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1.34-μm Nd:YVO_4 Laser Mode-Locking by $\chi^{(2)}$-Lensing in Periodically Poled Stoichiometric Lithium Tantalate

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Abstract: Self-starting $\chi^{(2)}$–lens mode-locking of a 1.34-μm Nd:YVO_4 laser using second harmonic generation in PPMgSLT is demonstrated. A train of 5.9 ps pulses with ~1 W average output power at 102 MHz is achieved.

OCIS codes: (140.3530) Lasers, neodymium; (140.4050) Mode-locked lasers; (140.3480) Lasers, diode-pumped.

1. Introduction

In the last decade, there is growing interest in passive mode-locking of Nd-lasers operating on the $^4F_{3/2} \rightarrow {}^4I_{13/2}$ transition around 1.34 μm. Such laser sources could be useful for a number of potential applications, in semiconductor industry, telecommunications and medicine. Although the passive mode-locking of Nd-lasers based on semiconductor saturable absorber mirrors (SESAM) is widely used technique in the spectral region around 1 μm, on the $^4F_{3/2} \rightarrow {}^4I_{13/2}$ transition it is problematic because of difficulties in the fabrication process and damage resistivity. With increasing the operating wavelength a lot of technical and engineering problems occur, generally limiting the optical quality of the SESAMs (high residual absorption and nonsaturable losses). Moreover each SESAM is designed and fabricated to operate only at specific wavelength. The first demonstration of passive mode-locking of a Nd-laser operating at 1.3 μm was in 1996 [1]. In this work stable CW mode-locked operation of Nd:YVO_4 and Nd:YLF lasers was reported, with moderate output power of 50 and 130 mW, respectively. Pulse duration of 4.6 ps in the case of Nd:YVO_4 and 5.7 ps in the case of Nd:YLF laser was achieved. Subsequently, few other groups demonstrated mode-locked operation of 1.34 μm Nd-lasers by different types of SESAMs, generally trying to improve their optical quality in order to achieve higher output power and long term stability of the system. The best results in terms of output power (1.05 W) were demonstrated only recently [2], with AlGaInAs based SESAM, with a pulse duration of 26.4 ps.

In this work we investigate an alternative mode-locking approach based on second order nonlinearity inside the laser cavity which utilizes negative $\chi^{(2)}$-lens formation in a SHG crystal assisted by nonlinear reflection of the so-called Frequency Doubling Nonlinear Mirror (FDNLM), an approach generally free of spectral limitation, allowing easier power scaling to the multi-watt level. This approach has been previously used for mode-locking of Nd-lasers emitting at 1.06 μm [3,4]. Here we demonstrate stable, CW mode-locking of an Nd:YVO_4 laser operating around 1.34 μm with average output power of ~1 W, comparable with the best results [2] and pulses as short as 5.9 ps, more than 4 times shorter than in [2] and comparable with the shortest durations demonstrated in [1].

2. Experimental set-up

The laser cavity is schematically shown in Fig. 1. The active element (AE) was a 9 mm long, *a*-cut, 1.5°-wedged Nd:YVO_4 crystal with 0.25 at. % doping. The end faces were antireflection (AR) coated for minimum losses at the laser wavelength. The laser crystal was mounted in a Cu holder whose temperature was stabilized at 25°C by circulating water. The Nd:YVO_4 laser was longitudinally pumped by the unpolarized radiation of a 50-W 808 nm laser diode bar coupled into a 400 μm optical fiber (NA=0.22). The output beam from the optical fiber was focused by a 1:1 reimaging unit and delivered onto the Nd:YVO_4 crystal with a spot radius of ~200 μm through the highly reflecting end mirror M which transmits the pump radiation (Fig. 1).

The nonlinear crystal (NLC) is PPMgSLT with 1 mol % doping and a thickness of 1 mm along the z-axis. The samples prepared were 5 mm wide and 10 mm long. Both 5×1 mm^2 faces were AR-coated for the fundamental and the second harmonic wavelengths. The period (14.7 μm) was designed for phase-matched SHG at 1342 nm and a temperature of 188°C. The nonlinear crystal was mounted in an oven with high precision (±0.1°C) temperature control.

The radius of curvature (RC) of the folding mirror M2 (RC=504 mm), the focal length of the AR-coated intracavity lens (80 mm), and the separations given in Fig. 1 were chosen to ensure beam radii of ~80 μm in the nonlinear crystal and ~200 μm in the position of the active element. Plane mirrors with different characteristics were employed as output couplers (OC).

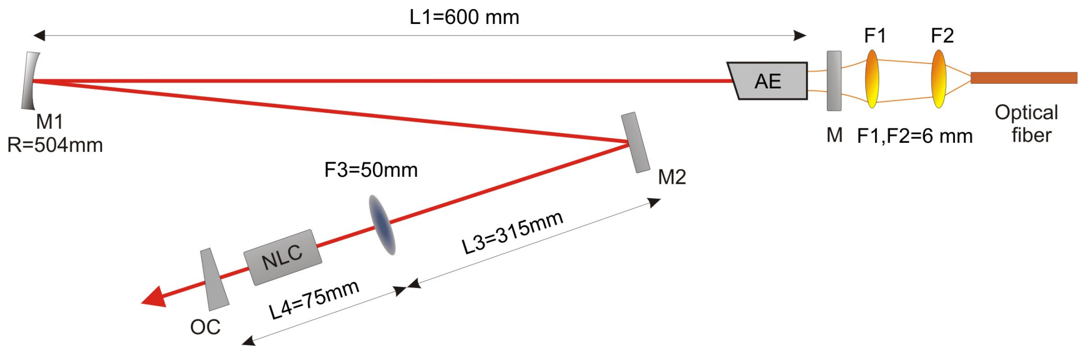

Fig. 1. Schematic of the laser cavity: F1, F2 - pump objective, AE - $Nd:YVO_4$ active element, M, M1, M2 - highly reflecting mirrors, F3 - focusing lens, NLC – PPMgSLT nonlinear crystal, OC - output coupler. The physical cavity length amounts to 1.23 m.

3. Experimental results and discussion

The measured normalized second-harmonic power versus temperature (Fig. 2) shows maximum conversion efficiency at 188.5°±0.5°C (holder temperature), and a FWHM of 4.6°C for the phase-matching curve. Stable passive mode-locking operation was observed, however, at higher temperatures, at 194.5±1°C for all output couplers used. This corresponds to SHG far from perfect phase matching in the first maximum of the temperature-dependent phase-matching curve. The phase-mismatched SHG introduces $\chi^{(2)}$ – nonlinear lens formation in the laser resonator. Mode-locking has been observed only on the right wing of phase-matching curve which corresponds to a negative $\chi^{(2}$-lens formation.

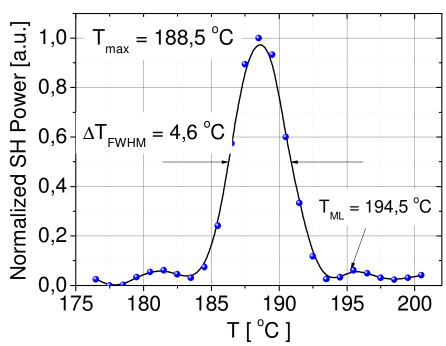

Fig. 2. (a) Normalized intracavity second-harmonic power divided by the squared fundamental power in the cw regime measured as a function of the crystal holder temperature

Mode-locked operation was studied with two different output couplers with high reflection at the second harmonic and transmission of 5% and 10%, respectively, at the fundamental wavelength. The highest output power and efficiency where achieved with output coupler with 10% transmittance at the laser wavelength and high reflectivity at the second harmonic. Figure 3(a) shows the measured average output power versus the pump power. The laser threshold is 3.7 W, while passive mode-locking is observed in the pump power region between 15.4 and 16.6 W. The maximum output power in the mode-locked regime is ~ 1 W and was obtained for a pump level of 15.4 W. Higher output power (up to 1.5 W) was generated with increasing pump power up to ~19 W. Although, the laser efficiency starts to decrease again a second region of stable mode locking operation was not observed, prevented by the multimode operation of the laser at higher pump level. Figure 3(b) shows the measured autocorrelation trace for this case which leads to an estimation of 6.9 ps for the pulse duration at FWHM (assuming $sech^2$ pulse shape).

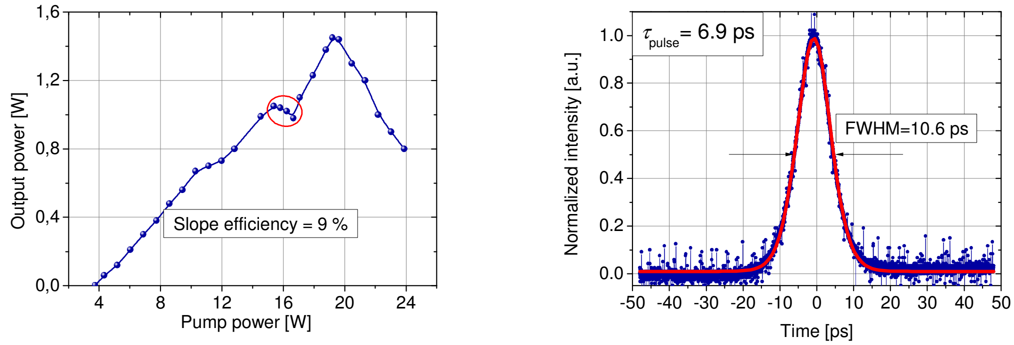

Fig. 3. (a) Input – output characteristics of the Nd:YVO_4 laser. Mode-locking region is marked by an oval, (b) autocorrelation trace and $sech^2$ fit with 10% OC.

However, slightly shorter pulses (5.9 ps) where achieved by replacing the 10% output coupler with one having 5% transmittance at the fundamental and high reflection at second harmonic (see Fig. 4(b)). The shorter pulse duration obtained in this case is a consequence of the higher intracavity intensity, i.e. stronger $\chi^{(2)}$ – nonlinear lens effect. However, the increased reflection of the output coupler also results in approximately 30% decrease in the average output power in mode-locking operation (Fig. 4(a)).

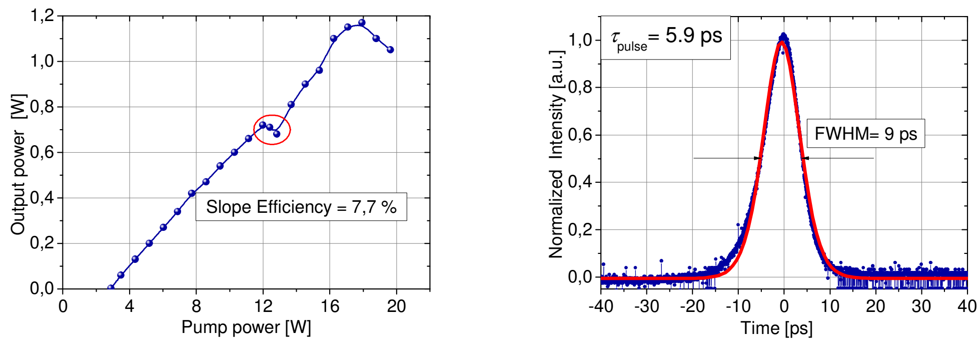

Fig. 4. (a) Input – output characteristics of the Nd:YVO_4 laser and (b) autocorrelation trace with $sech^2$ fit for a 5% OC. Mode-locking region is marked by an ovals

4. Conclusion

In conclusion, we have demonstrated the first realization of a stable and self-starting 1.3 µm mode-locking using $\chi^{(2)}$ negative-lens formation in PPMgSLT nonlinear crystal. This mode-locking is possible at pump power levels corresponding to the negative slope region of the input-output characteristics of the laser in continuous-wave (CW) regime. The output power of the order of 1 W is limited by the achievable output power in the stable TEM_{00} mode of operation in CW regime and further scaling seems possible by redesigning the laser cavity.

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