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Controllable transmission of vector beams in dichroic medium*

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Vector beams with spatially varying polarization distribution in the wavefront plane have received increasing attention in recent years. The manipulation of vector beams both in intensity and polarization distributions is highly desired and under development. In this work, we study the transmission property of vector beams through warm rubidium vapor and realize controllable transmission of vector beams based on atomic dichroism. By utilizing the linearly polarized beam and vector beams as the pump and probe beams in a pump–probe configuration, a spatially-dependent dichroism can be obtained, which leads to spatially varied absorption of the probe beam. The controllable intensity distribution of the probe beam, as a two-petal pattern, can rotate with the variation of the pump beam's polarization states. We experimentally demonstrate the mechanism of dichroism with linear polarization light and provide an explanation based on the optical pumping effect. Alternatively, the varying trend of the probe beam's intensity is also interpreted by utilizing the Jones matrix. Our results are thus beneficial for providing potential applications in optical manipulation in atomic ensembles.

Keywords: quantum optics, polarization, dichroism

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1. Introduction

Vector beams have attracted a lot of attention in recent years due to a number of applications.[1–5] These beams can be generated by a vector superposition of two Laguerre–Gaussian (LG) beams with orthogonal polarizations. The resultant beam has non-uniform spatial intensity, phase, and polarization distributions. If two LG beams have equal amplitude and equal but opposite orbital angular momenta, the resultant beam takes on spatially varying linear polarization distributions which are radial, azimuthal, or spiral, determined by the difference of phase between the two beams. How to control the spatial intensity and (or) the polarization distribution of the optical field is an important research topic due to its usefulness in many fields such as material processing, optical trapping, and manipulation.[6]

Dichroism is a well-known phenomenon that refers to the property of a material in which a beam with different polarization state traveling through it experiences a different absorption coefficient and refractive index. It has been applied in various fields including materials, physical optics, astronomy, and so on.[7–11] Linear dichroism plays an important role in the study of material properties. In 1815, Biot used tourmaline's dichroism to manufacture the first batch of tourmaline polarizer.[12] Due to the potential values of the linear dichroism, researchers also attempted to extend its adhibitions in other optical media.[13] Compared with linear dichroism, circular dichroism has attracted more attention, and has been used in many fields such as polarization spectroscopy.[14,15]

Alkali metal has been widely used in a lot of experiments such as electromagnetically induced transparency[16,17] and four-wave mixing[18,19] for many years due to its favorable coherence. At the same time, atomic vapor can present dichroism under certain conditions such as polarized modulation. The dichroism induced by a circularly polarized beam can greatly improve the sensitivity and resolution of spectroscopy via the optical pumping effect in atomic ensembles. Conversely, it can also influence the line shape of the spectrum.[20] Therefore people utilize vector beams[21–25] as a tool to study the relationship of dichroism and polarization. For example, researchers measured snap-shot optical polarization spectroscopy via four-wave mixing in semiconductor films.[26] The vector beams are beneficial for making single-shot polarization-dependent measurements or providing a means of preparing samples with position-dependent spin.[27] The interaction between spatially variant beams and a magnetically influenced rubidium (Rb) medium can control the circular birefringence optically and modulate the polarization of the vector beams.[28] Obviously, vector beams allow us to realize the detection of the spin of atoms in a spatially dependent manner, since they exhibit spatially varied polarization states. The dichroism in the samples can be evaluated from the spatial distribution of the probe signals without rotating the polarization of the pump signals.

In this paper, we study the propagation property of a vector beam in the dichroic atomic vapor. We find the spatial intensity distribution of the probe beam can be controlled by

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varying the polarized orientation of the pump beams. Compared with attenuation elements, the atoms can provide another platform to control the spatial intensity, and can also act as a polarization analyzer. Changing the different pump beam can efficiently modify the function of the atoms. A detailed process of dichroism induced by the optical pumping effect is presented to interpret our experimental results. The outline of this paper is as follows. In Section 2, we present the experimental setup and results. Different polarization combinations are tested and the intensity of the probe beams directly reflects the atomic dichroism. In Section 3, we discuss the phenomenon based on the optical pumping effect and explain it by the Jones matrix. In Section 4, we conclude briefly the principle of transmission of a vector beam in dichroic media.

2. Experimental setup and results

All experimental schematics can be illustrated by Fig. 1(a). A 780 nm extended cavity diode laser (Toptica DL pro) is used in our experiment. The laser beam is divided into two orthogonally polarized beams by a polarization beam splitter (PBS), where the reflected beam (about 1 mW) is used for the saturated absorption spectroscopy (SAS) to lock the laser frequency and the transmitted beam is used for the experiment. The transmitted beam is collected by a single-mode fiber (SMF) to improve the spatial mode. A telescope is used to expand the beam size. The following half-wave plate (HWP) and polarization beam splitter are used to alter the intensity of the beam. Then the beam with horizontally linear polarization is divided by a beam splitter (BS). The transmitted part is used as the probe beam whose intensity can be altered by neutral density filters (not shown in figure). The reflected part serves as the pump beam and forms a pump–probe configuration using several mirrors. The intensities of the probe and pump beams are fixed at 50 μW and 2 mW, respectively. The sizes of the probe and pump beams are nearly the same. The Rb cell has a length of 50 mm and is filled with enriched ^{87}Rb, which is shielded by a three-layer μ-metal. The temperature of the Rb cell is controlled at 63 °C. Here HWP 1 and HWP 2 are used to change the polarized direction of the input Gaussian beam. The optional Q-plate 1 and Q-plate 2[29] can transform the input Gaussian beam into a vector beam. It is worth noting that the polarized direction of the input Gaussian beam can directly influence the spatial polarized distribution of the output vector beam. By utilizing the combination of an HWP and a Q-plate, we can obtain different vector beams, such as radially, azimuthally, or spirally polarized beams. After passing through the cell, the probe beam is reflected by a BS and its profile can be resolved by a charge-coupled device camera (CCD). However, the diffusion and distortion in atoms influence the image of the probe beam, hence in some cases we use a lens to collect the probe beam before the CCD in the experiment (not shown in Fig. 1). Figure 1(b) shows typical saturated absorption spectroscopy of energy levels of $F_g = 1$ to $F_e = 0, 1, 2$ of the ^{87}Rb D_2 line. In our experiments, we lock the laser beam to the crossover transition of $5S_{1/2}$, $F_g = 1$ to $5P_{3/2}$, $F_e = 0, 1$.

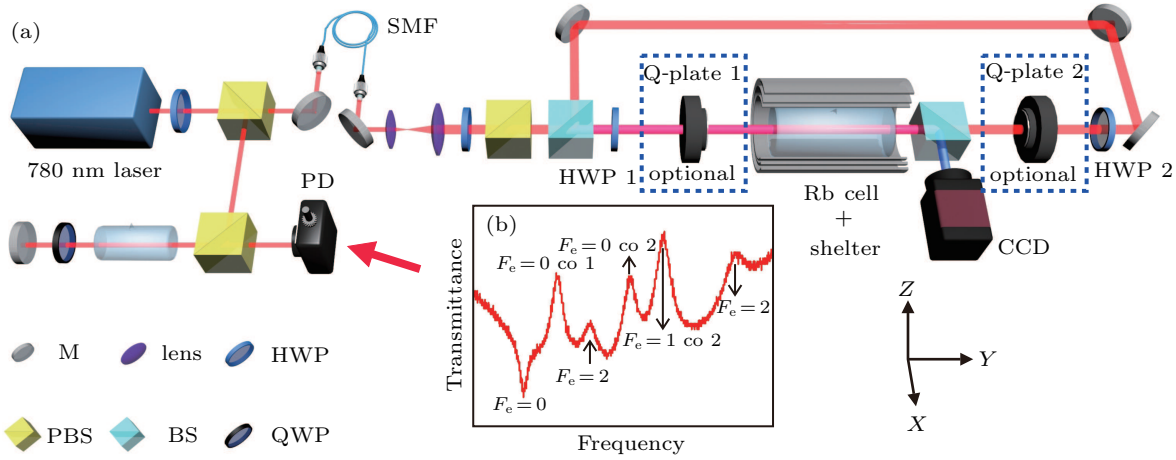


Fig. 1. (a) Experimental setup. SMF, single-mode optical fiber; L, lens; HWP, half-wave plate; QWP, quarter-wave plate; PBS, polarization beam splitter; BS, beam splitter; CCD, charge-coupled device camera; PD, photodetector. (b) Saturated absorption spectroscopy of the energy levels from F_g=1 to $F_e = 0, 1, 2$ of the ^{87}Rb D_2 line.

Firstly, we employ linearly polarized light as the pump beam (the Q-plate 2 in Fig. 1(a) is deprecated) and the radially or azimuthally polarized vector beam as the probe beam. The radially (azimuthally) polarized vector beam possesses spatially varying linear polarization in the beam cross-sections, and polarization along the radial (azimuthal) direction around its light center. When a radially (azimuthally) polarized vector probe beam passes through atomic media excited by a linearly polarized pump beam, the spatial intensity distribution of the probe can be modulated assisted by the atomic dichroism. Figure 2(a) is the experimental result of the radially polarized vector beam versus the linearly polarized pump beam. Here

we adjust the fast axis of HWP 2 at intervals of 15° to change the polarized orientation of the pump beam. The recorded profiles show that the probe beam splits into two sections and rotates with the orientation of the linearly polarized pump beam. Figure 2(b) is the experimental result of the azimuthally polarized vector beam and exhibits a similar phenomenon. The results can be summarized as follows: When the polarizations of the pump and probe beams are parallel to each other, the atomic media show strong absorption characteristics for the probe beam. However, the transmission occurs if the pump and probe beams have orthogonal polarizations. Thus we obtain and test the spatial dichroism of atomic media.

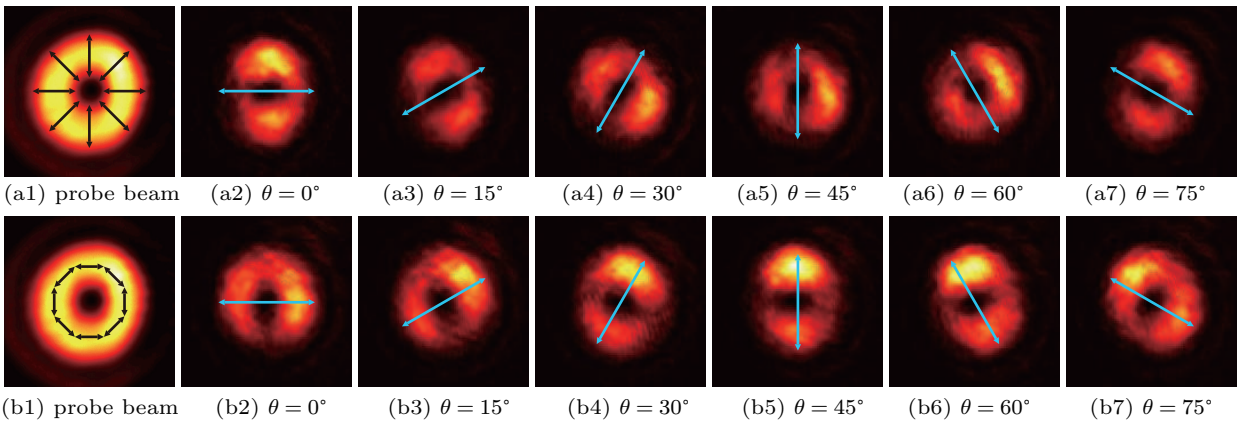


Fig. 2. Experimental results, where the probe beam is a (a) radially or (b) azimuthally polarized vector beam while the pump beam has linear polarization. θ is the angle between the optical axis and the horizontal direction, blue arrows represent the polarized direction of the pump beam.

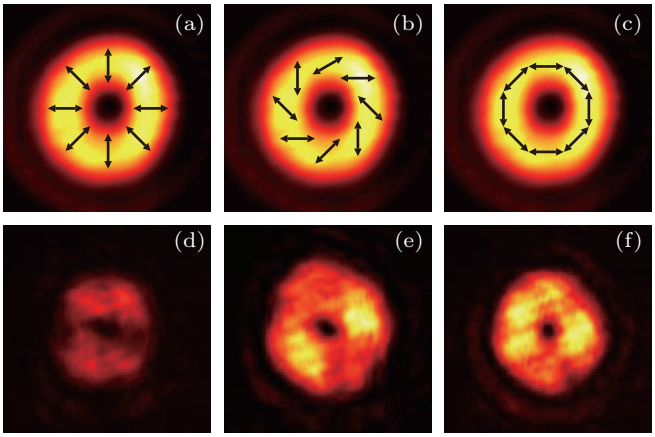


Fig. 3. Experimental results for different vector pump beams in the condition of radially polarized probe beam: (a) radially polarized pump beam, (b) generally polarized pump beam, (c) azimuthally polarized pump beam. (d)–(f) Experimental results for radially polarized probe beam (a lens was added before CCD for better image).

Then, we add Q-plate 2 after the HWP 2 and switch the pump beam among the radially, azimuthally, and spirally polarized vector beams as shown in Figs. 3(a)–3(c), respectively. At the moment, the probe beam always keeps a radially polarized state. The experimental results are shown in Figs. 3(d)–3(f), where the size of the hollow part of the intensity patterns is smaller than that in Figs. 3(a)–3(c) because we add a lens ($f = 100$ mm) for a better image of the probe beam. The profiles of each probe beam still keep their ring-shape and have regularity. The intensity of these three images is reduced from right to left. We also find that the minimum intensity can be received by using a radially polarized vector pump beam and the maximum value comes from the azimuthally polarized vector pump beam. The reason is that when a radially polarized probe beam interacts with atomic media excited by another radially polarized pump beam, the polarized states of each beam are parallel throughout the cross-section, thereby the probe beam experiences uniform absorption. The other two cases are similar, but the included angle between the polarizations of the probe and pump beams in the same position is different. In these situations, the probe and pump beams can be regarded as linearly polarized beams; the absorptive characters are only influenced by the included angle in the corresponding position rather than the polarization distribution. As for the results we mentioned above, the vector beam is more flexible in detecting dichroism of media than the single polarized beam. These configurations can also be used in making an atomic polarization analyzer or for the filtration of information.[30]

In fact, from these results we can find that the intensity profile of the probe beam represents the dichroism of media. Although there is much research on linear dichroism,[31–33] the relationship between the varying tendency and linearly polarized direction has not been summarized perfectly. Therefore we experimentally study the behaviors of linear dichroism and will provide an explanation based on the population of atoms in the next section. The experimental setup used to observe the linear dichroism is based on Fig. 1(a). Here the two Q-plates are removed. We choose the horizontally linearly polarized probe beam. The linearly polarized orientation of the pump beam is controlled by HWP 2 and starts from the horizontal direction. The experimental results are shown in Fig. 4, where the abscissa stands for the rotating angle of HWP 2 and the ordinate represents the normalized intensity, the blue stars are experimental data, and the red curve is obtained from theoret-

ical calculation by the Jones matrix (the detailed discussion is given in the next section). We can obtain the periodic variations of the transmitted intensity, where the experimental data and theoretical prediction are coincident. Meanwhile, the absorption (transmission) occurs when the polarized orientations of the probe and pump beams are parallel (orthogonal) to each other, which is consistent with the previous experimental results.

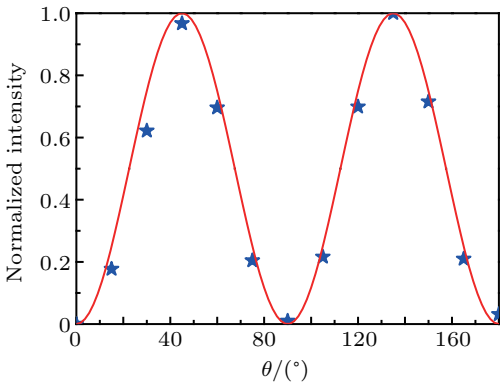


Fig. 4. The intensity variation of the horizontally linear polarized probe beam against the rotated angle θ. The fast axis rotated angle of HWP 2 is θ with respect to the horizontal direction. The blue stars are experimental data and the red curve is theoretical prediction.

3. Discussion

In this section, we explain the underlying principle of linear dichroism in the atomic medium by the optical pumping effect and Jones matrix. The laser frequency is locked to the crossover peak $F_g = 1$ to $F_e = 0$ and $F_e = 1$. The crossover signal appears when the probe beam is tuned at $F_g = 1$ to $F_e = 0$ and the pump beam is tuned at $F_g = 1$ to $F_e = 1$, or vice versa. Although the frequencies of the probe and pump beams are the same, moving atoms experience different frequency detuning from the counter-propagate probe and pump beams due to the Doppler effect, which is the reason that we can obtain the crossover signal in SAS.[34–36] Figure 5 shows the degenerate energy level diagram for $F_g = 1$ to $F_e = 0$ and $F_e = 1$ in the D_2 line of ^{87}Rb atoms. Suppose the pump beam is vertically polarized light and the probe beam has horizontal polarization, we can disassemble the pump beam into left-handed and right-handed circular beams.[31] According to the select rules, the pump beam will excite the transition with $\Delta m_F = \pm 1$. Figure 5(b) shows the situation when the atoms move towards the pump beam: the co-propagating probe beam couples the lower energy levels while the counter-propagating pump beam interacts with the higher energy levels. The intense pump beam could excite atoms to the $m_F = \pm 1$ ground energy level and let $m_F = 0$ empty, which leads to non-absorption of the weak probe beam. Figure 5(c) shows the opposite interaction when the atoms move along towards the probe beam, but get the same results. That is to say, in the case of orthometric polarization, absorption of the probe beam is decreased. Figures 5(d) and 5(e) show the situation when the probe and pump beams have the same polarization: the strong pump beam pumps atoms to the energy levels which can result in enhanced absorption of the probe beam. Based on the population of atoms influenced by the optical pumping effect, we explain the atomic dichroism. This might be a novel method for the manipulation of vector beams in atomic physics.

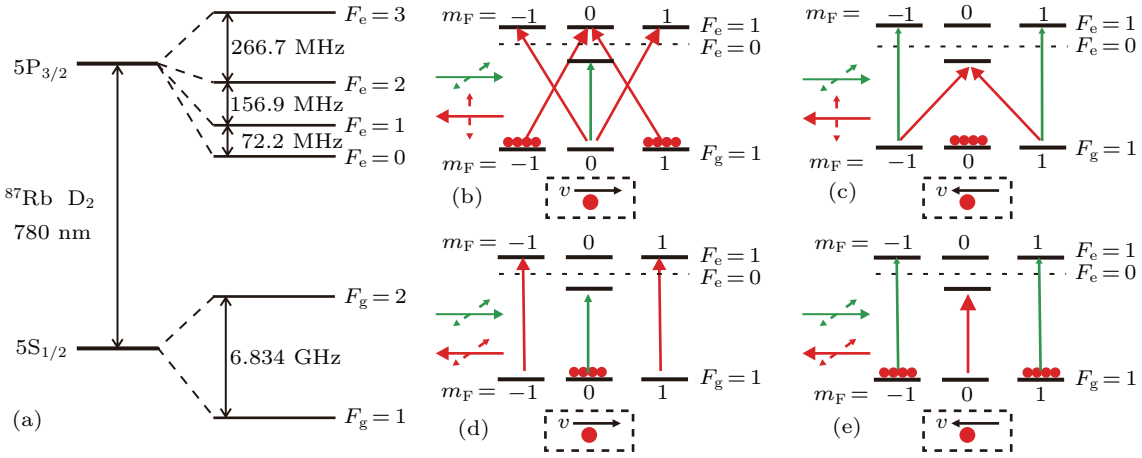


Fig. 5. Atomic transition schematic diagram of the cross peak of $F_g = 1$ to $F_e = 0$ and $F_g = 1$ to $F_e = 1$: (a) hyperfine energy level diagram of the D_2 line of ^{87}Rb atoms; (b), (c) orthometric polarization; (d), (e) parallel polarization. Red arrow: pump beam; green arrow: probe beam; red globules: Rb atoms; π, σ^+, σ^-: linear polarization, left-handed, and right-handed.

In the following, we use the Jones matrix[29] to analyze the experimental results. The combination of atoms and pump beam can be viewed as a polarization analyzer (linear in this work). The orthogonal component of the pump beam (compared to the probe beam) is the determinant reason for the transmission of the probe beam. The discussion of the Jones matrix can provide an available analysis, as it is widely applied to polarization optics. Changing the linearly polarized orientation of the pump beam in Fig. 4 is realized by an HWP, which means that the orthogonal component of the pump beam can be intuitively obtained based on the Jones matrix. The Jones matrix of an HWP can be described as

$$J_{\mathrm{HWP}} = \begin{bmatrix} \cos 2\theta & \sin 2\theta \\ \sin 2\theta & -\cos 2\theta \end{bmatrix}, \tag{1}$$

where θ is the angle between the fast axis of a wave plate and the horizontal axis. Meanwhile, the Jones matrix of the vector beam can be expressed as

$$J(\varphi) = \begin{bmatrix} \cos(p\varphi + \alpha_0) \\ \sin(p\varphi + \alpha_0) \end{bmatrix}, \tag{2}$$

where p is the order of the vector beam, φ is the azimuth, and α_0 is the initially polarized direction. When $p \neq 0$, equation (2) is a vector beam with varying polarization because of φ. For example, when $p = 1$, $\alpha_0 = 0$, the corresponding laser is a radially polarized beam, while $p = 1$, $\alpha_0 = \pi/2$ stands for an azimuthally polarized beam. In addition, when $p = 0$, equation (2) represents a linearly polarized beam. Therefore, in our work, the initial Jones matrix of the pump beam is

$$J_{\mathrm{H}} = \begin{bmatrix} \cos\alpha_0 \\ \sin\alpha_0 \end{bmatrix} = \begin{bmatrix} 1 \\ 0 \end{bmatrix}, \tag{3}$$

where $\alpha_0 = 0$ because the initially polarized orientation of the pump beam is the horizontal direction. Finally, we obtain the transformed polarized state of a horizontally linear polarized beam passing through the HWP, which is described by the Jones matrix as

$$J_{\mathrm{pump}} = \begin{bmatrix} \cos 2\theta & \sin 2\theta \\ \sin 2\theta & -\cos 2\theta \end{bmatrix} \begin{bmatrix} 1 \\ 0 \end{bmatrix} = \begin{bmatrix} \cos 2\theta \\ \sin 2\theta \end{bmatrix}. \tag{4}$$

The probe beam is also a horizontally linear polarized beam, so its Jones matrix is the same as equation (3). In equation (4), the matrix element $\cos 2\theta$ is the horizontally polarized component of the pump beam and the element $\sin 2\theta$ represents the vertically linear polarized component which is orthogonal to the polarized orientation of the probe beam. So the second term decides the transmitted intensity of the probe beam. Thus, the intensity of the transmitted probe beam can be expressed as

$$I \propto \sin^2(2\theta). \tag{5}$$

With equation (5), the theoretical prediction is perfectly anastomotic with the experimental results as shown in Fig. 4.

4. Conclusion

In summary, the transmission of vector beams passing though dichroic media is experimentally demonstrated in an atomic vapor with a pump–probe configuration. When the pump beam is a linearly polarized beam and the probe beam is a radially (azimuthally) polarized vector beam, we can obtain a two-petal pattern which rotates with the variation of the pump beam's polarized states. When the pump and probe beams are both vector beams, we can also observe the probe beam's intensity variation. These results can be interpreted by the Jones matrix and optical pumping effect. Based on these results, we can conclude that the transmission property of the vector beam is controlled by the dichroism of the atomic vapor. In this work, we only utilize the vector beams with varied linear polarization and low order to interact with atoms. When considering a high-order vector beam and a hybridly polarized beam, the spatial intensity distribution of the probe beam can be more flexible and controllable; we are conducting further research into this. The present work can contribute to optical fields such as vector beam manipulation in atomic ensembles.

References

[1] Christian M, Alexander J, Swverin F, Stefan B and Monika R M 2007 *New J. Phys.* **9** 78
[2] Zhan Q 2009 *Adv. Opt. Photonics* **1** 1
[3] Milione G, Evans S, Nolan D A and Alfano R R 2012 *Phys. Rev. Lett.* **108** 190401
[4] Han Y J, Liao G Q, Chen L M, Li Y T, Wang W M and Zhang J 2015 *Chin. Phys. B* **24** 115203
[5] Huan C, Ling X H, Chen Z H, Li Q G, Lv H, Yu H Q and Yi X N 2016 *Chin. Phys. B* **7** 074201
[6] Epstein M S, Bayer S, Bradshaw J, Voigtman E and Winefordner J D 1980 *Spectrochimica Acta Part B Atomic Spectroscopy* **35** 233
[7] Segura A, Artus L, Cusco R, Taniguchi T, Cassabois G and Gil B 2018 *Phys. Rev. Mater.* **2** 024001
[8] Lee Y S, Onoda S, Arima T, Tokunaga Y, He J P, Kaneko Y, Nagaosa N and Tokura Y 2006 *Phys. Rev. Lett.* **97** 077203
[9] Huang X W, Deng Z X, Shi X H, Bai Y F and Fu X Q 2018 *Opt. Express* **26** 4786
[10] Vershinin O I, Konyashkin A V and Ryabushkin O A 2018 *Opt. Lett.* **43** 58
[11] Mujumdar S and Ramachandran H 2004 *Opt. Communications* **241** 1
[12] Townsend M G 1970 *J. Phys. Chem. Solids* **31** 2481
[13] Tyrk M A, Gillespie W A, Seifert G and Abdolvand A 2013 *Opt. Express* **21** 21823
[14] Harris M L, Adams C S, Cornish S L, Mcleod I C, Tarleton E and Hughes I G 2006 *Phys. Rev. A* **73** 062509
[15] Huy D D, Geol M and Heung-Ryoul N 2008 *Phys. Rev. A* **77** 032513
[16] Fleischhauer M and Marangos J P 2005 *Rev. Mod. Phys.* **77** 633
[17] Cao M T, Zhang L Y, Yu Y, Ye F J, Wei D, Guo W G, Zhang S G, Gao H and Li F L 2014 *Opt. Lett.* **39** 2723
[18] Yu Y, Wang C Y, Liu J, Wang J W, Cao M T, Wei D, Gao H and Li F L 2016 *Opt. Express.* **24** 18290
[19] Cao M T, Yu Y, Zhang L Y, Ye F J, Wang Y L, Wei D, Zhang P, Guo W G, Zhang S G, Gao H and Li F L 2014 *Opt. Express.* **22** 20177
[20] Gozzini S, Fioretti A, Lucchesini A, Marmugi L, Marinelli C, Tsvetkov S, Gateva S and Cartaleva S 2017 *Opt. Lett.* **42** 2930
[21] Wang X L, Chen J, Li Y N, Ding J P, Guo C S and Wang H T 2010 *Phys. Rev. Lett.* **105** 253602
[22] Xi S X, Wang X L, Huang S, Chang S J and Lin L 2015 *Acta Phys. Sin.* **64** 124202 (in Chinese)
[23] Wang J M, He C J, Liu Y W, Yang F, Tian W and Wu T 2016 *Acta Phys. Sin.* **65** 044202 (in Chinese)
[24] Li Y, Zhu Z Q, Wang X L, Gong L P, Feng S T and Nie S P 2015 *Acta Phys. Sin.* **64** 024204 (in Chinese)
[25] Zhou Q Q, Shi J Z, Ji X M and Yin J P 2015 *Acta Phys. Sin.* **64** 053702 (in Chinese)
[26] Shigematsu K, Suzuki M, Yamane K, Morita R and Toda Y 2016 *Appl. Phys Express* **9** 122401
[27] Fatemi F K 2011 *Opt. Express* **19** 25143
[28] Liron S, Anat S, Eliran T and Uriel L 2016 *Opt. Express* **24** 4834
[29] Marrucci L, Manzo C and Paparo D 2006 *Phys. Rev. Lett.* **96** 163905
[30] Wang J W, Yang X, Li Y K, Chen Y, Cao M T, Wei D, Gao H and Li F L 2018 *Photonics Research* **6** 451
[31] Lee H S, Park S E, Park J D and Cho H 1994 *J. Opt. Soc. Am. B* **11** 558
[32] Budker D, Kimball D F, Rochester S M and Yachchuk V V 2000 *Phys. Rev. Lett.* **85** 2088
[33] Sullivan J P, Gilbert S J, Marler J P, Greaves R G, Buckman S J and Surko C M 2002 *Phys. Rev. A* **66** 042708
[34] Nakayama S 1997 *Phys. Scr.* **20** 64
[35] Geol M and Noh H R 2008 *J. Opt. Soc. Am. B* **25** 000701
[36] Banerjee A and Natarajan V 2003 *J. Opt. Soc. Am. B* **28** 001912