Evanescent-wave mirrors for cold atoms
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A high-power tapered semiconductor amplifier system

A laser amplifier system has been characterised which provides up to 200 mW output at 780 nm wavelength after a single-mode optical fibre. The system is based on a tapered semiconductor gain element that amplifies the output of a narrow-linewidth diode laser. Gain and saturation are discussed as a function of operating temperature and injection current. The spectral properties of the amplifier were investigated with a grating spectrometer. Amplified spontaneous emission (ASE) was observed as a spectral background with a full width half maximum of 4 nm. The ASE background was suppressed to below the detection limit of the spectrometer by a proper choice of operating current and temperature, and by sending the light through a single-mode optical fibre. The final ASE spectral density was less than 0.1 nW/MHz, i.e. less than 0.2% of the optical power. Related to a rubidium optical transition linewidth of $\Gamma/2\pi = 6$ MHz, this gives a background suppression of better than $-82$ dB. An indication of the beam quality is provided by the fibre coupling efficiency up to 59%. The application of the amplifier system as a laser source for atom optical experiments is discussed.

This chapter is based on the preprint

4.1 Introduction

The techniques of laser cooling and trapping of neutral atoms require stable, narrow-linewidth and frequency-tunable laser sources [11,12]. Commonly used systems for the near-infrared wavelengths are based on external grating diode lasers (EGDL) [117]. Optical feedback from a grating narrows the linewidth to less than 1 MHz and provides tunability. High-power single-transverse-mode diode lasers can provide up to 80 mW optical output at wavelengths below 800 nm. In this power range, diode lasers thus provide a less costly alternative to Ti:Sapphire lasers. If more power is required, the output of an EGDL can be amplified. Presently, there are three common techniques based on semiconductor gain elements: (i) Injection-locking of a single-mode laser diode [138,139] by seeding light from an EGDL results typically in 60 – 80 mW optical power at 780 nm wavelength. (ii) Amplification in a double-pass through a broad-area emitting diode laser (BAL) [161–167]. This yields an optical output of typically 150 mW after spatial filtering. A disadvantage is the relatively low gain of 10 – 15, requiring high seed input power. The BAL gain can be improved using phase conjugating mirrors in the seed incoupling setup [168]. (iii) Travelling-wave amplification in a semiconductor gain element with a tapered waveguide, a “tapered amplifier” (TA) [163,169–171]. Compared to a BAL this yields higher gain and higher power after spatial filtering. This approach requires much lower input and a less complex optical setup than a BAL. However, a TA gain element is considerably more expensive.

We have investigated a TA system that amplifies the narrow-linewidth seed beam of an EGDL and provides up to 200 mW optical output from a single-mode optical fibre. With the tapered gain element, characterised in this chapter, the system operates on the D2 (5S_{1/2} \rightarrow 5P_{3/2}) line of rubidium at a wavelength of 780 nm, see Fig. 3.7. Another gain element of the same type but with a different centre wavelength is used on the D1 (5S_{1/2} \rightarrow 5P_{1/2}) line at 795 nm. The input facet of the tapered gain element has the typical width (\approx 5 \mu m) of a low power single-transverse-mode diode laser. A seeding beam is amplified in a single pass and expanded laterally by the taper to a width of typically 100 – 200 \mu m such that the light intensity at the output facet is kept below the damage threshold and the beam remains diffraction limited (see e.g. Ref. [169]). The output power can thus be much larger than from a single-mode waveguide.

In previous work, TAs have been used as sources for frequency-doubling and pumping solid state lasers [172]. Apart from the achievable output power, frequency tunability of the narrow-linewidth output [173], simultaneous multifrequency generation [174], and spatial mode properties, including coupling to optical fibres [175–177] have been addressed.

In this chapter the broadband spectral properties of the TA are discussed. We have minimized the background due to ASE in the gain element by adjusting the operating conditions of the amplifier, i.e. temperature, injection current and seed input power. We have also investigated the coupling efficiency of the TA output to a single-mode optical fibre, and have found that the latter acts both as a spatial and as a spectral filter. The properties of three gain elements of the same type are
4.2 Amplifier setup

The amplifier system consists of a seed laser, the output of which is amplified in a single pass by the tapered gain element, as shown in Fig. 4.1. The TA output is coupled to a single-mode optical fibre (OFR, type PAF-X-5-780 fibre port, input beam dia. 0.9–1.8 mm). The seed laser is an EGD L with a linewidth of less than 1 MHz. It operates by a 60 mW single-mode laser diode (Hitachi, HL7851 G98) and provides 28 mW to seed the amplifier at 780 nm wavelength. Coupling of the seeding beam to the amplifier was realised by mode-matching the seed laser with the backward travelling beam emitted by the TA. The divergence angles from the seed laser emission and the backward directed TA emission are similar. Hence, sufficient mode-matching was obtained using identical collimation lenses for both (Thor-Labs, C230 TM-B, f = 4.5 mm, N.A. = 0.55). Additional mode shaping, e.g. with

Figure 4.1: Setup of the tapered amplifier system. Seed laser (EGDL), tapered gain element (TA), 60 dB optical isolators (OI), single-mode optical fibre (OF), optical spectrum analyser (SA) and grating spectrometer (GS). A top and side view of the gain element is shown with input and output collimators (IC, OC). A cylindrical lens (CL) compensates astigmatism (not to scale).
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Anamorphic prism pairs were not necessary. An optical isolator with 60 dB isolation protects the stabilised seed laser from feedback by the mode-matched beam of the amplifier (Gsänger Optoelektronik, type DLI1). The 5 mm aperture of the isolator is sufficiently large not to clip the elliptical seed beam.

The TA was a SDL 8630 E (Spectra Diode Laboratories, ser.no. TD310). According to the manufacturer’s data sheet, the output power ranged between 0.5 – 0.55 W within a wavelength tuning range of 787 – 797 nm, at an operating temperature of 21°C. The beam quality parameter is typically specified as $M^2 < 1.4$ [178]. The TA should be protected from any reflected light, because it will be amplified in the backward direction and may destroy the amplifier’s entrance facet. Hence, the output collimator has a large numerical aperture (ThorLabs, C330 TM-B, $f = 3.1$ mm, N.A.=0.68) and the beam is sent through a second 60 dB optical isolator (Gsänger, FR 788 TS). The plane of the tapered gain element is vertically oriented, so that diffraction yields a large horizontal divergence. The beam is then collimated similarly to the seed input, but yields a focus in the vertical plane. A cylindrical lens (Melles Griot, no. 01 LQC 006/076, $f = 100$ mm) compensates the astigmatism of the beam, so that the beam can couple to a single-mode optical fibre. The astigmatism correction is shown in Fig. 4.1 (see also Ref. [158]).

There is a considerable loss in optical power due to the isolator transmission. Taking also into account small reflection losses on the lens surfaces, we estimated the useful output power to be 78% of the power emitted by the TA facet. In the remainder of this chapter, all quoted powers are as measured with a calibrated power meter behind the optical isolator (Newport, meter 840-C, detector 818-ST, calibration module 818-CM). The narrow spectral line of the seed laser and amplifier output was monitored by an optical spectrum analyser with 1 GHz free spectral range and with 50 MHz resolution. The amplifier’s broad spectral background was analysed using a grating spectrometer with a resolution of 0.27 nm. Also the output of the single-mode fibre was recorded with the spectrometer.

The amplifier was provided as an open heat sink device, see Fig. 4.2. We mounted it on a water cooled base and stabilised it to the desired operating temperature within a few mK by a 40 W thermo-electric cooler. Thermal isolation from the ambient air and electromagnetic shielding were provided by a metal housing. When operating the amplifier at temperatures below the dew point, we flushed the containment with dry nitrogen. It is necessary to have a compact, stable mounting of the gain element and collimators. We mounted the collimators in a commercial xy-flexure mount to allow for lateral lens adjustment (New Focus, 9051 M fibre launcher). The axial z-adjustment was done by two translation stages (Newport, type UMR 3.5, travel 5 mm). All adjustments, except that of the z-direction of the output collimator, are accessible from outside. This proved to be very convenient for mode-matching the seed beam and also for compensating beam displacement of the TA output when changing temperature or current.
4.2 Amplifier setup

Figure 4.2: Construction of the tapered amplifier setup.
Figure 4.3: Temperature dependence of the unseeded amplifier at 1.2 A injection current. (a) spectra, (b) centre wavelength, (c) output power after optical isolator. Solid lines indicate linear fits.

4.3 Unseeded operation of the amplifier

When the TA receives no seed input, it operates as a laser diode. Thus, when the injection current, $I_{TA}$, is increased from zero, the optical output power indicates the lasing threshold [see Fig.4.4(a,b)]. Generally, both the operating wavelength and the optical power of a laser diode depend on the temperature. These properties are shown in Fig.4.3. The emission spectrum of the lasing gain element is almost Gaussian shaped, with a width of 4 nm ($1/e^2$ intensity). It appears as a background of ASE also in the spectra when operating the gain element as an amplifier (see below). The oscillatory structures on the spectra are artifacts of the spectrometer. In the fitted Gaussian spectra, we evaluated the centre wavelength at each temperature setting. It increases with temperature with a slope of 0.28 nm/K, typical for semiconductor lasers.

The temperature dependence of the output power is shown in Fig.4.3(c). We operated the TA within the specifications of the manufacturer’s data sheet that recommends to keep the optical power at the output facet below 550 mW. As the temperature increases, the conversion efficiency (mW/A) decreases and the threshold current increases. This can be seen in Fig.4.4(a,b) (open symbols) where the optical output power $P$ is plotted vs. the current $I_{TA}$ for two temperature settings. The threshold current of the unseeded TA increases from 0.78 A (5°C) to 0.86 A (14°C). From the slopes above threshold, we find that the conversion efficiency decreases from 0.7 W/A (5°C) to 0.5 W/A (14°C). In order to measure the unperturbed output of the unseeded TA, one has to prevent light emitted from the
4.4 Amplification of a seed beam

Amplification of a seed beam is evident in the output power of the TA. In Fig. 4.4(a,b), the output power for different values of the seed power, $P_{seed}$, is plotted for two temperature settings. For the larger seed inputs of 8.6 mW and 5.3 mW, respectively, the amplifier was well saturated. The saturation is evident from Fig. 4.4(c) where $P_{seed}$ was varied for injection currents from 0.8—1.3 A. With $P_{seed} \approx 4$ mW the device appeared to be saturated for all current settings. For $P_{seed}$ between 2—4 mW, the amplification ranged from 70—140, e.g. 320 mW output with 4 mW seed.

The spectral properties of the TA and in particular the suppression of ASE background are discussed in the following. Fig. 4.5 shows the power spectral density of the TA output before an optical fibre for 16° C and 5° C operating temperature. In both cases the amplifier was saturated with 28 mW seed input. For comparison also the corresponding spectra of the unseeded amplifier are shown. In saturation, the broad ASE background is distinguished from a narrow peak of the amplified seed signal. The width of the peak is given by the bandwidth of the spectrometer, 0.27 nm.
Figure 4.5: Spectrum of the amplifier output (before the fibre). The seed power was 28 mW, the injection current 1.2 A. Dashed curves are for unseeded operation. ASE is the background fraction of the total optical power $P$ and $\varepsilon$ is the ASE suppression for the power spectral density in units of mW/T (see text).

FWHM. Note that for the characterisation of the TA system, a different spectrometer was used than the PC-card spectrometer mentioned in Chap. 3. The linear dynamic range of the photomultiplier tube (PMT) which was used as a detector with the grating spectrometer, did not cover the entire dynamic range of 40 dB. Therefore, we used a calibrated neutral density filter (CASIX, type NDG 0100) when recording the large signal of the locked laser line. A filter transmission of 6.0 % (780 nm) and 5.1 % (795 nm) was measured and linearly interpolated between these wavelengths. The small gap in the right slope of the peak in Fig. 4.5(b) (at 10 dBm/nm) indicates where the signal recorded with the filter was joined to the ASE spectrum recorded without the filter. Within the dynamic range where it was used, we verified that the response of the PMT was linear to within 1%. By means of an optical spectrum analyser and Doppler-free spectroscopy on rubidium, we could also verify that the amplified beam was spectrally narrow, comparable to that of the EGDL.

The influence of the operating temperature is obvious first from the increased output power at lower temperature: 323 mW (16°C) and 410 mW (5°C), respectively. Second, both the peak level and total amount of ASE background are better suppressed at lower temperature. We attribute this to the shift of the gain profile of the TA toward the seed wavelength of 780 nm at a lower temperature [179]. The fraction of ASE background in the TA output is obtained by integrating the power spectral densities in Fig. 4.5, yielding 5.6 % (16°C) and 1.4 % (5°C), respectively.

More than the total ASE fraction, the important figure for atom-optical applications is the fraction of ASE within the natural linewidth of the atomic transition used. We define this ratio $\varepsilon$ by comparing the power in the peak with the ASE power in a bandwidth given by a typical atomic natural linewidth, e.g. $\Gamma/2\pi = 6$ MHz
for rubidium. At $16^\circ C$, the ASE peak value of $+2.5$ dBm/nm is then reexpressed as $22$ nW/Γ, or $7.9$ nW/Γ at $5^\circ C$, respectively. With $323$ mW in the narrow line, this leads to a suppression ratio $\varepsilon = -72$ dB, or $-77$ dB with $410$ mW, respectively. By an appropriate choice of the operating temperature one can thus optimize the spectral properties of the TA output. Even better suppression is achieved using an optical fibre as a *spectral* filter.

### 4.5 Spatial and spectral filtering by an optical fibre

For many applications, laser beam quality is an important property. A convenient method to obtain spatial filtering is to send the light through a single-mode optical fibre. An additional advantage of the fibre is a decoupling of the optical alignment between different parts of the experimental setup. Here, the coupling efficiency is discussed and the spectrum of the transmitted light is compared with the spectrum before the fibre. We observe that *spatial* filtering by the fibre is accompanied by *spectral* filtering. Evidently, the contribution of ASE in the TA beam is spatially distinguishable from the amplified seed signal.

The spatial mode properties of the saturated TA output were slightly different for different injection currents. Fig. 4.6(a,b) represents the fibre transmission vs. the current. The fibre coupling had been optimized for a current of $1$ A and the TA was saturated. A maximum transmission of $46\%$ was achieved. For comparison, with an unamplified EGDL, after circularising the beam using an anamorphic prism pair, a typical fibre transmission of $75\%$ was obtained. The slope in the transmission curve is probably due to a beam displacement caused by the current-dependent thermal load of the gain element. Such a displacement was also observed when the operating temperature was changed. With the fibre coupling thus optimized, light from the unseeded TA had less transmission than the amplified seed signal. Fig. 4.6(c,d) shows for a fixed current of $1$ A that the fibre transmission was almost independent of the seed input power, i.e. the beam shape did not change.

Also the light after the fibre was analysed using the grating spectrometer for an operating temperature of $5^\circ C$, see Fig. 4.7(a). For the saturated amplifier a spectral ASE background cannot be distinguished after the fibre, since the peak is identical with the spectrometer response function. (This response function was obtained by recording the spectrum of the narrow-linewidth EGDL laser. A similar response was also obtained using a HeNe laser.) Thus, we can only assign an upper limit of $0.2\%$ for the ASE contribution. The suppression ratio is $\varepsilon < -82$ dB, with an ASE level of less than $-12.5$ dBm/nm$= 0.7$ nW/Γ. This should be compared to the value of $\varepsilon = -77$ dB before the fibre, as in Fig. 4.5(b) for $5^\circ C$. For comparison, at $16^\circ C$ we found an ASE suppression of $-76$ dBm after the fibre.

The ASE background depends also on the degree of amplifier saturation, as shown in Fig. 4.7(b). The ASE fraction is plotted vs. seed power for light before and after the fibre. It decreases quickly as the TA saturates. From the spectra acquired before the fibre (△ △), it is evident that the increase of seed power into the saturated regime suppresses the ASE.
Figure 4.6: Transmission through a single-mode optical fibre. (a) Fibre input (▲) and output (▼) with 28 mW seed, and without seed (△ ▼); (b) fibre transmission with (●) and without (○) seed; (c) fibre input (▲) and output (▼) as a function of the seed power; (d) corresponding fibre transmission.

Figure 4.7: Spectral filtering by a single-mode optical fibre. (a) Saturation with 28 mW seed power at 1.2 A current, 130 mW power after the fibre, 410 mW before. ASE background is not distinguishable from the spectrometer response function after the fibre. (b) The ASE fraction depends on the saturation: fibre input (▲ △) and output (▼ ▼) at 1.2 A current. For comparison: fibre input with 1.45 A current (●).
4.6 Variations of individual gain elements

Optimal ASE suppression required a careful alignment of the mode-matched seed input, i.e. optimization of the TA saturation, whereas achieving maximum output power was less critical. It is also obvious from the figure, that larger gain of the TA with larger operating current improved the output spectrum (●).

Summarising the results of Sec. 4.4 and 4.5, the spectral properties of the TA can be optimized by choosing an appropriate operating temperature, spectral filtering with an optical fibre and saturation of the gain element.

4.6 Variations of individual gain elements

We compared the TD 310 gain element with two other gain elements of the same type (SDL 8630E). One gain element (ser. no. TD 430, 777 nm) was used in the setup described above. A second (ser. no. TD 387, 790 nm) was implemented in a commercial TA system (TUI Optics, TA 100) and operated on both the D2 and the D1 transition of rubidium at 780 nm and 795 nm, respectively.

For the different gain elements, we found considerable differences in their beam quality and consequently their fibre coupling efficiency. Whereas TD 310 and TD 387 showed a dominant double-lobe mode structure in the far field and permitted only a fibre transmission of 46%, the TD 430 beam showed a less pronounced lobe structure. Fig. 4.8 gives an impression of the collimated TD 430 beam profile, as imaged with a CCD video camera. Fibre coupling was achieved using the output collimator and the cylindrical lens to shape a “circular”, though slightly converging beam at the location of the fibre port. With this gain element, we could couple 59% to the fibre and obtained 200 mW after the fibre, with an ASE suppression of better than −84 dB. Note that already at its first usage, the TD 310 displayed a shadow in the near field of its amplified output beam. After approximately 100 hours of operation the gain element quickly degraded and became inoperable.

The amplification properties also showed striking differences among the gain elements. TD 430 has similar saturation properties as TD 310. For example, when seeded by a master oscillator, optimal spectral purity of the output was achieved when also the (amplified) output power was at maximum. In contrast, TD 387 operates as a laser oscillator rather than an amplifier, yielding saturated output power already without seed. Although the coatings of our gain elements were not specified by the manufacturer, the difference in behaviour suggests that TD 387 may have a larger reflectivity on the entrance facet, see e.g. Ref. [180]. Hence, the TD 387 requires (permanent) monitoring by a spectrometer in order to optimize

![Image of far field beam profile](image.png)

**Figure 4.8:** Far field beam profile of the TD 410 gain element.
seed incoupling and ASE suppression. The current of the TD 387 cannot be tuned continuously, because it shows discrete “locking-ranges”, resembling the injection-locking behaviour of single-mode diode lasers.

4.7 Far off-resonance dipole potentials with spectral background

In this section the consequences of a broad spectral ASE background for light scattering in optical dipole traps are estimated. A background that covers atomic resonances leads to extra resonant scattering. Usually the detuning δ for a dipole trap is chosen as large as possible, given the available laser intensity \( I_L \). The reason is that off-resonance scattering scales as \( \Gamma_{\text{OR}} \propto I_L/\delta^2 \) at low saturation and large detuning, whereas the dipole potential is only inversely proportional to the detuning, \( \mathcal{U}_{\text{dip}} \propto I_L/\delta \) (see e.g. Ref. [2] and Appendix A.3).

In the presence of resonant background the total scattering rate of the atoms is

\[
\Gamma' = \Gamma_{\text{OR}}' + \Gamma_R'.
\]

where \( \Gamma_R' \) represents the resonant scattering. For a fixed depth of the optical dipole potential this results in a maximum useful laser detuning, \( \delta_{\text{max}} \), at which the scattering rate of the atoms, \( \Gamma' \), is minimized. With low atomic saturation by a weak spectral background, we can write

\[
\Gamma_R' \approx \Gamma \frac{\pi}{4} \frac{\varepsilon I_L}{I_0}.
\]

The saturation intensity is, e.g., \( I_0 = 1.67 \text{ mW/cm}^2 \) for the D2-line of rubidium. Hence, with the restriction of a fixed potential \( \mathcal{U}_{\text{dip}} \), the two scattering contributions scale as \( \Gamma_{\text{OR}}' \propto 1/\delta \) and \( \Gamma_R' \propto \delta \), respectively. This results in the optimum detuning and minimum scattering rate,

\[
\delta_{\text{max}} = \pm \Gamma/\sqrt{2\pi\varepsilon},
\]

\[
\Gamma' = 2\sqrt{2\pi\varepsilon \mathcal{U}_{\text{dip}}/\hbar}.
\]

As an example we consider atoms cooled to a temperature of a few \( \mu \text{K} \) in optical molasses and require an optical potential depth of \( \mathcal{U}_{\text{dip}}/\hbar \approx 1 \text{ MHz} \). If the allowable scattering rate is, e.g., \( \Gamma_{\text{max}} < 100 \text{ s}^{-1} \), this yields a required background suppression \( \varepsilon < -110 \text{ dB} \) and an optimum detuning \( \delta_{\text{max}} \approx 760 \text{ GHz} \). Such a small background contribution is of course beyond the resolution of our spectrometric data, with which we observed at best an upper limit of 0.7 nW/\( \Gamma \) ASE spectral power, for a total power of 200 mW. This corresponds to a background suppression of \( \varepsilon < -84 \text{ dB} \). With a detuning of 760 GHz, the spatial extension of the optical potential is restricted to less than \( 250 \mu \text{m} \) width.

In principle, one could make use of the resonant photon scattering rate, \( \Gamma_R' \), as an experimental tool to investigate the ASE properties of a laser source. More specifically, \( \Gamma_R' \) appears as an additional source of heating and loss of atoms trapped in a far off-resonance optical dipole trap.
4.8 Conclusions

We have investigated a tapered semiconductor amplifier system, that provides 150–200 mW narrow linewidth output from a single-mode optical fibre, where the fibre transmission is up to 59%, depending on the actual gain element in use. The system requires less than 5 mW seed input to saturate with an amplification up to 140 at this seed level. The output of the amplifier includes a broad spectral background of amplified spontaneous emission. We have found three means of reducing this background: (i) Choosing the operating temperature such that the gain profile of the amplifier is shifted toward the amplified wavelength, (ii) filtering the output beam spectrally with a single-mode optical fibre, and (iii) saturating the amplifier with sufficient seed input power. With these measures, the ASE background is below the resolution of our spectrometer. That is, the ASE fraction is less than 0.2% of the optical power in the beam and the peak level is less than 0.1 nW/MHz. Relating the power spectral density of the background to the natural transition linewidth of rubidium (Γ/2π = 6 MHz), the ASE suppression is better than −82 dB. The atom-optical application of such an amplifier system with far off-resonance dipole potentials was discussed. A broad ASE background implies here an optimum laser detuning with which light scattering by atoms is minimized. A tapered amplifier system may be a lower-cost alternative to a Ti:Sapphire laser. The available single-transverse-mode optical power and spectral properties are similar to those of broad-area semiconductor laser amplifiers.
A high-power tapered semiconductor amplifier system