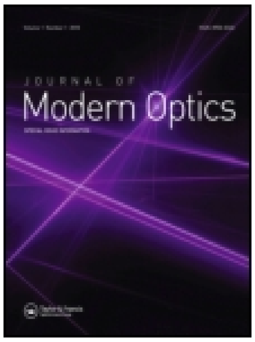

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Atom guiding along high order Laguerre–Gaussian light beams formed by spatial light modulation

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A spatial light modulator (SLM) has been used to create high quality Laguerre–Gaussian (LG) light beams, which have been used to study the guiding of cold rubidium atoms. The SLM allows real-time variation of the hollow guiding beam and permits direct comparison of the guided atom fluxes for different LG modes with minimal adjustment of the other optical components. It is demonstrated that, by increasing the azimuthal index l of the Laguerre–Gaussian beam, the radiation pressure pushing the trapped atoms may be reduced while maintaining the same guided flux. This is the first comparative study of hollow beam atom guiding, and further demonstrates the versatility of the SLM for studies in atom optics.

1. Introduction

The interaction of light and matter provides two key forces with which to influence the external degrees of freedom of atomic ensembles. The radiation pressure or scattering force occurs near resonance, and determines the process of laser cooling that can reach temperatures in the microkelvin range for a variety of atomic species [1]. The dipole or gradient force, which is central to creating guides and dipole traps for atoms, conversely uses a laser frequency either below (red-detuned) or above (blue-detuned) resonance: the detuning determines whether atoms are attracted to or repelled from the intensity maxima of the light field. These techniques are prerequisites for studies of atom optics [1], Bose–Einstein condensation and ultracold Fermi gases [2, 3].

Experiments in atom optics require a range of components analogous to those for light optics, such as guides, mirrors and lenses. The motivations for such work are potential applications in atom lithography, atom interferometry and studies of wave–particle duality. The guiding or channelling of slow, cold atomic ensembles

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is of interest for a number of studies: a remarkable example is the use of optical tweezers to translate Bose–Einstein condensed atoms between trap regions in order to replenish an atom laser source [4]. There also remains significant interest in the guiding of non-condensed atoms for standard atomic beams, the loading of fibre guides, and atomic clocks. These more conventional applications may present additional challenges, however, for the relatively energetic atoms require higher guiding potentials and are more likely to penetrate into anharmonic regions of the optical potential.

Most guiding geometries have so far exploited the red-detuned dipole force. Such geometries allow the use of simple Gaussian laser beams but, because the atoms are attracted into regions of high optical intensity, the guiding forces are accompanied by a significant scattering force. Blue-detuned optical guiding, where the light frequency is tuned above resonance, has the advantage that the atoms are then restricted to regions of intensity minima, and perturbations induced by the light field are thus minimized. Blue-detuned guiding of a cold atomic beam along a hollow, low-order Laguerre–Gaussian light beam has already been reported [5, 6], as has the guiding of cold atom clouds dropped from magneto-optical traps (MOTs) into hollow beams generated using axicon lenses [7] and hollow optical fibres [8]. These various schemes each have their merits, but these forms of beam generation are not true propagating modes and may show a significant change in transverse beam profile with propagation. The frequency detuning is also a key parameter, and the near-resonant guiding of Song *et al.* [7] is accompanied by significant radiation pressure, which can levitate or push the atomic cloud and which causes heating of up to 15 μK. When the detuning exceeds 10 GHz and the cloud is cooled in a molasses cycle, however, extended guiding can occur with relatively little heating [8].

Recently, we reported the guiding of a cold atomic beam along a co-propagating and inclined Laguerre–Gaussian (LG) beam [9]. In contrast with beams used in other guiding studies, Laguerre–Gaussian light beams propagate in free space without altering their transverse form. These beams are characterized by a radial and an azimuthal mode index, and the simplest radial profile, for all but the lowest azimuthal mode, resembles a single hollow ring. The azimuthal index l is the number of cycles of 2π phase incurred upon traversing the mode circumference; as the azimuthal index is increased, the ring becomes thinner and, for a given laser power, the dipole potential can be made greater while the radiation pressure within the ring is reduced. The optimization of hollow guides is crucial for the transport of quantum degenerate gases, many forms of atom interferometry, and ultra-stable atomic fountain clocks: in each case, any heating can be a serious drawback. The use of high-order Laguerre–Gaussian beams for atom guiding and channelling has been addressed theoretically in a previous paper [10].

There has been no previous experimental comparison of hollow beams for cold atom guiding, principally because each configuration would involve major changes to and optimization of the optical arrangement. Spatial light modulators allow most of these changes to be implemented simply by changing the computer-generated pattern. In recent work, we proposed the use of spatial light modulators for studies in atom optics [11]. They may create arrays of dipole traps [12, 13] and advanced forms of atom guides including Mach–Zender interferometers and beam splitters [11]. This technology may strongly underpin future studies of optical interactions in the field of cold atoms and Bose–Einstein condensates. Here, for the first time, we apply the spatial light modulator to cold atom transport by using the device for the real-time creation of the LG guide beams. This permits us to switch between different LG modes without other alteration of the optical apparatus, and presents a very powerful tool for the real-time comparison of hollow optical guides in the atom trap.

Significantly, our studies confirm the fidelity of the SLM as a tool for atom optics. In some configurations, the generation of vortices using these devices can result in azimuthal intensity variations [14] which would be detrimental to atom transport. Such corrugations are not limited to the use of SLMs, and result from the interference of various orders of the diffracted beam along with undiffracted light that lacks the azimuthal phase. We show here that by programming the SLM with off-axis blazed holograms to separate the diffraction orders, and attenuate the undiffracted beam, we can generate hollow optical guides that retain their integrity and offer no deleterious effects for atom guiding.

2. Laguerre–Gaussian light beams

The circularly symmetric Laguerre–Gaussian laser modes form a complete basis set and are usually denoted LG_p^l where l and p are the two integer indices that define the mode. The azimuthal index *1* refers to the number of 2π phase cycles around the circumference of the mode, while p indicates the number of off-axis radial nodes in the mode profile. The intensity of the mode LG_p^l is given by [10]

$$I(r,z) = \frac{2p!}{\pi(p+|l|)!}\frac{P_o}{w^2(z)}\exp\left(-2\frac{r^2}{w^2(z)}\right)\left(\frac{2r^2}{w^2(z)}\right)^{|l|}\left\{L_p^{|l|}\left(\frac{2r^2}{w^2(z)}\right)\right\}^2 \quad (1)$$

where the waist size at any position is given by

$$w(z) = w_o\sqrt{1+\left(\frac{\lambda z}{\pi w_o^2}\right)^2}. \quad (2)$$

Here, z is the distance from the beam waist, r is the radial distance from the beam axis, P_o is the power of the beam, λ is the wavelength, $w(z)$ is the radius at which the Gaussian term falls to $1/e$ of its on-axis value, w_0 is this value at the beam waist size, and L_p^l is the generalized Laguerre polynomial. We generate these modes using computer-generated holograms that are written directly onto the SLM. For atom guiding, the optical dipole potential is given by [8]

$$U(r,z) = \frac{\hbar\Delta}{2}\ln\left[1+\frac{I(r,z)/I_{sat}}{1+4(\Delta/\Gamma)^2}\right]. \quad (3)$$

$\Delta = \omega_L - \omega_0 - kv_z$ is the detuning of the laser frequency ω_L from the Doppler-shifted atomic resonance $\omega_0 + kv_z$. For our experiment on ^{85}Rb, the other parameters are the wavelength $\lambda = 780.2$ nm, the saturation intensity $I_{sat} = 16\,\mathrm{W\,m^{-2}}$ and the natural linewidth $\Gamma = 2\pi \times 6.1$ MHz; the z-dependence of the intensity profile may be neglected.

The spatial variation of the optical guiding potential hence reflects the intensity profile of the light beam employed. For $p = 0$ and $l > 0$ – the beams with which we are concerned in this study – the Laguerre–Gaussian beam forms a single ring of light with its maximum intensity at

$$r_l = w(z)\sqrt{\frac{l}{2}}. \tag{4}$$

The value of this maximum intensity is given at the waist ($z = 0$) by

$$I_{\max} = \frac{2}{\pi l!}\frac{P_0}{w_o^2} l^l \exp(-l) = \frac{P_0}{\pi r_l^2}\frac{l^{l+1}\exp(-l)}{l!}. \tag{5}$$

Stirling's approximation gives this to within 10% (2% for $l > 4$):

$$I_{\max} = \frac{P_0}{\pi r_l^2}\sqrt{\frac{l}{2\pi}} \tag{6}$$

and we thus see that the height of the optical potential barrier, for a given ring size, increases with the azimuthal index l. The barrier at the same time becomes sharper, reducing the region in which guided atoms experience the residual radiation pressure.

For a given laser intensity, the height of the resulting potential barrier is governed by the frequency detuning Δ, giving a maximum value at

$$\Delta_{opt} \approx \frac{\Gamma}{4}\sqrt{\frac{I_{\max}}{I_{sat}}}. \tag{7}$$

If $I_{\max} \gg I_{sat}$, this results in an optimized potential barrier height of

$$U(r) \approx \frac{\hbar\Delta \ln 8}{8}\sqrt{\frac{I_{\max}}{I_{sat}}}, \tag{8}$$

which, for a given ring size, is approximately proportional to $l^{1/4}$. Curtis and Grier have pointed out that constrained optical systems producing superpositions of Laguerre–Gaussian modes may be characterized by an even stronger dependence upon the azimuthal index l [14].

Although cold atomic ensembles typically penetrate only weakly into the potential barrier, they can nonetheless receive a significant push from radiation pressure there: in previous hollow beam guiding experiments using a near resonance hollow beam, this allowed levitation of the atom cloud [7]. The degree of penetration is dictated, for a given detuning, by the gradient of the hollow guiding potential, and the radiation pressure push should thus depend upon the order l of the LG beam used.

3. Experiment

Our source of cold ^{85}Rb atoms is a magneto-optical trap (MOT), shown schematically in figure 1. The main vacuum chamber is mounted on one flange of a six-way UHV cross, the whole apparatus being held at a base pressure of 10^{-9} mbar

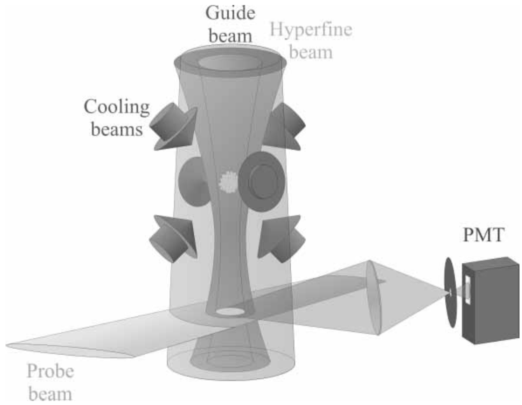

Figure 1. Experimental arrangement. Rubidium-85 is trapped in a standard magneto-optical trap. The hyperfine repumping beam is directed vertically down, along the direction of the guide beam, and is maintained when the other trap beams are extinguished to release the cloud. The atoms are detected, after travelling distances up to 5 cm (limited by optical access), by using a retro-reflected elliptical probe beam to excite fluorescence which is imaged on to a photomultiplier tube.

by a 25 ls^{-1} ion pump. An alkali metal dispenser releases rubidium vapour when approximately 4 A of current flows through it, and is positioned close ($\sim$15 cm) to the trapping region to allow accurate control of the rubidium pressure therein. Two coils are placed around the trap in an anti-Helmholtz configuration with their common axis horizontal. Each has around 80 turns and carries a typical current of 15 A, yielding a measured field gradient of $\sim$10 G cm^{-1}. Two circularized extended cavity diode laser systems [15] provide probing and repumping light respectively on the $F=3 \rightarrow F'=4$ and $F=2 \rightarrow F'=3$ transitions of ^{85}Rb. The main cooling laser is a Toptica TA100 tapered amplifier diode laser system, giving up to 400 mW at 780 nm. All lasers are frequency stabilized to better than 1 MHz. Cold atoms with a temperature around 160 μK accumulate into a cloud of approximately 1.8 mm in diameter containing 6×10^7 atoms.

When the MOT beams are subsequently extinguished, the atoms fall within the guide beam. In addition to gravity, the magnetic field gradient $\partial B/\partial r$ provides a force

$$F_{mag} = -g_F m_F \mu_B \frac{\partial B}{\partial r}, \tag{9}$$

which depends upon the angular momentum projection m_F, μ_B being the Bohr magneton. For the $F=3$ ground hyperfine state, the g-factor $g_F = 1/3$. The net downward acceleration hence varies from 0.4 g to 1.6 g, giving expected free-fall flight times of 60–120 ms in which an unguided atom cloud will expand to a radius of 7–15 mm. Any radiation pressure from the guide beam increases this acceleration, and expansion of the cloud during its flight to the detector will be correspondingly reduced.

The linearly polarized hyperfine repumping beam co-propagates with the guide and remains when the cooling beams are extinguished, ensuring that the atoms continue to return to the same hyperfine level (but not necessarily sub-state) and thus maintain the same guide beam detuning. A probe beam consisting of a sheet of light (1 mm by 5 mm) tuned to the cooling transition intercepts the atoms 3 cm below the trap region and an area of the subsequent atom fluorescence 4 mm in diameter is imaged onto a photomultiplier tube 15 cm away.

The LG guide beam is derived from a standing wave Ti : sapphire laser pumped by a 5 W 532 nm laser source, giving up to 700 mW of tunable radiation with a linewidth of around 200 MHz. The guide light is introduced into the chamber so as to co-propagate with the dropped cloud. Laguerre–Gaussian beams, with $p=0$ and various azimuthal index l, are formed using a spatial light modulator (Hamamatsu X8267) with an efficiency of 50%. The holograms combine a spiral phase shift with a blazed grating to yield LG beams in the first diffracted order and ensure that no undiffracted light is present at the centre of the guide beam (figure 2). We have

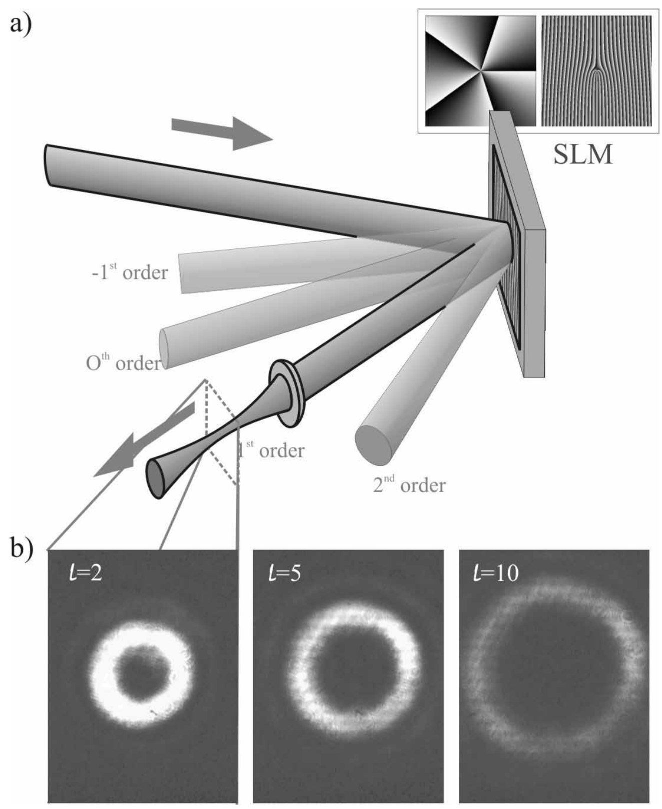

Figure 2. (*a*) Generation of Laguerre–Gaussian beams using a spatial light modulator. The SLM is encoded with a hologram (inset right, showing the spiral phase structure without and with the grating). A collimated beam is incident on the SLM and the output LG beam is then imaged into the trap at the desired size. The first diffracted order is used, to ensure that no undiffracted (zero-order) light is present in the centre of the LG beam. The profiles of the beams obtained are shown in (*b*).

verified that the LG beams are azimuthally uniform, with no discernable structure and an intensity variation of at worst ($l = 10$) 20% around the ring.

A LabVIEW program controls the phase and grating parameters of the hologram, allowing us to switch the LG beam in real time between different azimuthal orders. An optical telescope with a zoom facility readily allows one to adjust the beam waist below the atom cloud, so as to achieve the same ring radius regardless of azimuthal index. Overall, the system allows us to change easily and quickly between LG beams of various orders with no loss of optical alignment. The Rayleigh range of the guide beam is around 30 cm, so the guide may be treated as a non-diffracting tube over the experimental guiding distance.

4. Results

We have measured the fluxes of atoms guided by LG beams of various azimuthal index l, comparing beams of either equal beam waists w_0 (and hence differing ring sizes r_l) or equal ring sizes, whereby the radii of maximum intensity, r_l, were adjusted to the same value. In both cases, data were recorded for a series of laser detunings up to 10 GHz from resonance.

Initially, we studied the guiding of atoms by various LG beams of the same power, detuning and beam waist. In this regime, the ring size, r_l, increases with azimuthal index, an $l = 10$ beam having ~3 times the radius of an $l = 1$ beam, and the optical dipole potential falls correspondingly. For a detuning of 2 GHz, for example, a beam 1 mm in diameter with $l = 1$ produces a dipole potential of 570 μK, while for $l = 10$ the potential is only 190 μK. The data shown in figure 3 demonstrate that, while the arrival of the cloud at the probe region occurs for higher values of l at

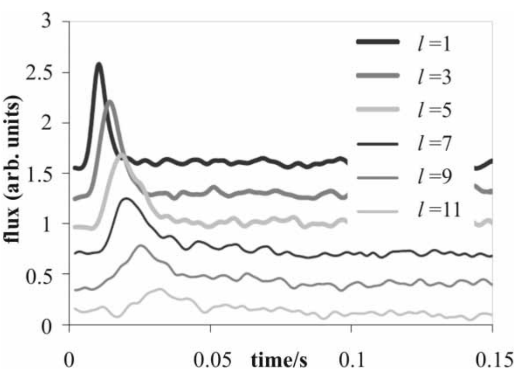

Figure 3. Guided atom fluxes for beams of fixed waist $w_0 = 0.9$ mm and detuning from resonance of 2 GHz. Increasing the index l of the LG beam increases the effective guide radius and results in a lower guiding intensity and darker beam centre. A reduction in the accompanying radiation pressure is indicated by the longer time of flight, approaching that of the unguided cloud. The $l = 3$ beam is best matched to the cloud beam size; the $l = 1$ beam gives a higher guiding potential but clips the edges of the cloud. The different results have been plotted at the same scale but have been separated vertically to aid viewing.

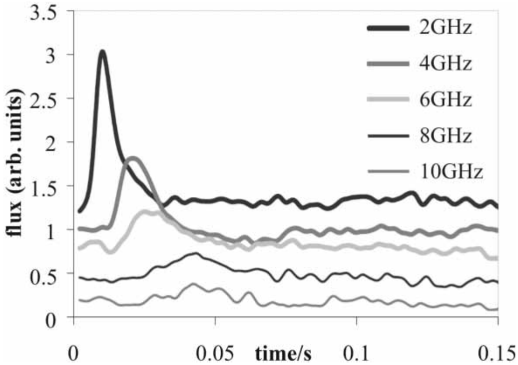

Figure 4. The effect of detuning on an $l = 1$ guide, equivalent to those in figure 3 but with detunings from resonance of 2, 4, 6, 8 and 10 GHz. The different results have been separated vertically to aid viewing.

times approaching the 60–120 ms expected for unguided atoms, it advances with decreasing l. This indicates that, as the azimuthal index is increased, the atom cloud is accelerated less by the radiation pressure associated with the guiding beam, thanks to the increasing ring size and darker beam centre. The effect of detuning further from resonance, which reduces the optical potential and scattering force without changing the beam profile, is shown for an $l = 1$ beam of the same waist, w_0, in figure 4.

As expected for potential barriers of greater or similar energy to the atomic sample, the total integrated fluence arriving at the detection region shows no significant change with l up to $l \approx 7$, the number of atoms observed being in each case around a factor of 10 greater than with the guide beam absent, when the signal is reduced to the same level as systematic noise associated with transients accompanying the release of the atom cloud. For the higher values of l, there is a slight fall. Calculation of the spontaneous scattering rate shows that for low l the cloud will incur a temperature increase of approximately 10 μK, which falls dramatically with increasing l in accordance with previous calculations [10]. Even the modest temperature increase of 10 μK would be highly detrimental to guiding clouds from optical molasses or a Bose–Einstein condensate within such a low l guide.

For a more direct demonstration of the effect of beam index upon the guiding characteristics, we repeated our experiments with beams whose waists w_0 were adjusted, using the zoom telescope arrangement, to give the same ring size (radius of maximum intensity), r_l, for each value of l. The ring size of 2.2 mm was chosen to be slightly larger than the cloud diameter. The resulting data, comparing various orders of LG beam, were readily obtained with no alteration whatsoever in alignment, emphasizing the versatility of the SLM in this experiment. Figure 5 shows results for detunings of 2 GHz and 5 GHz from resonance. We calculate the dipole potentials at 2 GHz to be 220 μK, 300 μK and 480 μK for $l = 3$, 5 and 12 respectively. These results, illustrating the acceleration of the falling cloud by radiation pressure from a co-propagating beam, reinforce those of Song *et al.* [7],

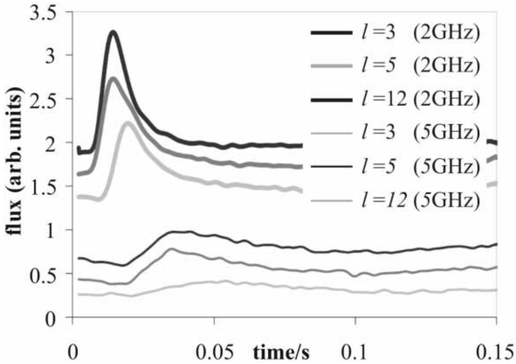

Figure 5. Time of flight profiles for atom clouds falling within guide beams of the same ring size but various azimuthal index l. The guide beams are 2.2 mm in diameter – slightly larger than the initial cloud itself – and are detuned from resonance by 2 GHz (thick lines) and 5 GHz (thin lines). The different results have been separated vertically to aid viewing.

who observed deceleration and levitation of falling atoms when using a counter-propagating hollow guide beam of low detuning. The total fluence guided by the $l = 12$ beam is around a half of that obtained with $l = 3$.

5. Conclusions and summary

We have demonstrated atom guiding along various high-order Laguerre–Gaussian light beams with azimuthal indices ranging from l to 12. These beams have on-axis minima that are retained during propagation in contrast to other hollow light beams examined for applications in atom optics. Our experiments confirm that, for a given ring radius, LG beams of high azimuthal index l offer larger potential barriers and lower radiation pressure effects than beams of lower index, yielding comparable fluxes to low l beams without the accompanying radiation pressure push. The guiding beam enhances the integrated atom flux reaching the detection region by an order of magnitude. High l Laguerre–Gaussian beams hence appear to offer significant advantages for the guiding of ultra-cold atoms and Bose–Einstein condensates.

We have shown the versatility of spatial light modulators for atom guiding applications, allowing in this case the *in-situ* variation of the order of the LG beam and thereby allowing the first comparative study of blue detuned atom guiding. Significantly, our use of a blazed, off-axis hologram results in no observable corrugation around the ring, in contrast to previous on-axis configurations. Our studies hence demonstrate the capability of the SLM to create robust optical guiding potentials with the fidelity necessary for atom optical applications.

High l Laguerre–Gaussian beams are an example of the complex optical fields that may readily be produced by spatial light modulation. For transport over greater distances, we envisage the use of Bessel light beams [10]. Future experiments will explore more refined light patterns for optical beam splitters and Mach–Zender interferometers [16] that may pave the way for advanced atom interferometry with quantum gases.

Acknowledgments

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