Laser-diode-pumped cw Nd:MgO:LiNbO$_3$ self-frequency-doubling laser around room temperature

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A laser-diode-pumped cw self-frequency-doubling laser has been achieved in Nd:MgO:LiNbO$_3$ crystal around room temperature. The second-harmonic output at $\lambda = 547$ nm to 8 mW was obtained with a miniature resonator in which only a crystal was included, without any extra intracavity component.

Nd:MgO:LiNbO$_3$ crystal combining the good laser properties of Nd^{3+} and excellent nonlinear properties of LiNbO$_3$ is a promising material for producing pure green lasers in a miniature laser that would be useful in practical applications such as laser medicine and high-speed photography. Using a dye laser as the coherent pump source, Fan *et al.* achieved the first cw operation of self-frequency-doubling with Nd:MgO:LiNbO$_3$ and obtained 1.1-mW second-harmonic output at a phase-matching temperature of approximately 152 °C.[1] Our laboratory reported the first successful cw Nd:MgO:LiNbO$_3$ self-frequency-doubling laser at room temperature.[2] Although in our experiments a green light output as high as 18 mW was generated, the laser was still pumped by $\lambda = 598$-nm dye laser radiation. The quite huge dye laser with an argon-ion laser pump source prevented miniaturization of the system. A self-frequency-doubling laser pumped by a laser diode (LD) is an optimal option. Cordova-Plaza *et al.* presented the first demonstration of LD-pumped laser oscillation in Nd:MgO:LiNbO$_3$ but output of only the fundamental wavelengths at $\lambda = 1085$ nm and $\lambda = 1093$ nm were obtained without self-frequency-doubling.[3]

The experimental arrangement is shown in Fig. 1. A Spectra Diode Laboratory Model SDL-2482-P1 laser diode was used as the pump source. The center wavelength of pump light was carefully aligned to approximately 809 nm, which is the crystal absorption peak for σ-polarized $(E \perp C)$[1,3] light. After rectifying and focusing the optical system the waist size of the pump laser was approximately 250 µm in Nd:MgO:LiNbO$_3$. The polarization of pump light coincides with σ polarization of the crystal to obtain higher pump efficiency.

The Nd:MgO:LiNbO$_3$ is the same as that used before in Ref. 2. The $3 \times 4 \times 20$ mm^3 crystal was doped with 0.21-wt. % Nd$_2$O$_3$ and 1.8-wt. % MgO. With longitudinal LD pumping the laser oscillates along the 20-mm-long edge. The *y* axis of the crystal is parallel to the 4-mm-long edge. The crystal was cut according to the phase-matching angle at room temperature as well as the pump heating effect (approximately 72.5 °C).[4] As mentioned in Ref. 2, at a pump level of 850 mW the dye laser at $\lambda = 598$ nm was used to measure the temperature of the crystal, which was 43 °C because of pump heating while the room temperature was maintained at 22 °C. In this case optimum phase matching was automatically reached without extra heating or cooling. At other pump levels the crystal had to be heated or cooled to maintain optimum phase matching. In the experiments with a LD pump source at $\lambda = 809$ nm the pump heating effect was not as strong as with a dye laser at 598 nm; therefore the crystal had to be heated to meet the phase-matching condition in the range of our available pump power. At the absorbed pump levels of from 220 to 870 mW, the control temperatures of the crystal ranged from 59 to 47 °C at a room temperature of 22 °C (Fig. 2). The crystal was placed in an oven, the temperature of which was controlled and stabilized by a homemade electronic feedback system to maintain optimum phase matching at differ-

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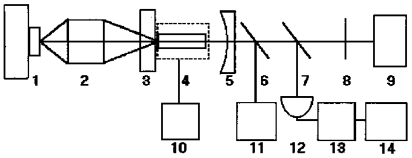

Fig. 1. Experimental setup for a LD-pumped Nd:MgO:$LiNbO_3$ self-frequency-doubling laser: 1, LD; 2, focusing system; 3, input coupler; 4, Nd:MgO:$LiNbO_3$ crystal; 5, output coupler; 6, 7, beam splitters; 8, filter; 9, power meter; 10, temperature controller; 11, monochromator; 12, detector; 13, oscilloscope; 14, plotter.

ent pump levels. The temperature control precision was ±0.01 °C. Both endfaces of the crystal were antireflection coated at the fundamental wavelength ($R_{1093\,\mathrm{nm}} < 0.4\%$). No attempt was made to oscillate the second-harmonic wave.

The input coupler of the laser is a plane mirror with reflectivities of $R_{809\,\mathrm{nm}} < 5\%$, $R_{1093\,\mathrm{nm}} > 99.7\%$, and $R_{547\,\mathrm{nm}} < 10\%$, respectively, for pump wave, fundamental wave, and second-harmonic wave. The output coupler is a mirror with 50-mm radius of curvature and reflectivities of $R_{1093\,\mathrm{nm}} > 99.7\%$ and $R_{547\,\mathrm{nm}} < 2\%$. The configuration of the laser was nearly half-confocal and the measured cavity length was approximately 40 mm, which corresponds to an equivalent cavity length of approximately 29 mm. The second-harmonic power from the output coupler was received and measured by a detector with filters that prevent the residual fundamental wave and pump laser from entering into the detector.

To achieve phase-matching for second-harmonic-generation in Nd:MgO:$LiNbO_3$, laser oscillation must have ordinary polarization ($E \perp C$, low-gain σ polarization), whereas the second-harmonic wave must have extraordinary polarization ($E \perp C$).[1] Usually a Brewster angle window can be inserted into the cavity to force the laser to oscillate in the low-gain σ polarization.[1] In our critically phase-matched crystal, the double refraction walk-off angle between π- and σ-polarized laser lines was approximately 1.18° and the walk-off width through the 20-mm-long crystal was approximately 410 μm. The diameters of the intracavity TEM_{00} modes for both π- and σ-polarized fundamental waves were less than 180 μm, so that the crystal could be used as a polarization selector to suppress the relatively strong π-polarization transition. By adjusting the orientation of the crystal and the cavity mirrors, we made the low-gain σ-polarization laser oscillate preferentially to achieve phase matching for second-harmonic generation in a simple resonator without a Brewster angle window. In the experiments the σ-polarized laser was adjusted to oscillate along the axis of the cavity and the π-polarized laser was completely suppressed.

Figure 2 shows the second-harmonic output power from the output coupler (a) and the optimal control temperature of the crystal (b) versus the absorbed pump power curves that are, respectively, the parabolic and linearity dependencies. The solid power curve is a least-squares fit to a parabola. The measured maximum second-harmonic ($\lambda = 547$ nm) output power from the output coupler was 8 mW at an absorbed pump power of 870 mW. The conversion efficiency (defined as the ratio of total second-harmonic output, in which the leakage of power from the input coupler has been counted, to absorbed pump power above the threshold[1]) was 3.5%/W. The absorbed pump power threshold was approximately 220 mW. Although the shape of the output beam spot resembled an ellipse, the spatial profiles of the output beam in both horizontal and vertical directions were fine Gaussian curves. The solid curve in Fig. 3 represents the recorded intensity profile in the horizontal direction with a pinhole detector to scan a section of the second-harmonic output beam at a distance of 2 m from the output coupler. The diameter of the pinhole was 0.5 mm and the scanning speed was 5 s/cm. The dashed curve in Fig. 3 represents the theoretical Gaussian curve that almost perfectly overlaps the experimental curve. The divergent angles of output green light in the horizontal and vertical directions were, respectively, 9 and 6 mrad. Since the beam spot of the fundamental wave is round we consider that this ellipticity of green light arises from the limited acceptance angle of the critical phase-matching process. The walk-off angle between the fundamental wave and the second-harmonic wave in our critical phase-matching crystal is approximately 1.42° and the diameter of the fundamental wave is approximately 180 μm. The efficient nonlinear interaction length for second-harmonic generation is just ap-

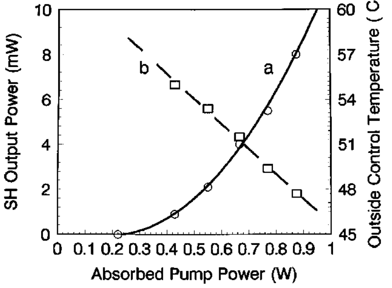

Fig. 2. Second-harmonic output from an output coupler versus (a) the absorbed pump power, and (b) the optimum outside controlled temperature.

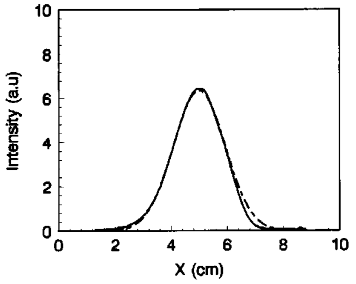

Fig. 3. Spatial profile of the second-harmonic output beam. The solid curve represents the recorded intensity profile and the dashed curve represents the theoretical Gaussian curve.

proximately 7.2 mm. The walk off leads to elliptical distortion of the TEM_{00} second-harmonic wave. On the other hand the spot sizes of intracavity laser beams cannot be miniaturized because of the walk-off effect. Therefore the efficiency of frequency doubling is further limited. This might be an inherent difficulty with the critical phase-matching system.

Although the laser operates in a single transverse mode, the multiple longitudinal modes still exist. Because of the coupling between the cavity modes the intensity noise of output green light is quite large. The intensity fluctuation of an output second-harmonic wave at an absorbed pump power of approximately 800 mW is approximately 15% (Fig. 4). To check the photorefractive damage of the $Nd:MgO:LiNbO_3$ crystal we observed the output power of the laser with a power meter under our highest available absorbed pump power (approximately 870 mW) for 40-min periods. For the duration of the observation period the output powers of both fundamental and second-harmonic waves did not exhibit any reduction.

Since we used a LD array as the pump source, the divergent angles of the pump beam were quite large (10° and 40°, respectively, in the horizontal and vertical directions) and the spatial profile was far from Gaussian. The 250-μm pump beam in the crystal was the minimum for our available focusing system, so that the pump power density was relatively lower. We tried to use a mirror with 100-mm radius of curvature as the output coupler instead of a mirror with 50-mm radius. For this case the waist size of the laser was approximately 260 μm, to match the mode volume of the laser and the section of pump beam. However, the second-harmonic output was weak because of the low intracavity power density of the fundamental wave and low conversion efficiency for second-harmonic generation. To obtain a higher intracavity intensity of the fundamental laser, we also built a nearly concentric resonator composed of two mirrors with 20-mm radius, but output of only 3-mW second-harmonic power was produced because the mode volume of the laser was too small compared to the dimension of the pump beam. In other words the crystal was too long to match a pump beam with large divergence. (After focusing and rectifying the optical system the divergent angles were approximately 2° and 10°, respectively, in the horizontal and vertical directions.) In fact only a small portion of the crystal was stimulated to lase, the remainder served as an absorber.

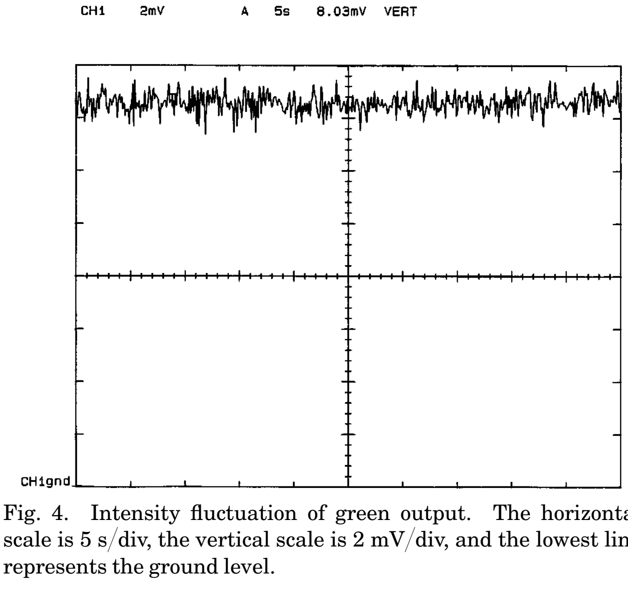

Fig. 4. Intensity fluctuation of green output. The horizontal scale is 5 s/div, the vertical scale is 2 mV/div, and the lowest line represents the ground level.

In summary, we have achieved a LD-pumped cw self-frequency-doubling laser of $Nd:MgO:LiNbO_3$ around room temperature in a miniature resonator. The conversion efficiency of this system was limited by the walk-off effect between the fundamental and second-harmonic waves. Compared with other intracavity doubling systems such as KTP with $Nd:YVO_4$,[5] the output power level and conversion efficiency are not satisfied even though the self-frequency-doubling laser offers the advantages of miniaturization and simplification. Improvement of the conversion efficiency for second-harmonic generation should be possible by decreasing divergence of the pump beam, optimizing the crystal length and the size of beams in the laser cavity as well using noncritical phase matching, and making the laser cavity resonant at the second-harmonic wavelength.

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