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# Collimation of a thulium atomic beam by two-dimensional optical molasses

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***Abstract.*** **The number of laser cooled and trapped thulium atoms in a magneto-optical trap is increased by a factor of 3 using a two-dimensional optical molasses which collimated the atomic beam before entering a Zeeman slower. A diode laser operating at 410.6 nm was employed to form optical molasses: The laser was heated to 70 °C by a two-step temperature stabilisation system. The laser system consisting of a master oscillator and an injection-locked amplifier emitted more than 100 mW at 410 nm and had a spectral linewidth of 0.6 MHz.**

***Keywords:*** *thulium, laser cooling, optical molasses, Blu-Ray laser diodes.*

## 1. Introduction

Enhancing a signal-to-noise ratio in developing new optical frequency standards is an important problem, which is solved by increasing the number of atoms participating in a measuring process. A similar problem arises in studying degenerated gases [1, 2].

At the Laboratory of active medium optics of the P.N. Lebedev Physics Institute, the promising optical frequency reference on the transition 1.14 μm of laser-cooled thulium atoms is investigated. We have earlier studied the laser cooling and trapping of thulium atoms in a magneto-optical trap (MOT) [3, 4]. The cooling was performed by the second harmonic radiation (with the wavelength of 410.6 nm) of a Ti:sapphire laser with a limiting output power of 100 mW. Raising the power gives the possibility to increase the number of atoms trapped in the MOT (due to optimisation of the Zeeman slower [5], employment of wider cooling beams and optical molasses [6]). In the present work we study the two-dimensional molasses at the wavelength of 410.6 nm used for increasing the flux of atoms in the MOT with a total light power of 130 mW.

For generating and amplifying radiation in a required wavelength range, one can employ the semiconductor lasers on ZnSe, SiC, and GaN-based compounds, which, subject to a doping level, may emit in the range 390–530 nm [7–13]. We employed the GaN semiconductor laser system operating at the wavelength of 410.6 nm, which was for the first time used for both laser cooling of thulium atoms and forming a two-dimensional optical molasses. It was of primary importance to demonstrate the possibility of replacing the complicated and expensive laser system comprising a ten-watt pump laser, single-mode Ti:sapphire laser, and frequency doubler with a simple and low-cost system based on laser diodes. This is important for both increasing the laser beam output power and possible practical employment of a thulium frequency reference. Earlier, operation of external-cavity diode lasers at wavelengths of 369 [14], 392 [15], and 420 nm [16] was reported. The semiconductor amplifier for a wavelength of 399 nm was realised [17] and was successfully employed for laser cooling of ytterbium atoms; besides, a laser system at the wavelength of 401 nm is used for laser cooling of erbium atoms at the Innsbruck University [6].

## 2. Semiconductor laser system

Presently, there are no commercially obtainable laser diodes possessing required characteristics at room temperature. We have created the laser system comprising a master oscillator and injection-locked amplifier. For the latter we used an SF-BW512P laser diode. The master oscillator comprised a PHR-803T laser diode, the aspheric objective (ThorLabs C610TME-A) with a focal length of 4 mm, and the diffraction grating (ThorLabs GH13-24U) in the Littrow configuration [18] (Fig. 1). With the grating (2400 mm$^{-1}$) approximately 10% of the radiation power diffracts to the first order, this radiation is brought back to the laser diode. For radiation outcoupling we used the zero diffraction order.

Unfortunately, at room temperature the centre wavelength of high-power and relatively cheap laser diodes used in Blu-Ray optical drives varies in the range 405–407 nm. The shift of the centre generation wavelength to 410.6 nm requires

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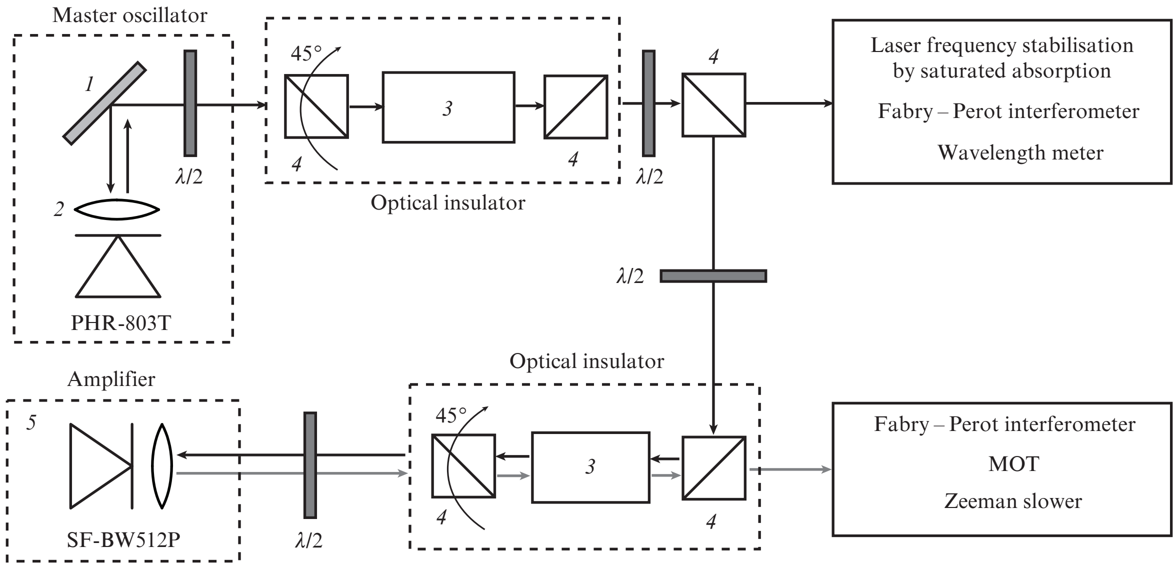


**Figure 1.** Schematic diagram of the laser system: (*1*) diffraction grating; (*2*) laser diode PHR-803T with an aspheric objective (master laser); (*3*) Faraday rotators; (*4*) polarisation beam splitters; (*5*) laser diode SF-BW512P (amplifier); ($\lambda/2$) phase half-wave plate.

considerable heating of the diode actually to the upper limit of 80 °C (Fig. 2). Since the width of the spectrum of the PHR-803T laser diode generating in a free running regime without grating is a few nanometres, the heating to 60 – 70 °C is sufficient for obtaining generation at the wavelength of 410.6 nm under the optical feedback with the grating. Diodes of the same kind may have slightly different centre wavelengths. At the temperature of 70 °C and injection current of 100 mA, from the three PHR-803T diodes available, diode 1 had the centre wavelength of 408.3 nm, diode 2 – 407.9 nm, and diode 3 – 409.2 nm. Thus, we have chosen diode 3 with the maximum wavelength.

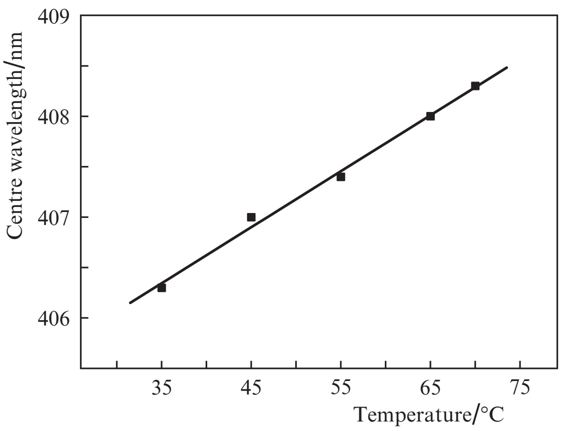


**Figure 2.** Centre wavelength of the laser diode PHR-803T in the free running regime vs. temperature (the injection current is 60 mA). The line slope is $55\times10^{-3}$ nm grad$^{-1}$.

Because of the strong dependence of length of external resonator on temperature (the corresponding frequency variation is 30 MHz mK$^{-1}$) we used the two-step temperature stabilisation capable of maintaining the temperature with the accuracy better than 1 mK under the laboratory temperature variation of ±3 °C.

Laser cooling of thulium atoms requires the exact matching with the wavelength of the cooling transition [$4f^{13}6s^2(J = 7/2, F = 4) \rightarrow 4f^{12}5d_{3/2}6s^2(J = 9/5, F = 5)$]. For stabilising the wavelength of a master laser relative to the cooling transition, we used the saturated absorption technique [19] (the scheme of the experiment is described in [20]).

## 3. Operation regime of the master oscillator

The wavelength of the master laser radiation was measured (to an accuracy of $10^{-3}$ nm) by an interference wavelength meter (Angstrom HighFinesse WM5). The wavelength was roughly adjusted by turning a grating, and more accurately by varying the injection current and temperature of the diode. In this way the wavelength was adjusted to 410.6 nm at a radiation power of 20 mW. The laser frequency was scanned within several GHz by changing the length of the external resonator with a piezoceramic element.

Subject to the injection current, a laser diode may operate as a single-mode or multimode device. The single-mode operation was tested by using a confocal Fabry – Perot scanning interferometer. The spectral width of the diode laser emission line was determined from beatings with the second-harmonic radiation of a Ti : sapphire laser. The spectral width of the latter was narrower than 100 kHz (Fig. 3).

The spectral width of the observed beat-signal corresponded to the master laser linewidth, which depended on a signal acquisition time. At the time shorter than 100 μs, the total FWHM was 0.6 MHz (Fig. 3). At longer times, the monotonic frequency drift was observed with the rate of 192 kHz s$^{-1}$ due to the gradual drift of the injection current and to thermal elongation of the external laser resonator.

The important parameter of laser radiation is the spectral purity of the latter. It was determined by heating the cell with metal thulium to a temperature of 750 °C, which provided the optical transparency of thulium vapours much above unity at a prescribed wavelength. In this case, the transmission of resonance radiation of cell was below the detection level, whereas the radiation in other longitudinal modes that are nonresonant with the atomic transition passed through the cell with-

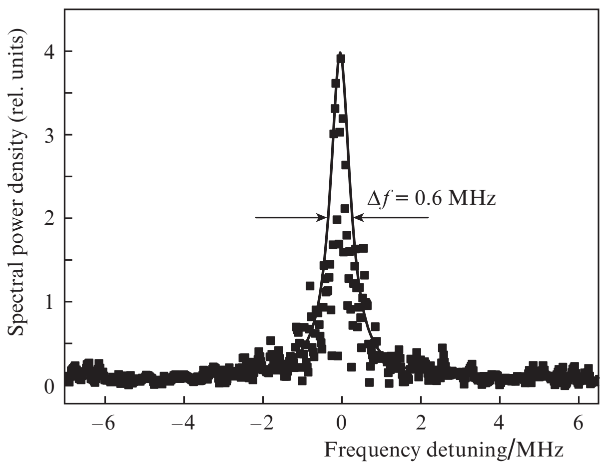


**Figure 3.** Discrete Fourier transform of the beating between the master semiconductor laser radiation and second harmonic of a Ti:sapphire laser. The solid curve is the Lorentz approximation. The full half-height spectral width is 0.6 MHz, signal accumulation time is 100 μs.

out absorption. By comparing the cell transmission with the laser adjusted to the resonance and with the switched-off laser one can get the upper estimate of the part of power comprised in other longitudinal modes. With the optimal adjustment of the injection current this part was 5%.

## 4. Injection locking

The injection-locked laser diode was used for increasing the output power of laser radiation [21]. The laser diode SF-BW512P (the centre wavelength is 405 nm at room temperature) without external resonator was used as an amplifier. The radiation power of the diode may reach 500 mW at a current of 0.5 A. Among three available diodes SF-BW512P with the centre wavelengths of 409.0, 407.5, and 407.4 nm (the temperature and injection current are 70 °C and 150 mA, respectively), we have chosen the first one with the greatest wavelength. It was experimentally shown that for stable injection locking it suffices to employ one-step temperature stabilisation.

For the initial emitter we used either the master diode laser described above or second harmonic of a Ti:sapphire laser (Fig. 4). In the first case, the power of introduced radiation (2–3 mW) was sufficient for obtaining 100 mW in the beam after the amplifier. A further increase in the output power was prevented by the optical feedback arising between the master laser and amplifier. While using the second harmonic radiation of the Ti:sapphire laser, the output power of the amplifier was above 200 mW at the injected light power of 4 mW. The emission spectrum of the laser amplifier was studied by using a Fabry–Perot scanning interferometer. It was found that under exact adjustment the spectrum comprised a monochromatic component without noticeable background.

The amplified radiation of the master laser was used for Zeeman slowing and trapping of thulium atoms (approximately $3\times10^4$ atoms, this number is limited by the number of atoms in the initial atomic beam) in a magneto-optical trap operating at a wavelength of 410.6 nm. From the viewpoint of laser cooling and atom trapping, operation of the semiconductor system was completely identical to the laser system with second harmonic of a Ti:sapphire laser. Nevertheless, the laser diodes at our disposal demonstrated transitions between various spatial modes, which resulted in power fluctuations and affected the long-term stability of the system. In this regard, we had to temporarily resign employment of the master laser diode, and in further experiments with optical molasses we used the second harmonic radiation of a Ti:sapphire laser as a master oscillator. However, we are planning to pass to a completely semiconductor laser system by selecting appropriate laser diodes for the master cascade.

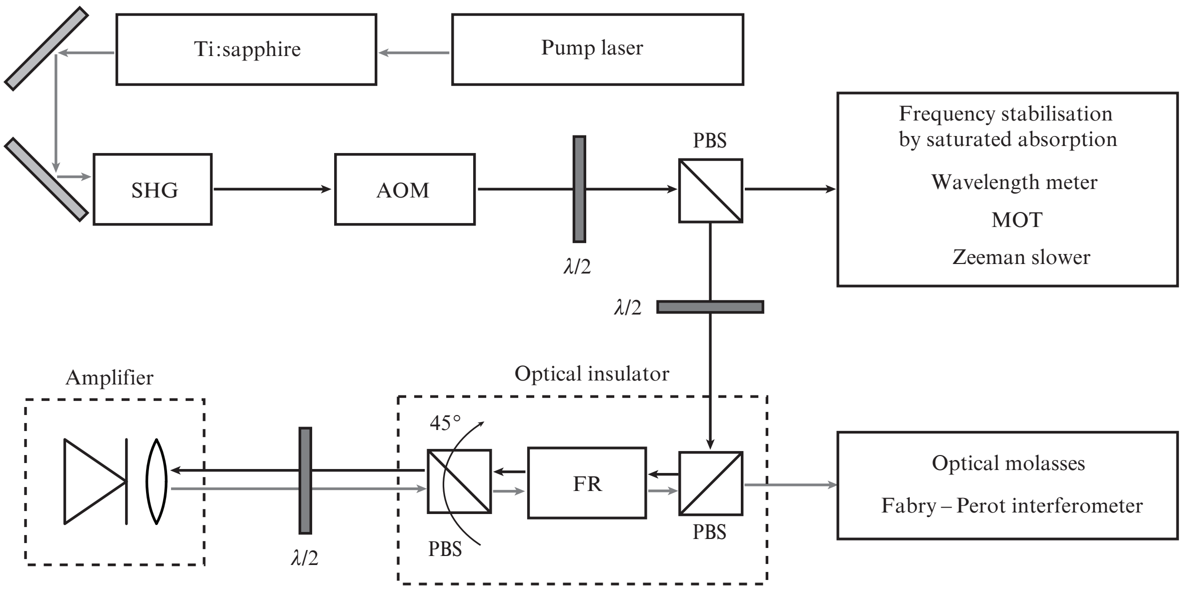


**Figure 4.** Schematic diagram of second harmonic amplifier. The pump laser is the solid-state laser with diode pumping operating at the wavelength of 532 nm; Ti:sapphire is the tunable single-mode laser on sapphire doped with titanium ions (the wavelength is 821.1 nm); SHG is an intracavity frequency doubler (410.6 nm); AOM is the acousto-optical modulator with a centre frequency of 200 MHz operating in two-pass scheme; amplifier is a laser diode with an aspheric objective (the focal length is 4 mm); PBS is the polarisation beam splitter; FR is the Faraday rotator.

## 5. Optical molasses

In the installation for optical cooling of thulium atoms [3] the latter are loaded into the MOT from an atomic beam. Since the limiting velocity needed for atom trapping in a thulium MOT is 30 m $s^{-1}$, whereas thermal velocities in the beam may reach 400 m $s^{-1}$, the atoms were deaccelerated by a oncoming laser field using the Zeeman slower thoroughly described in [5]. The diverging beam of atoms with the linear divergence angle of approximately 10° passes to the slower through the diaphragm D1 (Fig. 5). The opening angle of the atomic beam formed by the slower is less than 1°; hence, a considerable part of atoms from the input beam settles to the inner walls of the slower. Collimation of the input beam and increase in the flux of the atoms leaving the slower were realised by means of optical molasses. For this purpose, the light field was formed directly after the input diaphragm D1, which reduced the radial component of atom velocities. The field was produced by two anti-collinear laser beams [(*3*) in Fig. 5], which were orthogonal to each other and normal to the atomic beam direction. The radiation frequency was shifted red relative to the frequency of the cooling transition in thulium atom. Thus, directly in front of the entry to the Zeeman slower, the atoms are cooled in a transversal direction. The relatively small part of atoms possessing a moderate initial radial velocity component slow down, which, however, results in an increase in the number of the atoms trapped in the MOT. In experiments with Er atoms, the number of trapped atoms increased by approximately an order [6].

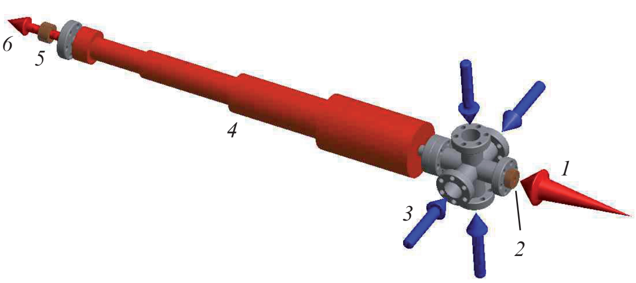


**Figure 5.** Setup used for forming two-dimensional molasses: (*1*) atomic beam leaving an oven; (*2*) input diaphragm D1; (*3*) four beams forming optical molasses; (*4*) Zeeman slower; (*5*) output diaphragm D2; (*6*) collimated beam of slowed atoms.

An optical molasses was formed by the radiation of the semiconductor amplifier fed by a fraction of a Ti:sapphire laser second harmonic radiation. The frequency of the amplifier radiation was tuned by using a two-pass acousto-optical modulator placed between the master laser and amplifier (Fig. 4). Such a scheme makes it possible to use up to 300 mW of radiation at the wavelength of 410.6 nm, actually increasing the power of the Ti:sapphire laser by a factor of three. In turn, trapping in the MOT and Zeeman slowing of atoms were realised by using the second harmonic radiation of the Ti:sapphire laser (similarly to [3, 4]).

Besides creation of optical molasses, the laser beams may also lead to the optical pumping from sublevel F = 3 to F = 4 of the ground state [3] and to transversal drift of atoms in the beam due to light pressure effect.

In the experiments we compared the number of atoms in MOT under switched on/off optical molasses by blocking the radiation from the amplifier. Since the luminescence signal from a cloud detected by a PMT is proportional to the number of trapped atoms the ratio of the luminescence signals provided information about the efficiency of molasses operation (Fig. 6).

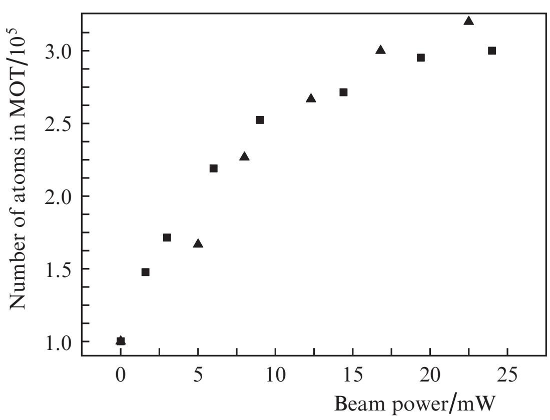


**Figure 6.** Number of atoms in the MOT vs. the power of one of the beams forming molasses at the molasses beam frequency detuning from the cooling transition frequency: 10 MHz (■) and 30 MHz (▲).

Since a residual longitudinal magnetic field from a Zeeman slower is present in the domain of the optical molasses created, at the negative frequency detuning beyond the line halfwidth ($\gamma/2$) the maximal effect was observed for the light polarisation along the atomic beam, i.e., when only $\pi$-transitions were excited without Zeeman shift. According to the Doppler theory of laser cooling, optical molasses under the exact resonance with the cooling transition should not reduce the average radial velocity of beam. However, in the magnetic field, which splits the magnetic components to several linewidths $\gamma$ (the field of 10 Gs will suffice), one of the transitions $\sigma^+$ or $\sigma^-$ may have a 'red' detuning from the corresponding Zeeman components. We observed an increased number of atoms in the MOT (by a factor of three) even with zero detuning, although under particular optimal polarisations of the beams. As expected, with the positive detuning exceeding $\gamma/2$, molasses makes the atomic beam even more diverging, which results in a reduced number of atoms in the MOT.

A transversal drift of the atomic beam may occur due to a noncollinearity of light beams in optical molasses or their nonorthogonality to the atomic beam. This effect is difficult to distinguish from optical molasses because it can also lead to an increase in the number of atoms in the MOT if the velocity distribution of atoms leaving an oven is not axisymmetric relative to the axis of the Zeeman slower.

Separation between the sublevels F = 3 and F = 4 is $\delta f \approx$ 1500 MHz; hence, at a temperature of $T$ = 1000 K the Boltzmann factor is $\exp(-h\delta f/kT) \approx 1$, which, taking into account degeneration in a magnetic quantum number, means that the levels F = 3 and F = 4 are occupied, respectively, by 7/16 and 9/16 of the total number of atoms in the beam. If all the atoms would be excited to the state F = 4, then the number of atoms in the MOT will increase by a factor of at most 16/9 $\approx$ 1.8, which is noticeably less than the experimentally observed three-fold increase. Hence, the optical pumping gives no complete explanation of the effect observed.

Thus, we succeeded in realising optical molasses, which leads to a collimation of atomic beam and increases the number of atoms trapped in the MOT. A further increase in the power of molasses beams has no benefits in the number of atoms due to the saturation effect at a prescribed frequency detuning from resonance (Fig. 6). An increased detuning and power only result in a negligible additional increase in the number of atoms in the MOT.

## 6. Conclusions

The semiconductor laser source for cooling thulium atoms at 410.6 nm is developed. It is based on a semiconductor laser diode and a semiconductor injection-locked amplifier. The spectral width of the output radiation is 0.6 MHz. The parameters mentioned are obtained at a considerable heating (up to 70 °C) of the diodes by employing a two-step temperature stabilisation. Laser cooling and trapping of thulium atoms in the MOT are demonstrated using the semiconductor laser system developed.

Operation of the two-dimensional optical molasses collimating a thulium atomic beam is investigated. In optimal conditions the optical molasses increases the number of atoms in the MOT by a factor of three. The semiconductor laser system and optical molasses will be employed in further experiments on secondary cooling and reloading atoms into an optical dipole trap, which requires a maximal possible number of preliminarily cooled and trapped atoms.

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