Mode-locked diode-pumped self-frequency-doubling neodymium yttrium aluminum borate laser

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As far as we know this is the first report on picosecond green-light generation from an actively mode-locked diode-pumped self-doubling neodymium yttrium aluminum borate (NYAB) laser. The pulse width is approximately 100 ps and is limited by imperfect antireflection coating and the intracavity doubling effect. The green average output power of this laser for mode-locked operation was more than 12 times higher than that for the continuous wave NYAB laser. The polarization state of the laser can be switched from ordinary to extraordinary rays by displacement of the pump spot. The polarization ratio can be better than 200 without any intracavity polarization element. © 1998 Optical Society of America

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1. Introduction

Compact green or blue diode-pumped solid-state lasers are attractive for a wide range of applications, e.g., high-density optical storage, color display, laser medicine, and optical testing. Many papers on continuous-wave (cw) diode-pumped green and blue solid-state lasers have been published.\(^1\) To achieve higher second-harmonic conversion efficiency, one must typically Q-switch or mode lock the fundamental laser to obtain a higher peak power than that of a cw laser. Green pulses with durations of 529 and 260 ps have been generated from actively mode-locked Nd:YAG lasers with an intracavity frequency-doubling crystal.\(^2,3\) In addition to higher average power than the cw laser, these compact green mode-locked lasers also exhibit lower noise fluctuations. An alternative and attractive approach to intracavity doubling is the use of a self-frequency-doubling crystal such as Nd:MgO:LiNbO\(_3\) (Ref. 4) and neodymium yttrium aluminum borate (NYAB).\(^5-7\) These crystals are interesting laser materials because they combine the laser properties of a doped ion with nonlinear optical properties of the host material. The cw and Q-switched operations of the diode-pumped self-frequency-doubling laser have also been reported.\(^4-6\) Here we report what we believe is the first picosecond green-light generation from a diode-pumped self-doubling NYAB laser by active mode locking. The pump-to-green conversion efficiency is as high as 2%, which is approximately twenty times higher compared with cw operation of the NYAB laser. We estimated the pulse width of the green light to be 100 ps by measuring the pulse width of the fundamental laser.

The experimental setup of the mode-locked NYAB laser is shown in Fig. 1. The laser is pumped by a fiber pigtail laser diode (SDL-2362-P3, \(\lambda = 808\) nm) with a fiber core diameter of 50 \(\mu\)m and a maximum output power of 0.7 W. By using coupling lenses we focused the pump beam to the NYAB laser crystal with a beam waist of \(\sim 30\) \(\mu\)m. The second-harmonic signal was generated by the nonlinear effect in the self-doubling NYAB crystal. The crystal had a dimension of 3 mm \(\times\) 3 mm \(\times\) 2 mm and was cut at a 32.9° angle for type I phase matching. The rear facet of the crystal was coated for high reflection (HR) at 1.06 and 0.53 \(\mu\)m and for high transmission at 0.8 \(\mu\)m. The front facet was antireflection (AR) coated at 1.06 and 0.53 \(\mu\)m. The fundamental laser emission from the NYAB crystal was collimated by an AR-coated lens with 15-cm focal length. A highly reflective flat mirror (\(R = 99.5\%\) at 1.06 \(\mu\)m, \(T = 85\%\) at 0.53 \(\mu\)m) was used to construct a high-Q cavity at the fundamental laser wavelength and to couple the output of the second-harmonic light.
An acousto-optic modulator with a carrier frequency of 41 MHz served as a mode locker and was placed adjacent to the end mirror. The cavity length was adjusted to approximately 183 cm to match the mode-locker frequency. We obtained the mode-locking operation of the fundamental laser by fine tuning the modulation frequency of the mode locker until maximum green output power was generated. The output of the laser is separated by a dichroic beam splitter for measurement of the pulse width of the fundamental laser and output power of the second-harmonic green light. A noncollinear intensity autocorrelator was used to measure the pulse width of the fundamental laser pulses.

Under mode-locked operation, the average circulated power of the intracavity fundamental laser is near the same level as that for cw operation. However, the average output power of the mode-locked green light increased significantly as shown in Fig. 2(a). As the pump power varies from threshold to 670 mW, the ratio of mode-locked green power to that of cw green power is 50 to 12. At a pump power of 670 mW, the green-light output power is 7.8 mW. The corresponding cw green power is only 0.6 mW at this pump power level. If we consider the green-light transmission of the acousto-optic modulator ($T \approx 70\%$) and the output coupling mirror, the average conversion efficiency of the output from the front facet of the NYAB crystal is 2.08%. Figure 2(b) shows the conversion efficiency of the mode-locked NYAB laser. The circulated power of 1062 nm was estimated by measuring the reflectance and the output power of the fundamental laser at the end mirror. The conversion efficiency increased linearly with the pump power from threshold to approximately 300 mW. It then remained nearly constant at the higher pump power, which we believe is the result of thermally induced deviation of the phase-matching angle for the NYAB crystal. An additional result is the reduction of its effective nonlinear coefficient. It is believed that the conversion efficiency could be optimized if the temperature of the laser crystal were controlled and tuned to fit the phase-matching condition. However, the optical distortion caused by thermal expansion and refractive-index change was still unavoidable at the higher pump level. We also measured the internal loss of the laser, which we performed by measuring the threshold pump power as a function of output coupling. Several output couplers with different reflectivities were used. The internal loss of the laser was determined to be 2.8%, which is due mainly to scattering and absorption in the NYAB crystal. With NYAB crystals of good optical quality, the output power and efficiency should be enhanced considerably.

Figure 3 shows a typical background-free autocorrelation trace of the fundamental laser output. The laser was pumped at 500 mW. We found that the trace was best fit by a Gaussian curve with a deconvoluted FWHM of 142 ps. The time–bandwidth product of the fundamental laser pulse is approximately 30 times that of the transform-limited value. Since the cavity is not resonant for the green output, we estimate that the Gaussian output pulse width of the green light is approximately $142/\sqrt{2} = 100$ ps. By varying the pump power from 300 to 670 mW, we determined that the fundamental pulse width changes between 140 and 160 ps. An intensity modulation with a period of 11.3 ps appears around the peak of the autocorrelation trace. Its origin is the

Fig. 2. (a) Average cw and mode-locked green output of the NYAB laser as a function of pump power. The ratio of mode locked to cw green output is also shown. (b) Second-harmonic conversion efficiency as a function of pump power.
residual reflection at the AR-coated facet of the crystal. This Fabry–Perot effect is also observed in the spectrum of the fundamental laser and second-harmonic light as shown in Figs. 4(a) and 4(b), respectively. It limits the phase-locked bandwidth to those modes within a single cluster with a bandwidth of ~10 GHz in the frequency domain. The corresponding fundamental laser pulse width is thus limited to greater than 40 ps. This effect could be eliminated by using a wedge-type NYAB crystal or one cut at the Brewster angle.

Another significant factor that affects the pulse width of the actively mode-locked laser is the internal doubling effect, which creates a larger loss in the peak of the fundamental laser pulse. Previously, Falk\textsuperscript{11} showed theoretically that the pulse width of an actively mode-locked laser with an intracavity frequency-doubling crystal is given by

\[
\tau_p = \frac{2\ln 2}{\pi \Delta f} \left[ \frac{\alpha}{\sqrt{2} g_0} \right]^{21/2} \left[ \frac{4\delta f_m g_0}{\alpha} \right]^{1/2},
\]

where \(\Delta f\) and \(f_m\) are, respectively, the laser transition bandwidth and modulation frequency; \(g_0\) is the small signal gain; \(\alpha\) is the doubling efficiency of the green light to the circulated fundamental laser; and \(\delta\) is the modulation depth of the mode locker. By substituting the experimental parameter of this NYAB laser, \(g_0 = 0.3\), \(\Delta f = 540\) GHz, \(f_m = 82\) MHz, \(\delta = 0.5\), and \(\alpha = 0.003\), we found \(\tau_p \approx 298\) ps. This value is two times higher than our experimental results. The origin of this discrepancy is under investigation. On the other hand, Eq. (1) also predicts that the pulse width is almost invariant as the pump power is increased from 300 to 670 mW. By substituting the measured doubling efficiency as well as the corresponding \(g_0\) into Eq. (1), the predicted pulse width changes only \(~15\%\) in this pumped region. The variation of the pulse width results mainly from the fluctuation of the second-harmonic generation efficiency within this pump range.

We have also investigated the polarization state of the laser beam and its effect on laser performance. Without any polarization selection element in the cavity, we found that the polarization of the fundamental laser is linearly polarized along the \(n_o\) direction of the laser crystal. The polarization ratio is approximately 200. To explain the above observation, we examined the threshold condition of the laser polarized along \(n_o\) and \(n_e(1)\). The pump threshold power is proportional to \((\omega_i^2 + \omega_p^2)\), where \(\omega_i\) and \(\omega_p\) are the beam waists of the fundamental laser beam and the pumping laser diode, respectively.\textsuperscript{12} The beam waists of the former polarized along \(n_o\) and \(n_e(1)\) are, respectively, 35.6 and 36.6 \(\mu\)m by use of the \(ABCD\) matrix calculation. The threshold pump power for the extraordinary laser beam is approximately 3\% higher than that of an ordinary beam. If we reduce the beam waist of the fundamental laser beam by replacing the focusing lens (150 mm) with a tighter-focusing lens \((f = 100\) mm), the threshold of the \(e\)-polarized fundamental beam is only 1.5\% higher than that of the \(o\)-polarized fundamental laser. In this case the polarization ratio is reduced to below 3 because of the smaller threshold difference between the two orthogonal beams. In addition, the green output power declines by a factor of 4 and the pulse width broadens to above 300 ps. By placing a Brewster-angle plate in the cavity, the polarization ratio can be enhanced. The plate, however, introduced a loss (~0.5\%) that increased the threshold pump power of the laser. The output power of the fundamental and second-harmonic lasers also decreased.

The polarization behavior of the laser could be explained by intrinsic gain differences of the two polarization states. However, the circulated fun-
damental laser beam could be operated with either TE or TM output at almost the same power level by adjusting an intracavity Brewster-angle plate. The effect of the intrinsic gain difference is thus determined to be quite small. The walk-off effect of the birefringent crystal can also be the cause for linearly polarized output. Since the resonator eigenmodes of the two beams with orthogonal polarization were spatially separated at the birefringent gain medium, the laser crystal also provided a function as a polarizing element. By small displacement of the position of the pumped spot along the extraordinary direction of the NYAB crystal, the polarization of the fundamental laser could be switched to the orthogonal direction. In this situation, the green output power of the NYAB laser is almost quenched. Further displacement of the pumped spot is observed to cause a high-order transverse mode of the laser output.

In conclusion, we report green-light generation from a self-frequency-doubling NYAB crystal by active mode locking. The pulse width of the fundamental laser was measured to be 142 ps and the estimated green pulse width is approximately 100 ps. The pumped beam to green-light conversion efficiency is 2%, which is 12 times that of the cw operation. By optimizing the beam size of the fundamental laser using a proper lens within the cavity, one can obtain linear polarization along the desired $n_e$ direction of the NYAB crystal. The polarization ratio can be better than 200 without any intracavity polarization element. The polarization state of the laser can be switched from ordinary to extraordinary rays by displacement of the pump spot.

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References