Available online at www.sciencedirect.com

SCIENCE DIRECT®

Optics Communications 217 (2003) 357–362

OPTICS COMMUNICATIONS

www.elsevier.com/locate/optcom

Efficient cw operation of diode-pumped Nd:YLF lasers at 1312.0 and 1322.6 nm for a silver atom optical clock

Y. Louyer [a,b,1], F. Balembois [b], M.D. Plimmer [a,*], T. Badr [a], P. Georges [b], P. Juncar [a], M.E. Himbert [a]

[a] Bureau National de Métrologie-Institut National de Métrologie, CNAM, 292 rue Saint-Martin, F75003 Paris, France
[b] Laboratoire Charles Fabry de l'Institut d'Optique, UMR 8501 du CNRS, Université Paris Sud, F91403 Orsay, France

Received 20 October 2002; received in revised form 10 December 2002; accepted 17 January 2003

Abstract

We describe the efficient cw operation of two Nd:YLF lasers at 1312.0 and 1322.6 nm for the development of a silver atom optical clock. For a simple linear cavity laser configuration investigated at these wavelengths, we have obtained an output power of 3.6 W at 1312.0 nm for 13.8 W of absorbed pump power ($\lambda = 806$ nm) and 4.8 W output at 1322.6 nm with 16.3 W pump. At 1312.0 nm, using a twisted-mode cavity, a single-frequency output power of 750 mW has been obtained. Single-frequency operation (450 mW) at 1322.6 nm was achieved using an intra-cavity solid etalon.

PACS: 06.20Fn; 39.25+k; 42.55Rz; 42.55Xi; 42.60By; 46.62Eh

Keywords: Solid-state lasers; Diode-pumped lasers; Twisted-mode laser; Atomic clocks; Silver atom

1. Introduction

The stability of an atomic clock is directly proportional to the quality factor of the resonance Q defined as the ratio between the resonance frequency and the observed linewidth [1]. In the best Cs fountain clock [2], the linewidth is close to 1 Hz giving a Q of about 10^{10}. If one were able to interrogate an optical transition with comparable linewidth and S/N one could improve the stability by a factor 5×10^4. Several projects to this end are being pursued in different laboratories worldwide with optical transitions both in laser-cooled atoms and single-trapped ions [3]. At the Bureau National de Métrologie-Institut National de Métrologie, we are developing an optical clock based on neutral silver [4,5]. Here the clock transition between the $4d^{10}5s\ ^2S_{1/2}$ ground level and the $4d^9 5s^2\ ^2D_{5/2}$ metastable level has an estimated

* Corresponding author. Tel.: +33-1-40-27-27-05; fax: +33-1-42-71-37-36.
E-mail address: plimmer@cnam.fr (M.D. Plimmer).
[1] The authors are grateful to J.D. Silver for his critical reading of the manuscript. Y.L. thanks the Ministère de la Jeunesse, de l'Education Nationale et de la Recherche for a research studentship. This work was supported by the Bureau National de Métrologie.

0030-4018/03/$ - see front matter
doi:10.1016/S0030-4018(03)01165-9

natural width of 0.8 Hz [6]. It can be excited either with a single photon at 330.6 nm or, as in our experiment, using two photons at 661.3 nm. In addition, sub-Doppler laser cooling has been achieved elsewhere using the E1 transition at 328 nm [7]. For both clock and cooling transitions, the lasers must be continuous, powerful, have high spectral purity and be precisely tunable. To excite the clock transition, our aim is to obtain 500 mW at 661.3 nm ideally with a linewidth below 1 Hz. For laser cooling at 328 nm, we are aiming for 100 mW with a sub-megahertz linewidth, the natural width of the cooling transition being 23 MHz. Several types of laser sources are available: red laser diodes (or frequency doubled IR ones), dye lasers and diode-pumped solid-state lasers.

Red laser diodes are the most convenient to use but lack sufficient power for the generation of tens of milliwatts at 328 nm. (A narrow output diode could, however, be used to excite the clock transition given an efficient power build-up cavity.) Tunable ring dye lasers are powerful (visible outputs of over 500 mW with DCM dye for typically 5 W of Ar^+ pump laser at 514 nm), but far more difficult to use. A diode-pumped solid-state laser represents an attractive option combining output power and frequency stability with ease of operation. Specifically, in a laser of this kind, the spectrum of frequency fluctuations is confined to low frequencies (<1 MHz) [10]. This contrasts with the situation encountered with dye lasers and laser diodes where the spectrum of frequency fluctuations extends to several megahertz or beyond. Consequently, frequency stabilisation of diode-pumped solid-state lasers is easier. For example, Nd:YAG has been used to make ultra-stable lasers for spectroscopy of In^+ ions [8] and gravitational wave detection [9]. In principle, other rare-earth-doped crystals should yield similar performances.

Neodymium-doped crystals exhibit many laser transitions around 1.3 μm. We have found that a laser based on Nd-doped $YLiF_4$ (henceforth Nd:YLF) [11–13] can be used to generate both 1322.6 and 1312.0 nm. Second harmonic generation of the former wavelength will yield 661.3 nm while twice frequency doubling the latter will provide 328 nm. Specifically, we used the emission lines peaking at 1321 and 1313 nm which are broad enough to include the wavelengths of interest [12]. According to the second harmonic generation efficiency measured for LBO in [14] at least 2 W of 1322.6 nm would be required to produce 600 mW at 661.3 nm. Moreover, the group of Boshier at Sussex University has obtained 80 mW at 328 nm by frequency doubling of a dye laser of output 600 mW at 656 nm (for spectroscopy of the He^+ 2S–3S transition) [15]. To obtain this amount of red radiation by second harmonic generation of a source at 1312.0 nm, about 2 W would also be required. In this paper, we describe our approach to produce first 1322.6 nm then 1312.0 nm and the results obtained therewith. In both cases, we show how single-frequency operation has been achieved.

Finally, we note that although the most stable visible laser thus far reported is in fact a dye laser [16], similar performances should be obtainable with solid-state sources of the kind described in the present paper.

2. The laser source

The laser gain element, Nd:YLF, is a uniaxial crystal. Consequently, there exist two fluorescence curves according to whether the laser beam polarisation is parallel or perpendicular to the extraordinary axis (*c*-axis). As mentioned in [12], the two central emission wavelengths correspond to either the π-polarised line at 1321 nm or the σ-polarised line at 1313 nm. Laser action at these wavelengths has been investigated in [17]. Here we report for the first time efficient cw laser operation at either 1322.6 nm or 1312.0 nm. Although the greatest absorption is obtained near 792 and 797 nm (see [12]), at the time of the experiments described here we had available only a pump diode operating near 808 nm. We fixed the pump wavelength at 806 nm in order to maximise the absorption. The pump source for our research was a 25 W fibre-coupled diode (Limo Model no. *HLU25F200*) with a centre wavelength 806 nm at 22 °C, fibre core diameter of 200 μm and a numerical aperture of 0.22. The pump focusing optics consists of two doublets. The first doublet with a 60 mm focal length collimates the pump beam.

The second 80 mm focal-length doublet focuses the beam pump to a spot size radius of 133 μm in the Nd:YLF rod. The crystal was mounted in a water-cooled copper heat sink maintained at a temperature of 16 °C and was anti-reflection coated at 1.3 μm and 808 nm on both facets. For both wavelengths we used a classical folded cavity shown in Fig. 1.

In our experiment the criteria for TEM_{00} operation were satisfied by setting the arm lengths to be $d_1 = 280$ mm and $d_2 = 300$ mm, resulting in a TEM_{00} radius in the rod of $\simeq$140 μm. The radii of curvature of the mirrors were $R_1 = 100$ mm and $R_2 = 500$ mm. The laser beam is collimated in the second arm where wavelength selective elements are inserted. For a given pump power, optimum output coupling was achieved for a transmission of $T = 2\%$. A selective element inside the resonator enabled us both to pick out one of the two 1.3 μm lines and thereafter to tune the laser wavelength. In this instance, we employed an uncoated solid etalon of thickness of 0.1 mm, corresponding to a free spectral range about 1 THz ($\simeq$6 nm) larger than the full width of the gain line. To characterise the laser we monitor simultaneously the wavelength and the output power as well as the transverse and longitudinal modes. First we analysed the output using a grating spectrometer (600 lines/mm) to check the laser is running on a single line. The laser cavity was adjusted to produce a circular diffraction spot indicating a single transverse mode TEM_{00}. The wavelength was then measured by a wavemeter (Burleigh Model WA-1100). The longitudinal modes were monitored using a scanning confocal Fabry–Perot interferometer (free spectral range 0.75 GHz, finesse 50) which also served to check the spectral purity of the laser. The laser power at 806 nm and 1.3 μm was determined using a power meter (Gentec TPM-300) with an accuracy of $\simeq$5%.

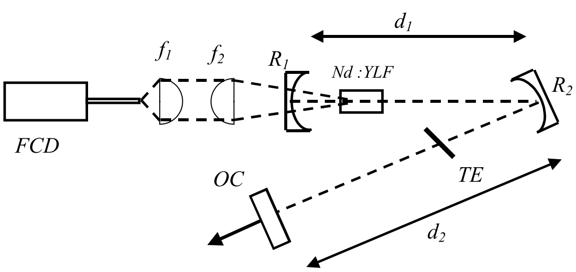

Fig. 1. Folded cavity standing-wave configuration for diode-pumped Nd:YLF laser used to generate 1312.0 and 1322.6 nm. Key: FCD, fibre-coupled diode; TE, Suprasil thin etalon; OC, output coupler ($T = 2\%$). Here $f_1 = 60$ mm, $f_2 = 80$ mm, $d_1 = 280$ mm, $d_2 = 300$ mm, $R_1 = 100$ mm, and $R_2 = 500$ mm.

3. Laser operation at 1322.6 nm

The second harmonic of the 1322.6 nm laser is destined to be locked to the very narrow silver clock transition. Here we describe both multi-mode and a single-frequency oscillation of the IR laser. To obtain single-line operation at 1322.6 nm, one must use a Nd:YLF crystal aligned so one of the two *a*-axes is parallel to the direction of propagation. By rotating an uncoated intra-cavity Suprasil plate (Fig. 1), one can tune the wavelength away from the emission maximum towards 1322.6 nm. At this wavelength, the laser polarisation is parallel to the extraordinary or *c*-axis. To generate the emission at 1322.6 nm, we tested crystals with three different Nd dopings: 0.5%, 0.7% and 1%. For 1% doping, thermal fracture of the rod occurs at around 14 W of absorbed pump power. Consequently, we limited the pump power to 12.6 W yielding an output of 3.3 W at 1322.6 nm. At 0.5% doping, thermal damage posed no problem because even at 25 W pump power (the maximum available), only 13 W was absorbed, generating 3.6 W of output. The best results were obtained for the intermediate Nd concentration, namely 0.7% for which we limited the absorbed pump to 16.3 W to avoid thermal damage. The output power as

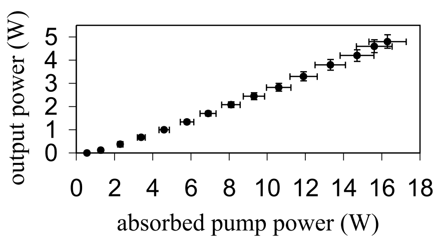

Fig. 2. Output power at 1322.6 nm versus absorbed pump power at 808 nm for standing-wave laser shown in Fig. 1 using an *a*-axis Nd:YLF crystal.

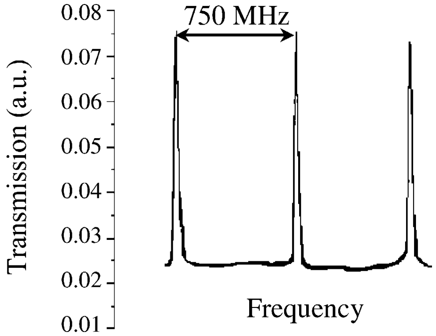

Fig. 3. Oscilloscope trace of transmission through a 0.75 GHz FSR confocal Fabry–Perot confirming single-frequency operation at 1322.6 nm of the standing-wave laser incorporating an intra-cavity etalon.

a function of absorbed pump power is shown in Fig. 2. At 1322.6 nm, 4.8 W is generated for an absorbed pump level of 16.3 W. The average slope efficiency is about 30%. The spatial mode is TEM_{00} while the laser wavelength is centred on 1322.6 nm with fluctuations of ± 0.05 nm. No sign of roll-off is present, thus indicating scope for further power-scaling. The output spectrum of the free-running *a*-axis Nd:YLF laser consists of a large number of longitudinal modes whose intensities and phases appear to fluctuate randomly. This is a result of spatial hole burning. In a preliminary experiment using the same cavity geometry as in Fig. 1 we prevented multi-mode oscillation by inserting a coated solid etalon in addition to the uncoated one described in Section 2. The second etalon had a reflection coefficient of $R = 0.6$ and thickness 0.3 mm. In this configuration, the laser ran single-mode for about 1 s before hopping. Moreover, the insertion of the second etalon cut the output power fivefold. Fig. 3 shows a typical oscilloscope trace of the Fabry–Perot transmission, indicating the presence of only a single, albeit fleeting longitudinal mode. A more robust single-mode laser should be achievable using a ring cavity and work to this end is in progress.

4. Laser operation at 1312.0 nm

Here we describe both multi-mode and single-mode operation of the 1312.0 nm laser (four times the frequency of which is destined for laser cooling of atomic silver). When laser polarisation is perpendicular to the Nd:YLF *c*-axis only emission on the 1313 nm line can be obtained. Such a crystal was studied using the linear cavity shown in Fig. 1. Here, the uncoated intra-cavity plate enabled us to tune the wavelength away from the peak of the gain towards 1312.0 nm. In this work, the only *c*-axis Nd:YLF crystal at our disposal had a 1% Nd doping and not the optimum 0.7%. Consequently, we limited the absorbed pump power to avoid thermal fracture resulting in a lower output power than expected at 1322.6 nm with a 0.7% Nd-doped gain medium. Fig. 4 shows the corresponding total output power as a function of absorbed pump power, the highest total output power being 3.6 W with an absorbed pump power of 13.8 W. The average slope efficiency (output power versus absorbed pump power) is about 25%. As with the 1322.6 nm system, the slope efficiency showed no sign of roll-off and hence scope for further power-scaling. Since we used a linear cavity, several longitudinal modes were present and the output spectrum was very chaotic.

An elegant solution for obtaining a single-frequency output without spatial hole burning is to keep a linear cavity but use circularly polarised light within the crystal instead. This "twisted-mode" cavity produces uniform gain saturation and hence avoids mode hops [18,19]. To achieve this with Nd:YLF requires a *c*-axis crystal so that the gain is independent of the orientation of the laser polarisation. The cavity geometry studied is

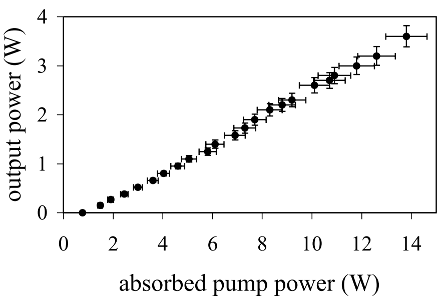

Fig. 4. Output power at 1312.0 nm versus absorbed pump power at 808 nm for a standing-wave laser shown in Fig. 1 with a *c*-axis Nd:YLF crystal.

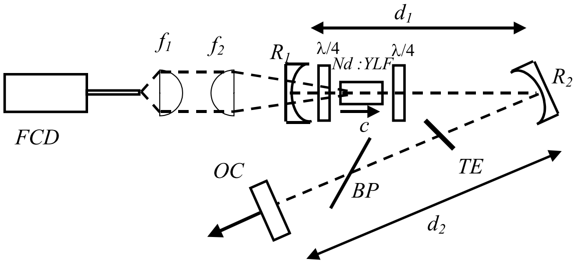

Fig. 5. Twisted-mode folded cavity for a diode-pumped c-axis Nd:YLF laser used to generate 1312.0 nm. Key: $\lambda/4$, low-order quarter-wave plates at 1.3 μm; BP, glass plate inclined at Brewster's angle; FCD, fibre-coupled diode; TE, Suprasil thin etalon; OC, output coupler ($T = 2\%$). Here $f_1 = 60$ mm, $f_2 = 80$ mm, $d_1 = 280$ mm, $d_2 = 300$ mm, $R_1 = 100$ mm, $R_2 = 500$ mm. The Brewster plate assures linear polarisation. The laser runs single-mode even without the thin etalon used only for frequency tuning.

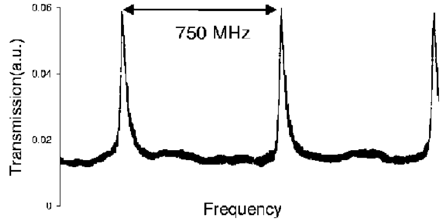

Fig. 6. Oscilloscope trace of transmission through a 0.75 GHz FSR confocal Fabry–Perot confirming single-frequency operation at 1312.0 nm of the twisted-mode folded-cavity laser incorporating an intra-cavity etalon (Fig. 5).

shown schematically in Fig. 5 where the rod is placed between two quarter-wave plates. Inside the rod, the sum of two counter-propagating circularly polarised waves gives rise to a standing wave of uniform intensity whose polarisation rotates with a period equal to the laser wavelength. A Suprasil Brewster plate serves to favour linear polarisation of the laser in the rest of the cavity. The axes of the two low-order 1.3 μm AR-coated quarter-wave plates are oriented at 45° with respect to the laser polarisation. Since the quarter-wave plates were not AR-coated at 808 nm, they were tilted at 10° to prevent feedback into the diode. The power fell by 17% compared to the case with normal incidence. The wavelength-tuning is achieved using the 0.1 mm Suprasil etalon. The laser ran in a TEM_{00} mode. By carefully aligning of the $\lambda/4$ plates, we achieved emission in a single longitudinal mode, without the need for a coated intra-cavity etalon. The spectral purity of the twisted-mode laser is illustrated in Fig. 6, which shows the transmission through a Fabry–Perot cavity scanned over 0.75 GHz (approximately three free spectral ranges of the laser cavity). The free-running laser spectrum was very stable with no mode hops over a few seconds, whatever the pump power (1–12 W). Such free-running stability is sufficient to allow further stabilisation, for example by simple side fringe locking [20] to a stable external cavity or more sophisticated techniques of locking to the resonance centre [21]. For the first time to our knowledge, a Nd:YLF twisted-mode cavity has been demonstrated. A single-frequency output of 750 mW has been obtained at 1312.0 nm for 12.3 W of absorbed pump power at 806 nm. However, with optimally designed components and coatings a single-frequency output power of 2 W should be within reach.

5. Conclusion

This paper provides the first demonstration of efficient, cw operation of diode-pumped Nd:YLF lasers at 1312.0 and 1322.6 nm. In a standing-wave cavity configuration, we have achieved 3.6 W of multi-mode TEM_{00} output at 1312.0 nm for 13.8 W of absorbed pump power and 4.8 W of TEM_{00} at 1322.6 nm for 16.3 W pump absorption. At 1312.0 nm, we have obtained 750 mW single-frequency operation using a twisted-mode cavity without the need for an intra-cavity thin etalon. At 1322.6 nm, single-frequency operation at up to 450 mW has been demonstrated with the insertion of a coated etalon. However, to obtain 2 W single-mode output at this wavelength, a different cavity configuration looks necessary to avoid spatial hole burning and hence mode hops (for example a ring laser). Finally, we note that diode-pumped solid-state lasers near 1.3 μm could also be useful for a calcium optical clock based on the 657 nm intercombination line [22] as well as for spectroscopy of atomic hydrogen (Balmer-α line or 2S–3S two-photon transition).

References

[1] J. Vanier, C. Audoin, The Quantum Physics of Atomic Frequency Standards, Adam Hilger, Bristol, UK, 1989.
[2] G. Santarelli, Ph. Laurent, P. Lemonde, A. Clairon, A.G. Mann, S. Chang, A.N. Luiten, Ch. Salomon, Phys. Rev. Lett. 82 (1999) 4619.
[3] P. Gill (Ed.), Proceedings of the Sixth Symposium on Frequency Standards and Metrology, St. Andrews, Scotland, 9–14 September 2001, World Scientific, Singapore, 2002.
[4] S. Guérandel, T. Badr, M.D. Plimmer, P. Juncar, M.E. Himbert, Eur. Phys. J. D 10 (2000) 33.
[5] T. Badr, S. Guérandel, M.D. Plimmer, P. Juncar, M.E. Himbert, Eur. Phys. J. D 14 (2001) 39.
[6] P.L. Bender, J.L. Hall, R.H. Garstang, F.M.J. Pichanick, W.W. Smith, R.L. Barger, J.B. West, Bull. Am. Phys. Soc. 21 (1976) 599.
[7] G. Uhlenberg, J. Dirscherl, H. Walther, Phys. Rev. A 62 (2000) 0634041.
[8] Th. Becker, M. Eichenseer, A.Yu. Nevsky, E. Peik, Ch. Schwedes, M.N. Skvortsov, J. von Zanthier, H. Walther, in: P. Gill (Ed.), Proceedings of the Sixth Symposium on Frequency Standards and Metrology, St. Andrews, Scotland, 9–14 September 2001, World Scientific, Singapore, 2002.
[9] F. Bondu, P. Fritschel, C.N. Man, A. Brillet, Opt. Lett. 21 (1996) 582.
[10] T.J. Kane, A.C. Nilsson, R.L. Byer, Opt. Lett. 12 (1987) 175.
[11] E.J. Sharp, D.J. Horowitz, J.E. Miller, J. Appl. Phys. 44 (12) (1973) 5399.
[12] L. Fornasiero, T. Kellner, S. Kück, J.P. Meyn, P.E.-A. Möbert, G. Huber, Appl. Phys. B 68 (1999) 67.
[13] T.M. Pollak, W.F. Wing, R.J. Grasso, E.P. Chicklis, H.P. Jenssen, IEEE J. Quantum Electron. QE-18 (2) (1982) 159.
[14] G.J. Hall, A.I. Ferguson, Opt. Lett. 19 (1994) 557.
[15] S.A. Burrows, S. Guérandel, E.A. Hinds, F. Lison, M.G. Boshier, in: S.G. Karshenboim, F.S. Pavone, G.F. Bassani, M. Inguscio, T.W. Hänsch (Eds.), The Hydrogen Atom Precision Physics of Simple Atomic Systems, Springer, Berlin, 2001, p. 303.
[16] B.C. Young, F.C. Cruz, W.M. Itano, J.C. Bergquist, Phys. Rev. Lett. 82 (1999) 3799.
[17] C. Rahlff, M.H. Dunn, B.D. Sinclair, W. Sibbett, in: Conference on Lasers and Electro-Optics, 1994 OSA Technical Digest Series, vol. 8, Optical Society of America, Washington, DC, 1994, p. 360.
[18] V. Evtuhov, A. Siegman, Appl. Opt. 4 (1965) 142.
[19] K. Wallmeroth, P. Peuser, Electron. Lett. 24 (1988) 1086.
[20] M.W. Hamilton, Contemp. Phys. 30 (1989) 21.
[21] R.W.P. Drever, J.L. Hall, F.V. Kowalski, J. Hough, G.M. Ford, A.J. Munley, H. Ward, Appl. Phys. B 31 (1983) 97.
[22] C.W. Oates, F. Bondu, R.W. Fox, L. Hollberg, Eur. Phys. J. D 7 (1999) 449.