Compact tunable diode laser with diffraction limited 1 Watt for atom cooling and trapping

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ABSTRACT

Since the introduction of laser-cooling techniques for neutral atoms, the enhancement of high-power lasers with excellent spectral and spatial quality has been an important research subject. We report a new principle of using high-power laserdiodes directly in an external cavity. The very compact design offers an output power of up to 1 W and an excellent beam quality ($M^2 < 1.2$). The coupling efficiency for a single mode fiber exceeds 60%. The center wavelength can be tuned between 775 nm and 785 nm. This laser operates single mode with a mode-hop free tuning range of up to 15 GHz without current modulation and a side-mode suppression better than 55 dB. Demonstrating 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.

Keywords: external cavity laser, tunable laser, diode laser, laserdiode, Bose Einstein condensate, BEC, high power diode laser, ECDL, diffraction limited, Rubidium absorption.

1. INTRODUCTION

Cold atom experiments have been revolutionized by the availability of powerful, narrow line width laser sources. Here we demonstrate a novel external cavity diode laser (ECDL) employing a high power tapered laser diode. This system greatly simplifies the experimental setup while increasing the available laser power up to 1 W.

Using high power laserdiodes directly in an external cavity configuration combines the high power of these diodes with the advantages of the external cavity: a narrow line width in the region of a MHz and good wavelength tunability[1] of more than 20 nm, in combination with ease of use and small dimensions. This makes this system a good replacement of common master-slave laser systems [2]. Figure 1 shows our schematic high power external cavity.

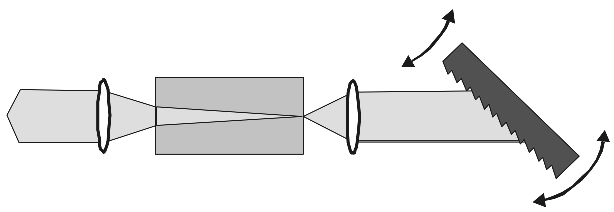

Fig. 1. The principle of the external cavity in Littrow configuration. The first order of the grating is reflected back into the diode to build the resonator. The light is coupled out of the rear facet of the diode. Wavelength tuning is achieved by moving the grating.

In this design the radiation, emitted from the antireflection coated front facet of a LD, is collimated and hits a holographic grating under Littrow angle. The light diffracted in the first order is reflected back into the LD to build the cavity. The light which is coupled out of the rear facet is used for the experiments. The wavelength change is achieved by tilting and translating the grating.
At the ‘usual’ Littrow configuration[1] the useable light is coupled out from the grating and not from the rear facet of the laserdiode, as this facet is often covered the laserdiode mounting. Such an external cavity diode laser (ECDL) 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, a parallel shift in the order of up to 10 µm appears, even with a beam correction mirror attached to the grating. 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 a number of advantages: We are able to design a high quality external cavity so there are no longer compromises required. 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 being 55 dB and better. Also the total tuning range as well as the mode-hop free tuning range are drastically improved and there is no longer a beam walk when changing the wavelength with adjusting the grating angle. In addition to 780 nm and 785 nm, we also tested other wavelengths regimes at 735 nm, 795 nm, 810 nm, 970 nm, 1010 nm and 1060 nm and further wavelengths regions are under investigation. These results are presented elsewhere. Most of the presented results were measured with a laser, which is tunable between 775 nm and 785 nm.

2. RESULTS AND DISCUSSION

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

1.1 Spectral Behavior

The total available tuning range of a laserdiode 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 above 1 W and a side mode suppression better than 55 dB. Figure 2 shows the side mode suppression of 57 dB, which we could achieve at 780 nm, analyzed with an optical grating spectrometer (ANDO AQ6315A). We measured that more than 95 % of the emitted power is within the laser line and only about 5 % is due to spontaneous emission background, which can be decreased further by using an optical filter. Using a custom made interference filter in front of the laser cavity we improved the side mode suppression to more than 70 dB as shown in figure 3. As this filter was designed for 785 nm and not for 780 nm, the ECDL was tuned to that wavelength.

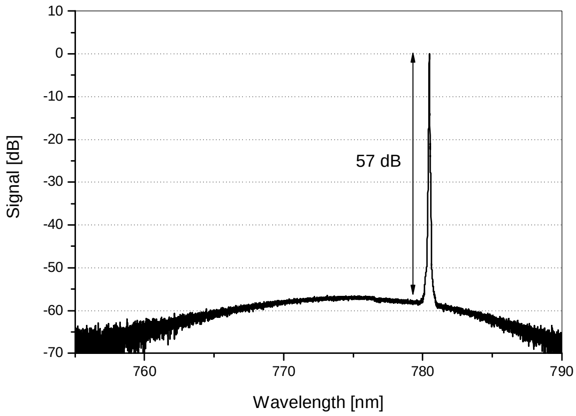

Fig. 2. Spectrum of our ECDL with a side mode suppression of 57 dB and an output power of 1 W at 780 nm.

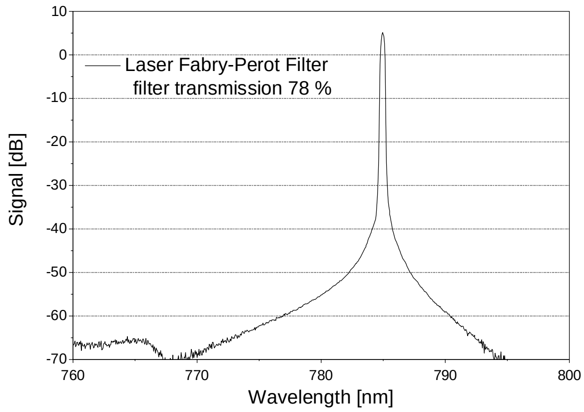

Fig. 3. Spectrum of the ECDL together with a filter resulting in a side mode suppression of 70 dB and an output power of 0.8 W at 780 nm. Peak is broadened because of the limited spectral resolution of the used analyzer system.

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. Wavelength tuning of the laser can be achieved by tilting the grating with a piezoelectric device or changing the LD current. By simultaneously changing the grating angle and the LD current the total mode-hop free tuning range can be extremely enlarged[3,4]. Here we demonstrate the tuning range for the more general case where only the grating is adjusted. In this case a mode-hop free tuning of about 15 GHz was achieved via tuning of the external cavity grating with the piezoelectric actuator without the additional current modulation. Using a simple current compensation this value can be doubled.

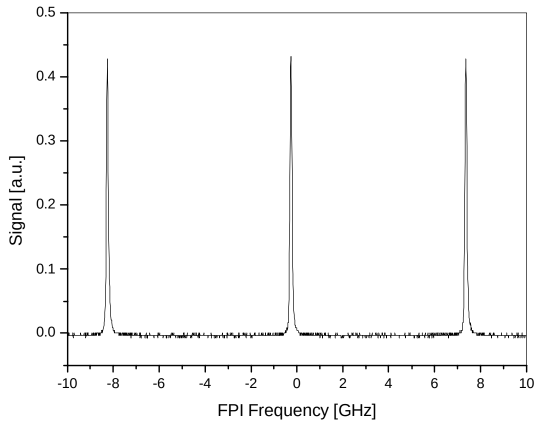

Fig. 4. Transmission of the scanning FP-cavity used to monitor the mode-hope free operation during a 15 GHz scan of the laser. Visible are the three longitudinal modes of the FPI.

We checked the mode hope free tuning behavior of our laser during a 15 GHz scan using a scanning Fabry-Perot-Interferometer (FPI), see Figure 4. 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.

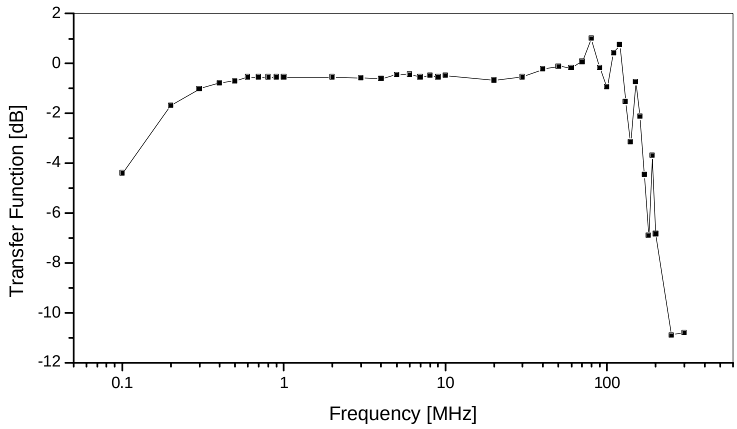

Fig. 5. Frequency response function of the current bias-tee modulation.

Furthermore the laser can be tuned via changing the current with a rate of 67 MHz/mA and a modulation frequency of up to 100 MHz. Figure 5 shows the frequency response function of the bias-tee, i.e. the modulation of the laser current divided by the applied modulation current as function of the modulation frequency. The bias-tee allows a direct modulation of the laser current with frequencies between 300 kHz and 100 MHz.

1.2. Beam profile

To get a good beam profile, the light from the rear facet was analyzed by a CCD camera (Coherent, LaserCam II – 1/2) while collimating and optimized the laser configuration. Figure 6 illustrates the beam profile of our high power laser.

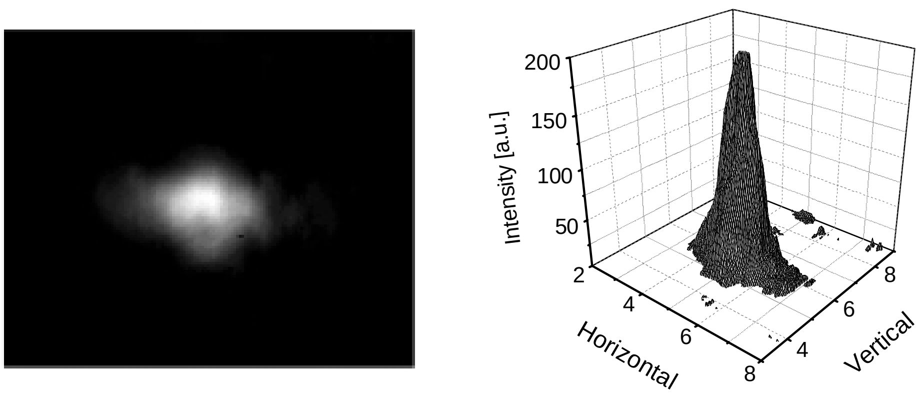

Fig. 6. The beam profile of the ECDL with an $M^2 < 1.2$. The fast axis is in the horizontal plane, while the slow is in the vertical.

The beam is almost round with a diameter of about 1.5 mm in slow- by 1.8 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 (Coherent, ModeMaster). With such a nearly Gaussian beam, coupling efficiencies of up to 60 % could be achieved into a single mode fiber for 780 nm.

1.3 Linewidth

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[4]. For high resolution spectroscopy or for laser cooling a small linewidth is essential. To keep the linewidth as small as possible, we performed a ultra-low-noise laserdiode current source with our ECDL and kept the whole setup on an optical table. We determined the linewidth of this laser system via a heterodyne experiment with a Littman laser system, which has a known linewidth of below 500 kHz in 1 ms.

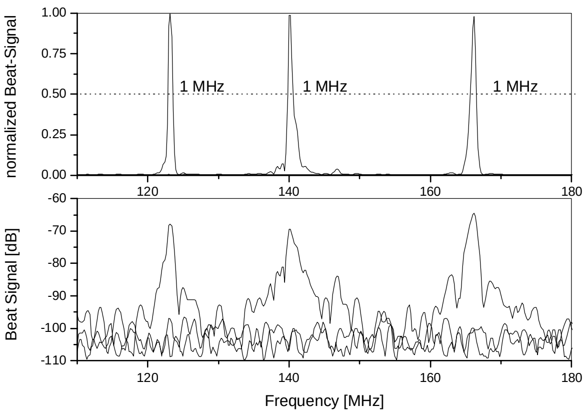

Fig. 7. Linewidth in 1 ms sweep time: 1 MHz.
Three independent scans are shown here.
Resolution bandwidth: 100 kHz

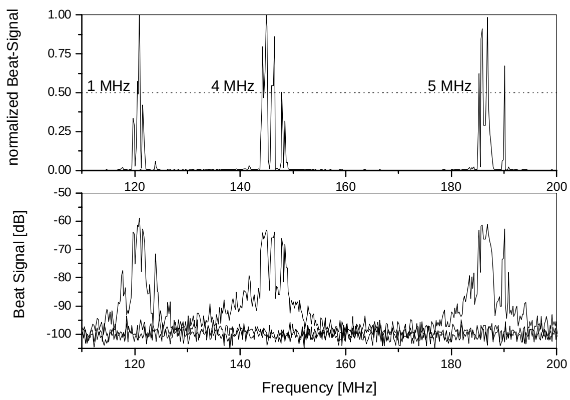

Fig. 8. Linewidth in 20 ms sweep time: < 5 MHz.
Three independent scans are shown here.

In the lower parts of the figures 7 and 8 the beat signals of three independent measurements are shown, which correspond to best-, normal- and worst-case (left to right). These measurements were linearized (upper parts) to determine the FWHM linewidth. Taking into account the measured linewidth of the Littman ECDL (500 kHz), the linewidth of the high power ECDL is lower than 1 MHz in 1 ms sweep time (100 MHz/ms) (Fig. 7) and in the dimension of below 5 MHz in 20 ms sweep time (5MHz/ms) (Fig. 8). In order to reach this excellent passive stability we developed a 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.

1.4. Tunability

To check the tuning behavior, which is needed for high resolution spectroscopy, an absorption spectrum of Rubidium was measured by a simple absorption experiment[5].
Using the piezoelectric actuator with a scan rate of up to 1 kHz for tuning the laser wavelength around 780 nm, the absorption lines of Rubidium can be easily obtained as shown in figure 9. This easy measurement demonstrates that the linewidth measured with the heterodyne experiment stays small even when tuning the wavelength rapidly.

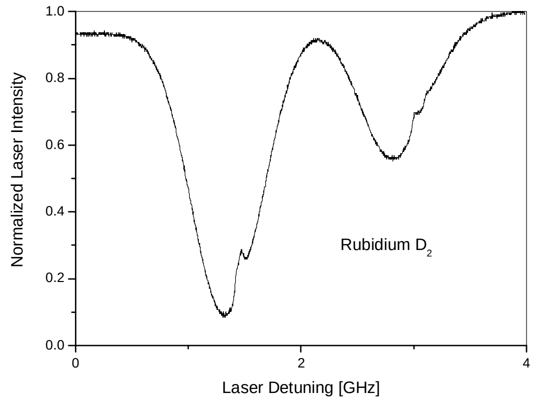

Fig. 9. Absorption profile of Rubidium.

Furthermore, this shows the good single mode tuning behavior while tuning with a rate of 1 kHz. The combination of high power and excellent tunability in a compact setup offers the potential that such a laser system can be used in various applications. For example such a laser should be very suitable for difference frequency generation a ligh source for high resolution spectroscopy. Furthermore the Rubidium measurement shows the high potential of this laser system for atom cooling or for cold atom experiments.

1.5 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.

Figure 10 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 wavelength stabilization applied to this laser at the time of measurement. These data show the excellent long-term stability due to the good thermal management.

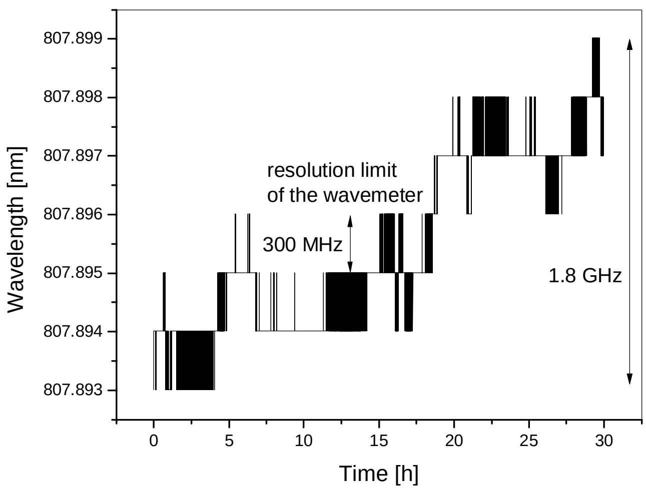

Fig. 10. The wavelength of the free-running laser. The excellent thermal management of the high power ECDL ensures a drift below 2 GHz in 30 h measurement time.

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

Bose-Einstein condensation experiments in magnetic traps require large atomic samples at very low temperatures. These can be supplied by magneto-optical traps (MOTs) and subsequent cooling by an optical molasses. The MOT and molasses requires laser intensities in the hundred-milliwatt range with a linewidth of less than a few megahertz. In addition the laser must be rapidly tuned by about 30 MHz for the molasses stage.

One of the crucial factors in the design of the MOT is the available laser power. Higher available laser powers allow larger beam diameters and thus larger trapping volumes; i.e. more trapped atoms. Also, the spatial distribution must be very well defined since any imbalance between the beams will result in an acceleration of the atoms by the light. We use a single-mode optical fiber to spatially filter the light as well as to decouple the laser-system from eventual vibrations. Our experiment had originally been designed to operate with a broad area diode laser system developed in our laboratory, which is capable of delivering – with considerable experimental effort – about 120 mW with sub-megahertz linewidth into a single mode fiber.[2] This allowed us to construct a six-beam MOT with a $1/e^2$ radius of 8 mm.

At AMOLF we focus on the physics of quantum gases close to the hydrodynamic limit and thus require large atom numbers.[6,7] Like most cold-atom experiments we pre-cool the atoms in a magneto-optical trap (MOT). The MOT is loaded from a $2D^+$-MOT, which delivers a flux of 5×10^9 atoms per second.[8] We can load within 5 seconds about 1.2×10^{10} atoms. After the molasses cooling the temperature is about 40 µK depending on experimental conditions. After transfer to the magnetic trap we have a few times 10^9 atoms at 50 µK and find after evaporative cooling about a million atoms in our ^{87}Rb condensate at 500 nK.

The cooling-laser used in the BEC experiment in Amsterdam

The optical setup is as follows. We couple about 120 mW from the high-power laser into a single mode fiber leading to the MOT optics. The coupling efficiency gives control over maximum MOT power[1]. A relay-mounted razor blade serves as electro-magnetically controlled optical shutter. We couple about one milliwatt into one arm of a polarization maintaining 50/50 fiber splitter with the other arm receiving light from our master laser. The resulting beat note between the two can then be used to control the frequency of the laser using a simple frequency offset lock.[9] Figure 11 shows a typical beat note between the two lasers. The frequency of the high-power laser can be switched by more than 30 MHz in one millisecond, which is crucial e.g. when switching from the MOT to molasses cooling.

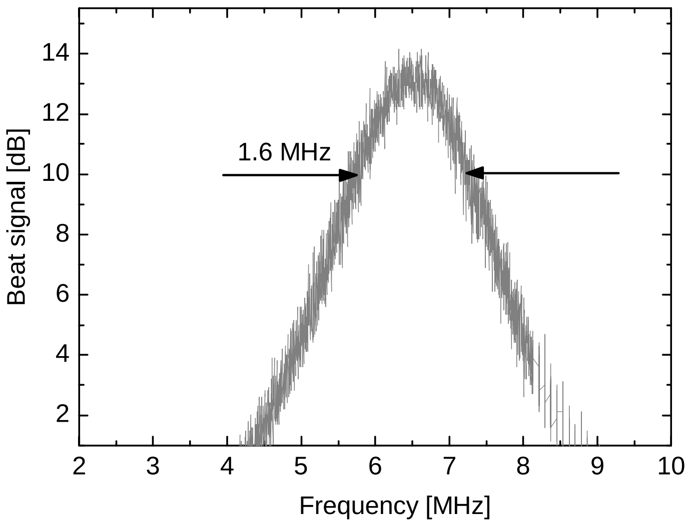

Figure 11:
Beat note between the power-laser and its reference laser. The resolution bandwidth of the spectrum analyzer was set to 30 kHz and the video bandwidth 100 Hz. The linewidth of the reference laser is below 300 kHz (FWHM). We can therefore conclude that the power laser has a FWHM linewidth of about 1.6 MHz if stabilized with a feedback loop to the grating.

In order to enhance the stability of the system in a sometimes noisy laboratory environment

[1] In order to profit from the larger laser power available from the high-power external cavity laser one would have to increase the size of the beams of the MOT thus increasing the capture volume

we placed the high-power laser on a bread-board in an aluminum box. Rubber feet isolate the box from the vibrations of the table, and the breadboard from the box. Over night, when we switch off all our lasers, we heat the breadboard resistively in order to reduce temperature fluctuations of the bread caused otherwise by the heat-load of the high-power laser diode. The laser is now operational within half of an hour of switch-on and stays in lock for several hours at a time (even if a large spanner is dropped on the optical table) requiring only infrequently minor adjustment of the laser current.

In summary, the compact, grating stabilized high-power laser greatly simplifies the design of our lasers and increases their reliability: the high-power laser can be frequency controlled using a simple offset lock to a reference laser without an acousto-optic modulator in combination with an injection-locked diode-laser.

3. CONCLUSION

We reported a new principle of using high power laserdiodes in an external cavity. The very compact design offers up to 1 W output power and an excellent beam propagation factor of $M^2 < 1.2$ in both directions. The laser system has a small linewidth in the MHz regime and is tunable without mode hops for about 15 GHz without the need for additional current compensation. We also demonstrated the high performance of the laser system in a BEC-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 figure 12.

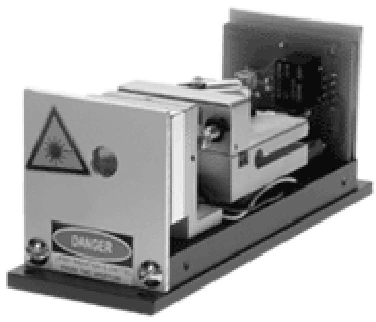

Fig. 12: Photograph of the laser system

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