$\chi^{(2)}$-Lens Mode-Locking of a High Average Power Nd:YVO$_4$ Laser

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Abstract: We report over 20 W, 6 ps, 170 MHz, passive mode-locking of a Nd:YVO$_4$ laser using $\chi^{(2)}$-lens formation in a LBO frequency doubling crystal. The laser is pumped at 808 nm with optical efficiency of 38%.
OCIS codes: (140.3530) Lasers, neodymium; (140.4050) Mode-locked lasers

Picosecond pulses with duration <10 ps have been generated by diode-pumped solid-state lasers using different configurations and mode-locking techniques for more than fifteen years. However, the average output power in most of the systems is limited and additional amplification is required in order to meet the requirements for material processing and precise micromachining. In this context picosecond lasers with high average power (>10 W) are of particular interest for a variety of scientific and industrial applications.

Among laser materials, neodymium-doped vanadate Nd:YVO$_4$ has been the most extensively studied and widely used in diode-pumped high average power continuous-wave (CW) and mode-locked lasers for the past two decades. Nd:YVO$_4$ has large emission cross-section and polarized emission attributed to its natural birefringence as well as capacity for being pumped efficiently by laser diodes. The major drawback which limits the output power of Nd:YVO$_4$ lasers is the poorer thermo-mechanical properties of the crystal in comparison with that of Nd:YAG.

Typically, multi-Watt operation of picosecond Nd:YVO$_4$ lasers has been demonstrated mainly using a mode-locking technique based on semiconductor saturable absorber mirrors (SESAMs) [1]. Although SESAMs are well established devices for lasers emitting around 1 µm, their residual absorption is an intrinsic drawback that limits the power scaling capabilities. An alternative approach for up-scaling the average power of picosecond Nd:YVO$_4$ lasers is a mode-locking technique based on $\chi^{(2)}$-lens formation in a nonlinear crystal for second harmonic generation (SHG). The higher damage threshold of SHG crystals and their lower residual absorption in comparison with SESAMs enable operation at high average power which value is limited by the maximum one achievable in CW TEM$_{00}$ output [2]. Although the intra-cavity SHG can be used in other mode-locking techniques [3, 4], $\chi^{(2)}$-lens mode-locking is advantageous to high power operation because it requires SHG crystals to operate far away from perfect phase-matching condition [2,4].

In this work we report $\chi^{(2)}$-lens mode-locking of a Nd:YVO$_4$ laser using a LBO SHG crystal. The laser generates 6 ps transform-limited pulses at 170 MHz with output power of 20.1 W. To our knowledge, it is the maximum output power achieved by a $\chi^{(2)}$-lens mode-locked laser.

The design of the mode-locked laser is based on a 810 mm long linear cavity (fig. 1). The active element is a 14 mm long 0.25 at. % doped *a*-cut Nd:YVO$_4$ crystal with an aperture of 3 × 3 mm^2. Both sides of the crystal are antireflection coated for the laser and pump wavelengths. It is mounted in a copper holder maintained at temperature of 25°C by circulating water. The active element is end pumped by two 808 nm, 400 µm, 0.22 NA fiber-coupled diode laser systems. The focusing systems F1-F2 ensure pump waist diameter of 600 µm in the active element.

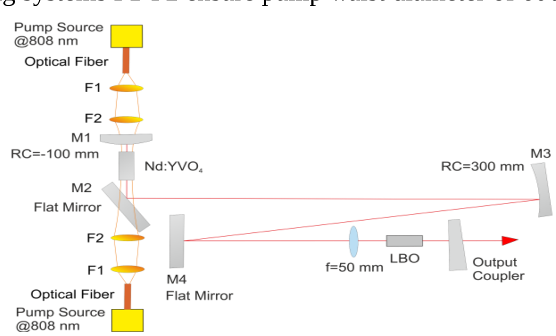

Fig. 1 Laser cavity layout. M1, M2, M3, M4: highly reflective at 1064 nm; M1: highly transmitting at 808 nm; output coupler: transmitting 50% at 1064 nm.

The optical cavity ensures single transverse mode operation by overlapping the cavity mode size with the pump waist in the active element. In order to compensate the influence of the thermal lens in the active element (f_{th}<100 mm) over the cavity transverse mode, a convex end mirror M1 with radius of curvature (RC) -100 mm is chosen. The SHG crystal is a 25-mm long lithium triborate LiB_3O_5 (LBO) with an aperture of 3×3 mm^2 cut at θ=90° and φ=11.2° in the *x*-y plane for type-I oo-e phase-matching. Its both faces are AR-coated for the fundamental and the second harmonic wavelengths. The phase matching conditions are controlled by adjusting the LBO orientation. The output coupler is a flat mirror with transmission of 50% at 1064 nm, optimized for maximum output power.

In order to obtain mode-locking, the LBO SHG crystal is detuned from perfect phase-matching condition and the position of the output coupler is optimized. The output power in self-starting mode-locking operation is 20.1 W at absorbed pump power of 53 W, corresponding to optical efficiency of 38% (fig. 2 (a)). The mode-locking operation is observed at the region of input–output characteristics close to the maximum achievable output power in CW operation, when the slope efficiency becomes negative. In this region increasing of the thermal lens power leads to strong change of the cavity mode size in the position of the active element. Therefore the efficiency drops due to non-optimum overlap with the pump waist. This non-optimum overlap however is compensated in mode-locking operation by the $\chi^{(2)}$-lens formation in the LBO nonlinear crystal. Hence, the output power of the $\chi^{(2)}$-lens mode-locked laser is limited only by the maximum output power achievable in CW TEM_{00} operation.

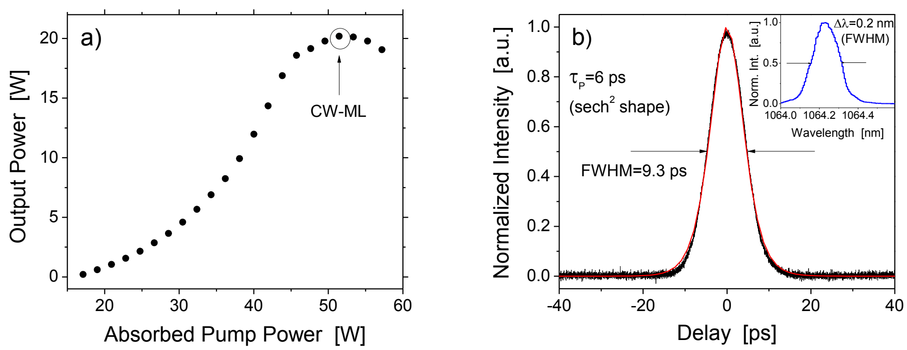

Fig. 2 (a) Input–output characteristics of the $Nd:YVO_4$ laser (the region of mode-locked operation is marked by the circle); (b) autocorrelation curve (black), fit assuming $sech^2$ pulse shape (red) and optical spectrum (inset).

The pulse duration is 6 ps assuming $sech^2$ pulse shape calculated from the measured autocorrelation curve (fig. 2 (b)). The measured optical spectrum has a FWHM of 0.2 nm at central wavelength of 1064 nm (fig. 2 (b) inset). The time-bandwidth product is 0.32, corresponding to transform limited pulses for $sech^2$ pulse shape. The pulse repetition rate is 170 MHz.

In conclusion, we demonstrate a high average power $Nd:YVO_4$ laser mode-locked using $\chi^{(2)}$-lens formation in a LBO nonlinear crystal. We achieve self-starting operation with pulse duration of 6 ps at repetition rate of 170 MHz. The output power of 20.1 W is the highest value for a $\chi^{(2)}$-lens mode-locked laser to the best of our knowledge.

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References

1. L. McDaonagh, R. Wallenstein, and A. Nebel, "111 W, 110 MHz repetition rate, passively mode-locked TEM_{00} $Nd:YVO_4$ master oscillator power amplifier pumped at 888 nm", Opt. Letters **32**, 1259–1261 (2007).
2. H. Iliev, I. Buchvarov, S. Kurimura, and V. Petrov, "High-power picoseconds $Nd:GdVO_4$ laser mode locked by SHG in periodically poled stoichiometric lithium tantalate", Opt. Letters **35**, 1016–1018 (2010).
3. G. Thomas, T. Omatsu, and M. Damzen, "High-power neodymium-doped mixed vanadate bounce geometry laser mode locked with nonlinear mirror", Appl. Physics B – Lasers and Optics **108**, 125–128 (2012).
4. S. Saltiel, I. Buchvarov , K. Koynov "Control of laser light parameters by chi((2)):chi((2)) nonlinear optical devices," Advanced Photonics with Second-Order Optically Nonlinear Processes, vol. 61, pp. 89-112, 1998.