Second harmonic generation in inhomogeneous $MgO:LiNbO_3$ waveguides*

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A fibre laser at 1111.6 nm is frequency doubled by two inhomogeneous $MgO:LiNbO_3$ waveguides and the output powers of 85 mW and 49 mW at 555.8 nm have been generated with the conversion efficiencies of 47% and 27% respectively. By analysing the second harmonic generation temperature tuning curves, we investigate the influence of the optical inhomogeneities upon the conversion efficiency. The final result shows that the efficiency difference is mainly affected by the optical inhomogeneities in our case.

Keywords: second harmonic generation, optical inhomogeneities, waveguide

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1. Introduction

Second harmonic generation (SHG) has many applications in optics.[1−6] For the applications at the level of a few hundred milliwatts, quasi-phase-matched (QPM) SHG in channel waveguides are rather attractive because of the waveguide modes interacting as entities and the two-dimensional spatial confinement provided by the waveguide.[1] The performance of the waveguide is determined by several factors.[2,3] Highly efficient frequency doubling of a fibre Bragg grating stabilized laser diode and a continuous-wave distributed feedback laser diode with QPM waveguides have been demonstrated recent years.[4,5] However, the optical inhomogeneities appearing in the waveguides limit the SHG performance.

It has been observed in an $LiNbO_3$ crystal and interpreted with a step index model by Nash *et al.*[7] and in a $nLiNbO_3$ waveguide by Bortz *et al.*[8] Helmfrid and Arvidsow[9] have introduced a model that assumes the phase mismatch term consisting of a linear and a parabolic part to interpret the optical inhomogeneities in the QPM waveguide. Lee *et al.*[10] have simulated this kind of variation by the temperature-gradient-control technique in a periodically poled $Ti:LiNbO_3$ channel waveguide. Near-stoichiometric $Ti:LiNbO_3$ strip waveguide with varied substrate refractive index in waveguide layer has also been reported recently.[11] The 5-mol.% MgO doped $LiNbO_3$ crystal has the advantage of having no green induced infrared absorption and photorefraction. Therefore, it is widely used in nonlinear waveguides. However, the investigation of SHG in an inhomogeneous $MgO:LiNbO_3$ waveguide has not been reported yet.

In this paper, we report QPM SHG of a fibre laser at 1111.6 nm in inhomogeneous $MgO:LiNbO_3$ waveguides. In order to investigate the influence of the optical inhomogeneities upon the SHG experimentally, two nominally identical waveguides were tested.

Under no pump depletion approximation, the envelope $A_{2\omega}$ of SHG field in a waveguide with length l is

$$A_{2\omega} = -\mathrm{j}\sqrt{\eta_0}A_\omega^2 \int_0^l \exp\left(-\mathrm{j}\int_z^l \Delta k \mathrm{d}z'\right)\mathrm{d}z, \quad (1)$$

where A_ω is the envelope of the input fundamental laser field, η_0 is the normalized conversion efficiency and Δk is the phase mismatch, $4\pi\Delta n_\mathrm{e}/\lambda - 2\pi m/\Lambda$, where Λ is the crystal poling period, m is the grating order, λ is the wavelength of the fundamental laser light and Δn_e is the refractive index difference, $n_\mathrm{e}^{2\omega} - n_\mathrm{e}^{\omega}$, where n_e^{ω} ($n_\mathrm{e}^{2\omega}$) is the fundamental (second harmonic) extraordinary refractive index of the nonlinear crystal.[1,7] The envelope function A_i ($i = \omega$, 2ω) is normalized to satisfy the power in each mode

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$P_i = |A_i|^2$, where P_i is the light power. In a homogeneous nonlinear waveguide, the axial phase velocity does not vary. The phase-matching tuning curve is predicted to be of a sinc^2 shape. In an inhomogeneous waveguide, axial inhomogeneities distort the ideal sinc^2 tuning curve. The phase mismatch is expressed as $\Delta k = \delta k + \gamma_1(z-\sigma_1)^2 + \gamma_2(z-\sigma_2)^3$, where δk is the normal phase mismatch caused by temperature or wavelength variation, γ_1 is the second-order coefficient of the phase mismatch along the propagation direction, σ_1 is the zero-point of the second-order variation, γ_2 is the third-order coefficient of the phase mismatch along the propagation direction and σ_2 is the zero-point of the third-order variation. The last two terms are the phase mismatch caused by optical inhomogeneities. Substituting the phase mismatch into Eq. (1), the SHG power can be expressed as

$$P_{2\omega} = P_{2\omega}^{(0)} \left| \int_0^l \exp\left(-\mathrm{j} \int_z^l [\delta k + \gamma_1(z-\sigma_1)^2 + \gamma_2(z-\sigma_2)^3] \mathrm{d}z' \right) \mathrm{d}z \right|^2 . \quad (2)$$

where we define the SHG power coefficient as $P_{2\omega}^{(0)} = \eta_0 P_\omega^2 l^2$.

2. Experiment

The experimental setup is shown in Fig. 1. The fundamental laser is a KEOPSYS fibre laser with a wavelength of 1111.6 nm, maximum output power of 500 mW, line-width smaller than 50 kHz and the TEM_{00} mode ($M^2 < 1.1$). In the experiment, two nominally identical waveguides manufactured by HC photonics were used and the periodically poled MgO:$\mathrm{LiNbO_3}$ crystal had 20.0 mm in length, 3.0 mm in width and 0.5 mm in thickness. Periodic poling was done by an electric field method. Polarization maintaining fibre with a length of 0.5 m was pigtailed in the front facet of the waveguide. The temperature of the waveguide crystals was PID controlled with an uncertainty less than 0.1 °C. The temperature distributions were uniform. Both the input and output sides of the waveguides were AR coated. The transmittance of the input (output) facet was larger than 97% (99%) at 556 nm, but larger than 95% (99%) at 1111.6 nm. The SHG and the fundamental light output from the waveguide were separated by a dichroic mirror. Thus the efficiency for coupling the fundamental light from free space into the waveguide I (II) through a single-mode polarization-maintaining fibre was 69% (87.5%). Absorption coefficient of the fundamental (SHG) wave was less than $1/m$ ($2/m$).[12]

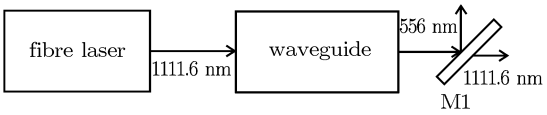


Fig. 1. Schematic diagram of the experimental setup. M1 is a dichroic mirror.

3. Experimental results and discussions

With the 51-mW fundamental laser power coupled into the waveguides, we measured the tuning curves of the waveguides I and II by scanning the waveguide temperature in the setup as shown in Fig. 1, respectively. It can be seen that there are asymmetric ripples in the tuning curves as shown in Fig. 2. The maximum SHG power is obtained at 58.8 °C (55 °C) for the waveguide I (II). We first fitted the experimental data with the single-step index model. The fitting results show that the single-step index model is not good enough for interpreting the optical inhomogeneities in the waveguides in our case. The multi-step and linear ramp models in which the tuning curve should be symmetric are also not good enough to interpret the experimental results.[7] The model that the phase mismatch varies parabolicly is also not enough as shown in Fig. 2.

Then, we fitted the experimental data with Eq. (2). As shown in Fig. 2, the cubic variation of the phase mismatch of the waveguides can explain the tuning curves very well. According to the QPM theory, we know that the phase mismatch may be caused either by the nonideal structures or the varying refractive index in the axial direction in the waveguide.[3,9] However, among various nonideal structures, the duty cycle errors and the missing reversals may exist in the periodically poled MgO:$\mathrm{LiNbO_3}$ (PPLN) fabricated by the electric field poling method in our case. Due to the nonaccumulating nature of the duty cycle errors, the width of the tuning curve is unaffected, with the ordinary sinc^2 dependence scaled by an overall factor. The missing reversals do not change the sinc^2 dependence either.[3] Therefore, we can conclude that the phase mismatches in the tuning curves as shown in Fig. 2 are caused by the varying refractive indices. From the fitting, we can obtain the axial variation of the refractive index difference along the waveguide at zero normal

phase mismatch. The value obtained for thermal refractive index coefficients ($\partial\Delta n_e/\partial T = 1.6\times10^{-5}/^\circ$C for the waveguide I and $\partial\Delta n_e/\partial T = 1.64\times10^{-5}/^\circ$C for the waveguide II) is in good agreement with the value $\partial\Delta n_e/\partial T = 1.67\times10^{-5}/^\circ$C calculated from the material parameters.[13] And we can also obtain the SHG power coefficients ($P_{2\omega}^{(0)} = 9.83$ mW for the waveguide I and $P_{2\omega}^{(0)} = 16.3$ mW for the waveguide II). By assuming seven regions with different refractive indices and interaction lengths inside the waveguides, we can also have a good fit. For each region, three fitting parameters are needed. However, too many fitting parameters are needed in this multiple region model. It may deviate from the real phenomena in the waveguide.

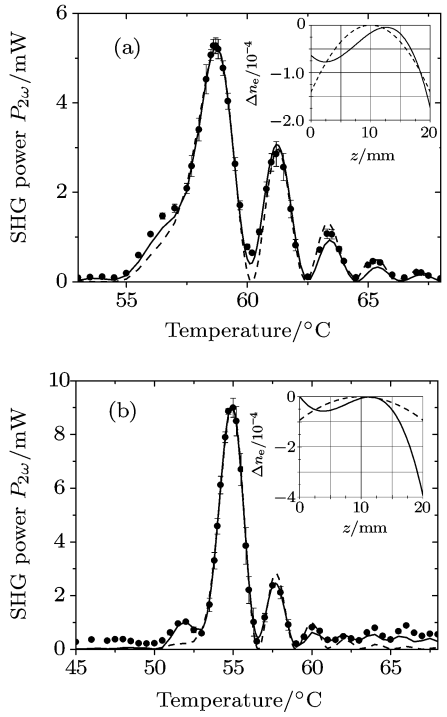


Fig. 2. SHG temperature tuning curves (solid circles) for (a) waveguide I, and (b) waveguide II measured at 51 mW coupled fundamental light power. The dashed (solid) line shows the calculated result when a parabolic (cubic) variation of the phase mismatch is assumed. The inset is the axial variation of the refractive index difference obtained from each calculation. The error bars represent errors of four independent measurements.

The SHG power versus the fundamental power is shown in Fig. 3. The green light power of 49 mW (85 mW) at 556 nm with a conversion efficiency of 27% (47%) was generated by the waveguide I (II) with the coupled fundamental power of 180 mW. The experimental data were fitted well by the equation $P_{2\omega} = P_\omega \tanh^2[(\eta_0 P_\omega)^{1/2} l]$, which indicates no thermal induced dephasing effect in the power range. From the SHG power coefficients of the two waveguides, it can be seen that around 60% of the efficiency difference is caused by the variation of the refractive index along the waveguide. The areas covered by the tuning curves are not affected by the refractive index inhomogeneities.[7,14] The integral of the SHG power with respect to the temperature of the waveguide I (II) is 17.77 (28.49) mW·°C. It indicates that around 62% of the efficiency difference is caused by the inhomogeneities. This is in good agreement with the fitting result (60%). And around 40% of the difference originates from other imperfections that do not change the shape of phase matching curve such as the reduced nonlinear coefficients, the change of the depth position of the grating etc.[14]

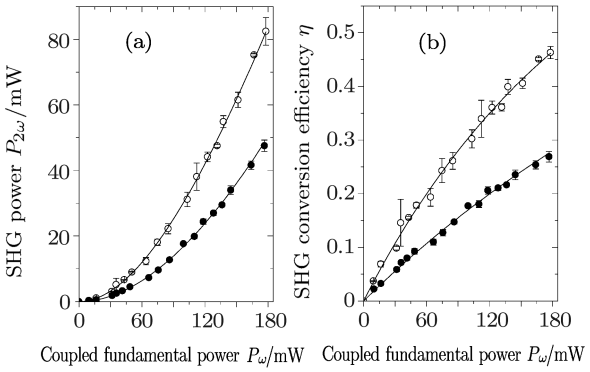


Fig. 3. (a) SHG output light power as a function of the fundamental light power coupled into the waveguide I (solid circles) and the waveguide II (open circles) with the corresponding fitting curves (solid lines). (b) The conversion efficiency as a function of the fundamental light power coupled into the waveguide I (solid circles) and waveguide II (open circles) with the corresponding fitting curve (solid line). The error bars represent errors of four independent measurements.

4. Conclusion

In conclusion, we have demonstrated efficient SHG in inhomogeneous MgO-doped $LiNbO_3$ waveguides with the high conversion efficiency up to 47%. By analysing the SHG temperature tuning curves and the normalized SHG conversion efficiencies of the two nominally identical waveguides, we found that waveguides with different extents of inhomogeneities have different conversion efficiencies. In addition, we have successfully quantized the axial variation of the refractive index difference of the waveguides with the cubic function.

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