Optics Communications 284 (2011) 1197–1201

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Lensing and waveguiding of ultraslow pulses in an atomic Bose–Einstein condensate

Devrim Tarhan [a,*], Alphan Sennaroglu [b], Özgür E. Müstecaplıoglu [b,c]

[a] Department of Physics, Harran University, Osmanbey Yerleşkesi, Şanlıurfa 63300, Turkey
[b] Department of Physics, Koç University, Rumelifeneri yolu, Sarıyer, Istanbul 34450, Turkey
[c] Institute of Quantum Electronics, ETH Zurich Wolfgang-Pauli-Strasse 16, CH-8093 Zurich, Switzerland

ARTICLE INFO

Article history:
Received 21 June 2010
Received in revised form 14 October 2010
Accepted 20 October 2010

Keywords:
Bose–Einstein condensate
Electromagnetically induced transparency
Ultraslow pulse propagation
Waveguides
Lenses

ABSTRACT

We investigate lensing and waveguiding properties of an atomic Bose–Einstein condensate for ultraslow pulse generated by electromagnetically induced transparency method. We show that a significant time delay can be controllably introduced between the lensed and guided components of the ultraslow pulse. In addition, we present how the number of guided modes supported by the condensate and the focal length can be controlled by the trap parameters or temperature.

© 2010 Elsevier B.V. All rights reserved.

1. Introduction

Quantum interference effects, such as electromagnetically induced transparency (EIT) [1,2], can produce considerable changes in the optical properties of matter and have been utilized to demonstrate ultraslow light propagation through an atomic Bose–Einstein condensate (BEC) [3]. This has promised a variety of new and appealing applications in coherent optical information storage as well as in quantum information processing. However, the potential of information storage in such systems is shadowed by their inherently low data rates. To overcome this challenge, exploitation of transverse directions for a multimode optical memory via three dimensional waveguiding of slow EIT pulse [4] has been recently suggested for BECs [5]. Transverse confinement of slow light is also quintessential for various proposals of high performance intracavity and nanofiber slow light schemes (See e.g. ref. [6] and references therein). Furthermore, temperature dependence of the group velocity of ultraslow light in a cold gas has been investigated for an interacting Bose gases [7].

A recent experiment, on the other hand, has drawn attention that ultracold atomic systems with graded index profiles may not necessarily have perfect transverse confinement due to simultaneously competing effects of lensing and waveguiding [8]. The experiment is based upon a recoil-induced resonance (RIR) in the high gain regime, employed for an ultracold atomic system as a graded index waveguiding medium. As a result of the large core radius with high refractive index contrast, and strong dispersion due to RIR, radially confined multimode slow light propagation has been realized [8]. As also noted in the experiment, a promising and intriguing regime would have few modes where guided nonlinear optical phenomena could happen [8].

It has already been shown that the few mode regime of ultraslow waveguiding can be accessed by taking advantage of the sharp density profile of the BEC and the strong dispersion provided by the usual EIT [5]. The present work aims to reconsider this result by taking into account the simultaneous lensing component. On one hand, the lensing could be imagined as a disadvantage against reliable high capacity quantum memory applications. Our investigations do aid to comprehend the conditions of efficient transverse confinement. On the other hand, we argue that because the lensing component is also strongly delayed with a time scale that can be observably large relative to the waveguiding modes, such spatially resolved slow pulse splitting can offer intriguing possibilities for creating and manipulating flying bits of information, especially in the nonlinear regime. Indeed, earlier proposals to split ultraslow pulses in some degrees of freedom (typically polarization), face many challenges of complicated multi-level schemes, multi-EIT windows, and high external fields [9]. Quite recently birefringent lensing in atomic gaseous media in EIT setting has been discussed [10]. The proposed splitting of lensing and guiding modes is both intuitively and technically clear, and easy to implement in the EIT setting, analogous to the RIR experiment.

The paper is organized as follows: After describing our model system briefly in Sec. 2, the EIT scheme for an interacting BEC is presented in Sec. 3. Subsequently we focus on the lensing effect of the ultraslow pulse while reviewing already known waveguiding results shortly in Sec. 4. Main results and their discussion is in Sec. 5. Finally, we conclude in Sec. 6.

* Corresponding author. Tel.: +90 414 3183578; fax: +90 414 3440051.
E-mail address: dtarhan@harran.edu.tr (D. Tarhan).

0030-4018/$ – see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.optcom.2010.10.068

2. Model system

We consider the oblique incidence of a Gaussian beam pulse onto the cigar shaped condensate as depicted in Fig. 1. Due to the particular shape of the condensate two fractions, the one along the long (z) axis of the condensate and the one parallel the short (r) axis, of the incident Gaussian beam exhibit different propagation characteristics. The r-fraction exhibit the lensing effect and focused at a focal length (f) while the axial component would be guided in a multimode or single mode formation.

The angle of incidence (θ) controls the fraction of the probe power converted either to the lensing mode or to the guiding modes. When both lensing and waveguiding simultaneously happen in an ultraslow pulse propagation set up, an intriguing possibility arises. Different density profiles along radial and axial directions translate to different time delays of the focused and guided modes. Due to the significant difference in the optical path lengths of guided and focused components, an adjustable relative time delay can be generated between these two components. As a result, these two components become spatially separated. The fraction of the beam parallel to the short axis of the condensate undergoes propagation in a lens-like quadratic index medium resulting in a change in the spot size or the beam waist of the output beam. We call this as the lensing effect and the corresponding fraction as the lensed-fraction. The fraction of the beam propagating along the long axis is propagating in weakly-guided regime of the graded index medium that can be described in terms of LP modes. This is called as the guiding effect and the corresponding fraction is called as the guided fraction. We use the usual Gaussian beam transformation methods under paraxial approximation to estimate the focal length. In addition our aim is to estimate time delay between these two fractions. The output lensed and guided fractions of the incident beam are delayed in time relative to each other. In general temporal splitting depends on modal, material and waveguide dispersions. For a simple estimation of relative time delay of these components, we consider only the lowest order modes in the lensed and the guided fractions, and take the optical paths as the effective lengths of the corresponding short and long axes of the condensate. In this case we ignore the small contributions of modal and waveguide dispersions and determine the group velocity, same for both fractions, by assuming a constant peak density of the condensate in the material dispersion relation.

3. EIT scheme for an interacting BEC

A Bose gas can be taken as condensate part and thermal part at a low temperature. Following ref. [11], the density profile of the BEC can be written by $\rho(\vec{r}) = \rho_c(\vec{r}) + \rho_{th}(\vec{r})$, where $\rho_c(\vec{r}) = [(\mu(T) - V(\vec{r}))/U_0]\Theta(\mu - V(\vec{r}))$ is the density of the condensed atoms and ρ_{th} is the density of the thermal ideal Bose gas. Here $U_0 = 4\pi\hbar^2 a_s/m$; m is the atomic mass; and a_s is the atomic s-wave scattering length. $\Theta(.)$ is the Heaviside step function and T_C is the critical temperature. The external trapping potential is $V(\vec{r}) = (m/2)(\omega_r^2 r^2 + \omega_z^2 z^2)$ with trap frequencies ω_r, ω_z for the radial and axial directions, respectively. At temperatures below T_c, the chemical potential μ is evaluated by $\mu(T) = \mu_{TF}(N_0/N)^{2/5}$, where μ_{TF} is the chemical potential obtained under Thomas–Fermi approximation, $\mu_{TF} = ((\hbar\omega_t)/2)(15Na_s/a_h)^{2/5}$, with $\omega_t = (\omega_z\omega_r^2)^{1/3}$ and $a_h = \sqrt{\hbar/(\omega_z\omega_r^2)^{1/3}}$, the average harmonic oscillator length scale. The condensate fraction is given by $N_0/N = 1 - x^3 - s\zeta(2)/\zeta(3)x^2(1-x^3)^{2/5}$, with $x = T/T_c$, and ζ is the Riemann-Zeta function. The scaling parameter s is given by $s = \mu_{TF}/k_B T_C = (1/2)\zeta(3)^{1/3}(15N^{1/6}a_s/a_h)^{2/5}$.

Treating condensate in equilibrium and under Thomas–Fermi approximation (TFA) is common in ultraslow light literature and generally a good approximation because the density of an ultracold atomic medium is slowly changing during the weak probe propagation. The propagation is in the order of microseconds while atomic dynamics is in millisecond time scales. Due to weak probe propagation under EIT conditions, most of the atoms remain in the lowest state [12]. The validity of TFA further depends on the length scale of the harmonic potential. If the length scale is much larger than the healing length, TFA with the harmonic potential works fine. The healing length of the BEC is defined as $\xi = [1/(8\pi n a_s)]^{1/2}$ [13] where n is the density of an atomic Bose–Einstein condensate and it can be taken as $n = \rho(0,0)$. We consider the range of parameters in this work within the range of validity of TFA. The interaction of the atomic BEC with strong probe and the coupling pump field may drive the atomic BEC out of equilibrium. This non-equilibrium discussion is beyond the scope of the present paper.

We consider, beside the probe pulse, there is a relatively strong coupling field interacting with the condensate atoms in a Λ-type three level scheme with Rabi frequency Ω_c. The upper level is coupled to the each level of the lower doublet either by probe or coupling field transitions. Under the weak probe condition, susceptibility χ for the probe transition can be calculated as a linear response as most of the atoms remain in the lowest state. Assuming local density approximation, neglecting local field, multiple scattering and quantum corrections and employing steady state analysis we find the well-known EIT susceptibility [1,14], $\chi_i, i = r,z$, for either the radial (r) or axial (z) fraction of the probe pulse. Total EIT susceptibility for the BEC in terms of the density ρ can be expressed as $\chi_i = \rho_i\chi_1$ in the framework of local density approximation. Here χ_1 is the single atom response given by

$$\chi_1 = \frac{|\mu|^2}{\varepsilon_0\hbar}\frac{i(-i\Delta + \Gamma_2/2)}{(\Gamma_2/2 - i\Delta)(\Gamma_3/2 - i\Delta) + \Omega_C^2/4}, \tag{1}$$

where Δ is the detuning from the resonant probe transition . For the ultracold atoms and assuming co-propagating laser beams, Doppler shift in the detuning is neglected. μ is the dipole matrix element for the probe transition. It can also be expressed in terms of the resonant wavelength λ of the probe transition via $\mu = 3\varepsilon_0\hbar\lambda^2\gamma/8\pi^2$, where γ is the radiation decay rate of the upper level. Γ_2 and Γ_3 denote the dephasing rates of the atomic coherences of the lower doublet. At the probe resonance, the imaginary part of χ becomes negligible and results in turning an optically opaque medium transparent.

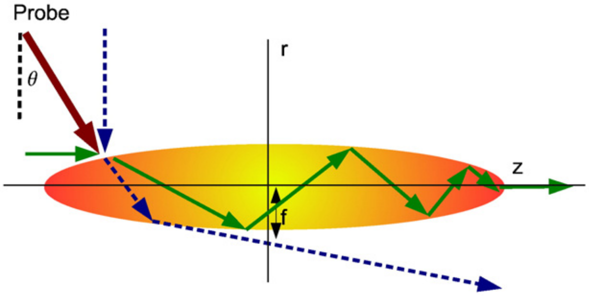

Fig. 1. Lensing and waveguiding effects in a slow Gaussian beam scheme with an ultracold atomic system.

4. Propagation of beam through a quadratic index medium

4.1. Lensing effect

We can neglect the thermal part of a Bose gas due to the high index contrast between the condensate and the thermal gas background so that $\rho = \rho_c$. We specifically consider a gas of $N = 8\times10^6$ ^{23}Na atoms with $\Gamma_3 = 0.5\gamma$, $\gamma = 2\pi\times10^7$Hz, $\Gamma_2 = 7\times10^3$ Hz, and $\Omega_c = 2\gamma$. We take $\omega_r = 160$ Hz and $\omega_z = 40$ Hz. For these parameters, we evaluate $\chi' =$

Download English Version:

https://daneshyari.com/en/article/10641261

Download Persian Version:

https://daneshyari.com/article/10641261

Daneshyari.com