MgO:LiNbO₃ Waveguide Second-Harmonic Generation Devices with Domain-Inverted Gratings Formed by 2-Step Voltage Application under UV Light

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1. Introduction

MgO:LiNbO₃ quasi-phase-matched (QPM) nonlinear-optic wavelength conversion devices have been studied for a variety of applications including green light source for laser display [1], wavelength converter for WDM optical network [2] and quantum photonic devices [3]. High voltage application at elevated temperature through periodic electrode is the common technique to form domain-inverted gratings for QPM in MgO:LiNbO₃ [4,5].

We have reported a simpler technique which does not require lithography process nor crystal heating [6]. Periodic intensity distribution of ultraviolet (UV) light was formed in a crystal, and high voltage was applied through planar electrodes at room temperature. UV illumination reduced effective coercive field, and domain-inverted gratings were obtained. However, the reproducibility and the uniformity of the grating were not sufficient for device application.

In this paper, we propose a modified method for formation of MgO:LiNbO₃ domain-inverted gratings, i.e., 2-step voltage application at room temperature under UV light. The method allows reproducible formation of uniform domain-inverted gratings. A waveguide QPM second-harmonic generation (SHG) device for pumping at 1.55 μm wavelength was fabricated and characterized, and reasonable performance was obtained. Applicability of the method for QPM device fabrication was demonstrated.

2. Two-step voltage application under UV light for domain-inverted grating formation

Figure 1 shows a setup of 2-step voltage application under UV light for formation of MgO:LiNbO₃ domain-inverted gratings. On a photomask with Cr grating pattern of 19.0 μm period, a z-cut MgO(5 mol%):LiNbO₃ crystal of 0.5 mm thickness was settled with the –z face down. The gap between the photomask and the crystal was 35 μm, which was a thickness of inserted spacers. The gap was filled with LiCl aqueous solution as a transparent uniform liquid electrode. Au thin film was deposited on the +z face, and a conductive rubber and Al block were put on it. The liquid electrode and the Al block were connected to a high voltage source with a series capacitor for monitoring the transferred charge. The area of the electrodes was 30x8 mm². For the first voltage application, the crystal was illuminated through the photomask by a UV light of 313 nm wavelength and ~1.6 mW/cm² intensity from an ultra high pressure Hg lamp. A voltage of ~1.5 kV was applied to the –z through the liquid electrode. The charge increased in proportion to time, and the current was about 5 μA. The voltage application was continued until the transferred charge became 300 μC. For the second application, a higher voltage of ~2.5 kV was applied without UV. Charge flow decreased with time and stopped naturally.

Domain structures after the first and second voltage applications were examined by chemical etching in HF:HNO₃ solution. By the first application, domain inversion took place in the UV-illuminated regions, yielding a domain-inverted grating of 19.0 μm period on –z. However, the inverted regions exist only in a shallow region of about 5 μm depth beneath –z. The depth was not enough for QPM devices. Domain structure on +z and cross section after the second application are shown in Fig 2(a) and (b). Domain inverted grating with high quality was obtained on +z, and the grating structure continued across the whole crystal thickness except the shallow region beneath –z face. The inverted regions obtained by the first application did not grow during the second application and inverted regions continuing across the crystal were newly formed in the regions without the first inversion. Experimental work is being continued to understand why such inverted regions were obtained.

3. Demonstration of waveguide QPM-SHG device

The domain grating on +z seemed to be suitable for waveguide QPM devices. A grating of period λ=19.0 μm and interaction length L=30 mm and channel waveguides were integrated to fabricate a MgO:LiNbO₃ waveguide QPM-SHG device for pumping at 1.55 μm wavelength. The waveguides were formed by selective proton-exchange in benzoic acid for 3 h at 200 °C using an Al mask with channel openings of 5.0 μm width and annealing for 4h at 370 °C in O₂. Propagation loss was measured by Fabry-Perot method to be αp=0.2 dB/cm for 1.55 μm wavelength.

SHG experiments were carried out at room temperature. Emission from an external cavity InGaAsP wavelength-tunable semiconductor laser was amplified by EDFA and coupled to the fundamental TM guided mode as a pump wave. QPM-SH wave was obtained for a pump wavelength of 1552.4 nm. The FWHM mode sizes were 8.3 x 6.3 and 1.6 x 1.2 μm² for the pump and SH waves, respectively. The output SH power PSH was measured at the output end of the waveguide, and the input pump power Pp was estimated by dividing measured transmitted pump power by waveguide loss exp(-αpL). Dependence of the SHG efficiency PSH/Pp on the pump power Pp is shown in Fig 3. The efficiency increased in proportion to Pp and the
normalized SHG efficiency \( P_{\text{SH}}/P_p^2 \) was 62±12 %/W. The uncertainty was caused by pump power fluctuation due to Fabry-Perot effect. The maximum SH power as high as 220 mW was obtained for \( P_p=587 \) mW with the SHG efficiency \( P_{\text{SH}}/P_p^2=38 \) %. Dependence of \( P_{\text{SH}}/P_p^2 \) on the pump wavelength is shown in Fig.4. The FWHM pump wavelength acceptance width was 0.44 nm, which was close to the theoretical prediction of 0.41 nm, indicating good uniformity of the QPM grating.

The measured normalized SHG efficiency was compared with theoretical prediction. The nonlinear coupled mode equations describing the SHG interaction under exact QPM with taking the propagation losses into account can be solved analytically under no pump depletion approximation (NPDA) to give the expression for normalized SHG efficiency [7] as

\[
\frac{P_{\text{SH}}}{P_p^2} = \kappa^2 L^2 \exp(-2\alpha_p L) \left[ \frac{\exp\left(\frac{\alpha_p - \alpha_{\text{SH}}}{2} L\right) - 1}{\frac{\alpha_p - \alpha_{\text{SH}}}{2} L} \right]^2.
\]

The nonlinear coupling coefficient \( \kappa \) was estimated by numerically calculating the overlap integral of SHG coefficient, measured mode profile of SH, and squared mode profile of pump. Using \( d_{33}=20 \) pm/V, \( \kappa \) was estimated to be 0.31 W\(^{-1/2}\) cm\(^{-1}\). Assuming the propagation loss for SH wave to be \( \alpha_{\text{SH}}=0.4 \) dB/cm, and putting \( \kappa=0.31 \) W\(^{-1/2}\) cm\(^{-1}\), \( L=30 \) mm, and \( \alpha_p=0.2 \) dB/cm to (1), we have a normalized efficiency of 64 %/W as an approximate theoretical value. The measured value 62±12 %/W agreed to this theoretical value within the accuracy of the measurement. This agreement indicated high applicability of the domain inverted gratings formed by the 2-step voltage application under UV light to waveguide QPM nonlinear optic devices.

3. Conclusions

Fabrication of MgO:LiNbO\(_3\) domain inverted gratings by 2-step voltage application at room temperature under UV light was proposed. A waveguide QPM SHG device was fabricated by the method, and high applicability of the method to QPM device fabrication was demonstrated.

References