Vol 15 No 1, January 2006
1009-1963/2006/15(01)/0116-10
Chinese Physics
© 2006 Chin. Phys. Soc.
and IOP Publishing Ltd

Diffracted field distribution from a knife-edge truncated semi-Gaussian beam as an atomic (molecular) mirror*

Zheng Ping(郑 萍)[a)b)], Gao Wei-Jian(高伟建)[b)], and Yin Jian-Ping(印建平)[a)†]

[a)] *Key Laboratory for Optical and Magnetic Resonance Spectroscopy, Ministry of Education, Department of Physics, East China Normal University, Shanghai 200062, China*

[b)] *Department of Physics, Suzhou University, Suzhou 215006, China*

(Received 4 April 2005; revised manuscript received 11 July 2005)

We investigate the diffraction characteristics of an incident Gaussian beam cut by a straight edge bounding a semi-infinite opaque plane using Kirchhoff scalar wave theory in the Fresnel limit, and propose a new and simple mirror scheme to reflect atoms by using the intensity gradient induced by a blue-detuned semi-Gaussian laser beam. The optical potential of the diffracted light of the knife-cut semi-Gaussian beam for ^{85}Rb atom and its spontaneous emission probability are calculated and compared with the performance of the evanescent-wave mirror. Our study shows that the optical potential of the diffracted light of the semi-Gaussian beam is far higher than that of the evanescent light wave, and the maximum normal velocity of the incident atoms can be far greater than that of the evanescent light wave under the same parameters, so the blue-detuned semi-Gaussian beam, as a novel atomic mirror, can be used to efficiently reflect cold atoms with a normal velocity of greater than 1 m/s. However, the intensity gradient (force) of the diffracted light of the semi-Gaussian-beam is much smaller than that of the evanescent light wave, so its spontaneous emission probability is greater than that from the evanescent-wave when the normal velocity of incident atoms is greater.

Keywords: semi-Gaussian beam, reflection of atomic beam, atomic mirror
PACC: 3280, 3280P, 4250, 4250V

1. Introduction

As early as 1929, Stern *et al* first demonstrated the reflection and diffraction of atoms from metallic and crystalline surfaces,[1] which can be regarded as the beginnings of atom optics. In recent years, there has been significant progress in atom optics. One of useful atom-optical elements is an atomic mirror,[2] which can be used to bend the atomic path in an atomic cavity,[3,4] atomic holography and atom interferometer, even to focus an atomic beam onto a surface for some applications in atom lithography or in a scanning atom microscope. There are two approaches to realize the reflection of atoms (i.e., to form atomic mirrors): the first one is the reflection of atoms from the surfaces, which was first demonstrated almost 70 years ago[1] and now developed into a useful tool in surface science;[5] and the second one is the reflection of atoms from repulsive potentials induced by optical electromagnetic fields[6−14] or static magnetic field.[15−20]

In 1982, Cook and Hill first suggested an electromagnetic mirror scheme to reflect atoms by using the gradient of the optical dipole potential induced by a blue-detuned evanescent light wave.[6] Since then, both theoretical and experimental studies of atomic reflection from a general or a surface-plasmon-enhanced evanescent wave have been performed,[7−13] and the corresponding normally incident velocity of an atomic beam was increased to ∼100 cm/s from 10 cm/s. In particular, a novel reflection cooling of sodium atoms in an evanescent light wave (ELW) was proposed and demonstrated experimentally.[14] However, since spontaneous emission of atoms in the ELW causes momentum diffusion and results in a broadening of the reflected atomic beam

*Project supported by the National Natural Science Foundation of China (Grant Nos 10174050 and 10374029), the Key Program of National Natural Science Foundation of China (Grant No 10434060), and by the Shanghai Priority Academic Discipline and the 211 Foundation of the Ministry of Education of China.
†Corresponding author. E-mail: jpyin@phy.ecnu.edu.cn

and also the severe loss of atomic coherence, a kind of new atomic mirrors using static magnetic field from a periodically-magnetized floppy,[15−17] or periodically-arranged magnets,[18] or a planar array of current-carrying wires[19,20] were proposed and demonstrated.[15−24] It is clear that there is no spontaneous emission effect of the reflected atoms from the magnetic mirrors, but the fabrication of these magnetic mirrors is much more complex than that of optical dipole mirrors.

It is well known that a blue-detuned and focused Gaussian beam can also be used to reflect cold atoms and form a Fabry–Perot interferometer[25] or a Fabry–Perot cavity.[26] In particular, when a collimated and blue-detuned Gaussian beam is focused by a cylindrical lens, an elliptical Gaussian beam (i.e., light sheet) can be generated behind the lens, and used to reflect cold atoms or form a pyramidal gravito-optical trap,[27] even to reflect the Bose–Einstein condensates[28] as an atomic mirror. But these blue-detuned beam mirrors have some disadvantages, such as 1) a narrow mirror width ($w \leq 0.2$mm[28]), 2) a poor surface flatness due to a Gaussian (or elliptical Gaussian) profile, and 3) a low intensity gradient and so on. However, when a blue-detuned and collimated Gaussian (or elliptical Gaussian) beam is diffracted by a semi-infinite plane, a semi-Gaussian beam (SGB) (or semi-elliptical Gaussian beam, SEGB) can be generated and used to efficiently reflect cold atoms as a simple and novel atomic mirror. Obviously, such an atomic mirror can overcome the shortcomings mentioned above.

It seems that the idea of using a knife-edged light beam as an atomic mirror is a common knowledge of the scientists, but how are the diffracted intensity distribution of the SGB and its intensity gradient? In what respect much does the maximum mean normal velocity of the incident atomic beam reflected by the SGB reach? How is the SGB mirror different from the ELW mirror in their performances? So far no answer has been given to these questions, and nobody has proposed the idea of using a blue-detuned SGB to reflect cold atoms. On the other hand, as early as 1969, the diffraction of Gaussian laser beam by a semi-infinite plane was calculated and measured.[29] After this, this diffraction question was further studied both theoretically and experimentally.[30] In these studies, only 1D diffracted intensity distribution was calculated, and nobody has given a simple theoretical model to describe the diffracted intensity distribution and discuss the potential applications of the SGB in atom optics. Therefore, it would be interesting and worthwhile to study these questions and compare the performances of the SGB mirror and ELW mirrors, and discuss the potential applications of the SGB mirror in atom optics.

In this paper, we propose a new mirror scheme to reflect atoms by using a blue-detuned SGB, and study the performance of this mirror. We also compare performances of the SGB and the ELW atomic mirrors. This paper is organized as follows: In Section 2 we propose a new atomic-mirror scheme, and describe the generation of a semi-Gaussian beam and its principle to reflect atoms. In Section 3, we calculate the relative diffracted intensity distributions of the SGB, and study the dependence of the intensity distributions on various parameters, such as the beam waist w, the transverse position y and the propagation distance z. We also perform the numerical fitting for the diffracted intensity distribution of the SGB in the x direction. In Section 4, the optical potential of the diffracted light of the SGB for ^{85}Rb atoms is calculated, and the maximum normal velocity of incident atoms and its spontaneous-emission probability are estimated. A comparison of performances of the SGB and the ELW mirrors is given. Main results and conclusions are summarized, and some potential applications of the SGB in atom optics are briefly discussed in the final section.

2. A new scheme of atomic mirror

The principle scheme to generate a semi-Gaussian beam (SGB) is shown in Fig.1. A Gaussian beam is propagating along the z direction, and its electric field distribution is given by

$$E_{\mathrm{GB}}(x,y,z) = E_0 \exp\left[-\frac{x^2+y^2}{w(z)^2}\right] \times \exp\left\{-\mathrm{i}\left[kz + k\frac{x^2+y^2}{2R(z)} - \Psi(z)\right]\right\}, \tag{1}$$

and

$$w(z) = w_0\sqrt{1+\frac{z^2}{z_0^2}}, \qquad z_0 = \frac{\pi}{\lambda}w_0^2, \tag{2}$$

where $E_0 = \sqrt{I_0} = \sqrt{P_0/\pi}/w(z)$, P_0 being the power of the incident Gaussian beam, $k = 2\pi/\lambda$ the wave

number, and $\Psi(z) = \tan^{-1}(z/z_0)$ is a phase shift due to the beam geometry. $w(z)$ and w_0 are the beam waists at z plane and z=0 plane, respectively. $R(z) = z\left[1 + \frac{z_0^2}{z^2}\right]$ is the curvature radius of the phase front.

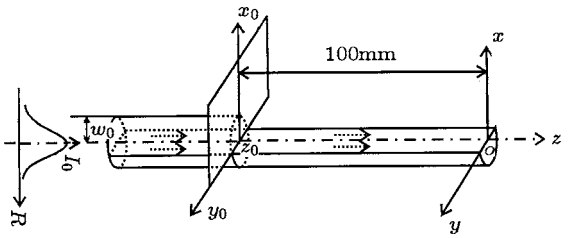


Fig.1. Principle scheme for generating a semi-Gaussian beam to form an atomic mirror.

When the straight bottom edge of a semi-infinite plate is vertically inserted into the Gaussian beam at $z = -z_0$ with the position of the edge coinciding with the centre of the beam, the upper half of the beam above the *yoz* plane is intercepted, and a semi-Gaussian beam (SGB) with a horizontal and upward surface will be generated after $z = -z_0$. In this case, the *yoz* plane of the SGB at x=0 is similar to a specular surface of an optical mirror (here the *yoz* plane is defined as a mirror surface or called the *yoz* reflecting surface), and its intensity distribution along the x direction will be determined by the straight-edge diffraction of the semi-infinite plate. When the incident Gaussian beam is blue-detuned, the *yoz* reflecting surface of the resulting SGB will generate a strong repulsive dipole force for neutral atoms, which can be used to form a simple atomic mirror. In Fig.1, the semi-infinite opaque plate is placed at $z = -z_0 = -100\,\mathrm{mm}$, the diffracting aperture is defined as $\sigma \equiv (x : 0 \to \infty, y : -\infty \to \infty)$, and a plane vertical to the SGB at any propagation position z is defined as diffracted plane.

3. Theoretical calculations and analysis

3.1. Intensity distribution $I(x)$ in the diffraction plane vertical to the SGB

From the Fresnel diffraction theory, the relative electric-field distribution in the diffractive plane perpendicular to the SGB at the propagation distance z_0= 100 mm (i.e. at z= 0 mm) behind the semi-infinite plane aperture is given by

$$E_{\mathrm{SGB}}(x,y,z) = \frac{1}{\mathrm{i}z\lambda E_0}\int_{-\infty}^{\infty}\int_{0}^{\infty} E_{\mathrm{GB}}(\xi,\eta,z) \times \exp\left\{\frac{\mathrm{i}k}{2z}[(x-\xi)^2+(y-\eta)^2]\right\}\mathrm{d}\xi\mathrm{d}\eta, \tag{3}$$

where E_{GB} is the electric field distribution of the Gaussian beam and given by Eq.(1), and the corresponding relative intensity is written as

$$I(x,y,z)/I_0 = E_{\mathrm{SGB}}(x,y,z)E^*_{\mathrm{SGB}}(x,y,z) = |E_{\mathrm{SGB}}(x,y,z)|^2 . \tag{4}$$

From Eqs.(1)–(4), we calculated the relative intensity distribution $I(x)/I_0$ in the diffractive plane vertical to the SGB along the x direction, and the result is shown in Fig.2 (see curve C). It is clear from Fig.2 that the relative intensity distribution near the *yoz* reflected surface of the SGB in the x direction is very steep and the maximum relative intensity is increased to ~ 1.342 from 1.000 (i.e., enhanced by $\sim$ 34 %). This shows that the intensity gradient near the *yoz* surface of the SGB is far greater than that of the Gaussian beam (or elliptical-Gaussian beam). Moreover, the oscillated intensity distribution after the maximum intensity position x_{M} results from the diffraction of straight edge of semi-infinite opaque plane.

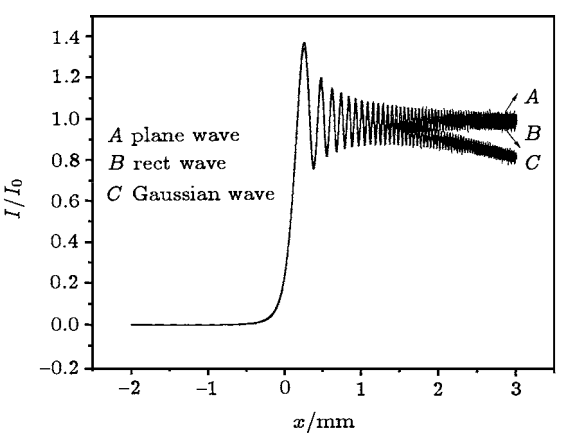


Fig.2. Relative diffracted intensity distributions $I(r)$ of a semi-plane wave (curve A), a semi-rectangle-profile beam (curve B), and a semi-Gaussian beam (curve C).

As a comparison, we also calculated the relative intensity distributions $I(x)/I_0$ in the diffracted plane of a semi-infinite plane wave (SPW) and a semi-rectangular-profile beam (SRB), and the results are shown in Fig.2 (see curves A and B). Here the field

distributions of the plane wave and rectangular-profile beam are described as, respectively,

$$E_{\mathrm{PW}}(x,y,z) = A_0 \tag{5}$$

and

$$E_{\mathrm{RB}}(x,y,z) = \begin{cases} A_0 & \sqrt{x^2+y^2} \le a, \\ 0 & \sqrt{x^2+y^2} > a, \end{cases} \tag{6}$$

where A_0 is the maximum field amplitude, and a is the radius of the rectangular-profile beam.

So the electric field distribution of the plane wave diffracted by the semi-infinite plane aperture is given by

$$\begin{aligned} E_{\mathrm{SPW}}(x,y,z) =& A_0 \frac{1}{\mathrm{i}k\lambda}\exp(\mathrm{i}kz) \\ & \times \int_0^{\infty} \exp\left[\mathrm{i}\frac{k}{2\pi}(x-\varsigma)^2\right]\mathrm{d}\varsigma \\ & \times \int_{-\infty}^{\infty} \exp\left[\mathrm{i}\frac{k}{2\pi}(y-\eta)^2\right]\mathrm{d}\eta \end{aligned} \tag{7}$$

and the electric field distribution of the rectangular-profile beam diffracted by the same semi-infinite-plane aperture is

$$\begin{aligned} E_{\mathrm{SRB}} =& A_0 \frac{1}{\mathrm{i}kz}\exp(\mathrm{i}kz) \\ & \times \int_0^{a} \exp\left[\mathrm{i}\frac{k}{2\pi}(x-\varsigma)^2\right]\mathrm{d}\varsigma \\ & \times \int_{-a}^{a} \exp[i\frac{k}{2\pi}(y-\eta)^2]\mathrm{d}\eta. \end{aligned} \tag{8}$$

It can be seen from Fig.2 that the maximum relative intensities of the diffracted plane wave and rectangular-profile beam are ~1.370 and ~1.368 respectively, which are nearly equal to that (~1.342) of the diffracted Gaussian beam, and the maximum intensities of three beams occur at the same position (x_{M}=0.24 mm). This shows that the intensity gradient near the *yoz* surface of the SGB is the same as that of the SPW and SRB. Of course, the oscillating intensity distributions of the three beams after the maximum intensity position (x_{M}=0.24 mm) are different, in which the decay of the oscillating part of the SGB is determined by its beam waist w.

3.2. Relationship between diffracted intensity $I(x)$ and beam waist w

The dependence of the relative intensity distribution $I(x)/I_0$ of the SGB diffracted light on the waist w of the Gaussian beam was studied, and the results are shown in Fig.3. In our calculation, we assumed that the propagation distance z_0=100 mm (i.e. z= 0 mm) and the beam waists w are 1 mm, 2.5 mm, 5mm, and 10 mm, respectively. We can find from Fig.3 that with the increase of the beam waist w from 1 mm to 10 mm, the maximum relative intensity will be increased from ~1.25 to ~1.37, and the decay of the oscillating part after the maximum intensity position x_{M} becomes slower. This shows that the intensity gradient near the *yox* reflecting surface of the SGB is almost not related to the beam waist w of the incident Gaussian beam, whereas the waist w only slightly affects the maximum normal velocity of incident atoms.

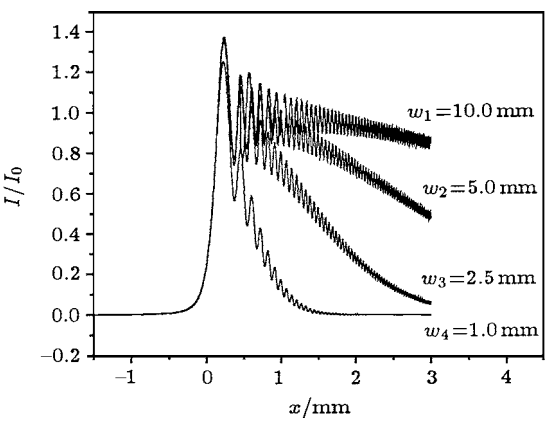


Fig.3. Relative diffracted intensity distribution $I(r)$ of the semi-Gaussian beam with the different beam waist w at the propagation distance z =100 mm.

3.3. Relation of diffracted intensity distribution $I(x)$ with coordinates y or z

To know the performance of whole *yoz* surface of the SGB as a mirror surface, we calculated the relative diffracted intensity distributions $I(x)/I_0$ at different transverse position y and different propagation distance z, the results are shown in Fig.4. In the calculation of Fig.4(a), we assumed that the propagation distance z_0=100 mm (z=0 mm), the beam waist w is 10 mm and the transverse position y is chosen to be 0 mm, ±1.0 mm, ±1.5 mm, ±2.0 mm, respectively. From Fig.4(a), we can see that when the transverse position y is increased from 0 mm to 2 mm, the maximum relative intensity (at z_{M}= 0.24) slowly decreased from 1.37 to 1.26. If the maximum relative intensity is decreased to 1.00 from 1.37, the corresponding transverse position y_{m} is defined as the half width of the SGB mirror. For example, when the waist w of the Gaussian beam is 10 mm, the width ($2y_{\mathrm{m}}$) of the SGB mirror will be limited to 8 mm (i.e. y_m = ±4.0 mm),

which is wide enough to reflect an atomic beam as an atomic mirror.

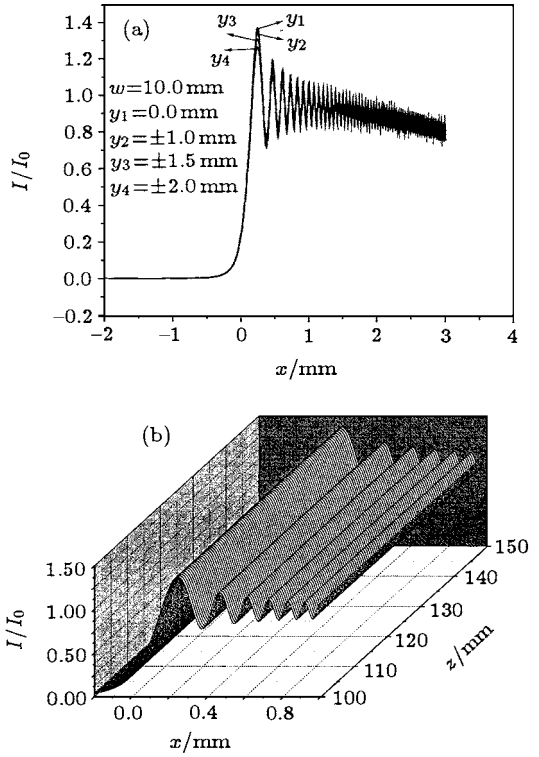


Fig.4. Relative diffracted intensity distributions $I(r)$ of the semi-Gaussian beam with (a) the different y value for the beam waist w=10 mm and at the propagation distance z =0 mm, (b) the different propagation distance z for the beam waist w=10 mm and the transverse position y=0 mm.

Similarly, Fig.4(b) shows the three-dimensional relative intensity distributions $I(x)/I_0$ near the *yoz* reflected surface of the SGB as a function of the coordinate x at different propagation distance z for the beam waist w=10 mm. It can be seen from Fig.4(b) that with the increasing of the propagation distance z, the maximum relative intensities and their diffracted intensity distributions are not changed. This shows that the length of the SGB mirror has not any limit. So our SGB mirror proposed here has a very smooth and infinitely-large specular surface.

3.4. Numerical fitting for the diffracted intensity of the SGB

In order to calculate the optical potential of the diffracted light of the blue-detuned SGB for the reflected atoms and its dipole force and spontaneous-emission probability, we performed numerical fitting for the relative diffracted intensity $I(x)/I_0$ before the maximum intensity position $x_{\rm M}$= 0.24 mm for w= 1 mm, 2.5 mm and 5 mm, and the results are shown in Fig.5. In our fitting, we used a Boltzmann equation

$$I_{\rm SGB}(x)/I_0 = \frac{A_1 - A_2}{1 + \exp\left(\dfrac{x - x_0}{d_X}\right)} + A_2 \qquad (9)$$

to fit the numerical results from Eqs.(3) and (4). In Eq.(9), A_1, A_2, x_0, and d_x are the four fitting parameters and are shown in Table 1. We can find from Fig.5 that there is good agreement between the results numerically calculated from Eq.(4) and the theoretical model from Eq.(9).

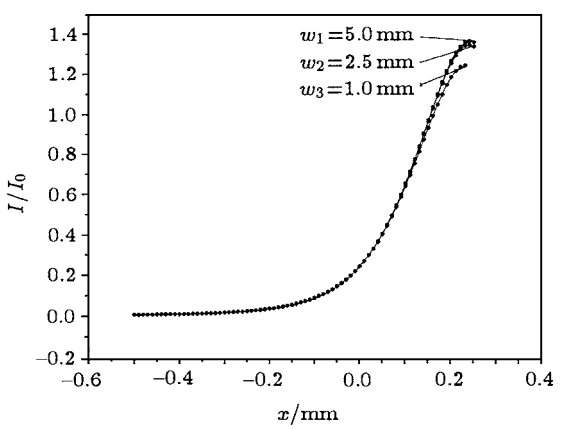


Fig.5. The solid curves are the theoretical curves from Boltzmann Eq.(6), and the black dots are the calculated numerical results from the Eq.(3) for the beam waists w= 1.0 mm, 2.5 mm and 5.0 mm, respectively.

Table 1. Fitting parameters for diffraction intensity distribution.

w/mm	1.0	2.5	5.0	10.0
A_1	0.01706	0.01670	0.01665	0.01664
A_2	1.63857	1.81751	1.84564	1.85278
x_0	0.13182	0.14277	0.14436	0.14476
d_x	0.07390	0.07491	0.07504	0.07508

4. Comparison of performances of the two mirrors

4.1. The absolute intensity distribution $I(x)$ near the mirror surface of the SGB

From Eqs.(3) and (4), the absolute intensity dis-

tribution $I(x)$ near the yoz reflecting surface of the SGB is rewritten as

$$I(x,y,z) = I_0 \left|E_{\mathrm{SGB}}(x,y,z)\right|^2 = \frac{P_0}{\pi w^2} \left|E_{\mathrm{SGB}}(x,y,z)\right|^2 . \quad (10)$$

Figure 6(a) shows the dependence of the diffracted intensity distribution on the power of incident Gaussian beam P_0 for the beam waist w= 10 mm and z=0 mm. It can be seen from Fig.6(a) that when P_0=1W, the maximum intensity is ~430mW/cm^2; while the laser power P_0 is decreased from 1W to 0.1W, the maximum intensity will be reduced from 430mW/cm^2 to 43mW/cm^2. Figure 6(b) shows the relationship between the diffracted intensity distribution and beam waist for the laser power P_0=1W. When the beam waist w=10 mm, the maximum intensity is ~430mW/cm^3; while the beam waist w is decreased from 10 mm to 1mm, the maximum intensity will be increased from ~430mW/cm^2 to 4×10^4mW/cm^2. From Fig.6, we know that in order to efficiently reflect atoms from our SGB mirror, we should choose a suitable beam waist and a high power so as to obtain a reflected intensity as high as possible. In addition, if the SGB is focused by a lens with a short focal length, we can obtain a focused SGB with a higher intensity gradient, which can be used to form a more efficient atomic mirror.

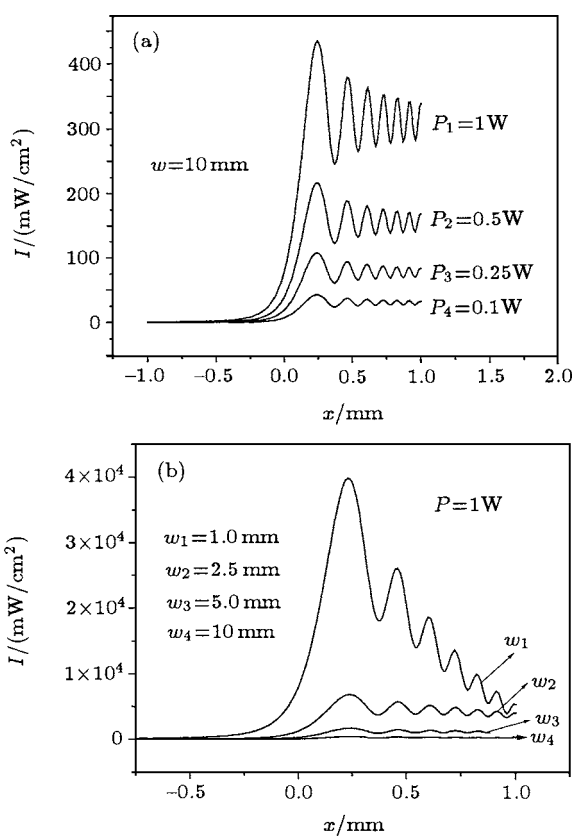


Fig.6. Absolute intensity distribution of the semi-Gaussian beam as a function of the coordinate x for (a) different laser power P_0 and the beam waist w= 5 mm, (b) different beam waist w and laser power P_0=1W.

In the reflection of atoms from an evanescent light wave (ELW), if an incident Gaussian beam is totally internally reflected at a dielectric-vacuum interface, the electric field of the ELW decays exponentially as[13]

$$E'(x,y,z) = E_0 \exp[-\alpha x - (y/w_y)^2 - (z/w_z)^2] \times \exp[\mathrm{i}k_z z], \quad (11)$$

where x and y,z are the coordinates perpendicular and parallel to the interface, respectively, and E_0 is the maximum electric field amplitude, $\alpha = \frac{2\pi}{\lambda}\sqrt{n^2\sin^2\Theta - 1}$, Θ is the incident angle of the Gaussian beam and n the refractive index of the media. k_z is the wave vector $\boldsymbol{k}$ parallel to interface, and w_y and w_z are the Gaussian beam waists in the y and z directions. When Θ=45°,the corresponding intensity of the evanescent light wave is given by

$$I(x,y,z) = \frac{P_0}{\sqrt{2}\pi w^2}\exp[-2\alpha x] \times \exp\left[-\frac{2y^2}{w_y^2} - \frac{2z^2}{w_z^2}\right] . \quad (12)$$

Obviously, the maximum intensity of the evanescent light wave will be smaller than that of the SGB with the same parameters of incident Gaussian beam.

It should be noted that the field intensity of the ELW can be enhanced by more than an order of magnitude by using surface plasmon (metal–dielectric interface)[10,13,31] or dielectric coating (multilayer dielectric structure),[32,33] and these intensity-enhancing factors are strongly dependent on the detuning of the incident beam, whereas for a free-space beam no such enhancing techniques are available, but the intensity of the SGB can also be enhanced by changing the shape of the cross section of the incident Gaussian beam under the condition of the specular area of the SGB mirror being unchanged. Such as, when an incident Gaussian beam with a waist of w_0=10 mm is replaced by an elliptical Gaussian beam with w_{y0}=10mm and w_{x0}=10μm, a semi-elliptical Gaussian beam (SEGB) will be generated, and the intensity of the SEGB will be enhance by 1000 times, while the specular area of the mirror will be not changed. Therefore, the intensity of the SGB (or

SEGB) can be always far greater than that of the ELW (or intensity-enhanced ELW) under the conditions of the same beam parameters (i.e., geometric sizes and power) and identical large detuning (i.e., for far-off-resonant beam) for reducing the spontaneous emission rate of cold atoms in the light.

4.2. The optical potential of the SGB mirror for ^{85}Rb atoms

An atom in a non-uniform electromagnetic field is acted on an optical dipole force proportional to the induced dipole moment of the atom and the gradient of the light field. It is well known that the reflection of a two-level atom from an SGB or an ELW mirror may be treated as the motion of an atom in an optical potential field, which can be described as[34]

$$U(x) = \frac{\hbar\Delta}{2} \ln\left[1 + \frac{I(x)/Is}{1 + 4(\Delta/\Gamma)^2}\right], \qquad (13)$$

where $I(x)$ is the intensity distribution in the normal direction of the SGB reflecting surface or ELW mirror, which can be given by Eq.(10) or Eq.(12). The parameter $\Delta = \omega_{\rm L} - \omega_0$ denotes the detuning of laser frequency ($\omega_{\rm L}$) from the atomic resonance (ω_0). In our calculation, we chose $\Delta = 1 \times 2\pi$GHz and used the following parameters: the saturation intensity $I_{\rm S} = 1.6{\rm mW/cm^2}$, the natural linewidth $\Gamma = 2\pi \times 6.1$MHz, and the wavelength $\lambda = 780$nm for ^{85}Rb atom.

Figure 7 shows the optical potential for ^{85}Rb atoms as a function of the normal position x for several beam waists (w= 1.0 mm, 2.5 mm, 5.0 mm, 10.0 mm). When the detuning $\Delta = 1 \times 2\pi$GHz and the laser power is 1W, the maximum optical potential will be decreased from 5.4mK to 66 μK as the beam waist w is increased from 1 mm to 10 mm. As expected, the height of the potential barrier falls rapidly with the increase of the beam waist w. Our calculation shows that if the detuning is reduced, the optical potential will be greatly increased, but the spontaneous-emission probability will also be greatly increased, which will be discussed in next subsection.

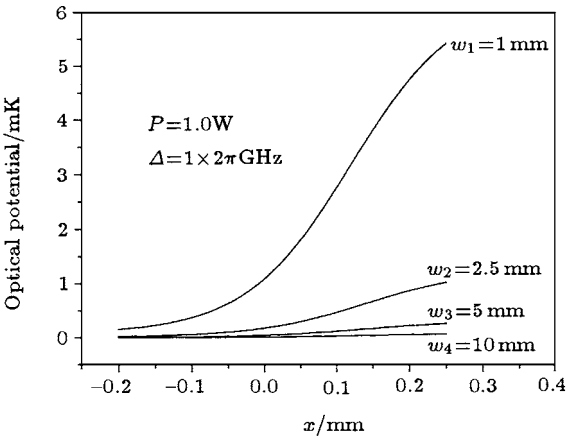


Fig.7. Optical potentials of the SGB diffracted light for ^{85}Rb atoms for different beam waist w, the laser power P_0= 1W and the detuning $\Delta = 1 \times 2\pi$GHz.

From the energy conservation ($E_{\rm k} = E_{\rm p}$), when the spontaneous emission effect of atoms during the reflection can be neglected, the maximum mean normal velocity $v_\perp$ of the incident atomic beam reflected by the blue-detuned SGB can be defined as,[9]

$$v_{\perp\max} = \left[\frac{2U_{\max}(x_{\rm M})}{m}\right]^{\frac{1}{2}}, \qquad (14)$$

where m is the atomic mass. Table 2 shows the corresponding maximum reflected normal velocity of the incident atoms for P_0=1W and Δ=1×2πGHz. It is clear from Table 2 that the maximum normal-velocity of the incident atoms reflected from the SGB mirror is far greater than that from the ELW mirror, and when $2w$=5.0 mm, the maximum reflected normal-velocity from the SGB mirror is $\sim$ 0.9m/s. When the incident angle θ of atomic beam is 1.5mrad,[10] the maximum grazing-incident velocity $v_{\rm i} = v_{\perp\max}^{\rm SGB}/\sin\theta$ of the atomic beam reflected from the SGB mirror can reach $\sim$ 600m/s.

Table 2. Maximum reflected normal-velocity of the incident atoms.

w/mm	1.0	2.5	5.0	10.0
$v_{\perp\max}^{\rm SGB}$/m·s^{-1}	1.5474	0.8959	0.5172	0.2764
$v_{\perp\max}^{\rm EW}$/m·s^{-1}	0.9775	0.3910	0.1955	0.0977

4.3. Comparison of optical potentials of the two mirrors

It is well known that when an atom approaches a medium surface, it will experience an attractive potential from the surface, which is so-called van der Waals attractive potential. For two-level atoms, the total potential $U_{\rm t}$ from the evanescent wave mirror is the sum of the repulsive optical potential $U_{\rm opt}$ and the

attractive van der Waals potential $U_{\rm vdw}$, and is given by

$$U_{\rm t} = U_{\rm opt} + U_{\rm vdw}, \tag{15}$$

where $U_{\rm opt}$ is given by Eqs.(12) and (13), and the van der Waals attractive potential can be written in a simple form as[35]

$$U_{\rm vdw}(r) = -\frac{3}{4f}\frac{n^2-1}{n^2+1}\frac{\hbar\Gamma}{(kr)^3}, \tag{16}$$

where f and k are the oscillator strength (=0.67) and the wave number, respectively.

From Eqs.(12)–(13) and (15)–(16), we calculated the total potential $U_{\rm t}$ from the evanescent wave mirror, the results are shown in Fig.8. It is clear from Fig.8 that with the increasing of the beam waist w from 1 mm to 10 mm, the total potential will be greatly reduced from 1.48mK to 23μK, which are far smaller than that from the SGB mirror (see Fig.7). Figures 7 and 8 show the comparison of optical potentials of the SGB and ELW mirrors. We can see from Figs.7 and 8 that with the same beam parameters such as P_0= 1W and w=5 mm, the maximum height of optical potential from the SGB mirror is 3 times higher than that from the ELW mirror, but the decay of the evanescent wave potential with the coordinate x is much faster than that of the SGB mirror.

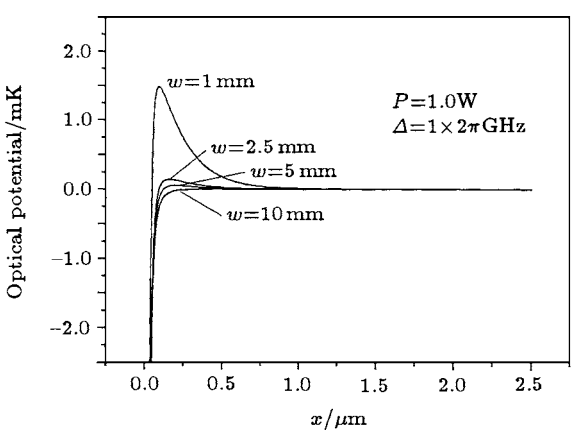


Fig.8. Total potential of the evanescent light wave for ^{85}Rb atoms for different beam waists w, the power P_0=1W and the detuning $\Delta = 1 \times 2\pi$GHz.

From Eqs.(15) and (16) or Fig.8, we can see that the attractive van der Waals potential greatly reduce the repulsive optical potential in the vicinity of the inner surface. If the kinetic energy of an ^{85}Rb atom approaching the inner surface is greater than the maximum value of the total potential, the atom will cross the potential barrier and will hit the surface and then stick there with high probability. Only the atoms hitting the evanescent wave close enough to the centre of the Gaussian beam will undergo a light shift large enough to reflect them.

4.4. Comparison of intensity gradient forces of the two mirrors

Using the optical dipole force from a blue-detuned inhomogeneous light field to reflect the atoms is the most promising physical realization of an atomic mirror, where the dipole force acting on the atoms is proportional to the field gradient

$$F = -\nabla U(x) = -\frac{\partial U(x)}{\partial x}. \tag{17}$$

Figure 9 shows the comparison of intensity gradient forces (i.e. optical dipole forces) of the SGB and ELW mirrors for P_0=1W, w=5mm and $\Delta = 1\times 2\pi$GHz. It can be seen from Figs.9(a) and 9(b) that under identical conditions, the optical dipole force from the SGB mirror is $\sim 7.5 \times 10^{-23}$N, which is greater than the gravity force (mg) by $\sim 1.5 \times 10^5$ times and smaller than that from the ELW mirror by $\sim$ 160 times, and the decay of the ELW dipole force with the coordinate x is much faster than that of the SGB dipole force.

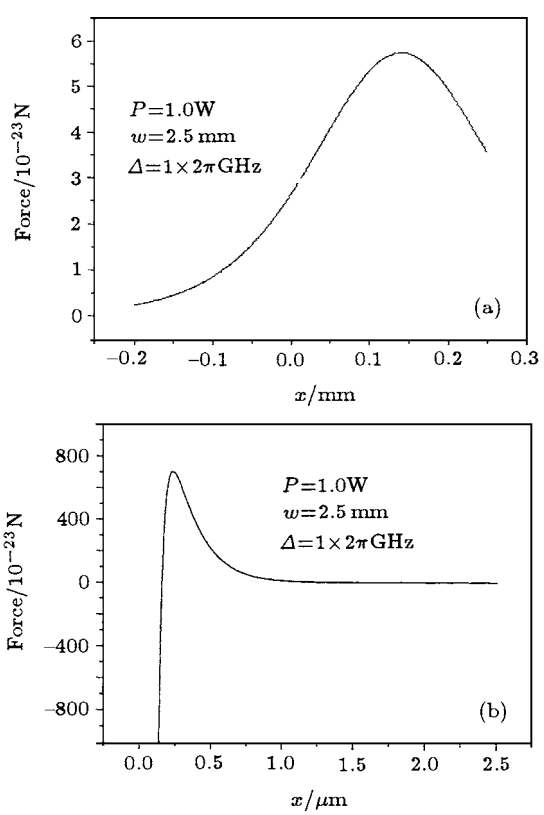


Fig.9. Comparison of the gradient forces of (a) the SGB mirror and (b) evanescent light wave for the laser power P_0=1W and the beam waist w=2.5 mm.

4.5. Comparison of spontaneous emission probabilities of the two mirrors

Spontaneous emission is a main disadvantage of optical-dipole atomic mirror because spontaneous emissions cause momentum diffusion, leading to a broadening of the reflected atomic beam and also destroy the mutual coherence between the incident and the reflected de Broglie matter waves.[12]

When an atom with a mass m and a velocity $v_\perp$ perpendicular to the reflecting surface enters into an inhomogeneous light field with a laser power P_0 and a detuning Δ, it will absorb some photons and then make corresponding spontaneous emissions, and its spontaneous-emission probability can be estimated by[36]

$$P_{\rm sp} = 1 - \exp\left(-\frac{mv_\perp x_{\rm apd}\Gamma}{\hbar\Delta}\right), \qquad (18)$$

where $x_{\rm apd}$ is the averaging penetrated depth of the reflected atom in the light field.

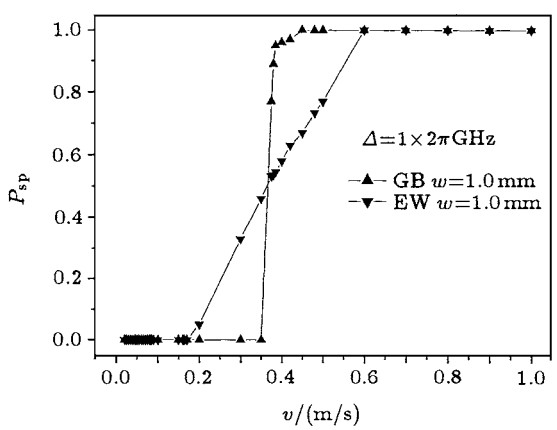


Fig.10. Spontaneous emission probability $P_{\rm sp}$ of the reflected ^{85}Rb atoms from the SGB and EW mirrors for the detuning $\Delta = 1 \times 2\pi$GHz and the beam waist w= 1 mm.

From Eq.(18), we calculated and compared the spontaneous-emission probabilities $P_{\rm sp}$ of the reflected atoms from the SGB and ELW mirrors, the results are shown in Fig.10. It is clear from Fig.10 that when the beam waist w is small, such as w= 1 mm, the spontaneous emission probability of the reflected atoms increased with the mean normal velocity of incident atoms, but the increase of the spontaneous emission probability of the reflected atoms from the SGB mirror is much faster than that from the ELW mirror, and the two curves cross at the velocity of $\sim$ 35 cm/s. Moreover, the spontaneous emission probability $P_{\rm sp}^{\rm SGB}$ of the reflected atoms from the SGB mirror is lower than that ($P_{\rm sp}^{\rm EW}$) from the ELW mirror at lower normal velocities (such as below 35 cm/s), whereas the $P_{\rm sp}^{\rm SGB}$ is greater than $P_{\rm sp}^{\rm EW}$ at higher velocity (e.g., above 35 cm/s). This can be explained as follows: the optical potential of the SGB mirror for the reflected atoms is far higher than that of the ELW mirror, the mean penetrating depth $x_{\rm apd}^{\rm SGB}$ of the atoms with a lower velocity in the diffracted light of the SGB is smaller than that ($x_{\rm apd}^{\rm EW}$) in the ELW light, so the $P_{\rm sp}^{\rm SGB}$ will be lower than the $P_{\rm sp}^{\rm EW}$ at the lower velocity. While the normal velocity of the reflected atoms is higher (e.g., above 35 cm/s), the $x_{\rm apd}^{\rm SGB}$ will exceed the $x_{\rm apd}^{\rm EW}$ since the dipole force $F^{\rm SGB}$ is far smaller than the $F^{\rm EW}$, so the $P_{\rm sp}^{\rm SGB}$ will be higher than the $P_{\rm sp}^{\rm EW}$ at the higher velocity.

5. Conclusions and discussions

A new and simple atomic mirror scheme using blue-detuned semi-Gaussian beam is proposed. We have calculated the diffracted intensity distribution from the SGB reflecting surface and its optical potential for ^{85}Rb atoms, and estimated the maximum normal velocity of the reflected atoms from the SGB and its spontaneous emission probability. We have also compared the performances of the SGB and ELW mirrors, and the main results and conclusions are as follows:

1) The relative diffracted intensity of the SGB reflecting surface is increased by $\sim$ 34 %, and its intensity gradient is nearly the same as that of the semi-plane wave or the semi-rectangular-profile beam and far greater than that of the Gaussian beam or elliptical-Gaussian beam, so a blue-detuned SGB can be used to efficiently reflect atomic beam as a novel atomic mirror, and the area of the SGB reflecting surface can be equal to a width of $4/5w$ times an infinite length. Under the same parameters of incident Gaussian beam, the performances of the SGB mirror, such as the area and smoothness (or flatness) of specular surface, are much better than that of the ELW mirror (or the Gaussian-beam mirror). Strictly speaking, a blue-detuned Gaussian beam (including focused Gaussian beam) or an elliptical Gaussian beam cannot be used as an atomic mirror because they have not a smooth specular surface with definite size.

2) The optical potential of the SGB mirror for neutral atoms is far greater than that of the ELW mirror with the same beam parameters, so the maximum normal velocity of incident atomic beam ($\theta = 90°$) reflected from the SGB mirror can be greater than 1m/s when the laser power P_0=1W, the beam waist

w=1 mm and the detuning Δ=1×2πGHz. In this case, when the incident angle θ of atomic beam is changed to ∼1mrad, the maximum grazing-incident velocity of atomic beam can be greater than ∼ 600m/s, which is much higher than that reflected from the ELW mirror.

3) The intensity gradient of the ELW mirror and its dipole force are greater than that of the SGB mirror by ∼ 160 times with the same beam parameters. When the normal velocity of the atoms is greater (such as greater than 35 cm/s), the spontaneous emission probability of the reflected atoms from the ELW mirror is lower than that from the SGB mirror. However, when the normal velocity is lower, spontaneous emission probability from the ELW mirror is always higher than that from the SGB mirror, this is because the optical potential of the SGB mirror for the reflected atoms is far greater than that of the ELW mirror. In addition, the creation of the SGB mirror is simpler than that of the ELW mirror, and the use of the SGB mirror and its manipulation and control for cold atoms in vacuum chamber are also more convenient and flexible than that of the EW mirror.

In short, the performance of the SGB mirror is better than that of the ELW mirror when the normal velocity of incident atoms is comparatively low (e.g., below 35 cm/s). Therefore, our proposed SGB mirror cannot only be used to efficiently reflect the atomic beam, but also has some other applications in atom optics. E.g., it can be used to form an atomic optical cavity (F–P cavity),[25,26] an atom grating and an optical conveyor belt[37] for cold atoms; it even may be used to trap cold atoms or cool neutral atoms by intensity-gradient cooling from the SGB itself,[38] and so on. Moreover, due to ac Stark effect, such a SGB mirror can also be used to reflect cold molecular beam, even to manipulate and control the motion of cold molecules, and so on.

References

[1] Stern O 1929 *Naturwissenschaften* **17** 391
[2] Adams C, Sigel M and Mlynek J 1994 *Phys. Rep.* **240** 143
[3] Balykin V I and Letokhov V S 1989 *Appl. Phys.* B **48** 517
[4] Wallis H, Dalibard J and Cohen-Tannoudji C 1992 *Appl. Phys.* B **54** 407
[5] Farias D and Rieder K H 1998 *Rep. Prog. Phys.* **61** 1575
[6] Cook R J and Hill R K 1982 *Opt. Commun.* **43** 258
[7] Balykin V I, Letokhov V S, Ovchinnikov Yu B *et al* 1988 *Phys. Rev. Lett.* **60** 2137
[8] Kasevich M A, Weiss D S and Chu S 1990 *Opt. Lett.* **15** 607
[9] Aminoff C G, Steane A M, Bouyer P *et al* 1993 *Phys. Rev. Lett.* **71** 3083
[10] Esslinger T, Weidemuller M, Hemmerich A *et al* 1993 *Opt. Lett.* **18** 450
[11] Deutschmann R, Ertmer W and Wallis H 1993 *Phys. Rev.* A **47** 2169
[12] Seifert W, Kaiser R, Aspect A *et al* 1994 *Opt. Commun.* **111** 566
[13] Seifert W, Adams C S, Balykin V I *et al* 1994 *Phys. Rev.* A **49** 3814
[14] Laryushin D V, Ovchinnikov Yu B, Balykin V I *et al* 1997 *Opt. Commun.* **135** 138
[15] Hughes I G, Barton P A, Roach T M *et al* 1997 *J. Phys.* B *At. Mol. Opt. Phys.* **30** 647
[16] Hughes I G, Barton P A, Roach T M *et al* 1997 *J. Phys.* B *At. Mol. Opt. Phys.* **30** 2119
[17] Saba C V, Barton P A, Boshier M G *et al* 1999 *Phys. Rev. Lett.* **82** 468
[18] Hinds E A and Hughes I G 1999 *J. Phys.* D *Appl. Phys.* **32** R119
[19] Drndic M, Johnson K S and Thywissen J H 1998 *Appl. Phys. Lett.* **72** 2906
[20] Drndic M, Drndi M, Zabow G *et al* 1999 *Phys. Rev.* A **60** 4012
[21] Poulsen U V and Molmer K 2000 *Eur. Phys. J,* D **11** 151
[22] Rosenbusch P, Hall B V, Hughes I G *et al* 2000 *Appl. Phys.* B **70** 709
[23] Rosenbusch P, Hall B V, Hughes I G *et al* 2000 *Phys. Rev.* A **61** 031404
[24] Kadio D, Houde O and Pruvost L 2001 *Opt. Lett.* **54** 417
[25] Wilkens M, Goldstein E, Tayor B *et al* 1993 *Phys. Rev.* A **47** 2366
[26] Santos L and Roso L 1998 *Phys. Rev.* A **57** 432
[27] Lee H J, Adams C S, Kasevich M *et al* 1996 *Phys. Rev. Lett.* **76** 2658
[28] Bongs K, Burger S, Dettmer S *et al* 2000 *J. Mod. Opt.* **47** 2697
[29] Pearson J E, McGill T C, Kurtin S *et al* 1969 *J. Opt. Soc. Am.* **59** 1440
[30] Otis G and Lit J W Y 1975 *Appl. Opt.* **14** 1156
[31] Yin J, Zhu Y, Wang W *et al* 1998 *J. Opt. Soc. Am.* B **15** 25
[32] Bennett C R, Kirk J B and Babiker M 2001 *Phys. Rev.* A **63** 033405-1
[33] Labeyrie G, Landragin A, Zanthier J Von *et al* 1996 *J. Opt: Quantum Semiclass. Opt.* B **8** 603
[34] Nesnidal R C and Walker T G 1996 *Appl. Opt.* **35** 2226
[35] Soding J, Grimm R and Ovchinnikov Yu B 1995 *Opt. Commun.* **119** 652
[36] Yin J, Zhu Y, Jhe W *et al* 1998 *Phys. Rev.* A **58** 509
[37] Schrader D, Kuhr S, Alt W *et al* 2001 *Appl. Phys.* B **73** 819
[38] Yin J, Gao W and Wang Y 2001 *Phys. Lett.* A **288** 9