All-Optical Gate Switches Employing the Quasi-Phase Matched Cascaded Second-Order Nonlinear Effect: Effect of Fabrication Errors

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Abstract-**We numerically calculate characteristics of all-optical gate switches using the cascaded second-order nonlinear effect in quasi-phase matched lithium niobate waveguides. Small amount of the domain length error causes significant decrease of the switching efficiency.**

I. INTRODUCTION

The cascaded $\chi^{(2)}$ effect in quasi-phase matched (QPM) lithium niobate (LN) waveguide devices can be applied to all-optical ultra-fast gate switches [1-12]. In these devices, the QPM wavelength can be arbitrarily controlled by the period of the $\chi^{(2)}$ grating. When the wavelength of the gate pulse is set to the QPM wavelength, the gate pulse can switch the signal pulse through the cascaded $\chi^{(2)}$ process. For example, in all-optical demultiplexing switches used in optical time-division multiplexed (OTDM) systems, the clock pulse restored from the received OTDM signal acts as the gate pulse for the switch [6,9].

In our previous papers, we have numerically shown the possibility of efficient ultra-fast operation of such switches [4,5,8,10]. However, in an actual case, the switching efficiency is much smaller than the value estimated from the numerical analyses [6,7,9]. This might be attributed to device fabrication errors of the QPM-LN waveguides [12].

In this paper, taking the fabrication errors into account, we numerically calculate the switching efficiency of the all-optical gate switches using the cascaded $\chi^{(2)}$ effect in QPM-LN waveguide devices. We find that the domain length error of the device decreases the switching efficiency significantly.

II. STRUCTURE AND PRINCIPLE

Figure 1 shows the structure of the all-optical gate switch using the cascade of second harmonic generation (SHG) and difference frequency mixing (DFM) in the QPM-LN waveguide device. The signal pulses are launched on the QPM-LN waveguide device together with the gate pulses. When the center wavelength of the input gate pulses is set to the QPM wavelength determined by the domain length d_{QPM}, the second harmonic (SH) of the input gate pulses is first generated. Hereafter, we refer to such frequency-doubled gate pulses as the SH gate pulses. Then, the DFM between the SH gate pulses and the signal pulses creates the switched pulses. Since the center

wavelength of the switched pulses is different from those of the signal and the fundamental and SH gates, the switched pulses can be filtered out by an optical bandpass filter (OBPF) with an appropriate bandwidth.

The maximum bit rate R_{max} processed by the QPM-SHG/DFM-LN waveguide switch is limited by crosstalk [4-12]. In the 1550-nm-band, the group-velocity mismatch (GVM) between the fundamental and SH gate pulses is as large as 350 ps/m. Due to such a large GVM, the walk-off delay is induced between these two pulses. The delayed SH gate pulse then overlaps with the bit of the signal succeeding the switched bit, generating crosstalk. For a given device length, the amount of crosstalk increases as the bit interval becomes shorter; hence, the crosstalk limits R_{max}. In our previous papers, we have both experimentally and numerically shown that the product of the device length and R_{max} is about 4 Gbps·m [4-12]. For example, R_{max} of the 2-cm-long device is 200 Gbps.
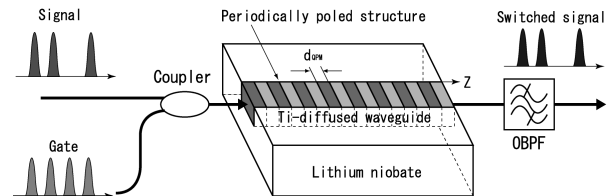

Fig. 1. Structure of the all-optical gate switch using the QPM-LN waveguide device.

III. TYPES OF DEVICE FABRICATION ERROR

In the QPM-SHG/DFM-LN waveguide device, we can consider three types of the fabrication error: random boundary position error, random domain length error, and random cross-section error.

As shown in figure 2 (a), the random boundary position error is the stochastic variation of boundary positions around ideal positions. This type of error can be found in the lithographic process with an accurate lithography mask, and the lengths of adjacent domains have a negative correlation.

The random domain length error shown in figure 2 (b) is the stochastic variation of the domain lengths. This type of error is attributed to the fabrication error of the lithography mask, and the lengths of adjacent domains are uncorrelated.

On the other hand, the random cross-section error shown in figure 2 (c) is the variation of the cross-section

area of the waveguide along the device length. This type of error can be found in the fabrication process of the waveguide by titanium-diffusion. As shown in reference [12], this type of error is apparently equivalent to the random domain length error. Therefore, in the following analyses, we investigate effects of the random boundary position error and the random domain length error.
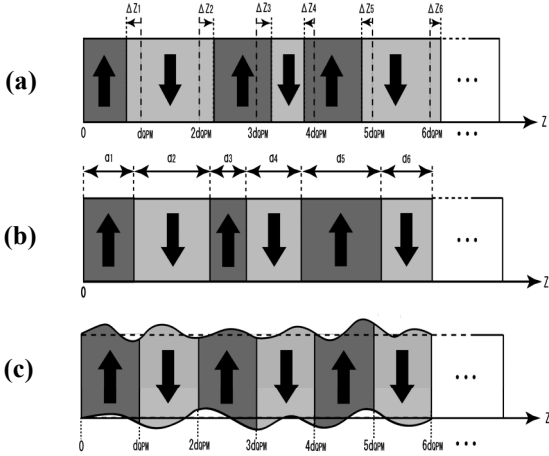

Fig. 2. Device fabrication errors. (a): Random boundary position error. (b): Random domain length error. (c): Random cross-section error.

IV. NUMERICAL RESULTS AND DISCUSSIONS

We consider a 2-cm-long QPM-LN waveguide device with an average domain length $<d_{QPM}>$ of 8.1 μm. This average domain length is required for SHG using d_{33} (= 25.9 pm/V) when the center wavelength of the input gate pulse is 1550 nm. The GVM between the fundamental and SH pulses is assumed to be 350 ps/m. The effective cross-section area of the waveguide is 12 μm². The center wavelength of the input signal pulse is set to 1520 nm. The input signal pulse completely overlaps with the input gate pulse. These input pulses are assumed to be Gaussian having the same pulse width parameter T_0 of 1 ps. The peak powers of the input gate and signal pulses are fixed at 1 W and 100 mW, respectively. In the analyses, we numerically calculate evolution of waveforms of the fundamental gate, SH gate, signal, and switched pulses along the device length by using the nonlinear coupled-mode equations given in reference [3].

First, we investigate effect of the random boundary position error shown in figure 2 (a). In the analyses, the boundary positions are assumed to have Gaussian distribution around ideal positions whose standard deviation is $<d_{QPM}>\times\Delta z$. Figure 3 (a) shows the switching efficiency η calculated as a function of Δz, where η is defined as the ratio of the peak power of the switched pulse to that of the input signal pulse. We find that η is almost independent of Δz. The reason is as follows: In the random boundary position error, the lengths of adjacent domains have a negative correlation as shown in figure 2 (a). In such a case, since the domain inversion period is preserved, the effect of this error is not accumulated.

Next, we investigate effect of the random domain length error shown in figure 2 (b). In the analyses, the domain lengths are assumed to have Gaussian distribution around ideal value $<d_{QPM}>$, whose standard deviation is $<d_{QPM}>\times\Delta d$. Figure 3 (b) shows η calculated as a function of Δd. We find that small amount of Δd causes significant

decrease of η. For example, η at $\Delta d = 2$ % is about 3 dB smaller than that at $\Delta d = 0$ %. The reason is as follows: In the random domain length error, the lengths of adjacent domains are uncorrelated as shown in figure 2 (b). In such a case, since the domain inversion period can no longer be preserved, the effect of this error is accumulated.

Thus, the domain length error of the QPM-LN waveguide device must be reduced significantly for high efficient operation.
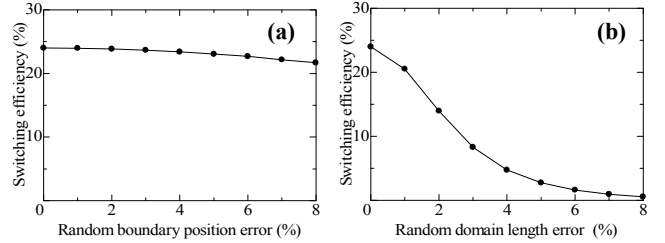

Fig. 3. (a): Switching efficiency η as a function of the random boundary position error Δz. (b): Switching efficiency η as a function of the random domain length error Δd.

V. CONCLUSIONS

We have numerically calculated the switching efficiency of the all-optical gate switch using the cascade of SHG and DFM in the QPM-LN waveguide device taking the fabrication errors into account. In the analyses, we have investigated the effects of the boundary position error and the domain length error of the device. We have found that the switching efficiency is almost independent of the boundary position error. On the other hand, we have found that small amount of the domain length error causes significant decrease of the switching efficiency.

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