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Frequency-stabilized Nd:YVO_4 thin-disk laser

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ABSTRACT We have developed a Nd:YVO_4 thin-disk laser at 914 nm with single-frequency operation and active frequency stabilization to a low-finesse reference cavity. The spectral density of laser frequency noise is analysed by means of noise measurements at the error point of the frequency control loop. To address the $3^1S_0 \rightarrow 3^3P_1$ magnesium intercombination line at 457 nm, we use an external frequency doubling stage based on periodically poled $KTiOPO_4$ for the generation of more than 150-mW output power at 457 nm. Optical beat signal measurements at 457 nm with a frequency-stable dye laser show a short-time line width of the thin-disk laser of less than 100 kHz.

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1 Introduction

Diode-pumped thin-disk lasers are all-solid-state light sources combining scalable high output power with excellent spatial beam quality and high conversion efficiency. Following a concept first demonstrated at the Institut für Strahlwerkzeuge (IFSW, University of Stuttgart) [1], thin-disk lasers have undergone a rapid development during recent years [2]. This was mainly triggered by their application in the material processing industry. Thin-disk lasers use an efficiently cooled thin disk of only a few hundred micrometres thickness as active medium. Thus, thermal beam distortions are reduced and highest spatial beam qualities even at high optical pumping intensities and output power levels are achieved. Commercial single-mode, single-frequency systems now reach output powers of 100 W with a nearly perfect Gaussian beam profile ($M^2 < 1.1$) [3]. In most disk lasers, Yb:YAG is used as gain material, lasing at a wavelength of 1030 nm. Single-mode, single-frequency Yb:YAG thin-disk lasers have also attracted interest from researchers in atomic physics. Applications include far-off-resonance dipole traps and – after frequency doubling – substitution of Ar^{3+} pump lasers at 515 nm. For these applications, a high output power, a good spatial mode quality and simple pumping by high-power diode bars are advantageous. Here, the single-mode emission spectrum and tunability achieved with passive intracavity elements (e.g. etalons and birefringent filters, see e.g. [4]) are fully sufficient. For spectroscopy, however, narrow emission line widths below 1 MHz and long-term frequency stability are required. Because of the restricted choice of available laser wavelengths, disk lasers are presently not widely used here. Yet, the spectrum of available wavelengths is expected to be greatly extended in the near future by using semiconductor structures as gain materials [5, 6].

Realizing highly stable and powerful laser light sources to address the $3^1S_0 \rightarrow 3^3P_1$ intercombination line at 457 nm is crucial for the further development of the magnesium optical frequency standard [7]. This wavelength is also of special interest for laser display technology and laser printing machines. Apart from the use of dye lasers, 457-nm light cannot be generated directly. Thus, an all-solid-state laser source at 457 nm typically involves second-harmonic generation of the 914-nm infrared fundamental, available from titanium–sapphire or amplified diode lasers. While the former have the disadvantage of requiring an expensive pump source, diode lasers with a subsequent amplifier stage exhibit an inferior mode quality and a broad amplified spontaneous emission background in their spectrum. In 2002, a Nd:YVO_4-based thin-disk laser emitting at 914.5 nm with high output power (5.8 W) was initially realized at the IFSW [8, 9]. Subsequently, the coincidence of the second harmonic of one laser emission line with the magnesium intercombination transition was demonstrated [10].

Based on this work, we have developed a stable-running and single-frequency laser system with an output power of about 1 W at 914 nm. We have set up an external ring res-

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onator for second-harmonic generation using periodically poled KTP and achieved an output power above 150 mW at 457 nm. The laser frequency is actively stabilized using a low-finesse reference cavity. We have studied the frequency noise spectrum of the free-running and the stabilized lasers by measuring the noise at the error point of the frequency-stabilization loop. For an independent characterization of the frequency noise and laser line width, we performed optical beat signal measurements at 457 nm with a frequency-stabilized dye laser.

The remainder of this article is structured as follows: in Sect. 2, we describe the thin-disk laser in the configuration optimized for stable single-mode, single-frequency operation. Section 3 deals with the optical setup and the external second-harmonic generation. Section 4 is dedicated to the active frequency stabilization. Conclusions and perspectives for further improvements of the system are given in Sect. 5.

2 Disk laser

The setup of the disk laser resonator, which is mounted on a granite base plate in order to achieve high mechanical stability, is shown in Fig. 1. A 0.3%-neodymium-doped YVO_4 crystal disk of thickness 320 µm serves as gain medium. For heat dissipation, the disk is mounted on a water-cooled copper heat sink. The water temperature is actively stabilized to 12.3 °C. The linear, semi-confocal laser resonator (length 28 cm) is formed by the high-reflection-coated back surface of the disk and the curved out-coupling mirror (reflectivity $R = 99.5\%$ at 914 nm, radius of curvature $r = 1$ m). This mirror is mounted on a piezoelectric transducer (PZT), which enables frequency modulation of the laser output. The waist of the Gaussian TEM_{00} laser cavity mode with 360-µm radius is located on the back surface of the laser disk.

In order to achieve 914-nm output wavelength the ${}^4F_{3/2} - {}^4I_{9/2}$ transition is used, which results in a quasi-three-level laser operation [9]. Lasing at 1064 nm on the strong ${}^4F_{3/2} - {}^4I_{11/2}$ transition is suppressed by antireflection coatings on the laser disk and the out-coupling mirror for this wavelength. The laser is pumped at 808 nm by two water-cooled and fibre-coupled diode laser bars with a total output power of 35 W at 40-A injection current. To increase the pumping rate, the pump beam is sent through the active medium 16 times by multiple reflection at the high-reflection-coated back surface of the disk and a parabolic mirror coaxial to the optical axis of the laser and additional reflecting prisms (not shown in Fig. 1) [2]. Longitudinal single-mode operation

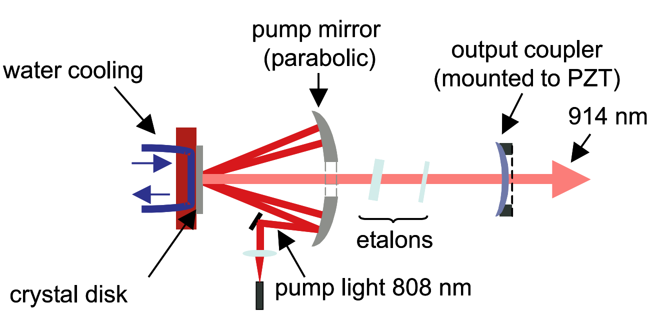

FIGURE 1 Thin-disk laser resonator and pump light configuration

is achieved using two uncoated intracavity quartz etalons of thicknesses 0.6 mm and 4 mm, respectively. Using resistive heating elements, both etalons are actively temperature stabilized to about 30 °C. With the laser tuned to the subharmonic of the magnesium intercombination transition (vacuum wavelength $\lambda = 914.47$ nm), an output power of 700 mW at 36.5-A diode current is achieved. At the same conditions but without etalons the laser operates longitudinally multi-mode with 1.7-W maximum output power.

By means of an intracavity electro-optic modulator (EOM), dye lasers and diode lasers with line widths in the Hertz and sub-Hertz regimes have been realized with high servo bandwidths of up to a few MHz [7, 11–13]. Unfortunately, an additional EOM is not applicable inside the cavity of our thin-disk laser because the additional optical loss would reduce the output power significantly due to the quasi-three-level laser operation.

3 Optical setup and frequency doubling

The optical setup of the complete laser system is shown in Fig. 2. The laser is protected against back reflections with a 60 dB optical isolator (LINOS). For the frequency stabilization, a small fraction of the infrared light is sent to the low-finesse reference cavity. An acousto-optic modulator (AOM) (Crystal Technology, 110 MHz) in double-pass configuration serves for high-frequency modulation of the laser frequency. After passing the AOM the light is mode matched and coupled into the external frequency-doubling cavity. Due to optical losses mainly caused by the isolator and the AOM, the laser output power of 700 mW is reduced to 380 mW in front of the frequency-doubling cavity.

The 914-nm laser light is frequency doubled to 457 nm using an external ring cavity with a 10-mm-long periodically poled $KTiOPO_4$ (ppKTP) crystal. Quasi-phase matching of the crystal is achieved by active temperature stabilization of the crystal to 48 °C. The bow-tie ring cavity is formed by two plane mirrors and two mirrors with 75 mm radius of curva-

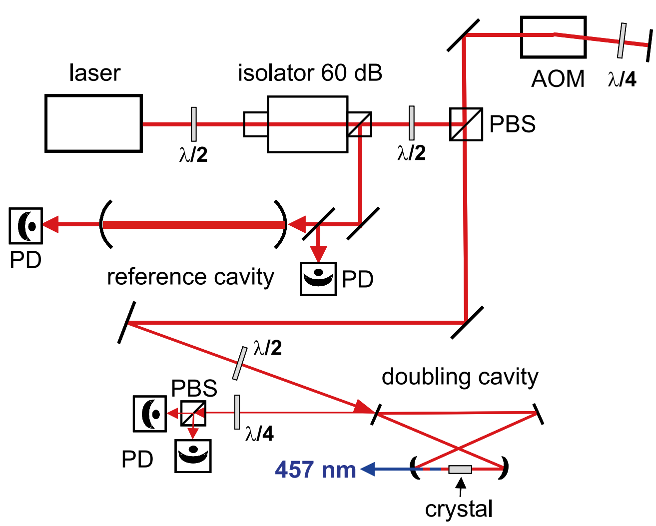

FIGURE 2 Optical setup of the laser system including reference cavity and external frequency-doubling cavity (without beam-shaping lenses). PD, photodetector; PBS, polarizing beam splitter; AOM, acousto-optic modulator

ture. The optical path length of the cavity is 34 cm. The two beam waist radii of this cavity geometry are calculated to be 49 μm in the centre of the crystal and 147 μm between the two plane mirrors. The infrared light is coupled into the cavity with 85% coupling efficiency through one of the plane mirrors. This input coupling mirror has an optical transmission of 6% at 914 nm. The doubling cavity is kept on resonance with the disk laser by applying the Hänsch–Couillaud locking scheme [14] and using a PZT which actuates the second plane mirror of the cavity. The bandwidth of the locking servo is about 1 kHz.

With the described cavity configuration and 380 mW of incident light at 914 nm, about 150-mW output power at 457 nm is generated. Taking into account the 85% cavity input coupling efficiency, which was determined by measuring the power reflected by the cavity in and out of resonance, an optical-to-optical frequency-doubling efficiency of 47% is achieved. This efficiency is limited by thermal lensing inside the doubling crystal. For our 10-mm-long crystal, numerical calculations according to Le Targat et al. [15] predict a theoretical maximum efficiency of 70% at 17-μm waist radius inside the ppKTP crystal. However, experimentally we have observed strong thermal lensing [15] for waist radii below 40 μm. This effect induces instabilities of the Hänsch–Couillaud lock and degrades the second-harmonic beam profile. Hence, as a compromise between stability and doubling efficiency, we have chosen an increased waist radius inside the doubling crystal. The observed doubling efficiency of 47% is slightly below the calculated maximum efficiency of 53% for the applied 49-μm waist radius with 4.5% optical transmission of the input coupling mirror.

Higher doubling efficiencies without degradation due to thermal lensing can be achieved with a longer doubling crystal. We have also calculated the doubling efficiency versus the waist radius for different crystal lengths using the method of Le Targat et al. [15]. The results show that an increase of the crystal length leads to a shift of the maximum of the doubling efficiency towards an increased waist radius. Thus, thermal lensing becomes less critical for longer doubling crystals. The calculations also predict a maximum achievable doubling efficiency with a crystal length of about 20 mm. Le Targat et al. have reported experimental results close to this theoretical maximum. They obtained 75% doubling efficiency with a 20-mm-long ppKTP crystal and 43-μm waist radius [15].

4 Frequency stabilization

For high-resolution spectroscopy of the magnesium intercombination transition a line width of the spectroscopy laser in the kHz range or below is required. In order to meet this demand we apply active frequency stabilization of our thin-disk laser. To our knowledge the results shown below represent the first in-depth report about the frequency noise and active frequency stabilization of a thin-disk laser.

Due to the observed large frequency noise amplitudes of the laser (see Fig. 3) we have chosen to follow the concept of a two-stage active frequency stabilization using optical reference cavities. Based on this concept the successful realization of narrow and ultra-narrow line width dye lasers and solid-state lasers has been reported [7, 11, 16]. We have set up and investigated a single active frequency-stabilization stage for the Nd:YVO_4 thin-disk laser. A low-finesse confocal reference cavity was chosen in order to obtain a robust locking and to be able to analyse the frequency noise of the stabilized and the free-running lasers with the same cavity. The cavity length of 75 mm corresponds to a longitudinal mode spacing of 1 GHz. The mirror reflectivity of about 50% at 914 nm determines the cavity line width, which was measured to be 390 MHz (FWHM). The cavity mirrors are mounted on a cylindrical quartz glass spacer to reduce thermal drift of the cavity eigenfrequencies. The spacer is mounted with rubber rings inside an aluminium housing for passive isolation against environmental temperature fluctuations. The cavity eigenfrequencies can be adjusted with a PZT which carries one of the cavity mirrors.

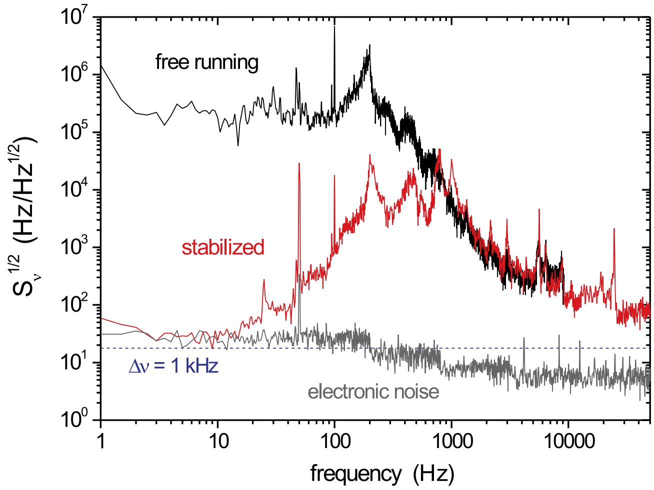

FIGURE 3 Spectral density of frequency fluctuations measured at the error point of the frequency stabilization with a FFT analyser. The free-running laser noise was observed with the servo loop opened and the stabilized laser noise with closed loop. The white-noise level that would correspond to 1-kHz line width is shown as a *dashed line*. Electronic noise: combined noise of the photodetectors and the FFT analyser

For the frequency stabilization, a transmission fringe locking setup has been implemented (see Fig. 2) which is sufficient for our purpose and does not limit the achieved frequency stability of the locked laser. The power transmitted by the cavity is detected with a photodiode and the laser is locked to the side of a transmission fringe. In order to avoid the conversion of power fluctuations into frequency fluctuations, the transmission signal is normalized by the use of an intensity reference signal. For that purpose a part of the incident light is separated with a beam splitter and detected with a second photodiode. Subsequently, the transmission signal is divided by the reference signal. The resulting error signal is amplified and fed to a servo amplifier with double integration [17], whose output steers the PZT which carries the end mirror of the thin-disk laser (see Fig. 1). Limited by the lowest mechanical resonance frequency of the PZT–mirror configuration, a servo bandwidth of approximately 1 kHz is achieved.

The noise spectrum of the electronic error signal of the frequency-stabilization servo was characterized using a fast Fourier transform (FFT) analyser (Fig. 3). The frequency noise of the free-running laser was measured with the servo loop opened and the laser tuned to the side of the transmission fringe. Due to the large cavity line width the laser frequency typically stays within the linear slope of the transmission fringe for a few seconds. Thus, the observed electronic noise can be translated into frequency noise. The measured spectrum shows large low-frequency noise amplitudes which are supposed to be mainly produced by vibration-induced length changes of the laser cavity. Especially, the water cooling of the thin-disk laser might contribute significantly to the measured noise amplitudes. A root-mean-square (rms) frequency noise of 13 MHz was calculated from the measured noise spectrum for Fourier frequencies between 1 Hz and 50 kHz.

With the laser stabilized to the cavity the frequency noise amplitudes are reduced for Fourier frequencies below 1 kHz (Fig. 3). In this case the noise spectrum of the error signal of the closed stabilization loop is observed. Thus, the measured noise amplitudes within the servo bandwidth of 1 kHz represent only a lower limit for the laser frequency noise amplitudes. Nevertheless, the characteristic maximum noise amplitudes between 100 Hz and 1 kHz Fourier frequency are supposed to represent the real laser frequency noise. This has been approved by determining the rms frequency noise by means of the optical beat frequency measurements described below. The maximum frequency noise amplitudes of the locked laser indicate that for Fourier frequencies above 100 Hz the noise suppression is limited by the gain of the locking servo and thus by the servo bandwidth. Thus, a future extension of the servo bandwidth will further reduce the frequency noise significantly. In Fig. 3 the combined contribution of the electronic photodetection noise and the noise of the FFT analyser, determined without light on the detectors, is also shown. The rms frequency noise of the stabilized laser, again calculated for Fourier frequencies between 1 Hz and 50 kHz from the measured noise spectrum, is reduced by a factor of 26 from 13 MHz (free-running laser) to 0.5 MHz.

For an independent comparison and verification of the measured in-loop frequency noise of the stabilized disk laser, we have performed optical beat frequency measurements at 457 nm using a highly stable dye laser. This laser was locked to a high-finesse reference cavity with a resulting laser line width of about 1 kHz at 457 nm [7].

The short-term beat signal of the thin-disk laser and the dye laser was measured with a spectrum analyser (Fig. 4). For the measurement a resolution bandwidth of 100 kHz was determined to be the minimum resolution bandwidth giving reproducible line width measurements. Thus, it represents a compromise between measurement time and resolution bandwidth. From the observed beat signal line width of less than 100 kHz a short-term line width of the disk laser below 100 kHz (FWHM) can be concluded. This is to our knowledge the smallest line width reported for a thin-disk laser so far. The rms noise of the beat frequency was 1 MHz in 1 s, which corresponds to 0.5 MHz rms noise at 914 nm. This value agrees with the rms noise calculated from the in-loop frequency noise spectrum of the stabilized laser (Fig. 3). The drift of the beat frequency was below 5 MHz in 100 s. The dye laser, which is used for spectroscopy of the intercombination line of neutral magnesium atoms [7], was tuned close to the atomic transition frequency. So, this beat-frequency measurement also demonstrates the tunability of the thin-disk laser to this transition frequency and the potential for the use as a spectroscopy laser for an atomic frequency standard based on neutral magnesium atoms.

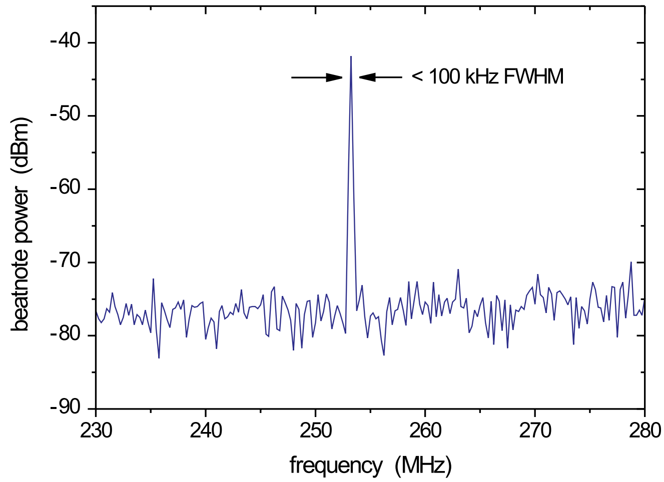

FIGURE 4 Optical beat note spectrum at 457 nm of the frequency-stabilized thin-disk laser and a dye laser stabilized to a high-finesse reference cavity. Resolution bandwidth 100 kHz, video bandwidth 100 kHz, sweep time 12.9 ms, frequency span 100 MHz

For future improvements we have also investigated the possibility to increase the servo bandwidth by using the AOM behind the 914-nm output of the thin-disk laser as a fast frequency actuator [18]. With the AOM acting for Fourier frequencies above 1 kHz and the PZT of the laser end mirror for lower frequencies we have extended the servo bandwidth to 20 kHz. From the noise spectrum of the closed-loop error signal of the stabilized laser a further reduced rms frequency noise of only 64 kHz was calculated for Fourier frequencies between 20 Hz and 50 kHz.

From the experimental results it can be concluded that a line width of the thin-disk laser on the kHz level or even below can be achieved in the future. This requires at least one evacuated reference cavity with high mechanical stability and larger finesse in order to ensure sufficiently small contributions of cavity length changes and servo offset fluctuations. Furthermore, the implementation of a new PZT–mirror configuration with a lowest mechanical resonance frequency increased to about 10 kHz is necessary in order to suppress the large laser frequency noise amplitudes by means of a higher servo gain. With a one-stage frequency stabilization using the laser mirror PZT and the AOM as frequency actuators and a servo bandwidth increased to about 100 kHz, a laser line width on the order of 1 kHz is achievable. Applying alternatively a two-stage frequency stabilization with two different reference cavities, even a laser line width on the Hertz level should be obtainable. Thereby, the first stage could use the mirror PZT and the second stage the AOM as frequency actuator. For the frequency stabilization of the second stage a vibration-isolated high-finesse reference cavity with a resonance line width in the lower kHz range is mandatory. In order to profit from a servo bandwidth on the order of 100 kHz, which exceeds the cavity resonance line width, a different frequency-locking technique has to be used which is not based on the cavity transmission signal. For the realization of ultra-narrow line widths, typically the Pound–Drever–Hall scheme based on the reflected light is used [19].

5 Conclusion

We have realized a Nd:YVO_4 thin-disk laser at 914 nm with longitudinal single-mode operation and active frequency stabilization. By external second-harmonic generation, an output power of 150 mW at 457 nm is generated, which is limited by thermal lensing inside the frequency-doubling crystal. The thin-disk laser is actively frequency stabilized using a low-finesse reference cavity. The frequency noise spectrum of the free-running laser and the stabilized laser was measured at the error point of the frequency-stabilization servo loop. The determined rms frequency noise of the stabilized laser of 0.5 MHz in a 50-kHz measurement bandwidth was confirmed by optical beat frequency measurements with a frequency-stable dye laser. With these beat signal measurements a short-time line width of the thin-disk laser of less than 100 kHz was observed. To our knowledge this represents the smallest line width of a thin-disk laser reported so far. The beat-signal measurements also demonstrate the tunability of the thin-disk laser to the intercombination line of neutral magnesium atoms and thus the applicability of the laser for high-resolution magnesium spectroscopy.

A future enhancement of the frequency-doubled output power is attainable by increasing the doubling efficiency from 47% to about 75% with a longer frequency doubling crystal. Thus, an output power of approximately 240 mW at 457 nm should be achievable. Improvements of the frequency stability are possible with an extended servo bandwidth using the AOM for high-frequency correction and a PZT–mirror configuration with an increased lowest mechanical resonance frequency. In combination with a reference cavity of higher mechanical stability and larger finesse a laser line width on the order of 1 kHz will be possible with a one-stage frequency-locking scheme. By applying a two-stage frequency stabilization with a second vibration-isolated high-finesse reference cavity, even a laser line width on the Hertz level should be realizable. This opens the possibility of applying thin-disk lasers in high- and ultra-high-resolution laser spectroscopy and other applications which require lasers with high frequency stability. For these tasks thin-disk lasers can provide excellent spatial beam quality at significantly higher output power levels than presently used laser sources, as e.g. dye lasers, master–slave configurations of diode lasers or other solid-state laser systems.

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