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 $\Lambda$-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.
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 $P_{b}$ 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 $3 \times 10^{-7}$ 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 ± 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, \( \Delta S_{1/2}, F = 4 \rightarrow 6P_{3/2}, F' = 5 \), 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 \( \delta \). 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, \( P_{\text{abs}} \), relative to the incident power, \( P_{\text{in}} \), 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]

\[
P_{\text{Cs}} = \frac{\Gamma}{2} \frac{s}{s + 1} \eta w_0 \approx 3.8 \text{ pW},
\]

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 \( 1 \sigma \) 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 \( \Gamma_N \) derived from a simple model of spectroscopy [33]

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

where \( w_0 \) is the Stark-shifted resonance frequency of \( \Delta S_{1/2}, F = 4 \rightarrow 6P_{3/2}, F' = 5 \), and \( \Gamma \) is the full width at half maximum (FWHM) of the transmission spectrum. In experiments, the measured FWHM is \( \Gamma = 7.6 \pm 0.3 \text{ MHz} \)—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 \( \Gamma_N = 9.7 \pm 0.5 \) with a Stark-shifted frequency at \( w_0 = 7.8 \pm 0.4 \text{ MHz} \) detuned from the free-space atomic resonance of transition. Knowing the trapped atomic number \( N \) and optical depth \( \Gamma_N \), we can infer an approximate optical depth per atom, \( \eta = \Gamma_N / N = 1.67\% \).

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, \( T(\delta) = \exp\left(-i\chi(\delta) \cdot L\right) \), and the linear susceptibility is given by

\[
\chi = \frac{4i\hbar \delta_{12}^2 N_0 / \epsilon_0}{\gamma_{21} - i\Delta_p + \frac{\Omega_e^2/4}{\gamma_{31} - i(\delta_p + \delta)}}.
\]

Above, \( L \) is the sample length of the trapped atoms, and \( 2\hbar \delta_{12} \) represents the dipole moment matrix element for the transition from \( \Delta S_{1/2}, F = 4 \rightarrow 6P_{3/2}, F' = 5 \). \( \epsilon_0 \) is the permittivity of vacuum, and \( N_0 \) is the total atomic
number. $\gamma_{21}$ indicates the coherence decay rate from $6P_{3/2}$ to $6S_{1/2}$ state. The decoherence rate $\gamma_{31}$ 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 $\delta_c$. 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 $10.9 \pm 0.4$ 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
\[ \chi = \frac{4i/g_0^2 N_0/\epsilon_0}{\gamma_{21} + \frac{\Gamma^2}{4} - \frac{\Gamma^2}{4} + \frac{\Gamma^2}{4} + \Gamma_3}, \]

where \( \gamma_{21}/2\pi \) is fixed to 7.6 MHz and \( L = 4i/g_0^2 N_0/\epsilon_0 \) to a constant of 32.2 obtained from figure 2 above. The square of Rabi frequency \( \Omega^2 = |1 - d \cdot E_s/\hbar|^2 \) 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 \( \gamma_{31}/2\pi = 53 \pm 16 \text{ kHz} \), 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]

\[ \Gamma = \Gamma_0\sqrt{1 + \frac{I}{I_s} + \Gamma_3}, \]

where \( \Gamma_0 \) represents the nanofiber-mediated decay rate of the trapped atoms. Due to the large distance of the atoms from the fiber surface, \( \Gamma_0 \) approximates to the spontaneous emission rate of the \( 8S_1/2 \) state in vacuum (\( \Gamma_0 \)) [15, 36]. That is \( \Gamma_0 \approx \Gamma_0 = 2\pi \times 1.82 \text{ MHz} \) [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 \( \Gamma_3 \) 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 \( \Gamma_3 \), to be \( 2\pi \times 5.9 \text{ MHz} \). Several effects contribute to the \( \Gamma_3 \) broadening: first, the inhomogeneous Zeeman broadening effect induced by the tightly confined trapping fields, which contributes about \( 2\pi \times 2.4 \text{ MHz} \) 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 \( 2\pi \times 3.2 \text{ MHz} \).

### 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 nano fiber surface. Based on a semiclassical model, we deduce the transmission efficiency of a typical EIT signal to be 35% with a decoherence rate at \( \gamma_{31}/2\pi = 79 \pm 26 \text{ kHz} \). 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 \( \Gamma_3 \) 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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### References

1. Petersen J, Volz J and Rauschenbeutel A 2014 Chiral nanophtonic waveguide interface based on spin–orbit interaction of light Science 346 67–71
2. Lodahl P, Mahmoodian S, Stobbe S, Rauschenbeutel A, Schneeweiss P, Volz J, Pichler H and Zoller P 2017 Chiral quantum optics Nature 541 473–80
3. Kimble H J 2008 The quantum internet Nature 453 1023–30
4. Goban A, Choi K S, Alton D J, Ding D, Lacrotte C, Pototschnig M, Thiele T, Stern N P and Kimble H J 2012 Demonstration of a state-insensitive, compensated nanofiber trap Phys. Rev. Lett. 109 033603
[5] Vetsch E, Retz D, Sagué G, Schmidt R, Dawkins S T and Rauschenbeutel A 2010 Optical interface created by laser-cooled atoms trapped in the evanescent field surrounding an optical nanofiber Phys. Rev. Lett. 104 203603
[6] van Loo A F, Fedorov A, Lalumière K, Sanders B C, Blais A and Wallraff A 2013 Photon-mediated interactions between distant artificial atoms Science 342 1494–6
[7] Sayrin C, Clausen C, Albrecht B, Schneeweiss P and Rauschenbeutel A 2015 Storage of fiber-guided light in a nanofiber-trapped ensemble of cold atoms Optica 2 353–6
[8] Sørensen H L, Bégou J B, Kluge K W, Laks J P, Sørensen A S, Müller J H, Polzik E S and Appel A 2016 Coherent backscattering of light off one-dimensional atomic strings Phys. Rev. Lett. 117 133604
[9] Corzo N V, Gouraud B, Chandra A, Goban A, Shereemt A S, Kupriyanov D V and Laurat J 2016 Large bragg reflection from one-dimensional chains of trapped atoms near a nanoscale waveguide Phys. Rev. Lett. 117 133603
[10] Sayrin C, Junge C, Mitsch R, Albrecht B, O’Shea D, Schneeweiss P, Volz J and Rauschenbeutel A 2015 Nanophotonic optical isolator controlled by the internal state of cold atoms Phys. Rev. X 5 041036
[11] Spillane S M, Pati G S, Salit K, Hall M, Kumar P, Beausoleil R G and Shahriar M S 2008 Observation of nonlinear optical interactions of ultralow levels of light in a tapered optical nanofiber embedded in a hot rubidium vapor Phys. Rev. Lett. 100 233602
[12] Hendrickson S M, Lai M M, Pittman T B and Franson J D 2010 Observation of two-photon absorption at low power levels using tapered optical fibers in rubidium vapor Phys. Rev. Lett. 105 173602
[13] Jones D E, Franson J D and Pittman T B 2014 Saturation of atomic transitions using subwavelength diameter tapered optical fibers in rubidium vapor J. Opt. Soc. Am. B 31 1997–2001
[14] Kien F L, Liang J Q, Hakuta K and Balayan V I 2004 Field intensity distributions and polarization orientations in a vacuum-clad subwavelength-diameter optical fiber Opt. Commun. 242 445–55
[15] Kien F L, Balayan V I and Hakuta K 2006 Scattering of an evanescent light field by a single cesium atom near a nanofiber Phys. Rev. A 73 013819
[16] Shen J T and Fan S 2005 Coherent photon transport from spontaneous emission in one-dimensional waveguides Opt. Lett. 30 2001–3
[17] Kien F L and Rauschenbeutel A 2014 Propagation of nanofiber-guided light through an array of atoms Phys. Rev. A 90 063816
[18] Solano P, Barberis-Blostein P, Fatemi F K, Orozco L A and Rolston S L 2017 Super-radiance reveals infinite-range dipole interactions through a nanofiber Nat. Commun. 30 1857
[19] Gouraud B, Maxein D, Nicolas A, Morin O and Laurat J 2015 Demonstration of a memory for tightly guided light in an optical nanofiber Phys. Rev. Lett. 114 180503
[20] Jones D E, Franson J D and Pittman T B 2015 Ladder-type electromagnetically induced transparency using nanofiber-guided light in a warm atomic vapor Phys. Rev. A 92 043806
[21] Kumar R, Gokhroo V and Chomnai S N 2015 Multi-level cascaded electromagnetically induced transparency in cold atoms using an optical nanofibre interface New J. Phys. 17 123012
[22] Kumar R, Gokhroo V, Deasy K and Chomnai S N 2015 Autler–Townes splitting via frequency up-conversion at ultralow-power levels in cold 40Kb atoms using an optical nanofiber Phys. Rev. A 91 053842
[23] Willis R T, Becerra F E, Orozco L A and Rolston S L 2009 Four-wave mixing in the diamond configuration in an atomic vapor Phys. Rev. A 79 033814
[24] Duan L M, Lukin M D, Cirac J I and Zoller P 2001 Long-distance quantum communication with atomic ensembles and linear optics Nature 414 413–8
[25] Ward J M, Maimaitii A, Le V H and Chomnai S N 2004 Contributed review: optical micro- and nanofiber pulling rig Rev. Sci. Instrum. 85 111501
[26] Brambilla G et al 2009 Optical fiber nanowires and microfibers: fabrication and applications Adv. Opt. Photon. 1 107–61
[27] Hoffmann J E, Ravets S, Grover J A, Solano P, Kordell P R, Wong–Campos J D, Orozco L A and Rolston S L 2014 Ultra-high transmission optical nanofibers AIP Adv. 4 067124
[28] Sagué G, Vetsch E, Alt W, Meschede D and Rauschenbeutel A 2007 Cold-atom physics using ultrathin optical fibers: light-induced dipole forces and surface interactions Phys. Rev. Lett. 99 163602
[29] Solano P, Fatemi F K, Orozco L A and Rolston S L 2017 Dynamics of trapped atoms around an optical nanofiber probed through polarimetry Opt. Lett. 12 2283–6
[30] Schlosser N, Reymond G and Grangier P 2002 Collisional blockade in microscopic optical dipole traps Phys. Rev. Lett. 89 023005
[31] Vetsch E 2010 Optical interface based on a nanofiber atom–trap PhD Thesis Johannes Gutenberg University Mainz
[32] Wolf S, Oliver S J and Weiss D S 2000 Suppression of recoil heating by an optical lattice Phys. Rev. Lett. 85 4249–52
[33] Grover J A 2015 Atom-trapping and photon-counting experiments PhD Thesis University of Maryland
[34] Gea–Banacloche J, Li Y Q, Liu S Z and Xiao M 1995 Electromagnetically induced transparency in ladder-type inhomogeneously broadened media: Theory and experiment Phys. Rev. A 51 576–84
[35] Khan S, Kumar M P, Bharti V and Natarajana V 2017 Coherent population trapping (CPT) versus electromagnetically induced transparency (EIT) Eur. Phys. J. D 71 38
[36] Qi X D 2018 Dispersive quantum interface with atoms and nanophotonic waveguides PhD Thesis University of New Mexico
[37] Marek J 1977 Radiative lifetime of the 8S, 9S and 7D level of Cs Phys. Lett. A 60 199–2