DESIGN AND FABRICATION OF $LiNbO_3$ WAVEGUIDE QPM-DFG WAVELENGTH CONVERTER FOR 1.5 μm BAND

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Introduction

Waveguide quasi-phase-matched (QPM) nonlinear optic devices [1] can perform a variety of wavelength conversion functions such as second-harmonic generation (SHG) [2,3] and difference frequency generation (DFG) [4,5,6]. The QPM-DFG devices for wavelength conversion of optical signals in the 1.5 μm band are extensively studied for application to DWDM systems. They offer several advantages such as a high efficiency, wide wavelength coverage with single material, wide bandwidth, and integration compatibility.

In this work we report design considerations, fabrication process and experimental results of $LiNbO_3$ waveguide QPM-DFG devices for the 1.5 μm band.

Device design

Fig. 1 illustrates a $LiNbO_3$ waveguide QPM-DFG wavelength converter. The device consists of a domain-inverted grating for QPM and a channel waveguide in a z-cut $LiNbO_3$ crystal. A signal wave of frequency ω_s, wavelength λ_s, power P_s, and a pump wave of ω_p, λ_p, P_p are coupled into a waveguide channel. Both waves are TM-polarized. A wave of frequency $\omega_d=\omega_p-\omega_s$, λ_d, P_d is generated by QPM-DFG interaction through the largest nonlinear optic tensor element, d_{33}. When the pump wave power depletion is negligible, the output DFG wave power is given by [1]

$$P_d(L) = P_s P_p \kappa^2 L^2 \left| \frac{\sinh\left(\sqrt{(\omega_s/\omega_d)\kappa^2 P_p - \Delta^2}\,L\right)}{\sqrt{(\omega_s/\omega_d)\kappa^2 P_p - \Delta^2}\,L} \right|^2 , \tag{1}$$

$$2\Delta = 2\pi\left(N_p/\lambda_p - N_s/\lambda_s - N_d/\lambda_d - 1/\Lambda\right), \tag{2}$$

where L is the interaction length, κ is the DFG coupling coefficient, Δ is the phase-mismatch, and N_p, N_s, N_d are the effective indices for λ_p, λ_s, λ_d. Fig. 2 shows DFG wavelength and QPM period dependent on signal and pump wavelengths, calculated by using extraordinary indices of bulk $LiNbO_3$ crystal for N_p, N_s, N_d. For wavelength conversion within the 1.5 μm band, pump wavelength of λ_p = 0.78 μm and QPM period of Λ = 18 μm are required. Fig. 3 shows the normalized DFG efficiency $\eta = P_d/P_sP_p$ and the signal/pump wavelength bandwidths dependent on the device length L, calculated by assuming a coupling

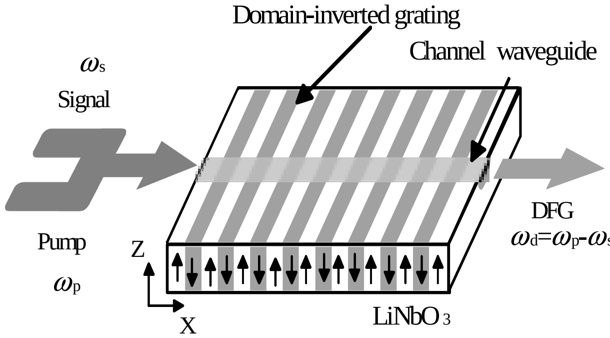

Fig. 1 $LiNbO_3$ waveguide QPM-DFG wavelength converter.

coefficient $\kappa = 1.5\ W^{-1/2}cm^{-1}$ for $8 \times 6\ \mu m^2$ / $3 \times 4\ \mu m^2$ signal/pump mode sizes [4]. The longer the interaction length L is, the higher the normalized DFG efficiency becomes. For longer L, the signal wavelength bandwidth $2\Delta\lambda_s$ is narrower. We designed a QPM-DFG wavelength converter for the 1.5 μm band. We determined the interaction length L to be 30 mm for obtaining well-balanced high efficiency and wide signal bandwidth matching to a 1.5 μm (C, L or S) band. A normalized DFG efficiency η of 2000 %/W for small pump power and a signal wavelength bandwidth of about 30 nm are expected.

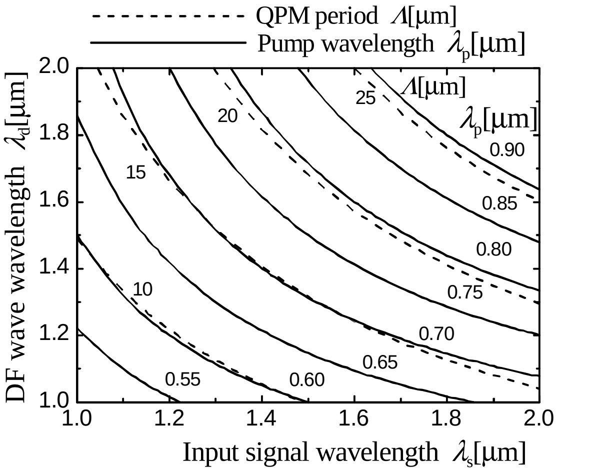

Fig. 2 Pump wavelength and QPM grating period required for wavelength conversion in $LiNbO_3$ QPM-DFG device.

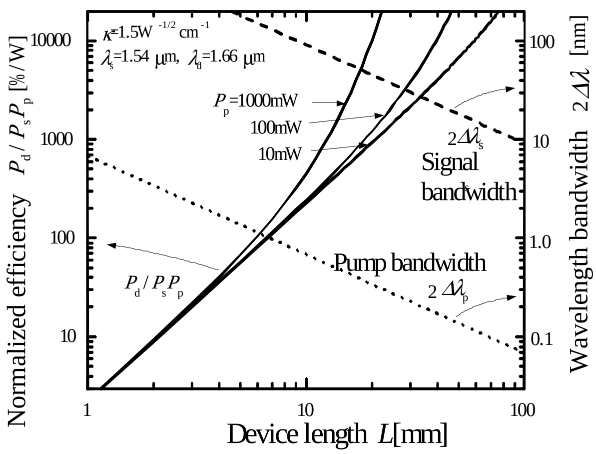

Fig. 3 Efficiency and bandwidths of DFG device.

Fabrication

A DFG device of L = 30 mm was fabricated. Fig. 4 shows a schematic illustration of fabrication of a domain-inverted grating by applying high voltage through liquid electrodes. At first a resist grating was fabricated by photolithography on the +z surface of a $LiNbO_3$ crystal of 0.5 mm thickness. The resist thickness was ~ 7 μm. The area of the resist grating pattern was $30 \times 20\ mm^2$, and the period ranged from 15.5 to 17.4 μm with 0.1 μm step. Filter papers immersed with LiCl solution were placed on both surfaces of the sample and used as the electrodes. The sample was held between two Al blocks, and a single voltage pulse of ~ 11 kV was applied . The pulse duration was automatically controlled to give a predetermined inversion charge[2]. The typical pulse duration was ~ 25 ms. Fig. 5 shows the domain-inverted grating on the +z surface and the cross-section after etching by $HF:HNO_3$ mixture. The ratio of the grating line width to the period was about 0.5, and the inverted regions continue through the entire crystal thickness. After the domain-inverted grating fabrication, an array of channel waveguides of 30 mm length was fabricated. The sample with Al mask of ~ 4 μm channel opening was proton exchanged in benzoic acid at 200 ℃ for 1.5 h. Then the sample was thermally annealed at

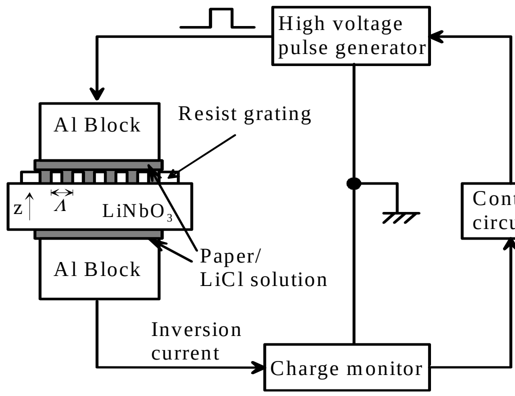

Fig. 4 Schematic illustration of fabrication of domain-inverted grating by applying voltage
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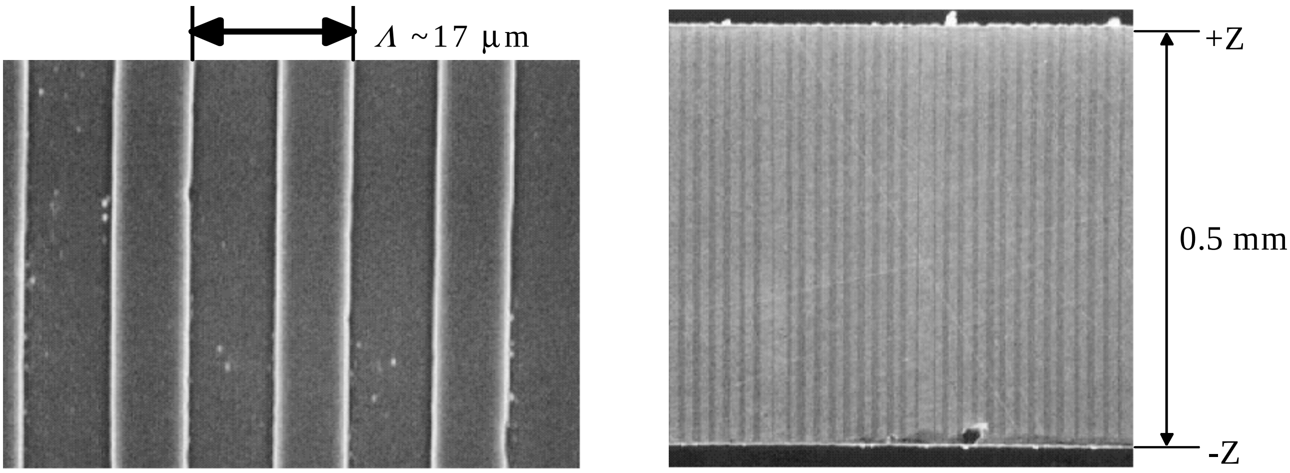
350 ℃ for 4 h in oxygen atmosphere. Finally the waveguide input/output ends were polished for end-fire coupling.



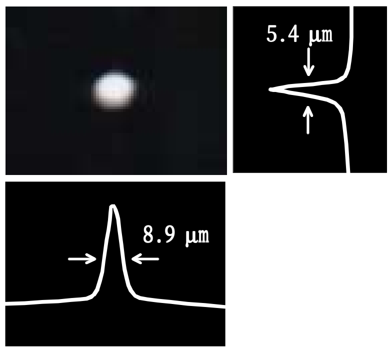
(a) +Z surface (b) Cross-section

Fig. 5 Domain-inverted grating structure after etching.

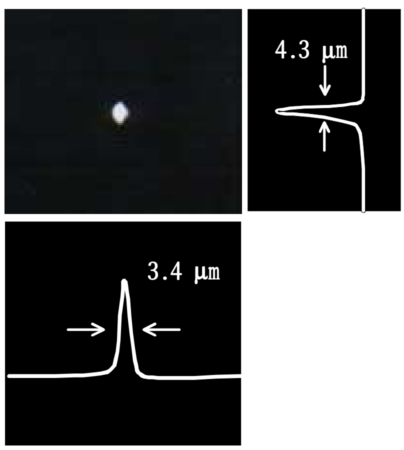
Experimental results

The SHG characteristics were measured for a preliminary experiment. A beam from an external cavity laser diode was coupled into a waveguide (Λ = 17.2 μm, L = 30 mm) through a × 20 objective. A QPM SH wave was obtained at 782 nm wavelength. Fig. 6 shows the near field patterns and the mode profiles of the pump wave and the SH wave. The FWHM mode sizes were 8.9 × 5.4 μm^2 and 3.4 × 4.3 μm^2 for the pump wave and the SH wave. Assuming co-centered Gaussian profiles with these mode sizes, the coupling coefficient was calculated as κ ~ 0.92 $W^{-1/2}cm^{-1}$, and this value gives 750 %/W as an estimate for normalized SHG efficiency for L = 30 mm. Theoretically, the normalized DFG efficiency is equal to the normalized SHG efficiency. Fig. 7 shows the measured SHG efficiency dependent on the pump power. The normalized SHG efficiency was 120 %/W. The efficiency was three times as high as that (40 %/W) of a device of 10 mm length previously fabricated by our group.

The DFG characteristics were measured in 1.5 μm band. Fig. 8 shows an experimental setup for the experiments. A Ti:Al_2O_3 laser was used as a pump source, and an external cavity laser diode was used as a signal source. A signal wave of λ_s = 1566 nm and a pump wave of λ_p = 782 nm were combined by a



(a) Pump wave (λ = 1563 nm)



(b) SH wave (λ = 782 nm)

Fig. 6 Near field patterns and intensity profiles of output waves in SHG experiment.

dichroic mirror and coupled in the waveguide. DFG wave of λ_d = 1561 nm was obtained. Fig. 9 shows the spectrum of the output signal and DFG waves. Signal wavelength bandwidth consistent with the theoretical value of 30 nm was obtained. A DFG wavelength conversion efficiency P_d/P_s = -27 dB was obtained for P_p = 1 mW. This result is roughly consistent with 120 %/W normalized DFG efficiency. The discrepancy between this result and the prediction is partly due to the fact that the actual mode profiles are not co-centered Gaussians. The reduction of the efficiency also seems to be due to propagation loss caused by slight waveguide surface damage produced in the high-voltage application process.

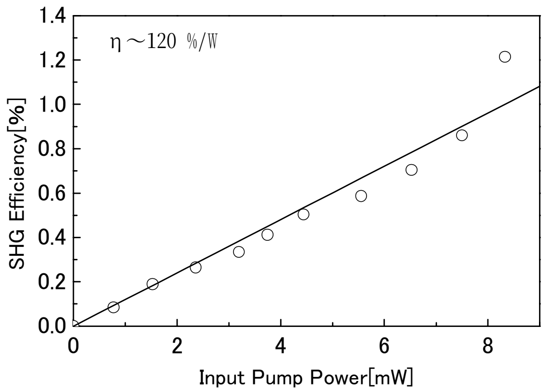


Fig. 7 SHG efficiency dependent on input pump power.

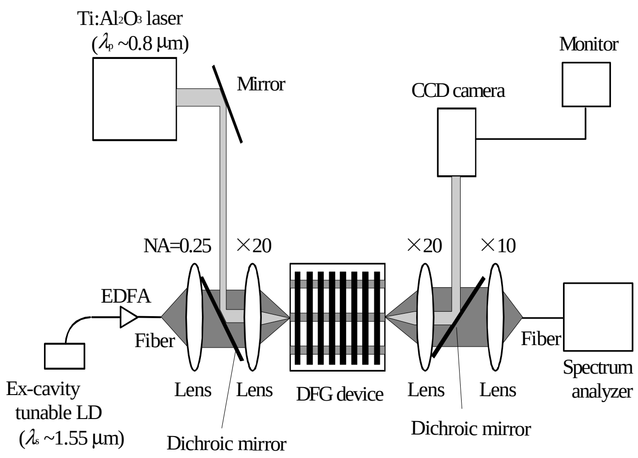


Fig. 8 Experimental setup for DFG.

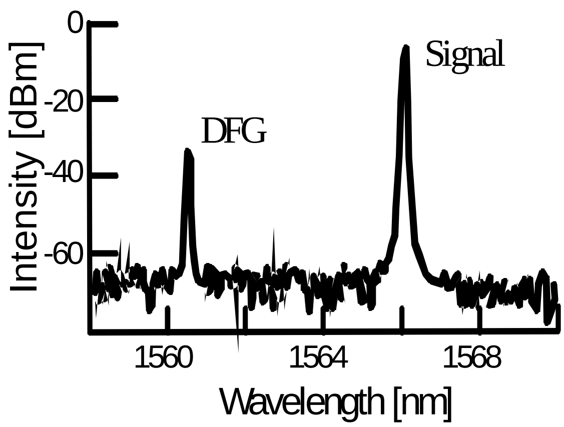


Fig. 9 Spectrum of output waves.

Conclusions

$LiNbO_3$ waveguide QPM-DFG wavelength converters were presented. A DFG device with interaction length of 30 mm was designed and fabricated. A normalized DFG efficiency of 120 %/W was obtained. Experimental work is in progress to improve the performances.

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