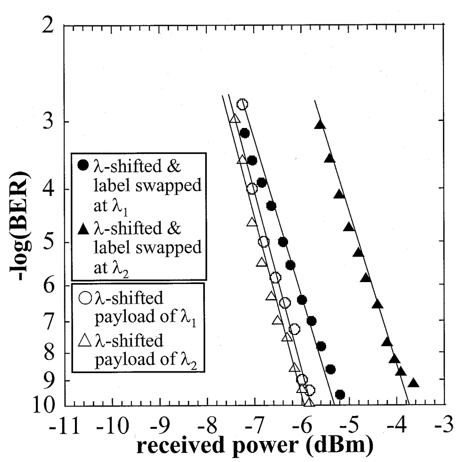

Fig. 7. BER curves for the module. Label swapping introduces a penalty of 1 dB and 2.5 dB for the WDM channels λ_1 and λ_2, respectively.

VI. Summary

Independent label swapping of individual channels in a WDM system is experimentally demonstrated. The channels are at 10 Gb/s. In addition to label swapping, wavelength conversion is also achieved. The method is bit-rate, label length, and format independent to ensure maximum transparent operation in MPLS networks. The $\sim$ 40-nm λ-shifting bandwidth of the PPLN waveguide is promising the accommodation of up to 10 WDM channels in a single module. Label swapping with this technique introduces less than 2.5 dB power penalty.

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