High efficiency, low cost holographic optical elements for ultracold atom trapping

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Abstract: We demonstrate a method of creating high efficiency, high fidelity, holographic optical elements for the generation of complex optical fields, in a low cost photopolymer, Bayfol HX. The desired optical field profile is generated by a spatial light modulator and written into an optically addressable photopolymer as a volume hologram. We demonstrate the utility of this approach by trapping a Bose-Einstein condensate of rubidium-87 atoms in the nodal plane of an $\mathsf{H}G_0,1$ mode generated by one of these holographic optical elements. We also extend this method to the generation holograms with twice the angular momentum per photon than can be generated with a given spatial light modulator.

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1. Introduction

A growing number of applications are being found for the complex spatial manipulation of optical fields via diffractive optics, including; optical trapping and manipulation of cold atoms [1], data transmission via orbital angular momentum multiplexing [2], the quantum entanglement of photons for various applications [3] and materials processing [4]. In particular, in the field of cold atom trapping far off resonant traps are useful for studying condensates in a variety of different geometries [5,6]. However, due to the limited damage thresholds of most optical fibers delivering the laser light to the atoms, high efficiency mode conversion from the output of the fiber to the desired optical potential is required for deep optical traps. Of particular interest are optical modes with high angular momentum, that are blue-detuned from resonance as the radial intensity profile of these modes approximates a power law, with the exponent approximately equal to twice the angular momentum of the mode [7]. These traps provide a ‘sharp’ walled radial potential, or flat bottomed trap, for cold atoms allowing the study of a uniform density condensate.

One approach to the spatial manipulation of optical fields is to use a spatial light modulator (SLM), a digitally addressable pixelated screen that can locally vary the phase or amplitude of the optical field on a pixel by pixel basis. In this regard, SLMs have found a great number of applications within a range of fields since their commercialisation, including; beam steering [8], holographic optical traps [9] and the formation of complex scalar fields [10]. These devices have proved themselves valuable, however a number of problems have been associated with these devices due to their physical structure, and how they are electronically addressed. These problems include; low total diffraction efficiency [11], time varying intensity profiles and low optical damage thresholds of the device. The low total diffraction efficiency into a single desired mode from an SLM arises due to two factors; the large number of modes formed from the phase (or amplitude) only holograms employed to manipulate the optical field arising from the two-dimensional (2D) nature of the device, and the periodic ‘black space’ between pixels used to reduce electrical crosstalk between the pixels. The pixelation caused by the space between pixels generates a number of diffracted orders upon reflection or transmission from or through the SLM screen, and can leave as little as \( \approx 50\% \) of the incident power in the undiffracted mode. Time varying intensity profiles arise due to an effect known as ‘phase flicker’ that is due to the pulsed modulation scheme used to address the pixels within the device [12]. This can lead to a time varying phase delay with a period on the order of 10 ms which can generate undesirable heating in cold atoms, and makes the SLM’s only useful in systems which evolve on timescales greater than 100 Hz. Phase flicker can be reduced by reducing the temperature of the liquid crystals in the display, but the effect has not been entirely removed [13].

For the generation of high angular momentum optical fields, SLMs must be able to generate large phase gradients azimuthally, as it is this phase gradient that transfers angular momentum to the optical field. The phase shift achievable per pixel (typically \( \approx 2\pi \)) and the number of pixels (resolution) of the SLM display, limits the achievable phase gradient, with the latter generally being the more restrictive. This limit is in practice further reduced as most techniques
for generating high-order orbital angular momentum states employ the SLM as a diffractive phase element also. This allows the optical modes generated by the SLM to be physically separated, generally achieved with a pair of relay lenses and a spatial filter at the focus of the first lens to select the desired mode. However when high angular momentum states are formed the spatial profiles in the fourier plane are overlapped due to the increased radius of the mode, and thus complete isolation cannot be achieved. This results in decreased fidelity of the desired field, and introduces asymmetries to the field arising from the asymmetry present in the diffraction grating.

2. Optically copying a spatial light modulator

A volume hologram can provide a superior alternative to an SLM whenever dynamic phase modulation is not required. Previously, computer generated holograms written into photographic films [14], or lithographically etched in glass [15] have been demonstrated to produce a range of optical fields however the production of these holograms is generally time consuming and expensive which limits their use in atom trapping experiments. Volume holograms can achieve greater total diffraction efficiencies compared to SLMs or 2 dimensional gratings, as the Bragg condition for diffraction allows for only two modes to be formed upon reconstruction (the undiffracted and the diffracted mode). Volume holograms also do not suffer from the pixelation losses of an SLM, as they are generally formed via a refractive index modulation within the material that is continuous, rather than pixelated.

Here we demonstrate how the photopolymer Bayfol HX may be used in conjunction with an SLM for the production of volume holograms of arbitrary complex optical fields. This technique allows one to effectively ‘copy’ the function of an SLM into the volume hologram with similar fidelity as the SLM, but without the associated problems of the SLM, with the process also being repeatable allowing any number of holograms to be made from a single SLM. These photopolymers are ≈16 µm thick and have been shown to achieve refractive index modulations ∆n ≥ 0.03, allowing them to achieve diffraction efficiencies on the order of ≈98% in both transmission and reflection geometries [17]. The refractive index modulation is the largest factor in determining the diffraction efficiency of the hologram, and depends on the total exposure dosage, the power density of the writing beams, the ratio of power in the reference and object beams and the spatial frequency at which the holograms are written [18, 19]. These properties make the photopolymer film a suitable choice for applications where one wishes to tailor the diffraction efficiency of the hologram while having independent control over other parameters of the hologram, such as the Bragg angle or the geometry (reflection versus transmission) of the hologram.

Other techniques have been employed to mitigate the negative aspects associated with SLMs, including; using an optically addressed SLM, printing amplitude modulating holograms with high quality laser printers [20] and recording onto photopolymerizable glass [21]. Our work improves on these techniques as it alleviates all the problems associated with SLMs, requires only a single SLM for the hologram forming process and utilises easily accessible materials. In addition, the range of patterns that can be written on the photopolymer can be extended beyond the capability of the SLM. We demonstrate this by generating a high order Laguerre–Gaussian mode with twice the angular momentum per photon that could be achieved with the resolution of our SLM.

3. Recording a volume hologram

To record a hologram, the desired optical field must first be generated with an SLM. We utilised a phase only, twisted nematic liquid crystal display (LCD) removed from a Hitachi CPA100 projector for our SLM. The LCD contains 1024x768 pixels, however, due to the circular geometry of the optical fields chosen to be recreated only the central 768x768 pixels were addressed. The LCD can produce ≈ 1.19π phase shift at 532 nm, which we calibrated via intensity measurements
Fig. 1. A schematic of the experimental set up used for recording transmission holograms. M, mirror; NPBS, non-polarising beam splitter cube; P, polariser; λ/2, half-wave plate; L, lens; SF, spatial filter; SLM, spatial light modulator. For recording reflection holograms the stage on which the hologram is mounted is rotated such that the object and reference beams enter the photopolymer on opposite surfaces.

from a series of binary phase holograms displayed upon the device [22]. Due to the limited phase shift provided by the LCD, we utilized the phase only complex valued spatial filter described by Arrizon et al. [10] to form the desired fields, as this technique only requires a phase modulation of \(1.17\pi\).

A schematic of our experimental set up is shown in Fig. 1. Laser light at a wavelength of 532 nm in a Gaussian mode with a \(1/e^2\) diameter of 2.2 mm from a continuous wave, frequency doubled, Nd:YAG laser, was first split by a non-polarising beam splitter cube to generate the object and reference beams used for recording the hologram, with each beam passing through a series of polarisers and half-waveplates to allow control of both the amplitude and polarisation of the modes. The reference and object beams were then spatially filtered with a 10 \(\mu\)m and 20 \(\mu\)m pinhole aperture before being magnified by 4X and 8X, respectively. The magnification of the reference beam was chosen such that the resulting hologram would be of a reasonable size for its intended use, while the object beam was expanded to create a nearly uniform intensity across the SLM. The object beam then diffracted off the SLM and passed through a pair of lenses that enabled the desired mode to be selected via spatially filtering in the Fourier plane. The spatially filtered object beam was then magnified to the same size as the reference beam, and then directed onto the photopolymer film at an angle of incidence (with respect to the normal of the surface of the photopolymer) equal to the angle of incidence of the reference beam, such that the total angle between the reference beam and object beam was \(\approx 49^\circ\).

A number of parameters may be varied when recording a hologram into the photopolymer to achieve optimal diffraction efficiency – these include the intensity of the light, exposure dosage, Bragg angle and fringe visibility. Typically we record holograms in transmission for their ease of incorporation into our experimental set-up, however, we have also recorded reflection holograms that exhibit similar performance. Empirically, we find that the angle the holograms are recorded
Fig. 2. HG$_{0,1}$ mode used to trap atoms in a blue detuned light sheet. a) Image of the intensity profile of the HG$_{0,1}$ mode at the focus of a lens. b) A fit (dashed lines) of a HG$_{0,1}$ intensity profile to the measured intensity profile (circles) taken along the green line shown in the image. c) An image of ultra cold rubdiium-87 atoms trapped within the nodal region of HG$_{0,1}$ mode (shown in 2(a)) formed from $\approx$50 mW of 532 nm laser light with a magnetic field providing the radial confinement of the atoms. Optical density is shown on the right hand side in arbitrary units.

at plays the largest role in the efficiency and fidelity of the reconstruction of the optical field. The angle between the beams not only determines the spatial frequency of the recording, which limits the achievable refractive index modulation due to the drift time required for the monomers [17], but it also determines the Bragg angle which in turn, for a transmission hologram, determines the optimal refractive index modulation for maximal diffraction efficiency. Hence, to optimise the diffraction efficiency of the recorded holograms we initially kept all experimental parameters constant apart from the angle between the reference and object beam.

To prepare the photopolymer it is desirable that the film first be attached to glass. This process first involves cleaning both the window the photopolymer is to be attached to, and the photopolymer film with a small amount of methanol to remove any dust which may cause additional fringes in the recording. The photopolymer film has a removable cover film which is then removed before the film is placed onto the centre of the window and rolled flat with a foam roller to remove any air bubbles. During the hologram recording process we directed one of the beams passing through the photopolymer onto a camera. As the recording progressed, each beam then began to diffract into the other beam, forming a beating interference pattern on the camera indicating the formation of a grating. This allowed us to determine if the refractive index had been ‘over modulated’ resulting in a reduction of diffraction efficiency, which we observe on the
camera as a reduction of the total power in the mode as the power densities in the reference and object beams were not balanced. The angle between the beams was then varied to find the angle that results in the optimal recording of the hologram, which typically manifests as a beating intensity pattern forming on the camera after \( \approx 0.1 \) s for beams with intensities on the order of \( \approx 1 \) mW cm\(^{-2} \). Once a suitable angle was found to produce over-modulation on the \( \approx 0.2 \) s time scale, the total recording power is then varied while keeping the exposure time constant, to maximise the diffraction efficiency. After a hologram has been recorded, the object beam is then blocked and the hologram played back with the reference beam to allow us to ascertain the quality of the hologram. During this quality check the reference beam saturates the remaining imaging monomers, fixing the hologram, after this no post treatment is required.

In ideal circumstances the intensity in the reference beam is matched to the object beam to increase fringe visibility for the recording. However, this is not possible for modes with spatially varying intensity profiles. Instead, we choose to increase the power in the reference beam until its intensity is greater than the object beam’s intensity everywhere over the entire area of the exposed photopolymer. Typical recording powers are on the order of 10 mW cm\(^{-2} \) with exposure times of \( \approx 0.2 \) s yielding total exposure dosages of \( \approx 2 \) mJ cm\(^{-2} \) for optimal diffraction efficiency and matching of the resultant intensity profile to the desired profile.

4. Holographic reproduction of a HG\(_{0,1}\) mode

To demonstrate the ability of the photopolymer to accurately reproduce a desired complex scalar field, and to measure the ‘efficiency’ of the photopolymer, a hologram of a Hermite-Gaussian HG\(_{0,1}\) mode [7] was recorded and used to trap a Bose–Einstein condensate (BEC) in the resulting potential. The mode is particularly useful for cold atom trapping as it can be used to generate quasi-2D optical potentials for the atoms in which the atoms are trapped in regions where the intensity, and hence scattering rate, is low [1]. Figure 2(a) shows the intensity profile of the focused HG\(_{0,1}\) mode generated by one of our holograms illuminated by a Gaussian beam. Fig. 2(b) shows a lineout of the intensity profile (circles) through the centre, with a fit (dashed line) to the data for comparison. As can be seen, our holograms can generate the desired complex field with high fidelity, in this case the spatial overlap of the two modes is \(95\%\).

For a single, phase only hologram the overall efficiency, \( \eta_{\text{Tot}} \), of converting from the incident mode into the desired mode is limited by the spatial overlap of the two modes. Hence, the overall efficiency is given by

\[
\eta_{\text{Tot}} = \frac{P_D}{P_D + P_T} \leq \eta_{\text{SO}} \eta_{\text{H}},
\]

where \( P_D \), \( P_T \) are the powers in the diffracted and transmitted modes, respectively, \( \eta_{\text{SO}} \) is the normalised spatial overlap of the intensity profiles of the two modes and \( \eta_{\text{H}} \) is the diffraction efficiency of the hologram. For a HG\(_{00}\) mode being converted to a HG\(_{0,1}\) \( \eta_{\text{SO}} \) is \(54\%\), this thus being the upper limit on \( \eta_{\text{Tot}} \). For our recorded hologram, \( \eta_{\text{Tot}} \) was measured to be \( \approx 50\% \), and as our reconstructed field has a large spatial overlap of the reconstructed field with the desired mode (95%). This indicates that our holograms can almost achieve the highest mode conversion efficiency limit for a single, phase only hologram.

This holographic HG\(_{0,1}\) mode was incorporated into our BEC apparatus to provide confinement of our rubidium-87 atoms in one dimension, resulting in an oblate condensate. Briefly, we form a BEC of approximately \( 1 \times 10^5 \) atoms in a red-detuned (attractive) crossed dipole trap [23], in the \( F = 2, m_F = 2 \) ground state. A quadrupole magnetic field, produced by a pair of coils in anti-Helmholtz configuration, is ramped on until the vertical (axial) gradient reaches approximately 15 G cm\(^{-1} \). A magnetic bias field is applied in the vertical direction to push the quadrupole field zero to approximately 1 mm above the atoms. At this position, the vertical component of the magnetic field gradient is approximately linear and levitates the atoms against gravity, while the radial (horizontal) components produce a potential with a trapping frequency of approximately
Fig. 3. Optical setup for recording large angular momentum modes. The optical setup used to record the hologram with twice the angular momentum per photon achievable by diffraction from just the SLM; all labels are as in Fig 1. The difference in the number of reflections each mode undergoes must be an odd integer in order for the modes to be mirror images of each other.

\[ \omega_\perp = 2\pi \times 8 \text{ Hz} \]

The red-detuned trap is then ramped off over 150 ms, while a blue-detuned (repulsive) potential formed by the holographic HG mode is simultaneously ramped on to a total power of 50 mW.

The HG mode generated by the holographic element has a waist of 700 \( \mu \text{m} \), designed to maximise \( \eta_{\text{Tot}} \) by mode matching with the collimated output of an optical fibre. The diffracted order is demagnified by a factor of 2, before passing through a \( f = -50 \text{ mm} \) cylindrical lens, aligned with the axis of the mode. The virtual image of the (vertically) focussed mode is relayed onto the atoms with a \( f = 250 \text{ mm} \) spherical lens in 2\( f \) configuration, resulting in a mode with waists of approximately 30 \( \mu \text{m} \) and 350 \( \mu \text{m} \) in the vertical and horizontal directions, respectively. The combined holographic and magnetic trapping potential has trap frequencies of \( \omega_z \approx 2\pi \times 100 \text{ Hz} \) and \( \omega_\perp \approx 2\pi \times 8 \text{ Hz} \), as measured by parametric heating [24] and observing centre of mass oscillations, respectively. We have verified that the atoms remain condensed after the transfer to this trapping configuration by observing bimodal atomic distributions in time-of-flight imaging with small thermal components after several seconds of hold time, demonstrating that these holograms have both the efficiency and stability to be used in BEC experiments. In Fig.2(c), the in-trap atomic distribution is shown via absorption imaging, after the aspect ratio of the trap has been increased to improve visibility of the atoms. This change in aspect ratio was achieved by moving the quadrupole centre to approximately 1 cm above the atoms, reducing the radial confinement to \( \omega_\perp \approx 2\pi \times 2 \text{ Hz} \).

To test the viability of the photopolymer for traps requiring high optical powers, we focussed our 532 nm laser to a \( \approx 20 \mu\text{m} \) waist onto a hologram of a diffraction grating, and measured the ratio of the diffracted mode compared to the transmitted mode for a range of powers. We saw no variation in the ratio of the diffracted versus transmitted power when increasing the total power in the beam up to 10 W, corresponding to a peak intensity of \( \approx 1 \text{ MW cm}^{-2} \), at which point other optics in the beam path were damaged limiting our ability to measure further. In comparison,
Fig. 4. An optical field containing $160\hbar$ of orbital angular momentum, generated using a transmission hologram recorded using the optical setup in Fig.3. a) The intensity distribution of the optical field. The (green) line is the intensity along a line bisecting the image vertically b) The interference of the optical field with its mirror reflection, verifying the high angular momentum state.

commercial SLM damage thresholds, provided by the manufacturers, are typically on the order of $1\ \text{W cm}^{-2}$.

5. Generating holograms of large angular momentum optical modes

To generate optical modes with greater angular momentum per photon than can be achieved with a given spatial light modulator, limited by either number of pixels available or the achievable phase shift per pixel of the SLM, we used the interference of a Laguerre–Gaussian (LG$_{0,l}$) mode [7] with its mirror image. This method relies upon the interference effects of the Laguerre-Gaussian modes to circumvent the limitations applied by the SLM. When an optical field reflects off a surface, the mirror image of the spatial mode is formed. For an LG$_{0,l}$ mode, which has an azimuthal phase $\exp(i\theta l)$, where $\theta$ is the azimuthal angle and $l$ is the azimuthal order of the mode, reflection from a mirror corresponds to simply reversing the sign of the azimuthal order, $l \rightarrow -l$, as the intensity profile is invariant under reflection, this is similar to how circularly polarised light reverses handedness upon reflection. Utilising this property, we form the interference of a LG$_{0,l}$ mode with its mirror image (LG$_{0,-l}$) by splitting the LG$_{0,l}$ mode generated from the SLM with a non-polarising beam splitter cube and then recombining the two Laguerre–Gaussian beams onto the photopolymer with a pair of mirrors, as shown in Fig. 3. The interference of the LG$_{0,l}$ mode and its mirror image in the photopolymer form a forked grating with $2l$ splittings in the fork, as the resultant hologram must transfer twice the angular momentum either individual Laguerre–Gaussian mode contains, to convert from the LG$_{0,l}$ mode to the LG$_{0,-l}$ mode. This experimental set up is particularly suitable for hologram formation as the non-polarising beam splitter cube ensures that the polarisation of each mode is maintained and the power in each mode is balanced. Separating the object and reference beam only a small distance before interfering the two beams also allows path differences to be minimised and thus any vibrations in the system to have minimal effects upon the two separate paths.

Using this technique, we generated an optical field with $160\hbar$ of orbital angular momentum per photon. The optical field, focussed with a $f = 150\ \text{mm}$ lens, is shown in Fig. 4(a), along with the azimuthally averaged, radial intensity profile. The optical field has the thin ring structure.
of a \( \text{LG}_{0,l} \) mode with large \( l \), with the peak to peak diameter of the ring being 1.6 mm, while a Gaussian fit to estimate the thickness of the ring results in a \( 1/e^2 \) width of 40 \( \mu \text{m} \). The intensity variation over the central 1.48 mm is less than 1\%. A power law with an exponent of 100 fits the average radial intensity profile before the maximum with a \( R^2 \) value of 0.94. These values suggest the optical field would be a suitable optical trap for experiments requiring either a very flat bottomed potential or particularly sharp walls. Furthermore, total mode conversion efficiency for this hologram was on the order of 50\%. An interferogram of the optical field with its mirror image is shown in Fig. 4(b). The resulting interference pattern shows 320 fringes, as expected for the interference of a \( \text{LG}_{0,160} \) mode with a \( \text{LG}_{0,-160} \) mode. This technique can further be extended however, by using the newly recorded hologram to generate the initial optical modes, a new hologram could then be recorded with twice the angular momentum of these mode, with the process being repeatable until the desired angular momentum per photon is achieved.

6. Conclusion

Here we have demonstrated a technique for creating cost-efficient, high efficiency, high fidelity holographic optical elements for ultracold atom trapping through the use of a spatial light modulator and Bayfol HX photopolymer. This method can be widely employed as all required equipment is readily available and inexpensive, allowing laboratories to test and create their own holographic elements in house for a variety of purposes. We have also demonstrated a technique for generating optical modes with greater angular momentum than can be achieved by our SLM, allowing the generation of large flat bottomed uniform traps for ultracold atoms.

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