Optically polarized selection in atomic vapor and its application in mapping the polarization distribution

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Abstract

Based on the dichroism induced by the optical pumping effect, a novel and effective configuration to select an arbitrary polarization distribution is proposed. The influence of the distribution of atoms in different Zeeman sub-levels is the main cause to realize the measurement or ‘filtration’ of the state of polarization. A detailed process of the optical pumping effect in our configurations is presented in the theoretical analysis. In the experiment, the flexible function of the atomic medium, such as a polarizer or a polarized filter can efficiently be realized by different polarizations of the pump beam. Four different kinds of vector beams are tested and the ability to analyze any kind of beam with arbitrary polarization distribution is proven in agreement with the prediction. This work has potential applications in atomic physics and polarization optics. Furthermore, it can provide a reference to atom-optical elements and atom-optical devices.

1. Introduction

An important feature of the light is the state of polarization (SOP), as it plays a vital role both in classical and quantum physics [1, 2] and the measurement of SOP is extremely important. Classical polarization analysis is based on the combination of a quarter-wave plate and a linear polarizer and by recording and combining definite intensities of light, the polarization state can be characterized in terms of the four Stokes polarization parameters [3, 4]. Beyond that, to exactly measure the polarization states of light, different methods or devices are developed, such as interferometric methods [5–7], diffractive methods (the polarization grating) [8, 9], imaging methods [10] and lots of helpful polarimeters [11–16]. These methods basically depend on the fabrication process of plasmonic metamaterials or the optical device. When the laser interacts with this medium, various responses of different polarization states can be obtained from the intensity profile or the spectrum in order to detect the polarization. Besides, the combination of birefringent elements [17, 18], a multi-core fiber [19] or a few vortex phase elements [20] can also realize the detection of polarization states.

Recently, the generation, study and application of vector beams (VBs) has become quite appealing due to their favorable symmetry and their spatially variant polarization [21–23]. Generally speaking, the analysis of the polarization distribution of VBs is indispensable for its current applications, for example, for quantum information or optical manipulation. Furthermore, the analysis of VBs is also crucial in order to comprehend or manipulate this kind of beam. Aiming for the measurement of the polarization state of VBs, a series of work has emerged: a novel interferometric method for spatially resolved analysis of VBs [7], a method for simultaneously measuring polarization and the phase of arbitrarily polarized beams by digital holography [24], using vortex phase elements to detect the focused incident beam polarization state [20] and a novel configuration that can perform space-variant polarization measurements in real time [25].

However, there are still issues that need to be resolved. On the one hand, most polarization analyzers need special design or processing of materials, which is hard and expensive. On the other hand, a complicated light
path is difficult to satisfy the efficiency and stability of the system. Hence, a more convenient and effective measuring method is desired. Here a novel method is presented for the measurement of the polarization states of a light wave with arbitrary polarization based on atoms in a counter-propagated pump-probe configuration. By changing the different polarization of the pump beam, the interaction can efficiently realize the specified function of the atomic medium. Utilizing the dichroism induced by the optical pumping effect, the atomic medium can act as a polarizer and a polarization filter, including linear or circular polarization.

In this paper, we first study and describe the principle of dichroism induced by the optical pumping effect. From the theoretical prediction, this dichroism can clearly exhibit the ability of polarization selection based on the atomic medium. The experimental results show that the absorption and transmission of the probe beam can be altered by the pump beam, not only in its intensity but also its polarization distribution. Compared with other systems, this configuration is not complicated and the stability requirement is not so strict. The radially polarized probe beam is measured with this configuration and further verification measurements are carried out to test the polarization filter ability of the atomic system by analyzing the transmitted part of the probe beam. By testing four different kinds of VBs respectively, the ability to analyze any kind of beam with arbitrary polarization distribution is realized. Finally, maps of polarization states are reconstructed with measured parameters based on atoms, which are in agreement with the prediction.

2. Theoretical analysis

First it is necessary to qualitatively explain the principle of dichroism induced by the optical pumping effect. All polarized beams in this work are defined along the direction of beam propagation, so one can clearly define the handedness of circular polarization. The signs $\pi$, $\sigma^+$, $\sigma^-$ and $\sigma^0$ indicate a linear polarization parallel to the quantization axis ($\pi$), a linear polarization perpendicular to the quantization axis ($\sigma^+$), a left circular polarization ($\sigma^-$) and a right circular polarization ($\sigma^0$), respectively. Here the same monochromatic light is used to form probe and pump beams. The energy level in one crossover transition ($F_g = 1$ to $F_e = 0$ and $F_g = 1$ to $F_e = 1, D_2$ line) of $^{87}$Rb is employed, which typically exhibits the ability of dichroism [26–28]. The moving atoms experience different frequency detuning from the counter-propagating probe and pump beams due to the Doppler effect, one have to analyze the interaction of light and atoms from two opposite orientations. Various polarization combinations of probe and pump beams can lead to different dichroism, whereas the main factor will depend on the quantization axis which relies on the polarization of the pump beam.

2.1. Principle of linear dichroism based on atoms

In order to deal with the linear dichroism in atoms [29], it is appropriate to choose the quantization axis as the same as the direction of polarization of the pump beam and here the pump beam with the linear polarization ($\pi$) is employed. In this situation, two types of configuration are basically considered as shown in figures 1(a) and (b), respectively.

Figure 1(a) is the case when probe and pump beams have the same linear polarization. According to the transition selection rules of atoms, the pump beam excites the transition with the $\Delta m_F = 0$ and pumps atoms to the other Zeeman sub-levels ($m_F = \pm 1$) as shown in figure 1(a1), which can result in enhanced absorption of the probe beam. One can obtain the same results when the movement of atoms is in opposite direction, which is illustrated in figure 1(a2). However, when the linear polarization of the probe beam is perpendicular to the pump beam, it excites the transitions with $\Delta m_F = \pm 1$ [30, 31]. The sub-level with empty population leads to less absorption of the weak probe beam as shown in figure 1(b). That is to say, the combination of a vapor of atoms and a linearly-polarized pump beam can be viewed as a linear polarization analyzer. The linearly polarized orientation of probe and pump beams are the key factors to determine the function of this analyzer. The absorption (transmission) occurs when the linearly polarized orientation of probe and pump beams are parallel (orthogonal) to each other.

2.2. Principle of circular dichroism based on atoms

Circular dichroism in atoms can be realized by using an intense pump beam in the circularly polarization state to polarize the atoms [29]. This will result in differences in the absorption coefficient between a right and left circularly polarized probe beams. The quantization axis in this condition is still defined as the polarization axis of the pump beam and the pump beam is chosen as $\sigma^+$ or $\sigma^-$. In this situation, any SOP of probe beam can be viewed as a superposition of two basically circular polarization with different amplitude and phase [31]. This is investigated by changing the SOP of the probe beam between linear and circular polarization. The maximum (minimum) absorption will appear for two beams with the same (different) circular polarization [32]. In this part, we just figure out the interaction of atoms with a circularly-polarized pump and a linearly-polarized probe beam, as shown in figure 2.
In figure 2(a1), the strong pump beam with $\sigma^-$ optically pumps atoms to the $m_F = -1$ energy level, so other ground energy levels are empty. When a weak probe beam with $\sigma^+$ interacts with the atoms, it can lead to intense absorption of the $\sigma^-$ part and transmission of the $\sigma^+$ part of the probe beam, since polarized atoms actually ‘see’ an opposite circular polarization from the probe. The situation in figure 2(a2) is quite the same as the condition in figure 2(a1), and the only difference is that the transmission is slightly lower. Figure 2(b) is the opposite condition when the pump beam is $\sigma^+$. Such a combination of atoms and a circularly-polarized pump beam can be viewed as a circular polarization filter. One can alter the function of the filter by changing the SOP of the pump beam.

3. Experimental setup and results

According to the above analysis, next step is to verify its correctness in the experiment. The VBs can be generated by use of many methods, like interferometric superposition method [33–35] and polarization transformation elements [36, 37]. In our experiment, the Q-plate ($m = 1$) is used to generate VBs. An external cavity diode laser (Toptica DL pro) with its wavelength 780 nm is used to form the pump and probe beams and a single-mode fiber.
is applied to improve the spatial mode (not shown in figure). Figure 3(a) shows the primary experimental setup for realizing the dichroism induced by optical pumping effect. The pump beam passes through PBS1 to ensure that a linearly polarized beam is prepared. Subsequently, a combination of HWP1 and QWP1 converts the linearly polarized beams into any single-polarized beams one desired. It should note that when the pump beam is reflected by the BS, its (linear) horizontal and vertical states of polarization are not changed, while other single-polarized states can be inverted to their orthogonal states by the reflection [1]. For the probe beam, the combination of HWP2, Q-plate and QWP2 can generate the VBs to be tested. Furthermore, the probe beam passes through a BS and is detected by a charge-coupled device camera. The intensities of pump and probe beams are fixed at 2 mW and 40 μW approximately by using neutral density filters (not shown in figure), respectively. All the sizes of pump beams used in the experiment are larger than the corresponding probe beams, since it makes the distribution of atoms more uniform. The Rb cell has a length of 50 mm and is filled with enriched ⁸⁷Rb gas. A three-layer-metal magnetic shield is used to isolate the cell from ambient magnetic fields. The cell is heated to 60 °C by a temperature controller. In the experiment, the laser is locked to one crossover signal \( F_g = 1 \) to \( F_e = 0 \) and \( F_g = 1 \) to \( F_e = 1, D_2 \) line) of \(^{87}\text{Rb}\).

Utilizing this setup, first the radially polarized probe beam is measured and further verification measurements are carried out to test the polarization filter ability of the atomic system by analyzing the transmitted part of the probe beam. The corresponding measurement results are displayed in figure 4. Figures 4(a)–(a6) are the corresponding intensity distribution of the probe beams and their polarization distribution. For a linearly polarized pump beam, the experimental results show a two-label pattern, which is similar to VBs passing through a linear analyzer. The atomic medium shows strong absorption characteristics for the probe beam when the polarization of the pump and probe beams is parallel to each other. In contrast, transmission occurs if the pump and probe beams have orthogonal polarization. This phenomenon is the linear dichroism induced by the optical pumping effect. As for a circularly polarized pump beam, the profile of the probe beam still holds a donut shape. Since the radially polarized beam contains only linear polarization with varied orientation, the influence of the pump beam is homogenous and symmetrical. The polarization distribution of each result by traditional Stokes parameter measurement is also checked. The SOP of the transmitted probe beam keeps well its orthogonality with the SOP of the pump beam, which is in agreement with the prediction as discussed in section 2. Utilizing this configuration, one can realize polarization projection or filter an unwanted polarization of the probe beam, based on the atom vapor.

For the purpose of verification, other three kinds of VBs are chosen to test the accuracy of the Stokes parameter measurement based on atoms. The higher-order VBs are generated by cascading two Q-plates and a HWP [38], while a QWP is applied to generate the hybridly VBs. In our configuration, the Stokes parameters can be rewritten as:

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**Figure 3.** (a) The experimental setup. QWP: quarter-wave plate; HWP: half-wave plate; M: mirror; PBS: polarization beam splitter; BS: beam splitter; CCD: charge-coupled device camera. (b) Four kinds polarized distributions of VBs for probe beams. (Green: Left circular polarization; Blue: Right circular polarization; Black lines: linear polarization) (c) Six states of polarization for pump beams.
where $I_{\text{SOP}_{\text{pump}}}$ stands for the intensity of probe beam when the pump beam is chosen corresponding state of polarization.

The normalized Stokes parameters of each beam are shown in the figure 5. In comparison with the theoretical distribution, the experimental results show that the feasibility of this configuration. The map of the polarization states is reconstructed by measured parameters based on atoms, as shown in figure 6, which are in agreement with the definition. It proves that an atomic medium can be an efficient candidate for mapping the polarization of light. In addition to the beam in figure 6, this atom-based configuration can also be used to other spatial mode or polarization distribution of light.

**Figure 4.** Experimental results of radially polarized VB and the corresponding polarization distribution. The arrow in the top left corner of each figure represents the SOP of pump beam. (Green: Left circular polarization; Blue: Right circular polarization; Black lines: linear polarization) (a1) Horizontal linear polarization for the pump beam ($H_{\text{pump}}$). (a2) Vertical linear polarization for the pump beam ($V_{\text{pump}}$). (a3) Diagonal linear polarization for the pump beam ($D_{\text{pump}}$). (a4) Anti-Diagonal linear polarization for the pump beam ($AD_{\text{pump}}$). (a5) Left circular polarization for the pump beam ($L_{\text{pump}}$). (a6) Right circular polarization for the pump beam ($R_{\text{pump}}$).

**Figure 5.** Theoretical definition (The first and third lines) and experimental results (The second and fourth lines) of Stokes parameters. (a) Radially polarized VB. (b) Second-order VB. (c) Hybridly polarized VB. (d) Hybirdly second-order VB.

\begin{align}
S_0 &= I(V_{\text{pump}}) + I(H_{\text{pump}}), \\
S_1 &= I(V_{\text{pump}}) - I(H_{\text{pump}}), \\
S_2 &= I(AD_{\text{pump}}) - I(D_{\text{pump}}), \\
S_3 &= I(L_{\text{pump}}) - I(R_{\text{pump}}),
\end{align}
Since the dichroism is induced by the optical pumping effect when utilizing a specifically polarized pump beam, one can realize the manipulation and filtration of a probe beam of arbitrary polarization. This is a novel application for the measurement of polarization based on an atomic medium. In fact, using light to manipulate the atomic medium is convenient and effective. The miniaturization and integration of this configuration will be feasible in the future.

4. Conclusion

Aiming to analyze the polarization distribution of arbitrary VBs, a novel configuration is proposed based on dichroism induced by the optical pumping effect in an atomic medium. By utilizing the influence of the distribution of atoms in different Zeeman sub-levels, we show that polarization selective absorption in a VB can be realized. The configuration of the experiment is convenient and effective. By changing the polarization of the pump beam, one can realize a flexible function of the atomic medium, such as a polarizer or a polarized filter. By testing four different kinds of VBs respectively, the ability to analyze any kinds of beams with arbitrary polarization distribution is proven. Finally, the maps of polarization states reconstructed by measured parameters based on the atomic medium are in agreement with the prediction.

Light interacting with atomic ensembles is a high-profile topic. Alkali metal atoms have been widely used in a lot of fields such as quantum optics and quantum communication due to their excellent coherence [39–43]. It can also provide a fast and controllable platform for light manipulation based on anisotropy or nonlinear effect of atoms [44–47]. This work has potential applications in atomic physics and polarization optics, furthermore, it can provide a reference to atom-optical elements and atom-optical devices.

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