Numerical Analyses of All-Optical Retiming Switches Employing the Cascaded Second-Order Nonlinear Effect in Quasi-Phase Matched Lithium Niobate Devices: Effects of Device Fabrication Errors

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Abstract-**We analyze characteristics of all-optical retiming switches using the cascade of second harmonic generation and difference frequency mixing in quasi-phase matched lithium niobate waveguides with consideration for the device fabrication errors. While the switching efficiency and the retiming function are independent of the random duty-cycle error, the random period error causes significant deterioration of the output signal.**

I. INTRODUCTION

In high-speed optical communication systems such as the optical time-division multiplexed (OTDM) systems, achievable transmission distance is ultimately limited by the timing jitter of the transmitted signal. The timing jitter is caused by noise induced fluctuations in the carrier frequency (group velocity) of individual pulses in the transmitted signal. Therefore, there has been considerable interest in performing ultra-fast retiming all-optically, and many kinds of all-optical retiming switches have been proposed so far [1]–[7].

Among them, all-optical retiming switches employing the cascade of second harmonic generation (SHG) and difference frequency mixing (DFM) in quasi-phase matched (QPM) lithium niobate (LN) waveguide devices are an attractive candidate due to their abilities such as ultra-fast response, low noise, compactness, integration compatibility, and high stability [5]–[7]. However, an actual QPM-LN waveguide device has several types of fabrication errors. Therefore, the switching efficiency is smaller than the value estimated from the theoretical analyses [8]. In addition, the device fabrication errors might also affect the retiming function of the switch.

In this paper, taking the device fabrication errors into account, we numerically analyze all-optical retiming characteristics of the QPM-LN waveguide devices.

II. OPERATION PRINCIPLE

Figure 1 illustrates an all-optical retiming switch using the QPM-LN waveguide device. We use transmitted OTDM signal pulses in the return-to-zero (RZ) format as gating pulses. The signal pulses with a timing jitter are launched on the QPM-LN waveguide device together with a clean clock pulse train with a fixed repetition rate. The clock pulses are restored from the signal pulses, and used as gated pulses.

The QPM wavelength is determined by the domain inversion period $2d_{\mathrm{QPM}}$, where d_{QPM} is each domain length. When the center wavelength of the input signal pulse is set to the QPM wavelength, its second harmonic (SH) is first generated. Then, DFM between the SH signal pulse and the target clock pulse generates the wavelength-converted signal pulse, 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 pulse can be filtered out by an optical bandpass filter (OBPF) with an appropriate bandwidth. The timing jitter of the output wavelength-converted signal pulses can be suppressed because the input fundamental signal pulses switch the clean clock pulse train with a fixed repetition rate [5]–[7].

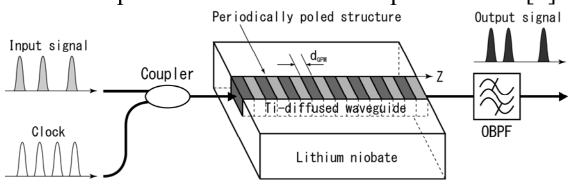

Fig. 1. Structure of an all-optical retiming switch using the quasi-phase matched lithium niobate waveguide device.

III. DEVICE FABRICATION ERRORS

In the QPM-LN waveguide devices, we can consider three types of device fabrication errors: random duty-cycle error, random period error, and random cross-section error [8]. As we can see from Fig. 2 (a), the random duty-cycle error is referred to as the stochastic variation of boundary positions around ideal positions. This type of error can be found in the lithographic process with an accurate mask. The processing steps, including photolithography, lift-off, and outdiffusion, would cause this error. In this case, the lengths of adjacent domains have a negative correlation. This means that the value of the QPM wavelength is preserved along the device length z.

The random period error shown in Fig. 2 (b) is referred to as the stochastic variation of the domain inversion period. In the lithographic process, it should be attributed to the fabrication error of the lithography mask. In this case, the domain inversion period is fluctuated along z because the lengths of adjacent domains are uncorrelated. This means that the value of the QPM wavelength is fluctuated along z.

On the other hand, the random cross-section error is the stochastic variation of the cross-section area of the waveguide. This type of error can be found in the fabrication process of the waveguide by titanium-diffusion, and fluctuates the value of the propagation constant of the waveguide along z. Since this fluctuation results in the fluctuation of the QPM wavelength along z, the random cross-section error is apparently equivalent to the random period error. Therefore, in

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the following analyses, we investigate effects of the random duty-cycle error and the random period error.

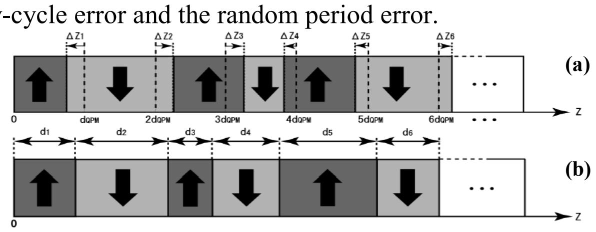

Fig. 2. Device fabrication errors of the quasi-phase matched lithium niobate. (a): random duty-cycle error. (b): random period error.

IV. Numerical Results and Discussions

We consider a 10-mm-long QPM-LN waveguide device with an average domain length of 8.1 μm. The device length is optimized for the operation at the bit rate of 200 Gbps [6],[7]. The average value of the domain length is required for SHG using the maximum nonlinear optical tensor element d_{33} (= 25.9 pm/V) of the LN crystal when the center wavelength of the input fundamental signal pulse is 1550 nm. The group-velocity mismatch between the fundamental and second harmonic 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 200-Gbps RZ pulses having a normally distributed timing jitter are launched on the QPM-LN waveguide device 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. The peak powers of the input signal and clock pulses are 50 mW and 5 mW, respectively. All input pulses are assumed to be Gaussian having the same pulse width parameter T_0 of 1 ps. The input signal pulses precede the input clock pulse train by 0.9 ps for improving the switching efficiency and the timing-jitter transfer characteristics of the switch [7]. We numerically calculate evolution of waveforms of the fundamental signal, SH signal, clock, and wavelength-converted signal pulses along z by using the nonlinear coupled-mode equations [6]–[8].

Firstly, we investigate the retiming performance of an ideal QPM-LN waveguide device, where the domain length is fixed at 8.1 μm along z. An eye pattern of the input signal and that of the output wavelength-converted signal in such a case are shown in Figs. 3 (a) and (b), respectively. From Fig. 3 (a), the timing jitter of the input signal is calculated to be 160 fs, whereas from Fig. 3 (b), the timing jitter of the output signal is calculated to be 71 fs. This result shows effectiveness of the retiming function of the ideal QPM-LN waveguide device.

Secondly, we investigate the effect of the random duty-cycle error. In the analyses, the boundary positions are assumed to have a Gaussian distribution around the ideal positions, whose standard deviation is set to 0.405 μm (5 % of the average domain length). Figure 4 (a) represents an eye pattern of the output wavelength-converted signal in such a case. The timing jitter of the output signal is calculated to be 71 fs. We find that the retiming function and the switching efficiency are independent of this type of error. The reason is as follows. In the random duty-cycle error, the lengths of adjacent domains have a negative correlation as shown in Fig. 2 (a). In this case, since the value of the QPM wavelength is preserved along z, the effect of this error is not accumulated.

Finally, we discuss the effect of the random period error. In the analyses, the domain lengths are assumed to have a Gaussian distribution around the ideal value of 8.1 μm, and its standard deviation is also set to 0.405 μm (5 %). An eye pattern of the output wavelength-converted signal in such a case is shown in Fig. 4 (b). We find that small amount of the random period error causes significant deterioration of the output signal. Moreover, this type of error also causes decrease in the switching efficiency. The mechanism can be explained in the following way. In the random period error shown in Fig. 2 (b), the lengths of adjacent domains are uncorrelated. In this case, since the value of the QPM wavelength can no longer be preserved along z, the effect of this error is accumulated. Thus, the random period error must be reduced significantly for realizing the retiming function.

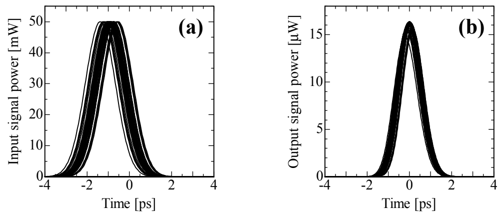

Fig. 3. Retiming performance of the ideal device. Eye pattern of the input signal at 200 Gbps (a) and that of the output signal (b).

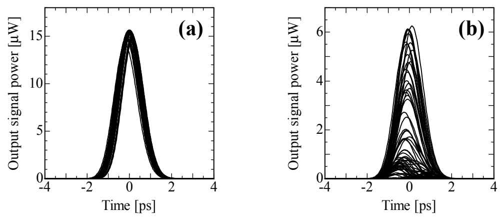

Fig. 4. Eye patterns of the output wavelength-converted signal. (a): random duty-cycle error of 5 %. (b): random period error of 5 %.

V. Conclusions

We have numerically calculated the performance of the all-optical retiming switches employing the cascade of SHG and DFM in the QPM-LN waveguide devices with consideration for the device fabrication errors. We have found that while the retiming function is independent of the random duty-cycle error, small amount of the random period error causes significant deterioration of the output from the switch.

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