Quantum Electronics **50** (6) 530 – 536 (2020)

https://doi.org/10.1070/QEL17343

Atom femtosecond optical trap based on spectrally filtered laser radiation

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Abstract. **We have examined the use of alkali metal (rubidium) vapour for spectral filtering of broadband pulsed laser light that is used to produce a femtosecond pulsed optical dipole trap. It has been shown that, even at large detuning of the centre emission frequency from the frequency of atomic transitions, spectral components present in the wings of the laser emission line are capable of heating localised atoms, thus reducing their lifetime in the atomic trap. Using atomic vapour for filtering the laser emission spectrum, we have suppressed its spectral components resulting in heating. This has made it possible to increase the lifetime of atoms in the pulsed optical dipole trap to a value comparable to their lifetime in an optical trap formed by narrow-band cw laser light.**

Keywords: *optical dipole trap, pulsed light, atomic vapour.*

1. Introduction

The first experimental studies concerned with the laser cooling [1] and trapping [2] of neutral atoms used alkali metal atoms. A variety of basic studies [3] and practical applications [4] require that the range of elements that can be cooled and localised with the use of optical fields be extended. The major challenge in this context is to implement processes for laser cooling of atoms. The reason for this is that the absorption lines of most atoms lie in the UV spectral region, for which no efficient light sources are available [5]. It is due to this that laser cooling has so far been demonstrated for only a limited number of atoms [6]: 26 elements whose absorption spectra fall in the visible and near-IR spectral regions.

Optical localisation of atoms does not require any laser sources with a frequency in resonance with that of atomic transitions, but the depth of the optical potential is inversely proportional to the laser frequency detuning from the frequency of an atomic transition [7], which leads to a small potential depth at large frequency detuning. The decrease in the depth of the optical potential can be compensated for by increasing the laser light intensity, but this approach presents a number of technical difficulties related to the use of high-intensity light.

Laser sources for cooling and localisation are especially necessary in the case of atoms whose transition frequencies lie in the UV spectral region. Of most interest are hydrogen and antihydrogen atoms, which can be used in basic research [8]. Also interesting and practically important are the cooling and localisation of atoms that are used in organic chemistry (carbon, oxygen and nitrogen) [5]. All the above elements have absorption lines suitable for cooling and localisation and lying in the UV spectral region. At present, only pulsed laser sources emitting in the UV spectral region are mainly available [9]. The few cw lasers are multimode and have a narrow frequency tuning range and low power. In connection with this, it is planned that UV radiation for atom cooling and trapping will be ensured by nonlinear conversion of light from pulsed laser sources (second, third and high harmonic generation).

A theoretical analysis of laser cooling with the use of pulsed laser light was presented by Kielpinski [5]. Like in the first experiments on laser cooling of atoms with cw lasers, pulsed cooling was demonstrated for alkali metal atoms using pico- and femtosecond pulses [10, 11]. In addition, Clarke et al. [12] and Shiddiq et al. [13] demonstrated optical localisation of rubidium atoms using picosecond light pulses. At the same time, attempts to localise atoms using femtosecond light pulses were unsuccessful for a long time, even though such localisation was possible according to theoretical predictions [14, 15]. This was thought to be mainly due to the photoassociation of atoms in the optical potential, which can be an effective loss channel for atoms in a trap [16].

Further detailed investigation of atom heating processes in a pulsed optical potential made it possible to optimise laser beam parameters so that femtosecond localisation of atoms became feasible. This allowed us to localise rubidium atoms using femtosecond light pulses [17]. In the case of optical atom localisation, the following main channels for atom losses from an optical potential can be distinguished: (1) interaction with residual vapour, (2) atom photoassociation processes in the optical potential, (3) momentum diffusion processes due to dipole force fluctuations and (4) momentum diffusion processes due to resonance photon scattering. As shown by Afanasiev et al. [17], the main physical process responsible for the heating of atoms in a pulsed optical potential is momentum diffusion driven by dipole force fluctuations. Moreover, pulsed localisation revealed

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Received 11 March 2020; revision received 27 March 2020
Kvantovaya Elektronika **50** (6) 530 – 536 (2020)
Translated by O.M. Tsarev

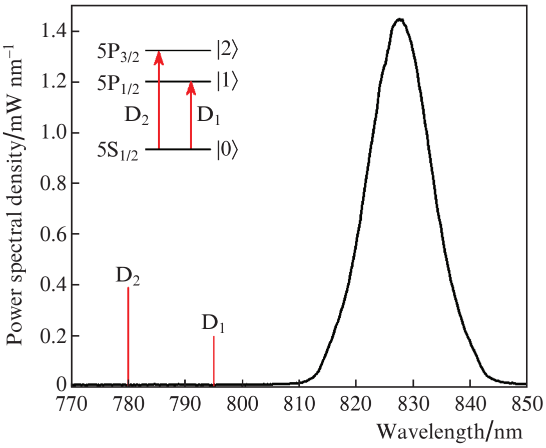

Figure 1. Power spectral density of the light used to localise atoms and the position of the absorption lines of Rb atoms.

its characteristic feature due to the extremely broad spectral composition of light: the spectral components (at wavelengths of 780 and 795 nm) present in the wings of the laser emission line and close to atomic resonance can cause heating of localised atoms. In this work, we propose and demonstrate a method for eliminating quasi-resonance components in the laser emission spectrum through the absorption of these components by dense rubidium atomic vapour in an outer cell. This made it possible to perform narrow-band spectral filtering of the localising light. In this paper, we examine this filtering method in the case of the localisation of rubidium atoms in a pulsed optical potential.

2. Spectral properties of pulsed light

As pointed out earlier, the use of ultrashort laser pulses for cooling and localising neutral atoms will make it possible to extend the range of atoms that can be used in atomic optics. At the same time, in going from continuous-wave narrow-band light to pulsed light, it is necessary to take into account its spectral width and mode composition. In particular, ensuring proper interaction of atoms with optical comb frequencies made it possible to cool them [10]. If pulsed light is used for atom localisation, it is also necessary to take into account its spectral composition. The reason or his is that, even at large laser frequency detuning from the frequency of an atomic transition, the optical field contains spectral components that are in resonance with atomic transitions owing to the broad spectral composition of the light. This is particularly important of one uses femtosecond light pulses whose spectral width can reach 10–50 nm, which considerably exceeds the spectral width of a laser source operating in continuous mode.

The possibility of atom localisation in an optical dipole potential is based on the fact that heating processes due to resonance scattering of laser photons by a localised atom are suppressed because of the large laser frequency detuning [18]. The presence of spectral components of light in resonance with optical transitions of atoms leads to effective heating of the atoms (an increase in the energy of the atoms in the optical potential) and, as a consequence, a decrease in the lifetime of atoms in this potential. It is this situation which occurs when femtosecond light pulses are used. In such a case, the spectral width of laser emission is comparable to the laser frequency detuning from the atomic transition frequency. As a result, the localising light contains a small fraction of light whose wavelength is in exact resonance with the wavelength of the absorption line of atoms.

To localise rubidium atoms, Afanasiev et al. [17] used femtosecond light pulses with a centre wavelength of 825 nm and spectral width of 15 nm. Rubidium atoms have two absorption lines, at wavelengths $\lambda_{D_1} = 795$ nm and $\lambda_{D_2} = 780$ nm, which correspond to transitions from the $5S_{1/2}$ ground state to the $5P_{1/2}$ and $5P_{3/2}$ excited states. Figure 1 shows the emission spectrum of laser pulses used to investigate rubidium atom localisation, together with the position and relative intensities of the absorption lines of rubidium atoms. The strength of the D_1 line is half that of the D_2 line, but the localising light frequency detuning for it ($\Delta_{D_1} = 30$ nm) is smaller than that for the D_2 line ($\Delta_{D_2} = 45$ nm).

The average laser output power was 20 mW. It is seen from Fig. 1 that the spectral power in the region of the absorption lines of rubidium is low. However, it differs from zero because the emission spectrum of a mode-locked pulsed laser is limited by the spectral gain bandwidth of the active medium and lies in the range 750–900 nm in the case of a Ti:sapphire laser. Results of additional measurements with band-pass filters show that, in a spectral range equal to the absorption linewidth of rubidium (6 MHz), the power at the frequencies of the D_1 and D_2 lines is ~140 (P_{D_1}) and ~0.56 pW (P_{D_2}). The considerable difference in power is due to the fact that the D_1 line is close to the centre frequency of the pulsed laser. If such laser light is focused onto an area 8 μm in radius, these powers correspond to intensities $I_{D_1} = 70$ μW cm^{-2} and $I_{D_2} = 0.28$ μW cm^{-2}. These intensities are extremely low compared to the saturation intensity of atomic transitions: $I_{D_1}^{\text{sat}} = 4.49$ mW cm^{-2} and $I_{D_2}^{\text{sat}} = 2.50$ mW cm^{-2} for ^{85}Rb in the case of linearly polarised light [19]. In continuous mode, the laser operates predominantly on a few competing frequency modes, and the power spectral density in the region of the absorption lines of rubidium is negligible.

Let us estimate the lifetime of rubidium atoms in an optical potential when they interact with additional resonance bichromatic laser light having the above intensities. To this end, it is necessary to estimate the rate of photon scattering by an atom. This can be done by finding a steady-state atom population distribution in a three-level medium with a common ground state (Fig. 1).

The $5S_{1/2}$ ground state is denoted as $|0\rangle$, and the $5P_{1/2}$ and $5P_{3/2}$ excited states, as $|1\rangle$ and $|2\rangle$, respectively. Dipole-allowed transitions are only possible between the following states: $|0\rangle \to |1\rangle$ and $|0\rangle \to |2\rangle$. The $|0\rangle \to |1\rangle$ transition corresponds to the D_1 line of rubidium, with a wavelength $\lambda_{D_1} = 795$ nm, and the $|0\rangle \to |2\rangle$ transition corresponds to the D_2 line, with a wavelength $\lambda_{D_2} = 780$ nm. The dynamics of such a system when it interacts with a bichromatic field comprising two components that have intensities I_1 and I_2 and are in resonance with the $|0\rangle \to |1\rangle$ and $|0\rangle \to |2\rangle$ transitions, respectively, can be described using equations for a density matrix:

$$\frac{d\rho_{11}}{dt} = i\Omega_1(\rho_{01} - \rho_{10}) - \Gamma_1\rho_{11},$$

$$\frac{d\rho_{22}}{dt} = i\Omega_2(\rho_{02} - \rho_{20}) - \Gamma_2\rho_{22},$$

$$\frac{d\rho_{01}}{dt} = i\Omega_1(\rho_{11} - \rho_{00}) - \frac{\Gamma_1}{2}\rho_{01}, \quad (1)$$

$$\frac{d\rho_{02}}{dt} = i\Omega_2(\rho_{22} - \rho_{00}) - \frac{\Gamma_2}{2}\rho_{02},$$

$$\rho_{00} + \rho_{11} + \rho_{22} = 1,$$

where Ω_1 and Ω_2 are the Rabi frequencies of the $|0\rangle \to |1\rangle$ and $|0\rangle \to |2\rangle$ transitions, respectively, and $\Gamma_1 = 2\pi\times5.75$ MHz and $\Gamma_2 = 2\pi\times6.07$ MHz are natural widths of the excited states. In this system of equations, we assume that the probability of exciting an atom from the $|0\rangle$ state to the $|1\rangle$ ($|2\rangle$) state by a laser field at the frequency of the $|0\rangle \to |2\rangle$ ($|0\rangle \to |1\rangle$) atomic transition with an intensity I_2 (I_1) is low compared to the probability of the resonance transition. This assumption is valid at typical experimental light intensities.

In a steady state, we have

$$\frac{d\rho_{11}}{dt} = \frac{d\rho_{22}}{dt} = \frac{d\rho_{01}}{dt} = \frac{d\rho_{02}}{dt} = 0$$

and the solution to this system of equations has the form

$$\rho_{00} = \frac{(1 + \frac{1}{2}s_1)(1 + \frac{1}{2}s_2)}{(1 + s_1 + s_2 + \frac{3}{4}s_1s_2)},$$

$$\rho_{11} = \frac{\frac{1}{2}s_1(1 + \frac{1}{2}s_2)}{(1 + s_1 + s_2 + \frac{3}{4}s_1s_2)}, \quad (2)$$

$$\rho_{22} = \frac{\frac{1}{2}s_2(1 + \frac{1}{2}s_1)}{(1 + s_1 + s_2 + \frac{3}{4}s_1s_2)},$$

where

$$s_i = \frac{I_i}{I_i^{\text{sat}}} = 2\left(\frac{\Omega_i}{\Gamma_i}\right)^2$$

is the saturation parameter of the $|0\rangle \to |i\rangle$ $(i = 1, 2)$ transition.

At typical experimental laser field intensities, calculations give the following steady-state populations: $\rho_{00} \approx 0.992$, $\rho_{11} \approx 7.7 \times 10^{-3}$ and $\rho_{22} \approx 5.6 \times 10^{-5}$. Even though the dipole moment of the atomic transition corresponding to the D_1 line of rubidium is smaller than that for the D_2 line, a considerably larger fraction of the excited state population is concentrated at the $|1\rangle$ level (in the $5P_{1/2}$ state). The reason for this is that resonance light intensities are considerably lower than saturation intensities and, hence, the absorption remains linear. At the same time, the intensity of the light interacting with the $|0\rangle \to |1\rangle$ transition is several orders of magnitude higher than that of the light interacting with the $|0\rangle \to |2\rangle$ transition because the D_1 line is close to the centre frequency of the pulsed laser.

The sought rate of photon scattering by an atom is given by $R_i^{\text{sc}} = \Gamma_i\rho_{ii}$. Since an atom receives a recoil momentum in each scattering event, the photon scattering rate determines the momentum diffusion coefficient D of the localised atom [20]. In the three-level system under consideration, the total momentum diffusion coefficient is given by

$$D = D_1 + D_2 = \frac{1}{2}\sum_{i=1,2} R_i^{\text{sc}}(\hbar k_i)^2, \quad (3)$$

where $\hbar k_i$ is the recoil momentum for the scattering of a photon with a wavenumber k_i. Under the conditions of the experiment being described, we have $D = 9.7 \times 10^{-50}$ J kg/s. The momentum diffusion coefficient determines the lifetime of an atom in an optical potential, which can be estimated as the time τ needed for the energy of an atom of mass m to increase by the depth of the localisation potential, U_0 [21]:

$$\tau = \frac{U_0 m}{D}. \quad (4)$$

If pulsed laser light is used for atom localisation, there is no steady-state optical potential. Nevertheless, the depth of the potential can be estimated using average intensity parameters [13]. This is possible because the laser pulse repetition rate $f_{\text{rep}} = 80$ MHz far exceeds the frequency of atomic oscillations in the potential well [17]. The depth of the optical potential produced by linearly polarised light with average intensity I and centre frequency ω_{las} for rubidium atoms with atomic transition frequencies ω_{D_1} and ω_{D_2} corresponding to the D_1 and D_2 lines and an atomic transition frequency ω_0, with no account for the fine splitting of excited states, can be estimated using the well-known relation [7]

$$U_0 = \frac{\pi c^2 \Gamma}{\omega_0^3}\left(\frac{1}{\omega_{\text{las}} - \omega_{D_1}} + \frac{2}{\omega_{\text{las}} - \omega_{D_2}}\right)I. \quad (5)$$

If 20-mW laser light with a centre wavelength $\lambda = 825$ nm is focused to a spot radius of 8 μm, the depth of the potential is $U_0 = 1 \times 10^{-27}$ J = 74 μK. According to (4), the lifetime of atoms in an optical dipole trap, limited by momentum diffusion, is 1.5 ms. This short lifetime is due to the heating of the atoms by the localising field spectral components that are in resonance with the D_1 and D_2 absorption lines of Rb atoms. The contributions of the D_1 and D_2 lines to the atom lifetime are $\tau_{D_1} = 1.5$ ms and $\tau_{D_2} = 185$ ms.

3. Spectral filtering of light

It follows from our calculations that the spectral distribution of pulsed light has a strong effect on the lifetime of atoms localised in a pulsed optical dipole trap. To increase the lifetime of atoms in an optical potential, it is necessary to suppress the spectral components of the localising field at the absorption frequencies of Rb atoms. Under the experimental conditions of this study, the shortest measurable lifetime of atoms in an optical potential is ~100 ms. According to our calculations, to reach this lifetime the power of the spectral components that are in resonance with the rubidium lines should be reduced by 70 times.

The power of the corresponding spectral components of the localising field can be reduced in several ways. The simplest one is to use a notch filter. This approach has a serious drawback. The operation of such a filter relies on interference effects, so, passing through the layered structure of the filter, pulsed light of short duration breaks up in the time domain into a sequence of pulses. Such a configuration cannot be considered as a pulsed optical dipole trap with a particular pulse duration.

An effective solution to the problem of spectral filtering is to use a rubidium atomic vapour cell as a spectrally selective filter. When laser light passes through an optical cell filled with saturated rubidium vapour, the vapour absorbs light at the absorption frequencies of the Rb atoms. Absorption coefficients depend on the length of the cell and its temperature, which determines the concentration of atoms in the cell [22].

Figure 2 shows laser light transmission spectra of a cell with isotopically natural rubidium atomic vapour near the D_2 absorption line at different temperatures. The transmission spectra were obtained at a laser light intensity below the saturation intensity. With increasing temperature and, hence, atomic vapour concentration, the absorption coefficient increases. Thus, a heated rubidium atomic vapour cell can be used as a notch filter [23].

At cell temperatures above 70 °C, the selective absorption is so strong that the resonance spectral components of the laser light have no effect on the dynamics of atoms in the trap, and the lifetime of the atoms in the optical dipole trap formed by the light transmitted through the cell increases. It should be noted that, owing to the Doppler effect, light is absorbed in a broad spectral range, which further reduces the possibility of photon scattering in the wings of the absorption lines of the localised atoms. As the temperature is raised to 200 °C, individual absorption lines merge and the rubidium vapour cell becomes an effective notch filter with a bandwidth of ~8 GHz. The absorption spectrum near the D1 line of rubidium is similar in shape to that in Fig. 2 [24].

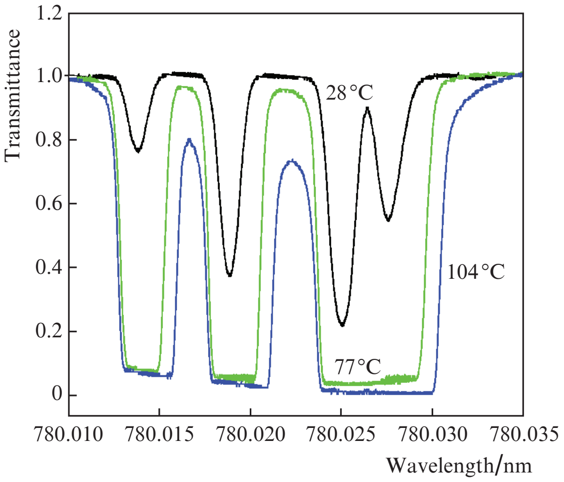

Figure 2. Transmission spectra of a cell with saturated Rb atomic vapour near the D_2 absorption line at different temperatures.

It is worth noting two features of using a vapour cell as a filtering component.

First, when femtosecond laser pulses propagate through a dense absorbing medium under our experimental conditions, their shape does not undergo any significant changes: such changes occur only if the centre frequency of the pulses lies near absorption lines [25].

Second, the use of a rubidium atomic vapour cell in conjunction with broadband pulsed laser light is analogous

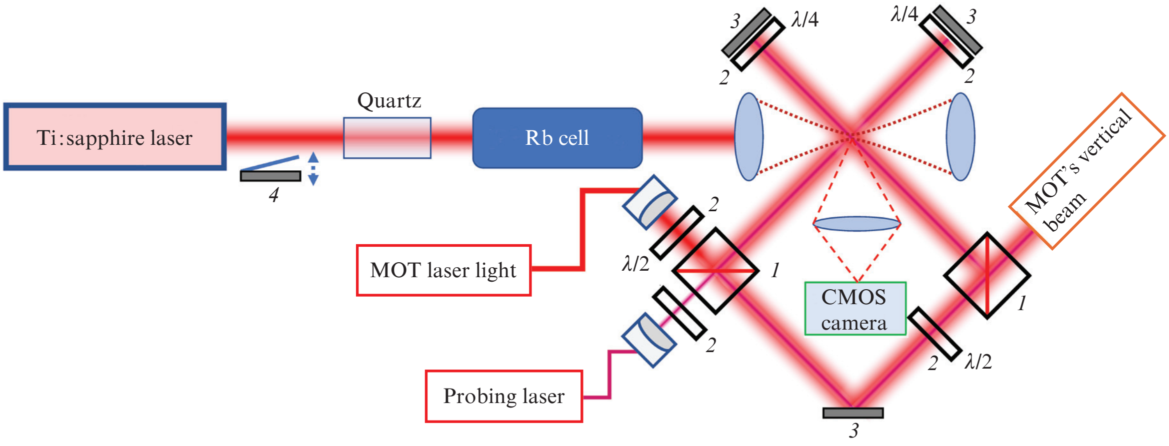

Figure 3. Schematic of the experimental setup used to study the effect of spectrally selective light filtering on the lifetime of atoms in a pulsed optical trap: (*1*) polarising beam splitter, (*2*) phase plate, (*3*) mirror, (*4*) mechanical shutter.

to frequency comb spectroscopy, a method developed in recent years [26]. In that method, the spectrum of an element of interest is obtained by assessing the absorption of the spectral components of an optical comb that correspond to absorption frequencies. The selective frequency filtering of pulsed light proposed by us for producing an optical dipole potential corresponds to the limiting case of frequency comb spectroscopy. Central to our approach is a complete absorption of the spectral components corresponding to the excitation frequencies of atomic transitions of atoms being localised.

4. Experimental setup

The effect of spectrally selective filtering of femtosecond pulses on the lifetime of localised atoms was studied using 420-fs pulses. The lifetime of atoms in an optical trap was measured as a function of rubidium atomic vapour cell parameters. The absorption in the cell was controlled by varying its temperature.

Figure 3 shows a schematic of the experimental setup. The formation of cooling and probing laser fields was described in detail elsewhere [27]. The procedure used to measure the lifetime of atoms in an optical potential was similar to that reported by Afanasiev et al. [17].

A key component of the experimental setup was a vacuum chamber with a residual vapour pressure of $\sim 7 \times 10^{-10}$ Torr. To localise atoms in the optical dipole trap, they were precooled in a magneto-optical trap (MOT). Subsequent sub-Doppler cooling of atoms allowed the temperature to be lowered to 40 μK. The kinetic energy of atoms at this temperature is comparable to a 74-μK depth of a potential well produced by pulsed laser light with an average power of 20 mW focused onto an area of 8-μm radius (average intensity $I = 9.95 \times 10^3$ W cm^{-2}). The pulsed optical dipole trap was produced by a Ti : sapphire laser with a pulse duration of 50 fs and a spectral bandwidth of 15 nm (the emission spectrum of the laser is shown in Fig. 1).

To suppress the momentum diffusion driven by dipole force fluctuations due to the high laser pulse peak intensity [17], the pulse duration was increased. To this end, the laser beam was passed through a 19.5-cm-thick quartz glass plate. Because of group velocity dispersion, the laser pulse duration increased to ~420 fs. Thus, the optical dipole trap was produced by chirped laser light whose spectral composition was determined by laser oscillator parameters.

After the pulse duration was increased, the beam was directed to a rubidium vapour cell for spectrally selective filtering. Similar to those used previously [28, 29], the cell was made from sapphire and had YAG windows. The use of these materials allowed us to heat the cell to a temperature of 250 °C using a three-compartment furnace. The vapour temperature was determined from the temperature of the cell extension containing a macroscopic amount of rubidium. The temperature of the cell windows was 10 °C above that of the cell extension to prevent rubidium condensation on the windows. When light was passed through the cell, the spectral components of the light that were in resonance with the Rb atoms were effectively absorbed.

Next, the laser beam was focused into the MOT region. The loading of atoms into the dipole trap was begun 300 ms before switching off the MOT. After the loading of atoms into the optical potential, the laser beam and magnetic field producing the MOT were switched off. We experimentally determined the lifetime of atoms in the optical potential. To this end, the number of atoms localised in the optical potential was measured as a function of trapping time. The trapping time was determined as the time interval between the instant when the MOT had been switched off and the instant when the optical dipole trap had been switched off by a mechanical shutter. The atoms in the dipole trap were detected by measuring the intensity of atomic Rb fluorescence excited by resonance light having the same spatial configuration as the light used to produce the MOT. To reduce the background signal from the rubidium atoms in the vacuum chamber, the diameter of the laser beams used for probing (1.2 mm) was considerably smaller than the diameter of the MOT beams (10 mm). The magnetic field was switched off simultaneously with the MOT and remained switched off during probing (to avoid MOT formation from the vapour coming from the vacuum chamber). The use of this probing scheme allowed us to detect atoms in the optical molasses configuration [30], which offered the possibility of increasing the probing time and signal-to-noise ratio. The fluorescence of the atoms in the trap was recorded using a Hamamatsu ORCA-Flash 2D camera (C11440).

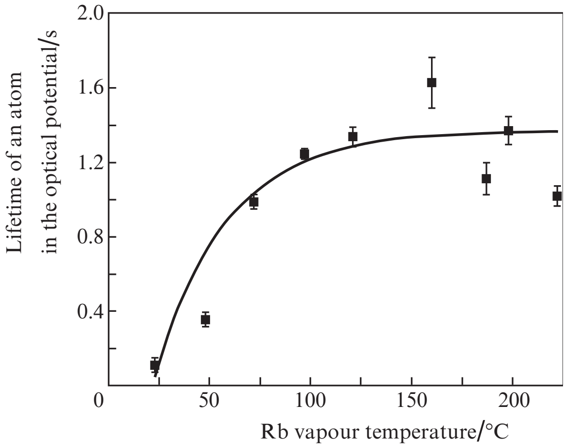

Figure 4. Effect of the rubidium atomic vapour cell temperature on the lifetime of atoms localised in the optical potential produced by pulsed laser light.

5. Discussion

Figure 4 illustrates the effect of the rubidium atomic vapour cell temperature on the measured lifetime of atoms localised in the optical potential produced by pulsed light. It is seen that raising the temperature of the atomic vapour and, hence, the concentration of atoms in the cell leads to an increase in the lifetime of the atoms localised in the pulsed optical trap. The maximum lifetime reached is 1.2 s, which is comparable to the lifetime of atoms in a trap formed by continuous-wave narrow-band light with the same optical potential parameters (1.4 s). The distinction between the lifetimes of atoms in the pulsed optical trap and cw trap can be accounted for by two physical effects: (1) high heating rate of atoms in the pulsed trap compared to a cw trap due to dipole force fluctuations (as a consequence of the high peak pulse intensity) and (2) photoassociation processes, which lead to losses of atoms in traps and have a high rate in the pulsed trap [17].

Note that, in the absence of a rubidium atomic vapour cell in the path of pulsed light, we failed to detect atom localisation. This means that the lifetime of atoms in the potential produced by broadband pulsed light without selective filtering is far shorter than 50 ms. This time limitation is related to the shortest possible trapping time of atoms in the optical potential under the experimental conditions of this study.

6. Conclusions

In this work, we have proposed and demonstrated a method for increasing the lifetime of atoms in a femtosecond pulsed dipole trap using selective filtering of the spectrum of the broadband pulsed light producing the optical potential. It has been shown that, if femtosecond light pulses are used for atom localisation in a dipole trap, even at large detuning from atomic resonances the spectrum of the localising field contains light at wavelengths in resonance with absorption lines of Rb atoms. These spectral components of the laser light lead to heating of the atoms due to resonance photon scattering and, as a consequence, they escape the region of the optical potential.

To perform spectrally selective light filtering, we used resonance absorption of laser light in dense Rb atomic vapour. This made it possible to effectively suppress the spectral components at resonance frequencies of Rb atoms and increase the lifetime of atoms in a pulsed optical dipole trap.

Dense alkali metal vapour is being used increasingly in controlling laser light parameters. Note e.g. the development of high-power alkali metal atomic vapour laser sources [31], investigation of van der Waals interaction [32], coherent population trapping [33], laser source emission frequency stabilisation [34] and spatial and spectral coherent control over atomic states with the use of pulsed light [35, 36]. A characteristic feature of the above examples is optimal temperature parameters of the atomic vapour used. As shown in this work, a proper choice of atomic vapour parameters allows one to increase the localisation time of atoms in pulsed dipole traps. This is of particular importance in producing atom cooling and localisation systems with the use of UV light.

In conclusion, note that, when femtosecond light pulses are used for atom localisation in an optical dipole potential, several factors resulting in the heating and loss of localised atoms should be taken into account. First, the large spectral width of pulsed light can lead to an increase in the efficiency of atom photoassociation processes in the localisation potential [12]. Second, as shown earlier [17] one should take into account the heating of atoms due to dipole force fluctuations at a high peak intensity of localising light. Finally, as shown in this study, additional spectral filtering of localising pulsed light is necessary to completely exclude the spectral components that are in resonance with absorption lines of the atoms being localised. Therefore, atom localisation in a pulsed dipole trap can be achieved only when all the above factors are adequately taken into account.

Acknowledgements. This work was supported by the Russian Foundation for Basic Research [Project Nos. 18-02-00429 (experimental work) and 19-29-11004 (theoretical analysis of the resonance field heating of atoms)].

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