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Nd:YVO$_4$ Laser Mode-Locking at 1.34 µm by Negative $\chi^{(2)}$-Lens Formation in an Intracavity BIBO Crystal

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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 BiB$_3$O$_6$ is demonstrated. Pulses as short as 3.7 ps and average powers reaching 1.3 W at 120 MHz are achieved.

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

Passive mode-locking of Nd-lasers operating on the $^4F_{3/2} \rightarrow {}^4I_{13/2}$ transition around 1.34 µm is interesting for applications in semiconductor industry, telecommunications and medicine. Semiconductor saturable absorber mirrors (SESAMs), widely used for passive mode-locking around 1 µm, are more difficult to fabricate for the 1.3 µm spectral range and show relatively high residual absorption and nonsaturable losses. The first SESAM mode-locked Nd-lasers operating near 1.3 µm produced moderate output powers of 50 mW (Nd:YVO$_4$) and 130 mW (Nd:YLF) [1] with pulse durations of 4.6 ps and 5.7 ps, respectively. Subsequent reports on mode-locked 1.34 µm Nd-lasers by different types of SESAMs in general aimed at increasing the output power and improving the long term stability. The best results in terms of average output power (1.05 W) were demonstrated only recently [2], with AlGaInAs based SESAM, but the pulse duration from this Nd:YVO$_4$ laser amounted to 26.4 ps.

Negative $\chi^{(2)}$-lens formation in an intracavity SHG crystal assisted by nonlinear reflection of the so-called Frequency Doubling Nonlinear Mirror (FDNLM) is an alternative CW passive mode-locking technique, allowing easier power scaling because it is not based on absorption. This approach is generally free of spectral limitations and has been previously used for mode-locking of Nd-lasers emitting at 1.06 µm [3,4]. Here, we apply it for CW mode-locking of a Nd:YVO$_4$ laser operating around 1.34 µm with a BiB$_3$O$_6$ (BIBO) intracavity SHG crystal, achieving simultaneously high average output power (~1 W) and short (3.7 ps) pulse duration.

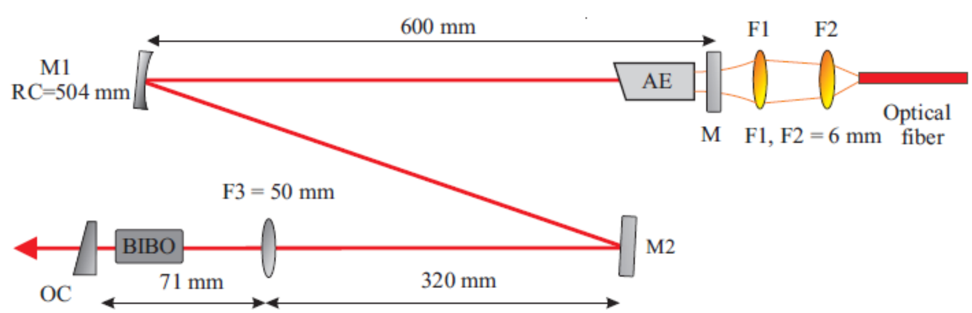

Fig. 1. Schematic of the laser cavity: F1, F2 - pump objective, AE - Nd:YVO$_4$ active element, M, M1, M2 - highly reflecting mirrors, F3 - focusing lens, OC - output coupler. The physical cavity length amounts to 1.23 m.

The laser cavity is schematically shown in Fig. 1. The active element (AE) is a 9 mm long, AR-coated, *a*-cut, 1.5°-wedged Nd:YVO$_4$ crystal with 0.25 at. % doping, maintained at a temperature of 20°C. The laser was longitudinally pumped by the unpolarized radiation of an 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 through the plane end mirror M which transmits the pump radiation. The 7-mm long BIBO with an aperture of 3×3 mm^2 was cut at θ=9° and φ=0° in the x-z plane for type-I oo-e phase-matching. It was AR-coated for the fundamental and the second harmonic wavelengths. Phase-matching was adjusted by the critical angle θ, while its temperature was maintained at 25°C. The Nd:YVO$_4$ laser operates in π-polarization

Phase-mismatched SHG in BIBO introduces nonlinear $\chi^{(2)}$-lens in the laser resonator. Consequently, mode-locked operation was obtained only when tilting the nonlinear crystal in one direction far from perfect phase-matching, corresponding to negative nonlinear lens formation. Mode-locking was studied with two output couplers (OC), transmitting 5% and 10% at the fundamental, both highly reflective at the second harmonic. Figure 2 shows

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the measured average output power versus the incident pump power with the 5% OC. The laser threshold was at an incident pump power of 2.7 W and mode-locking occurred between 12 and 13.2 W. The maximum output power in mode-locked operation reached 0.9 W, at a pump level of 12.5 W. Higher average powers (~1.2 W) were generated with increasing pump power (up to ~17 W) but no second region of stable mode-locking operation was observed because of multimode operation.

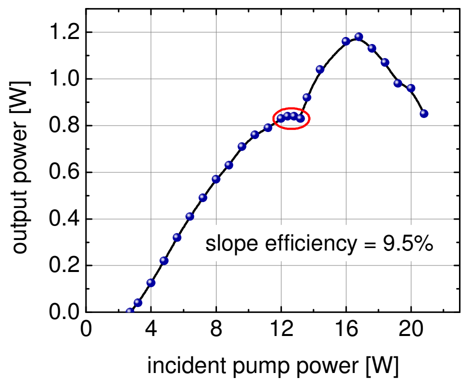

Fig. 2. Laser ouput power vs. diode pump power in CW mode of operation with 5% OC. The mode-locking range is marked by the red oval.

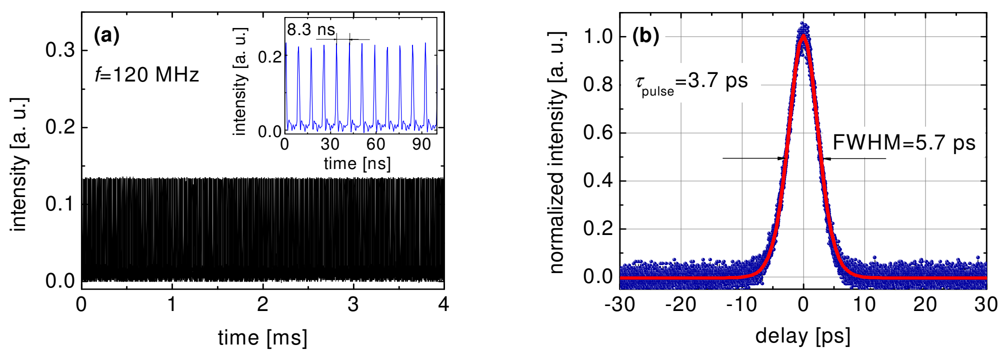

Fig. 3. (a) Oscilloscope trace of the mode-locked pulse train recorded by a fast photodiode. The inset shows the individual pulses. (b) Intensity autocorrelation function measured by non-collinear SHG in $LiIO_3$: data (blue curve) and $sech^2$-pulse fit (red curve).

A fast photodiode oscilloscope trace of the output of the mode-locked laser, over a 4 ms time scale (longer than the time scale for Q-switching and relaxation oscillations) is shown in Fig. 3a together with the individual pulses. The pulse amplitude peak to peak instability does not exceed 1%. The FWHM of the measured autocorrelation trace, 5.7 ps (Fig. 3b), corresponds to a pulse duration (FWHM) of 3.7 ps assuming $sech^2$ pulse shape, the shortest achieved so far for this transition of Nd-lasers. At the cost of slightly lengthened pulse duration (5.3 ps) which is related to the lower intracavity intensity and weaker nonlinear lens effect, we were also able to achieve the highest average power in the steady state mode-locked regime, 1.3 W, using the 10% OC.

In conclusion, we achieved stable and self-starting 1.34 µm mode-locked laser operation of Nd:YVO_4 using $\chi^{(2)}$ - negative lens formation in a BIBO intracavity SHG crystal. Such mode-locking is possible at pump power levels corresponding to the first negative slope region of the input-output power dependence in CW operation. The average output power in the mode-locked regime is limited by the power achievable in stable TEM_{00} mode in CW regime and further scaling should be possible by redesigning the cavity taking into account the thermal lens formation.

Projects DO/02/134, DNTS 02/2 funded by the Bulgarian ministry of science and education are acknowledged.

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