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Stokes identification in an atomic ensemble using a filtering system*

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Polarization filtering and atomic cell filtering are applied in the identification of Stokes signals in an atomic ensemble, and reduce the noise to a level of 10^{-5} and 10^{-4} respectively. Good Stokes signals are then obtained. In this article the two filtering systems and the final Stokes output are presented, and the optimization of the polarization filtering system is highlighted.

Keywords: quantum communication, Stokes, filtering
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1. Introduction

Quantum communication holds promise for long-distance secure message transmission using quantum entanglement and attracts lots of groups to engage in research into related fields.[1−28] But due to the losses and decoherence of photons in the communication channel, the fidelity decreases exponentially with channel length, which makes direct communication between remote locations almost impossible. In recent years, the Duan–Lukin–Cirac–Zoller (DLCZ) protocol,[1] a possible solution for the problem of long distance quantum communication, has received much attention. This scheme combines entanglement generation, connection, and built-in purification through the coherent manipulation between the quantum states of atomic ensembles and photons using spontaneous-Raman-type processes. Among several schemes of quantum memory, the DLCZ scheme is regarded as hopeful and studied experimentally in both cold[1,3−14,16−18] and hot[2,5] atomic ensembles. This includes the coherent manipulation of atomic states through the Raman process in an atomic ensemble;[1,2,9,12,13−15] entanglement of the atomic states[7,10,11,16] and realization of the building block of the quantum repeater.[17,18]

In the DLCZ[27] protocol, a quantum bit is stored in the collective state of the atomic ensemble, and operation of the collective state is realized by operating the highly correlated Stokes signal. According to Ref.[15], the rate of excitation of the collective state is only 10^{-9}, which means that, to generate one Stokes photon, we need 10^9 incident photons, which form the huge background.

Thus, excellent Stokes identification is required, which is the bottleneck of DLCZ protocol implementation.

In this paper, polarization and atomic cell filtering systems are both presented, by which we successfully extract the Stokes signal out of the background. The details in optimization of the polarization filtering and the temperature effect in the atomic cell filtering are also described.

2. Setup of the atomic ensemble

The experimental setup is shown in Fig.1. In a duty cycle, we turn on the pump laser firstly to pump the atoms from the exciting state to the base state, and then close the pump, and then we open the write laser to generate the collective state. As the magnetic field of the earth can affect the atom's energy level, we put the Rb sample into a magnetic shielding set (not labelled in Fig.1).

The signals generated from the setup in Fig.1

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were passed through a Fabry–Perot (F–P) (Finesse 200, 7.5 GHz FSR, transmission 10%) and the output of this F–P was collected by a multimode fibre and fed to the single photon detector. This allows us to analyse the intensity of different frequency components and single out the Stokes and anti-Stokes signals after the polarization filter and frequency filter by optically pumped atomic cells and narrow band (band pass=1 nm) filters. The laser used as the write beam has a maximum power of 80 mW. The lasers are locked at the respective fine structures of the ^{87}Rb absorption peaks, and frequency detuning and pulse generation are achieved by feeding the lasers through a series of acousto-optic modulators (AOMs).

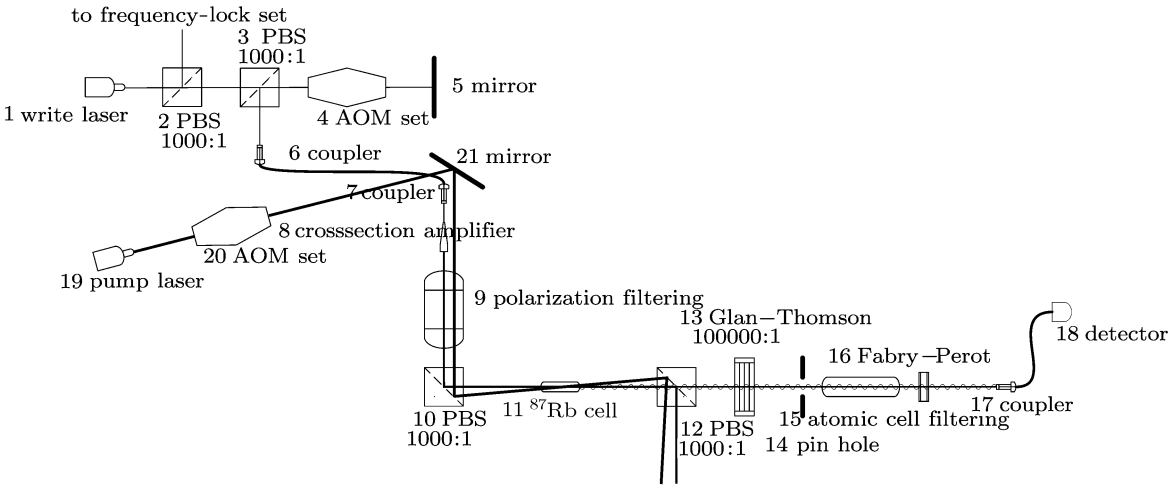


Fig.1. Scheme of experiment for generation of atomic collective states.

3. The polarization system

As shown in Fig.2, the polarization filtering system consists of a fibre coupler, a Glan–Thompson lens, a $\lambda/4$ wave plate, two $\lambda/2$ wave plates, two polarizing beam splitters (PBS) and a single-photon detector. The Glan–Thompson lenses are used to polarize the write light to a high level and the PBS is used to prevent the write light from propagating in the direction toward the detector. This filtering system marks the signal and write lasers with polarization perpendicular to each other and is used in the identification. The extinction ratio R_e is defined as $R_e = P_t/P_r$. Here P_t is the power of the transmitted light with polarization in the parallel direction and P_r is the reflected light with polarization in the perpendicular direction. For the Glan–Thompson lens and the PBS the extinction ratios are 10^5:1 and 10^3:1, respectively.

Several steps are taken to reduce the ratio between write leakage power I_0 and write light power I_i. Firstly, a $\lambda/2$ wave plate (A) is adjusted to retrieve the maximum transmission of the write laser for the Glan–Thompson. Then after aligning PBS_1 to the same polarization direction as the Glan–Thompson, a power of 64 mW is achieved as the maximum I_i. Applying the same alignment to PBS_2 as PBS_1, a power of 12 μW is achieved as I_0 and the corresponding R_e is 2×10^{-4}.

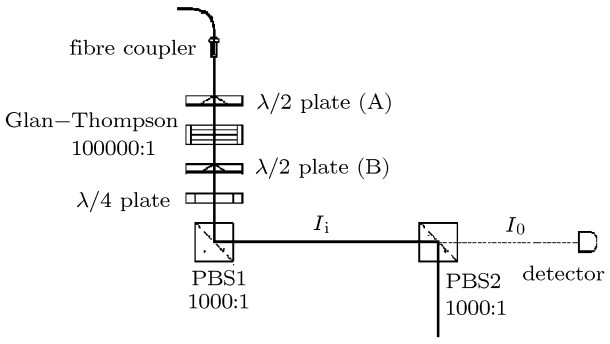


Fig.2. Scheme of polarization filtering.

If s is regarded as perpendicular polarization and p is regarded as parallel polarization the input light

could be written as

$$\begin{pmatrix} A_p \\ A_s \end{pmatrix},$$

in this experiment, $|A_s| \gg |A_p|$. The output I_0 is

$$\begin{pmatrix} A_{p'} \\ A_{s'} \end{pmatrix} = \begin{pmatrix} X & Y \\ \gamma & \omega \end{pmatrix} \begin{pmatrix} A_p \\ A_s \end{pmatrix}, \tag{1}$$

where $\begin{pmatrix} X & Y \\ \gamma & \omega \end{pmatrix}$ is the matrix for the combination of all the possible polarization variations during the light propagation and X, Y, γ, ω are parameters all correlated with phase information. I_0 is expressed as

$$\begin{pmatrix} XA_p + YA_s \\ \gamma A_p + \omega A_s \end{pmatrix}. \tag{2}$$

Considering the extreme ideal case $X \approx Y \approx \gamma \approx \omega = 0$, there will be no output with current input. However due to the error in alignment and imperfectness of the PBS and even the circular birefringence of the Rb vapour etc., the $X \approx Y \approx \gamma \approx \omega = 0$ will differ from 0. Figure 3 is the depiction of PBS_1 in Fig.2. It follows

$$\overrightarrow{\text{Out}} = \hat{L}_2 \hat{R} \hat{L}_1 \overrightarrow{\text{In}}, \tag{3}$$

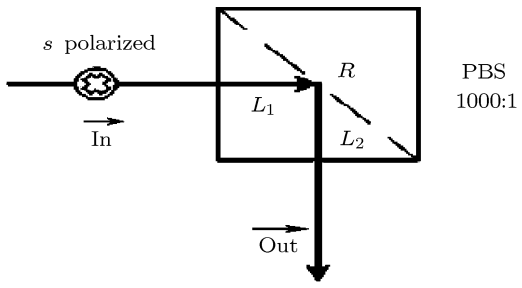


Fig.3. Propagation of polarized light through PBS.

where $\overrightarrow{\text{In}}$ is the Jones vector of input light, $\overrightarrow{\text{Out}}$ is the output and $\hat{L}_2$, $\hat{R}$, $\hat{L}_1$ are the propagation matrix parameters in PBS, which are

$$\hat{L}_1 = R_\theta \begin{pmatrix} \mathrm{e}^{\mathrm{i}\, n_o l_1} & 0 \\ 0 & \mathrm{e}^{\mathrm{i}\, n_e l_1} \end{pmatrix} R_\theta^{-1},$$

$$\hat{L}_2 = R_{\theta''} \begin{pmatrix} \mathrm{e}^{\mathrm{i}\, n_o l_2} & 0 \\ 0 & \mathrm{e}^{\mathrm{i}\, n_e l_2} \end{pmatrix} R_{\theta''}^{-1},$$

$$\hat{R} = R_{\theta'} \begin{pmatrix} r_{p'} & 0 \\ 0 & r_{s'} \end{pmatrix} R_{\theta'}^{-1}, \tag{4}$$

where R_θ is the angle transform matrix between the input s–p coordinate and the o–e coordinate defined by the PBS; θ' is the angle between the o–e coordinate with the s'–p' coordinate defined by the reflection plane; θ'' is the angle between the s–p coordinate and the o–e coordinate defined by the PBS. For reflection $\theta'' = \theta'$, and the detail of angle transform is

$$R_\theta = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix},$$

if θ, θ' are not 0, the output would be an elliptical light. But the difference of θ, θ', θ'' from 0 still can be neglected. In Eq.(2), not all X, Y, γ, ω are required to be 0 to get the best polarization filtering. Since PBS_2 is used to reflect the s polarized light from the PBS_1, then the p component of the output would be made to a minimum $XA_p + YA_s \approx 0$. The imperfectness of PBS is quite small, thus θ, θ' and θ'' are close to 0. It follows that Y must be a very small number. With the consideration that $A_p \ll A_s$, $XA_p + YA_s$ could be adjusted very small with correct alignment, and this alignment may not need to be perfect. As long as XA_p and YA_s are small numbers, they can be adjusted to cancel each other. The principle of such cancellation could be understood by a detailed analysis of a quarter wave plate and a half wave plate. The function of a $\lambda/2$ wave plate is

$$\begin{pmatrix} A_{p'} \\ A_{s'} \end{pmatrix} = R_\theta \begin{pmatrix} 1 & 0 \\ 0 & -\mathrm{i} \end{pmatrix} R_\theta^{-1} \begin{pmatrix} A_p \\ A_s \end{pmatrix}. \tag{5}$$

If every $\theta = 0$, then $\hat{L}_2 \hat{R} \hat{L}_1 = \begin{pmatrix} A & 0 \\ 0 & B \end{pmatrix}$, where both A, B are complex numbers, and the output would be

$$\begin{pmatrix} A & 0 \\ 0 & B \end{pmatrix} \begin{pmatrix} A_p^{\text{in}} \\ A_s^{\text{in}} \end{pmatrix} = \begin{pmatrix} AA_p^{\text{in}} \\ BA_s^{\text{in}} \end{pmatrix}. \tag{6}$$

The PBS decides $A_s^{\text{in}} \gg A_p^{\text{in}}$, and $r_s \gg r_p$, thus $|A| \ll |B|$ and the output is a perfect s polarized light as input. Here θ is the angle between the fast axis of the $\lambda/4$ wave plate and the s direction. With this matrix we find

$$\begin{pmatrix} A_{p'} \\ A_{s'} \end{pmatrix} = \begin{pmatrix} f_p(\theta) \\ f_s(\theta) \mathrm{e}^{\mathrm{i}\,\delta(\theta)} \end{pmatrix}. \tag{7}$$

In the s–p coordinate system, the input to the PBS system $\begin{pmatrix} A_{p'} \\ A_{s'} \end{pmatrix}$ becomes an elliptical light. The phase

and the p, s components are related and cannot be adjusted freely. Once θ is fixed in the experiment, $f_p(\theta)$, $f_s(\theta)$ and the relative phase $\delta(\theta)$ will all be fixed. The p, s components' amplitude can be adjusted further by a $\lambda/2$ wave plate without affecting $\delta(\theta)$. The effect of adjustment of the half wave plate is

$$\begin{pmatrix} A_{p'} \\ A_{s'} \end{pmatrix} = R_{\theta'} \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} R_{\theta'}^{-1} \begin{pmatrix} A_p \\ A_s \end{pmatrix}, \quad (8)$$

where θ' is the angle between the fast axis of the half wave plate and the s direction.

Put Eq.(8) into the $XA_p + YA_s$ but replace A_p and A_s with the output from the half wave plate and quarter wave plate. We have basically

$$XA_p + YA_s = X|f_p(\theta, \theta')| + Y|f_s(\theta, \theta')|\mathrm{e}^{\mathrm{i}\,\delta(\theta)}. \quad (9)$$

Based on this result, we can firstly adjust the θ of the $\lambda/4$ wave plate to make $Y\mathrm{e}^{\mathrm{i}\,\delta(\theta)} \approx -X$ then we adjust θ' to change the f_p and f_s to make the cancellation complete.

With the above method the polarization filtering is optimized by placing a $\lambda/4$ wave plate and a $\lambda/2$ wave plate between the Glan–Thompson and PBS, when a minimum I_0 is achieved, which is 0.101 μW.

4. Selective absorption by the atomic cell

The principle of atomic filtering is to adjust the gaps between the energy levels of the atoms in the cells to achieve resonance with the frequency of the write laser and signals. As required by our experiment, the frequency of the write laser and signals are both 1 GHz shifted to the absorption line of the natural Rb atom, so they cannot interact with the natural Rb atom. But to extract the signals out of the write laser, we need a Rb cell to absorb the write laser. So we use the magnetic field to blue-shift the absorption line. According to Steck's calculation[28] which is depicted in Fig.2, the ^{87}Rb cell is placed in a magnetic field with magnitude less than 0.1 T and heated to 61.5 °C, and $|5^2S_{1/2}, F = 2\rangle \rightarrow |5^2S_{3/2}, F = 3\rangle$ pumping light is applied to the cell; a magnetic splitting filtering spectrum is achieved. As showed in Fig.5, the upper line is the write laser spectrum before the 1 GHz blue-shift, the lower line is the laser spectrum line after the 1 GHz blue-shift. The vertical line on the left of Fig.5 indicates the write laser frequency and the vertical line on the right indicates the final output Stokes signal. The precise measurement comes to a result of filtering efficiency around $1\times10^4 : 1$ and the transmission efficiency is more than 70%, which satisfies the experimental requirement.

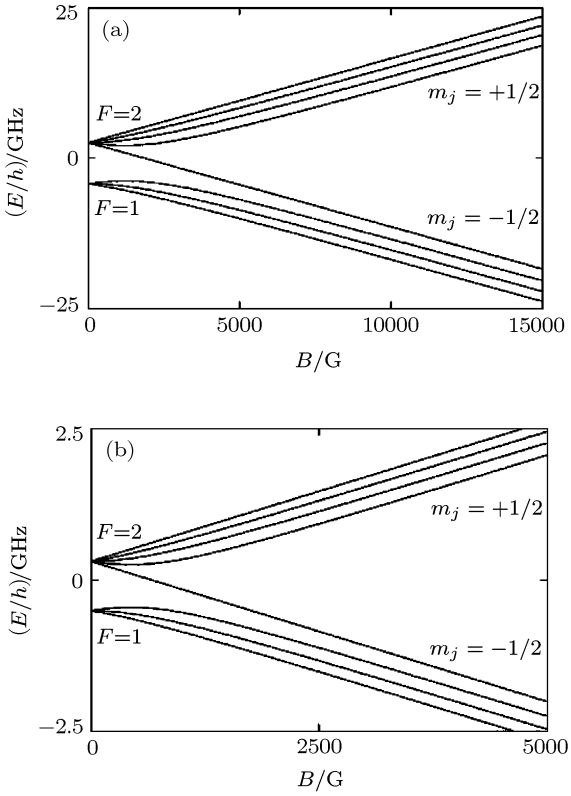


Fig.4. Splitting of the energy levels ^{87}Rb $5^2S_{1/2}$ (a) and ^{87}Rb $5^2P_{1/2}$ (b) in the magnetic field (1 G=10^{-4} T).

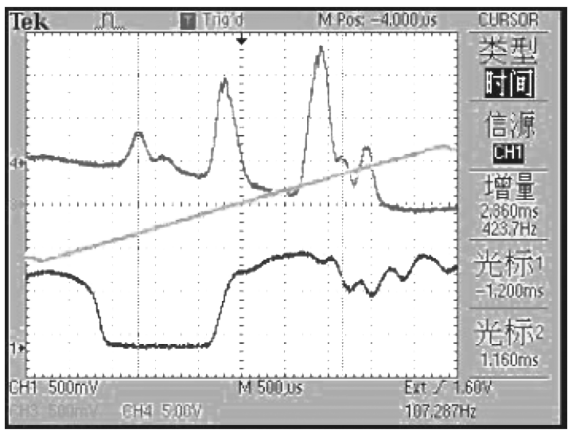


Fig.5. Magnetic splitting filtering spectrum.

5. Results and discussion

After applying the two filtering techniques described above into the experimental setup, good Stokes signal identification is achieved.

For a more detailed understanding of the atomic cell filtering performance, the study is performed at different temperatures and shown in Fig.6. As the temperature drops, the intensity of the write laser increases to a level of the same magnitude of the pumping light, while the Stokes signal varies slightly. This proves that the expected performance of the atomic cell filtering is achieved. The Stokes signals survive and the leakage of the write laser is fully absorbed. The leakage of the pumping light is quite close to the Stokes signal in frequency thus cannot be absorbed by the atomic cell. But it can be discriminated later by making use of the time difference.

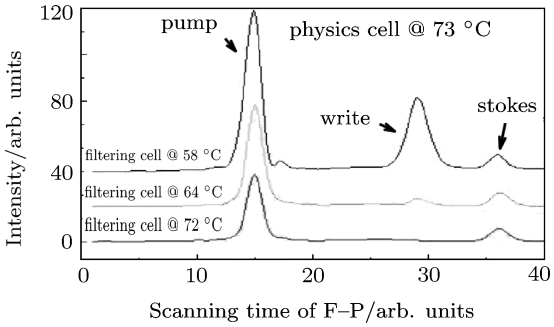


Fig.6. Spectrum of the transmitted signal after the filtering system at different temperatures of the filtering cell.

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