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Narrow-bandwidth diode-laser-based blue and ultraviolet light source

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ABSTRACT A compact, tunable and narrow-bandwidth laser source for blue and ultraviolet radiation is presented. A grating-stabilized diode laser at 922 nm is frequency-stabilized to below 100 Hz relative to a reference resonator. Injection of the diode-laser light into a tapered amplifier yields a power of 0.5 W. In a first frequency-doubling stage, more than 200 mW of blue light at 461 nm is generated by use of a periodically poled KTP crystal. Subsequent second-harmonic generation employing a BBO crystal leads to about 1 mW of ultraviolet light at 231 nm.

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1 Introduction

Diode-laser sources are nowadays a widely used tool for spectroscopy, atomic physics and quantum optics, combining high reliability, tunability and robustness with small size, low cost and ease of maintenance. Presently, diode lasers cover the spectrum from red to infrared almost continuously and additionally provide radiation at selected wavelengths in the blue and far infrared. With the advent of tapered amplifiers (TAs) [1, 2] – currently available from 730 to 1080 nm – the drawback of the usually moderate output power of a single-mode diode laser can be overcome by using a diode laser and a TA in series. A wide range of applications is thus afforded [3–5], increasing the versatility of this type of laser. In particular, the higher output power allows the benefits of diode lasers to be transferred to the green, blue and even ultraviolet (UV) parts of the spectrum by means of second-harmonic generation (SHG). Here, frequency doubling has been efficiently accomplished in recent years by using periodically poled crystals [6–10]. Another drawback of diode lasers, their high intrinsic frequency instability, has been partially overcome in the past by using an extended-cavity design where the width of the broad diode laser output spectrum is reduced to typically below 1 MHz by the optical feedback from a grating [11]. Further improvement can be achieved by stabilizing the diode laser onto an external, monolithic high-finesse Fabry–Pérot interferometer serving as a reference cavity.

This paper describes a frequency-stable power-amplified diode-laser system at 922 nm with efficient frequency doubling to 461 nm and thereafter to 231 nm that combines the benefits mentioned above. The laser system is used to perform sideband cooling of a single In^+ ion in a radio-frequency trap by excitation of the $5s^2\,{}^1S_0 \rightarrow 5s5p\,{}^3P_1$ intercombination line at 230.6 nm [12]. Another transition of In^+, the $5s^2\,{}^1S_0 \rightarrow 5s5p\,{}^3P_0$ line at 236.5 nm, is investigated as a reference for a frequency standard of unprecedented accuracy and stability [13]. The diode-laser system described here represents a first step towards realization of a transportable optical frequency standard on the basis of In^+.

2 Setup

A grating-stabilized diode laser with 30 mW of output power at 922 nm serves as a master laser; 20 per cent of its light is used for frequency stabilization onto a reference cavity. This part of the beam is first led in double pass through an acousto-optical modulator, to allow fine tuning of the laser frequency, and thereafter coupled via a single-mode fiber into the reference resonator. The main part of the light is seeded into a TA, resulting in an output power of ~ 0.5 W at the same frequency. The infrared light is then frequency-doubled a first time in an external enhancement cavity by means of a periodically poled KTP crystal, yielding more than 200 mW of blue light at 461 nm. A second external frequency-doubling stage using a BBO crystal generates 1 mW of UV light at 231 nm. The scheme of the setup is shown in Fig. 1.

3 Master laser

The master laser is a standard extended-cavity diode laser (ECDL) in Littrow configuration [14]: a single-mode diode at 922 nm with an output power of 30 mW and antireflection (AR)-coated front facet is frequency-controlled by the feedback of the first diffraction order of a grating. Due to the high-quality AR coating, the tuning range of the ECDL is rather large, from 880 nm to 960 nm.

For active frequency stabilization, the laser frequency is locked onto the resonance of a monolithic Fabry–Pérot interferometer (FPI) with a finesse of 11 000 (linewidth ~ 100 kHz). The cavity spacer (length: 12 cm) of the FPI is

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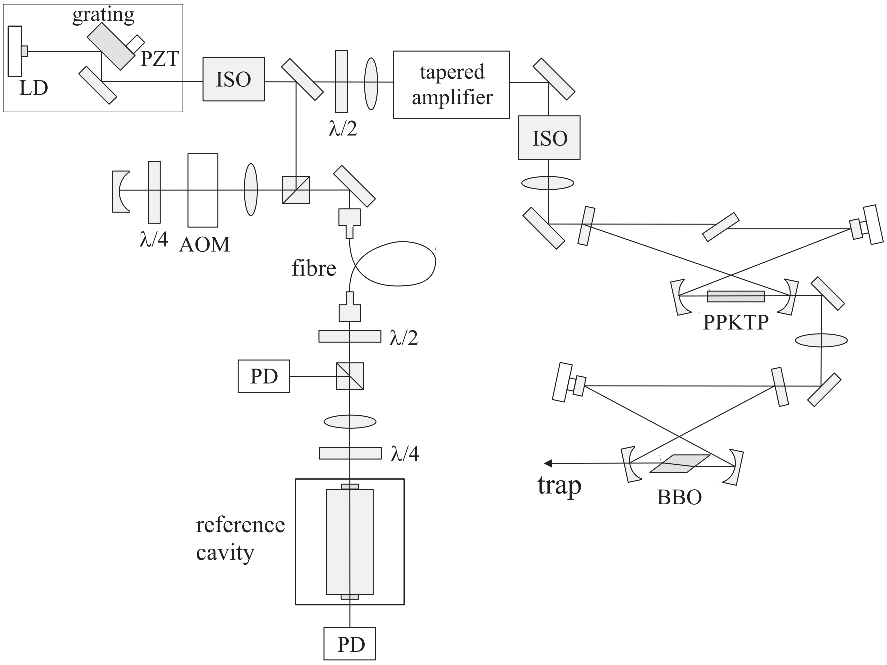

FIGURE 1 Scheme of the setup. LD, laser diode; PZT, piezo-actuator; ISO, optical isolator; PD, photodiode; AOM, acousto-optical modulator; for details see text

made from Zerodur and rests on two viton O-rings in a U-shaped stainless-steel block which itself is supported by viton stripes. To isolate this setup from the environment, it is kept at a pressure of 10^{-8} mbar in a vacuum chamber temperature-stabilized at 27.6 °C to within 20 mK. The vacuum chamber is placed without any further vibration isolation on the optical table and is covered with styrodur and soft rubber in order to suppress acoustic perturbations.

For the frequency stabilization onto the reference cavity we use the Pound–Drever–Hall locking technique, where the sidebands required for the lock are generated by modulating the master laser current at 10 MHz. The error signal is applied to the laser current with a bandwidth of about 500 kHz.

We investigated the frequency fluctuations of the master laser in both the free-running and the actively stabilized regimes: in the first case, we used the broad resonance of an additional low-finesse cavity as a frequency discriminator. In the second case, we analyzed the error signal of the frequency lock in closed loop. A Fourier analysis of the frequency fluctuations both in the free-running regime and with the locking servo system switched on is shown in Fig. 2.

A Fourier transformation of the frequency noise spectrum allows us to estimate the laser linewidth. For the free-running laser this leads to a value of below 500 kHz. In order to investigate the laser linewidth as a function of the external cavity length, the distance between the front facet of the diode and the grating was set to different values (2, 4 and 8 cm). For frequencies above 100 kHz (up to 5 MHz) the frequency noise is slightly reduced with the increase of the ECDL length, as expected [15]. However, no noticeable effect on the laser linewidth was observed, since the main frequency noise contribution, at around 30 kHz, is not affected by this variation.

For the case of active frequency stabilization of the laser the Fourier transform of the frequency noise is plotted in Fig. 3. It shows a frequency stability relative to the reference resonator (quality of lock) better than 100 Hz. The contributions of different parasitic effects, such as residual amplitude modulation, spurious interferences, etc., to the locking fidelity are estimated to be small at the present level of accuracy.

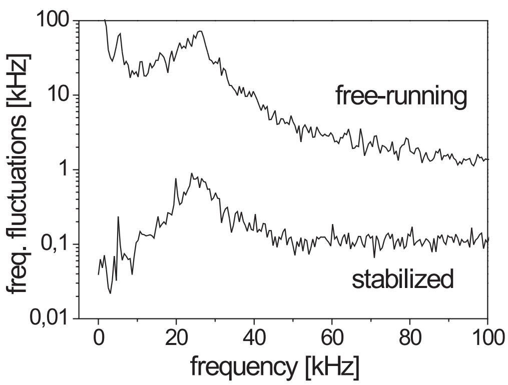

FIGURE 2 Frequency noise spectrum of the ECDL in the free-running and frequency-stabilized regimes (distance between diode and grating: 2 cm)

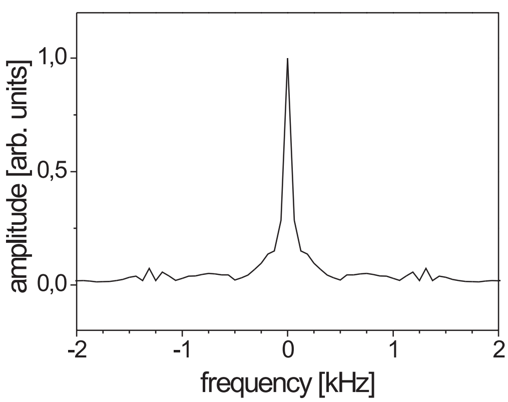

FIGURE 3 Fourier transformation of the frequency noise showing a quality of lock of the ECDL relative to the reference cavity below 100 Hz

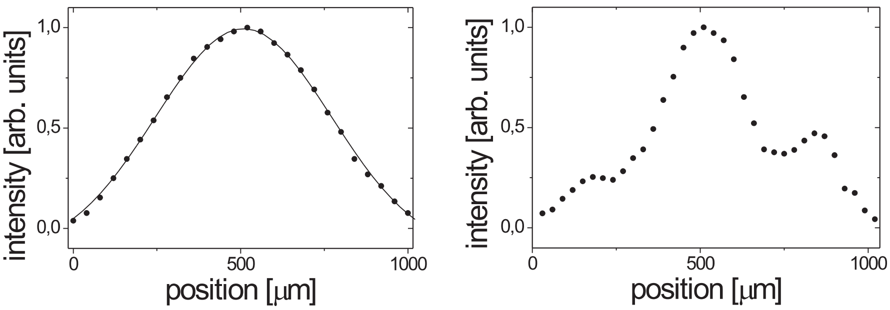

FIGURE 4 Beam profile of the TA output in the far field along the axis perpendicular to the long axis of the tapered gain region for different amplifier currents: an almost Gaussian mode is obtained for 1600 mA (output power: 0.5 W) (*left*), whereas the mode is distorted for 2800 mA (output power more than 1 W) (*right*)

The quality of this stabilization is at present mainly restricted by the bandwidth of our servo system; work is under way to overcome this limitation. A frequency stability of an ECDL relative to a reference cavity at the level of a few hertz was recently demonstrated [16].

With the achieved quality of lock, the absolute frequency stability of our laser is mainly determined by the length stability of the reference resonator. The latter depends on the isolation of the reference cavity from environmental perturbations. Our investigations of different kinds of cavity supports led us to estimate an absolute frequency stability of the laser of < 10 kHz. Decoupling the reference resonator more efficiently from external vibrations, e.g. by active vibration isolation supports [17], would further reduce the laser linewidth. With improved frequency stabilization schemes at the decahertz level and below, diode lasers become an attractive laser source for ultra-high-resolution spectroscopy [18].

4 Tapered amplifier

Single-pass traveling wave amplifier diodes with a tapered gain geometry (tapered amplifiers) allow efficient amplification of laser radiation up to cw output powers of several watts [19]. Tapered amplifiers thus allow the advantages of diode lasers, such as reliability, tunability and ease of maintenance, to be combined with high single-mode output power.

We use a TA with a central wavelength of 925 nm that can be efficiently used from 900 to 960 nm [20]. The 25-mW infrared light from the ECDL is first passed through a 40-dB optical isolator and a $\lambda/2$ plate and then coupled via an aspherical lens into the TA. For the subsequent second-harmonic generation the output-mode structure of the TA plays an important role. It was attempted to optimize this mode structure, first by mode cleaning the input beam with the help of a single-mode optical fiber and secondly by beam shaping the elliptical input mode with anamorphic prisms. In both cases no significant improvement could be seen. This can be understood by considering the internal geometry of the amplifier [19]: the narrow waveguide behind the input facet itself works as a mode-selective element. However, a strong dependence of the output-mode structure on both the input beam alignment and the amplifier current was observed. Figure 4 shows an optimized output-beam shape in the far field for different amplifier currents, at 1600 mA and 2800 mA, respectively.

In the first case, at a TA output power of 0.5 W, an almost Gaussian beam profile is obtained in both transverse directions (although remaining astigmatic). Here, more than 75 per cent of the power can be coupled into the external enhancement resonator used for the first frequency doubling. In the second case the achieved output power is above 1 W, but the mode structure is strongly non-Gaussian in both transverse directions and only a small fraction of the TA light can be mode-matched to the enhancement resonator.

As far as amplified spontaneous emission (ASE) is concerned, the characteristics of this type of TA differ from the ones previously observed [21]. No noticeable dependence of the ASE on the input laser power has been observed: the ASE is constant, on a level of 50 mW at an amplifier current of 1600 mA ($T = 18\,°C$). The spectral intensity of the ASE is 37 dB below the narrow-band coherent emission.

Important for usage of an ECDL in series with a TA in high-resolution spectroscopy is the frequency fidelity of the amplifier. For analyzing this property, the output of the TA is heterodyned with the master laser frequency. For this purpose the frequency of the TA output is shifted with an acousto-optical modulator and the beat signal between the TA input and output beams is observed. The result is shown in Fig. 5. The width of the beat signal is determined by the resolution of the spectrum analyzer (100 mHz), indicating that the TA does not introduce significant spectral broadening.

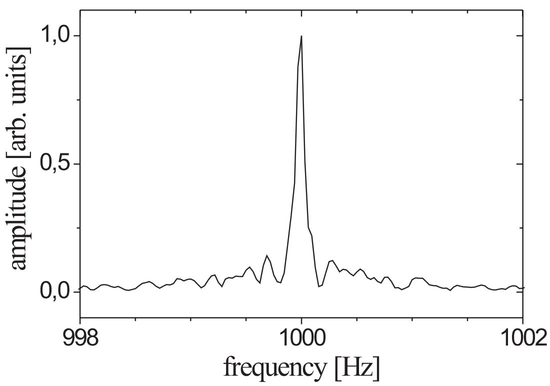

FIGURE 5 Beat signal between input and output beams of the TA, showing a resolution-limited linewidth of 100 mHz

5 Frequency doubling

Efficient second-harmonic generation for a broad range of frequencies in the visible spectrum has been achieved in recent years by using periodically poled ferroelectric crystals [6–10]. In comparison with traditional birefringent phase matching, larger effective non-linear coefficients are accessible through quasi-phase matching, which can additionally be achieved in a non-critical interaction configuration for any

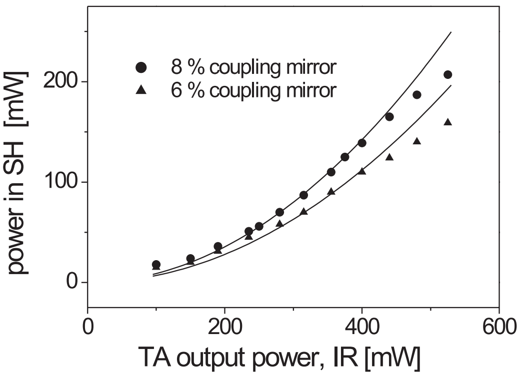

FIGURE 6 Intra-cavity SHG as a function of TA output power for two different coupling mirrors, with 6 and 8 per cent transmission coefficients. The *solid lines* are parabolic fits to the data

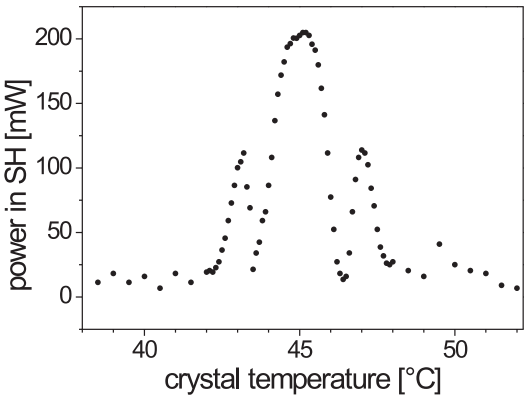

FIGURE 7 Temperature dependence of intra-cavity SHG with a PPKTP crystal

wavelength combination within the transparency range of the non-linear medium [22].

For frequency doubling of the TA light at 922 nm, we use a 20-mm-long PPKTP crystal [23], AR-coated on both sides for infrared and blue radiation. Scattering and absorption losses of the crystal are at a level of 1–2 per cent. To increase the output power at 461 nm, the crystal is placed inside a double-*z* enhancement resonator with a coupling mirror with 8 per cent transmission. The total resonator optical path length is 580 mm. The crystal is placed between two concave mirrors (radius of curvature $r = 100$ mm, optical distance 124 mm) leading to a beam waist inside the crystal of 45 μm along both symmetry axes, close to the optimum value [24]. The crystal temperature can be tuned between 25 °C and 60 °C with a stability of below 100 mK. One of the four resonator mirrors is mounted on a PZT and actuated to keep the cavity resonant with the incoming laser light by means of the Hänsch–Couillaud locking technique [25]. To generate the error signal, a Brewster plate is additionally placed inside the cavity.

Optimum quasi-phase matching was achieved at a crystal temperature of 44.9 °C. At this temperature the power at 461 nm as a function of the infrared TA output power is shown in Fig. 6 for two different coupling mirrors.

With an 8 per cent coupling mirror and a TA output power of 520 mW, we achieve a maximum of 205 mW of cw blue light, corresponding to an overall optical-to-optical efficiency of 40 per cent. For infrared powers above 400 mW the SH power increases more slowly than quadratic because the infrared intensity in the cavity is depleted by the high conversion efficiency.

The blue output power of the frequency-doubling stage as a function of the crystal temperature is shown in Fig. 7. A temperature acceptance bandwidth of 1.8 K (FWHM) is observed at the central resonance, in agreement with the value expected on the basis of the temperature dependence of the indices of KTP [9]. Compared with the sinc^2 behavior that one would expect for the case of single-pass quasi-phase-matched SHG, the presence of the cavity leads to strong enhancement of the side maxima relative to the main peak. This is due to the fact that the fundamental power in the cavity is limited by the conversion losses, so that a lower single-pass conversion efficiency leads to a stronger build-up of the fundamental wave.

In a second enhancement resonator (total optical path length 280 mm), birefringent type-I phase-matched SHG from 461 nm to 231 nm is performed by means of a 7-mm-long BBO crystal with Brewster-cut end facets. The BBO crystal is placed between two concave mirrors ($r = 50$ mm, optical distance 59 mm), the beam waist inside the crystal being close to the optimum value of 23 μm [24]. For stabilizing the enhancement resonator onto the blue light, the Hänsch–Couillaud locking technique is applied a second time. To protect the hygroscopic BBO crystal from condensing water, it is kept at a temperature of about 70 °C. At optimum phase matching, with a blue input power of 200 mW, more than 1 mW of UV light at 231 nm is achieved.

6 Conclusion

We have presented a compact and versatile laser source for tunable narrow-bandwidth blue and ultraviolet radiation. An ECDL at 922 nm is frequency-stabilized to a reference cavity at a level below 100 Hz. Seeding the master laser light into a TA, an infrared power of 520 mW with an almost Gaussian beam profile is obtained. Possible spectral broadening due to the TA is shown to be below 100 mHz. Efficient quasi-phase-matched frequency doubling by means of a periodically poled KTP crystal results in more than 200 mW of blue light at 461 nm. More than 1 mW of ultraviolet light at 231 nm is generated by birefringent phase-matched frequency doubling using a BBO crystal. Due to the high tunability of all components of this setup combined with its reliability and ease of maintenance, such a laser system can be useful for a wide range of applications in high-resolution spectroscopy and quantum optics.

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