Eur. Phys. J. D **44**, 141–149 (2007)
DOI: 10.1140/epjd/e2007-00144-3

THE EUROPEAN PHYSICAL JOURNAL D

Acceleration of cold Rb atoms by frequency modulated light pulses

J.S. Bakos[1,a], G.P. Djotyan[1], P.N. Ignácz[1], M.Á. Kedves[1], M. Serényi[2], Zs. Sörlei[1], J. Szigeti[1], and Z. Tóth[1]

[1] Research Institute for Particle and Nuclear Physics of the Hungarian Academy of Sciences, Budapest 114, P.O. Box 49, Hungary
[2] Research Institute for Technical Physics and Material Science of the Hungarian Academy of Sciences, Budapest 114, P.O. Box 49, Hungary

Received 13 September 2006 / Received in final form 30 November 2006
Published online 4 May 2007 –

Abstract. The displacement of Rb atoms in a magneto-optical trap (MOT) caused by the force of a finite time series of counter-propagating frequency modulated light pulse pairs is measured as a function of the chirp of the pulses. The frequency modulated light pulses induced ^{85}Rb 5^2S$_{1/2}$ $F = 3 \leftrightarrow$ ^{85}Rb 5^2P$_{3/2}$ $F' = 2, 3, 4$ excitation and de-excitation of the atoms. The result of this excitation de-excitation process is a force causing the acceleration and, consequently, the displacement of the maximum of the spatial distribution of the trap atoms. The time dependence of the populations of the levels of the atom are calculated — including also the ^{85}Rb 5^2S$_{1/2}$ $F = 2$ and $F' = 1$ states — as the result of the interaction with the finite train of counter propagating frequency modulated light pulses by the solution of the Bloch equations. As the result of the measurement the interval of the chirp of the frequency modulated light of given intensity where the transitions take place, are determined. The results of the experiment and the expectation on the basis of model calculations are in qualitative agreement.

PACS. 32.80.Lg Mechanical effects of light on atoms, molecules, and ions – 32.80.Pj Optical cooling of atoms; trapping

1 Introduction

Frequency modulated light pulses can cause, for instance, adiabatic transitions among atomic energy levels in case of appropriate pulse parameters. The adiabatic transition (AT) induced by frequency modulated light pulses in the case of two level atoms is well-known (see for instance [1] and references therein). The theory of AT can be found in many textbooks, for instance [2]. The process was thoroughly investigated in many experimental and theoretical works (see references in [3]). There are also many theoretical and experimental investigations of the AT where two light beams and three levels of the atoms are involved in the process (for instance cascade transitions among three levels [4]). Peculiarities appear when transition is possible to more than one level [5]. One of these is the favoured population increase of the level getting to resonance first during the frequency sweep of the light pulse when the frequency range of the frequency modulated light cover many atomic resonances [6]. The AT is investigated even in the case of molecules when the transition is possible to many levels because the frequency of the light sweeps over many resonance frequencies [7]. The transition probability, consequently the population of the various levels can not be calculated by the relatively simple formulas of the adiabatic transition in this case. It depends on the parameters of the levels and the light in a very complicated way and is given by the solution of the Schrödinger equation for probability amplitudes of the levels involved.

The AT is the way to transfer mechanical momentum to an atomic ensemble without increasing its temperature. This process is used to deflect atomic beams [8]. The efficiency of the deflection depends on the efficiency of the transfer of mechanical momentum from the light to the atom. Therefore, it depends on the efficiency of the AT which is smaller than 1 in the case of many level atoms.

The efficiency of the transfer of momentum from the light beam to the atom was investigated. For this purpose excitation and consecutive de-excitation of a bunch of cool Rb atoms (in the transitions ^{85}Rb 5^2S$_{1/2}$ $F = 3 \leftrightarrow$ ^{85}Rb 5^2P$_{3/2}$ $F' = 2, 3, 4$) were induced by finite time series of frequency modulated pairs of counter-propagating laser pulses. The atoms were cooled in magneto-optical trap before the interaction. The result of the interaction was the displacement of the maximum of the spatial distribution of the atoms from his initial position. This displacement depends on the number of pulses in the series and the

[a] e-mail: bakos@rmki.kfki.hu

parameters of the light pulses i.e. on the peak intensity and the chirp of the pulses.

The light beams of the trap were also present during the interaction. Namely the presence of the trap beams causes only about twenty percent reduction of the displacement observed without trap beams.

The displacement of the atoms depending on the chirp of the light pulses was measured at a given peak light intensity. It was found that the displacement of the atoms was larger for series of back and forth propagating light pulse pairs than for the train of light pulses propagating only in one direction in a restricted interval of the chirp of the pulses. Otherwise the displacement of the trap atoms was always smaller for back and forth propagating pulses than for pulses propagating only in one direction. Consequently, there was "adiabatic like" transition up and down, excitation and de-excitation, in defined interval of the chirp.

We can conclude that the momentum transferred from the light to the atom in the direction of the first $(+\xi)$ light pulse is larger for the case of to and fro propagating light pulses than for pulses propagating only in one direction. Outside of this interval of the chirp the transferred momentum is always smaller than in the case of pulses propagating into one direction.

In the experiment, the frequency of the light consecutively coincides with energy levels of the atom during a light pulse. Consequently, this case can not be treated as being that of the two level atoms. Therefore, in order to get more detailed insight into the processes under consideration, a computer code for the solution of Bloch equations for density matrix elements was assembled. The code takes into account the effect of the frequency modulated light pulses, the spontaneous decay of the excited states and the effect of an additional light beam re-pumping the atoms from the lower ground state $5^2S_{1/2}$ $F = 2$ to the upper one $5^2S_{1/2}$ $F = 3$. It describes the temporal behavior of the populations, fine and hyperfine structure coherences of the six hyperfine (two ground $5^2S_{1/2}$ $F = 2, 3$ and four excited $5^2P_{3/2}$ $F' = 1, 2, 3, 4$) levels of the ^{85}Rb atoms [9].

The result of the simulation coincides with the result of the experiment if the instantaneous finite bandwidth of the frequency modulated light is also taken into account. According to both the theory and the result of this experiment one can conclude that "adiabatic like" transition takes place in a comparatively narrow window of the chirp in the case of multilevel Rb atoms at the given intensity of the frequency modulated light pulses. This result is unexpected on the basis of the simplified extension of the theory related only to the case of two levels.

In the paper the experimental arrangement consisting of a MOT and the set-up generating frequency modulated light pulses is described in Section 2. The measurement of the chirp of the generated light pulses is also described here. The measurement of the displacement of the trap atoms as the function of the chirp of the light pulses are described in Section 3. Computer simulation and discussion of results are also given in Section 3. Summary and conclusions can be found in Section 4.

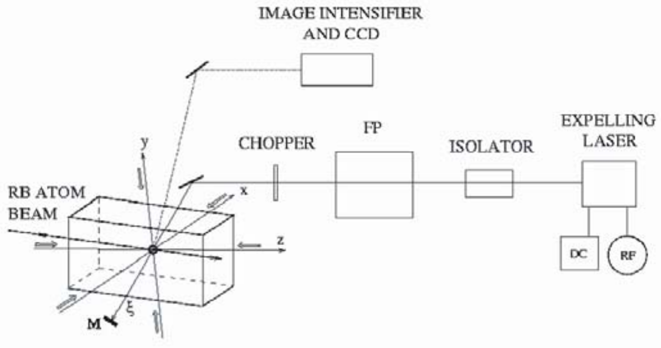

Fig. 1. The experimental arrangement. The MOT is in a glass cube. x, y, z are the directions of the trap beams indicated by arrows. Rb atom beam covers the atom loss of the trap. M mirror reflects the light of the diode laser frequency modulated by the RF source. The offset of the frequency modulation is determined by the DC voltage supply. FP is the Fabry-Perot interferometer of finesse 40. The chopper is the moving part of an electric relay.

2 Experimental apparatus and generation of frequency modulated light pulses

2.1 The experimental set-up

The experimental arrangement can be seen in Figure 1. The Magneto-Optical Trap (MOT) is of the known construction [10]. The three circularly polarized laser beams retro reflected by mirrors forming $\sigma^+ - \sigma^-$ configuration cross each other in the center of the quadrupole magnetic field. Semiconductor diode laser is used as the source of the trap light beams. The frequency of the laser is stabilized with a precision better then 1 MHz using the fluorescence light of an atomic beam. The frequency of the light is tuned to under the $5S_{1/2}$ $F = 3 \rightarrow 5P_{3/2}$ $F' = 4$ resonance transition frequency of the ^{85}Rb atoms by about 20 MHz. Another semiconductor, Lamb dip frequency stabilized laser is used for re-pumping the atoms in the transition $5S_{1/2}$ $F = 2 \rightarrow 5P_{3/2}$ $F' = 3$. The diameter of the atomic cloud in the trap is about one millimeter. The temperature of the atoms is in the region of some μK as it is calculated from the measurement of the free expansion of the trap atoms. More details can be found in [10].

A train of frequency modulated pulses propagating in the $\pm\xi$ directions interacts with the atoms of the trap. The time period between the pulses of the train is 60 ns. The pulses of the train return to the trap in the $-\xi$-direction with a time delay of 3 ns after being reflected by a mirror (M). Consequently the atoms interact with a train of to and fro propagating pulse pairs.

If the adiabatic criterion for the transition ^{85}Rb $5^2S_{1/2}$ $F = 3 \leftrightarrow {}^{85}$Rb $5^2P_{3/2}$ $F' = 4$ is fulfilled [1] i.e.

$$e_{fkt} = R\tau \geq 1 \tag{1}$$

and

$$b_{fr} < R^2 \tag{2}$$

R is the Rabi frequency, τ is the duration of the light pulse and b_{fr} is the chirp, the atoms are excited by the first $(+\xi)$ pulse and return to the ground state induced by the returning $(-\xi)$ pulse. The atoms receive $+2\hbar k$ momentum in the ξ-direction according to the theory of adiabatic passage of two level atoms [11]. $\hbar$ is the Planck constant and k is the wave number of the light wave. The motivation of the experiment is to measure the transmitted momentum in the case of real, multi-level atom.

If the reflection mirror (M) is removed the atoms are excited by the $(+\xi)$ pulses receiving $+\hbar k$ momentum. The excited atoms return to the ground state spontaneously and get no more momentum in this returning process on average.

2.2 The principle of generation of frequency modulated pulses

The frequency modulated light is generated by sinusoidal modulation of the current of a semiconductor laser diode [8]. The frequency of the modulation is 16.7 MHz. The result of the modulation is a peak to peak frequency excursion between 1.5 and 2.4 GHz depending on the voltage of the modulation from 2.5 to 3.5 V peak to peak on the diode laser input resistance 50 Ω. This frequency excursion usually used in the experiments $a_{mf} = 1.9$ GHz in Figure 2. The resonance frequencies of the transitions from the upper ground level to the upper three excited levels ^{85}Rb $5^2P_{3/2}$ $F' = 4, 3, 2$ subtracted that of the $5S_{1/2}$ $F = 3 \rightarrow 5P_{3/2}$ $F' = 4$ transition are marked in the figure with horizontal lines (h, i and k).

The light pulses were generated transmitting the frequency modulated light of the diode through a Fabry-Perot interferometer (FP) tuned to the resonance of the ^{85}Rb $5^2S_{1/2}$ $F = 3 \leftrightarrow$ ^{85}Rb $5^2P_{3/2}$ $F' = 4$ transition (h line). The full frequency width at half maximum intensity of the interferometer is $\Delta\nu_{fwhm} \approx 500$ MHz. Therefore the other two transitions of the atom can be also excited if all the three levels are inside the extreme values of the frequency modulation. Trains of pulses of 10 ms long are formed by a chopper. The moving part of an electrical relay served as the chopper.

Figure 2 shows the configuration of the experiment schematically. The frequency at the working point $(g(i_0))$ of the modulation (i.e. the offset, the frequency of the laser diode without modulation) — can be changed by changing the d.c. current of the diode (i_0). Curve (e) shows the time (t) dependence of the frequency deviation $(\Delta\nu(t))$ of the diode laser from the resonance frequency of the ^{85}Rb $5^2S_{1/2}$ $F = 3 \leftrightarrow$ ^{85}Rb $5^2P_{3/2}$ $F' = 4$ transition as the result of the modulation. Simply sinusoidal dependence of the frequency on time is assumed here. This is confirmed by experimental results (see later).

Light pulses are formed always when the laser frequency crosses the resonance of the Fabry-Perot interferometer (FP) i.e. when the detuning from the atomic resonance crosses the zero value. The time at the peak of these light pulses versus the offset is specially measured

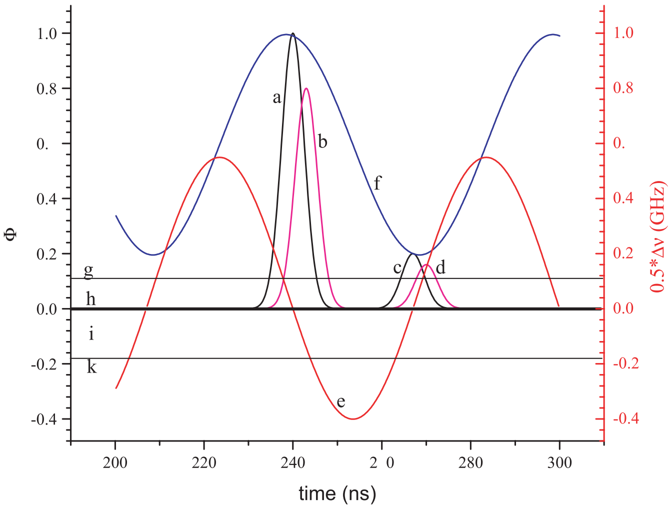

Fig. 2. (Color online) The time and amplitude scenario of the measurement. The light pulses (a), (c), are formed at zero crossing of the modulated frequency (e) of the diode laser. Curves (b), and (d) are the reflected pulses. $\Delta\nu$ is the frequency deviation from the resonance frequency of the ^{85}Rb $5^2S_{1/2}$ $F = 3 \leftrightarrow$ ^{85}Rb $5^2P_{3/2}$ $F' = 4$ transition. The amplitude of the light pulse (a) is normalized to 1. The amplitude of other pulses is normalized by the amplitude of the (a) pulse. Φ is the normalized amplitude. The time function of the current of the laser diode is (f). Curves (h), (i) and (k) are the ^{85}Rb $5^2S_{1/2}$ $F = 3 \leftrightarrow$ ^{85}Rb $5^2P_{3/2}$ $F' = 4, 3, 2$ transition frequencies extracted the frequency of the ^{85}Rb $5^2S_{1/2}$ $F = 3 \leftrightarrow$ ^{85}Rb $5^2P_{3/2}$ $F' = 4$ transition frequency. The (frequency) offset of the working point of the modulation from the resonance of the FP interferometer i.e. from the resonance frequency of the ^{85}Rb $5^2S_{1/2}$ $F = 3 \leftrightarrow$ ^{85}Rb $5^2P_{3/2}$ $F' = 4$ transition is (g).

(see below). The time function of the chirp is calculated from this time versus offset function (see later).

The train of light pulses starts at $t = 0$. Curve (a) of Figure 2 demonstrates the fifth pulse with "downward" chirp of the pulse train when the decreasing frequency of the laser diode crosses the FP resonance. The pulse (b) of Figure 2 is the pulse reflected by the end mirror and follows the light pulse (a) with 3 ns delay. The pulses (a) and (b) propagate into the $+\xi$- and $-\xi$-direction (see Fig. 1). For the simplicity, the pulses are taken as of Gaussian shape here. The amplitude of the $+\xi$ pulse is normalized to 1 in the figure at $g = 0$. Φ is the normalized amplitude. The amplitude of the $-\xi$ pulse is normalized by the amplitude of the $+\xi$ pulse. The amplitude of this pulse is smaller than that of pulse (a) because of the loss of intensity in the reflection and the excess propagation path.

Light pulse is generated also when the frequency of the light crosses again the FP resonance moving "upward" after the minimum. The amplitude of this pulse depends on the (frequency) offset of the working point (g) of the modulation. The amplitude of this pulse

– is minimum at zero offset because of the about 90° phase lag between the time function of the frequency of the radiation and that of the current (f) — consequently the intensity — of the laser diode at the

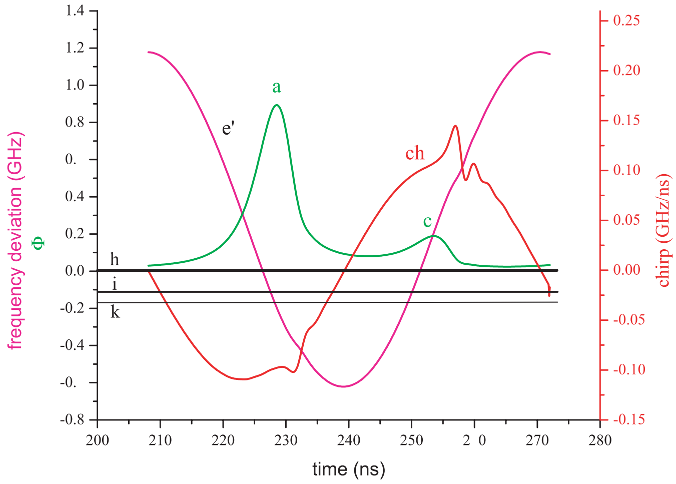

Fig. 3. (Color online) The "ringing" of the Fabry-Perot interferometer. (e′) is the frequency curve of the transmitted light pulses (a) and (c) modified by the ringing of the interferometer. Curve (ch) is the chirp calculated from the curve (e′). Curves (h, i, k) are the "transition frequencies" of the Rb atoms.

modulation frequency 16.7 MHz; (the current is normalized to 1 in the figure);
- is comparable to that of pulse (a) at offset $g = \pm a_{mf}/2$.

The reflected light pulse is delayed by 3 ns (pulse (d)). The amplitude of pulses (c) and (d) is normalized by the amplitude of pulse (a) in Figure 2.

2.3 Numerical simulation of the light pulse formation by Fabry-Perot interferometer

Special care was taken to the choice of the speed of the frequency modulation in order to avoid the ringing of the FP interferometer [12]. For that purpose, the inequality

$$\eta = \frac{\omega' \tau_s}{(\Delta\omega_{fwhm}/2)} \leqslant 1 \tag{3}$$

has to be fulfilled according to the expression (18) of the paper [12]. ω' is the time derivative of the frequency and

$$\Delta\omega_{fwhm} = 2\pi\Delta\nu. \tag{4}$$

The time constant of the interferometer

$$\tau_s = \frac{2FL}{\pi c}. \tag{5}$$

F, L and c are the finesse, the distance of the FP plates and the speed of light. The η factor is between 0.06 and 0.2 depending on the chirp in our measurements.

The — assumed till this time — harmonic time function of the frequency deviation (line (e) in Fig. 2) and that of the chirp is modified only slightly as the result of ringing on the basis of computer modeling using the expressions (14) of [12] (see the (e′) and the line (ch) of Fig. 3).

This modification on the chirp

- takes place far from the time when the frequency of the laser (line (e′)) crosses the energy levels (h, i, k);
- takes place when the frequency of the laser is more then 500 MHz away from the resonances of line-width about 6 MHz (fwhm).

The line with the pulses (a) and (c) shows the intensity of the light pulses formed by the FP taking into account the effect of the ringing also.

The position of the trapped atoms was measured by an image intensified CCD camera. The details of the geometry of the measuring set-up are published in [10]. The exposure time and the whole interaction time were usually 125 μs and 280 μs respectively.

In order to see the effect of the influence of the trap beams they were switched off for the time of the interaction with the frequency modulated pulses in some cases of the measurement. There was only about 20 percent difference in the displacements of the maximum of the atomic distribution. Consequently the force of the frequency modulated pulses is far larger than the restoring force of the trap. Therefore the trap beams were on during the interaction and the observation time in most cases. The picture of the trapped atoms was taken with the light of the fluorescence excited by the trap laser beams. The spatial distribution of the trapped atoms was determined by measuring the spatial intensity distribution which is digitized and stored in the memory of a PC. The position of the maximum intensity of the fluorescence of the trapped atoms is calculated. In one point of the parameters of the measuring run twenty measurements were taken and the mean and the variance as error are calculated.

2.4 Measurement of the chirp of the frequency modulated light pulses

The chirp equals the tangent to the frequency curve (e) of Figure 2 at the point where the curve (e) crosses the resonance h of the atomic transition $5S_{1/2}$ $F = 3 \rightarrow 5P_{3/2}$ $F' = 4$. Namely the light pulse is formed here because the Fabry-Perot interferometer has peak transmission also at this point.

Therefore the frequency of the light has to be measured depending on the time. For that purpose the shape of the transmitted pulses formed by the FP interferometer is measured by a fast photodiode and registered with a digital storage oscilloscope at various offset values (see Fig. 4).

The frequency offset is proportional to the offset of the current of the diode laser which is proportional to the value of a micro-dial of a potentiometer regulating the current of the diode. The unit of gradation of the micro-dial (M) is used as the unit of current, consequently, as the unit of the offset.

As the first step the time of the maximum of the pulses is determined versus the value of the micro-dial as a dummy parameter.

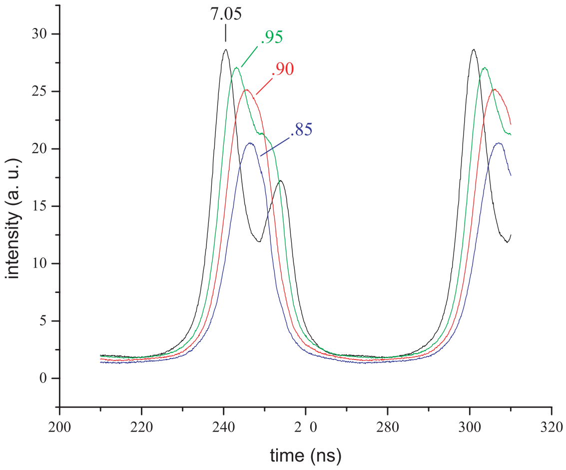

Fig. 4. (Color online) The measured frequency modulated light pulses formed at various offsets given by the value of a micro dial M (see the figure and the text).

As the second step the time integrated spectrum of the diode laser is measured simultaneously. This spectrum depending on the value of the micro-dial is taken by using a CCD camera at the exit of a spectrograph and a Fabry-Perot interferometer in series. The picture is digitized and stored in the memory of the PC. The end points of the band spectrum of the laser diode light caused by the modulation are measured. The frequency of the end points of the band determines the offset frequency versus the value of the micro-dial.

The measured time of the maximum values of the pulses versus the value of the micro-dial and the offset frequency versus the value of the micro-dial gives the frequency versus time function.

For the calibration of the zero value of the offset a light beam separated from one of the light beams of the trap is used. (This is frequency stabilized to 20 MHz below the Rb atomic transition.) The result of the measurement can be seen in Figure 5 together with a fitted sine function (see also Fig. 2). Sine function is fitted to the measurement data because the preceding comparison of the result of the simulation (Fig. 3 curve e′) with the assumed sine function (Fig. 2 curve e) shows little deviation from each other.

The chirp can be calculated by numerical derivation of this frequency versus time function. The result can be seen in Figure 6.

The frequency of the laser diode crosses the resonance of the ^{85}Rb $5^2S_{1/2}$ $F = 3 \leftrightarrow$ ^{85}Rb $5^2P_{3/2}$ $F' = 4$ transition "downward" at 240 ns as can be seen in Figure 5. The chirp is -90 MHz/ns at this time as can be seen in Figure 6. Similarly the "upward" crossing is at 267 ns and the chirp is 92 MHz/ns.

3 Measurement of the atomic displacement, computer simulations and discussion of the results

The aim of the experiment is the determination of the position of the maximum intensity of the fluorescence of

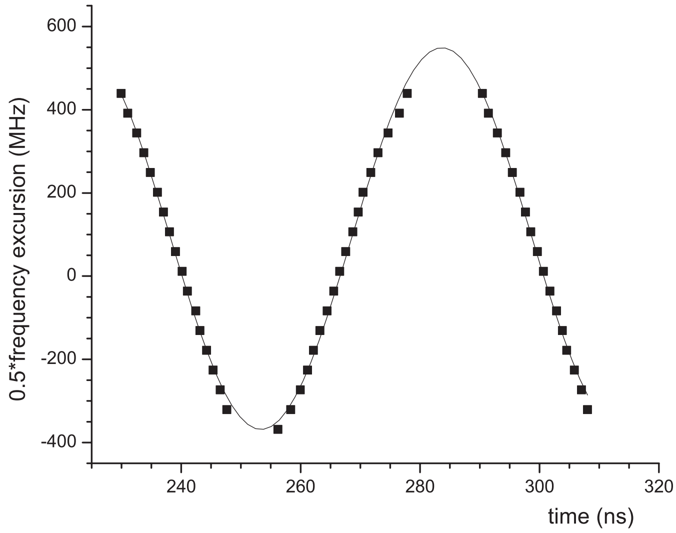

Fig. 5. The frequency excursion versus time function of the frequency modulated light. Points are the results of measurement. Continuous curve is the fitted harmonic function.

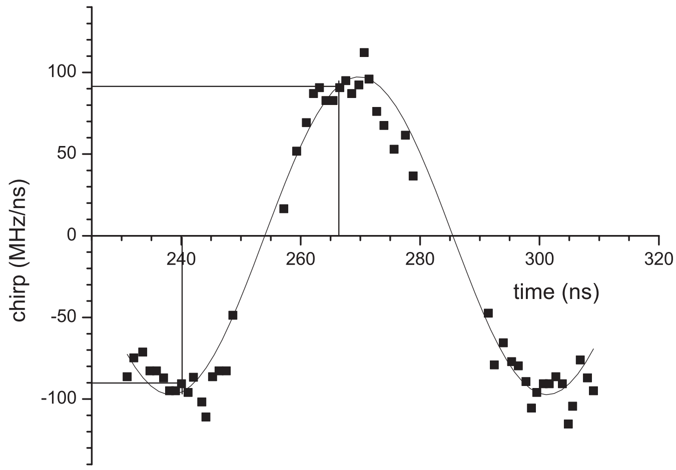

Fig. 6. The time function of the chirp of the diode laser light calculated from the data of Figure 4. Continuous line is a fitted harmonic function.

the trapped atoms depending on the chirp of the light pulses at given intensity of the frequency modulated light. The chirp depends on the offset of the working point of the diode laser.

In the first step the fluorescence light distribution of the trapped atoms without the influence of the light pulse train of chirped frequency is measured using the image intensifier and the CCD camera. The picture is digitized and stored in the memory of the computer. The position of the maximum of the distribution (ξ_0) is searched and registered by a program. In the following $\xi_0 = 0$ is assumed.

In the second step the frequency modulated pulse train propagating only into the $+\xi$-direction is let to interact with the atoms in the trap for 280 μs long and in the second half of this time duration a picture is taken by the CCD camera with 125 μs exposure time. The trapped atoms are excited by every pulse of the train and return to one of the ground states spontaneously. The result is the force acting on the atoms in the $+\xi$-direction. The atoms move under influence of this force to the position characterized by the new value of the position of the maximum of the fluorescent light distribution i.e. of the maximum of the spatial distribution (ξ_1) in the coordinate system where $\xi_0 = 0$.

In the third step the M mirror is shifted into the ξ light beam reflecting it. The reflected light pulse arrives to the trapped atoms with 3 ns delay. (The life time of the excited states is 27 ns.) The time and the duration of the exposure of the camera and time duration of the interaction with the train of these pulse pairs (propagating into the $+\xi$- and $-\xi$-direction) are the same as in the second step. The light pulse arriving first and propagating into the $+\xi$-direction excites the atom while the back reflected light pulse induces de-excitation. In the simplest case the momentum transferred to the atom is $2\hbar k$. According to this simplest expectation the force is doubled in comparison to that case of the second step. In any case, larger force is expected in the third step than in the second one if the de-excitation of the atoms is induced by the light. I.e. the momentum transmitted to the atom in the de-excitation process is in the same direction as that of the excitation. The atoms move under the influence of this force to a new position. The maximum of the fluorescent light distribution i.e. the maximum of the spatial distribution will be (ξ_2).

Dividing the result of the measurement of the third step by the one of the second step, $\xi_2/\xi_1 \geq 1$ is expected if the "up and down" transitions induced by the counterpropagating pulses. (In other words, the ratio of the displacement of the maximum of the spatial distribution of the trapped atoms caused by the back and forth $\pm\xi$ propagating pulses and of that caused only by $+\xi$ pulses is expected to be larger then one in case of induced transitions.)

Adiabatic transitions are expected if the inequalities (1) and (2) are fulfilled. The indication that adiabatic transition takes place may be that the experimentally observed ratio of the displacements of the maximums of the density distributions (of the trap atoms for the case of $\pm\xi$ beams and that only of the $+\xi$ beam) is $A' = \xi_2/\xi_1 \geqslant 1$.

The one ($+\xi$) beam displacement increases gradually with small but increasing chirp (see Fig. 7b curve b). Namely the frequency of the laser crossing the (h) line of Figure 2 "downward" induces excitation and the transfer of $\hbar k$ momentum in the $+\xi$-direction. The following "upward" crossing induces also transition, de-excitation and the transfer of $\hbar k$ momentum in the opposite direction. This second, opposite momentum transfer gradually disappears as the result of the decreasing intensity at the "upward" crossing of the frequency. Namely, the light intensity of the second pulse decreases with the rise of the time between the "downward" and "upward" crossings (see curve f of Fig. 2). To avoid the influence of this effect on the result it is better to use the ratio $A = \xi_2/\overline{\xi_1}$ instead of A'. $\overline{\xi_1}$ is the mean of ξ_1 outside of the transient region.

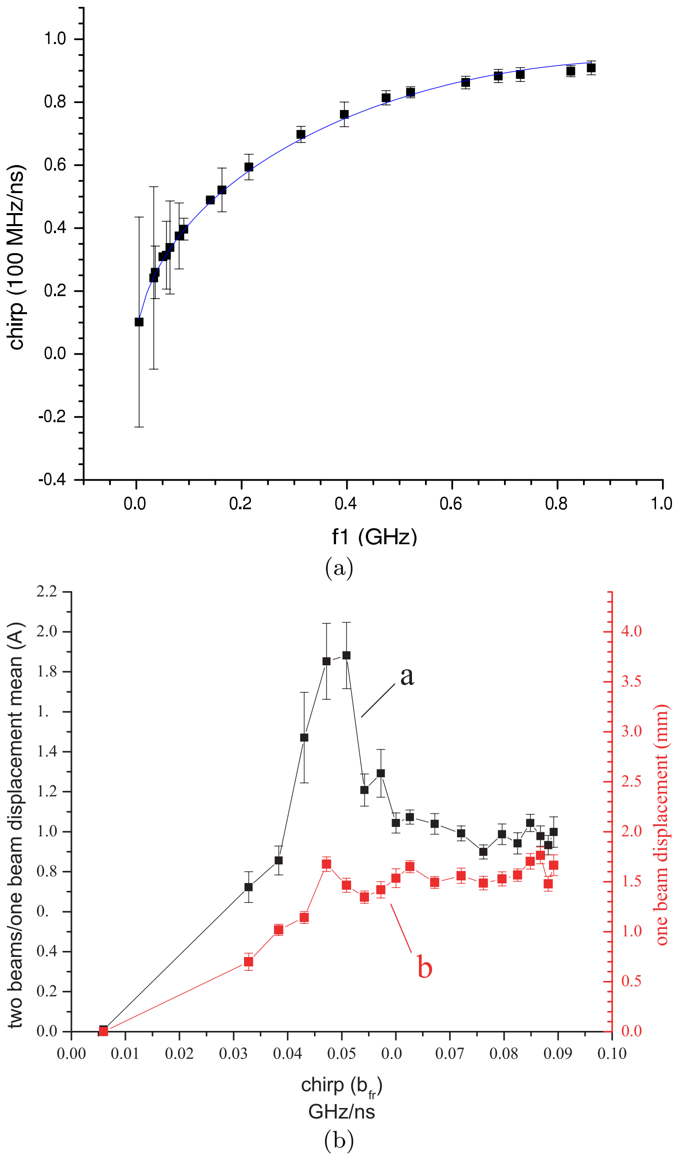

Fig. 7. (Color online) (a) The points with error bars show the result of the chirp measurement depending $f1 = a_{mf}/2 - g(i_0)$ i.e. on the offset (g) of the working point of the frequency modulation. The continuous curve is a fitted function assuming harmonic time function of the chirp. (b) The (two/one beam) ratio of the excursions (A) from the equilibrium state of the maximum of the spatial distribution of ^{85}Rb atoms of a MOT under the influence of a series of frequency modulated light pulses propagating in two opposite versus only in one direction (curve a). This ratio depends on the value of the chirp. Curve b is the displacement of the maximum of the trap atom distribution caused only by the ($+\xi$) light beam.

This ratio depends on the value of the chirp $A(b_{fr})$. This ratio depending on the chirp is measured experimentally by changing the offset (g) and performing the above described three steps of the measurement at every value of the offset i.e. at that of the chirp. The result of the measurement of the ratio $A(b_{fr})$ (curve a) can be seen in Figure 7b. The chirp was measured as described above

(Sect. 2.4) and the result with the standard deviations can be seen in Figure 7a as the function $f1 = a_{mf}/2 - g(i_0)$. The continuous curve is the theoretical fit assuming sinusoidal dependence of the light frequency on time.

As can be seen in Figure 7b, the displacements of the atoms of the trap is larger in case of $\pm\xi$ beams than in that of $+\xi$ beam only in a restricted interval of the chirp from about 40 MHz/ns to 75 MHz/ns. Otherwise the ratio of the two beam/one beam displacement is fluctuating around 1 or smaller then one.

In order to get detailed insight into the processes under consideration, a computer code for the solution of Bloch equations for density matrix elements taking into account spontaneous decay of the excited states was assembled to describe the temporal behavior of the populations, fine and hyperfine structure coherences of the six hyperfine, two ground $5^2S_{1/2}$ $F = 2, 3$ and four excited $5^2P_{3/2}$ $F' = 1, 2, 3, 4$ levels of the ^{85}Rb atoms [9]. In these simulations, the upper ground state $5^2S_{1/2}$ $F = 3$ and the $5^2P_{3/2}$ $F' = 2, 3, 4$ levels of the ^{85}Rb atoms are involved in interaction with the frequency modulated counter propagating laser pulses of given peak intensity. The re-pumping process of the atomic population from the lower lying ground state is also simulated by including interaction with the re-pumping laser radiation in resonance with the $5^2S_{1/2}$ $F = 2 \rightarrow 5^2P_{3/2}$ $F' = 3$ transition. The intensity of this re-pumping laser is 1.8 mW/cm^2.

The fit to the measured laser pulses (see Fig. 4) used in the simulation. The free running diode laser has a finite line-width. This line-width measured without modulation is 27 MHz. It is assumed that this line-width remains the same when the diode is frequency modulated by modulating the current. This line-width causes an increase in the intensity of the light at which the conditions for the adiabatic passage are fulfilled. This finite line-width of the radiation is taken into account in the simulation.

Adiabatic process which results in two/one beam displacement ratio greater than one takes place at comparatively small chirp according to results of our measurement. The chirp is small near to the extreme value of the sinusoidal changing light frequency. The slower the change of the frequency the larger the pulse duration is at the exit of the Fabry-Perot interferometer (FP). If the extreme value of the light frequency curve approaches the resonance of the FP interferometer (i.e. the offset approaches the value $g = \pm a_{mf}/2$, see Fig. 2), the two light pulses formed in the period of decreasing frequency and in that of increasing frequency are merged. Moreover the amplitude of the light pulse formed with increasing frequency is comparable to the one formed with decreasing frequency (see Fig. 8). Therefore the Bloch equations have to be solved for to and fro propagating pulses of complicated amplitude and frequency properties (see Fig. 8 curves (a–c) with peak at the zero crossings of the frequency curve (e1)). These are the shapes of the measured light pulses (see Fig. 4).

The offset (g) is around 0.93 GHz in the case of Figure 8. Curves (b–d) represents the reflected pulse arriving to the trapped atoms with 3 ns delay propagating into the opposite $-\xi$-direction. The amplitude of the pulse (a)

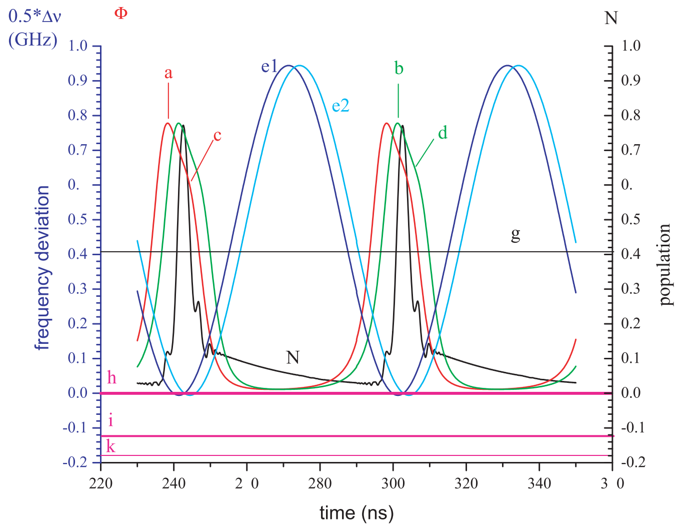

Fig. 8. (Color online) The time and amplitude scenario of the measurement. Curve (N) is the time function of the population of the ^{85}Rb $5^2P_{3/2}$ $F' = 2, 3, 4$ states normalized to one. Curve (e1) is the frequency deviation ($\Delta\nu$) from the resonance frequency of the ^{85}Rb $5^2S_{1/2}$ $F = 3 \leftrightarrow {}^{85}$Rb $5^2P_{3/2}$ $F' = 4$ transition. The amplitude of the light pulse (a) is normalized to 1. Φ is the normalized amplitude. Curves (h), (i) and (k) are the transition frequencies subtracted the frequency of the ^{85}Rb $5^2S_{1/2}$ $F = 3 \leftrightarrow {}^{85}$Rb $5^2P_{3/2}$ $F' = 4$ transition. The (frequency) offset of the working point of the modulation from the resonance of the FP interferometer i.e. from the resonance frequency of the ^{85}Rb $5^2S_{1/2}$ $F = 3 \leftrightarrow {}^{85}$Rb $5^2P_{3/2}$ $F' = 4$ transition is (g). The light pulses formed at zero crossing of the modulated frequency (e1) of the diode laser. Curves (a), (c), and (b), (d) are merged at this offset $g = 0.93$ GHz. Curves (b)–(d) are the reflected ($-\xi$) pulses and (e2) is the frequency function of the reflected pulses.

is normalized to 1 at maximum intensity. The amplitude of other pulses is normalized by the amplitude of the (a) pulse. The normalized amplitude of the pulse is Φ.

The (k) and (i) lines represent the resonance frequencies of the other two hyperfine transitions ^{85}Rb $5^2S_{1/2}$ $F = 3 \leftrightarrow {}^{85}$Rb $5^2P_{3/2}$ $F' = 3, 2$. Only the resonance (h) is crossed by the (e1), (e2) frequency curves in this case. (e2) is the frequency of the reflected light pulse. The sum of the population of the three excited levels ^{85}Rb $5^2P_{3/2}$ $F' = 2, 3, 4$ calculated by the computer is represented by curve (N). The population of all Rb states involved in the interaction is normalized to 1. The parameters are the same in the experiment and in the simulation.

The value of the chirp at the crossings of the (h) line is ± 16 MHz/ns and the minimum of the frequency curve is -12 MHz. The maximal intensity of the chirped light pulse of 0.11 W/cm^{2}is taken in the calculation. The criterion for adiabatic transition (1) is $e_{fkt} = 9.8$ as in the experiment. It is remarkable that sudden population increase and afterwards a population decrease of the excited levels appear as the result of the interaction with the frequency modulated light pulses (see curve (N)). The transferred momentum in the interaction with pulses propagating to and fro is larger than that in the interaction with only one pulse

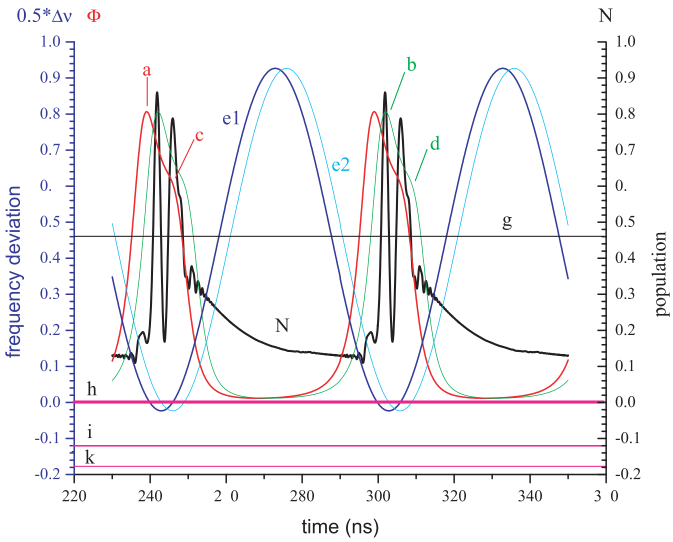

Fig. 9. (Color online) The time function (N) of the population of the ^{85}Rb 5^2P$_{3/2}$ $F' = 2, 3, 4$ states normalized to one under the influence of counter propagating frequency modulated pulses together with the time and amplitude scenario of the measurement. All the data are the same as in case of Figure 7 except (g). In this figure $g = 0.9$ GHz.

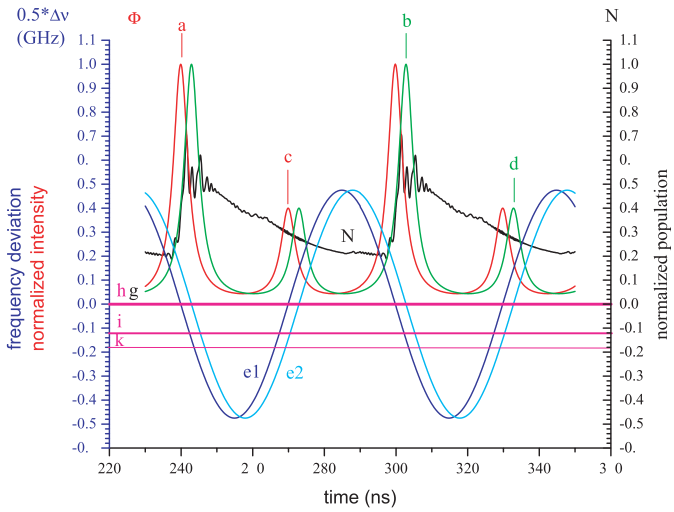

Fig. 10. (Color online) The time function (N) of the population of the ^{85}Rb 5^2P$_{3/2}$ $F' = 2, 3, 4$ states normalized to one under the influence of counter propagating frequency modulated pulses together with the time and amplitude scenario of the measurement. All the data are the same as in case of Figure 8 except (g). In this figure $g = 0$ GHz.

propagating in $+\xi$-direction. The experimentally observed momentum is smaller for $\pm\xi$ beams than for $+\xi$ beam at this chirp.

If the offset of the frequency modulated pulses is $g = 0.90$ GHz the pulses of decreasing and increasing frequency crossing are separated more from each other than in the case of Figure 8 (see Fig. 9).

The value of the chirp at the crossings of the (h) line is ± 30 MHz/ns and the minimum of the frequency curve is -47 MHz. The maximum of the intensity of the chirped light is 0.33 W/cm^2. The criterion for adiabatic transition (1) is $e_{fkt} = 8.4$ as in the experiment. It is remarkable that there are two excitation de-excitation processes at the crossings of the frequency curves following each other in three nanosecond time intervals. The transferred momentum is the highest.

Greater displacement for $\pm\xi$ beams than for $+\xi$ beam i.e. $A \geq 1$ was observed experimentally in the interval of the chirp from 39 to 71 MHz/ns (see Fig. 7b). The experimentally observed maximum of the displacement is at the chirp about 47–51 MHz/ns. Consequently, the experimentally observed interval of the chirp where $A \geq 1$ seems to be at little higher chirp value then that would be expected according to the change of population of levels given by the code.

At zero offset the chirp has maximum value 99.5 MHz/ns at the (h) line (see Fig. 10). The light pulses (a) and (c) of decreasing and increasing frequency are clearly separated in time. The amplitude of the pulse of increasing frequency is far smaller than that of decreasing frequency. The latter seems to have no influence on the atoms (see curve (N)). The atoms are partially excited by the light pulse of larger amplitude and decay exponentially after some oscillation of small amplitude of the population.

The maximal intensity of the chirped light is 0.81 W/cm^2. The criterion for adiabatic transition (1) is $e_{fkt} = 4.0$ as in the experiment. The experimentally measured displacement of the atoms caused by to and fro propagating pulses does not differ from that caused only by $(+\xi)$ pulses. This is verified by the calculation which shows only excitation induced by the light pulses. There is not de-excitation but exponential decay of the population. Transferred momentum to the atom in average is not expected in this decay phase.

4 Summary and conclusions

The displacement of the maximum of the spatial distribution of Rb atoms caused by frequency modulated light pulse pair propagating opposite to each other is measured in a MOT in dependence of the chirp of the pulses. This displacement is compared to that caused by light pulses propagating only in one direction. The frequency modulated pulses are produced by transmitting the frequency modulated light of a diode laser through a Fabry-Perot interferometer tuned to the resonance frequency of the ^{85}Rb 5^2S$_{1/2}$ $F = 3 \leftrightarrow$ ^{85}Rb 5^2P$_{3/2}$ $F' = 4$ transition. The chirp was measured by using a spectrometer combined with a Fabry-Perot interferometer and a fast photodiode. The chirp of the light pulses was determined depending on the offset of the working point of the modulation from the ^{85}Rb 5^2S$_{1/2}$ $F = 3 \leftrightarrow$ ^{85}Rb 5^2P$_{3/2}$ $F' = 4$ transition frequency. The intensity of the pulses changed depending on the chirp but the criterion for the adiabatic transition $R\tau > 1$ was always fulfilled. (R is the Rabi frequency and τ is the full width of the pulse at half maximum.) It was found that the ratio of the two measured displacements is larger than one showing that adiabatic transitions take place. The adiabatic transition was observed in only a limited region of the chirp in contradiction to the usual expectation. The deviation from the usual expectation may be explained by the simultaneous interaction of the light with many levels of the atom. The experiment is modeled by numerical solution of the Bloch equations. The simulation, at least qualitatively, confirms the results of the experiment.

This work was supported by the Research Fund (OTKA) of the Hungarian Academy of Sciences under Contracts Nos. T038274, 034141, T031981, T42773; and by the GVOP-KMA230.

References

1. V.S. Malinovsky, J.L. Krause, Eur. Phys. J. D **14**, 147 (2001)
2. P. Meystre, M. Sargent III, *Elements of Quantum Optics*, 2nd edn. (Springer-Verlag, Berlin Heidelberg, New-York, London, Paris, Tokyo, 1992)
3. N.V. Vitanov, T. Halfmann, B.W. Shore, K. Bergmann, Ann. Rev. Phys. Chem. **52**, 763 (2001)
4. B. Broers, H.B. van Linden van den Heuvell, L.D. Noordam, Phys. Rev. Lett. **69**, 2062 (1992); F. Balling, D.J. Maas, L.D. Noordam, Phys. Rev. A **50**, 4276 (1994); D.J. Maas, C.W. Rella, P. Antoine, E.S. Toma, L.D. Noordam, Phys. Rev. A **59**, 1374 (1999)
5. P. Pillet, C. Valentin, R.-L. Yuan, J. Yu, Phys. Rev. A **48**, 845 (1993)
6. J.S. Melinger, S.R. Gandhi, A. Hariharan, J.X. Tull, W.S. Warren, Phys. Rev. Lett. **68**, 2000 (1992)
7. J.S. Melinger, S.R. Gandhi, A. Hariharan, D. Gosvani, W.S. Warren, J. Chem. Phys. **101**, 6439 (1994)
8. M. Cashen, O. Rivoire, L. Yatsenko, H. Metcalf, J. Opt. B: Quantum Semiclass. Opt. **4**, 75 (2002)
9. G.P. Djotyan, J.S. Bakos, G. Demeter, P.N. Ignácz, M.Á. Kedves, Zs. Sörlei, J. Szigeti, Z.L. Tóth, Phys. Rev. A **68**, 053409 (2003)
10. J.S. Bakos, G.P. Djotyan, P.N. Ignácz, M.Á. Kedves, M. Serényi, Zs. Sörlei, J. Szigeti, Z. Tóth, Eur. Phys. J. D **39**, 59 (2006)
11. A. Nebenzahl, A. Szöke, Appl. Phys. Lett. **25**, 327 (1974)
12. M.J. Lawrence, B. Wilke, M.E. Hussman, E.K. Gustafson, R.L. Byer, J. Opt. Soc. Am. B **16**, 523 (1999)