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Self-focusing of CW laser beam with variable radius in rubidium atomic vapor

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ABSTRACT

Self-focusing of cw laser beam in a rubidium atomic vapor was studied. The beam radius and power at the entrance of a rubidium vapor cell were variable parameters. A steep grow of the self-focusing threshold power for the small beam radius (≤30 μm) was observed. Our experimental data are in a qualitative agreement with the recently published theoretical results obtained for a conventional non-resonant gas. Additional experiments in the resonance and transparent non-resonant media are suggested in order to check and extend our measurements.

1. Introduction

Self-focusing of electromagnetic beam in media is one of the most interesting nonlinear effects in optical physics [1]. The concept of self-focusing was formulated in 1962 [2]. A theoretical model of the effect was developed in 1964 [3,4]. Self-focusing and filamentation of the optical field were observed in transparent media [1] and in absorptive resonance gases [1,5,6].

Conditions for propagation of the optical beam in a linear medium or in a nonlinear medium are different. Intensity distribution of Gaussian beam in free space (vacuum) depends on the axial and transverse coordinates z and r [7] and described by equation:

$$I\,(r,z) = \frac{2P}{\pi w\,(z)^2} exp(-\frac{2r^2}{w\,(z)^2}), \tag{1}$$

where P is the power of the optical beam, $w(z)$ is the radius of the beam. The beam has a minimal radius ($w(0) = w_0$) at the beam waist. The radius of the beam $w(z)$ depends on the distance z from the waist. The expansion law for the optical beam radius $w(z)$ is expressed as

$$w\,(z)^2 = w_0^2 \left(1 + \frac{\lambda z}{\pi w_0^2}\right)^2. \tag{2}$$

A suitable thin lens with focus length f can be used for a conversion of the optical beam with the radius $w_{01}(0)$ to the beam with the radius $w_{02}(f)$ in the focal plane. When a relation $\pi w_{01}\,(0)^2 \gg \lambda f$ is satisfied, the next equation is applicable for the accurate evaluation of $w_{02}(f)$ [8]:

$$w_{02}\,(f) \approx \frac{\lambda}{\pi w_{01}(0)} f. \tag{3}$$

The optical beam can induce a lens-like modification of the refraction index in a nonlinear medium due to the Kerr effect

$$n(r,z,I) = n_0 + n_2 I(r,z). \tag{4}$$

In such medium the expansion law for the optical beam is different to compare with the free space. According to the theoretical model of [3] for the optical beam with a critical power P_{cr} the diffraction expansion may be compensated by the optically induced Kerr lens. A simple formula for the critical power P_{cr} is presented in [3]

$$P_{cr} = \xi \left(\frac{\lambda^2}{4\pi n_0 n_2}\right), \tag{5}$$

where the dimensionless factor ξ is order of 2. According this formula, the critical power is independent on the optical beam radius. Results of calculations by using the formula (5) are in satisfactory agreement with results of many experiments where self-focusing processes were investigated by using optical beams with relatively large radius ($w_0 >$ 50 μm) [1].

The detailed theoretical consideration of a propagation of the Gaussian shaped beam in the transparent nonlinear medium was performed in [9]. The self-focusing threshold power was defined for the beam

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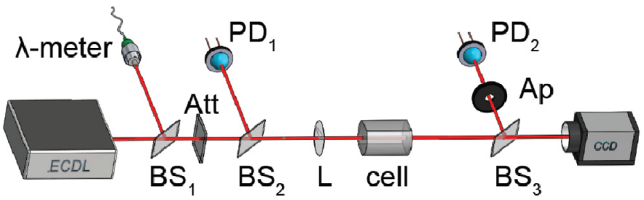

Fig. 1. Scheme of experimental setup: *ECDL* is external cavity diode laser, BS_1, BS_2, BS_3 are beamsplitters, *λ-meter* is wavemeter Angstrom, *Att* is variable attenuator, *L* is lens, *cell* is heated vapor cell, *CCD* is imaging digital camera, PD_1 and PD_2 are photodetectors, *Ap* is variable aperture.

propagation when the wave front becomes flat after propagating some distance through the nonlinear media. For small transverse sizes of the input beams ($w_0 < 50$ μm) a steep grow of the threshold was predicted and discussed. Recently a preliminary experimental confirmation of these theoretical results was published [10]. The optical beam was focused by using different lenses on a cell with a rubidium atomic vapor. Variation of the self-focusing threshold power was observed.

In the present paper the propagation of an optical beam with the variable radius in an atomic rubidium vapor was studied. The optical beam was focused on the entrance window of the vapor cell. The dependence of the self-focusing threshold power on the input beam radius was measured. The experimental data were compared with theoretical results obtained by using a technique developed in the work [9].

2. Experimental arrangement

The experimental study was performed with the rubidium atomic vapor. A natural abundance of ^{85}Rb (72.2%) and ^{87}Rb (28%) was used. Scheme of our experimental setup is presented in Fig. 1. The cw external cavity diode laser (ECDL) was used as a source of a narrow band emission (laser linewidth ≤ 1 MHz). The laser frequency was tuned to D_2-line of rubidium ($\lambda = 780$ nm). The first beamsplitter BS_1 sent a small part of the output laser light to a wavemeter. The another two beamsplitters BS_2 and BS_3 sent the laser light to the photodetectors PD_1 and PD_2.

The studies of self-focusing were performed by using a rubidium vapor cell with garnet windows (cell length 6 cm). A short description of the similar cell is presented in [11]. The atomic number density N of the rubidium vapor was defined by the temperature of a coldest part of the cell [12]. Due to temperature gradients in the cell the accuracy of atomic density measurements was evaluated at the level of 10%. The absorption spectrum of the rubidium vapor at a room temperature ($N \approx 10^{11}$ cm^{-3}) is shown in Fig. 2. The Doppler width $\Delta\omega_D$ of the atomic transitions was the order of $2\pi\times0.5$ GHz. (In the present work the spectral widths are defined as FWHM.) The Doppler width was more than the hyperfine splitting (hf-splitting) of the excited states $5P_{3/2}$ in ^{85}Rb and ^{87}Rb atoms.

The recorded absorption spectrum shows four well resolved resonances with widths order of 1 GHz. On these Doppler-broadened resonances one can see the narrow deeps obtained by using the standard pump-probe technique for the Doppler-free saturation spectroscopy [13, 14]. The presence of the narrow saturation resonances confirms the absence of a buffer gas in the vapor cell, and indicates the hf-structure of the upper $5P_{3/2}$ states. Each Doppler-broadened resonance is a combination of three hf-transitions. The natural linewidth $\gamma_{nat}/2\pi$ of each hf-transition is equal to 6 MHz. The resonances 1 and 2 represent sets of the hf-transitions $5S_{1/2}(F=3) \rightarrow 5P_{3/2}(F'=2,3,4)$ and $5S_{1/2}(F=2) \rightarrow 5P_{3/2}(F'=1,2,3)$ in ^{85}Rb atoms. The resonances 3 and 4 represent sets of the hf-transitions $5S_{1/2}(F=2) \rightarrow 5P_{3/2}(F'=1,2,3)$ and $5S_{1/2}(F=1) \rightarrow 5P_{3/2}(F'=0,1,2)$ in ^{87}Rb atoms.

The self-focusing was investigated the hot rubidium vapor with the atomic number density $N = 5.7\times10^{13}$ cm^{-3}. Self-focusing of the optical beam with variable radius was observed for laser detuning 9 GHz from

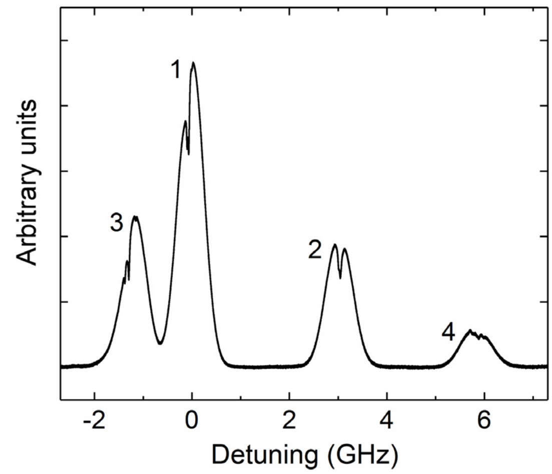

Fig. 2. Optically saturated absorption spectrum of the rubidium vapor at a room temperature.

the frequency of the hf-transition $5S_{1/2}(F=3) \rightarrow 5P_{3/2}(F'=4)$ in ^{85}Rb atoms.

For better understanding experimental results and comparison with theoretical results we estimated the "Kerr" coefficient n in Eq. (4). The refraction index can be calculated by using relations for of the gas of two-level atoms from the textbook [15]. As the first step we considered an isolated resonance transition in the atomic vapor. For large detuning of the laser frequency ω_{las} from the transition frequency ω_{ab} in our consideration only the homogeneous width of atomic transition can be taken into account. In the atomic vapor the homogeneous width of the selected resonance transition is a linear combination of the natural width γ_{nat} and the dipole–dipole interactions induced width Γ which is proportional to the atomic number density N [16]. Under our experimental conditions the interatomic interactions induced width ($\Gamma/2\pi = 5.7$ MHz) is less than natural width ($\gamma_{nat}/2\pi = 6$ MHz). In this case a possible influence of the optical saturation on the width Γ can be neglected [17,18]. Therefore in our analysis the common expression for the homogeneous width ($\gamma_{nat} + \Gamma$) was used.

The next Eqs. (6) and (7) from [15] for a two-level atomic system were applied for calculations of n_2:

$$\chi^{(3)} = \frac{\alpha_0(0)}{3\omega_{ba}/c}\left[\frac{\Delta T_2 - i}{(1+\Delta^2 T_2^2)^2}\right]\frac{2\varepsilon_0 c}{I_s^0}, \tag{6}$$

where $\alpha_0(0)$ is unsaturated, line-center absorption coefficient, ε_0 is dielectric constant for vacuum, I_s^0 is saturation intensity of the atomic transition a → b, the relaxation time T_2 is $2/(\gamma_{nat}+\Gamma)$.

$$n_2 = \frac{3}{4n_0^2\varepsilon_0 c}\chi^{(3)}. \tag{7}$$

For our case, where relations $(n_0^2 - 1) \ll 1$ and $(1 \ll \Delta^2 T_2^2)$ were satisfied for all hf-transitions, the next simplified equation is applicable

$$n_2 \approx \sum_j \frac{\lambda\alpha_{(j)}}{\left(\Delta_{(j)}T_2\right)^3}\frac{1}{4\pi I_S^{(j)}}. \tag{8}$$

Here the subscripts and superscript (j) show parameters which described one of the hf-transitions in ^{85}Rb and ^{87}Rb. For example, detuning $\Delta_{(j)}$ corresponds to $(\omega_{las} - \omega_j)$. Our estimate of n_2 is of 2×10^{-12} m^2/W with possible uncertainty 30%. This value is several orders above n_2 for the non-resonant transparent gases [15]. It allows us to investigate self-focusing processes in the atomic rubidium vapor by using a low power cw laser.