Reduction of interference fringes in absorption imaging of cold atom cloud using eigenface method

Xiaolin Li (李晓林)[1,2], Min Ke (柯 敏)[1,2], Bo Yan (颜 波)[1,2], and Yuzhu Wang (王育竹)[1,2]

[1]*Key Laboratory for Quantum Optics, Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, Shanghai 201800*

[2]*Center for Cold Atomic Physics, Chinese Academy of Sciences, Shanghai 201800*

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Eigenface method used in face recognition is introduced to reduce the pattern of interference fringes appearing in the absorption image of cold rubidium atom cloud trapped by an atom chip. The standard method for processing the absorption image is proposed, and the origin of the interference fringes is analyzed. Compared with the standard processing method which uses only one reference image, we take advantage of fifty reference images and reconstruct a new reference image which is more similar to the absorption image than all of the fifty original reference images. Then obvious reduction of interference fringes can be obtained.

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In the experiments, almost everything about the cold atom cloud or Bose-Einstein condensate (BEC) is obtained by optical probing which mainly consists of absorption imaging and fluorescence imaging[1]. The former is more important because of higher signal-to-noise ratio (SNR) and accuracy. Absorption imaging is done by illuminating an atom cloud with a laser beam which is resonant to some energy levels of the atoms and absorbed by the atom cloud. The bigger optical density the atom cloud has, the more absorption and the darker shadow there appear. Afterwards the shadow is cast onto a charge-coupled device (CCD) camera with a set of imaging lenses. According to the absorption imaging, we can obtain an important parameter, the optical density (OD) of atom cloud, which is a necessary base for the further analysis. OD of an atom cloud at position (y, z) is calculated by[1]

$$\mathrm{OD}(y,z) = \ln \frac{I_{\mathrm{abs}(y,z)} - I_{\mathrm{bg}(y,z)}}{I_{\mathrm{ref}(y,z)} - I_{\mathrm{bg}(y,z)}}, \tag{1}$$

where $I_{\mathrm{abs}(y,z)}$ for the absorption image and $I_{\mathrm{ref}(y,z)}$ for the reference image are the distributions of probing light intensity with and without the atom cloud respectively, and $I_{\mathrm{bg}(y,z)}$ is the background light intensity distribution without the probing beam and the atom cloud (x axis is along the direction of probing beam and the imaging plane y-z in CCD chip is perpendicular to x axis). We used the continuous, 780-nm, single transverse mode, frequency locked laser with $\sim$ 1-MHz linewidth as the probing laser. Because of excellent coherence of the laser beams, interference fringes are easily observed both in $I_{\mathrm{abs}(y,z)}$ and $I_{\mathrm{ref}(y,z)}$. If there is no mechanical vibration of the optical elements and the probing beam shown in Fig. 1, the interference fringes in $I_{\mathrm{abs}(y,z)}$ and $I_{\mathrm{ref}(y,z)}$ will be identical and there will not be interference fringes in $\mathrm{OD}(y, z)$ calculated by Eq. (1). But actually vibration is unavoidable and the interference fringes cannot be reduced completely, for example, both switching on the shutter of the CCD camera and the fans for cooling of the CCD camera may be a source of vibration. As shown in Fig. 1, the probing laser passes through two polarized beam splitters (PBSs), one wave plate, one quartz cell, and one lens, and casts onto the CCD chip. We should pay attention that the quartz cell is not coated by reflection-reducing coating and there is a glass plate for protecting CCD chip which is also uncoated. In addition to those, the other elements are coated by excellent reflection-reducing coating on every optical surface. There are two kinds of possible interference fringes: equal inclination interference and equal thickness interference[2]. The former may be produced by the probing beam which is not exactly 90° incident on the quartz cell and imaged by the lens; the latter may be created by a pair of unparallel surfaces, for example the glass plate in front of the CCD chip. Empirically if the peak optical density is bigger than 1, the SNR of the OD image is good enough for fitting and further analysis (maybe much different in various experimental setups). This is easily to be satisfied in common cold atom experiment or BEC experiment. But in our experiment on atom chip[3], the peak OD is usually much smaller than the former, especially after a long time of flight where the OD has already severely reduced and become close to the order of the interference fringes. Then it is difficult for the OD image to fit. The interference fringes should better be reduced much below the order of the absorption image for the further experiment. In the experiment we

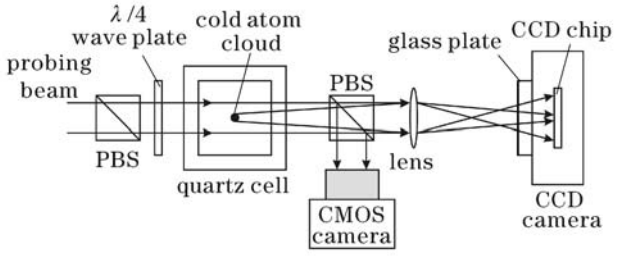

Fig. 1. Probing laser optical setup for absorption imaging.

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find that the patterns of the interference fringes change in position and intensity almost randomly. If we take many reference images and sometimes there will be one of them coinciding with the absorption image much better than the others. If we can find the best reference image or should better reconstruct a new reference image, the interference fringes can be gotten rid of by using Eq. (1) more clearly. We find that this process is similar to the face recognition which is a highly developed field and there are many algorithms that we can borrow ideas from.

In this letter we introduce the eigenface method[4−6] which is widely used in face recognition into the imaging process of absorption imaging of atom cloud. It is well known that face recognition needs to select a correct face photo from thousands of face photos in a huge database. It is a difficult task to compare the unknown face photo with the face database one by one. However, scientists have invented many methods and algorithms to simplify the search process, and one of them is eigenface method. Eigenface method constructs a set of orthogonal vectors from every face photo in the database and the number of the set of vectors is much smaller than the original face database. And every orthogonal vector is called an eigenface. Then every face photo projects on the set of eigenface and the projection is a set of vectors Ω. Also the unknown face photo I_{unknown} projects on the set of eigenface and one projection vector ω is gotten. We compare ω with every vector in Ω and find the most coincidental vector position in Ω and then the face photo is determined. If applying this method into the process of the absorption imaging, we take many original reference images, construct a set of orthogonal reference images, and use them to reconstruct a new reference image which has an optimized phase difference compared with the absorption image $I_{\text{abs}(y,z)}$.

At first we obtain several original reference images I_1, I_2, $\cdots$, I_M and absorption image I_{abs} as shown in Fig. 2(a), and every image is a two-dimensional (2D) $j \times k$ matrix (for example, $j = 400$ and $k = 500$) and the matrix elements furnish the counts of the pixels in the CCD chip. Before the latter step, we should preprocess the absorption image because the absorption image is different from the reference image and there is a shadow of atom cloud in the absorption image. In order to reduce the effect of the shadow on the process, we set the pixels around the shadow to zero in the absorption image I_{abs}. After the preprocessing, we represent every 2D reference image I_i as a vector Γ_i $(jk \times 1)$ by putting every row of I_i into one row one by one. Secondly we calculate the average face vector Ψ where

$$\Psi = \frac{1}{M}\sum_{n=1}^{M}\Gamma_i. \tag{2}$$

Every vector Γ_i is subtracted by average face vector Ψ and we obtain $\Phi_i = \Gamma_i - \Psi$. For the absorption image I_{abs}, also we have Γ_{abs} and Φ_{abs}. Thirdly we calculate the covariance matrix C,

$$C = \sum_{N=1}^{M}\Phi_n\Phi_n^{\mathrm{T}} = AA^{\mathrm{T}},$$

$$A = [\Phi_1, \Phi_2, \cdots, \Phi_M], \tag{3}$$

where the eigenvector of C is just so called eigenface U_i. But the dimension of C $(jk \times M)$ is so huge that it is difficult to calculate its eigenvector. It can be proved that the eigenvectors of AA^{T} and $A^{\mathrm{T}}A$ have the relation $U_i = AV_i$ where V_i are the eigenvectors of $A^{\mathrm{T}}A$ which has a smaller dimension $(M \times M)$ and can be calculated easily[7]. We should pay attention that the eigenvector number of AA^{T} and $A^{\mathrm{T}}A$ is different and so we merely obtain the subset of the eigenvectors of AA^{T}. But it can be proved that the eigenvectors of AA^{T} calculated from the eigenvectors of $A^{\mathrm{T}}A$ correspond those biggest eigenvalues among all of eigenvalues of the AA^{T}[7], which are enough for the image processing although we only obtain the subset of the eigenvectors of AA^{T}. The eigenface U_i $(i = 1 - M)$ is the most important aspect in the method, the corresponding eigenvalue furnish the information weight of every eigenface U_i. The bigger eigenvalue means that the corresponding eigenface contains more information. For example we have taken fifty reference images and calculated the eigenface U_i and the corresponding eigenvalue. As shown in Fig. 3, U_2 and U_3 have bigger eigenvalues and more patterns of the fringes

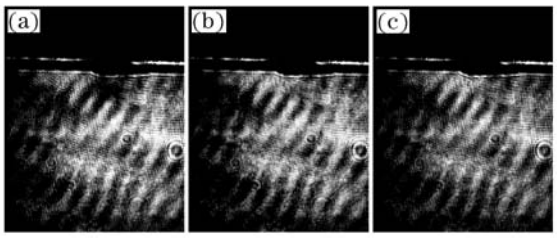

Fig. 2. (a) An absorption image I_{abs}, (b) the calculated new reference image I_{newref}, (c) a selected reference image taken by the CCD camera directly. Every image is 400×500 pixels in size, (a) and (c) are taken by an Andor DV434BV CCD camera.

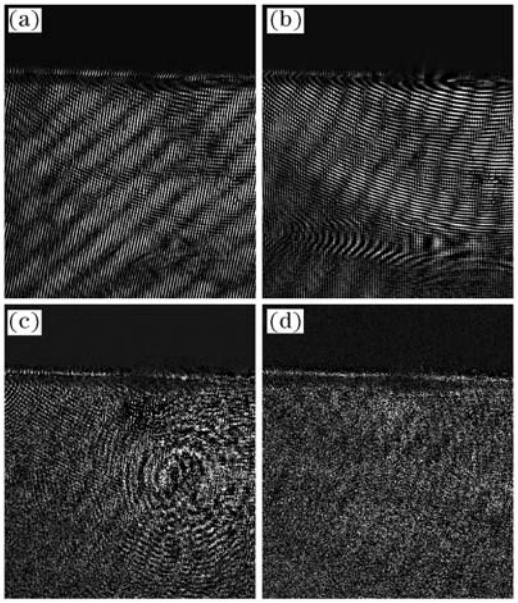

Fig. 3. Four "eigenfaces" U_2, U_3, U_{16}, U_{48} selected from the eigenvectors U_i and recovered to 2D $j \times k$ matrices. Their sizes are identical to those in Fig. 2. The corresponding eigenvalues are 0.297, 0.120, 5.96×10^{-4}, and 8.11×10^{-5}.

can be seen. U_{16} and U_{48} have much smaller eigenvalues and merely blurred fringes can be seen. In other words, U_2 and U_3 contain more information than U_{16} and U_{48}. Therefore we need not maintain all of the eigenface U_i and only the ones with bigger eigenvalues should be considered. Afterwards we project the $\Phi_{\rm abs}$ on the eigenface U_i and new reference image can be denoted by

$$\Gamma_{\rm newref} = \sum_{i=1}^{M} (U_i^{\rm T} \Phi_{\rm abs}) U_i. \tag{4}$$

We select fifteen eigenfaces corresponding to the bigger eigenvalues for Eq. (4) among all of the fifty eigenfaces. The biggest one among the remnant is an order smaller than the selected ones. At last we add $\Gamma_{\rm newref}$ by the average face vector Ψ and recover it to the 2D $j \times k$ matrix form $I_{\rm newref}$ in which the pattern of the interference fringes can be very similar to the absorption image. The new $I_{\rm newref}$ is shown in Fig. 2(b) which seems like an original reference image shown in Fig. 2(c). Then we can use standard method shown in Eq. (1) to obtain the OD. We can see that the fringes in Figs. 4(a) and (c)

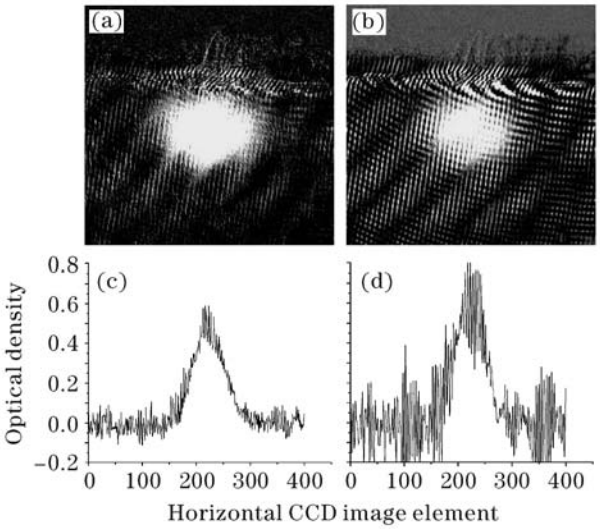

Fig. 4. (a) and (c) Optical density distribution calculated by Eq. (1) using the new reference image $I_{\rm newref}$, (b) and (d) optical density distribution using a randomly original reference image I_i. (a) and (b) are the 2D images, (c) and (d) are horizontal one-dimensional (1D) profiles of (a) and (b) along the atom cloud center.

with the eigenface method are less than those in Figs. 4(b) and (d) with the standard method. The interferences fringes in Figs. 4(b) and (d) are in the same order of the atom cloud absorption signal and it is difficult to fit. If we select different original reference images, there will appear various SNRs, which may become enough big but is random and cannot be controlled by us, but using the new reference image, we can obtain a bigger SNR steadily as shown in Figs. 4(a) and (c) and the fringes are compressed smaller than the absorption signal.

In summary, we introduce the eigenface method to reconstruct a new reference image $I_{\rm newref}$ which is more similar to the absorption image than the original reference image. Then we can obtain the OD distribution in standard method. Compared with using the original reference image, the eigenface method provides us with a much bigger SNR and reduces the interference fringes below the order of the absorption image signal. But the remnant fringes are still apparent and the effect is not as good as we think. More discrete analysis is wanted and maybe we can combine other methods such as space filter with the eigenface method.

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