Generation of a Dark Hollow Beam by Four Steps Phase Plate and Its Application for manipulating the Cold Atoms*

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ABSTRACT

In this paper, we propose a new scheme to generate a dark hollow-beam, which includes dark hollow-beam optical pipe and hollow-beam optical dipole trap, through using a system composed of a four steps phase plate and a spherical lens. This kind of light beam can be used to focus, guide and trap the cold atom. We also calculate the intensity distributing and characteristic parameters of a dark hollow-beam and the optical dipole potential which manipulate the cold atoms of $^{85}$Rb. At last, we analyze and demonstrate the experimental feasibility of the scheme.

Key Word: dark hollow-beam optical pipe, dark hollow optical dipole trap, atomic lens, cold atom guide and trap.

1. INTRODUCTION

In recent years, with the fast development of atom optics, the laser manipulated cold atoms [1-2] has become one of research hot points in atom optics. In particular, the atomic guide with a blue-detuned dark hollow beam (DHB) was proposed [3] and studied both theoretically [4,5] and experimentally [6]. Since laser guiding technique of cold atoms using the DHBs has many advantages [7], such as a smaller dark spot size, a minimal light shift of atomic internal levels, a lower photon-scattering rate, a lower atomic loss rate from photon-assisted collisions, a higher intensity gradient and so on, it would be interesting and worthwhile to generate some new DHBs and explore their new applications.

Since 1990’s, various techniques have been used to generate the DHBs, such as geometrical optics [8], mode-conversion [9], optical holography [10], computer-generated holography [11], transverse-mode selection [12] and hollow fibers [3], nonlinear optical method [13,14], and some good results have been obtained. But there are still many deficiencies in these techniques and can not suit well to the experimental research of the atomic optics. In this paper, we propose a new scheme to generate DHB, which includes dark hollow-beam optical pipe (DHBOP) and hollow-beam optical dipole trap (DHBODT), by using a system composed of a four steps phase plate and a spherical lens. It can be used to focus, guide and trap the cold atom. The experimental method and technique are very simple and convenient. In the following, we will introduce the physical idea of this scheme, compute the intensity distributing of the DHBs, analyze the relation between geometrical parameters of the DHBs and optical system parameters, and compute the optical dipole potential that manipulates the cold atoms of $^{85}$Rb.

2. THE SCHEME OF GENERATING A DHB BY A FOUR STEP PHASE PLATE

Fig.1 shows a scheme generating a DHB. The phase plate is composed of four cells of square, the length of each side of the cell is $a$ (illustrated in Fig.1(a)), the phase value of each cell is $0$, $\pi/2$, $\pi$, $3\pi/2$, respectively. The phase plate is called four steps phase plate. Through combination of the phase plate and spherical lens and illuminated by TEM$_{00}$ mode Gaussian laser beam (Fig.1(b)), we can obtain the DHBOP encircles the lens axis. On the other hand, the full closed DHBODT can be obtained if it is illuminated by two orthogonal Gaussian laser beam showed in Fig.1(c).

The physical idea of the scheme can be explained as below: the phase plate in Fig.1(a) has reverse phase and equal area in the first and the third quadrant and so on in the second and the fourth quadrant. At the same time, the phase plate is symmetric to the lens axis. When a Gaussian laser beam perpendicular to the phase plate illuminates it, the four light beams generated by the phase plate for their phase differences will overlying one another and generate interference. The results of the interference are that the intensity in the axis is zero while in the places that deviate from the axis there

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must be a maximum intensity distributing encircling the axis and form a DHBOP. A full closed DHBODT can be obtained when the phase plate is illuminated by the laser beam showed in Fig.1(c).

![Fig1 dark hollow-beam optical pipe and dark hollow optical trap scheme](image)

### 3. THEORETICAL COMPUTATION AND ANALYSIS

#### 3.1 Intensity distribution computation of DHBs

The phase plate showed in Fig. 1(a) combines with spherical lens, where the center of them is coincidence. In the beam path of Fig.1 (b), we define the direction of lens axis as z axis, any plane perpendicular to the axis as $x_0y_0$ plane, the plane of the phase plate as $xoy$ plane and $z=-f$ ($f$ is the focal length of the lens and the thickness of the phase plate and lens is ignored.). The transmittance functions of the phase plate and lens are:

$$g(x, y) = \text{rect}\left[\frac{x-a/2}{a}, \frac{y-a/2}{a}\right] + \exp\left(\frac{i\pi}{2}\right)\text{rect}\left[\frac{x+a/2}{a}, \frac{y-a/2}{a}\right]$$

$$-\text{rect}\left[\frac{x+a/2}{c}, \frac{y+a/2}{c}\right] + \exp\left(\frac{i3\pi}{2}\right)\text{rect}\left[\frac{x-a/2}{c}, \frac{y+a/2}{c}\right]$$

$$t(x, y) = \exp\left\{-\frac{i\pi}{\lambda f}\left[(x^2 + y^2)\right]\right\}$$

where rect(x) is the rectangle. When TEM$_{00}$ mode Gaussian laser beam illuminates vertically and beam waist is in the plane of the phase plate($z=-f$), the light vibration illuminated on the phase plate is:

$$u(x, y, -f) = \sqrt{\frac{2p_0}{\lambda f}} \exp\left[-\frac{x^2 + y^2}{w_o^2}\right]$$

and $P_0$ is the output power of the laser, $w_o$ is waist radius. According to Fresnel diffraction theory, the vibration of the light wave field on the plane of $x_0, oy_0$ is given by (assuming the constant phase factors are omitted):
$$U(x_o, y_o, z) = \frac{1}{\lambda(z + f)} \iint u(x, y, -f) \cdot g(x, y) \cdot t(x, y) \cdot \frac{\exp\left\{ -i\pi \left(\frac{2(x^2 + y^2)}{\lambda(z + f)} \right) \right\}}{\lambda(z + f)} \, dx \, dy$$ (4)$$

when \ a > 2w_o, \ the \ influence \ of \ a \ to \ the \ integral \ of \ formula \ (4) \ can \ be \ omitted, \ so \ intensity \ distributing \ is:

$$I_f(x_o, y_o, z) = \pi P o^2 \exp[-2\pi(z_o^2 + y_o^2)\zeta^2] \cdot \left[ \text{erfi}(\pi x_o \sqrt{\zeta})^2 + \text{erfi}(\pi y_o \sqrt{\zeta})^2 \right]$$ (5)$$

In formula (5), \ \zeta = c / \sqrt{1 + b^2}, \ \ \zeta = c^2 \cdot (1+i)b, \ b = \pi w_o^2 / \lambda f (f + z), \ c = w_o / \lambda f + z, \ \text{erfi}(x) \ are \ imaginary \ error \ function. \ The \ intensity \ distribution \ on \ focus \ of \ the \ lens \ is:

$$I_{f_1}(x_o, y_o, 0) = \pi P \beta^2 \exp[-2\pi(x_o^2 + y_o^2)\beta^2] \cdot \left[ \text{erfi}(\pi x \beta) + \text{erfi}(\pi y \beta) \right]$$ (6)$$

where \ \beta = w_o / \lambda f . \ In \ formula \ (5) \ and \ (6), \ the \ first \ term \ on \ the \ right \ is \ the \ result \ of \ Gaussian \ light \ beam \ diffraction, \ square \ plus \ of \ the \ two \ imaginary \ error \ function \ in \ the \ second \ term \ is \ the \ result \ of \ four \ light \ beam \ interference \ generated \ by \ the \ phase \ plate \ modulation. \ With \ series \ form \ of \ \text{erfi}(\pi \sqrt{\zeta}),$$

$$\text{erfi}(\pi \sqrt{\zeta})^2 = \frac{4\pi(cx)^2}{\sqrt{1+b^2}} + \frac{8\pi^3(cx)^4}{3(1+b^2)^{3/2}} + \frac{8(7-2b^2)\pi^5(cx)^6}{45(1+b^2)^{3/2}} + \cdots$$ (7)$$

one \ can \ obtain \ that \ formula \ (5) \ and \ (6) \ are \ overlying \ of \ Laguerre-Gaussian \ functions \ LG_{\ell}^m . \ It \ is \ easy \ to \ see \ that \ intensity \ is \ zero \ on \ z \ axis \ and \ the \ maximum \ of \ the \ intensity \ around \ z \ axis \ generates \ DHBOP. 

When \ illuminated \ by \ the \ light \ beam \ showed \ in \ Fig.1(c), \ two \ DHBOPs \ will \ cross \ vertically \ and \ a \ DHBODT \ will \ be \ obtained. \ Intensity \ distributing \ of \ the \ DHBODT \ is \ the \ plus \ of \ the \ two \ DHBOPs, \ central \ intensity \ is \ zero. 

3.2 Characteristic analysis of the DHBs

In order to study DHBs further, several special parameters must be defined to characterize the properties of a DHB as follows:

1) Effective intensity: The maximum intensity that can form an equal intensity close aureole on the plane perpendicular to the DHBOP axis is defined as the effective intensity \( I_{hp} \) of the DHBOP on that plane; the maximum intensity that can form an equal intensity close curved surface in the DHBODT is defined as the effective intensity \( I_{ht} \) of the DHBODT.

2) Radial width: On the cross section of the DHBOP and inside of it, the radial instance of two points where intensity equals effective intensity is defined as the radial width \( l_{pw} \) of the DHBOP. On the section traverse the dark center of the DHBODT and inside of it, the radial instance of two points where intensity equals effective intensity is defined as the radial width \( l_{tw} \) of the DHBODT.

3) Dark spot size: On the cross section of the DHBOP and inside of it, the radial instance of two points where intensity equals half effective intensity is defined as the dark spot size \( l_{dpw} \) of the DHBOP. On the section traverse the dark center of the DHBODT and inside of it, the radial instance of two points where intensity equals half effective intensity is defined as the dark spot size \( l_{dtw} \) of the DHBODT.

The parameters character the DHB are relative to the optical system parameters, such as \( \lambda, \ w_o, \ f \). Because the intensity distribution of (5) and (6) is complex, it is difficult to derive their analytical relation. We calculate the characteristic parameters of the different DHBOP by using the same laser power \( p_o = 1000mW \), different wavelength, beam waist radius and the focal length. Table 1, 2, 3 show the results. We can derive the approximate relations from these data as follows:

Effective intensity \( I_{hp} \), radial width \( l_{pw} \) and dark spot size \( l_{dpw} \) of the DHBOP on the lens focal plane are, respectively:
When the ratio between laser beam waist radius and focal length $w_o/f$ is not very small, i.e. $w_o/f > 1.5\%$, intensity distribution of the DHBOP is symmetrical to lens focal plane. Farer from the focal plane, effective intensity $I_{hp}$ is smaller and radial width $\lambda_{pw}$ is longer. In the distance to focal plane $z = \Delta z = 1.674 \left( f / w_o \right)^2$, effective intensity is $1/e^2$ of which in focal plane and radial width is 5.2 times longer. Intensity distribution around the focus is similar with the doughnut. When the ratio $w_o/f$ is very small, effective intensity change not much in a long distance along optical axis. For example, Table 3, $w_o/f = 1/600$, shows that effective intensity change is smaller than 20% in the range from $z = 0$ to $z = f/2$. Fig.2(a) and (b) show the intensity distribution contour of the DHBOPs on $xoz$ plane generated by TEM$_{00}$ mode Gaussian laser ($\lambda = 0.78 \mu m$, $P_n = 1000mW$) illuminating and $w_o = 5mm$, $f = 30mm$, $w_o = 0.5mm$, $f = 30cm$, respectively.

\[
\begin{align*}
I_{hp} &= 0.89P_n \left( w_o / \lambda \right) f^2 \\
I_{pw} &= 0.376 \left( \lambda / f / w_o \right) \\
I_{dpw} &= 0.231 \left( \lambda / f / w_o \right)
\end{align*}
\]

(8)

### Table 1: The parameters of several dark hollow-beam optical pipes of $w_o/f=1/6$.

<table>
<thead>
<tr>
<th>$\lambda$ (µm)</th>
<th>Z(µm)</th>
<th>-47</th>
<th>-23.5</th>
<th>-15</th>
<th>0</th>
<th>15</th>
<th>23.5</th>
<th>47</th>
</tr>
</thead>
<tbody>
<tr>
<td>$w_o = 50mm$</td>
<td>$I_{hp} (10^9 W)$</td>
<td>5.48</td>
<td>13.69</td>
<td>20.33</td>
<td>40.65</td>
<td>20.32</td>
<td>13.69</td>
<td>5.48</td>
</tr>
<tr>
<td>$f = 300mm$</td>
<td>$l_{pw} (\mu m)$</td>
<td>9.08</td>
<td>5.17</td>
<td>3.50</td>
<td>1.76</td>
<td>3.50</td>
<td>5.17</td>
<td>9.08</td>
</tr>
<tr>
<td>$w_o = 5mm$</td>
<td>$I_{hp} (10^9 W)$</td>
<td>5.51</td>
<td>13.58</td>
<td>20.45</td>
<td>40.65</td>
<td>20.2</td>
<td>13.58</td>
<td>5.44</td>
</tr>
<tr>
<td>$f = 30mm$</td>
<td>$l_{pw} (\mu m)$</td>
<td>9.12</td>
<td>5.16</td>
<td>3.50</td>
<td>1.76</td>
<td>3.50</td>
<td>5.17</td>
<td>9.12</td>
</tr>
<tr>
<td>$w_o = 0.5mm$</td>
<td>$I_{hp} (10^9 W)$</td>
<td>7.04</td>
<td>21.99</td>
<td>42.14</td>
<td>162.6</td>
<td>41.87</td>
<td>21.87</td>
<td>6.98</td>
</tr>
<tr>
<td>$f = 3mm$</td>
<td>$l_{pw} (\mu m)$</td>
<td>6.76</td>
<td>4.56</td>
<td>3.46</td>
<td>0.88</td>
<td>3.46</td>
<td>4.56</td>
<td>6.84</td>
</tr>
</tbody>
</table>

### Table 2: The parameters of the dark hollow-beam optical pipe of $w_o = 5mm$, $f = 30cm$, $P_n = 1000mW$, $\lambda = 0.78\mu m$.

<table>
<thead>
<tr>
<th>$\lambda$ (µm)</th>
<th>Z(µm)</th>
<th>-4.7</th>
<th>-2.35</th>
<th>-1.5</th>
<th>-0.75</th>
<th>0</th>
<th>0.75</th>
<th>1.5</th>
<th>2.35</th>
<th>4.7</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_{hp} (10^9 W)$</td>
<td>5.518</td>
<td>13.8</td>
<td>20.45</td>
<td>31.07</td>
<td>40.65</td>
<td>20.2</td>
<td>13.58</td>
<td>5.44</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$l_{pw} (\mu m)$</td>
<td>90.2</td>
<td>51.6</td>
<td>34.8</td>
<td>23.0</td>
<td>21.0</td>
<td>10.8</td>
<td>51.6</td>
<td>91.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$l_{dpw} (\mu m)$</td>
<td>48.3</td>
<td>29.7</td>
<td>21.0</td>
<td>14.1</td>
<td>14.1</td>
<td>14.1</td>
<td>21.0</td>
<td>29.8</td>
<td>48.8</td>
<td></td>
</tr>
</tbody>
</table>

### Table 3: The parameters of the dark hollow-beam optical pipe of $w_o = 0.5mm$, $f = 30cm$, $P_n = 1000mW$, $\lambda = 0.78\mu m$.

<table>
<thead>
<tr>
<th>$\lambda$ (µm)</th>
<th>Z(cm)</th>
<th>-16</th>
<th>-14</th>
<th>-12</th>
<th>-10</th>
<th>-8</th>
<th>-6</th>
<th>-4</th>
<th>-2</th>
<th>0</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_{hp} (10^9 W)$</td>
<td>40.9</td>
<td>43.12</td>
<td>44.25</td>
<td>45.73</td>
<td>47.3</td>
<td>48.36</td>
<td>47.97</td>
<td>45.35</td>
<td>40.65</td>
<td>34.95</td>
<td></td>
</tr>
<tr>
<td>$l_{pw} (\mu m)$</td>
<td>350</td>
<td>311.4</td>
<td>266</td>
<td>232.4</td>
<td>205.4</td>
<td>195</td>
<td>179.2</td>
<td>169.6</td>
<td>176.8</td>
<td>193</td>
<td></td>
</tr>
<tr>
<td>$l_{dpw} (\mu m)$</td>
<td>184.2</td>
<td>174</td>
<td>156.4</td>
<td>138.8</td>
<td>125</td>
<td>113</td>
<td>105.6</td>
<td>104</td>
<td>109</td>
<td>118.2</td>
<td></td>
</tr>
</tbody>
</table>
Using the beam path showed in Fig.1(c), when the ratio \( \frac{w_o}{f} \) is not very small and two DHBOPs cross at the focus, the DHBODT which effective intensity is very large and geometric size is very small can be generated. Assume \( w_o = 5 \text{mm} \), \( f = 30 \text{mm} \), \( P_n = 1000 \text{W} \), \( \lambda = 0.78 \mu\text{m} \), we can obtain effective intensity of the optical dipole trap \( I_{\text{Dip}} = 5.4 \times 10^5 W/m^2 \), width on x, y, z direction \( l_{\text{mx}} = l_{\text{nc}} = 2.5 \mu\text{m} \), \( l_{\text{my}} = 1.4 \mu\text{m} \), dark spot size on x, y, z direction \( l_{d,\text{mx}} = l_{d,\text{nc}} = 1.34 \mu\text{m} \), \( l_{d,\text{my}} = 0.9 \mu\text{m} \). When the ratio \( \frac{w_o}{f} \) is very small and two DHBOPs cross at the half focal length \( (z = -\frac{f}{2}) \), the DHBODT which geometric size is very large can be generated. Assume \( w_o = 0.5 \text{mm} \), \( f = 300 \text{mm} \), \( P_n = 1000 \text{mW} \), \( \lambda = 0.78 \mu\text{m} \), also we can get \( I_{\text{Dip}} = 4.2 \times 10^4 W/m^2 \), \( l_{\text{mx}} = l_{\text{nc}} = 340 \mu\text{m} \), \( l_{\text{my}} = 200 \mu\text{m} \), \( l_{d,\text{mx}} = l_{d,\text{nc}} = 190 \mu\text{m} \), \( l_{d,\text{my}} = 130 \mu\text{m} \). The intensity contour of the two traps on xoy, plane is showed in Fig.3.

![Intensity contour line of dark hollow-beam optical pipe](image1)

(a) \( \lambda = 0.78 \mu\text{m} \), \( w_o = 5 \text{mm} \), \( f = 30 \text{mm} \)

(b) \( \lambda = 0.78 \mu\text{m} \), \( w_o = 0.5 \text{mm} \), \( f = 30 \text{cm} \)

![Intensity contour line of dark hollow optical trap](image2)

(a) \( \lambda = 0.78 \mu\text{m} \), \( w_o = 5 \text{mm} \), \( f = 30 \text{mm} \)

(b) \( \lambda = 0.78 \mu\text{m} \), \( w_o = 0.5 \text{mm} \), \( f = 30 \text{cm} \)

4 THE POTENTIAL APPLICATION AND FEASIBILITY ANALYSIS

4.1 The potential application of the DHBs

The DHB by four steps phase plate discussed before has many applications in manipulating cold atoms and cold molecules. When a two-level atom moves in an inhomogeneous light field, it will experience an optical dipole force and result in an optical dipole potential \([7]\)

\[
U_{\text{Dip}}(\vec{r}) = \frac{\hbar \delta}{2} \ln \left[ 1 + \frac{I(\vec{r})/I_s}{1 + 4(\delta/\Gamma)^2} \right]
\]

\( \delta \)

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where \( \delta \) is the detuning of the laser frequency \( \omega_l \) from the atomic resonance frequency \( \omega_a \). \( I(\vec{r}) \) is the intensity distribution of the light field, \( I_s \) and \( \Gamma \) are the saturation intensity and natural linewidth of the atomic transition, respectively. For the \(^{85}\text{Rb} \) D\(_2\) line, \( I_s = 1.6 \text{mW cm}^{-2} \), and \( \Gamma = 2 \pi \times 6.1 \text{MHz} \). When the light field is blue-detuned \((\delta > 0)\), the potential is repulsive, and the atoms will be repelled to the minimum of the light field. Therefore, atoms may move along the track that the intensity is minimum or be trapped in the minimum of the light field. The DHBOP and DHBODT showed in Fig.2 and Fig.3 may have significant applications in manipulating cold atoms.

To the DHBOP showed in Fig.2 (a), the effective intensity \( I_{ep} \) is very large on lens focal plane. Consider D\(_2\) line of \(^{85}\text{Rb} \), assume detuning \( \delta = 2 \pi \times 10 \text{GHz} \). According to formula (9), dipole potential can be \( U_{Dp} = 1.3 \text{K} \), the diameter of the pipe on focal plane is very small and rapidly become large on the two side of the focal plane. Because this distribution of the dipole potential can focus atomic beam like optical lens focusing photon beam, we call it atomic lens\(^{[15]}\). Fig.4 shows the dipole potential contour, 1mK, 0.5mK, 0.1mK, its distribution on \( xOz \) plane. We can see that the radius of 0.1mK contour is 0.93nm on the focal plane, this shows it can focus the cold atoms, which moves along z direction and temperature is below 0.1mK to a range that radius is less than 0.93nm.

The DHBOP showed in Fig.2 (b) can be used to guide cold atoms in a long distance. Consider D\(_2\) line of \(^{85}\text{Rb} \), also assume detuning \( \delta = 2 \pi \times 10 \text{GHz} \), we can find that the largest and smallest dipole potential corresponding to the effective intensity from \( z=0 \) to \( z=-16 \text{cm} \) is 6.66mK and 5.65mK, respectively.

The two DHBODTs showed in Fig.3 all can be used to trap cold atoms, in which the ratio \( \omega_f/\omega_o \) is not very small has the characteristic of large intensity and small volume. When illuminated by 1000mW laser, the effective intensity of the optical dipole trap showed in Fig.3 (a) is \( I_{o} = 5.4 \times 10^{10} \text{W/m}^2 \), and the corresponding optical dipole potential can be 1.38K high. Even if reduce the laser power to 1mW, we see that dipole potential still can be 65.6mK. Consider the effective intensity contour approximately as gyroscopic ellipsoid, trap volume is \( V_o = 4.58 \times 10^{-12} \text{cm}^3 \), while the density of cold atom gas from a standard optical molasses\(^{[16]}\) is at \( 10^{11} \text{ to } 10^{14} \text{ cm}^{-3} \) order of magnitude, so this small volume optical dipole trap can realize single atom trap. Many atoms trapping condition can be obtained when illuminated by a laser beam first, which forms an atomic lens optical field to focus cold atoms to get high atom density around the focus, then by the second laser beam. This can be used to research cold atom collide at the state of adiabatic compression. When the ratio \( \omega_f/\omega_o \) is very small, the optical trap volume is very large and the trapped atoms are also in a large number. To the optical dipole trap showed in Fig.3 (b), the optical dipole potential is 4.58mK, trapping volume is \( 1.2 \times 10^{-3} \text{ cm}^3 \), and the number of trapping atom is in order magnitude of \( 10^7 \text{ to } 10^9 \).

### 4.2 Feasibility analysis of the scheme

The optical components and optical path used in the scheme are very simple. Four steps phase plate can be etched by micro-electronics technology on transparent medium plate, the etching depth of each step is \( \lambda/4(n-1) \), where \( n \) is refractive index of the medium. Focal lens is the ordinary optical spherical lens, illuminating light wave is the familiar TEM\(_{00}\) mode Gaussian laser beam, which can be broadened to the necessary waist radius by using lens system. It is easy to see that the scheme can be realized conveniently.
5 CONCLUSION

In this paper, we propose a new scheme to generate a DHB, which includes DHBOP and DHBODT, through using a system composed of a four steps phase plate and a spherical lens. This kind of light beam can be used to focus, guide and trap the cold atom. We calculate the intensity distribution and characteristic parameters of a DHB and the optical dipole potential that manipulate the cold atoms of $^{85}\text{Rb}$. The result shows that when the ratio $w_0/f$ is not very small, the DHBOP can focus cold atoms as atomic lens, the DHBODT has the characteristic of small volume and large intensity to trap single atom; when the ratio $w_0/f$ is very small, the DHBOP can be used to guide cold atoms in a long distance, the volume of the DHBODT is $10^{-5} \text{cm}^3$ order of magnitude and the number of trapping cold atoms can be $10^7 \sim 10^8$ order of magnitude. At last, we analyze the experimental feasibility of the scheme. It shows that no matter the facture of the components or design of optical path are simple and convenient.

REFERENCES