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Xiateng Qin(秦夏腾), Yuan Jiang(蒋源), Weixin Ma(马伟鑫), Zhonghua Ji(姬中华),Wenxin Peng(彭文鑫), and Yanting Zhao(赵延霆)

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Observation of V-type electromagnetically induced transparency and optical switch in cold Cs atoms by using nanofiber optical lattice

Xiateng Qin(秦夏腾)[1,2], Yuan Jiang(蒋源)[1,2], Weixin Ma(马伟鑫)[1,2], Zhonghua Ji(姬中华)[1,2,†], Wenxin Peng(彭文鑫)[3], and Yanting Zhao(赵延霆)[1,2,‡]

[1] *State Key Laboratory of Quantum Optics and Quantum Optics Devices, Institute of Laser Spectroscopy, Shanxi University, Taiyuan* 030006, *China*
[2] *Collaborative Innovation Center of Extreme Optics, Shanxi University, Taiyuan* 030006, *China*
[3] *State Grid Chongqing Electric Power Research Institute, Chongqing* 404100, *China*

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Optical nanofiber (ONF) is a special tool to achieve the interaction between light and matter with ultralow power. In this paper, we demonstrate V-type electromagnetically induced transparency (EIT) in cold atoms trapped by an ONF-based two-color optical lattice. At an optical depth of 7.35, 90% transmission can be achieved by only 7.7 pW coupling power. The EIT peak and linewidth are investigated as a function of the coupling optical power. By modulating the pW-level control beam of the ONF-EIT system in sequence, we further achieve efficient and high contrast control of the probe transmission, as well as its potential application in the field of quantum communication and quantum information science by using one-dimensional atomic chains.

Keywords: optical nanofiber, optical lattice, V-type electromagnetically induced transparency, optical switch

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1. Introduction

Electromagnetically induced transparency (EIT) is a significant nonlinear optical effect in light–matter interaction with potential applications in quantum information, quantum computing and high-resolution laser spectroscopy.[1–3] The simplest three-level EIT system consists of three types: Λ-type, ladder-type and V-type. The V-type EIT is special for several reasons. Firstly, the realization of EIT process in V-type system does not involve the population trapping, so that people can clearly distinguish different coherent processes.[4] Secondly, because the V-type excitation uses the counter-propagation beams with a larger residual Doppler width, it can be used as a unique spectroscopic technique for velocity discrimination.[5] In addition, the residual absorption in the V-type system is effectively suppressed by optical pumping, which enable high contrast spectroscopy signals for precision measurement.[6] Based on these special characteristics, many researchers have investigated the V-type EIT theoretically and experimentally, mostly in atomic vapor and cold atomic cloud.[7–10]

In recent years, optical nanofiber (ONF) has become an important research tool in nonlinear optics.[11,12] Using evanescent fields of ONF, researchers have demonstrated many EIT effects and their corresponding applications. In the aspect of Λ-type EIT-ONF system, Kien *et al.*[13] theoretically studied the propagation characteristics of guided light on the surface of the nanofiber. Gouraud *et al.*[14] realized single-photon pulse optical storage based on an ONF-cold atom cloud system. Sayrin *et al.*[15] further succeeded in achieving the storage of light pulses in optical lattice based on nanofiber. Regards to ladder-type EIT-ONF system, Jones *et al.*[16] and Liu *et al.*[17] successively achieved EIT based on the ONF-warm rubidium and cesium atoms system by using coupling field with a power of mW-level. Kumar *et al.*[18] demonstrated optical switching based on ONF-cold atom cloud system. Su *et al.*[19] experimentally demonstrate the ladder-type EIT in one-dimensional atomic lattices near an ONF. Specially, V-type EIT was successfully realized in nanofibers-based thermal rubidium vapor by Spillane *et al.*[20] However, due to the influence of the transit-time dephasing and Doppler broadening, the power of control beam they used is on the order of nW and the spectral width they obtained is on the order of hundreds of MHz. They proposed that the nonlinear effect of pW-level could be achieved in cold atoms.

In this paper, we investigate V-type EIT of Cs atoms confined in nanofiber optical lattices. These lattices are formed by using red and blue two-color lasers detuning with atomic resonance respectively, both of which pass through the evanescent field of ONF. The cold atoms are trapped in the optical lattices, forming a one-dimensional atomic chain. The evanescent field interact efficiently with the atoms, due to the strong evanescent confinement, the power of control beam can be as low as pW level. We also demonstrate the characteristics of transmission and the full width at half maximum (FWHM) of the V-type EIT. High contrast, optical switching at kHz rate is further demonstrated.

†Corresponding author. E-mail: jzh@sxu.edu.cn
‡Corresponding author. E-mail: zhaoyt@sxu.edu.cn

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2. Experimental setup

In this experiment, we taper the standard single-mode fiber (FiberCore SM800-5.6-125) into an ONF with a waist length of 5 mm and a diameter of 500 nm by a "flame brush" technology.[21,22] The schematic diagram of the nanofiber is shown in Fig. 1(a). When the diameter of the fiber is less than the laser wavelength, part of the input power can propagate on the surface of the fiber as the evanescent field,[23] which supports the interaction between the guided light with the atoms.

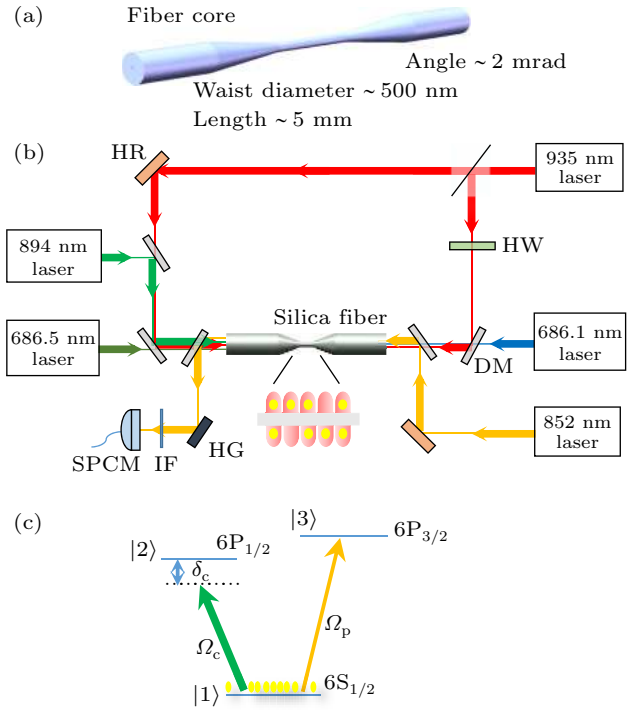


Fig. 1. (a) Schematic diagram of nanofiber. (b) The main optical path diagram of V-type EIT. SPCM: single photon counter module; DM: dichroic mirror; HR: high reflection mirror; HG: holographic grating; HW: half wave-plate; IF: interference filter. (c) Energy level diagram of V-type EIT. The probe laser (852 nm) is fixed at the resonance transition of $|6S_{1/2}, F=4\rangle \rightarrow |6P_{3/2}, F'=5\rangle$, and the coupling laser (894 nm) is scanned the transition of the $|6S_{1/2}, F=4\rangle \rightarrow |6P_{1/2}, F'=3\rangle$.

The optical scheme is shown in Fig. 1(b). We choose a laser of magic wavelength to form a light lattice to confine the atoms so as to suppress the AC Stark shift to the D2 probe transition. For the purpose, we use a pair of counter-propagating red detuned laser at 935 nm, and two blue detuned lasers at 686.1 nm and 686.5 nm with the same polarization direction. The atom is loaded into the antinode of the red detuned standing wave. At the same time, the repulsive potential formed by the parallel polarized blue detuned traveling wave makes the atom more stable at the antinode. This can effectively reduce a series of problems caused by atomic thermal motion.[24] In this case, the power of red detuned laser is 0.4 mW and the power of the blue detuned laser is 5 mW for each beam. According to the theoretical results,[25] a double chain of atomic traps with a depth of 0.35 mK is formed at distance of 173 nm from the surface of the nanofiber after considering our experimental parameters. Within each sub-wavelength trap of the optical lattices, the collision blocking effect ensures that there is at most one atom or no atoms during the trap loading and the maximum loading rate of 50%-theoretically.[26] At the beginning of the experiment, cesium atoms are cooled by the magneto-optical trap (MOT) to 60 μK. Then a sub-Doppler molasses process runs for 5 ms and cold atoms are loaded into the nanofibers lattice. The whole loading cycle takes 1.8 s. The resulting optical density of trapped atoms in the lattices seen by the guided D2 probe light is about 7.35. The lifetime of the lattice trap as measured by resonance absorption method is 5.03 ms. Compared with the optical lattices formed by non-magic wavelengths,[19] the shorter lifetime of the atoms is mainly due to strong scattering by the standing wave trapping potential at 935 nm which is close to the 852 nm transition line. The 852 nm probe laser and 894 nm coupling laser are counter-propagating through ONF to construct the array of atoms. A single photon counter module (SPCM) records the probe transmission for the V-type EIT signal within 1 ms. In order to eliminate the influence of reflected laser in fiber and stray light in environment entering the SPCM, we placed the holographic grating and the interference filter in front of SPCM.

Figure 1(c) shows the energy level diagram of V-type EIT. The probe laser is locked to the resonance frequency of the $|6S_{1/2}, F=4\rangle \rightarrow |6P_{3/2}, F'=5\rangle$ probe transition and the coupling laser is scanned across the $|6S_{1/2}, F=4\rangle \rightarrow |6P_{1/2}, F'=3\rangle$ control transition. Here δ_c is the detuning of the couple laser from the control transition.

3. Results and discussion

3.1. V-type EIT

As shown in Fig. 2, when the coupling laser power is 7.7 pW, a typical transmission spectrum of V-type EIT is obtained. We use the given linear polarizability Eq. (1) to fit it[27] and obtain that the transmittance of the probe light is 90% and the FWHM is 1.4 MHz:

$$\chi = \frac{3\lambda^3 \Gamma_1 N_{\rm at} \mathrm{i}\,(1+Q) K_2 \Omega_2^2}{8\pi^{3/2} \kappa\mu Q K_1 \left(4K_0 K_1 - \Omega_2^2\right)}, \tag{1}$$

where its associated parameters are given by

$$K_0 = \delta_{\rm p} - \delta_{\rm c} + \mathrm{i}\gamma_{12}, \tag{2a}$$

$$K_1 = \delta_{\rm p} - \delta_{\rm c} + \mathrm{i}\left(\gamma_{13} + Q\gamma_{23}\right), \tag{2b}$$

$$K_2 = \delta_{\rm p} - \delta_{\rm c} + \mathrm{i}\gamma_{13} + \mathrm{i}\gamma_{23}\left(1 + \frac{(Q-1)\Gamma_{\rm t}}{\Gamma_2 - \Gamma_{23} + 2\Gamma_{\rm t}}\right), \tag{2c}$$

$$Q = \sqrt{1 + \frac{\Omega_2^2}{\gamma_{23}\Gamma_2}\left(1 + \frac{\Gamma_2 - \Gamma_{23}}{2\Gamma_{\rm t}}\right)}. \tag{2d}$$

Here $N_{\rm at}$ represents the atomic number density; the Doppler-broadened limit is $\Gamma_1 \ll \kappa\mu$;[28] μ represents the velocity of the atoms; the wave velocity is $\kappa = 2\pi/\lambda$; Ω_2 is the Rabi

frequency of the coupling beam; δ_p and δ_c represent the frequency detuning of probe laser and coupling laser respectively; the decay rate γ of each energy level is defined as $\gamma_{ij} = (\Gamma_i + \Gamma_j)/2$ with $i, j = 1, 2, 3$; the spontaneous decay rate is Γ; and $\Gamma_3 = 0$, $\Gamma_{13} = \Gamma_1$, $\Gamma_{23} = \Gamma_2$, $\Gamma_t = 2\mu/(\sqrt{\pi}d)$ indicate the decay rate of the transmission time with the diameter of the laser beam.[29,30]

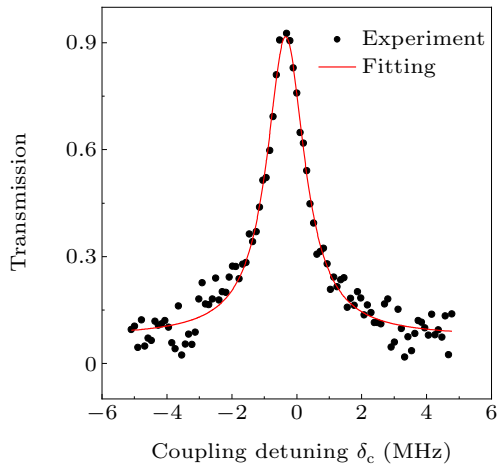


Fig. 2. V-type EIT based on nanofiber optical lattices. When the coupling optical power is 7.7 pW, the fitting result shows that the transmittance is 90% and the FWHM is 1.4 MHz.

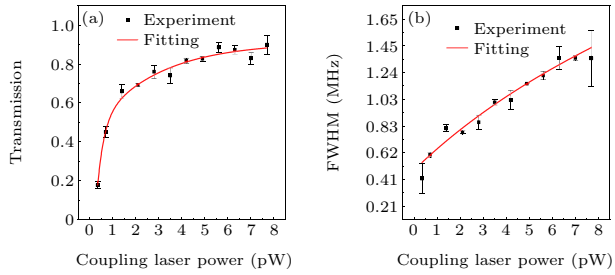


Fig. 3. The EIT transmission and FWHM are investigated as a function of the coupling optical power. (a) Experimental date points (black square dots) and fitting curves (red solid line) of V-type EIT transmission. The transmission of V-type EIT tends to saturation with the increase of coupling laser power, and the peak value reaches 90%. (b) Experimental date points (black square dots) and theoretical simulation (red solid line) of V-type EIT FWHM. The FWHM of the V-type EIT increases as coupling power increases.

We investigate the change of transmission with different coupling laser powers. To ensure linear optical response, the power of the probe laser is kept at 1 pW. It is represented in Fig. 3(a). Fitting the experimental data, we can get that the saturated transmittance is 90%. Figure 3(b) shows the relationship between the FWHM and the coupling laser power, which can be described by the power broadening formula given by the following equation:[31]

$$\beta_c = \tau_0 \sqrt{1 + \frac{I}{I_s}} + \beta_b, \tag{3}$$

where β_c express the power broadening of the coupling field, τ_0 is the decay rate of the atoms trapped in nanofiber optical lattices,[32] and I_s is saturation parameter in transition process, which is defined as $I_s = \pi hc/3\lambda^3\tau$. τ is the decay lifetime of $6P_{3/2}$ state,[33] I is the strength of the evanescent field at the position of the atoms, β_b is a broadening parameter relative to the traditional EIT, and its influence includes Zeeman effect, Doppler broadening effect and lattice scattering effect.[19] The large errors at extremal values of coupling beam measured here are accidentally larger than other values.

In our experiment the cold atoms are confined in the lattices formed by two counter-propagating lasers. This structure allows the confined atoms to have larger optical density than normal cold atomic cloud in nanofiber system due to longer interaction time and stronger quantum coherence, inducing much lower power for control beam in our experiment.

Based on the study of V-type EIT characteristics, a variety of related experiments can also be investigated, such as measuring Bohr magnetons, enhancing the optical nonlinear effect of the medium, thus achieving the purpose of promoting the interaction of the dark state polaron,[34] and more importantly, promoting the research of all optical quantum logic gates.[35] Here, we will further explore the properties of optical switch, thereby improving the exploration of nanofiber as quantum communication.

3.2. Optical switch

Because of the unique effect of V-typed EIT, we demonstrate the optical switch on the nanofiber system. The probe laser frequency is locked at $|6S_{1/2}, F = 4\rangle \rightarrow |6P_{3/2}, F' = 5\rangle$ transition of Cs atom, and its power is 1 pW. The coupling laser frequency is fixed at $|6S_{1/2}, F = 4\rangle \rightarrow |6P_{1/2}, F' = 3\rangle$ transition, and the coupling laser power is 7.7 pW. We control the switch of the coupling laser by modulating acousto-optical modulation (AOM), which gives a 5 kHz square wave signal. We get the change in the transmittance of the probe laser when the coupling laser is modulated. We measure the transmission of photons with (black square dots) and without (red circle dots) atoms in the optical lattices and the results are shown in Fig. 4. When the coupled laser is turned off, an obvious tailing phenomenon can be seen, and if the tailing problem wants to be solved, the V-type atomic system needs to be placed in the optical bistability mode to enhance the anti-interference ability of the atomic system.[36] This is related to factors such as the intensity of the coupled laser or the surrounding stray magnetic field.[37]

At present, all optical switches are faced with problems such as slow switching speed and low working efficiency. As far as the current optical communication system is concerned, nanofiber is undoubtedly the one of choice. We believe that our research will contribute to the development of quantum communication.

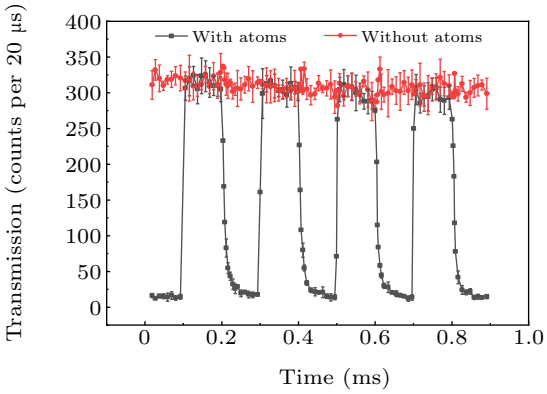


Fig. 4. Optical switch based on 5 kHz on-off modulation of the coupling beams. The transmission of photons in optical lattices with (black square dots) and without (red circular dots) atoms is represented.

4. Conclusion

In conclusion, we have investigated V-type EIT of cold atoms trapped by optical lattice through the evanescent field of ONF. EIT signals as a function of coupling laser intensity are investigated in detail. A typical EIT signal with transmittance of 90% and FWHM of 1.4 MHz is obtained at a coupling laser power of merely 7.7 pW. Finally, the highly efficient, high contrast control of probe transmission in the ONF V-type EIT system allows us to implement an optical switch, with a coupling power of merely 7.7 pW, to efficiently control the transmission of a single mode probe light. We noticed that the switching speed is significantly higher than those in similar efforts where the optical switch is implemented in a MOT.[18] The demonstration has not yet achieved switching with the highest speed possible by the ONF system. We have discussed the difficulty in detail and laid a possible path for future problem solving, so as to realize efficient optical switches for quantum communication and quantum information science.

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