Compact Tuneable External Cavity Diode Laser with Diffraction Limited 1 W optical power, and their application in BEC and CRDS

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ABSTRACT

The combination of high power, small linewidth and rapid tuneability is essential for many fields in high resolution spectroscopy. Furthermore these optical features are essential for laser-cooling techniques. Enhancement of high power lasers with excellent spectral and spatial quality is currently an important research subject.
The requirements for a laser system applied in both fields of application are demanding: a mode-hop free tuning range of a few GHz, with a linewidth in the order of 1MHz and an output power of a few 100mW.
We report a very compact external cavity diode laser system (ECDL) with an output power of up to 800mW with an almost Gaussian shaped beam quality (M^2<1.2). The coupling efficiency for a single mode fibre exceeds 60%. The centre wavelength can be preadjusted within the tuning range of 20 nm. This laser operates single mode with a mode-hop free tuning range of up to 15GHz without current compensation and a side-mode-suppression better than 50dB at different wavelength between 730 and 1060nm.
To demonstrate the suitability for neutral atom cooling we used this laser as light source in the production of a BEC of over a million ^{87}Rb atoms. In addition we approved this light source for high resolution spectroscopy, more precisely for the Cavity-Ring-Down-Spectroscopy (CRDS). Our ECDL was part of a MIR-light source which utilizes difference-frequency-generation in PPLN. At the wavelength of 3.3µm we were able to perform a high resolution absorption measurement of 50ppb Ethane.
Both applications clearly demonstrate the suitability of this laser for high-precision measurements.

Keywords: external cavity laser, tunable laser, diode laser, laser diode, Bose Einstein condensate, BEC, high power diode laser, ECDL, diffraction limited, Rubidium absorption, CRDS, cavity ring down

1. INTRODUCTION

The requirements for a laser system applied in this field of Bose-Einstein condensation (BEC) and in high resolution spectroscopy are demanding: a mode-hop free tuning range of several GHz, with a linewidth in the order of 1 MHz and an output power above 100 mW after coupling a single mode fiber is required. In the past, such requirements were fulfilled by a master-slave configurations of an external cavity diode laser with an amplifying high power broad area laser diode (LD)[1]. In this case a low power ECDL, which can be tuned several GHz without showing a mode-hop, was performing the low linewidth. This master-laser light is coupled into a high power slave-diode, which amplifies the optical power to the required regime. The disadvantage of this amplification technique is, that the master-slave configurations can be difficult to align by non-experts and tend to be maintenance intensive. Our goal in this presentation was the evaluation of high power diode lasers in this kind of applications.
In order to demonstrate the suitability of this light source for high resolution spectroscopy, we tested our laser system in an ultra sensitive absorption technique called Cavity-Ring-Down-Spectroscopy (CRDS)[2,3,4,5]. It is based on the measurement of the decay rate of light confined in a high-finesse cavity. Cavity ring-down spectroscopy with cw lasers is an unique tool for trace gas detection because it combines high sensitivity and fast response.
Our high power ECDL was part of a MIR-light source which utilizes difference-frequency generation in a periodically poled $LiNbO_3$ (PPLN) crystal pumped by two single-frequency solid state lasers. Fig. 1 shows the schematic setup of the DFG-laser based cavity ring-down spectrometer. Two solid state laser systems are used: our widely tunable external-cavity diode laser and a diode-pumped monolithic Nd:YAG ring laser. Both laser beams are collinearly focussed into the non-linear crystal using several lenses. The PPLN crystal is 5 cm long and both sides AR-coated. The crystal is

structured by 21 stripes, each 0.9X 0.5 mm^2 wide, with periods ranging from 20.6 µm to 22.6 µm. The generated DFG radiation is mode-matched to the ring-down cavity with two lenses. The mirrors of the cavity have a reflectivity of 99.985% at 3.3 µm wavelength.

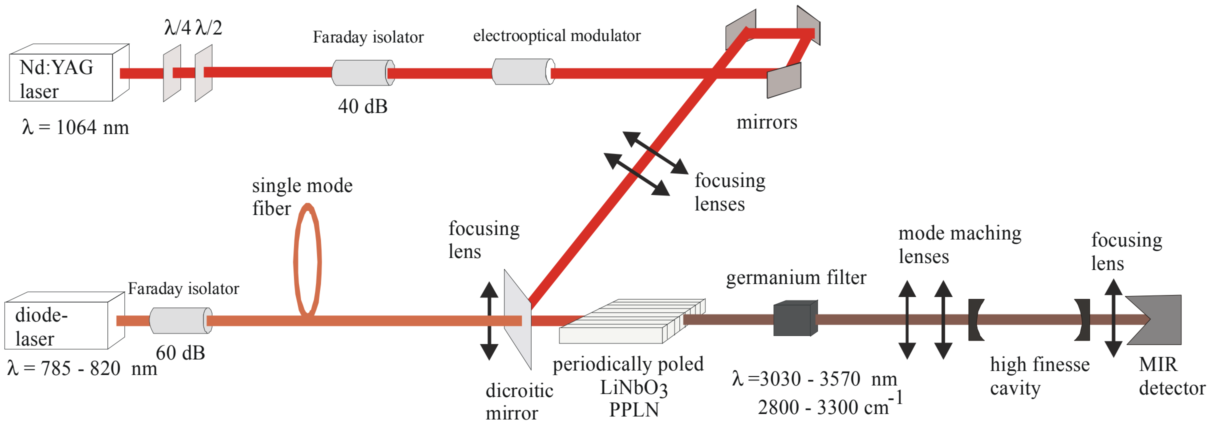

Fig. 1: Schematic setup of a difference-frequency laser combined with a high-finesse cavity.

With the resulting laser light at 3.3 µm we were able to perform a high resolution absorption measurement of 50 ppb ethane. The wavelength around 3 µm is ideally suited for this measurement technique since various atmospheric or medical relevant molecules show a characteristic fingerprint absorption. The combination of a compact light source with a suitable CRDS-set-up results in a portable trace-gas analyzer with high sensitivity and high specificity which is required for various environmental and medical applications[6].
In order to fulfill these high resolution spectroscopy requirements, combined with the need for high power to generate a difference frequency laser source in the MIR region, we redesigned the external cavity setup in Littrow configuration. Using high power laser diodes directly in an external cavity configuration combines the high power of these diodes with the advantages of the external cavity: a narrow linewidth in the region of a MHz and good wavelength tunability[7] of more than 20 nm, as well as an ease of use and a small dimension. This makes this system a good replacement for common master-slave laser systems [8]. Fig. 2 shows our schematic high power external cavity.

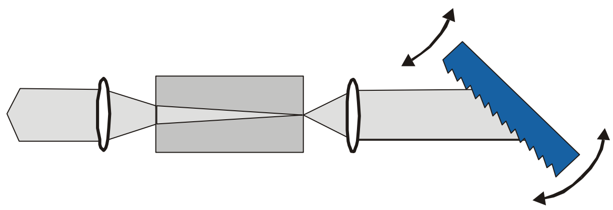

Fig. 2: The principle of the external cavity in Littrow configuration. The first order of the grating is reflected back into the diode to build the resonator. The light is coupled out of the rear facet of the diode. Wavelength tuning is achieved by moving the grating.

In this design the radiation, emitted from the antireflection coated front facet of a LD, is collimated and illuminates a holographic grating by the Littrow angle. The light diffracted in the first order is reflected back into the LD to build the cavity. The laser light is coupled out of the rear facet, while the light coming from the zeroth order of the grating is used for power monitoring. The wavelength change is achieved by tilting and translating the grating.

At the 'common' Littrow configuration[7] the laser beam is coupled out via the diffraction grating and not via the rear facet of the laser diode, as this facet is often covered by the laser diode mounting. Such an external cavity diode laser design has several drawbacks: In order to achieve high output power, there is the need for operating the grating in low efficiency mode. Gratings have a high reflectivity of 90 % for P-polarized light and a low reflectivity of 10 % for the S-polarized light. When using the grating for a high power ECDL this results in a poor polarization ratio between TE and TM emission. Furthermore, this non-optimized resonator quality leads to a poor side mode suppression in the order of 40 dB. Another drawback of this design is the beam walk of the out-coupled laser beam. During a 30 GHz wavelength scan even with a beam correction mirror attached to the grating, a parallel shift in the order of up to 10 µm appears. This causes serious problems with the stability, e.g. when coupling into a single mode fiber or amplification stages.

Our new design uses the rear facet of the diode laser chip for coupling the laser light out of the system. This has several significant advantages: We are able to design a high quality external cavity without any compromises. The polarization ratio is now improved by the cavity and typical values are well above 1:200. The side mode suppression of the laser system has drastically improved with typical values of 55 dB and better. Also the total tuning range as well as the mode-hop free tuning range are drastically improved. There is no longer a beam walk with changing the wavelength via adjusting the grating angle. In addition to 780 nm and 785 nm, we also tested other wavelengths regimes around 735 nm, 795 nm, 810 nm, 970 nm, 1010 nm and 1060 nm. Further wavelength regions are under investigation and will be presented elsewhere.

2. RESULTS AND DISCUSSION

Our very compact design offers an output power of up to 1 W around 780 nm, 800 nm and 1060 nm. In this section we report our investigations of the most important characteristics of such high power laser systems. We discuss the power characteristic, the spatial beam quality, the sidemode suppression, linewidth, and tuning behavior of our high power laser. Furthermore we performed a BEC experiment and an high resolution absorption experiment, which shows the excellent suitability of such high power ECDL for these kind of experiments.

1.1 The Power Characteristic

We have measured the P-I curves for our high power diode laser after antireflection coating the inner facet of the diode with and without external resonator as shown in Fig. 3. Without an external resonator there is no threshold obtainable, with the external resonator the laser has a threshold of 1065 mA and a slope efficiency of 0.69 W/A after threshold with a maximum output power of 1000 mW.

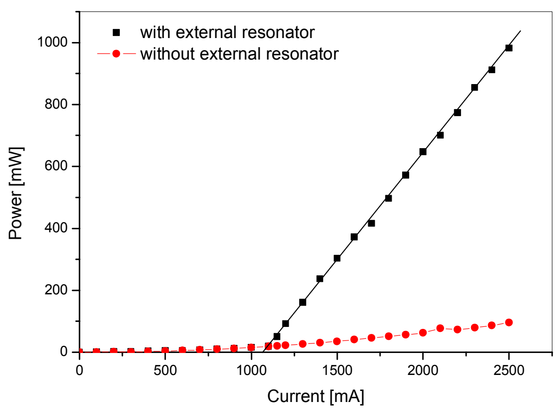

Fig. 3: Power characteristic of a high power diode in an external cavity configuration. Dots: without external cavity; Squares: with external cavity

1.2 The Spectral Behavior

The total available tuning range of a laser diode in an external resonator is determined by its gain profile. With an antireflection coated front facet, the high-power tapered diode can be tuned via grating-tuning from 775 nm to 785 nm with an output power from the rear facet of more than 1 W and a side mode suppression better than 55 dB. Fig. 4 shows the side mode suppression of 57 dB, which we could achieve at 780 nm, analyzed by an optical grating spectrometer (ANDO AQ6315A). We measured that more than 95 % of the emitted power is within the laser line and only approximately 5 % is due to spontaneous emission background, which can be decreased further by using an optical filter.

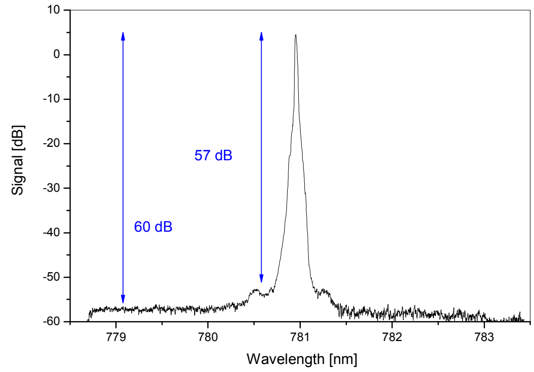

Fig. 4: Spectrum of our ECDL with a side mode suppression of 57 dB and an output power of 1 W at 780 nm.

Often, e.g. for spectroscopic applications, the mode-hop free tuning range at a certain wavelength is more important than the total tuning range. To characterize the mode-hop free tuning range, a few mW of the total optical power were directed into a scanning Fabry-Perot interferometer (Burleigh, FPI-SA-91) with a free spectral range of 8 GHz. While tuning the laser via the piezoelectric actuator we observed the change of the single mode frequency with this FPI. The tuning rate of the piezoelectric actuator is 0.2 nm/100 V. We achieved a mode-hop free tuning range of more than 15 GHz. Another possibility is to tune the wavelength by changing the LD current. The laser can be tuned in this way with a rate of 67 MHz/mA and with a modulation frequency of up to 100 MHz.

By simultaneously changing the grating angle and the LD current the total mode-hop free tuning range can be extremely enlarged[9,10]. Using a simple current compensation this mode-hop free tuning range can be doubled. The combination of high power and excellent tunability in a compact setup offers the potential to use such a laser system in various applications. For example such a laser would be very suitable for difference frequency generation with a high conversion efficiency.

1.3. The Beam profile

To mode-match the laser beam to the fundamental transverse mode of the ring-down cavity a good beam quality of the laser is essential. Fig. 5 illustrates the beam profile of our high power laser.

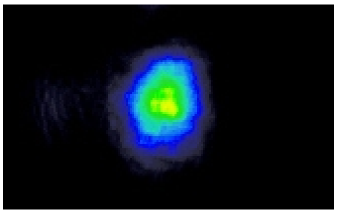

Fig. 5: The beam profile of the ECDL at a wavelength of 810 nm with an $M^2 < 1.2$. The fast axis is in the horizontal plane, while the slow is in the vertical.

The picture of the CCD camera (Coherent, LaserCam II – 1/2) shows a homogenous beam profile, which is nearly circular. The measurements with a beam analyzer (Coherent, ModeMaster) shows that the laser has only a small astigmatism. This results in an ellipticity with a ratio of 1:1.2. For other wavelengths this ratio may increase up to 1:3. We therefore designed a beam correction optic which compensate this astigmatism to zero.
For the 810 nm laser such beam correction is not necessary. The beam profile is nearly circular with a diameter of about 1.2 mm in slow- by 1 mm in fast-axis at a distance of 50 cm. The M^2 factor is better than 1.2 in both directions, as measured with a beam analyzer. With this nearly Gaussian beam, coupling efficiencies of up to 60 % could be achieved into a single mode fiber for 780 nm.

1.4 The Long term Stability

The mount for the laser diode has been optimized for thermal stability. Therefore, the high power diode is soldered into a gold-coated copper collimator, which is specially designed for high heat conductivity. The laser is mounted on a proper heat sink with a surface temperature below 28°C.
Fig. 6 shows the measurement of the wavelength drift of the free-running high power ECDL. The measurement was performed with a wavemeter (Burleigh, WA 1000), which has a resolution of 300 MHz. There was no active wavelength stabilization applied to this laser during the measurement. These data show an exceptional long-term stability due to the excellent thermal management.

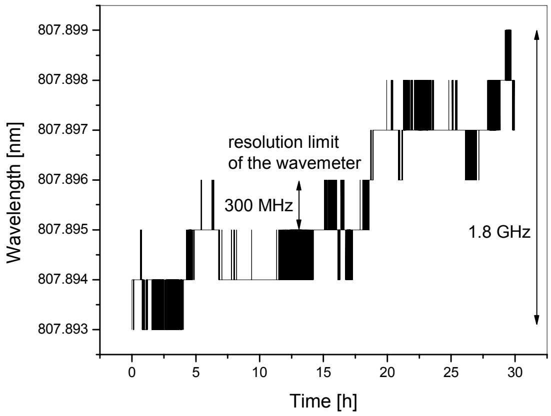

Fig. 6: The wavelength of the free-running laser. The excellent thermal management of the high power ECDL ensures a drift below 2 GHz in 30 h measurement time.

1.5 The Linewidth

Another important feature of the laser is its spectral linewidth. In order to achieve good coupling to the high-finesse ring-down cavity a pure TEM_{00} mode profile and a small linewidth are desired. We determined the spectral linewidth of the high power diode laser via a heterodyning experiment with a low power Littman laser system. This laser operates in the same wavelength region and shows a spectral linewidth below 500 kHz in 1 ms. To keep the linewidth as small as possible, we performed a ultra-low-noise laser diode current source with our ECDL. We determined the linewidth of our high power laser system in Littrow configuration to 1 MHz in 1ms and 2 MHz in 10 ms as shown in Fig. 7.
The linewidth of an ECDL is mainly determined by acoustic vibrations and the injection current noise of the current source. Acoustic vibration disturbances are present on a time scale of 10 s while injection current noise is determinable on a time scale of 10 ms[10].
In order to reach this good passive stability we developed an ultra-low noise 3A current source. These measurements demonstrate the excellent performance of our ultra-low noise 3 A current source. The determined linewidth of our high power laser is comparable with the linewidth of a low-power ECDL.

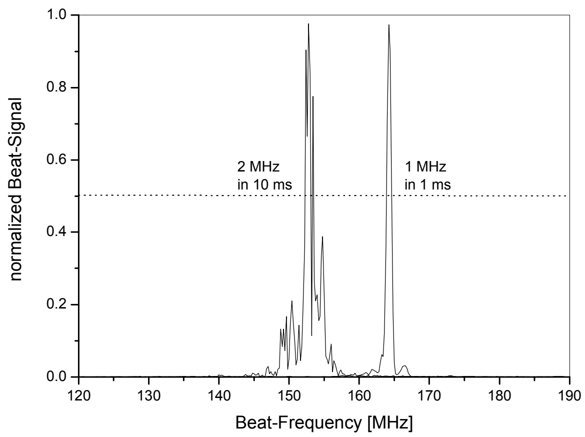

Fig. 7: Linewidth in 1 ms and 10 ms sweep time. Resolution bandwidth: 100 kHz

A serious requirement on pumping a high finesse cavity is that the linewidth of the pump laser needs to be below the linewidth of the cavity modes. In the case that the laser linewidth is larger than the width of the resonance modes, only a small fraction of the incident radiation will be coupled into the cavity. This results in weak build-up events and again lower effective transmission. The resonance modes of the used high-finesse cavity have a width of only 14 kHz. Fig. 8 shows the transmitted power of the DFG laser system using a high power ECDL as a pump source through the high finesse cavity. The laser beam is mode-matched to the fundamental transverse modes of the ring-down cavity by two lenses. The laser frequency is sinusoidally modulated (modulation frequency:100 kHz, modulation depth: 1 MHz). Each time the laser frequency is in exact resonance with the cavity mode, an increase of the transmitted laser power can be observed at the detector. The maximum fraction of incident light transmitted through the cavity on resonance is ~3 %. This power loss is due to the unavoidable light absorption and scattering inside the mirrors. The upper graph in Fig. 8 show the behavior of the same DFG-laser system using a master-slave configuration as light source. The transmission of the DFG-laser system is for both pump laser systems the same.

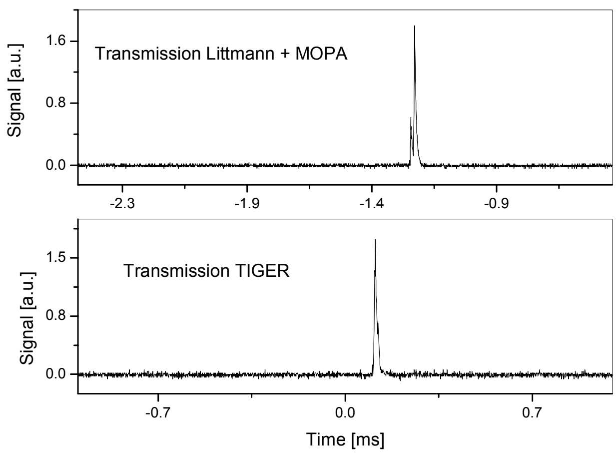

Fig. 8: Laser power transmitted through the cavity while the laser frequency is sinusoidally modulated.

1.6 The Cavity leak-out signal

The DFG laser beam is mode-matched to the TEM_{00} mode of the ring-down cavity by means of two lenses. Since the DFG-frequency is modulated, the ring-down cell is periodically excited. Furthermore, we use the modulation to lock a signal TEM_{00} cavity mode to the DFG by adjusting the length of the ring-down cell. As soon as the transmitted intensity exceeds a certain threshold, a trigger pulse is released, which shuts of the DFG via an electro optical modulator inside the beam of the Nd:YAG laser (see Fig. 1). The subsequent decay of the cavity field is monitored by the photo detector and transferred by a 12 bit analog-to-digital conversion card to the control computer. The decay time of the leak-out signal is determined by fitting a single exponential to the data[11]. Fig. 9 shows the experimental and fitted decay signal of the ring down cavity, using our high power diode as pump source for the DFG laser system. We determined a decay time of 8.33 µs for the empty cavity.

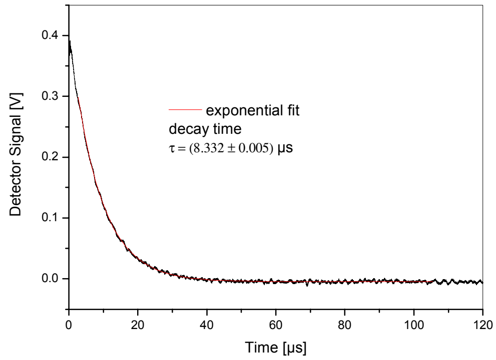

Fig. 9: Experimental leak-out signal versus time, single shot. The decay time given by an exponential fit is 8.33 µs.

1.7 The Trace-gas analysis

The capability of the high power diode laser as pump source for the DFG-laser system was evaluated for cw-cavity ring down absorption measurement of ethane at a wavelength of 3.3 µm. In this spectral region the ethane molecules show a characteristic fingerprint spectrum. For the absorption measurement the ring-down cell was flushed with a sample gas mixture consisting of 50 ppb ethane in grade 5 nitrogen. The flow rate was controlled by an electronic mass-flow controller to be 100 cm^3/min^{-1} at standard temperature and pressure conditions (1013 mbar, 298 K). In order to reduce the pressure broadening of the spectral line the pressure inside the cavity was 100 mbar. The corresponding gas system is described in detail Reference[12]. Fig. 10 shows the measured ethane spectrum. The frequency of the DFG-laser system is tuned via the piezoelectric transactor at the grating of our the high power diode laser.

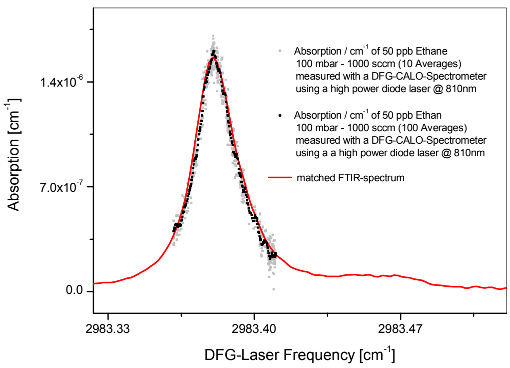

Fig. 10: Experimental spectra of 50 ppb ethane in grade 5 nitrogen. Pressure: 100 mbar. Solid line: data from FTIR[13], scaled to 50 ppb concentration.

1.8 The high-power diode laser in a cold atom experiment

To demonstrate the suitability for neutral atom cooling we used this laser as a high power light source in the production of a BEC of over a million ^{87}Rb atoms. This experiment was performed at the Institute for Atomic and Molecular Physics (AMOLF) in Amsterdam. The laser was used as a tunable, narrow-linewidth power-source for the magneto-optical trap. For this purpose it was locked with a variable frequency-offset relative to a master-laser, which itself was stabilized on a Doppler-free saturation dip in a rubidium vapor cell. The use of a frequency-offset lock simplifies the experimental apparatus considerably as it eliminates the use of acousto-optical modulators and injection locked lasers. Using approximately 130 mW of optical power delivered by a single mode fiber, we have been able to load within 8 s about 10^{10} atoms in a magneto-optical trap at a temperature of 40 µK. Half of these were transferred to a magnetic Ioffe-Pritchard trap and RF-evaporation cooled to below the transition temperature for Bose-Einstein condensation yielding a condensate of almost one million atoms (Fig. 11). This clearly demonstrates the suitability of this laser system for high atom number cold atom experiments.

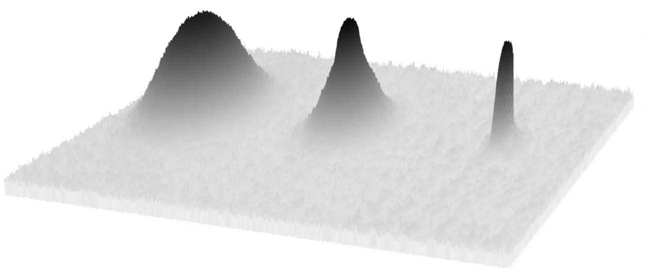

Fig. 11: Formation of a BEC by forced RF-evaporation in a Ioffe-Pritchard magnetic trap.

Left: Pure thermal cloud.
Centre: Two component cloud.
Right: Almost pure BEC.

3. CONCLUSION

We reported of a new principle of using high power laser diodes in an external cavity. The very compact design offers up to 1 W output power and an excellent beam quality with a beam propagation factor of $M^2 < 1.2$ in both directions. The laser system has a small linewidth in the MHz regime and is tuneable without mode-hops for more than 15 GHz without the need of additional current compensation. We have also demonstrated the high performance of the laser system with a BEC-experiment, as well as with a CRDS-experiment. This study is a proof of the high potential of the ECDL as a cost effective alternative to amplified laser systems. A photograph of the laser system is shown in Fig. 12.

Fig. 12: Photograph of the laser system and driver

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