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Power Characteristics of cw Second-harmonic Generation in Periodically Poled $LiNbO_3$

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ABSTRACT

We verified through a noncritical phase-matched second-harmonic generation experiment that the periodically-poled $LiNbO_3$ (PPLN) had a large effective nonlinear optical coefficient, demonstrating that the QPM grating was uniform throughout the entire length of PPLN. The quasi-phase matching temperature was 193.4°C. The maximum SHG output power at the fundamental power of 2.0 W was found to be 18.0 mW; generated second-harmonic beam was found to have no photorefractive effect.

Key words **:** ***Periodically poled $LiNbO_3$ (PPLN), Quasi-phase matching, Second-harmonic generation, Photorefractive effect***

1. Introduction

Efficient second-harmonic generation (SHG) for quasi-phase matching using periodically-poled reversal has been investigated in bulk with such compounds as $LiNbO_3$ (PPLN), $LiTaO_3$ (PPLT), $KTiOPO_4$ (PPKTP) as well as in waveguide devices.[1-8] Quasi-phase matching in PPLN allows nonlinear interactions between waves polarized along the z-axis, for which the largest 2^{nd}-order nonlinear optical coefficient can be used. Visible interactions according to the dispersion relation of $LiNbO_3$ generally require samples with domain period of 2~15 μm. At a fundamental wavelength of 1.06 μm, the coherence length for second-harmonic generation in $LiNbO_3$ is about 6.5 μm.

Quasi-phase matching (QPM) always permits noncritical phase matching and the use of the large diagonal nonlinear optical coefficients d_{33}, which are inaccessible with birefringent phase matching. Noncritical phase matching and a high effective nonlinear optical coefficient d_{eff} are necessary for high second-harmonic (SH) power and high conversion efficiency in applications. The optimization of the power efficiency of SHG is of primary importance in a number of applications, especially when continuous wave (cw) beams with relatively low peak power are frequency doubled. If the input light field is a Gaussian beam, the dynamics of SHG is determined by the power of the input beam, the spatial shape of the input beam, its confocal parameter, the Poynting vector walk-off length, the phase matching condition, and so on.

As is well-known, the relation between the beam width and the lens can be represented by $w_f = \frac{\lambda f}{\pi w_0}$, $2z_0 = \frac{\pi n w_f^2}{\lambda}$, where w_f is the beam width of the beam focused by lens L1, w_0 is the beam width of the fundamental beam, f is the focal length of lens L1, λ is the wavelength of the fundamental beam, n is the refractive index, and $2z_0$ is the *confocal length.* The beam divergence behind lens L1 with the fundamental beam through the spatial filter consisting of two apertures is smaller than the fundamental beam of the normal setup. The existence of an optimum for the beam waist is the result of the best compromise between the beam focalization, which tends to increase the efficiency, and the diffractive spread, which tends to reduce the efficiency. The second-harmonic generation by Gaussian beam is needed to investigate the effect of the diffraction of such beams. The output power characteristic of second-harmonic generation on the beam cross-sectional area requires that the beam be focused onto the nonlinear crystal.[9,10]

In this paper, we investigate the output power characteristics of second-harmonic generation and the beam width dependence of the incident fundamental beam in PPLN.

2. Experimental

The setup for cw second-harmonic generation in PPLN is shown in Fig. 1. The optimized conditions of the fundamental beam were 50 cm (the distance between pinhole#1 and pinhole#2), 3 mm (the diameter of pinhole#2), and 4 mm (the diameter of pinhole #2). The beam quality factor M^2 of the improved fundamental beam after spatial filtering was about 2.3. The PPLN was a 20-mm-long crystal with 0.5-

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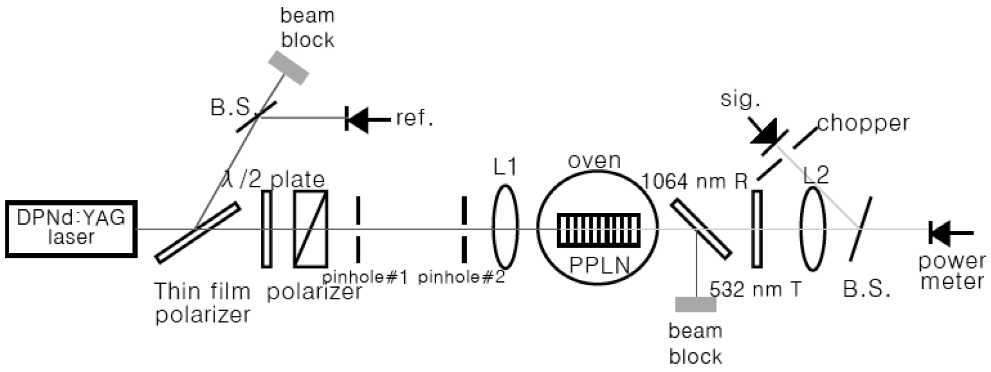

Fig. 1. cw second-harmonic generation setup for 6.5 μm-period PPLN.

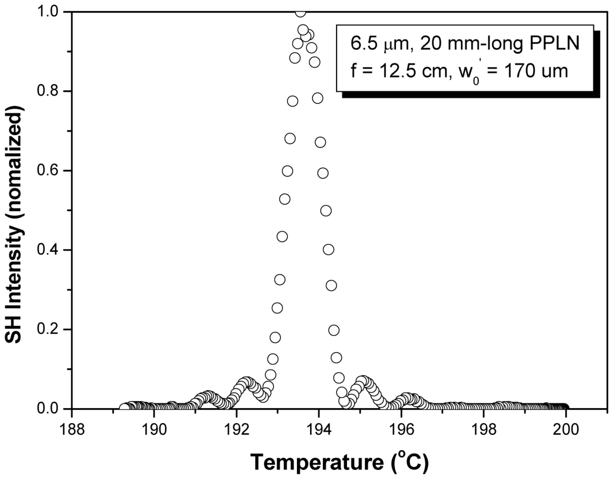

Fig. 2. 532 nm output second-harmonic intensity versus temperature for Nd:YAG SHG.

mm-thickness. The grating period was 6.5 μm. Diode-pumped solid-state Nd:YAG (λ=1064 nm) of the fundamental beam with diameter of 3 mm was used. For the noncritical phase-matching condition, a thin-film polarizer and half-wave plate were used. Temperature of the specimen was oven-controlled within ±0.1°C. Fundamental beam width focused by lens was 80, 90, 130 and 150 μm. In order to filter only the output signal of the second-harmonic generation we used a 1064 nm HR mirror and 532 nm pass filter; signal was detected with use of a photodiode.

3. Results and Discussion

Fig. 2 shows a second-harmonic generation temperature tuning curve for 6.5 μm-period 20-mm-long PPLN. The observed phase-patching temperature was 193.4°C. The full-width half maximum (FWHM) of temperature was about 0.8°C. The measured phase-matching temperature agrees comparatively with the predicted phase-matching temperature that was determined with a temperature-dependent Sellmeier equation for $LiNbO_3$ and with a 6.5 μm-period.[11,12] The good agreement of the theoretical prediction shows the domain periodicity, the material dispersion and the uniform temperature control along the whole crystal.

The optical homogeneity can be determined from the characteristics of the second-harmonic generation intensity versus temperature because second-harmonic generation curve must follow the sin*c*-function if the crystal has uniform homogeneity.

In order for the shaping to create an undistorted flat top beam or a Gaussian-like beam, the input beam must be Gaussian. If the input beam does not have the proper profile, then measurements will tell the user that adjustments to the source beam must be made before attempting to perform the laser beam shaping. To obtain an improved fundamental input beam, we performed spatial filtering by using two apertures (below setup in Fig. 1). In Table 1, the power dependence and the beam width of fundamental beam are listed. The second-harmonic power has the following relation.[13]

$$\begin{aligned} P_{SH} &\propto \{\chi^{(2)}\}^2 \\ &\propto I^2 \\ &\propto L^2 \end{aligned} \tag{1}$$

where P_{SH} is the second-harmonic power, I is the fundamental beam intensity and L is the crystal length.

When the fundamental beam intensity was increased two times, the second-harmonic power increased about four times beyond the theoretical prediction in all situations. The difference between theoretical and experimental values could stem from absorption by the fundamental and the harmonic beams, which gave rise to thermal effects and apparent shifts in the phase-matching temperature. In our improved condition, the maximum second-harmonic power obtained was 18.0 mW at the fundamental intensity of 2.0 W.

At the fundamental beam intensity of 1.0 W, obtained second-harmonic power approached the theoretically calculated second-harmonic power according to beam width increase. These results show that the second-harmonic intensity relates to the divergence of the fundamental beam. In Table 1, we list our results. In our experiment, the incident surface of the PPLN had a no anti-reflection coat-

Table 1. Properties of SH Power for a Pump Beam with Various Focal Lengths

Focal length (mm)	Beam width (μm)	SH power(@ 1.0 W) (mW)	Max. SH power(@2.0 W) (mW)
50	80	5.6	18.0
75	90	5.4	17.9
100	130	2.6	9.7
125	150	2.2	8.0

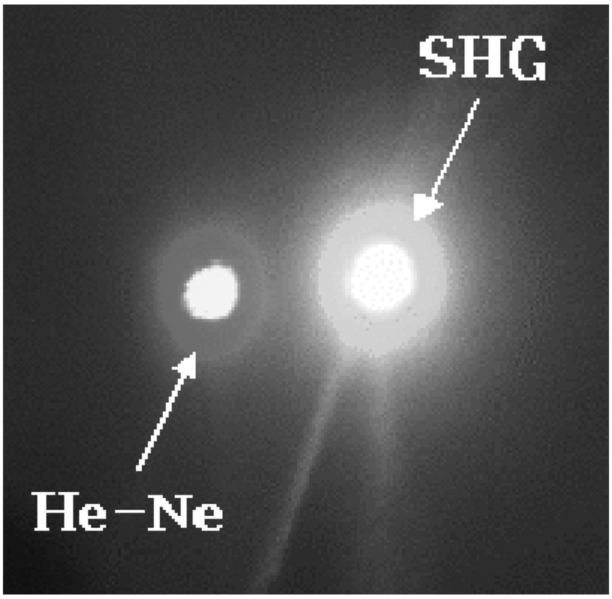

Fig. 3. Photograph of comparison between 10 mW He-Ne beam and generated second-harmonic beam.

ing of about 1064 nm (i.e. 15% loss of fundamental intensity); generated second-harmonic wave has a reflection of 15% on the output surface. Then, the effective 2nd-order nonlinear-optical coefficient, $\chi^{(2)}_{333}$, has a large value.

Fig. 3 shows a photograph of comparison between the 10 mW He-Ne beam light and the generated second-harmonic beam light of our experiment. Generated second-harmonic beam has no photorefractive effect and maintains stability within about 2%.

4. Conclusions

In the second-harmonic generation temperature tuning curve for 6.5 μm-period 20-mm-long PPLN, the observed phase-matching temperature was 193.4℃. The output power dependence and the beam width dependence of the second-harmonic generation in PPLN agree comparatively with the theoretically calculated value. The maximum second-harmonic power obtained was 18.0 mW at the fundamental intensity of 2.0 W; generated second-harmonic beam has no photorefractive effect.

Acknowledgments

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