Generating 500 mW for laser cooling of strontium atoms by injection locking a high power laser diode

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We report on the generation of 500 mW of spectrally pure laser light at the 460.86 nm transition used for laser cooling of strontium atoms. To this end we inject a high power single mode laser diode with light from a stabilized extended cavity diode laser. To optimize and monitor the injection status and the spectral purity of the slave diode we developed a novel technique that uses a single passive optical element. A narrow band interference filter generates a suitable monitoring signal without any additional electronics for post processing of the data. Our method greatly simplifies the daily operation of injection locked laser diodes and can be easily adapted to other wavelengths of interest.

1 INTRODUCTION

Laser cooled strontium atoms are used as an atomic reference for high precision and accurate optical lattice clocks [1, 2, 3], quantum simulation and computing [4, 5] and were recently proposed to detect gravitational waves [6, 7] and search for dark matter [8]. Mobile strontium lattice clocks would have far-reaching applications like GPS, time scales and relativistic geodesy [9, 10]. For laser cooling of strontium at the 461 nm transition laser diodes became only recently available. Therefore most setups so far traditionally employed relatively complex systems based on second harmonic generation (SHG) delivering output powers up to 600 mW [11].

As an attractive alternative to SHG systems, direct diode lasers at 461 nm with output powers in the range of 100 mW appeared as a commercial product several years ago (Nichia, NDB4216). This enabled using only a fraction of the power from a single frequency master laser that can be amplified by a slave high power laser diode through the injection locking technique [12]. Several slave diodes, in some cases 10 or even more, can be used if needed to achieve the required output power [13]. Such amplified diode laser systems were already developed for laser cooling of Ytterbium at 399 nm [14] while some setups needed to operate with a much higher number of slave diodes [15]. Ideally one would use a single diode laser in combination with an amplifier chip in the so called MOPA configuration. Such chips are in development but they are not commercially available yet at the moment [16, 17].

Here we report the generation of 500 mW single frequency laser light by injection locking a high power single transverse mode laser diode with a master laser at 460.86 nm. The obtained output power is comparable to commercial available SHG systems [11] in a simpler setup with lower total electric power consumption for a fraction of the cost, while being also more compact. For the analysis and optimization of the injection locking we use a single optical element, a narrow band interference filter (IF). The power transmitted through the filter generates a signal with a high signal to noise that indicates the quality of the injection locking state. The signal can also be potentially used for active stabilization of the injection lock [18]. We analyze the injection lock behaviour for different slave currents and injection powers from the master laser. The demonstrated high power injection locked laser approach is universal and can be used in a variety of experiments utilizing laser cooled strontium atoms and other setups where injection locking is also utilized.

2 EXPERIMENTAL SETUP

Figure 1: A schematic of our setup. Light from the master laser is coupled into a fibre and injects a high power slave laser diode with an output power of 500 mW. A small fraction of the slave beam is transmitted through a backside polished mirror (M1) and is used for monitoring of the injection lock quality using the transmitted power through the interference filter (IF). See main text for more details.

The experimental setup for the injection locking and characterization is shown in Figure 1. The slave laser is a single mode high power GaN laser diode (Nichia NDB4916E) that recently became available. The sample diode has a free running center wavelength around 460.5 nm and an output power of 500 mW at its nominal operation current of 338 mA. The diode is housed in a collimation tube and the output is collimated with an aspheric lens (NA = 0.6). Light from the diode passes through an optical isolator with Polarizing Beamsplitting Cubes (PBS) on both sides and λ/2 wave plate in front of
the isolator maximizes the transmission to 86%. An optical fibre delivers up to 3 mW from the master laser to the setup. This light is injected into the slave diode using the rejection port of the optical isolator as shown in Figure 1.

To maximize the spatial mode overlap between the master and the slave we couple first light from the slave in an optical fibre. Afterwards we turn the slave current off and couple the master light reflected from the slave front facet into the same optical fibre. The slave laser mode is elliptical with a 1:3 aspect ratio. A cylindrical lens pair after the isolator (see Figure 1) is used to circularize the high power slave laser output beam for better efficiency for fiber coupling.

The output from the slave is coupled into the main fibre that goes to the switching and distribution board with a coupling efficiency of 65%. Two mirrors are used to maximize the fibre coupling. One of the mirrors has a polished backside (labeled M1 in Figure 1). This mirror transmits approximately 1% of the slave light. A narrow interference filter (IF) with a bandwidth (FWHM) of 0.2 nm at 463 nm designed at the incident angle of 0° is placed after this mirror. The filter is mounted into a precision rotation stage. The transmitted slave power is monitored by an amplified photo diode. The filter transmission is angle dependent [19] and the filter angle is rotated to maximize the transmission of the locked master when the slave is turned off. The optical spectrum of the slave is analyzed with a fibre coupled grating-based laser wavemeter with a spectral resolution of 0.02 nm was placed either before or after the IF for the following measurements.

2.1 High power diode spectrum analysis

Figure 2: Transmission spectra of the free running laser diode at an injection current of 338 mA (dotted grey) and for different interference filter angles and thus transmission wavelengths. (solid colors). One clearly sees that the filter is able to transmit only a small portion of the spectrum, and strongly suppress the rest.

First we explore the filtering properties of our IF filter. The optical spectrum of the free running slave laser diode at an injection current of 338 mA is recorded with the wavemeter. This spectrum is shown in Figure 2 (grey dashed) and was taken without the IF, while all other spectra in Figure 2 were taken with the IF inserted into the beam path. Since the bandwidth of our IF filter is much narrower than the spectrum of the free running slave laser diode, we change the filter angle in small increments to tune the center of the filter transmission. Figure 2 shows the filtering performance of the interference filter for the the entire tuning range of filter angles spanning approximately 2 nm. It is immediately apparent that the 0.2 nm wide IF filter can reliably transmit a narrow band from the full slave spectrum.

Several sources in the literature report that GaN diodes have internal modes separated ≈ by 0.05 nm [20]. Some of the filtered spectra in Figure 2 reveal multiple closely spaced modes, but they cannot be reliably resolved with the spectrometer resolution.

2.2 Narrow band interference filter for monitoring the injection lock of a laser diode

Figure 3: The photo diode signal after the IF obtained by scanning the slave diode current by 20 mA at a rate of 100 Hz for three different injection power levels from the master. Partially injected regions are marked with the A and B. The inset zooms on the plateau region, the current range where the slave is fully injection locked. The master laser was locked to an atomic transition during this measurement. (See main text for more details)

While optimizing and monitoring the quality of the injection lock can be done with the wavemeter alone, or like already demonstrated with a scanning Fabry–Pérot cavity [21]. These devices are relatively complex, costly and require additional driving electronics. Especially in the case of Fabry–Pérot cavities the transmission signal can show one single peak only, but not necessarily all the power of the slave is in the desired frequency mode [18]. Utilizing an IF that combines the filtering qualities of a filter cavity, but with a higher bandwidth, no scanning and/or fitting of signal is necessary and the power transmitted through the IF generates a signal directly proportional to the optical power in the desired mode of the slave diode. This will be presented and analyzed in this subsection.

The usefulness of the IF filter as an injection lock monitor relies on a precise alignment of the filter angle, so that the transmission is centered on the optical wavelength of the locked master. To achieve this, we first repeat the procedure described in Section 2 to ensure that the beam overlap is optimized. Then we use the master light transmitted through the back polished mirror and optimize the IF filter angle for maximum...
transmission and therefore maximum photo diode signal. We want to emphasize, that the beam pick off for the IF filter monitor can be installed anywhere in the beam path of the slave. The IF and its photo diode detector can be made very compact and therefore included non-invasively almost anywhere in the beam path. Either after a fibre, in a unused beam splitter port, or inside one of the fibre collimators that deliver light to the experiment.

To explore the injection dynamics of the slave diode we scan the slave current 20 mA around its operation point at a rate of 100 Hz and observe the photo diode signal behind the IF filter with an oscilloscope. The obtained photo diode signals for different master injection powers are shown in Figure 3. The signal for an injection power of 0.7 mW is shown in Figure 3 in green. The photo diode value and therefore the power of the master frequency component in the slave spectrum increases when the slave current is scanned from a higher current to a lower one. There is no region where the photo diode power is constant over some slave current range for this low injection power. Such a power plateau would have indicated that the slave is fully injection locked (meaning that the slave laser operates at the same frequency as the master) [18].

For 1.5 mW (blue curve in Figure 3) such a plateau can be seen at a slave current around 337.5 mA. In addition a small second region where the slave diode is partially injection locked is visible (marked with the letter A). Such partially injection locked regions were already reported [14]. For 2.7 mW a 0.3 mA wide plateau around 337.0 mA can be seen where the slave diode is fully injection locked (orange curve in Figure 3) along with a second partially injected region (marked with the letter B). An inset in Figure 3 enlarges the plateau region. All these measurements were carried out and verified simultaneously with the constant monitoring of the wavemeter.

The monotone increase of the photo diode signal allows for a side of fringe lock very close to the plateau using the slave current as an actuator and stabilizing the slave injection lock fraction slightly below 100 %. Alternatively one can recenter the slave current to the centre of the plateau at regularly time intervals [18, 15] since the injection lock is stable over long period of time and only occasional centering is needed. We want to indicate a shift of the injection lock region to smaller slave currents as a function of injection locked power as shown in Figure 3. We believe this is mostly due to the frequency pulling effect and resulting hysteresis.

2.3 Injection locking quality and stability

The injection locking performance of the slave laser was also investigated with a wavemeter. Figure 4 shows three different spectra. The free running diode without a filter is shown in blue. One can clearly see that the free running wavelength is centered around 459.5 nm with no significant components at 460.86 nm (the strontium cooling transition). The same spectrum, but with the IF inserted into the beam path is shown in Figure 4 in green. Since the filter strongly suppresses the spectrum of the free running slave diode the exposure time of the wavemeter was increased by a factor of 80 to obtain a visible signal. The unwanted slave modes are strongly filtered in this case.

Figure 4: Measurements of spectra with and without filter at 338 mA injection current. The blue curve shows the free running laser diode without the IF in the beam path. The green curve is measured under the same conditions but with the filter inserted (Since the optical attenuation of the IF is very high outside its pass band the exposure time of the wavemeter was increased by a factor of 80 to obtain a visible signal). The orange curve shows the fully injected slave diode (recorded without a filter).

The spectrum of the fully injection locked slave diode measured without any filtering from the IF is shown in Figure 4 in orange. All the integrated power of the free running slave diode is concentrated in this one optical mode. In this case only one optical mode, the mode of the master laser is present and no other modes could be resolved. In addition we observe that the height of the peak detected by the wavemeter is at its maximum, showing that the optical power is not distributed over additional modes [18]. Other slave modes are suppressed in this case and a maximum IF transmission corresponds to a maximal slave injection quality. Even though the slave laser free-running frequency is more than 1 nm away, the injection can pull the frequency and achieve stable locking. On the other hand, if the free running laser wavelength coincides with the master, the injection locking can be more stable and efficient in general. This could be changed in the future by a selected diode with a wavelength that matches closer the one of the maser. Alternatively one could heat the slave diode (1 nm increase in the center frequency requires a temperature increase by 20 K) to the expense of a potential shortened lifetime.

It should be pointed out that although the free running diode spectrum has no visible frequency components at the master seed frequency, we are still able to achieve full slave injection. Optimizing the heat transfer in the diode mount and acoustic shielding of the free beam path between master and slave should lead to a better long term stability of the lock [18]. Nevertheless after turning off the current scan and careful adjustment of the slave current, the slave stays fully injection locked over multiple hours without any intervention. This is worth mentioning due to the fact that our setup is located in a fairly busy lab and is not shielded against any disturbances in the environment.
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3 Conclusion

We generated 500 mW output power of a spectrally pure single frequency in the blue region of the spectrum from a single laser diode by injecting the diode with light from an ECDL master laser locked to an atomic transition in Strontium-88. The required power needed to achieve a full injection in our case is with less than 3.0 mW. Utilising the wavelength selective transmittance of a narrow band IF filter allows us to generate a signal suitable for optimizing and monitoring the injection lock quality, as well as provides a possible method for servo and maintain the injection locking for long period of continuous operation.

A slave laser diode mount designed for better thermal and mechanical stability should improve the long term stability of the lock and a slave laser diode with a free running wavelength closer to the one of the master might lead to improved performance as well.

These output power levels are en par with more complex, larger and expensive systems based on SHG generation. The low output power required from the master, allow to inject multiple slave laser diodes with a single master. For experiments where higher laser power is needed, this is a simple and effective solution.

Using the injecting master and slave laser configuration presented here, a complete strontium optical lattice clock could be operated in the future [22]. This would greatly reduce the complexity, size, power consumption and robustness of such a clock.

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