PROCEEDINGS OF SPIE

SPIEDigitalLibrary.org/conference-proceedings-of-spie

Front Matter: Volume 10120

SPIE.

Optimizing beams with transverse vortices

Daryl Preece,[1,*] **Halina Rubinsztein-Dunlop**[2]

[1]*Department of Nano Engineering, University of California, San Diego, 9500 Gilman Drive, La Jolla, CA 92093-0448*
[2]*School of Mathematics and Physics, University of Queensland, St Lucia, Brisbane,4702, Australia*

*Corresponding author: dpreece@ucsd.edu

ABSTRACT

It is widely known that beams that have optical vortices along the direction of propagation can be easily created in the laboratory. However, it is less well known that it is possible to create beams that have vortices transversely through the beam waist. Despite much work on beams with parabolic trajectories the creation of beams with transverse vortices are not well understood. Recently such beams have been created in the laboratory with computer-generated holograms. Though such beams can be created relatively easily, optimization of the vortex structure requires generation of the correct kinoform for the optical system. Imprecise application of such kinoforms can generate multiple vortices at the beam focus, which may not be optimal in many experimental applications. In this paper, we discuss the properties of such beams and investigate the optimal geometry for creating beams with transverse vortices. Applications for beams with transverse vortices may exist in optical micromanipulation, quantum communications and microscopy.

INTRODUCTION

An optical vortex is a point in an optical field where all waves destructively interfere to produce a “phase singularity” [1,2]a point with zero intensity and an undefined phase. Though these points are often thought of as a dark point in propagating beams such as the center of the well-known Laguerre-Gaussian Beams. To understand them more fully one must consider the full three dimensional evolution of the vortex. In fact optical vortices are not confined to a lines parallel to the direction of propagation. Vortex lines can form loops, or even knots [3], which may enter or exit a light beam at different points.

It is possible however to rotate the path of these vortex lines. Most simply by generating a field, which is off center to the optic axis. This was done by Vasnetsov[4] by using a superposition of Bessel beams. However, perhaps, a more simple way to rotate the vortex structure of the beam is to apply a coordinate transform of the original beam in such a way as to preserve the phase, intensity and momentum information of the original beam. Here we discuss the optimization of a vortex, which has been rotated by 90 degrees to form a transverse optical vortex[5,6].

CREATING BEAMS WITH TRANSVERSE VORTICES

There are variety of different ways of creating beams with angular momentum in the laboratory: by using spiral phase plates[7], cylindrical lens pairs[8], or often by using holograms[9]. Computer-generated holograms have become a common tool in many microscopy, optical trapping and photonics laboratories to generate non-Gaussian beams.. A phase only spatial light modulator (SLM) can imparts an azimuthal phase shift to a Gaussian beam to produce a beam with orbital angular momentum.

In order to rotates an optical vortex in the around the beam focus and thus create a transverse vortex. It is possible to rotate beams through the application of a geometric transform, which is an analogue to the Wigner transform. However, in here we are dealing with a purely scalar wave. Geometrically rotation can be regarded, as a transformed symplectic basis of the traditional Heisenberg relation, in which angular momentum is conjugate to angular position. Therefor, a positional shift and scaling are required to rotationally transform a beam. To perform large angle rotations, it is necessary to consider the Gouy phase shift when applying any transform past 90 degrees.

Complex Light and Optical Forces XI, edited by David L. Andrews, Enrique J. Galvez,
Jesper Glückstad, Proc. of SPIE Vol. 10120, 1012008 · © 2017 SPIE
CCC code: 0277-786X/17/$18 · doi: 10.1117/12.2251628

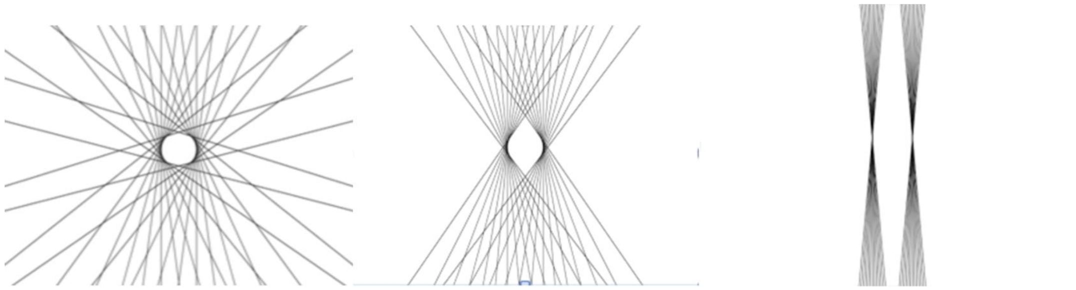

Figure 1 The paths of rays focusing around a vortex with different constriction of the aperture: left unconstricted to right tightly constricted.

While doing transformation we must also bear in mind that in any practical situation the spatial frequencies in any system are restricted by the size of the aperture of the objective lens. This in turn restricts the parabolic arc of the beam in the transverse direction. As shown in the Figure 1, by varying constriction of the aperture, the quality of the resultant discrete vortex changes.

In order to maximize the available spatial frequencies, we concentrate on beam dynamics in a focal system, which has a large numerical aperture. However, to understand the restriction of spatial frequencies it is worth remembering that in a system with a long focal length relative to the size of the optical aperture it is difficult form discrete vortices (Figure 1(b,c)). As the ratio of aperture radius to focal length gets smaller the angles at which the k vectors of incoming plane waves can contribute to the vortex are restricted.
This manifests itself as a fragmentation of the single central vortex into a series of off centre vortices. Which tend as the aperture is restricted still further to condense into phase discontinuities running in the direction of propagation. .

The structure outlined above means that for practical purposes beams with well controlled transverse vortices and well defined symmetric intensity patterns are difficult to make as such beams are reliant on very specific focal parameters.

OPTIMISING TRANSVERSE ROTATING BEAMS

In order to create a beam with a functional single vortex at the center an iterative beam shaping algorithm was employed. The beam-shaping algorithm was used to modify the intensity around the center of the beam. In order to create a beam with a loosely donut shaped intensity pattern in the transvers plane.
The basic concept of the algorithm is illustrated in he Figure 2. First, the beam is propagated forward by solving the Huygens- Fresnel integral (numerically) at each plane, and then weighting the result intensity towards the desired goal intensity while maintain the phase information. Then the beam is propagated into the far field conjugated and re-propagated backwards again, as the intensity is weighted to a desired intensity. This process is repeated for 5-10 iterations, at which point the algorithm has usually converged. Typically convergence occurs quickly with computing time approximately 1 min for128x128x128 pixels on Intel duo processor.
The Figure 3 shows simulation of intensity distribution of transverse vortex created by using interactive beam shaping algorithm.

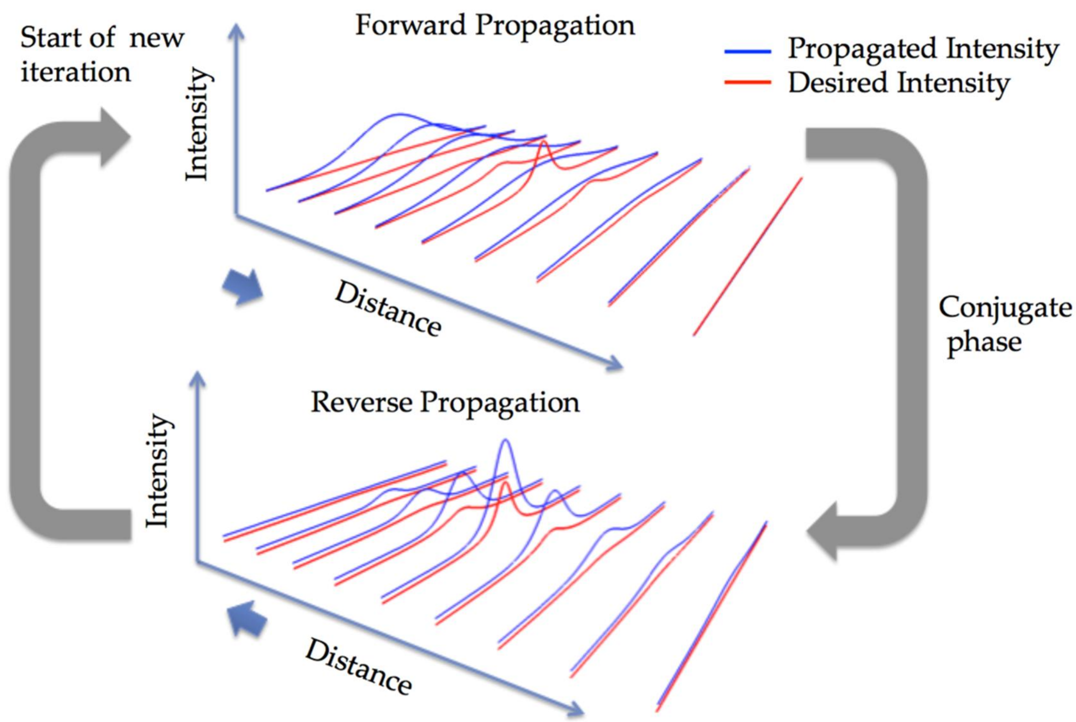

Figure 2 Diagram showing how a light beam is shaped by propagation and weighting of the incoming beam.

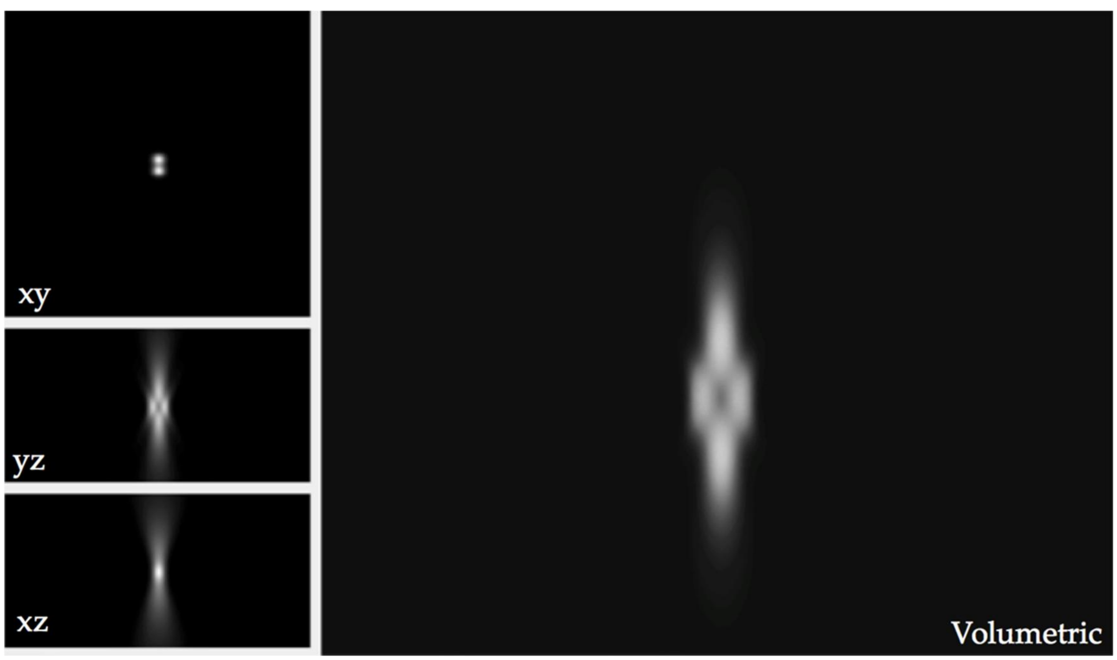

Figure 3. Simulation of the intensity distribution of a transverse vortex produced after the iterative beam-shaping algorithm. Cross sections of the volumetric rendering of the optical field.

Since no idealized optical intensity exists for a transverse optical vortex, we use the solution to the radial wave equation for one electron at hydrogen atom. This is normally expressed in terms of its radial and spherical components and is similar to the solution for the scalar wave equation for the Laguerre-Gaussian beam. The resultant intensity pattern can form a 3 dimensional donut shaped intensity pattern, which also has an azimuthal phase gradient in the direction of propagation.This patter can be scaled to the beam and then used as a goal intensity for the algorithm.

Conclusions

In the paper we discussed how transverse vortices with a “donut like” ring of intensity around them can be generated experimentally with computer-generated holograms and proper kinoforms. Such vortices can be generated in a diffraction limited system if proper account is taken of the focal parameters of the lenses. However, more study is needed to understand full scale of generation of such vorticies and the constraints of transverse vortices in photonics and bio-photonics applications.
Transverse vortices could be used for novel microscopy techniques. Such as Light sheet microscopy or Stimulated Emission Depletion microscopy.
Transverse vortices may also find applications in optical trapping.

References

1. Nye JF. Natural Focusing and Fine Structure of Light: Caustics and Wave Dislocations. 1999:328.
2. Nye JF, Berry M V. Dislocations in Wave Trains. *Proc R Soc A Math Phys Eng Sci*. 1974;336(1605):165-190. doi:10.1098/rspa.1974.0012.
3. Leach J, Dennis MR, Courtial J, Padgett MJ. Vortex knots in light. *New J Phys*. 2005;7:55.
4. Vasnetsov M V., Pas’ko VA, Soskin MS. Analysis of orbital angular momentum of a misaligned optical beam. *New J Phys*. 2005;7. doi:10.1088/1367-2630/7/1/046.
5. Aiello A, Marquardt C, Leuchs G. Transverse angular momentum of photons. *Phys Rev A*. 2010;81(5):53838. doi:10.1103/PhysRevA.81.053838.
6. Bekshaev AY. Oblique section of a paraxial light beam: criteria for azimuthal energy flow and orbital angular momentum. *J Opt A Pure Appl Opt*. 2009;11(9):94003. doi:10.1088/1464-4258/11/9/094003.
7. BEIJERSBERGEN MW, COERWINKEL RPC, KRISTENSEN M, WOERDMAN JP. HELICAL-WAVE-FRONT LASER-BEAMS PRODUCED WITH A SPIRAL PHASEPLATE. *Opt Commun*. 1994;112(5-6):321-327.
8. Beijersbergen M, Allen L, Van Der Veen H, Woerdman J. Astigmatic laser mode converters and transfer of orbital angular momentum. *Opt Commun*. 1993;96(1-3):123–132.
9. Heckenberg NR, McDuff R, Smith CP, White a G. Generation of optical phase singularities by computer-generated holograms. *Opt Lett*. 1992;17(3):221.