Characteristics of All-Optical Retiming Switches Using Periodically Poled Lithium Niobate Waveguides: Effects of Input Timing of Data Signal

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***Abstract*-We numerically calculate characteristics of all-optical retiming switches employing the cascaded second-order nonlinear effect in periodically poled lithium niobate waveguides. Appropriate time-offset of the input signal can reduce the timing jitter while improving the switching efficiency.**

I. INTRODUCTION

The cascaded $\chi^{(2)}$ effect in periodically poled lithium niobate (PPLN) waveguides has realized efficient wavelength conversion and optical phase conjugation in the optical communication band at 1550 nm [1]. In these devices, the quasi-phase matching (QPM) wavelength can be arbitrary controlled by the period of the $\chi^{(2)}$ grating.

Since the cascade of second harmonic generation (SHG) and difference frequency mixing (DFM) in the PPLN waveguides has the same effect as four-wave mixing in the third-order nonlinear devices, the cascaded $\chi^{(2)}$ effect can also be applied to all-optical gate switches [2]–[6]. For example, in all-optical demultiplexing switches for optical time-division multiplexed (OTDM) systems, the clock pulse restored from the received OTDM signal acts as the gate for the switch.

In this paper, we numerically study retiming characteristics of all-optical gate switches using the PPLN waveguides with consideration for the input timing of the signal and clock pulses. The switching efficiency and the timing jitter suppression can be simultaneously improved when we apply an appropriate time offset between the signal and clock pulses.

II. PRINCIPLE OF ALL-OPTICAL RETIMING

Figure 1 illustrates how retiming function shows up in the PPLN waveguides. The transmitted OTDM signal pulses, which have the timing jitter, are launched on the device together with a clean clock pulse train with a fixed repetition rate. As shown in Fig. 1 (a), when the center wavelength of the input signal pulse is set to the QPM wavelength, its second harmonic (SH) is first generated (Fig. 1 (b)). Then, DFM between the SH signal pulse and the center clock pulse generates the wavelength-converted signal pulse (Fig. 1 (c)), which is the output from the switch. The center wavelength of the wavelength-converted signal pulse is different from those of the fundamental signal, SH signal, and clock pulses. Therefore, the wavelength-converted signal can be filtered out by an optical bandpass filter with an appropriate bandwidth. The timing jitter of the output signal can be suppressed because the input signal switch the clean clock pulse train.

As the device becomes longer, the switching efficiency is improved. However, in this case, crosstalk is induced in the bit duration succeeding the switched bit (Fig. 1 (c)). The origin of the crosstalk can be explained in the following way. In the case of LN devices using the maximum nonlinear optical tensor element d_{33}, the group-velocity mismatch (GVM) between the fundamental signal pulse in the 1550-nm-band and its SH is as large as 350 ps/m. Due to such a large GVM, the SH signal pulse is delayed with respect to the fundamental signal pulse (Fig. 1 (b)). The delayed SH signal pulse then overlaps with the bit of the clock succeeding the switched bit, and crosstalk is induced in the succeeding bit duration (Fig. 1 (c)). Since the crosstalk causes the power penalty for the output signal pulses, the optimum device length for a given bit rate $1/T_{\rm bit}$ is determined by the crosstalk.

On the other hand, when we compensate for such a walk-off delay, the switching efficiency is improved. At the input port of the switch, the signal pulse precedes the center clock pulse to be switched by $T_{\rm offset}$ (Fig. 1 (a)). Therefore, near the launching end, the generated SH signal pulse also precedes the center bit of the clock pulses. During propagation, the SH signal pulse is delayed due to the GVM, overlaps the center clock pulse, and finally passes it by (Fig. 1 (b)). As $T_{\rm offset}$ is increased, the interaction length between the SH signal pulse and the center clock pulse is also increased, resulting in an improvement in the switching efficiency. However, in this case, crosstalk in the bit duration preceding the switched bit is increased because the time difference between the preceding bit of the clock and the time-shifted signal pulse becomes too small (Fig. 1 (c)). Therefore, $T_{\rm offset}$ is limited by the crosstalk induced in the preceding bit duration.

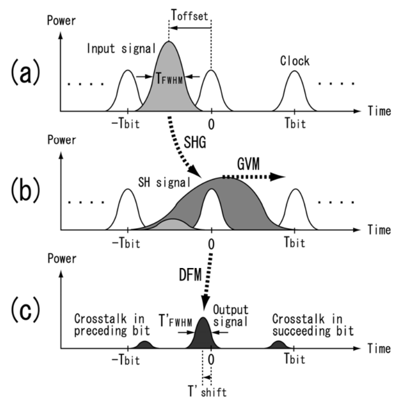

Fig. 1. Principle of all-optical retiming in PPLN waveguides and walk-off compensation by applying initial time offset.

III. STATIC RETIMING CHARACTERISTICS

We consider a 1-cm-long PPLN waveguide with a domain inversion period of 16.2 μm. The device length is optimized for the operation at the bit rate of 200 Gbps [5]. This period is required for SHG using d_{33} (= 25.9 pm/V) when the center wavelength of the input fundamental signal pulse is 1550 nm. The GVM between the fundamental and SH pulses is assumed to be 350 ps/m. The effective cross-section of the waveguide is 8 μm^2. The center wavelength of the input clock pulse is set to 1520 nm. The peak powers of the input signal and clock pulses are 50 mW and 5 mW, respectively. Duty cycle of the input pulses is set to 1/3, and all input pulses are assumed to be Gaussian having the same full width at half-maximum T_{FWHM} of 1.67 ps. In the analyses, we numerically calculate evolution of waveforms of the fundamental signal, SH signal, clock, and wavelength-converted signal along the device length by using the nonlinear coupled-mode equations [4].

Figure 2 (a) shows the output time shift T'_{shift} as a function of T_{offset}, where T'_{shift} is defined as the shift of the pulse peak position from that of the clock pulse (Fig. 1 (c)). The horizontal and vertical time scales are respectively normalized by T_{FWHM} and T'_{FWHM}, the latter being the full width at half-maximum of the output pulse. The relation between T_{offset} and T'_{shift} indicates a transfer characteristic of timing jitter from the input to the output. The timing of the output signal pulses can be pulled near to the clock pulses to prevent the fluctuation of the input timing. The suppression of the timing jitter can be achieved when $dT'_{shift}/dT_{offset} < 1$. The ratio of the timing jitter of the output signal to that of the input signal is estimated below 50 % for 0.2 ps $\leq T_{offset} \leq$ 4.0 ps. The maximum suppression will be observed for the offset around 2.1 ps, though this value should not be employed as seen below.

Figure 2 (b) shows the peak power P_{out} of the output signal pulse calculated as a function of T_{offset}. The value of T_{offset} maximizing P_{out} is 0.9 ps. Meanwhile, the dependence of P_{out} on T_{offset} indicates that the fluctuation of the input timing can be converted into the output power fluctuation. The output power can also be stabilized for the offset around 0.9 ps, where $dP_{out}/dT_{offset} = 0$.

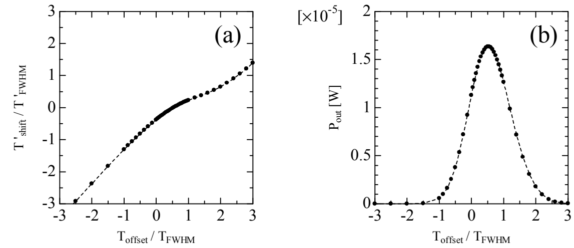

Fig. 2. Retiming characteristics. (a): Temporal shift of the output as a function of the initial time offset. (b): Output peak power as a function of the initial time offset.

IV. Eye Patterns and Effect of Initial Time Offset

In order to investigate the impact of the retiming function of the device on the transmission system, we numerically calculate eye patterns of the output signal pulses for various T_{offset} values. In the analyses, 200-Gbps RZ pulses having a normally distributed timing jitter are launched on the PPLN waveguide as the input signal, where the pulses are patterned by the 2^7–1 pseudo-random bit sequence. The input clock pulse train has a repetition rate of 200 GHz.

An eye pattern of the input signal pulses with T_{offset} = 2.1 ps and that of the output signal pulses are shown in Figs. 3 (a) and (b), respectively. The standard deviation of the initial timing jitter is calculated to be 160 fs. Clearly, a severe power fluctuation is introduced in the output.

On the other hand, Figs. 4 (a) and (b) are those eye patterns when T_{offset} = 0.9 ps, showing effectiveness of the retiming function. From Fig. 4 (b), the standard deviation of the transferred timing jitter and the standard deviation of P_{out} are calculated to be 71 fs and 0.31 μW, respectively. Thus, the initial time offset should be set to 0.9 ps to achieve jitter suppression and efficient conversion while avoiding the increase in the output power fluctuation. These results are in good agreement with those estimated from Figs. 2 (a) and (b).

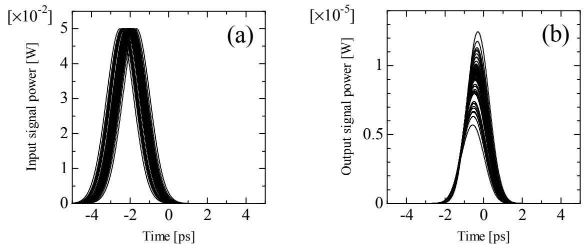

Fig. 3. Jitter transfer characteristic. (a): Eye pattern of the input signal pulses with a initial time offset of 2.1 ps. (b): Eye pattern of the output signal pulses.

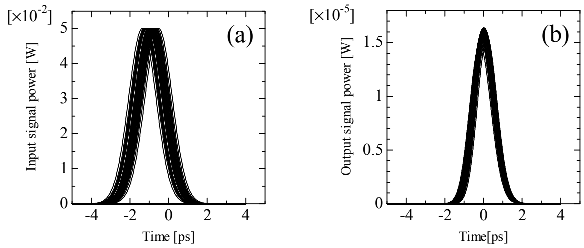

Fig. 4. Eye pattern of the input signal (a) and that of the output signal (b) when the initial time offset is 0.9 ps.

V. Conclusions

We have numerically analyzed characteristics of the all-optical retiming switches employing the cascaded $\chi^{(2)}$ effect in the PPLN waveguides with consideration for the input timing of the signal pulses. We have found that both the jitter suppression and the efficient conversion can be simultaneously achieved when we manage the initial time offset between the signal and clock pulses.

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