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A broad emitter diode laser system for lithium spectroscopy

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Abstract. A laser system based on injection locking of a broad emitter diode laser operating at a wavelength of $\lambda = 671\,\text{nm}$ has been realized. With an injected power of 9.6 mW, 130 mW output power of the broad emitter diode laser is achieved. The broad emitter diode laser operates in a single spectral mode and its eigenmodes can be suppressed by more than 30 dB. By modulation of its operation current, sidebands of the laser frequency can be created. The laser system has been used to operate a magnetooptical trap for ^{7}Li atoms. With 70 mW of laser power, 10^7 atoms have been loaded from a nearby thermal source.

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The investigation of magnetically trapped alkali atoms has become an exciting field of interest in recent years culminating in the observation of Bose–Einstein condensation [1] of rubidium, sodium, and lithium. Among the alkalies, lithium is of particular interest as there are two stable isotopes, a boson ($^7_3$Li, $I = \frac{3}{2}$) and a fermion ($^6_3$Li, $I = 1$). To approach the regime of quantum degeneracy the sample is cooled by forced evaporation of the fast atoms in a magnetic trap. In the case of ^{6}Li, however, evaporative cooling at low temperatures, at which interatomic collisions are dominated by s-wave scattering, will not work. Because of the fermionic character of ^{6}Li, s-wave scattering of two ^{6}Li atoms in the same magnetic substate is forbidden by the Pauli principle and elastic collisions freeze out at temperatures below 100 μK. To overcome this, ^{6}Li can be stored simultaneously with ^{7}Li in the same magnetic trap. Evaporative cooling of ^{6}Li then is possible due to collisions with the ^{7}Li background gas.

Simultaneous storage of both lithium isotopes in the same magnetic trap requires a magnetooptical trap [2] for both isotopes. Thus laser radiation with two frequency components is necessary to excite the transitions $^2S_{\frac{1}{2}}(F = 2) \leftrightarrow {}^2P_{\frac{3}{2}}(F = 3)$ in the case of ^{7}Li and $^2S_{\frac{1}{2}}(F = \frac{3}{2}) \leftrightarrow {}^2P_{\frac{3}{2}}(F = \frac{5}{2})$ in the case of ^{6}Li (D_2 lines). These transitions correspond to wavelengths of $\lambda = 670.962\,\text{nm}$ (^{7}Li) and $\lambda = 670.977\,\text{nm}$ (^{6}Li) and are separated by 10 GHz. The natural linewidth is 6 MHz. If the two magnetooptical traps are to be operated by the same laser, the second frequency can be generated by an electrooptic modulator as a sideband of the laser frequency. The intensity of one of the sidebands cannot be used and the situation is complicated further by the fact that in the two magnetooptical traps the Li atoms have to be repumped into the trapped hyperfine state by a suitable repumping frequency. The hyperfine splitting of the $^2S_{\frac{1}{2}}$ state is 803 MHz in the case of ^{7}Li and 228 MHz in the case of ^{6}Li. The generation of the repumping frequencies would require two additional electrooptic modulators and so the laser intensity would be reduced further. The use of two separate laser systems appears to be more favorable. Laser radiation at $\lambda = 671\,\text{nm}$ with power in the range of 100 mW is commonly generated by dye lasers. High power is essential to achieve a large capture range and a high number of atoms in the magnetooptical trap. An alternative to these expensive and cumbersome laser systems is the recently developed high-power diode lasers.

1 Broad emitter diode lasers as light source for spectroscopy

For our spectroscopic purposes the bandwidth of the laser should be smaller than the natural linewidth of the atomic transition of interest, which is about 6 MHz. This requires the use of single-mode lasers. Moreover, Doppler cooling of Li atoms becomes more efficient with increasing laser power. With larger detuning of the cooling laser to the red, the velocity up to which atoms can be cooled increases and a higher fraction of atoms emitted from a thermal source can be caught in a magnetooptical trap. However the intensity of the laser has to be sufficiently large to saturate the transition at which the magnetooptical trap is operated even if the laser is detuned to the red. In addition high intensity allows for a larger geometric capture range with a given intensity.

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Commercial single-mode diode lasers operating near $\lambda = 671$ nm provide an output power of 30 mW at best, which is limited by the ratio of output power to the size of the output facet. Too large an output intensity will result in irreversible damage of the laser diode facet. To overcome this restriction, the active layer at the p–n junction of the laser diode where the laser radiation is generated can be enlarged such that the intensity at the output facet remains constant. A typical size of the active region of such a broad emitter diode laser is about 1000 µm (length) × 100 µm (width) whereas the width in the case of a single-mode diode laser is just about 4 µm. However, broad emitter diode lasers do not operate in a single spatial and spectral mode. Several transverse modes run simultaneously and so the spectral bandwidth of a free-running broad emitter diode laser is of the order of several nanometers. Moreover the beam profile is not Gaussian. Coupling of the transverse modes leads to the formation of two characteristic side lobes in the far field pattern of the emitted radiation. This feature is also well known from laser diode arrays [3]. To achieve operation in a single spectral mode the technique of injection locking can be used. By injecting laser radiation at the desired wavelength into the broad emitter diode laser a fixed phase relation is imposed on its eigenmodes and they are locked to the injected frequency. The center wavelength of the free-running broad emitter diode laser has to be as close as possible to the wavelength of the injected light. As the quality factor Q of diode laser resonators is quite low, the locking range $\Delta\omega_{\text{lock}} = 2\frac{\omega_0}{Q}\sqrt{\frac{I_1}{I_0}}$ [4] is quite large and so diode lasers are particularly suitable for injection locking (ω_0, I_0: frequency and intensity of the free running laser, I_1: injected intensity).

2 Experimental setup and results

The output of an injection-locked broad emitter diode laser operating at $\lambda = 670$ nm has been used to pump a Cr:LiSAF laser [5]. In contrast we are interested in the use of such a laser system for spectroscopic purposes.

A broad emitter diode laser (Coherent S-67-500C-100C) with a front facet 100 µm wide has been investigated. The maximum output for free-running operation is 500 mW at a current of 1000 mA. The threshold current is 420 mA. The dielectric coating of the chip facets provided by the manufacturer was not altered. The rear facet is highly reflecting. The active layer of the broad emitter diode laser is oriented in the $x - z$ plane. So the output is diffraction limited in the y direction and a collimator (Melles-Griot 06GLC001, numeric aperture 0.61, $f = 6.5$ mm) is placed such that the output beam of the broad emitter diode laser is collimated in the y direction. At currents slightly above threshold the output without injection consists of two clearly separated side lobes that emerge under a small angle relative to the optical axis. At higher currents the side lobes become less pronounced but are still present. The setup is shown in Fig. 1.

The injected light is provided by a grating-stabilized single-mode diode laser (master laser) [6] with 9.6 mW power available for injecting the broad emitter diode laser (slave laser). The master laser is isolated by an optical isolator (40 dB). To achieve proper injection locking the injected

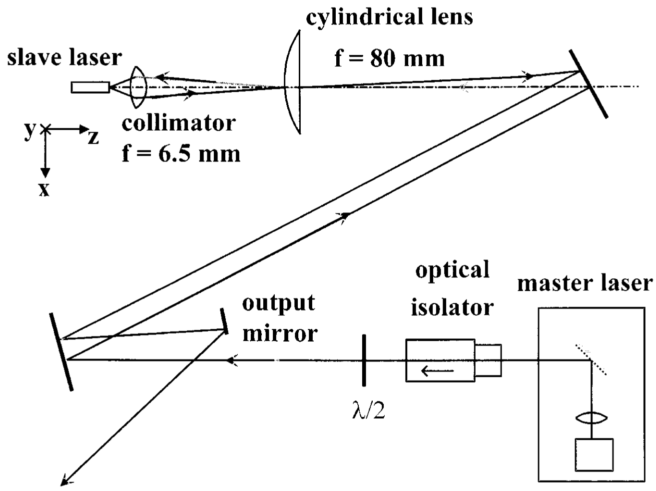

Fig. 1. Setup for injection locking. The cylinder lens is slightly displaced in the x direction from the optical axis to achieve injection of light collimated in the x direction and focussed in the y direction under a small angle of about 6° relative to the optical axis. Under these conditions proper injection locking of the broad emitter diode laser occurs

light has to be collimated in the x direction and an angle of incidence of about 6° relative to the optical axis has to be adjusted. This is done by the cylindrical lens ($f = 80$ mm) which is slightly displaced from the optical axis in the x direction to achieve off-normal incidence on the front facet of the slave laser and which forms a telescope with the collimator ($f = 6.5$ mm). This mode-matching scheme is also suggested by numerical modelling [3, 7] and supported by our experimental observation. Other mode-matching schemes, for example adjustment of the injected mode to one of the transverse modes of the broad emitter diode laser, were not succesful. To control the adjustment the front facet of the broad emitter diode laser is monitored by a CCD camera. The polarizations of the injected light and of the output of the broad emitter diode laser are linear and have to be parallel. To achieve injection locking the injected beam is overlapped with one of the side lobes of the broad emitter diode laser. If possible the focal length of the collimator of the master laser has to be chosen such that this overlap is optimized, but injection locking also occurs when this is not exactly the case. In our case the master laser beam and the side lobes of the slave laser beam had an elliptical cross section (length: width $\approx 3:1$) and the diameter of the slave laser side lobes is 1.5 times the diameter of the master laser beam. When the slave laser is operated only slightly above threshold, injection locking manifests itself by a sudden increase of the intensity of the side lobe that is not injected. Only this side lobe is reflected by the output mirror. The intensity of the injected side lobe is reduced when injection locking occurs. Once injection locking is established the current can be increased gradually. Typically there are some well-defined values of the current at which injection locking works best. These values are temperature dependent and so stable operation requires a temperature stabilization of the broad emitter diode laser better than 10 mK. At currents higher than 670 mA injection locking is no longer possible with injected powers up to 9.6 mW.

Up to this current the eigenmodes of the broad emitter diode laser are suppressed completely and 92% of the total

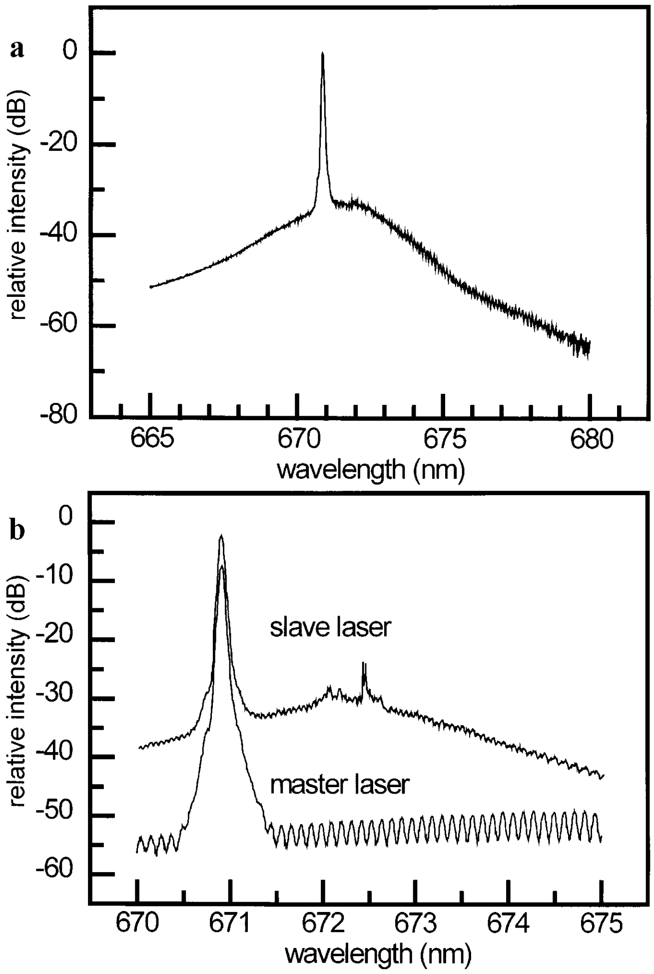

Fig. 2. a A small amount of the laser radiation emitted by the slave laser was coupled into an optical fiber and processed by an optical spectrum analyzer. 92% of the total output power is at the injected wavelength and all eigenmodes of the slave laser are suppressed. **b** Same as Fig. 2a but with slightly imperfect injection locking to illustrate the eigenmodes of the broad emitter diode laser. For comparison of the line positions, the master laser was monitored too. The injection-locked slave laser has the same linewidth as the master laser. The oscillations at low intensities are due to the detection system

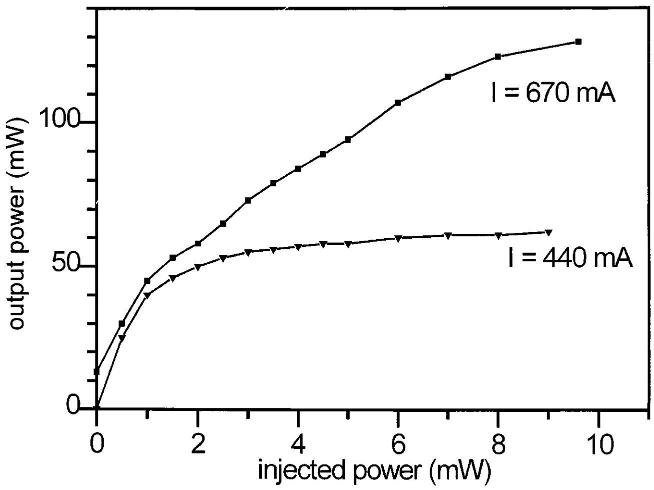

Fig. 3. Output power of the injection-locked slave laser. With 9.6 mW injected laser power 130 mW output power can be achieved. At low driving currents of the slave laser, 55 mW output power can be achieved with only 3 mW input power

output power is emitted with the injected frequency. The remainder is a spectrally broad background that reflects the gain profile of the broad emitter diode laser (Fig. 2a). The spectral linewidth of the output beam is comparable to the linewidth of the master laser. The maximum output power for single-mode operation is 128 mW at an injected power of 9.6 mW (Fig. 3). Higher injection powers are likely to increase the attainable output power in single-mode operation. 50 mW output power can be achieved with injected powers of less than 4 mW. In this case the slave laser has to be operated only slightly above threshold. The whole setup is mounted firmly on an aluminum plate and so mechanical realignment is only necessary once a week.

3 Manipulation of Li atoms with the injection-locked broad emitter diode laser

The output beam of the injection-locked broad emitter diode laser has been used to operate a magnetooptical trap for ^{7}Li. The ^{7}Li atoms have been emitted from a nearby thermal source. The master laser has been stabilized 25 MHz red-shifted relative to the D_2 atomic resonance $^2S_{\frac{1}{2}}(F=2) \leftrightarrow {}^2P_{\frac{3}{2}}(F=3)$. The repumping frequency has been generated by passing the laser through an electrooptic modulator. The elliptical shape of the cross section of the output beam of the injection-locked broad emitter diode laser has been corrected by an anamorphic prism pair and a tilted lens ($f = 150$ mm) has been used to correct for astigmatism. With 70 mW total laser power in the three retroreflected beams of the magnetooptical trap 8×10^6 atoms have been captured. The same number of ^{7}Li atoms is achieved when a Ti-Sapphire laser of the same power and wavelength that operates in a TEM_{00} mode is used. So the spatial and spectral quality of the injection-locked broad emitter diode laser has been confirmed to be sufficient for our application.

When operating the slave laser at low currents (450 mA) sidebands of the emitted laser frequency can be created by modulating the current. Thus electrooptic modulators for creating the repumping frequency can be avoided. With a modulation of the injection current of the slave laser at 803 MHz (this is the hyperfine splitting of the $^2S_{\frac{1}{2}}$ state of ^{7}Li), 20% of the total output power has been transmitted into the first sideband. Injection locking still is possible and no eigenmodes of the slave laser occurred at an output power of 60 mW.

To increase the number of ^{7}Li atoms in a magnetooptical trap operated by a Ti-Sapphire laser, the injection-locked broad emitter diode laser can be used to slow ^{7}Li atoms emitted from an oven and flying towards the capture region of the magnetooptical trap. The frequency of the injection-locked broad emitter diode laser has been shifted by 200 MHz to the red relative to the atomic transition $^2S_{\frac{1}{2}}(F=2) \leftrightarrow {}^2P_{\frac{3}{2}}$ (F=3). The sideband has been used to repump the ^{7}Li atoms into the state accessible to the carrier frequency. This procedure increased the number of atoms caught in the magnetooptical trap by a factor of four.

In addition a set of permanent magnets has been introduced to generate a spatially varying field that keeps the atoms in resonance with the laser while being slowed. The deceleration range of this Zeeman retarder is 7 cm and the number of ^{7}Li atoms in the magnetooptical trap has been increased by a factor of 10.

4 Summary

We realized a laser system for lithium spectroscopy that provides output powers up to 130 mW. It operates in single mode and is suitable for operating a magnetooptical trap.

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References

1. M.H. Anderson, J.R. Enster, M.R. Matthews, C.E. Wieman, E.A. Cornell: Science **269**, 189 (1995)
2. E.L. Raab, M. Prentiss, A. Cable, S. Chu, D. Pritchard: Phys. Rev. Lett. **75**, 2631 (1987)
3. J.M. Verdiell, R. Frey, J.P. Huignard: IEEE J. Quantum Electron. **27**, 396 (1991)
4. A. Siegman: *Lasers* (University Science Books, Mill Valley, CA 1986)
5. R. Knappe: Dissertation Universität Kaiserslautern (Shaker Verlag, Aachen 1997)
6. L. Ricci, M. Weidemüller, T. Esslinger, A. Hemmerich, C. Zimmermann, V. Vuletic, W. König, T.W. Hänsch: Opt. Commun. **117**, 541 (1995)
7. M.K. Chun, L. Goldberg, J.F. Weller: Opt. Lett. **14**, 272 (1989)