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Observation of ladder-type electromagnetically induced transparency with atomic optical lattices near a nanofiber

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Abstract

Tapered nanofiber is an efficient tool for enhancing light–matter interactions. Here, we experimentally demonstrate the ladder-type electromagnetically induced transparency (EIT) in one-dimensional atomic lattices near an optical nanofiber (ONF). A typical EIT signal is well fitted from experimental data according to a semiclassical model and implies a transmission nearly 35%. We investigate the dependence of EIT transmission on the coupling power and its saturation condition. In addition, we show a large fraction of the transmission spectral broadening is induced by lattice effects. Our results may pave the road towards generating correlations and entanglement through four-wave mixing with ONFs, which may facilitate the realization of efficient quantum optical networks.

1. Introduction

In recent years, the optic-mediated coupling has raised great interests owing to the promising applications in novel nanophotonic sensors, quantum simulations and quantum networks [1–3] . However, the traditional free-space focusing limits the coupling rate and connectivity of fiber networks. Optical trapping schemes employing tapered optical nanofibers (ONFs) [4, 5] provide novel platforms in enhancing light–matter interactions [6]. Through the optical lattice generated by the evanescent field surrounding an ONF, two atomic chains could be trapped near the surface of the ONF to construct one-dimensional atomic ensembles, which are accompanied with many significant characters. Firstly, the large optical depth of trapped atomic arrays in such a geometry could lead to efficient quantum information storage [7], Bragg reflections [8, 9] and optical diodes [10]. Secondly, the small transverse section of the guided modes along the ONF could induce nonlinear interactions and low-power saturation [11–13]. Thirdly, the fluorescence from spontaneously decayed atoms could also be coupled into the ONF for precise detection [14, 15]. Last but not least, the presence of the ONF modifies the properties of adjacent vacuum fields and photon transportation [16, 17], which could result in super- and sub-radiance of the atoms trapped nearby the ONF surface [18].

Recently, based on Λ-type electromagnetically induced transparency (EIT) using ONFs, remarkable works on coherent storage of probe pulses have been implemented in cold atomic clouds [19] and trapped atomic arrays [7], respectively. In latter experiment, an ultra-narrow EIT window (dozens of kilohertz) is realized with a coherent light and well cooled trapped atoms in an optical lattice. Several microseconds of storage time are realized with extremely low-power of control field on the order of picowatt. It is a great progress of quantum information storage for all-fiber-based optical systems. In a warm rubidium vapor, one ladder-type EIT experiment is reported using ONF [20], which demonstrate coherent polarization control of the signal field by exploiting a circularly polarized coupling beam. On the other hand, the Ladder-type EIT and Autler–Townes splitting effect have also been observed through an ONF in cold atoms [21, 22]. However, for a nanofiber trapped atomic lattice, there is still no relevant report on the ladder-type EIT experiments.

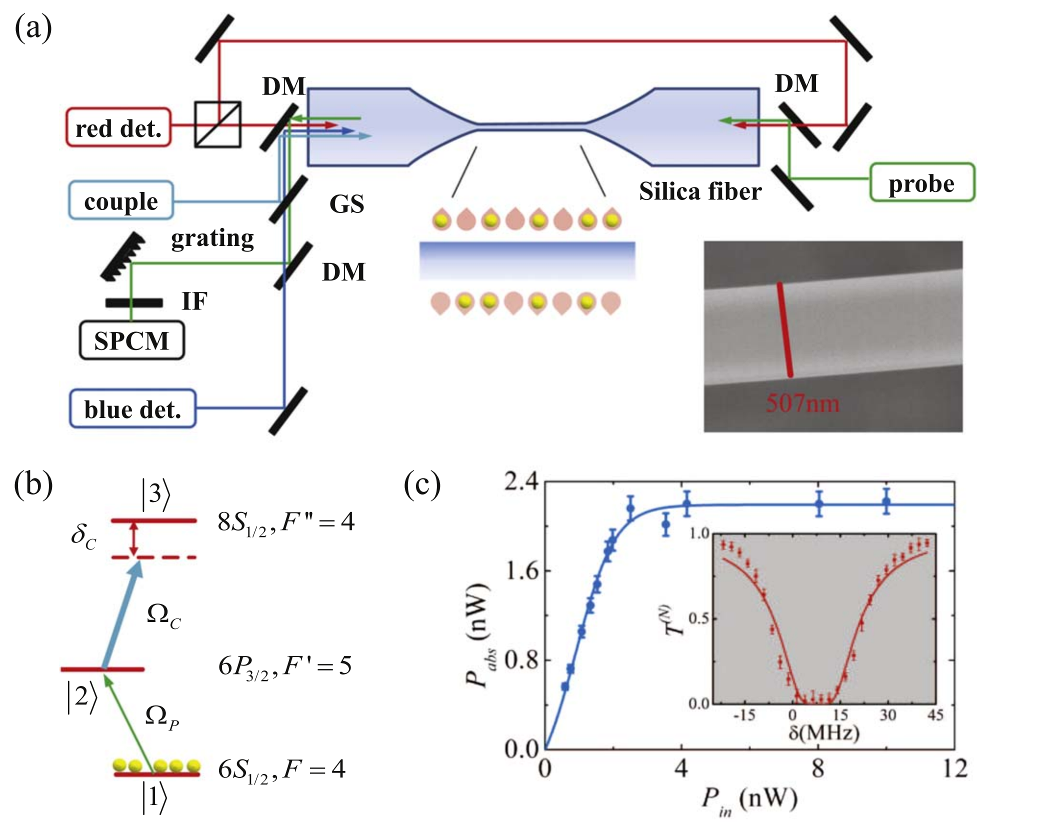

Figure 1. (a) Optical scheme of the ladder-type EIT with an ONF. The inset shows the SEM picture indicating the diameter of the ONF's waist. DM: dichroic mirror. GS: glass substrate. IF: interference filter. SPCM: single photon counter module. (b) Energy level diagram. The probe light is fixed at the resonance transition of $6S_{1/2}$, $F = 4 \rightarrow 6P_{3/2}$, $F' = 5$, and the frequency of the coupled light is scanned over the transition $6P_{3/2}$, $F' = 5 \rightarrow 8S_{1/2}$, $F'' = 4$ with a frequency detuning, δ_c. (c) Saturated measurement of the power absorption P_{abs} by the trapped atoms. The blue solid line is fitted following a generalized Beer's law. The inset shows the normalized transmission spectrum with an input power of 1 pW for the probe light.

In this paper, we demonstrate the ladder-type EIT in one-dimensional cesium optical lattices constructed by an ONF. Due to the fact that atoms are in two arrays of fixed trapping sites, the ladder-type EIT efficiently avoids the transit broadening and Doppler effect arising from the thermal motions. In addition, the long lifetime of trapped atoms and the large optical depth ensure the whole ensemble coherently processes in ladder-type EIT. The cascaded emissions from $8S_{1/2} \longrightarrow 6P_{3/2} \longrightarrow 6S_{1/2}$ pave the road towards generating correlations and entanglement via four-wave mixing [23, 24], which facilitates the implementations of quantum optical networks [3].

2. Experimental methods

2.1. Nanofiber fabrication

In preparing our experiments, a tapered ONF is stretched from a standard single mode fiber (Fibercore SM800-5.6-125) by a 'flame-brushing' technique [25–27]. The ONF is shaped so that the linear taper angle is designed to be 2 mrad. Once the diameter is decreased to be 12 μm, the ONF is transformed to an exponential profile until reaching a uniform waist diameter of 500 nm over a length of 5 mm. The diameter of the waist region is confirmed to be 507 nm by scanning tunneling electron microscope (SEM), which is roughly the same as the designed diameter (500 nm). In a vacuum of 3×10^{-7} Pa, the tolerant power of the tapered ONF is over 30 mW owing to high transmission (99.5%). The designed diameter of the ONF simultaneously guarantees the single-mode transmission and high intensity of the guided evanescent field near the ONF surface [28, 29].

2.2. Optical lattices and EIT system

The experimental setup is shown in figure 1(a). The trapped lattice is created by a pair of counter-propagating red-detuned lasers (1064 nm), an orthogonally polarized blue-detuned traveling laser (780 nm), and the short-range Van der Waals potential from the nanofiber surface. The atoms are ultimately trapped on both sides of nanofiber, which are located at the antinode position of the standing wave constructed by the red-detuned lasers.

The blue-detuned traveling laser with an orthogonal polarization makes a repulsive potential to further localize the trapped atoms into the optical lattice. The power of each red-detuned laser is 2.2 mW, and 25 mW for the blue-detuned laser, which induce two chains of trapping sites with a depth of 0.4 mK and a distance of 230 nm away from the ONF surface. The optical lattice induces a sub-wavelength confinement in three spatial dimensions, which results in the collisional blockade effect [30]. Thus, at most one atom can be filled into a trapping site. After released from the magneto-optical trap, atoms are cooled to 36 μK through a 20 ms molasses progress and loaded into the optical lattice guided by the ONF. The maximum loading rate is limited to 50% due to the blockade effect [30]. The exponential decay constant of trapped atoms is 110 $\pm$ 20 ms. Accompanied with the counter-propagated coupling light (795 nm), a probe light (852 nm) transmits through the atomic array and is subsequently detected by a single photon counter module (SPCM, Excelitas. SPCM-AQRH-15) for observing the ladder-type EIT. A holographic grating (Thorlabs. GH13-18V) and an interference filter (Semrock. LL01-852-12.5) are placed before the SPCM to isolate the stray and reflected light from trapping beams. Because of Raman scattering effect induced by the strong trapping lights in fiber, there is still a background photon count in the probing read. To minimize this background, in an experiment circle, the probe pulse is triggered back on and detected again after releasing the trapped atom array, which is used as a reference to be subtracted from the previous photon counting to retrieve the EIT signal.

Figure 1(b) shows the energy level diagram of the ladder-type EIT. The probe light is fixed at the resonance transition, $6S_{1/2}$, $F = 4 \rightarrow 6P_{3/2}$, $F' = 5$, and the coupling light scans over the $6P_{3/2}$, $F' = 5 \rightarrow 8S_{1/2}$, $F'' = 4$ transition with a frequency detuning notated as δ_c. Thus, there would be only one EIT window to be observed when the coupling laser is scanned.

To determine the number of trapped atoms, the saturated measurement of the absorbed power, P_{abs}, relative to the incident power, P_{in}, is investigated and shown in figure 1(c). The blue solid line is fitted in accordance with a generalized Beer's law that describes the saturation model [31]. When the probe frequency is tuned to the Stark-shifted resonance, the ultimate measured saturation power is approximately 2.2 nW. Given the radiated power from a single saturated cesium atom [5]

$$P_{Cs} = \frac{\Gamma}{2}\frac{s}{1+s}\hbar w_0 \approx 3.8 \text{ pW}, \tag{1}$$

we infer the number of trapped atoms near the ONF being $N \approx 580$.

In figure 1(c), the inset with gray background shows the normalized transmission spectrum averaged over 10 experimental circles, in which the error bars correspond to 1δ statistical errors in photon counting statistics. The probe pulse's power (exposure time) is set to 1 pW (1 ms) to avoid the recoil heating effect arising from off-resonant Raman scattering [32]. Based on the transmission spectrum presenting a Lorentzian lineshape, we can obtain the resonant optical depth d_N derived from a simple model of spectroscopy [33]

$$T(w) = \exp[-d_N\frac{1}{1 + 4(w - w_0)^2/\Gamma^2}], \tag{2}$$

where w_0 is the Stark-shifted resonance frequency of $6S_{1/2}$, $F = 4 \rightarrow 6P_{3/2}$, $F' = 5$, and Γ is the full width at half maximum (FWHM) of the transmission spectrum. In experiments, the measured FWHM is $\Gamma = 7.6 \pm 0.3$ MHz—larger than the intrinsic natural linewidth (5.2 MHz), which is mainly due to the inhomogeneous Zeeman broadening induced by vector light shifts [4] and photon scattering effects. The fitted result marked by the red solid line allows a resonant optical depth $d_N = 9.7 \pm 0.5$ with a Stark-shifted frequency at $w_0 = 7.8 \pm 0.4$ MHz detuned from the free-space atomic resonance of transition. Knowing the trapped atomic number N and optical depth d_N, we can infer an approximate optical depth per atom, $\eta = d_N/N = 1.67\%$.

3. Results and discussions

A typical transmission spectrum of ladder-type EIT of ONF trapped atoms is shown in figure 2. The probe power is chosen to be 1 pW during 1 ms operation period and the coupling power is set to 58 nW. The calculation of the ladder-type EIT marked by the red solid line is performed based on a semiclassical model [34], in which the probe transmission can be expressed as follows according to Beer's law, $T(\delta_c) = \exp(-\mathrm{i}\chi(\delta_c)\cdot L)$, and the linear susceptibility is given by

$$\chi = \frac{4\mathrm{i}\hbar g_{12}^2 N_0/\epsilon_0}{\gamma_{21} - \mathrm{i}\delta_p + \frac{\Omega_c^2/4}{\gamma_{31} - \mathrm{i}(\delta_p + \delta_c)}}. \tag{3}$$

Above, L is the sample length of the trapped atoms, and $2\hbar g_{12}$ represents the dipole moment matrix element for the transition from $6S_{1/2}$, $F = 4 \rightarrow 6P_{3/2}$, $F' = 5$. ϵ_0 is the permittivity of vacuum, and N_0 is the total atomic

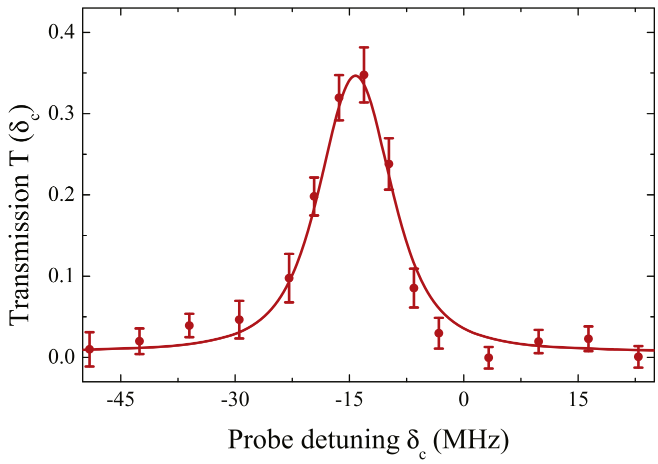

Figure 2. Experimental demonstration of ladder-type EIT based on ONF trapped atoms. Each dot is averaged from 10 experimental runs with the error bars representing 1δ statistical errors in photon statistics. The frequency of coupling light is scanned over $6P_{3/2}$, $F' = 5 \rightarrow 8S_{1/2}$, $F'' = 4$ transition with a frequency detuning δ_c. The theoretically fitted profile yields a transmission of 35% with the FWHM of 10.9 ± 0.4 MHz.

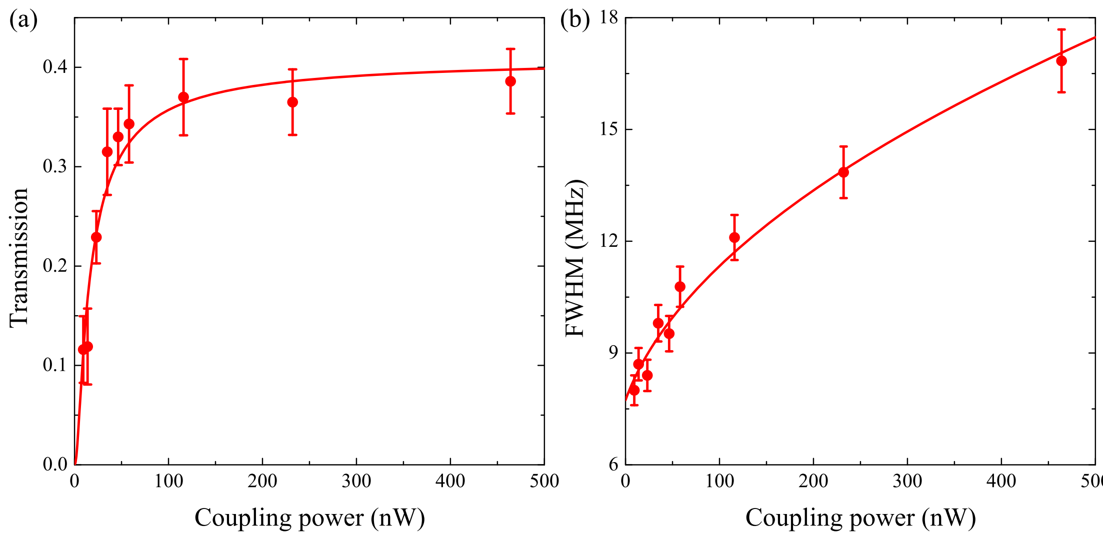

Figure 3. Characterize the ladder-type EIT, in which the power of probe light is set to 1 pW, and the frequency is set to the Stark-shifted resonance. Theoretically fitted curves are both indicated by red solid lines. (a) The normalized transmission of the ladder-type EIT as a function of the coupling power. (b) The FWHM of EIT as a function of the coupling power.

number. γ_{21} indicates the coherence decay rate from $6P_{3/2}$ to $6S_{1/2}$ state. The decoherence rate γ_{31} represents the loss of coherence between the $6S_{1/2}$ and $8S_{1/2}$ states, a coherence resulting from the coherent driving of two allowed transitions via the intermediate $6P_{3/2}$ level. The frequency of the probe light is fixed to the Stark-shifted resonance of transition from $6S_{1/2}$, $F = 4 \rightarrow 6P_{3/2}$, $F' = 5$ ($\delta_p = 0$), and the coupling light is scanned over the $6P_{3/2}$, $F' = 5 \rightarrow 8S_{1/2}$, $F'' = 4$ transition with a frequency detuning at δ_c. After fixing the coherence decay rate $\gamma_{21}/2\pi$ at 7.6 MHz measured from figure 1(c), we attain the decoherence rate, $\gamma_{31}/2\pi = 79 \pm 26$ kHz, and the Rabi frequency of the coupling light, $\Omega_c/2\pi = 3.1 \pm 0.5$ MHz. Based on the fitted curve, the FWHM of the ladder-type EIT is measured as 10.9 ± 0.4 MHz, and the transmission is about 35%. Considering the detuning of the coupling light from the resonance frequency, $\delta_c/2\pi = -14.2$ MHz, and the Stark shift of 7.8 MHz from the absorption resonance frequency, we conclude that the overall Stark shift of the excited state $8S_{1/2}$, $F'' = 4$ induced by the trapping potential is −22 MHz.

Figure 3(a) shows the dependence of normalized transmission of the ladder-type EIT on the coupling power with trapped atoms nearby an ONF. The power of probe light is fixed to 1 pW, and its frequency is chosen to be resonant with Stark-shifted transition, $6S_{1/2}$, $F = 4 \rightarrow 6P_{3/2}$, $F' = 5$. According to equation (3), at the line center of the EIT window ($\delta_p = 0$, $\delta_c = 0$), the susceptibility could be reduced to

$$\chi = \frac{4i\hbar g_{12}^2 N_0/\epsilon_0}{\gamma_{21} + \frac{\Omega_c^2/4}{\gamma_{31}}}, \tag{4}$$

where $\gamma_{21}/2\pi$ is fixed to 7.6 MHz and $L \cdot 4i\hbar g_{12}^2 N_0/\epsilon_0$ to a constant of 32.2 obtained from figure 2 above. The square of Rabi frequency $\Omega_c^2 = |-\mathbf{d} \cdot \mathbf{E}_c/\hbar|^2$ is proportional to the intensity (or power) of the coupling light. Using equation (4) and Beer's law, the experimental data is fitted and marked by the red line in figure 3(a) indicating a saturate transmission at 40%. When the power of coupling light is fixed to 58 nW, we can deduce the decoherence rate to be $\gamma_{31}/2\pi = 53 \pm 16$ kHz, which is consistent with the number obtained from figure 2. Figure 3(b) shows the relationships between the FWHM of the ladder-type EIT and the coupling power, which may be described as a power broadening given by [35]

$$\Gamma = \Gamma_0' \sqrt{1 + \frac{I}{I_s}} + \Gamma_b, \tag{5}$$

where Γ_0' represents the nanofiber-mediated decay rate of the trapped atoms. Due to the large distance of the atoms from the fiber surface, Γ_0' approximates to the spontaneous emission rate of the $8S_{1/2}$ state in vacuum (Γ_0) [15, 36]. That is $\Gamma_0' \approx \Gamma_0 = 2\pi \times 1.82$ MHz [37]. In equation (5), I_s is the saturation parameter for the transition, and I is the local intensity of the evanescent field at the atom positions. Here, we add a parameter Γ_b indicating an additional broadening part compared with the conventional linewidth of EIT. In figure 3(b), We fit the experimental data of the total FWHM following equation (5) and determine Γ_b to be $2\pi \times 5.9$ MHz. Several effects contribute to the Γ_b broadening: first, the inhomogeneous Zeeman broadening effect induced by the tightly confined trapping fields, which contributes about $2\pi \times 2.4$ MHz to the total spectrum broadening; second, the Doppler broadening effect arising from the phonon modes of atoms in the optical lattices, which typically causes a spectral broadening smaller than 300 kHz; last but not least, the lattice scattering effect of the probe light passing through the periodic lattice structure of trapped atoms, which contributes more than $2\pi \times 3.2$ MHz.

4. Conclusion

In conclusion, we have demonstrated the ladder-type EIT in one-dimensional atomic chains trapped in ONF lattices. We observe that about 580 atoms are trapped and placed 230 nm away from the nanofiber surface. Based on a semiclassical model, we deduce the transmission efficiency of a typical EIT signal to be 35% with a decoherence rate at $\gamma_{31}/2\pi = 79 \pm 26$ kHz. The dependence of EIT transmission on the coupling power is also investigated and the fitted function agrees well with the experimental data. From the dependence of EIT's FWHM on the coupling power, the additional broadening part Γ_b is identified. Two causes are mainly responsible for this broadening effect. One is the state-dependent light shifts due to the confined trapping field. The other one is the enhanced photon scattering in presence of the atomic lattices. These results may pave the road towards generating correlations and entanglement in quantum optics through four-wave mixing and facilitate the realization of efficient quantum optical networks.

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