Nd:YLF laser at 1.3μm for calcium optical clocks and precision spectroscopy of hydrogenic systems

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We describe single-frequency operation of a diode-pumped Nd:YLF laser in the range 1311.9–1317.2 nm. It can be used for the interrogation of the clock transition in calcium (1314.0 nm) or spectroscopy in hydrogen and metastable singly ionized helium (1312.6 nm). By using a twisted-mode cavity, we have obtained output powers of 830 and 970 mW at 1312.6 and 1314.0 nm, respectively, in a single longitudinal mode. © 2003 Optical Society of America

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1. Introduction

There is currently great interest in the development of optical clocks with the ultimate aim of redefining the SI second. The advantage of optical clocks compared with their microwave counterparts stems from the higher-quality factor of the resonance. For narrow optical transitions, this can reach 10^{15} (compared with 10^{10} for the best Cs fountain clock).[1] Because of its narrow linewidth (400 Hz) and insensitivity to first order to electric and magnetic fields, the calcium atom is one such candidate. The intercombination line in calcium $4s^2\ ^1S_0\ (m = 0) \rightarrow 4s4p\ ^3P_1\ (m = 0)$ at $\lambda = 657.0$ nm[2] has been studied by several groups and its frequency already measured with a femtosecond optical comb generator.[3,4] In the field of ultrahigh-resolution spectroscopy, lasers are essential tools for probing fundamental theories. Hydrogenic systems are studied for tests of quantum electrodynamics and determination of fundamental constants. Doppler free spectroscopy of the He^+ $2S$–$3S$ resonance (excited by two photons at 328.1 nm) should provide a precise measurement of the $2S$ Lamb shift.[5–7] A measurement of the $2S$–$3S$ interval in hydrogen (two photons at 1312.6 nm) would help to better determine the Rydberg constant and serve as a consistency check of values for the $1S$–$2S$ (Ref. 8) and $1S$–$3S$ intervals[9] in the same atom. Research on all these difficult projects has involved use of either tunable dye lasers or extended-cavity visible laser diodes. The former provide outputs of several hundred milliwatts but are expensive, notoriously capricious in their behavior, and require considerable adjustment and maintenance. The latter are more user-friendly but generally less powerful. We are developing diode-pumped solid-state lasers as an alternative to these sources. These are more robust and easier to use than dye lasers, and, even with easily designable cavities, their free-running instantaneous linewidths are considerably lower. Frequency stabilization to narrow their short-term jitter is thus facilitated. Moreover, they are more powerful than single-mode laser diodes.

For the projects described above, diode-pumped Nd-doped $YLiF_4$ (hereafter Nd:YLF) appears to be a good candidate because it has emission lines around 1313 and 1321 nm. Pioneering research on this crystal was performed by Fornasiero *et al.*[10] Figure 1, drawn from their paper, shows emission spectra for both π and σ polarized light. The gain is different according to whether the electric vector of the radiation is polarized parallel (π) or orthogonal (σ) to the *c* axis of the crystal. This fact allows one to favor one or the other of the emission bands. We have already demonstrated that a Nd:YLF laser can operate at single mode at 1322.6 nm, the second harmonic of which (661.3 nm) should be useful to interrogate the silver atom clock transition.[11,12] It can also emit at

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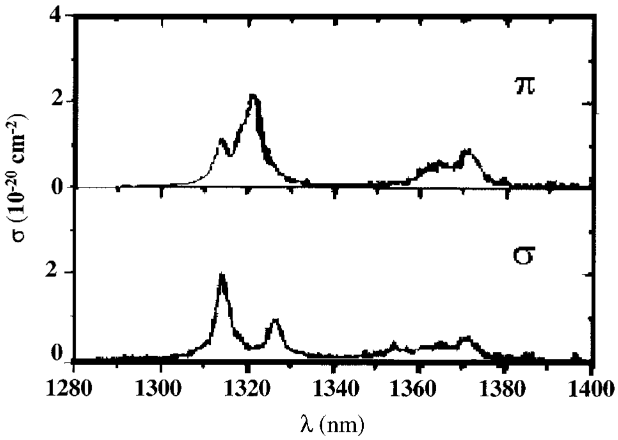

Fig. 1. Variation of the emission cross section of Nd:YLF around 1.3 μm from Ref. 10. (© Springer Verlag 1999, reproduced by permission of the authors). The dependence of the cross section on the laser polarization enables one to select either the band near 1313 nm (our case) or the band near 1322 nm.

1312.0 nm, which would be useful for sub-Doppler cooling of the silver atom on the D2 resonance line at 328 nm (second harmonic of 1312.0 nm).[13] In this paper we concentrate on the study of Nd:YLF laser emission in the range of 1311.9–1317.2 nm. Combined or not with nonlinear conversion stages, a Nd: YLF laser should be useful for spectroscopy of H (1312.6 nm), He^+ (1312.6 nm → 328.1 nm), and Ca (1314.0 nm → 657.0 nm).

2. Experimental Setup

As can be seen from Fig. 2, taken from the Internet pages of Poly-Scientific (Northrop Grumman Space Technology Synoptics),[14] Nd:YLF exhibits several absorption lines between 792 and 808 nm. For a pump polarization perpendicular to the *c* axis (our case), the largest absorption occurs at 797 nm, but powerful cw diodes at this wavelength are hard to come by. In our experiment, we pump the crystal at 806 nm using

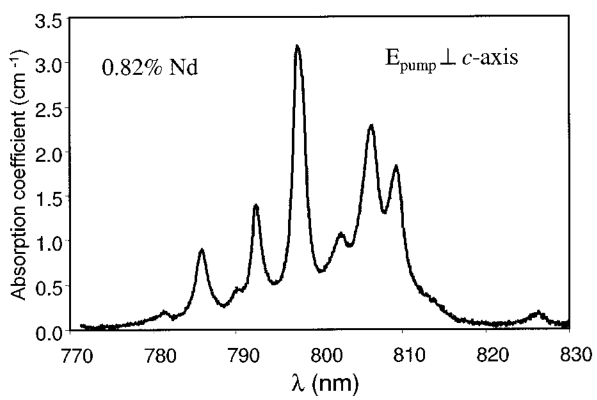

Fig. 2. Absorption spectra for Nd:YLF.[14] Data © Northrop Grumman Space Technology Synoptics, used by permission thereof. In our experiments we pumped on the 806-nm line because of the unavailability at the time of powerful diode lasers at 797 nm. Our own crystal was Nd doped at 0.7%, close to the value shown in the figure.

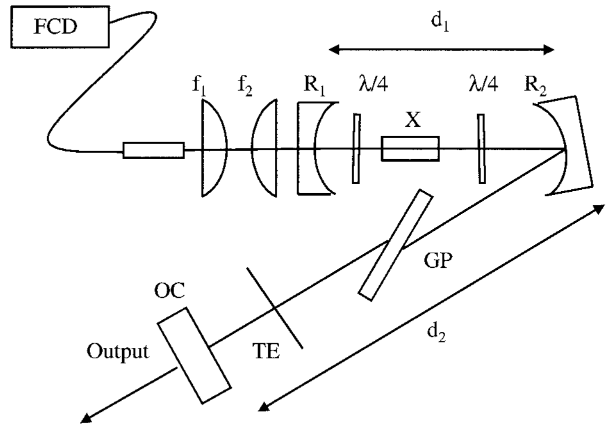

Fig. 3. Twisted-mode folded cavity for a diode-pumped *c*-axis Nd: YLF laser. X, *c*-axis Nd:YLF crystal; FCD, fiber-coupled diode; λ/4, low-order quarter-wave plates at 1.3 μm tilted at 10° to avoid interference effects; GP, glass plate inclined at Brewster's angle; TE, thin etalon; OC, output coupler ($T = 2\%$). Here $f_1 = 60$ mm, $f_2 = 80$ mm, $d_1 = 280$ mm, $d_2 = 300$ mm, $R_1 = 100$ mm, and $R_2 = 500$ mm. The Brewster plate assures linear polarization. The laser ran single mode even without the thin etalon used only for frequency tuning.

a beam-shaped 25-W diode laser (Limo Model HLU25F200) coupled into a multimode fiber with a numerical aperture of 0.22 and a core diameter of 200 μm. The output beam is collimated with a 60-mm doublet and focused in the crystal with an 80-mm doublet giving a beam waist of approximately 135 μm at 806 nm. The YLF rod (length 7 mm, section 3 × 3 mm^2) has a 1% Nd concentration and is mounted in a water-cooled cooper heat sink maintained at a temperature of 16 °C. The Nd:YLF oscillator is built as a folded three-mirror cavity (Fig. 3). The resonator consists of a spherical input mirror (radius of curvature $R_1 = 100$ mm), a tilted fold mirror ($R_2 = 500$ mm), and a plane output coupler. The laser cavity round-trip optical length of ≈580 mm corresponds to a longitudinal-mode spacing of 260 MHz. The input mirror has a dielectric coating to assure a maximum transmission at 806 nm (99%) and a maximum reflection at 1.3 μm (≥99.8%). The transmission of the output coupler is 2%, corresponding to the optimum of output power. The arms have lengths $d_1 = 280$ mm and $d_2 = 300$ mm. The laser is operated in a TEM_{00} mode with a beam waist of radius 140 μm in the crystal located at 30 mm from the input mirror. In the second arm of the resonator where the laser beam is parallel, we insert frequency-selective elements and a polarizer. Because of spatial hole burning, single longitudinal operation can be relatively difficult to obtain with linear cavities by use of a solid-state gain medium. To avoid this phenomenon, following the idea first demonstrated by Evtuhov and Siegman,[15] we chose to implement a twisted-mode cavity.[16,17] Here the spatial variation of the population inversion disappears and single-mode operation can easily be obtained because Nd:YLF has homogeneously broadened transition lines. In this configuration, two counterpropagating

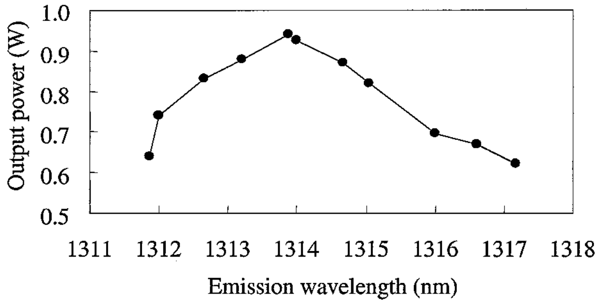

Fig. 4. Tuning curve of the twisted-mode cavity *c*-axis Nd:YLF laser around 1314.0 nm for an absorbed pump power of 12 W at 806 nm.

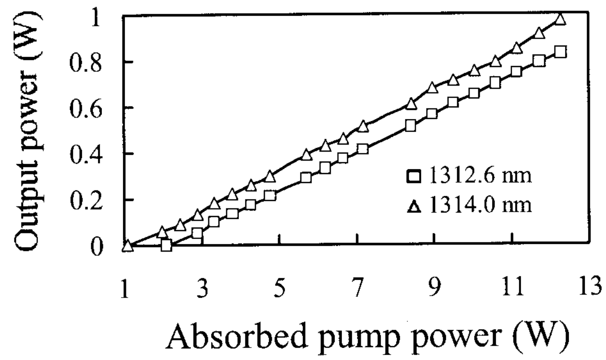

Fig. 5. Single-frequency output power of the twisted-mode cavity *c*-axis Nd:YLF laser at 1312.6 and 1314.0 nm as a function of absorbed pump power at 806 nm.

left-hand and right-hand circularly polarized waves should traverse the gain medium. Inside the rod, the sum of these two waves gives rise to a standing wave of uniform intensity that forces the laser to run single frequency. Because the crystal is birefringent, the rod must be cut in such a way that the *c* axis lies along the propagation axis of the laser beam. In this case only, Nd:YLF behaves as an isotropic optical medium that leaves the polarization states of the beams unmodified. The Nd:YLF crystal is placed between two low-order quarter-waves plates antireflection-coated for 1.3 μm. Because these quarter-wave plates are not antireflection-coated at 808 nm, they are tilted at 10° to prevent destructive feedback into the pump diode. Approximately 20% of the power pump was reflected by the first quarter-wave plate. A 0.3-mm-thick glass plate oriented at Brewster's angle served to polarize the laser beam. The wavelength, tuned with an intracavity etalon (uncoated Suprasil, thickness 0.1 mm), was monitored by a Burleigh WA-1100 wavemeter. To analyze the mode structure we employed a confocal Fabry–Perot cavity (free spectral range 750 MHz, finesse ≃50 for $\lambda = 806$ nm).

3. Results

Although the laser operated in a single-frequency and TEM_{00} mode even without an intracavity etalon, the insertion of the Suprasil plate into the cavity improved the stability of the longitudinal mode. The output maximum was centered around ≃1313.8 nm with a full width at half-maximum of the gain curve of ≃4 nm. Figure 4 shows the output power when the laser is tuned with the tilted etalon, with the absorbed pump power fixed at 12 W. The results for laser output power versus absorbed pump power at 1312.6 and 1314.0 nm are displayed in Fig. 5. We limited the absorbed pump power to 12.3 W to avoid thermal damage to the rod. The 1312.6-nm Nd:YLF laser had a threshold at an absorbed pump power of 2.1 W and produced a maximum single-frequency cw output of 830 mW in a linearly polarized TEM_{00} beam. For 1314.0 nm, the threshold was only 1.1 W, and the maximum single-frequency output power was 970 mW. The slope efficiencies were approximately 8% in each case. In Fig. 6 we show a typical oscilloscope trace of the Fabry–Perot transmission at 1312.6 nm, indicating the presence of only a single longitudinal mode. The free-running laser spectrum (i.e., without any servo loop to lock the laser frequency) was stable with no mode hops over a few seconds, even with 12 W of absorbed pump power. This is sufficient to allow further stabilization, for example, by simple side-fringe locking.[18] Greater output power should be achievable by use of (i) zero-order quarter-wave plates antireflection coated for both pump and emission wavelengths, (ii) a longer crystal with lower doping, and (iii) a pump laser at 797 nm.

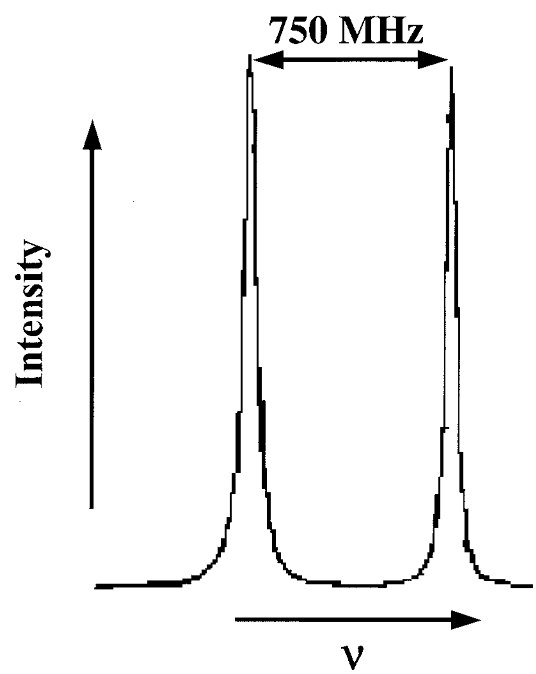

Fig. 6. Oscilloscope trace of transmission through a confocal Fabry–Perot interferometer (free spectral range 750 MHz) confirming single-frequency operation of the twisted-mode cavity *c*-axis Nd:YLF laser at 1312.6 nm.

4. Conclusion

We have developed a diode-pumped single-frequency c-axis Nd:YLF laser operating in the range of 1311.9–1317.2 nm. Tunable cw single-frequency high-power operation of this laser is achieved, yielding output powers of 830 mW at 1312.6 nm and 970 mW at 1314.0 nm with slope efficiencies of 8%. This device could play an important role in the field of high-resolution spectroscopy of hydrogenic systems, laser cooling of calcium atoms, and the development of optical clocks.

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