Narrow bandwidth interference filter-stabilized diode laser systems for the manipulation of neutral atoms


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Abstract

We present and investigate different external cavity diode laser (ECDL) configurations for the manipulation of neutral atoms, wavelength-stabilized by a narrow-band high transmission interference filter. A novel diode laser, providing high output power of more than 1 W, with a linewidth of less than 85 kHz, based on a self-seeded tapered amplifier chip has been developed. Additionally, we compare the optical and spectral properties of two laser systems based on common laser diodes, differing in their coating, as well as one, based on a distributed-feedback (DFB) diode. The linear cavity setup in all these systems combines a robust and compact design with a high wavelength tunability and an improved stability of the optical feedback compared to diode laser setups using diffraction gratings for wavelength discrimination.

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1. Introduction

Diode laser systems have become an attractive light source with versatile applications in many fields of modern physics, such as telecommunication or the manipulation of atoms. The atom optical experiments in the field of e.g. quantum degenerated gases [1] or metrology [2] with their future space-based experiments [3–5] make high demands on the laser systems. The challenge is to design compact and robust laser configurations offering a narrow linewidth and a high output power.

In this article, we compare four different laser systems, based on a narrow-band high transmission interference filter, as presented in [6,7]. The laser designs offer an improved stability and tunability compared to grating-based setups combined with convincing spectral properties. In particular, we study a novel laser design, based on a self-seeded tapered amplifier, in the following called tapered laser (TL). The TL provides a high output power and a narrow spectral bandwidth combined with a higher stability, yielding a better performance than self-seeded tapered amplifier lasers using a grating for wavelength discrimination. In addition, the TL offers a simplified setup compared to the well-established master-oscillator-power-amplifier (MOPA)-system [8]. Furthermore, we study three ECDL-systems which differ in their implemented medium power laser diode (<100 mW), thus leading to different properties, such as wavelength tunability and output power of the lasers. We implemented two common laser diodes, with and without an AR-coating, as well as a DFB-diode in the ECDL-systems.

The article is organized as follows: We begin in Section 2 with the general description of the studied laser configurations. The characterization of the ECDL-setups follows in Section 3.1. Finally, we discuss the properties...
of the new high output power laser prototype in Section 3.2.

2. Laser configurations

The basic setup for the three ECDLs, described in [7] is illustrated in Fig. 1a. The emitted light from the laser diode is collimated by an aspheric lens (CL) \((f = 3.1 \text{ mm})\) with a high numerical aperture \(NA\) of 0.68. A part of the collimated light is back reflected to the laser diode by a partially transmitting mirror (OC). Different reflectivities \(R\) are used for the three lasers, respectively. Together with the laser diode, the out-coupling mirror forms the external cavity of the laser with a total length of 70 mm. The length of the cavity can be modified by displacing the out-coupler with a piezo-electric transducer (PZT). A higher stability of the optical feedback is obtained by placing an aspheric lens \((L_1)\) with \(f = 18.4 \text{ mm}\) in front of the out-coupler in focal length distance (cat eye configuration). The out-coupled light is then collimated by a second identical lens \((L_2)\). The interference filter \((IF)\) is placed inside the cavity. As it was presented in [7], the interference filters have 90% transmission and a FWHM of about 0.3 nm. By varying the filter's angle of incidence relative to the optical axis the wavelength can be coarsely adjusted. The advantage of this design is that the wavelength discrimination and the optical feedback are performed by two independent elements, the interference filter and the out-coupler [7]. In combination with the linear design of the setup, the interference filter-stabilized configuration offers a higher stability and tunability compared to the Littrow design [6,9]. Furthermore, the wavelength dependent spatial displacement of the out-coupled beam is reduced compared to grating-stabilized setups.

We investigated the implemented laser diodes [10] for the three ECDL-systems with respect to their different spectral properties and their application in the manipulation of atoms. The laser diode in laser 1 is a common laser diode with a center wavelength \(\lambda_c\) of 783 nm and without an AR-coating. With a reflectivity of 30% for the out-coupler we obtain stable laser operation. A laser diode with an AR-coated front facet and with \(\lambda_c = 770\) nm was chosen for laser 2, providing a broad wavelength tunability. Here we use a reflectivity of 20% for the out-coupler. In laser 3 a DFB-diode with a specified linewidth of less than 2 MHz and a center wavelength of \(\lambda_c = 780\) nm is implemented. Due to this intrinsic narrow linewidth we chose an out-coupler with \(R = 20\%\).

The design of the tapered laser is illustrated in Fig. 1b. It is based on a self-seeded tapered amplifier (TA), emitting light in both output directions. The backward emitted light is focused with an aspheric lens \((L'_1)\) with \(f = 4.5 \text{ mm}\) and \(NA = 0.55\) on a HR coated mirror (M) which forms together with the front facet of the TA the 77 mm long external cavity of the TL. We could observe an unstable multi-mode operation, arising from parasitic feedback of the following collimation optics, using a common TA-chip with an AR-coating on both sides. To suppress this disturbing effect we increased the feedback of the TL-cavity by implementing a TA-chip with a low reflectivity at the front facet and an AR-coated back facet [10]. An interference filter (IF) is set up in between the mirror and the TA. The back reflected light is seeding the TA chip. In the gain medium of the TA the light is amplified and finally emitted from the front facet. Due to the high asymmetry of the output aperture we use an aspheric lens \((L'_2)\) with \(f = 4.5 \text{ mm}\) and \(NA = 0.55\) as well as a cylindric lens \((L'_3)\) with \(f = 80 \text{ mm}\) to collimate the astigmatic output beam. The laser, the beam-shaping optics and a following optical isolator are shielded by a foamed material to reduce acoustic noise. For passive stabilization, the laser bodies of the TL as well as of the other three lasers are milled from a single solid block of Certal. The block and the diode are independently temperature controlled.

3. Characterization of the laser systems

In this section, we present and discuss the optical properties of our laser systems, such as the linewidth and the wavelength tunability. We also characterize the output power and the spatial mode quality. The relevant properties of the ECDL-configurations are summarized in Table 1. The characterization of the tapered laser is discussed separately in Section 3.2.

3.1. Properties of the ECDL-configurations

For the determination of the linewidth of each laser, at 780 nm, a series of beat measurements have been taken. The beat notes of each possible combination of two lasers permit an estimation of the linewidth for each laser. The full width half maximum (FWHM) squared of the beat signal is given by the sum of the squared linewidths of two

Fig. 1. Schematic drawing of the laser configurations 1–3 in (a) and of the tapered laser in (b). The optical elements laser diode (LD) or tapered amplifier (TA), collimation lens (CL), interference filter (IF), out-coupler (OC) or mirror (M), piezo-electric transducer (PZT) and lenses \((L_{1,3})\) as well as \((L'_{1,3})\) for the cat eye configuration and collimation purposes are displayed.
uncoupled lasers. As an example, the beat signal at 410 MHz of laser 1 and laser 3, both free-running, is shown in Fig. 2. The instantaneous linewidth can be calculated by determining the FWHM of a Lorentzian fit of the distribution’s flanks for frequencies with \( |\nu - \nu_0| > 0.5 \) MHz. Due to technical frequency noise the center frequency is distributed randomly and can be fitted with a Gaussian function for \( |\nu - \nu_0| < 0.5 \) MHz.

The values for the linewidths of each free-running laser are summarized in Table 1. The broadened linewidths for all lasers are between 120 kHz and 150 kHz determined by the Gaussian fit. We obtain an instantaneous linewidths for the three lasers of approximately 8 kHz determined via a Lorentzian fit.

The wavelength of the ECDL can be coarsely adjusted by varying the angle of incidence of the interference filter relative to the optical axes or by changing the temperature of the laser diode. A fine wavelength adjustment can be achieved by changing the resonator length with the PZT or by modifying the supply current of the diode. During the measurements we kept the diode’s temperature constant. Changing the filter’s angle of incidence leads to a wide wavelength tunability of several tens of nm as shown in Fig. 3. The jump of the laser mode during the wavelength tuning is due to the jump to the adjacent transmission peak of the interference filter. The inset in Fig. 3 shows the transmission curve of the interference filter. A broad transmission minimum between 680 nm and 930 nm is observable. Within that valley, several sharp transmission peaks separated by about 33 nm arise, limited here by the resolution (1 nm) of the spectrometer [11]. We achieve wavelength tunabilities between 11 nm and 32 nm for the three lasers (see Table 1).

Due to the difference in the physical dimensions of the diodes, the current dependent frequency tunability differs for the three configurations, as can be found in Table 1. Stable operation just on the same diode mode is assured within several tens of GHz for all lasers. However, mode competition due to the ECDL-configuration leads of course to mode instabilities which can be compensated by changing the resonator length. By varying only the PZT voltage, single-mode operation for the three lasers can be assured within a span of about 2 GHz, limited by the length of the external cavity. With the combination of PZT and current tuning, a mode-hop-free tuning range of several GHz can be accomplished.

A further important property is the output power \( P \) of the lasers which depends on the properties of the implemented diode as well as on the feedback which is mainly determined by the reflectivity of the out-coupler. Since the linewidth also depends on \( R \), it is necessary to make a compromise between small linewidth and high output power. For an optimal operation current we achieve output powers between 30 mW and 39 mW, measured before going through an optical isolator. The values for the power as well as the values for the threshold of the three lasers are summarized in Table 1.

Another criterion of the lasers is the spatial mode profile which is necessary for a well-defined manipulation of atoms or for the efficiency of fiber coupling. We characterized the profile by measuring the beam shape with a CCD-camera at a distance of about 20 cm from the lasers. By fitting a Gaussian function to the distribution’s cross-section, we could coarsely estimate the purity of the spatial mode profile. All lasers provide a major fraction of the TEM\(_{00}\) mode in their profile. The best performance could be realized with laser 3, where the distribution corresponds with 99.6% to a Gaussian fit. Furthermore, we reach efficiencies of over 72% for lasers 1 and 3 for the injection of the laser beam into a single-mode fibre. We inject 63% for laser 2, where the AR-coating is responsible for a slightly worse spatial mode shape.
Table 1
Optical and spectral properties of the characterized ECDL-configurations

<table>
<thead>
<tr>
<th>LD feature</th>
<th>Laser 1</th>
<th>Laser 2</th>
<th>Laser 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Non-AR</td>
<td>AR</td>
<td>DFB</td>
</tr>
<tr>
<td>Linewidth $\Delta v$ (kHz) (Gaussian)</td>
<td>$130 \pm 25$</td>
<td>$150 \pm 25$</td>
<td>$120 \pm 25$</td>
</tr>
<tr>
<td>Linewidth $\Delta v$ (kHz) (Lorentzian)</td>
<td>$8 \pm 2$</td>
<td>$8 \pm 2$</td>
<td>$8 \pm 2$</td>
</tr>
<tr>
<td>LD current tun. (GHz)</td>
<td>$33$</td>
<td>$43$</td>
<td>$28$</td>
</tr>
<tr>
<td>Current sen. (MHz/mA)</td>
<td>$92$</td>
<td>$87$</td>
<td>$62$</td>
</tr>
<tr>
<td>Filter tun. (nm)</td>
<td>$11$</td>
<td>$32$</td>
<td>$19$</td>
</tr>
<tr>
<td>PZT tun. (GHz)</td>
<td>$2.3$</td>
<td>$2.3$</td>
<td>$2.1$</td>
</tr>
<tr>
<td>$P$ (mW) (@ supply current (mA))</td>
<td>$34$ (100)</td>
<td>$39$ (110)</td>
<td>$30$ (113)</td>
</tr>
<tr>
<td>$I_{\text{threshold}}$ (mA)</td>
<td>$23$</td>
<td>$36$</td>
<td>$30$</td>
</tr>
<tr>
<td>Estimation TEM$_{50}$ (%) (Gaussian fit)</td>
<td>$99.4$</td>
<td>$95.8$</td>
<td>$99.6$</td>
</tr>
</tbody>
</table>

Though the lasers are very similar, they offer different advantages. Laser 1 is an economic and attractive alternative, due to the low costs of the implemented laser diode. The large wavelength tunability of laser 2 makes this system interesting for experiments including dual species manipulations like atomic potassium (766 nm) and rubidium (780 nm). Laser 3 offers slightly better properties compared to the other two lasers concerning the linewidth and spatial mode profile.

We also measured the linewidth of a laser similar to laser 3 but without the interference filter. In this case we obtained a linewidth which is two times bigger than for the IF-stabilized laser. Mode instabilities due to a possible conflict of the two frequency selective elements in the design of laser 3, the filter and the integrated grating structure in the diode, have not been observed.

From the accomplished characterization, we can summarize that all the three lasers are versatile tools for experiments concerning the precise manipulation of atoms. Due to their brilliant spectral properties, the utilization as a Raman-laser [12] or for detection purposes are interesting applications for these lasers.

3.2. The tapered laser

As we will discuss in the following, the self-seeded tapered amplifier prototype offers an attractive alternative to other high power diode laser systems. To deduce the linewidth of the TL we measured the beat note, shown in Fig. 2, between the free-running TL and laser 1, locked to a Rb-transition. With the Gaussian fit of the center region we obtain a FWHM of 200 kHz and thus a broadened linewidth of 187 kHz ± 12 kHz for the tapered laser.

For the instantaneous linewidth of the TL we obtain less than 5 MHz with respect to the carrier frequency the background, which is dominated by the contributions of the amplified spontaneous emission, is 40 dB smaller compared to the carrier signal.

Due to the cavity length of 77 mm, the mode-hop-free tunability with the PZT is about 2 GHz. The sensitivity of the laser frequency for current variations was determined to 19 MHz/mA. A sweep of several GHz without mode-hopping can be observed for a combined PZT-current tuning. The specified current noise of the current driver which is about ≈5 μA converts with the measured frequency sensitivity for current variations of 19 MHz/mA into a frequency noise in the order of several tens of kHz. Thus the dominant contribution for the broadening of the linewidth is the noise of the current driver.

The power characteristic is a remarkable feature of the new TL-design. High output power of 1.24 W at a supply current of $I_{\text{TA}} = 2$ A before going through the optical isolator has been reached. We obtain a slope of 1081 mW/A and a threshold current of $I_{\text{th}} = 0.9$ A for the power characteristic.

The spatial mode profile is similar to that of a MOPA-system. This turns out from the comparable injection efficiencies into a single mode fibre which is in the case of the TL approximately 51%. Similar injection values have been achieved with MOPA-systems [8].

For a further consideration we discuss the feedback properties of the TL. As it was introduced in [7] the feedback $F$ depends strongly on the waist $w_0$ at the mirror’s surface. The feedback, normalized by the reflectivity, against a disturbance of the mirror with respect to the optical axes is given by

$$F = e^{-(\pi x w_0/\delta)^2}$$

for a small tilt with the angle $\alpha$ and by

$$F = \left(1 + \frac{\delta^2 w_0^2}{\pi^2 w_0^2} \right)^{-1}$$

for a displacement $\delta$. According to the formula, the reduction of the feedback due to a tilt increases with an increasing waist size, what sets an upper limit for $w_0$. On the other hand, $w_0$ must not be chosen to small to assure stability of the feedback against displacements of the mirror. A waist of 10 μm as realized in the ECDL-configurations as well as a waist of about 1 mm for a collimated beam in the TL-cavity leads to an unstable, multi-mode operation of the TL. As an optimal compromise we realized a waist of about 40 μm at the mirror’s surface. Disturbances of $F$ due to a tilt of the mirror are negligible for this value of $w_0$.

The new laser system offers many advantages compared to grating-stabilized self-seeded TA-systems or MOPA-systems. In the tapered laser the interplay between angular and displacement sensitivity is easier to control compared to Littrow designs [7] by choosing an adequate beam waist. A further advantage of the IF-based system is that the wavelength dependent spatial displacement of the beam...
for a tuning of the interference filter, due to the small length which is approximately 0.5 mm of the IF, is strongly reduced. It is even more reduced than in the presented ECDL-configuration, due to the out-coupling at the front facet of the TA. In addition, the TL offers a more compact and simplified setup with a base area of $16 \times 7 \text{ cm}^2$, providing lower costs compared to conventional MOPA-lasers, where a master and an amplifier system are required.

4. Conclusion

In the presented work compact and robust laser configurations have been realized based on the wavelength discrimination via narrow-band interference filter. The novel tapered laser with its high output power of more than 1 W combined with best spectral properties, reaching a linewidth of less than 85 kHz, offers a very promising alternative to state-of-the-art systems. The presented laser systems are currently implemented in atom optical experiments for cooling and trapping purposes of different atomic species (Rb, K).

Acknowledgement

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References

[10] The implemented laser diodes are the following: Sharp: laser 1: GH0781JA2C, eagleyard Photonics: laser 2: EYP-RWE-0790-04000-0750, laser 3: EYP-DFB-0780-00080-1500, TL: modified TA-chip at 780 nm; for the exact value of the reflectivity of the front facet, we would like to refer to eagleyard Photonics. The interference filter which has been used in all lasers is a custom-made product of Research Electro-Optics.
[11] A spectral analysis of the interference filter has been performed in the Laser Zentrum Hannover by I. Balasa.