Off-Axis Spiral Phase Mirrors for Generating High Intensity Optical Vortices

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In this work, we present a novel and practical method for generating optical vortices in high-power laser systems. Off-axis spiral phase mirrors are used at oblique angles of incidence in the beam path after amplification and compression allowing for the generation of high-power optical vortices in almost any laser system. An off-axis configuration is possible via modification of the azimuthal gradient of the spiral phase helix and is demonstrated with a simple model using a discrete spiral staircase. This work presents the design, fabrication, and implementation of off-axis spiral phase mirrors in both low and high-power laser systems. © 2020 Optical Society of America under the terms of the OSA Open Access Publishing Agreement

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1. INTRODUCTION

The generation and application of laser beams carrying orbital angular momentum (OAM) has become one of the forefront research areas of laser engineering today. Laser-matter interactions with beams carrying OAM at relativistic intensities is an area of recent study and has been drawing attention from the laser-plasma community. While there has been significant theoretical interest [1–3], there have been few experimental studies [4–6] due to difficulties associated with generating OAM beams in high-power laser systems.

Classically, an electromagnetic wave carrying OAM propagates with a helical wavefront contrary to the planar wavefronts of most high-powered lasers today. The pitch of the helical wavefront Q, indicates the quantity of OAM in the beam and is typically an integer multiple of the beam wavelength $Q = LA$ where L is the topological charge. Imprinting a helical wavefront into the beam gives an additional parameter for controlling both existing and new regimes of laser-matter interactions. One of the more intriguing properties of OAM beams is the unbounded angular momentum density, that is, they can carry any amount of OAM per photon [7]. This contrasts with circularly polarized beams which are limited to contain no more than one unit of spin angular momentum $\hbar$ per photon. Coupling additional photon angular momentum to a plasma allows for new phenomena such as the generation of relativistic azimuthal electron currents [1], strong axial magnetic fields [8], and twisted betatron radiation [9], to name just a few.

Spiral phase plates (SPP’s) [10, 11] are a simple and economical method for generating OAM beams. Their ability to generate high purity, low-power OAM modes is limited only by the wavefront quality, pulse duration, and near-field spatial homogeneity. High-power, short-pulse laser systems face problems with SPP’s as the transmitted wavefront is altered temporally and spatially due to non-linear effects such as group velocity dispersion, self-phase modulation and self-focusing. Alternatively, OAM beams may be generated through q-plates and cylindrical mode converters but require specialized polarization and input laser modes not generally available in high-power laser systems [7]. Spatial light modulators are a diffractive optical element providing a flexible method for generating OAM beams as they allow for in-situ adjustment of the diffraction pattern enabling fine tuning of the OAM mode in real time. While suitable for low-power laser systems, their damage threshold is too low for the fluence of high-power lasers. Spiral phase mirrors (SPM’s) were introduced in normal incidence configurations to overcome some of the nonlinear issues associated with SPP’s [12], but are restricted for use in high-powered lasers as they can retro-reflect damaging amounts of energy into the laser amplifier and compressor.

There have been a few successful experiments published in which an OAM mode has been demonstrated at high-power. In one of these, a spiral phase plate was inserted in the low-power...
front end of the laser system yielding an asymmetric OAM mode after amplification [4]. Another used various methods to generate high-power OAM beams including plasma holograms [5], a SPP, and a diffractive fork grating after amplification [6]. While these methods were successful to generate high-power OAM beams, their implementation is not straightforward for many high-power laser systems, particularly those with large diameter, short pulse, or high energy beams. To experimentally realize OAM beams at high-power, an ideal device would be inserted into a beam line after amplification and compression where the ejected super-Gaussian or flat-top beam is then mode converted into an OAM beam with maximal conversion efficiency, and with minimal spatio-temporal beam aberrations. This device would require a high damage threshold and the flexibility to be manufactured for large diameter beams with minimal cost.

In this paper we introduce the concept of an off-axis spiral phase mirror (OASPM) that enables conversion of fundamental laser modes to OAM modes in almost any high-power laser system. The OASPM is successfully demonstrated in both low and high-power laser systems with high conversion efficiency and high symmetry beams. The experimental results are compared to theoretical calculations in the paraxial limit.

2. OFF-AXIS SPIRAL PHASE MIRRORS

To transform a spiral phase mirror (SPM) to the off-axis case, we consider a stepped spiral phase mirror as shown in Figs. 1(a) and 1(c) [11, 12]. A stepped SPM uses a helical spiral staircase imprinted on the mirror surface that transfers OAM to the beam through reflection. Discretization of the spiral into a staircase-like surface simplifies manufacturing while having a minimal impact on the OAM beam quality [11, 13]. Fig 1(c), shows a stepped SPM with 16 steps of equal angular spacing for the normal incidence case, a red dotted circle is used to illustrate the laser spot imprint on the mirror. The azimuthal angle of each step sector measured from the horizontal plane can be calculated through reflection. Discretization of the OASPM via electron beam evaporation, we found that the staircase step height and is therefore negligible compared to the step edge width. Through fabrication of the OASPM via electron beam evaporation, we found the step edge width to be of the order of 100μm primarily as a result of mask position uncertainty as masks are interchanged. The corresponding area of the step edges relative to the total surface area of a large diameter beam (> 100mm) is around 1% and assumed to have a negligible effect on the focal spot. Much sharper edges could be produced using microelectronic fabrication techniques.

![Fig. 1.](image)

Fig. 1. a) The retro-reflecting configuration of a normal incidence (SPM); b) The oblique angle of incidence to an (OASPM), shown here at 45°; c) Front view of a stepped SPM indicating the step angle φ from horizontal and circular laser beam outline in red; d) Front view of a stepped OASPM indicating the step angle β relative to the horizontal plane and the elliptical laser beam outline in red.
3. CHARACTERIZATION OF OFF-AXIS SPIRAL PHASE MIRRORS

Several OASPM prototypes of various topological charge and diameter were manufactured using the University of Alberta’s nanofabrication facility. Using electron beam evaporation, titanium and gold were deposited onto pre-polished glass mirror substrates of flatness \( \lambda/10 \). Titanium was used as an adhesion layer of roughly 25nm thick, followed by a 200nm layer of gold to ensure a high reflectivity across the entire surface. Sequential layers were then deposited on the mirror surface using a set of 5 aluminium masks. The masks were based on the designs of Sueda et al. [11] with modified sector angles according to Eq. (1).

The modified angles were cut using a CNC water-jet from 3mm aluminium plate. The step deposition thickness was determined by Eq. (2), and monitored during deposition using a crystal thickness monitor. For a 16 step, \( L = 1 \) OASPM designed to work at 45° with a 632.8nm HeNe beam, we find the step sector angles given in Fig. 1d), and calculate each step height \( h \) to be 27.97nm.

Converting a Gaussian near-field beam to an OAM beam with integer topological charge \( (L = \ell) \), will produce a far-field focal spot intensity given by the following formula [14, 15],

\[
I(r, \ell) = \left( \frac{I_0}{4} \right) r^{-2} e^{-r^2} \left[ J_{\ell-\frac{1}{2}} \left( \frac{r^2}{2} \right) - J_{\ell+\frac{1}{2}} \left( \frac{r^2}{2} \right) \right]^2
\]

Here, \( I_0 \) is the peak intensity of the \( \ell = 0 \) beam, \( \ell \) is the azimuthal mode integer, \( I_0(X) \) is the modified Bessel function of the first kind, \( r \) is the normalized radius \( r/w_0 \) in the far-field plane where \( w_0 \) is the Gaussian beam waist parameter in the far-field defined as \( w_0 = \lambda f/\pi R_0 \). Here \( \lambda \) is the wavelength of the laser, \( f \) is the focal length of the lens, and \( R_0 \) is the Gaussian beam waist in the near-field.

Fig. 2. Illustration of an \( L = 1, N = 12 \) stepped OASPM in \( \varphi - z \) coordinates. The green dotted line represents a continuous OASPM \( (N \to \infty) \), and the red lines indicate light rays at a given incidence angle \( \theta_i \).

Fig. 3. Theoretical and experimental focal spots of a Gaussian

and an \( L = 1 \) OAM beam from a collimated \( R_0 = 4.5mm \) HeNe

beam using a 750mm focal length lens. a) Theoretical Gaussian focal spot; b) Experimental Gaussian focal spot; c) Theoretical \( \ell = 1 \) OAM focal spot; d) Experimental \( L = 1 \) OAM focal spot.
Fig. 4. Theoretical and experimental focal spots generated with a 3J, 30fs laser. a) Theoretical focal spot ℓ = 0. b) Experimental focal spot L = 0. c) Theoretical focal spot ℓ = 1. d) Experimental focal spot L = 1. e) Theoretical focal spot ℓ = 2. f) Experimental focal spot L = 2.

ℓ = 0, 1, 2 respectively. Fig. 4b), d), and f), show the measured focal spots with the corresponding peak intensities assuming the laser delivers 3J in 30fs to the focal spot. The peak intensity of the theoretical ℓ = 0, 1, 2 focal spots are calculated also assuming 3J in 30fs in the focal spot. From this it is clear to see a large discrepancy between the theoretical ℓ = 0 peak intensity and the experimental result, but with the higher order modes, we find better agreement between theory and experimental peak intensity. The images were taken by directly imaging the focal spot through a long working distance objective and with the laser operating in a low energy configuration (1mJ/shot), after which focal spot peak intensity was calculated assuming the total energy on focus. It is clear that there is an asymmetry in the experimental OAM focal spot rings. We believe this is primarily a consequence of spatial inhomogeneities in the laser intensity near-field profile, small contributions from defects in the OASPM, and residual focusing aberrations such as astigmatism. While we worked hard to minimize these effects on the beam, it was not possible to completely remove beam asymmetries in the given system.

4. CONCLUSIONS

In this paper, we have introduced and demonstrated that it is possible to efficiently mode convert a high-power laser into OAM beams using OASPM’s. OASPM’s are a cost effective, and simple method to mode convert almost any high-power laser to an OAM mode of desired topological charge. We have successfully demonstrated the generation of OAM modes with charge L = 1, 2 using the OASPM with peak intensities above 2 × 10^{19} W cm^{-2}. We found some asymmetries in our focused modes and believe this to be a result of near-field spatial inhomogeneities, manufacturing defects in the OASPM, and focusing aberrations such as astigmatism. We believe that these OAM modes are the highest intensity generated to date and that the OASPM is a tool that can open up the field of study of high-intensity OAM modes in the near future.

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