

# All-Optical Address Extraction for Optical Routing

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**Abstract**—This paper describes the optical circuit that enables to extract address from a transmitted cell in an all-optical manner. Nonlinear optical loop mirrors (NOLM's) are used as all-optical switches in order to confirm the operation of the proposed circuit. The control pulses synchronized with address bits are generated from the transmitted cell. The address bits are successfully extracted without any electronic control circuit. The factors that limit an attainable bit rate are discussed. If we use NOLM composed of a 2-km-long fiber, 110 Gb/s is attainable for the 4 ps FWHM input pulse with RZ format.

**Index Terms**—All-optical process, NOLM, optical routing.

## I. INTRODUCTION

**D**EMAND for broadband-integrated service digital network (B-ISDN) requires ultrahigh link capacities [1], [2]. Since all-optical routing scheme enables ultrahigh-speed operation, suitable combinations of optical switch and network are expected to provide ultrahigh capacities.

In order to transmit an information to its destination, it is indispensable to recognize the address of cell in the routing system. The switches used in the optical routing system are to be controlled with optical address signals extracted from the transmitted cell. But, in most cases, switches are still controlled by electrical signals [3], [4].

Control pulses synchronized with address bits are needed for the routing system to operate correctly. Therefore, the synchronization between control pulses and address bits is one of the important issues in constructing all-optical routing systems [5], [6]. In the works reported so far, the synchronous signal can be regenerated under a certain condition in an all-optical manner. For example, truly periodic bit sequence is required to establish stable clock recovery in [6]. Moreover, the recognition of address relies on an electrical scheme. To the best of our knowledge, there is no report stating that the extraction of address from a transmitted cell is achieved in an all-optical manner.

In this paper, we propose the optical circuit that enables to extract the address from a transmitted cell in an all-optical manner. The switching control pulses are generated from the transmitted cell, and are synchronized with address bits. They are utilized to extract address bits from the cell. As compared with conventional approach, no electronic logic is needed to

extract address bits. The proposed scheme provides a way toward realizing all-optical routing systems.

Section II describes the optical circuit that enables to extract the address from a transmitted cell in an all-optical manner. The experimental results are presented in Section III. In Section IV, we discuss the factors that limit the transmission bit rate in the proposed circuit, and estimate the attainable bit rate. Finally, Section V gives the conclusion of this study.

## II. CONFIGURATION OF ROUTING CIRCUIT

We propose the optical circuit shown in Fig. 1 with which address bits are extracted from transmitted cells in an all-optical manner [7]. The circuit consists of three blocks, i.e., a control pulse generator, a control pulse splitter and an address extractor. A part of transmitted cell ( $\lambda = 1568$  nm) propagates through the fiber delay line (DL1) and is processed as an information signal in the optical switch (SW2).

The rest of the cell is input in the interferometer, in which the delay time of path2 is set to be  $1.5T$ . In order to generate a control pulse, a pair of start pulses is added ahead of address bits as shown in Fig. 2(a). The interval of two start pulses is  $1.5T$ , where the period of address and data bits is  $T$  [8]. When the input signal of peak power  $P_{in}$  [Fig. 2(a)] enters the interferometer, the pulse streams appearing in path1 and 2 [Fig. 2(b) and (c)] interfere to generate a pulse sequence shown in Fig. 2(d). Two kinds of pulses with peak powers  $P_{in}$  and  $P_{in}/4$  are generated, if any loss is ignored in the interferometer.

The pulse output from the interferometer is amplified by an erbium doped fiber amplifier (EDFA1), and is applied to the optical switch (SW1) as a control pulse. CW light of 1530 nm wavelength is switched by the control pulse ( $\lambda = 1568$  nm) in SW1. As a result, the pulse whose wavelength is converted into 1530 nm is obtained as the output of SW1.

The wavelength-converted pulse propagates through the band pass filter1, and is split into a pulse stream. The number of split pulses is set to be equal to that of address bits contained in the transmitted cell. To obtain the control pulse stream synchronized with  $N$  address bits, the delay lines are set to give the delay times of  $T$ ,  $2T$ ,  $\dots$ , and  $(N - 1)T$ . The circuit shown in Fig. 1 corresponds to the case of two address bits.

The control pulse stream ( $\lambda = 1530$  nm) synchronized with the address bits are amplified by EDFA2. The address bits transmitted through the delay line1 are extracted in SW2 by applying the amplified control pulse stream. The switched address bits of wavelength 1568 nm is transmitted through the band-pass filter2, and the remaining part of transmitted cell is output through the filter3.

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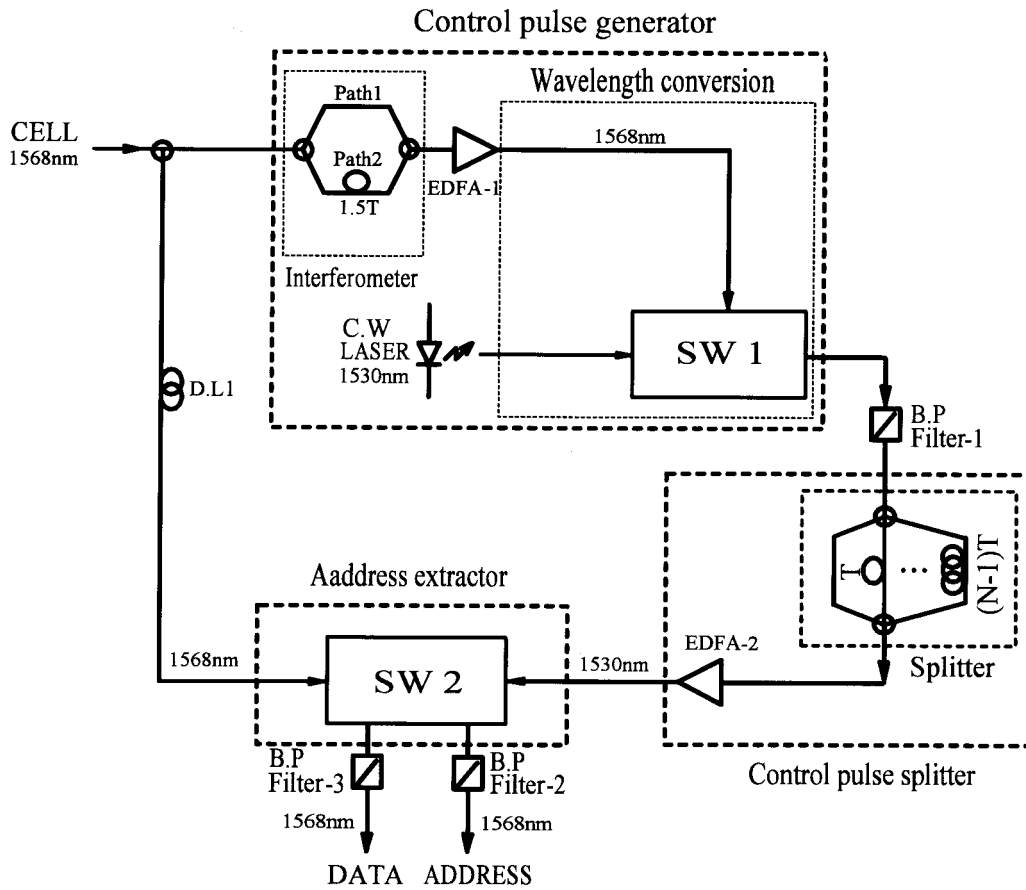


Fig. 1. The proposed optical circuit for extracting address bits.

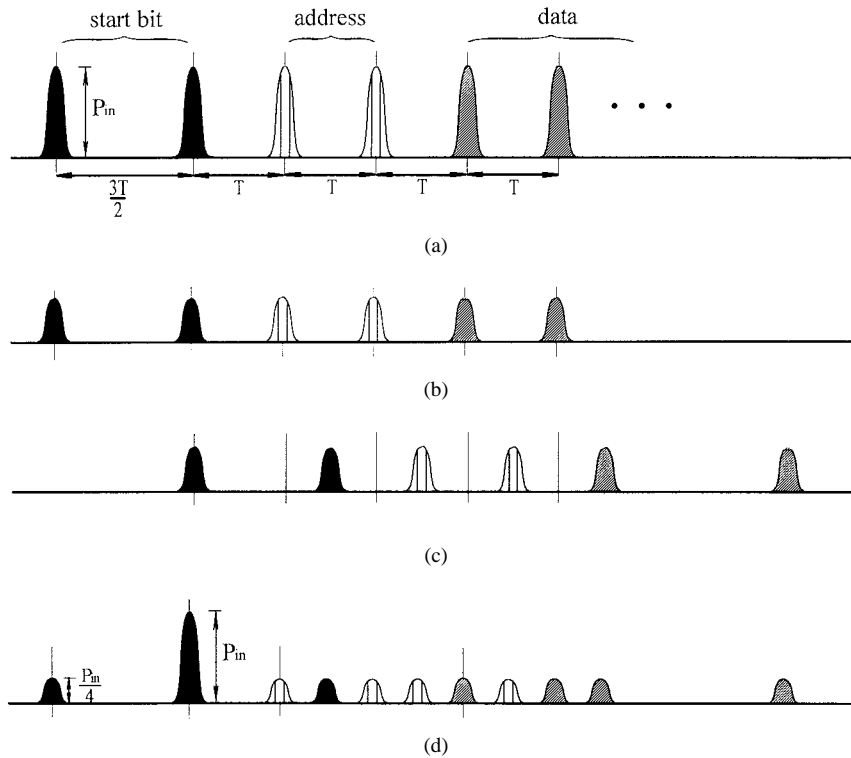


Fig. 2. Schematic illustration of the interferometer operation: (a) input signal, (b) output of path1, (c) output of path2, and (d) output of the interferometer.



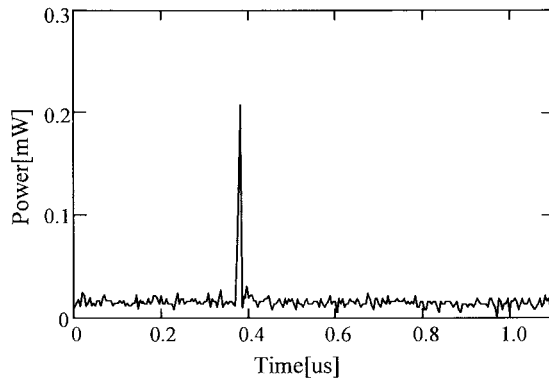


Fig. 5. Wavelength-converted 1530 nm control pulse generated in NOLM1.

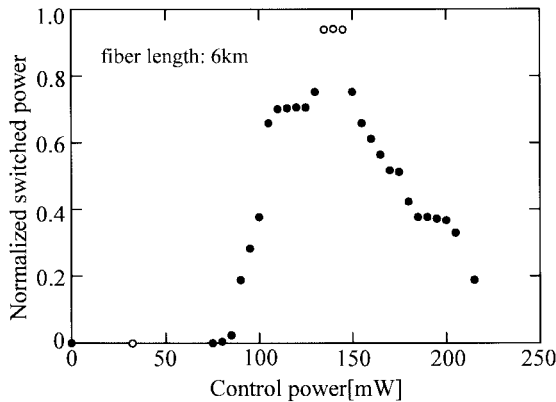


Fig. 6. Measured switching characteristic of NOLM1.

The lengths of fiber loop in NOLM1 and NOLM2 are 6 and 10 km, respectively. The WDM coupler used in the NOLM has 50/50 coupling at the signal wavelength (1530 nm in NOLM1 and 1568 nm in NOLM2) and 100/0 coupling at the control wavelength (1568 nm in NOLM1 and 1530 nm in NOLM2).

An optical pulse train with a pulse interval of  $1.5T$  and  $T$  is generated from a 1568 nm DFB laser in the optical transmitter that is directly modulated by an electronic pattern generator. The width and period  $T$  of address and data bits are 10 and 120 ns, respectively, which are limited only by the facilities available in the experiment. A 1 mW CW light of 1530 nm wavelength is supplied from a tunable laser for wavelength-conversion.

The experimental results associated with the interferometer are shown in Fig. 4. Fig. 4(a) shows the input signal which consists of two start, two address and one data bits. The interval between start bits is set to be  $1.5T = 180$  ns. The signals propagated through path1 and path2 are shown in Fig. 4(b), while Fig. 4(c) shows the output of the interferometer. Clearly observed in Fig. 4(c) is that only the pulse labeled as 2 has the peak power equal to that of the input pulse  $P_m$ , and that others have  $P_m/4$ . The output pulse stream is supplied to control NOLM1 after being amplified by EDFA1. The intense pulse was amplified to the peak power of 120 mW, while the peak power of weak pulses was 30 mW.

We could obtain a single wavelength-converted control pulse by adjusting the polarization state of the CW light so as to suppress the output corresponding to weak control

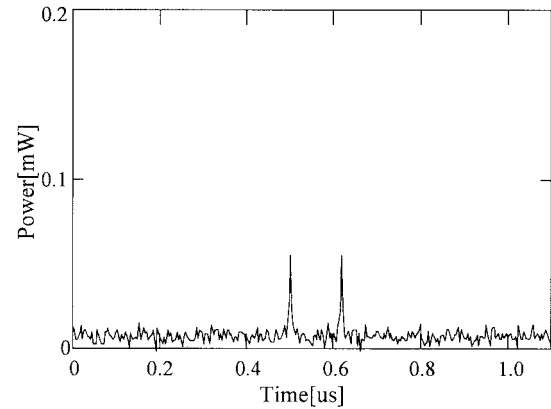
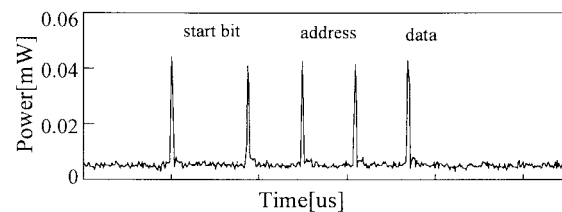
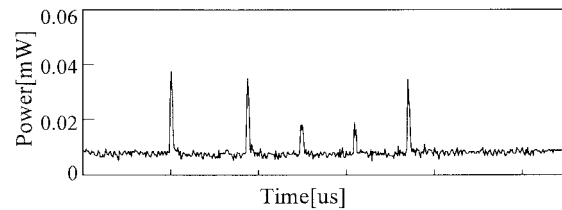


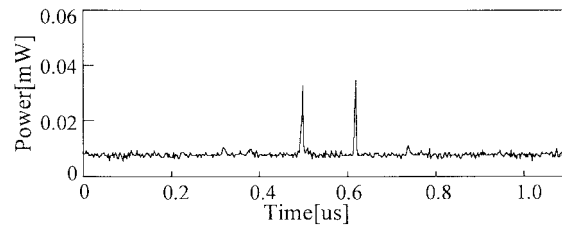
Fig. 7. Control pulses synchronized with address bits.



(a)



(b)



(c)

Fig. 8. Demonstration of address bit extraction: (a) input signal, (b) signal appearing in the reflected port, and (c) extracted address bits.

pulses appearing in Fig. 4(c). The output of NOLM1, i.e., the wavelength-converted pulse, is shown in Fig. 5. For this polarization state of CW light, the switching characteristic of NOLM1 was measured as shown in Fig. 6. By virtue of this nonlinear characteristic, weak pulses appearing in Fig. 4(c) were effectively suppressed at the sacrifice of increased control power required for the maximum switching ratio.

The wavelength converted control pulse (Fig. 5) is split into two pulses synchronized with address bits as shown in Fig. 7. We used a NOLM composed of a 10 km-long fiber as SW2. From theoretical consideration with the assumption of  $n_2 = 3.2 \times 10^{-20} \text{ m}^2/\text{W}$  and 0.25 dB/km fiber attenuation, the required power to switch the NOLM completely is estimated to

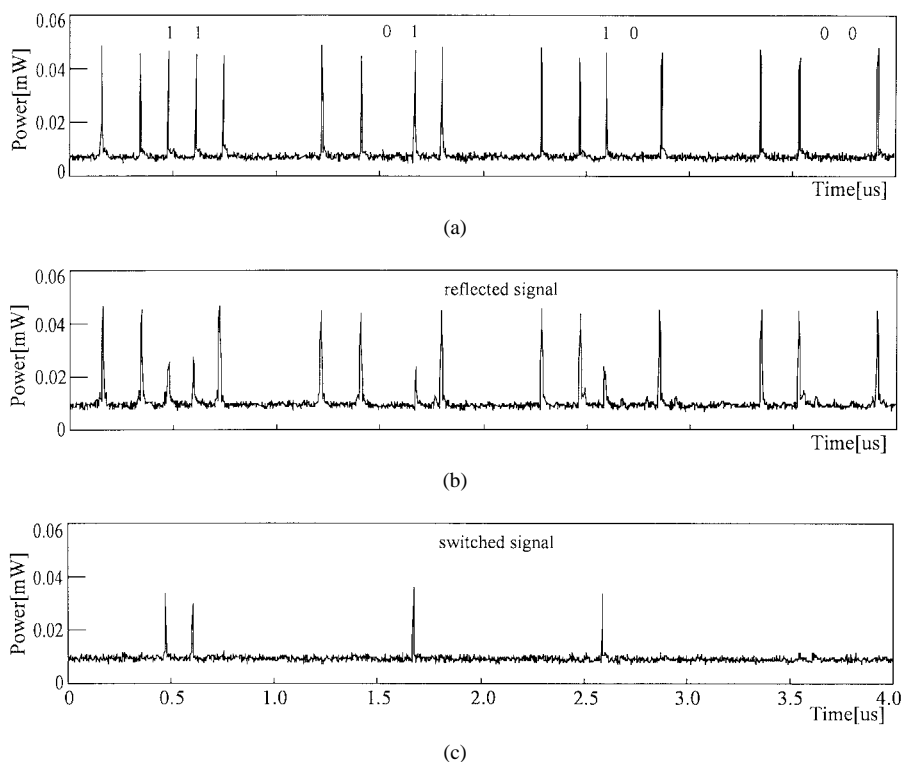


Fig. 9. Demonstration of address bit extraction for sequential cell input: (a) input signal, (b) signal appearing in the reflected port, and (c) extracted address bits.

be 75 mW. The peak power of the control pulses is amplified to 75 mW by EDFA2.

The experimental results of address extraction are shown in Figs. 8 and 9. Fig. 8(a) shows the cell input in NOLM2, which is transmitted through DL1. The cell has a return-to-zero (RZ) bit pattern which includes the address bits labeled as “11” and a data bit “1.” By applying the synchronized control pulses shown in Fig. 7, the input cell is divided into two parts. The signals appearing in the reflected and transmitted ports of NOLM2 are shown in Fig. 8(b) and (c), respectively, which were measured through a band pass filter ( $\lambda = 1568$  nm). Clearly shown is that only address bits are successfully extracted from the transmitted port. The other bits of input signal are output from the reflected port, which includes a remaining portion of address bits. The reason why the address bits were not switched completely is explained mainly by the insufficient peak power of control pulses. The measured peak power of control pulses transmitted through a WDM coupler was 57 mW, while the output of EDFA2 was 75 mW. The loss is caused by optical components. Also, the fact that the width of control pulse generated in NOLM1 becomes narrower than the input pulse width affects the insufficient switching. In order to overcome this, a pulse width compensator must be inserted between NOLM1 and NOLM2.

Fig. 9 shows the experimental results when cells having addresses “11,” “01,” “10,” and “00” are input sequentially. We obtain the address bits correctly from these sequential cells.

The switching ratio of NOLM, defined as the ratio of switched power to input power, was measured as a function of the control peak power. The results are shown in Fig. 10, where the length of fiber loop  $L$  is taken as a parameter. In this

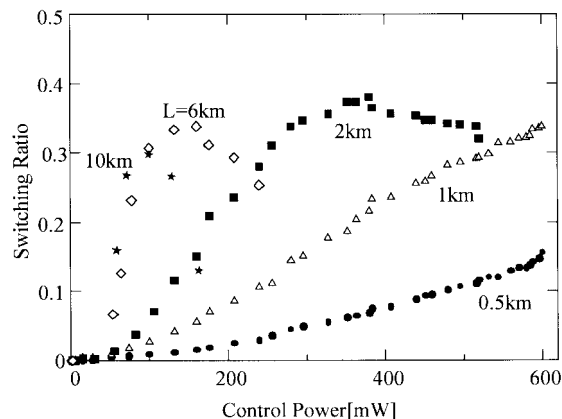


Fig. 10. Measured switching ratio of NOLM. The length of fiber loop is taken as a parameter.

case, the polarization state of control pulse was set so as to give the maximum switching ratio at the control power as low as possible. In case of  $L = 6$  km, the maximum switching ratio 0.35 was obtained for the control peak power of 145 mW. The calculated switching ratio is shown in Fig. 11. An attenuation coefficient of 0.25 dB/km,  $A_{\text{eff}} = 50.24 \mu\text{m}^2$  and  $n_2 = 3.2 \times 10^{-20} \text{ m}^2/\text{W}$  are assumed in the calculation to characterize the fiber. In case of  $L = 6$  km, the maximum switching ratio of 0.85 is obtained for the control peak power of 109 mW. The discrepancy between the measured and calculated results can be explained by optical losses included in the experimental circuit, e.g., connector losses and the insertion loss of components.

Rather long fibers were used to construct switches in our experiment. This is mainly due to the limited power of

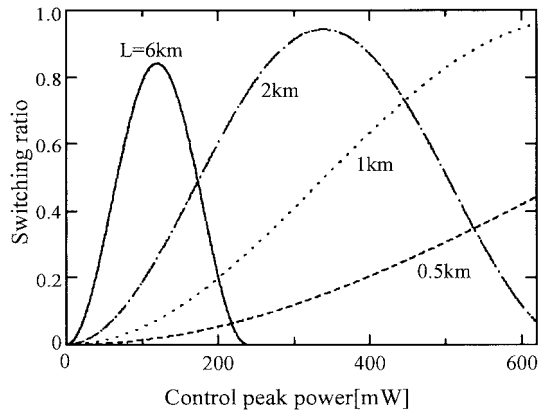


Fig. 11. Calculated switching ratio of NOLM.  $L$  is the length of fiber loop.

control pulses, which is caused by optical losses included in the present circuit. Although we used optical connectors to connect fiber components, losses can be reduced by applying fusion splicing. This contributes to reduce the fiber length without increasing the required control power. In addition, the length of fiber loop used in NOLM2 can be reduced inversely proportional to the output power of CW laser. If we use a 5 mW CW laser instead of 1 mW, a 2-km-long fiber can be used in NOLM2 without degrading the switching ratio.

#### IV. DISCUSSIONS

In this chapter, we discuss theoretical limitations on the proposed circuit from the viewpoint of optical control power and attainable bit rate. In the experiment, we used NOLM as an optical switch because of its relatively low switching power. Since the NOLM requires a long interaction length with good optical confinement, nonlinear effects such as stimulated Brillouin scattering (SBS) [12]–[14], stimulated Raman scattering (SRS) [12], [13], and self-phase modulation (SPM) [12], [15] must be considered. Also, the chromatic dispersion that limits bit rate must be taken into account. We will discuss the worst case that the input signal is composed of a sequence of bit “1” with RZ format.

SBS depletes the optical power in forward direction, and leads to the distortion of waveform when the optical signal is intense. The critical power of SBS for CW light in a 6- and a 10-km-long fiber is estimated to be 7.2 and 4.6 mW, respectively [12]. Let us consider the asynchronous transfer mode (ATM) cell format that consists of five-octet address plus 48-octet data field. Intense pulses synchronized with address bits are input in NOLM2 as control pulses. The average power of 7.2 and 4.6 mW for the five-octet address corresponds to the peak power of 153 and 98 mW, respectively, when pulses are square shaped with a duty ratio of 0.5. We can ignore SBS, when the control pulse is less intense than these values. SRS can be ignored, because it has much less gain than SBS [12].

When the optical pulse is intense, it experiences phase modulation through SPM. Phase retardation varies depending on the power of lightwave. Thus, SPM gives cause to a distortion of pulse waveform. A delay time due to SPM is approximately given by  $n_2 PL / (cA_{\text{eff}})$  where  $c$ ,  $P$ , and  $L$  indicate the velocity of light in vacuum, a instantaneous power

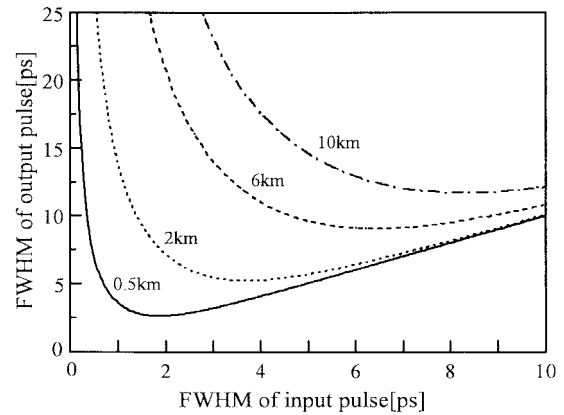


Fig. 12. Pulse broadening versus input pulse width. The length of fiber is taken as a parameter.

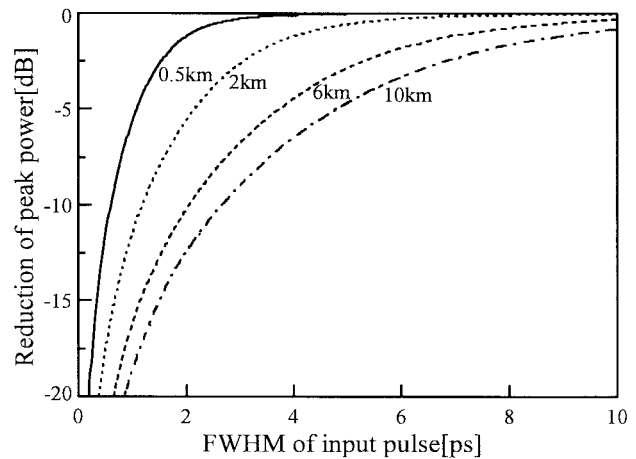


Fig. 13. Reduction of peak power versus input pulse width. The length of fiber is taken as a parameter.

and a fiber length, respectively. The pulse peak experiences maximum delay within a single pulse. Even when the peak power is 500 mW in a 10-km-long fiber, the maximum delay due to SPM is 11 fs which is negligible for the transmission bit rate of 1 Tb/s and less.

Besides nonlinear effects mentioned above, pulse broadening in optical fiber occurs by the chromatic dispersion [16]. We estimated the pulse broadening by assuming an input pulse with a Gaussian shape in a temporal scale. The calculated full width at half maximum (FWHM) of output pulse is shown in Fig. 12 as a function of the FWHM of input signal. The calculation was carried out using a dispersion parameter of 2 ps/nm/km estimated from the experimental condition. When the input pulse with 4 ps FWHM propagates through a 2-km-long, a 6-km-long and a 10-km-long fiber, the FWHM of output signal broadens to 5.3, 11, and 17.5 ps, respectively.

A decrease of output peak power is shown in Fig. 13 as a function of the FWHM of input signal. The peak power of input pulse with 4 ps FWHM reduces by 1 and 5 dB after propagating through a 2- and a 6-km-long fiber, respectively. When the width of input signal is more than 100 ps, the pulse broadening and the peak power reduction due to dispersion can be neglected for the fiber length used in this experiment.

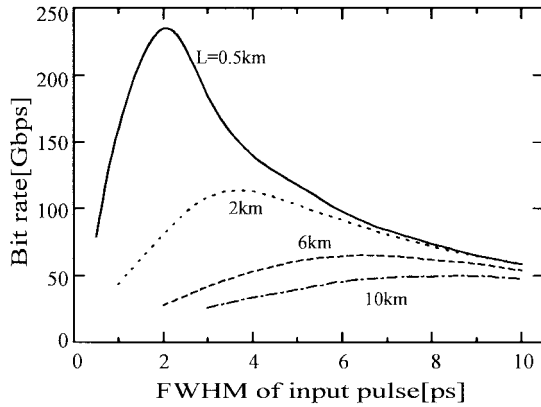


Fig. 14. Calculated attainable bit rate versus input pulse width. The length of fiber is taken as a parameter.

Let us estimate the bit rate with which the proposed circuit can operate. The switches are the same kinds of NOLM used in the experiment, and the connector loss is ignored. Under these conditions, SRS and SPM can be ignored, but the dispersion and SBS must be considered. In particular, the pulse broadening due to the dispersion mentioned above severely affects the attainable bit rate of the circuit. Since intense control pulses are input in NOLM2 more densely than in NOLM1, limitations are examined in NOLM2.

The fiber length of NOLM depends on the available control power. In the experimental circuit, it was approximately 300 mW. If the control pulse with 310 mW peak power is available, the maximum switching ratio is obtained in the NOLM with a 2-km-long fiber loop. When five-octet address bits are extracted from 53-octet ATM cell, the control pulses of 310 mW peak power with 0.5 duty ratio correspond to an average power of 15 mW. SBS can be ignored, since the SBS critical power for CW light is calculated to be 23 mW in case of a 2-km-long fiber.

As shown in Fig. 12, in case of a 2-km-long fiber, the FWHM of output pulse takes a minimum value of 5.3 ps, when the pulse with 4 ps FWHM is input. We estimate the attainable bit rate as a function of input pulse width under the condition that the neighboring output pulses superpose at  $e^{-2}$  level with respect to the peak of Gaussian profile. The result is summarized in Fig. 14. When the fiber length is 2 km, 110 Gb/s is attainable for the input pulse with 4 ps FWHM.

A solid line in Fig. 15 shows the pulse waveform switched in NOLM2 with a 2-km-long fiber loop. The FWHM of input pulse is 4 ps. In this figure, a broken and a dotted line indicate the waveforms of control and input pulses, respectively. From this figure, it can be observed that the switched address bits can be recognized without superposition.

## V. CONCLUSIONS

We proposed the optical circuit that extracts address bits from the transmitted cell in an all-optical manner. We successfully demonstrated the experiment in which the address bits are extracted from the transmitted cell in the proposed circuit. The attainable transmission bit rate that can be treated in this

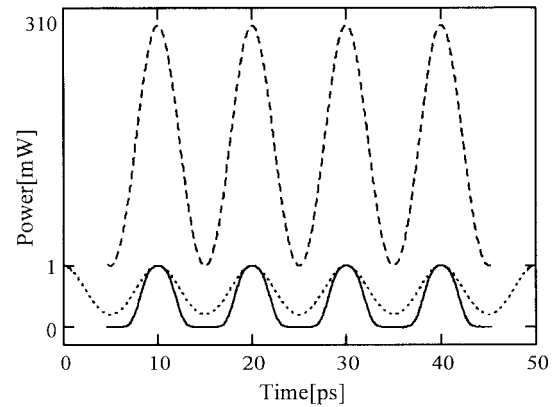


Fig. 15. Waveforms of switched (solid line), input signal (dotted line), and control (broken line) pulses.

circuit was estimated. When we use the input pulse of 4 ps FWHM, bit rate of 110 Gb/s can be attained with a 2-km-long fiber loop mirror. By utilizing the extracted optical address signals, the transmitted data can be routed all-optically. We believe the proposed scheme provides a way toward all-optical routing systems.

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