Applied Physics B (2020) 126:26
https://doi.org/10.1007/s00340-020-7377-7

Applied Physics B
Lasers and Optics

Atom femto trap: experimental realization

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Received: 6 November 2019 / Accepted: 4 January 2020 / Published online: 16 January 2020

Abstract
In this work, we demonstrate the trapping of rubidium (Rb) atoms in a pulsed optical dipole trap formed by femtosecond laser radiation with a pulse duration as small as 70 fs. The atom localization in such trap strongly depends on the heating of the atoms caused by the momentum diffusion due to the dipole force fluctuations. The atom femto traps can be used for localization of atoms others than alkaline and alkaline earth atomic elements by conversation of pulsed laser radiation of visible or near infrared to UV spectral.

1 Introduction

The main advances in the quantum simulations [1], computations [2] and metrology [3] are based on achievements of laser cooling and trapping of neutral atoms and ions. Alkaline and alkaline earth atoms are the dominant elements in this area. This is owing to their spectrum properties which allow for cooling and trapping with conventional laser sources of near infrared spectral range. The absence of narrow-band and frequency-tunable laser sources in the ultraviolet (UV) spectrum limits the application of the laser cooling and trapping methods for other atoms and molecules. These other elements include widespread atoms in organic chemistry such as hydrogen, carbon, oxygen, and nitrogen, as well as technologically interesting atoms such as chromium, indium, silver, and aluminum, which have resonant absorption frequencies in the blue and UV region of the spectrum. There are numerous applications of such atoms in astrophysics [4], precision measurements [5] and technology [6]. For example, optical cooling and trapping with UV radiation could be applied for precision experiments with anti-atoms such as anti-hydrogen [7].

The development of new approaches for laser cooling and trapping in the UV spectral range can be achieved with conventional pulsed laser radiation sources that can be converted into UV radiation with a high efficiency. This approach is expected to be the best way of atom optical dipole trapping in UV region. From this point of view the experimental investigation of laser cooling and trapping with pulsed laser radiation are of high demand. In the field of atom optics, pulsed laser radiation has been already used for narrowing the velocity distribution of atoms [8–10] and for investigation of the radiative force induced by frequency-comb excitation [11]. Laser cooling approach was investigated theoretically [12, 13] and experimentally for atoms [14] and ions [15, 16]. In paper [17], it was proposed to use two-photon transitions to cool atoms with pulsed laser radiation. An experimental demonstration of such an approach was implemented [18]. Recent experimental works [14, 18] show that the efficient laser cooling with pulsed laser radiation needs the powerful sources of radiation even in ordinary used spectrum region (visible, IR). The efficiency of conversation of pulsed to UV spectral range depends on the peak laser intensity. Because of these the pulsed lasers with a femtosecond pulse duration seem more preferable for future applications in UV spectral range. But experimentally it appeared challenging to use femtosecond laser radiation for atom trapping— until now there are no papers demonstrating atom femto trap.

For the first time, a pulsed laser light was theoretically considered in [19] to form a stable atom trap. The proposed scheme was later used in the first realization of dipole trapping of atoms [20]. In addition, the first experimental implementation of the atom localization using a sequence of ultrashort picosecond pulses was carried out by the Riis et al. [21]. The main conclusions from their experiments were as follows: (1) the atom localization in both the pulsed and the

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continuous modes were equivalent; and (2) it was assumed that the primary factor preventing the impulse trapping of the atoms was the photoassociation process.There is only one published attempt to trap atoms by dipole force of femtosecond pulses [22]. In this paper, the author investigated the optical dipole trapping with pulsed laser radiation. The experimental demonstration of trapping with femtosecond pulsed radiation was unsuccessful. The trapping was demonstrated only with picosecond laser radiation. It was mentioned that the main reason for the absence of trapping in case of femtosecond laser radiation is the losses due to the process of photoassociation arising because of the broadband spectrum of femtosecond radiation. But this assumption was without experimental verification. Trapping with femtosecond laser radiation was theoretically considered in [23, 24]. In this work, we experimentally demonstrate for the first time the trapping of rubidium atoms by femtosecond laser radiation and investigate the basic physical processes (photoassociation and dipole force fluctuations) that determine the atom localization. Rubidium atom is the excellent test object in fundamental research in the field of laser cooling and trapping for hydrogen, anti-hydrogen and many other elements.

2 Main features of atom trapping by pulsed laser field

Dipole traps for neutral atoms are formed due to the interaction of the atoms with a spatially inhomogeneous electromagnetic field [25]. Continuous laser radiation can form a stationary minimum potential in which the atoms are localized. The situation is different when the atoms are trapped by a pulsed laser radiation. Here, the trapping regime essentially is non-stationary. If the repetition rate of the laser pulses is greater than the oscillation frequency of the atoms in a potential, then the force acting on the atom can be averaged over a sequence of pulses [26]. In this case, the forces acting on the trapped atom in continuous and pulsed dipole traps are the same if the averaged intensities in the two types of dipole traps are equal. Within the framework of such a model, we can expect the same behavior of atoms in both types of traps. This was confirmed by experimental studies of the atom trapping by laser with a pulse duration of 100 ps and a repetition rate of 80 MHz [27].

The losses of the trapped atoms are determined by the following factors, such as their collision with the background vapors, photoassociation (light-assisted losses due to inelastic collisions) [28–30], and momentum diffusion due the atom–laser interaction [19]. It is known that the momentum diffusion is determined by factors that are due to (1) the random direction of the spontaneously emitted photons, (2) the fluctuation of the radiation pressure force, and (3) the fluctuation of the dipole force [31]. When a CW laser radiation is used for atom trapping, as a rule, only the first factor mentioned above is essential for the lifetime of the atom in the trap. Then the heating rate of the atom in the trap is determined by the rate of spontaneous photon emission Γ_{sc}, which is of the order of $I_0(\Gamma/\Delta)^2$. Here, I_0 is the intensity of the laser field, Δ is the detuning of the laser frequency from the atomic transition frequency, and Γ is the width of the atomic transition. The heating of the atoms due to the fluctuations of both the radiation pressure force and the dipole force can be neglected. This approach is valid only for small values of the saturation parameter s of the atomic transition: $s \ll 1$.

Let us consider the interaction of an atom with a single pulse of the laser field to determine the momentum diffusion. The saturation parameter $s(r,t) = \frac{\Omega(r,t)^2}{2(\Delta^2+\Gamma^2/4)}$, where $\Omega(r,t) = d_{21}E(r,t)/\hbar$ is the Rabi frequency; $E(r,t)$ is amplitude of the electric field; d_{21} is the matrix element of the dipole moment. The amplitude of electric field, in the case of pulsed laser radiation, depends on the coordinate of atom in the optical dipole trap and time: $E(r,t) = E(r)e^{-1.385\frac{t}{\tau_p}}$, where $E(r)$ is the spatial dependence of the focused electric field amplitude and τ_p is the duration of Gaussian-shaped laser pulse [32]. When an atom interacts with a pulsed laser field, the peak value of the saturation parameter is no longer small. It becomes comparable to unity for average intensity values that are commonly used to create dipole traps with CW laser radiation, namely at an average power $P = 200$ mW and at the following laser light parameters: radius of the laser beam $r_0 = 10$ μm, frequency detuning $\Delta = 50$ nm, and pulse duration $\tau_p = 100$ fs the peak value of saturation parameter is $s_p = 0.2$. In this case, the large value of the saturation leads to a significant increase in the momentum diffusion due to the fluctuations of the dipole force. This fact, apparently, was not taken into account in the experimental work [22] on the pulse trapping of the atoms, in which the localization of the atoms by the pulsed radiation of femtosecond duration was failed to achieve.

To estimate the heating rate due to the fluctuations of the dipole force, let us consider a laser field of the focused Gaussian beam that is propagated along the z axis, and linearly polarized along the x axis with a focusing radius r_0. The amplitude $E(r,t)$ of such beam depends not only on the coordinates [33], but also on time [32]. The momentum diffusion constant $D_{df}(r,t)$) due to the fluctuation of the dipole force is described by the following semiclassical expression [31]:

$$D_{df}(r,t) = \hbar^2\alpha^2(r,t)\Gamma\frac{s(r,t)}{4(1+s(r,t))^3}\left(1+\frac{3\Gamma^2-4\Delta^2}{\Gamma^2+2\Delta^2}s(r,t)+3s^2(r,t)+\frac{\Gamma^2+4\Delta^2}{\Gamma^2}s^3(r,t)\right) \quad (1)$$

where $\alpha(r,t) = \nabla\Omega(r,t)/\Omega(r,t)$ is the spatial and time-dependent logarithmic Rabi frequency gradient. As can be seen from Eq. 1, a distinctive feature of the dipole force fluctuations is the absence of the saturation of the diffusion coefficient with increasing intensity of the laser field ($\lim_{s\to\infty} D_{df}(r,t) \sim s(r,t)$). It is this effect that imposes restrictions on the localization of atoms in standing waves [34].

The lifetime of an atom in a trap is defined as the time required for the atom to acquire energy equal to the depth of the potential well, by the momentum diffusion process: $\tau_{\text{trap}} = mU_0/\langle D_{df}(r,t)\rangle$, where m is the atomic mass; U_0 is the potential depth of the trap; and $\langle D_{df}(t)\rangle = \frac{1}{V}\int_r D_{df}(r,t)dr$ is momentum diffusion parameter averaged over the localization region. In case of interaction with a single laser pulse, the average atomic kinetic energy increase is determined by the expression $\langle E\rangle = \frac{1}{m}\int_{-\tau_p}^{\tau_p}\langle D_{df}(t)\rangle dt$. Then the lifetime of the atom in the trap can be written as follows:

$$\tau_{\text{trap}} = \frac{U_0}{\langle E\rangle \nu}, \tag{2}$$

where ν is repetition rate of the pulsed laser radiation.

Figure 1 shows the results from the calculation of the atom lifetime due to the dipole force fluctuations in a pulsed dipole trap according to Eq. (2) where momentum diffusion $D_{df}(r,t)$ was calculated by the Eq. (1). The atom lifetime was calculated as a function of the average laser field intensity of pulsed laser radiation estimated as average laser power divided by the area of laser beam in the focus, for three different laser pulse durations: 70 fs, 150 fs and 300 fs. The calculations were performed for Rb atoms trapped in the field of focused pulsed laser radiation (radius of the focused spot is $r_0 = 8\,\mu$m) with the wavelength 825 nm and repetition rate 80 MHz. The potential depth was estimated according the common formula for optical dipole trapping for CW laser radiation [25] where the intensity of CW laser was replaced by the average intensity [27]. It is seen from the Fig. 1 that the lifetime of the atoms in a trap formed by the pulsed radiation of femtosecond duration is extremely short. Furthermore, this lifetime increases with (1) an increase in the pulse duration (with the average intensity of the laser field fixed) and (2) a decrease in the average intensity of the trapping field (with the pulse duration fixed). This is because in both the cases there is a decrease in the peak intensity of the laser radiation, and as a consequence, a decrease in the heating due to the momentum diffusion of the atoms caused by the dipole force fluctuations. The calculated lifetime limited by both the fluctuations of the radiation pressure force and the photon scattering is about 330 s. The above calculation is only an estimate, since Eq. (1) for the diffusion coefficient was obtained in the stationary case of an atom interacting with a laser field. For proper calculation

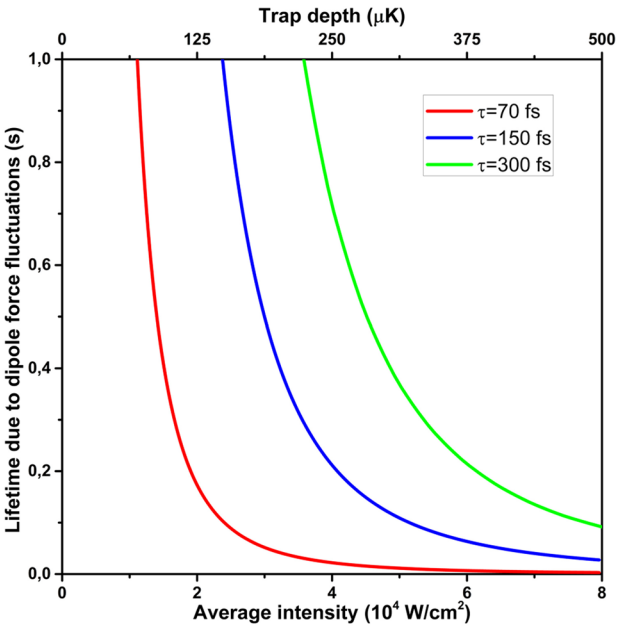

Fig. 1 Lifetime of atoms due to dipole force fluctuations in a pulsed dipole trap, depending on laser average intensity for different pulse durations

of momentum diffusion, non-stationary interaction of atom with pulsed laser field should be considered. This case is out of consideration of this paper.

From the calculations carried out, we conclude that to achieve localization of the atoms by a pulsed laser radiation of femtosecond duration, it is necessary to reduce the peak intensity of the laser radiation. To achieve the atom trapping with small pulse durations (of the order of a hundred femtoseconds), it is necessary to reduce the average intensity of the laser radiation. However, a decrease in the average intensity of the laser leads to a decrease in the depth of the potential well of the trap (see Fig. 1), which means that it is necessary to use an ultra-cold ensemble of the atoms to load a pulsed dipole trap.

3 Experiment

The experimental setup for this study is shown in Fig. 2a. We used Rb atoms for the investigating the atom trapping with a pulsed laser radiation. The loading of the dipole trap was carried out from a magneto-optical trap (MOT) in a vacuum chamber with a residual gas pressure of 7×10^{-10} Torr. With the use of a sub-Doppler cooling scheme, the atom's temperature was 40 μK which was measured with ballistic expansion method. To form the dipole trap, a titanium-sapphire (Ti:Sapphire) laser was used with two different regimes, in one as CW laser and the other as pulsed laser with 50 fs pulse duration and 80 MHz repetition rate.

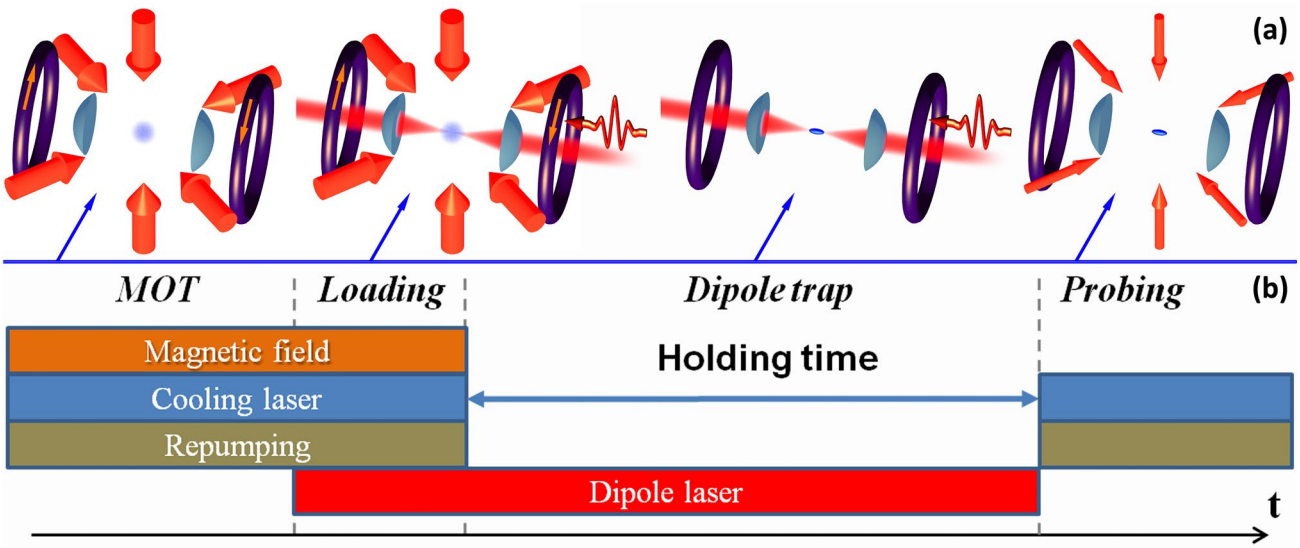

Fig. 2 **a** Schematic of the experimental setup for the localization of atoms by femtosecond pulsed laser radiation; **b** the time sequence of the experimental procedure

The central wavelength and the spectrum width of the pulsed laser were 825 nm and 13 nm respectively. The laser beam was focused into the MOT region with an aspherical lens of 31 mm focal length. The radius of the laser beam in the focus (r_0) was 8 μm. Another lens was used to output the laser beam from the vacuum chamber. The laser beam before entering the vacuum chamber passed through a cell containing vapors of Rb atoms at a temperature of 120 °C. This made it possible to remove from the laser radiation any spectral components resonant with the Rb atoms to prevent the action of the resonant force of the light pressure on the atoms.

A schematic of the experimental setup for the localization of the Rb atoms by femtosecond pulsed laser radiation, as well as the temporal sequence of the experiment is shown in Fig. 2. Initially, cooling and repumping lasers with a magnetic field were switched on to form the MOT. The magnetic field gradient was formed by two coils placed outside the vacuum chamber. The gradient of the magnetic field in the direction of the laser beams in the horizontal plane was 2 Gs/cm, while the same in the vertical direction was 4 Gs/cm. Additional magnetic coils were located around the vacuum chamber to compensate the earth's magnetic field. The frequency of the cooling laser radiation was stabilized with saturation absorption spectroscopy technique in the rubidium vapours and red detuned by $2\Gamma = 2\pi \times 12$ MHz with respect to the absorption frequency of ^{85}Rb atoms ($F = 3 \rightarrow F' = 4$). The cooling and accumulation of atoms in the MOT lasted 10 s. Next, sub-Doppler cooling of the atoms (by increasing the frequency red detuning up to 5Γ of the cooling laser and reducing its power) occurred for 50 ms. At the end of the cooling cycle, the cooling and repumping lasers, as well as the magnetic field, were turned off. The diameter of a MOT cloud was 1 mm with 10^9 cm^{-3} cold atoms concentration. The dipole laser was switched on 300 ms before the MOT lasers and the magnetic fields were switched off. The amount of trapped atoms was detected by fluorescence after switching off the dipole laser. For this, the cooling and repumping lasers were switched on with a smaller spatial diameter (with no magnetic field). The fluorescence from the localized atoms was recorded with a two-dimensional Hamamatsu ORCA-Flash camera (C11440). The lifetime of the trapped atoms was explored by measuring the number of atoms as a function of the holding time (it is the time from the switching off of the MOT till the time the atoms were detected; see Fig. 2).

We carried out trapping of the Rb atoms with two different pulse durations, namely 70 fs and 150 fs, and with the same spectral width. To realize this, we used a small intensity of laser light that corresponds to a small saturation parameter s to avoid high heating rate due to the dipole force fluctuations. The spectral width of the laser radiation (13 nm) was determined by the parameters of the Ti:Sapphire laser resonator. Because the spectral width of the femtosecond laser radiation was greater than frequency detuning, we did not use active stabilization of femtosecond laser frequency. The pulse duration was determined by the spectral dispersion of the optical elements along the propagation path. We used 65 mm long transparent quartz cylinder to stretch the pulse duration from 70 to 150 fs. Thus, the dipole trap was formed by the train of positive chirped laser pulses [32]. The pulse duration was measured with Michelson interferometer-based autocorrelator (Spectra-Physics).

The experimental results from the measurement of the lifetime of the atoms trapped by the femtosecond laser light with a pulse duration of 70 fs are shown in Fig. 3a. The measurements were carried out with an average laser power of 15 mW, which corresponded to an average intensity of about 7.5×10^3 W/cm^2 and a dipole trap depth of 40 μK. The lifetime of the atoms in the pulsed dipole trap with these parameters was 140 ms. With a decrease in the average intensity of the laser radiation, an increase in the lifetime of the localized atoms was observed (Fig. 3b). In addition, there was simultaneously a decrease in the number of localized atoms. This was owing to the small depth of the trap potential, comparable to the temperature of the atomic ensemble. With an increase of the average laser intensity, we have measured the same exponential-type behavior of number of trapped atoms after switching off the trapping laser, similar to the dynamics shown in Fig. 3a.

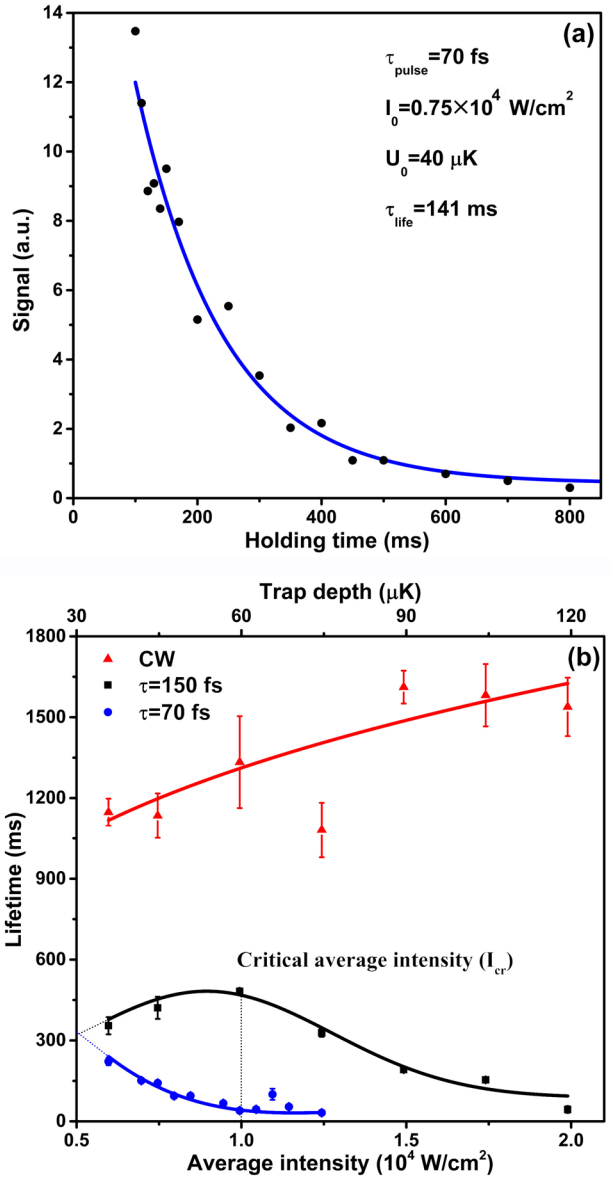

Fig. 3 Lifetime of the trapped atoms versus average intensity of the laser for 70 and 150 fs pulse durations, and CW laser radiation

Figure 3b shows the dependence of the lifetime of the trapped atoms on the average intensity of the laser radiation (and, by extension, the depth of the trap). The dependence is presented for two pulse durations, namely 70 and 150 fs. Also shown in the figure, there is the same dependency for the case in which CW laser radiation was used for dipole trapping. Fitting curves were selected as the best fitting: Gauss function for trapping with pulsed laser and power function in case of CW. It can be seen that for a pulse duration of 70 fs, the atoms' lifetime monotonically decreases with an increase of the laser intensity. At a pulse duration of 150 fs, a similar behavior is observed under intensities higher than the critical average intensity $I_{\mathrm{cr}}(150\ \mathrm{fs}) = 1 \times 10^4$ W/cm^2. Such dependency of the atoms' lifetime can only be explained by the critical peak intensity of the laser pulse, above which an additional heating of the atoms in the dipole trap starts to affect the lifetime. This heating is determined by the momentum diffusion due to the dipole force fluctuations. Under such conditions, we trapped about 320 atoms to the CW trap and 150 atoms in a femto trap.

The critical average intensity I_{cr} for the pulse duration of 150 fs should be twice higher than in case of 70 fs. From this, it can be easily determined that the critical average intensity for the pulsed dipole trap with 70 fs pulse duration, i.e., $I_{\mathrm{cr}}(70\ \mathrm{fs})$ should be about 0.5×10^4 W/cm^2. The lifetime for the dipole traps formed by the 70 fs and 150 fs pulse should be the same under intensities lower than 0.5×10^4 W/cm^2 because the lifetime would not depend on the dipole force fluctuations in this region. Unfortunately, this intensity corresponds to the potential well of about 30 μK, which is lower than the temperature of our atomic ensemble. For this reason, we could not experimentally investigate this regime. However, as can be seen from Fig. 3b, extrapolation of the fitting curves gives the same result, i.e., approximately 300 ms for the lifetime for an average intensity of 0.5×10^4 W/cm^2 for the pulsed dipole traps formed by the 70 fs and 150 fs pulses.

For comparison purpose, Fig. 3b also shows the results of the measurement of the lifetime of atoms trapped in the dipole trap formed by the CW laser radiation at a wavelength of 825 nm. Unlike in the pulsed regime, here, with an increase in the intensity of the laser radiation, a monotonic increase in the lifetime of the atoms in the dipole trap is observed. This growth is due to the increase in the depth of the potential of the trap.

It should be noted that another possible heating mechanism as mentioned in other publications [21] is the photoassociation of atoms. However, the photoassociation of

atoms does not depend on the peak intensity of the laser radiation, but on the spectral width and the average intensity. With the dominance of the photoassociation over the process of momentum diffusion due to dipole force fluctuation, the dependence of the atoms' lifetime on the average intensity would be the same for different pulse durations under our experimental conditions (the spectral width of laser radiation is the same for 70 fs and 150 fs cases). As can be seen from Fig. 3b, the main evidence of the role of the dipole force fluctuation in the heating mechanism is the difference in the lifetime dependence on the average intensity at the various pulse durations.

We note big difference of measured atom lifetimes in a pulsed femto trap- the lifetime ($\tau_{\text{trap}}^{\text{pulse}}$) is less than 500 ms, compared to CW ($\tau_{\text{trap}}^{\text{cw}}$) laser trap- the lifetime is longer than 1000 ms, Fig. 3. The difference is a consequence of different physical picture of losses in both types of traps: (1) collisions of trapped atoms with the background vapors is the main channel of losses in CW laser trap, (2) the dipole force fluctuations, the photoassociation process and collisions with background vapors are responsible for losses in a femto trap. Our analysis shows that at moderate trapping laser intensities (below the critical value I_{cr}) losses in a femto trap are limited to collisions with background vapors and the photoassociation process only. This helps to estimate the photoassociation rate through measurements of lifetimes of CW and femto trap. Indeed, the lifetime measurements of CW atom trap helps to measure losses rate due to scattering with the background vapors: $\Gamma_{\text{bg}} = \Gamma_{\text{cw}} = \frac{1}{\tau_{\text{trap}}^{\text{cw}}}$. Then photoassociation losses can be simply calculated as follows:

$$\Gamma_{\text{pa}} = \frac{1}{\tau_{\text{trap}}^{\text{pulse}}} - \Gamma_{\text{bg}} = \frac{1}{\tau_{\text{trap}}^{\text{pulse}}} - \frac{1}{\tau_{\text{trap}}^{\text{cw}}} \tag{3}$$

In case of atom trapping with pulsed laser radiation with 150 fs pulses duration at the average intensity of $I = 0.7 \times 10^4$ W/cm^2, which is lower than the critical laser intensity ($I_{\text{cr}}(150\text{ fs}) = 1 \times 10^4$ W/cm^2), the $\tau_{\text{trap}}^{\text{pulse}} \approx 0.43$ s and $\Gamma_{\text{bg}} = 0.8$ s^{-1}. Thus the ptotoassociation rate $\Gamma_{\text{pa}} = 1.5$ s^{-1} at the chosen trapping laser intensity. At the assumption of a linear dependence of the photoassociation rate on the average laser intensity $\Gamma_{\text{pa}} = R_{\text{pa}} I$ (where R_{pa} is the proportionality coefficient), it is possible to estimate the photoassociation rate at higher intensities. Thus, for $I = 2 \times 10^4$ W/cm^2, the photoassociation rate Γ_{pa} should reach values about 4.3 s^{-1}.

The knowledge of the photoassociation rate helps to account the momentum diffusion rate Γ_D using an expression: $\Gamma_{\text{pulse}} = \Gamma_{\text{bg}} + \Gamma_{\text{pa}} + \Gamma_D$ in case of $I > I_{\text{cr}}$. At a trapping laser intensity of an atom femto trap equals $I = 2 \times 10^4$ W/cm^2, the measured Γ_{pulse} equals 11.1 s^{-1} and $\Gamma_{\text{bg}} = 0.6$ s^{-1}. Thus, the value of the loss rate due to the momentum diffusion is equal to $\Gamma_D = 6.2$ s^{-1}. We note that this value is higher than the photoassociation rate losses and is the main channel of losses in a femtotrap at trapping laser intensities higher than the critical value. Besides, this value is higher than its estimated value from the theoretical data presented in Fig. 1. The last can be attributed to the inapplicability of the semiclassical theory of momentum diffusion for pulsed trapping.

4 Conclusion

The results obtained from our study demonstrate the experimental realization of the trapping of neutral atoms (Rb in this case) using a 70 fs pulsed laser radiation for the first time. From the experimental measurements and estimates, we conclude that in the dipole trapping of the atoms with femtosecond laser radiation, the main limiting process is the heating due to the fluctuations of the dipole force.

The use of pulsed radiation to localize atoms opens up a number of hitherto unexplored possibilities in the control of the neutral atoms. First of all, it is the dipole trapping of atoms others than alkaline and alkaline earth atomic elements using UV spectral radiation. It gives the possibility to expand the range of cold atoms applications, especially in the field of antimatter and fundamental physics (for example, dipole trapping of hydrogen and anti-hydrogen). In this case, the main advantage of femtosecond laser radiation in comparison with picosecond is the higher efficiency of frequency upconversion. But our results show that the high peak intensity of pulsed laser radiation increases the heating rate due to momentum diffusion. It should be kept in mind under experimental realisation of laser cooling and trapping in UV spectral region. The best way of atom dipole trapping in UV region is to use a femtosecond laser radiation for a high efficiency of UV generation with a consequent stretching of pulsed UV laser radiation to decrease the laser peak intensities.

Furthermore, the interaction of trapped atom with pulsed radiation is periodic. Between the pulses, atom is free of any interactions with external fields. So the trapping with pulsed laser radiation opens up the way for investigation of a free and at the same time trapped atoms. Such approach of pulsed interaction with localizing field is used to avoid Stark shift of resonance lines in quasi-pulsed experiments [35]. Pulsed dipole trapping of atoms is also a promising approach for the efficient generation of narrow-band single photons [26, 36]. Additionally, trapping with pulsed laser radiation can be used for investigation of chaotic behavior of trapped atom caused by pulsed interaction with localizing potential [23].

Acknowledgements We thank Victor Zadkov for helpful discussions. The reported study was funded by RFBR according to the research project N18-02-00429.

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