Passively mode-locked 914-nm Nd:YVO$_4$ laser

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We demonstrate what is to our knowledge the first mode-locked Nd:YVO$_4$ laser operating on the $^4F_{3/2}-^4I_{9/2}$ transition at 914 nm. Using a semiconductor saturable-absorber mirror for passive mode locking, we have obtained 3-ps pulses at a repetition rate of 233.8 MHz. The laser is based on a standard delta cavity and is pumped by a Ti:sapphire laser. We obtained an average output power of 42 mW through one mirror and an accumulated output power of ≈150 mW (through all cavity mirrors) at a pump power of 1.4 W. © 2005 Optical Society of America

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In the past few years the $^4F_{3/2}-^4I_{9/2}$ transition near 900 nm of the neodymium ion has attracted a lot of attention mainly for generation of visible light in the blue spectral range by means of frequency doubling. Most publications have concentrated on continuous-wave operation, demonstrating as much as 5.35 W of output power from a Nd:YAG laser[1] and 2 W at the doubled frequency from a Nd:YVO$_4$ thin-disk laser.[2] Using an external-cavity semiconductor laser and a Nd-doped fiber amplifier produced as much as 11 W of output power at 938 nm.[3] A Nd-doped fiber amplified passively Q-switched Nd:YVO$_4$ laser has been demonstrated to produce 10.4 W of output power at 914 nm, which was used to generate as much as 3 W in the blue.[4] Nd:YVO$_4$ is preferable for laser display applications, as the second harmonic at 457 nm is in the deep-blue region. Mode-locked operation can take advantage of the high pulse peak power for efficient frequency doubling and was demonstrated by Hofer *et al.* in a Nd-doped fiber laser[5] and by Kellner *et al.* with a Nd:YAlO$_3$ bulk laser.[6] For data transmission applications, $^4F_{3/2}-^4I_{9/2}$ Nd lasers have the advantage of a shorter wavelength, which is more easily detectable with silicon photodiodes, than, e.g., 1064 nm.

Operating Nd:YVO$_4$ at 914 nm is somewhat difficult, mainly because of the quasi-three-level nature of the laser system, as discussed in Refs. 7 and 8. The lower laser level is only 433 cm^{-1} above the ground state, which results in a high lower-state population of 5% at room temperature. In addition, the laser cross section is only 4×10^{-20} cm^2 at 914 nm,[9] compared with 114×10^{-20} cm^2 at 1064 nm.[10] This relatively small cross section leads to a high lasing threshold that has to be minimized by use of a high pump intensity and an optimized crystal length. To prevent lasing at 1064 nm, high cavity losses at 1064 nm have to be introduced. For passive mode locking we use a semiconductor saturable-absorber mirror (SESAM).[11–13] The lower laser cross section at 914 nm, compared to 1064 nm, has the consequence that a higher intracavity power is required for stable mode locking without Q-switching instabilities.[14] At least this is so if an inverse saturable-absorption effect in the SESAM or elsewhere in the cavity cannot be used to suppress these instabilities.[15,16]

We use a standard delta cavity, as shown in Fig. 1. Mode matching with the small laser mode size in the gain medium is achieved by pumping longitudinally with good beam quality. We use a Ti:sapphire pump laser, which provides as much as 1.4 W of output power with an M^2 value of 1.1 and 1.6 in the sagittal and tangential directions, respectively. The pump power incident upon the crystal is 10% lower owing to losses in the lens and in mirror M$_2$. The pump spot radius is 23 μm (sagittal) × 29 μm (tangential). The polarization of the pump light as well as the optical axis of the Nd:YVO$_4$ crystal is in the tangential plane. The Brewster-angled crystal, made by ITI Electro-Optics Corporation, is a cut, 1 mm long, and 0.5% neodymium doped. The length was chosen to be

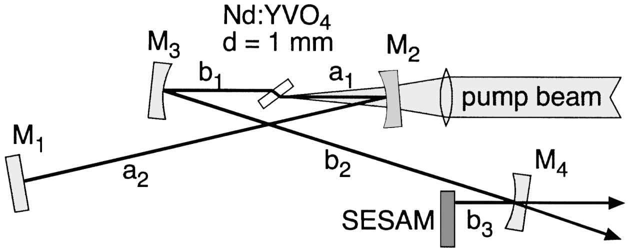

Fig. 1. Schematic of the Ti:sapphire laser pumped cavity. Arm lengths are as follows: a$_2$, 176 mm; a$_1$, 39 mm; b$_1$, 57 mm; b$_2$, 331 mm; b$_3$, 35 mm. Radii of curvature of mirrors: M$_2$, 75 mm; M$_3$, 100 mm; M$_4$, 75 mm; d, thickness of the laser crystal.

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close to the optimum length for a low lasing threshold as discussed in Refs. 7 and 8. Nd:YVO$_4$ has a $^4F_{3/2}$ lifetime of 90 μs, and the emission cross section of the $^4F_{3/2}$–$^4I_{9/2}$ transition is $\sim 4 \times 10^{-20}$ cm^2.[9] The radii of the laser mode in the gain medium are 33 μm × 70 μm by design. To suppress parasitic oscillation at 1064 nm, most of the cavity mirrors have high transmission at this wavelength, introducing a total power loss of 27 dB (99.8%) per round trip. This is much larger than the round-trip loss of ~2.5% at 914 nm. Passive mode locking was achieved by introduction of a SESAM as one of the end mirrors. The spot radii are designed to be 49 and 57 μm in the sagittal and tangential directions, respectively. The SESAM has a modulation depth (maximum reflectivity change) of (0.75 ± 0.13)%. Its saturation fluence is (84 ± 13) μJ/cm^2, and the recovery time is 4.3 ps. For mode-locked operation we had to replace output-coupling mirror M$_1$ with a highly reflecting mirror to increase the intracavity power. Otherwise the intracavity power would have been too low to overcome Q-switched mode locking because most of the coatings of our laser mirrors had been designed for operation near 808 nm and therefore introduced a considerable amount of parasitic loss (in total, 1.5%) at 914 nm. The strongest output beam now emerges from mirror M$_4$ with $T_{\mathrm{oc}} = 0.4\%$, and the parasitic loss introduced by the cavity mirrors is 1.1%.

We obtained as much as 42 mW of average output power (in one beam through mirror M$_4$) at a pump power of 1.4 W (1.25-W power incident upon the crystal), which corresponds to a slope efficiency of 4.9% and a lasing threshold of 0.49 W of pump power (Fig. 2). With the total 914-nm transmission from a single output-coupling mirror (and otherwise highly reflecting mirrors) we would expect an output power of ≈150 mW. The beam quality was measured, and we found M^2 values of 1.2 and 1.3 in the sagittal and tangential directions, respectively.

The laser is mode locked with a repetition rate of 233.8 MHz without Q-switching instability. Q switching would show up as side peaks in the radio-frequency spectrum (Fig. 3) at a difference frequency of ~100 kHz. The spectrum also shows no beating of transverse modes (Fig. 3 inset). From the optical spectrum (Fig. 4) we can see that the laser is indeed operating on the $^4F_{3/2}$–$^4I_{9/2}$ transition and that the 1064-nm line is strongly suppressed. The peak emission wavelength is 914 nm (Fig. 5). The Gaussian fit to the spectrum has a full width at half-maximum of 1.5 nm. We have always observed two dips in the spectrum, at 913.5 and 914 nm. This spectral region contains several water-vapor absorption lines that are most likely responsible for the notable deformation of the optical spectrum. The autocorrelation trace (Fig. 6) shows a clean Gaussian pulse with a full width at half-maximum of 3 ps; this corresponds to a time–bandwidth product of 1.6, which is 3.6 times the transform limit for Gaussian pulses. We attribute the high time–bandwidth product to the high group-delay dispersion of ≈700 fs^2 per round trip introduced by the laser crystal. We have tried to compensate for the group-delay dispersion with a prism pair in (elongated) arm a$_2$ (Fig. 1) of the cavity. However, the additional losses introduced by the

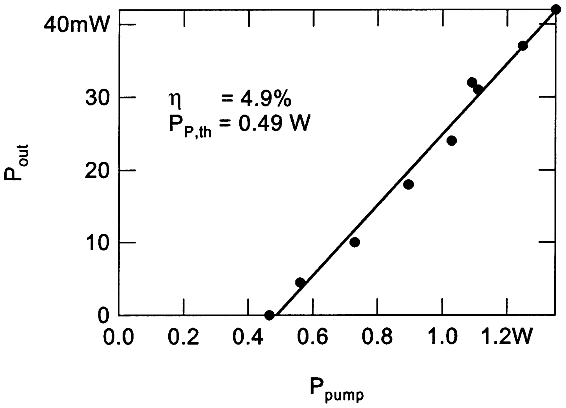

Fig. 2. Output power (in one of the beams through mirror M$_4$) as function of pump power. The pump power incident upon the crystal is 10% less owing to losses in the lens and the pump mirror.

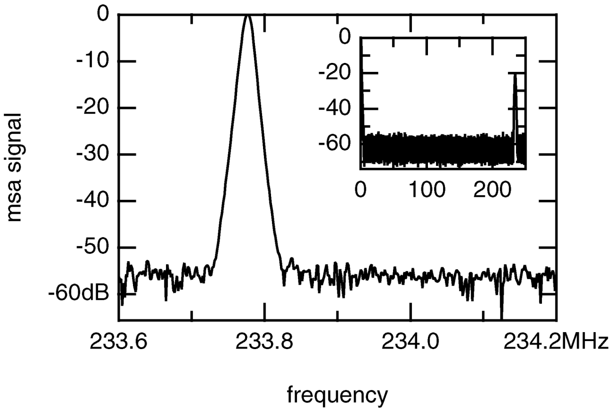

Fig. 3. The radio-frequency spectrum of the output power shows a repetition rate of 233.77 MHz. Q-switched mode locking would cause side peaks at a difference frequency of ≈100 kHz. Resolution bandwidth, 10 kHz. The spectrum is free of beat notes that could be caused by multiple transverse beam modes (inset). Resolution bandwidth, 1 MHz.

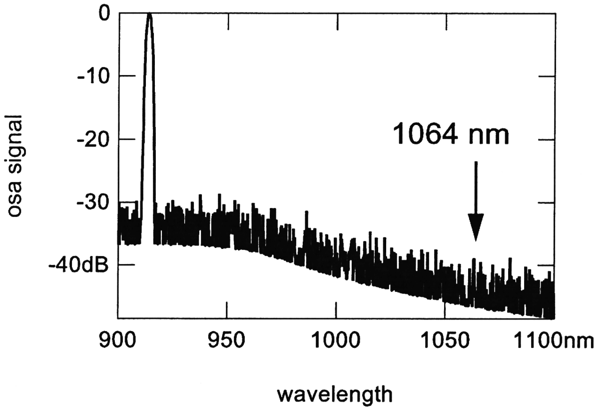

Fig. 4. The laser is operating at 914 nm while the 1064-nm line is strongly suppressed. The resolution bandwidth of this spectrum is 2 nm. The noise floor is given by the optical spectrum analyzer (osa), not by amplified stimulated emission.

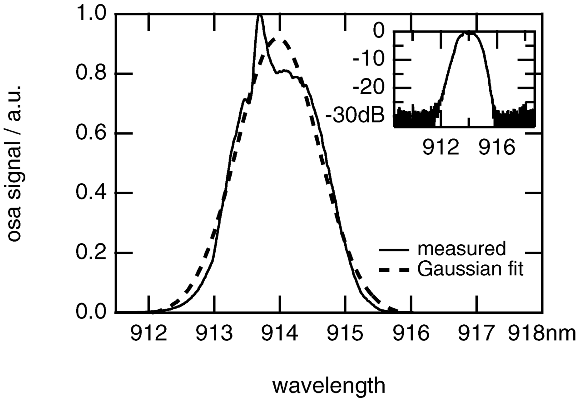

Fig. 5. The optical spectrum is centered at 914 nm and has a full width at half-maximum of 1.5 nm (Gaussian fit); osa, optical spectrum analyzer. The resolution of the measurement is 0.1 nm. Inset, optical spectrum on a logarithmic scale (resolution, 0.1 nm).

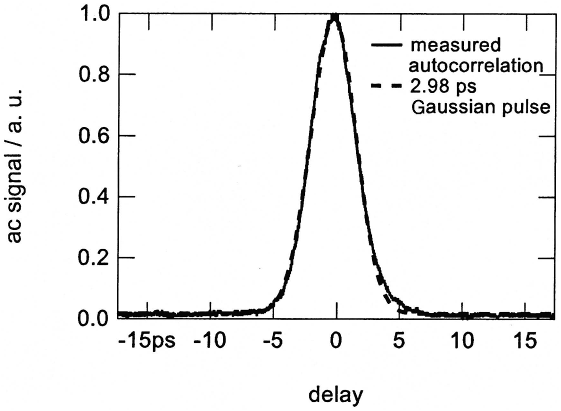

Fig. 6. Measured autocorrelation trace.

prism pair have been too high, preventing the laser from reaching lasing threshold. It may be possible to prevent these losses by dispersion compensation with chirped mirrors; otherwise the other parasitic losses in the cavity will have to be reduced.

On reducing the pump power we found that mode locking is stable down to an output power of 31 mW, where the laser switches to continuous-wave operation. We observed no Q-switched mode locking between these two regimes of operation. The output power at which continuous-wave mode locking becomes unstable (the so-called QML threshold[14]) would have been expected to be 95 mW, but the discrepancy can be explained as being due to significant uncertainties in the mode radii, the output coupler's transmission, and the SESAM parameters.

In conclusion, we have presented what is to our knowledge the first mode-locked Nd:YVO$_4$ laser operating on the $^4F_{3/2}-^4I_{9/2}$ transition at 914 nm. We obtained 42 mW of average output power in 3-ps Gaussian pulses at a repetition rate of 233.8 MHz. The width of the optical spectrum was 1.5 nm, corresponding to 3.6 times the width of a time–bandwidth limited pulse. We believe that subpicosecond pulses could be achieved by use of dispersion compensation, preferably achieved with chirped mirrors. With the total 914-nm transmission from a single output-coupling mirror and otherwise highly reflecting mirrors (instead of mirrors with transmissions of a few tenths of a percent each) we would expect an output power of ≈150 mW.

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