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High-power diode-pumped nonlinear mirror mode-locked Nd:YVO$_4$ laser with periodically-poled KTP

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Abstract. We demonstrate a high-power nonlinear mirror (NLM) mode-locked Nd:YVO$_4$ laser with a periodically poled KTP (PPKTP). With a 10-mm-long PPKTP crystal, 5.6 W of average power with 20-ps of pulse duration was generated at 18-W of pump power. Compared with conventional type-II KTP crystal with the same length, the stability against the Q-switched mode-locking (QML) is significantly increased with PPKTP in NLM laser; and the pulse duration was also considerably reduced.

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Picosecond solid-state lasers with multiwatt average power and multikilowatt peak powers are usually required for efficient wavelength conversion. Recently, several schemes based on passive mode locking techniques were presented to reach average power levels in the multiwatt regime [1–4]. One of these techniques called nonlinear mirror (NLM) mode locking was first demonstrated by Stankov [5]. This device consists of a combination of a frequency doubling crystal and a dichroic mirror with high reflectivity for the second harmonic and partial reflectivity for the fundamental. With this approach, the highest power ever reported was 3.4-W generated from a diode-pumped Nd:YVO$_4$ laser with a KTP crystal [4]. Since the pulse duration generated from NLM is strongly impaired by the effect of the group velocity mismatch (GVM) of the fundamental and the second harmonic waves, several group-delay-compensation techniques were proposed to reduce the pulse width [6].

Near forty years ago, Armstrong [7] pointed that the phase velocity mismatch can be compensated by periodic reversal of the sign of the nonlinear coefficient to achieve quasi-phase-matched (QPM) second harmonic generation, which increases the acceptance angle and makes the alignment less critical. In the past five years a group of nonlinear crystals such as LiNbO$_3$, LiTaO$_3$, and KTP were periodically poled by an electric field to be used for QPM doubling and to provide a higher effective nonlinear coefficient. These new nonlinear materials enable researchers to use them in device applications.

In this letter, we present a high-power diode-pumped NLM mode-locked Nd:YVO$_4$ laser by use of a periodically poled KTP (PPKTP) crystal. To our knowledge, this is the first time the use of a PPKTP crystal to generate multiwatt cw picosecond solid-state laser source. The output performance is compared with the result obtained by use of a conventional type II phase-matched KTP.

The PPKTP crystal was with 10 the poling period of 9.0-μm (ISORAD/ZEBRA Crystals). The input and output facets of the crystal were antireflection coated for the fundamental and the second-harmonic wavelengths. Figure 1 is the basic outline of the laser setup. The pump power is a 20-W fiber-coupled diode-laser array (FAP-81-20C-800-B) with the output wavelength of the lasers at 25 °C ranging from 807 to 810-nm. The fibers were drawn into round bundles of 0.8-mm diameter and a numerical aperture of 0.18. Focusing lens with 20-mm focal length and 85% coupling efficiency was used to re-image the pump beam into the laser crystal. The waist diameter of the pump beam was around 400 μm. The a-cut 0.3-at.% 10-mm-length Nd:YVO$_4$ crystal was 0.5° wedged and coated for highly reflectivity at 1064-nm ($R > 99.9\%$) and high transmission at 808-nm ($T > 95\%$) on one side and the other side was antireflection coated at 1064-nm. The Nd:YVO$_4$ crystal with low doping concentration was used to

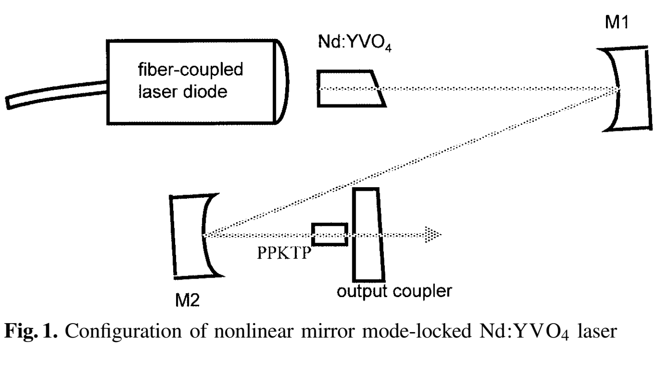

Fig. 1. Configuration of nonlinear mirror mode-locked Nd:YVO$_4$ laser

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avoid the thermally induced fracture. The laser crystal was wrapped with indium foil and mounted in a water-cooled copper block. The water temperature was maintained at 17 °C. The cavity was designed to easily allow mode matching with the pump beam, and to provide the proper spot size in the nonlinear crystal. The optimal spot size in the nonlinear crystal was experimentally found to be around 40 μm. The resonator consisted of two spherical mirrors M1 and M2 with radii of curvature of 50 cm and 10 cm and with high 99.9% reflectivity at 1064 nm, separated by 60 cm. Both the tilting angles of M1 and M2 are kept as small as possible (full angle between the beams $< 5°$) in order to minimize the cavity astigmatism. The output coupler was 1.0° wedged flat mirror with 99.9% reflectivity at 532 nm and with 69% reflectivity at 1064 nm. The total cavity length was around 1 m. For comparison, two conventional type-II KTP crystals with lengths of 3-mm and 10-mm were respectively used to generate NLM pulses.

When the laser runs cw on the TEM_{00} mode the output power was 6.6-W at a pump power of 18-W. To force the laser in the mode locking regime the nonlinear crystal was suitably positioned close to the output coupler, and its inclination was finely adjusted around the phase matching direction. Mode locking could be optimized with the help of a fast photodiode and a power spectrum analyzer or an oscilloscope.

Figure 2 shows the average mode-locked output power versus pump power for the PPKTP and two different type-II KTP crystals. A typical oscilloscope trace of the mode-locked pulse train is also shown in Fig. 2. For a 3-mm-long type-II KTP crystal, the cw mode-locking (CML) threshold pump power was found to be around 7.5-W and the slope efficiency was somewhat lower for pump power up to 12-W. For 10-mm type-II KTP and 10-mm PPKTP crystals, the CML threshold pump powers were lower and nearly the same as the lasing threshold, and their slope efficiencies were higher than 40% for pump power up to 18-W. It can be found that the mode-locking threshold and the output power obtained with the PPKTP crystal were not better than the results obtained with a type-II KTP crystal having the same length. Even so, experimental results show that the PPKTP crystal provides a superior immunity from Q-switched mode-locking (QML) instabilities. The main difficulty in passive mode locking of a high-power solid-state laser is to overcome the tendency of the laser toward QML states [8]. Figure 3a and 3b show the typical CML and QML pulse trains recorded with a digital oscilloscope (LeCroy 9362, 500 MHz bandwidth) and a fast Si PIN photodiode with a rise time of ~ 0.35 ns. Note that because of aliasing effects on the digital oscilloscope, the Fig. 3a and 3b do not show individual pulses; however, the CML and QML states are clearly defined. With a conventional type-II KTP crystal in the nonlinear mirror mode locking, it was found that a slightly incorrect orientation of the nonlinear crystal would lead the laser to a self-Q-switched regime, as shown in Fig. 3b. However, if the PPKTP crystal was used in nonlinear mirror mode locking, the laser itself significantly increases the stability against QML. Note that the pulse duration in QML is several times longer than that in

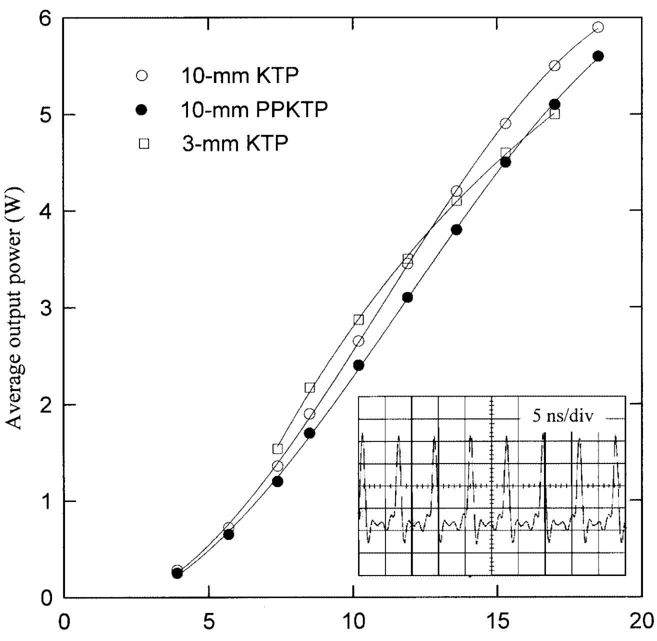

Fig. 2. The average mode-locked output power versus pump power for the PPKTP and two different type-II KTP crystals. The *inset* shows the typical 148-MHz pulse train emitted from the laser

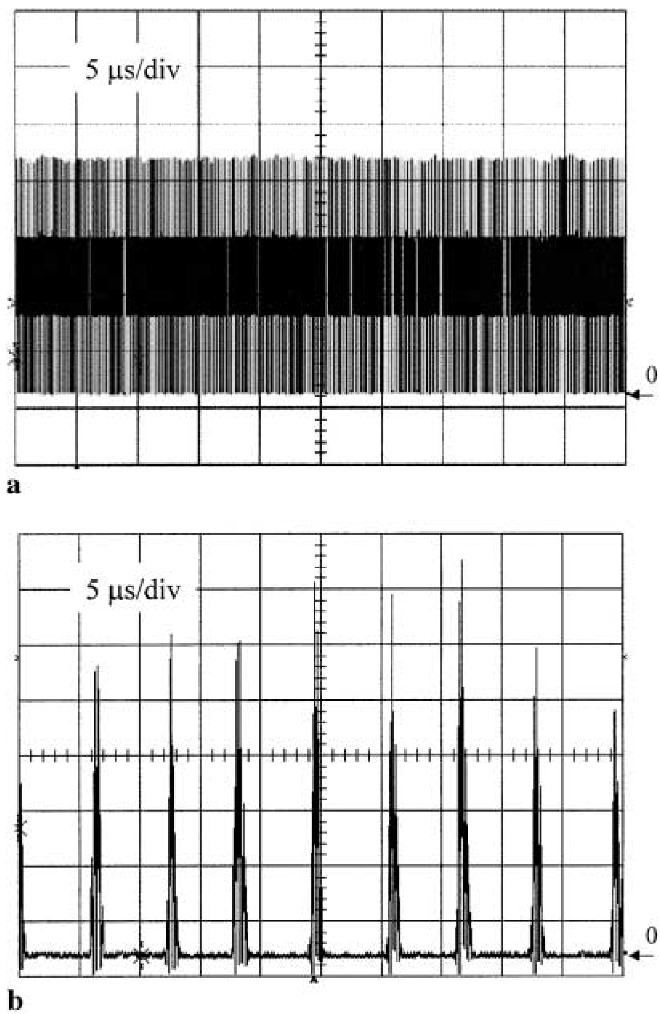

Fig. 3a,b. The typical oscilloscope trace for cw mode locking (**a**) and Q-switched mode locking (**b**) pulse trains. Note that because of aliasing on the digital oscilloscope, the figures do not show individual pulses; however, the CML and QML states are clearly defined

CML. Experimental result indicates that the stability against QML is not sensitive to the spot size on the nonlinear crystal, but sensitive to the alignment of the nonlinear crystal. Therefore, the larger acceptance angle provided by the PPKTP may be the reason why the QML tendency is reduced.

At 18-W of pump power, greater than 5.6-W of average power at a repetition rate of 148 MHz was generated from the $Nd:YVO_4$/PPKTP mode-locked laser, in which the output performance shows very good long-term stability with amplitude fluctuations of less than 3% over hours-long operation without any cavity realignment. The beam quality factor at the maximum output power was around 1.3. The degradation of the beam quality arises mainly from the thermally induced aberration. The conversion efficiency of the pump power into output power was about 31% for CWML operation. Recently, Burns et al. demonstrated a higher CML output power (> 20-W) from side-pumped $Nd:YVO_4$ laser by using strain-compensated saturable quantum-well Bragg reflectors with ∼ 21% optical conversion efficiency [9]. Although thermal lensing and fracture hinder scaling end-pumped laser to higher power, the present mode-locked laser offers a lower threshold of CML behavior and higher optical conversion efficiency. Scaling the present mode-locked laser with good efficiency is currently under way.

The pulse duration was measured using an autocorrelator (KTP type II interaction) in collinear configuration. Figure 4 shows the autocorrelation traces ($sech^2$ fit) for the pulse trains obtained with different nonlinear crystals. It can be seen that with the 10-mm type-II KTP crystal the pulse duration was measured to be 30 ps, whereas with the same length PPKTP crystal the pulse duration was down to around 20 ps. From Sellmeier equations, the time delays arising from GVM in a double pass through the type-II KTP and PPKTP are approximately equal to 8.4 ps/cm and 12.4 ps/cm, respectively. The pulse duration obtained with the type-II KTP was found to be significantly longer than the limit set by the GVM, which represents a notable physical contribution to the pulse lengthening beyond the time delay due to the GVM in the type-II KTP. Indeed, the type-II KTP in combination with the uniaxial crystal $Nd:YVO_4$ that discriminate the polarization eigenmodes may lead to the Lyot filtering effect, thus reducing the available gain bandwidth. On the other hand, the noncritically phase matched type-I PPKTP has the advantage of allowing a broader spectral bandwidth for mode-locking operation, although its time delay due to the GVM is longer than that of type-II KTP. Therefore there is little room for any significant physical contribution to pulse duration beyond the limit set by the GVM with a PPKTP in NLM operation. Figure 4 also shows that the pulse duration decreases for a shorter nonlinear crystal. With a 3-mm type-II KTP crystal the pulse duration was as short as ∼ 10 ps. However, as shown in Fig. 2, the pump threshold to reach CML operation increases dramatically with the 3-mm type-II KTP crystal so that in practice a trade-off should be made between short pulses and mode-locking threshold. Nevertheless, a shorter PPKTP crystal should permit us to reach shorter pulse duration and to have lower CML threshold simultaneously.

Finally, we used the experimental result to estimate the intracavity power in the nonlinear crystal for CML threshold. The intracavity intensity was estimate to be 1 kW/cm^2. Substituting the threshold intensity into the formula for SHG conversion and using Stankov's analysis [5], the modulation depth R was calculated to be around 0.7% for the present experiment.

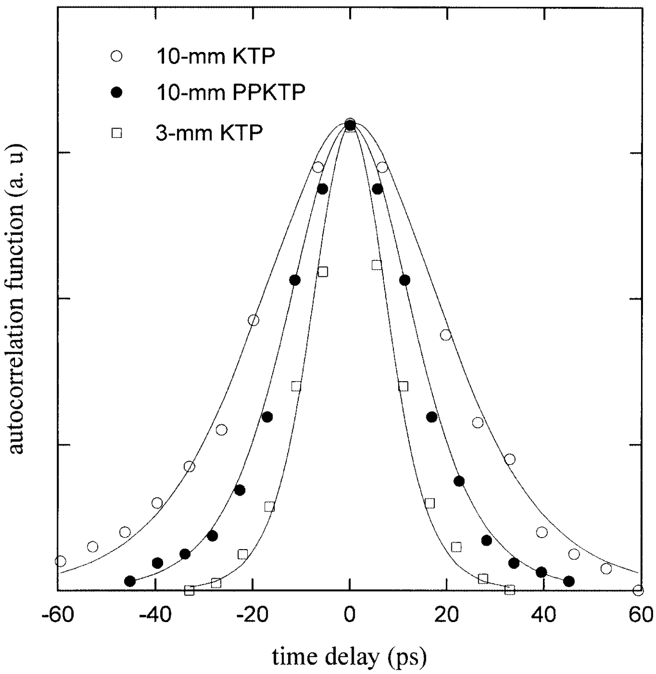

Fig. 4. Autocorrelation curves ($sech^2$ fit) of the pulse duration for the PPKTP and two different type-II KTP crystals

We have demonstrated the use of PPKTP crystal to obtain a high-power diode-pumped $Nd:YVO_4$ laser in NLM mode-locking mode. 5.6 W of average power with 20-ps of pulse duration was generated at 18-W of pump power. Compared with conventional type-II KTP crystals, using PPKTP crystal in NML mode-locked laser can enhance the stability against QML because PPKTP provides high nonlinear efficiency for non-critical phase matching. Additionally, the PPKTP crystal leads to shorter pulse duration than conventional type-II KTP crystal with the same length because the PPKTP provides a broader spectral bandwidth. The influence of the PPKTP length on the NLM mode-locked laser is currently under way.

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