Vortex Lens

Introduction

In various laser applications, there is a need to convert a Gaussian laser beam into a donut-shaped energy ring. Our Vortex lens achieves exactly that.

Typical applications include:

- Solar coronagraphs (astronomy)
- High-resolution microscopy
- Optical tweezers for particle trapping & manipulation
- Lithography
- Quantum optics

This application note is meant to aid the user's understanding of the functionality and performance parameters of our Vortex diffractive element.

Principal of Operation

The Vortex lens is a unique optic, whose structure is composed entirely of spiral or helical phase steps, whose purpose it is to control the phase of the transmitted beam. The winding „staircase" surface structure is depicted in the Figure 1 immediately below:

The total etching depth from the top to bottom of „staircase" is a function of the design wavelength and the substrate's optical index. Generally, this depth is of the same order of magnitude as the design wavelength.

Therefore, each vortex lens is wavelength specific.

If a customer wishes to use a vortex lens for a slightly shifted wavelength, we can simulate upon request what performance is expected.

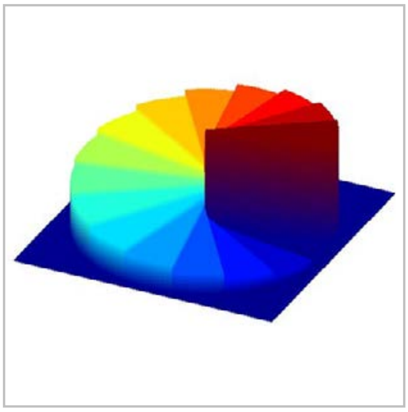


Figure 1: Winding „Staircase" surface profile of diffractive Vortex lens.

Topological Charge

The topological charge, denoted in the relevant literature as m, refers to the number of 2π cycles (i.e. „staircases“) that are etched around 360 degree turn of diffractive surface. In Fig.1 above, one „staircase“ cycle covers entire 360° turn of surface, so m=1 for that vortex lens. In Fig.2 below, the surface profiles are illustrated for vortex lenses with m=2, m=3 and m=4.

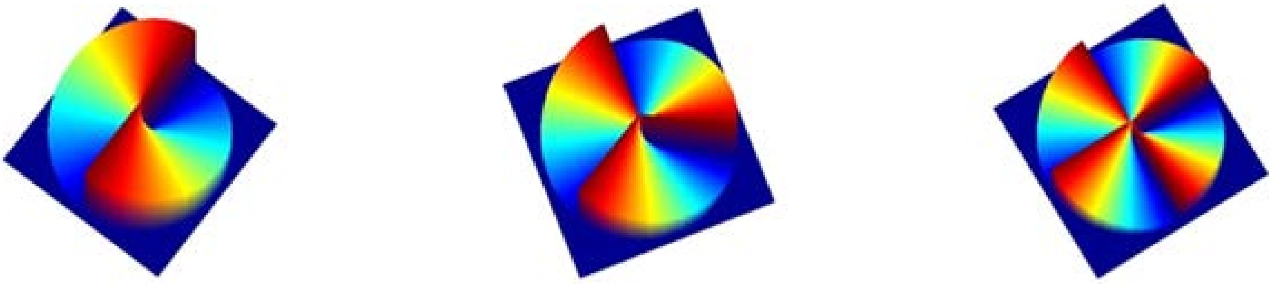


Figure 2: Surface profiles for V-lenses with m=2, m=3 and m=4.

One main effect of a higher topological charge is an increase in the angular moment of the vortex beam by a factor of m. Another effect is to magnify the ring intensity pattern dimensions by a factor of m, as illustrated in the below simulation.

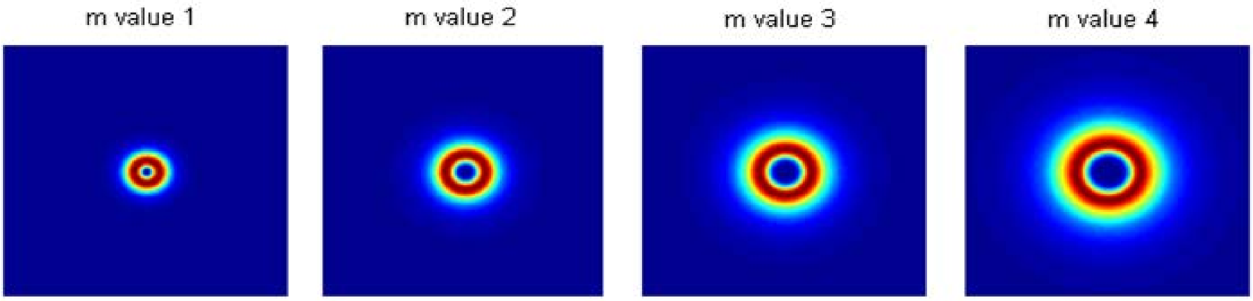


Figure 3: Simulated „far-field“ intensity images of Vortex beams with variable m value.

Design Considerations

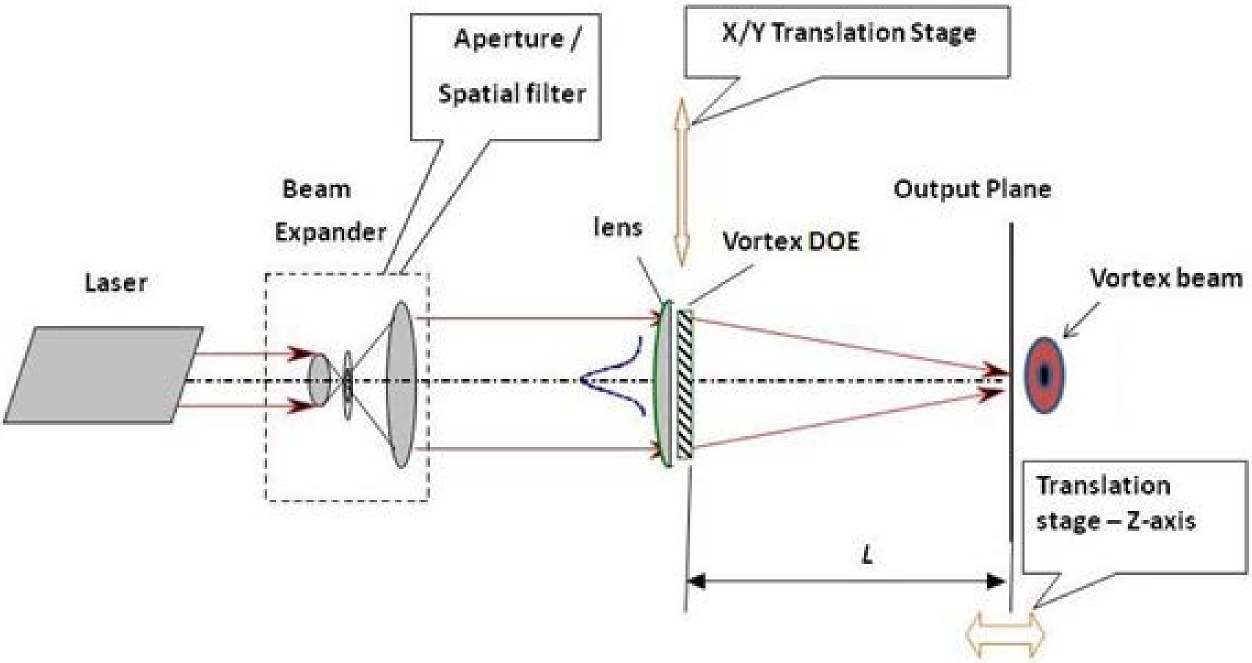


Figure 4: Typical Set-up for Vortex beam system.

The Vortex lens requires as input a collimated Single Mode (TEM00) Gaussian input beam, which it converts to a TEM01 axially symmetric mode.

The spatial filter consists of a focusing lens, a small aperture in the focal plane, and a collimating lens. The spatial filter aperture acts to reduce parasitic modes. By manipulating the focal lengths of these two lenses, the spatial filter can also be used as a beam expander.

The advantage of working with a larger input beam is twofold. First, a larger beam reduces somewhat the sensitivity of the output to DOE alignment tolerances. Secondly, a larger input beam will enable achieving a smaller vortex spot, which is often a desired outcome in many applications.

The two translation stages in fig.4 above are meant to give the user precise control of elements' locations, to reduce tolerance effects. This is discussed further in the section on Tolerances.

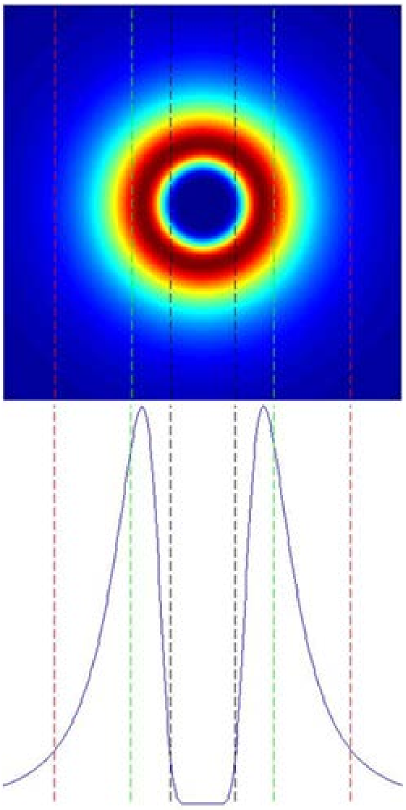
All optics in the beam path should be of high quality, i.e. low irregularity figure, so as not to introduce wave-front errors which could degrade performance. This includes mirrors which should have high flatness specification. Here, too, a larger beam size incident on the mirror will reduce its sensitivity to localized aberrations.

It is recommended to work with the Vortex lens in the waist of the laser. Nonetheless, if the beam has a small divergence angle (<1°), there should not be any noticeable effect on the output quality, but only on the exact working distance.

If, due to mechanical or other constraints, the DOE will be located at a distance from the beam waist, it is important to take this distance into consideration, along with the beam divergence, in the designing of the DOE. Otherwise, the resultant wave-front aberration can generate an interference/ripple pattern over the output beam, whose intensity will grow as a function of the DOE's distance from waist and the divergence angle.

When designing the desired output Vortex beam size, it is important to be familiar with the physical limits of the minimum spot size. The formula for the diffraction-limited spot diameter at 1/e2 follows:

$$\frac{4\times L\times \lambda}{\pi \times D}\times M^{2} = D.L.spotsize$$



L: Working Distance

λ: Wavelength

D: Input Beam Size

M2: M2 value of input laser beam

In this illustration below,the Vortex spot sizeat 1/e2, the size of the hole in center at 1/e2 and the transfer region will be express in term of diffraction-limits (DL) given by the above formula.

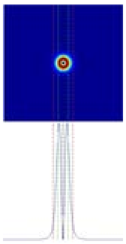
In the pictures, the vortex spot size is the distance between the two red lines, the hole size is the distance between the two black lines and the transfer region is the distance between the first red line and the first green line.

„m=7“

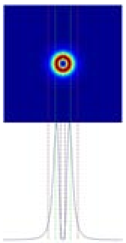
ring size: 8.93 DL

hole size: 1.965 DL

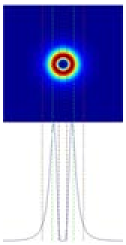
transfer region: 2.306 DL



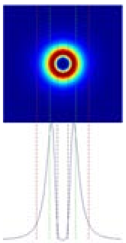
m=1



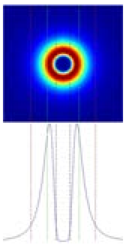
m=2



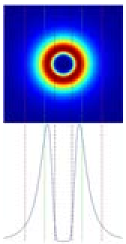
m=3



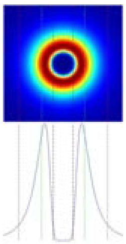
m=4



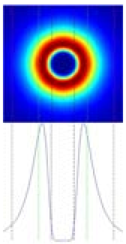
m=5



m=6



m=7



m=8

Characteristics

- High power threshold
- High efficiency: >90%
- Sensitivity to X-Y displacement: 5% of the input beam, in order to keep acceptable performance.
- Rotation insensitive: For round shape.
- Sensitivity to working distance: smaller than 50% of the spot size in order to keep acceptable performance.

Link to the video:

http://www.holoor.co.il/Diffractive_optics_Applications/Application_Notes_VortexLens.htm

Sensitivity to Alignment and Beam Centricity

When one goes about designing a set-up that includes a DOE, one should take care to ensure control and stability of these system parameters.

As depicted in the typical set-up of figure 4, accurate translation stages, high quality laser beams, spatial filter and beam expander all contribute to the stability of the optical system.

The performance specifications depend on the relative displacement. Therefore, the system can be made less sensitive by expanding the input beam prior to the design. For example, for an input beam of 10mm diameter, a 5% tolerance gives 0.5mm, while for a beam diameter of 2mm, a 5% tolerance affords only 0.1mm.

Simulated Effects of Tolerances on Vortex Beam Profile

The best performance will be obtained for a well-positioned perfectly aligned part, located precisely in the plane of the nominal working distance. To illustrate the sensitivity of Vortex performance to different tolerance parameters, several graphs are included here for a standard Vortex lens (WD: 100 mm, λ: 633nm).

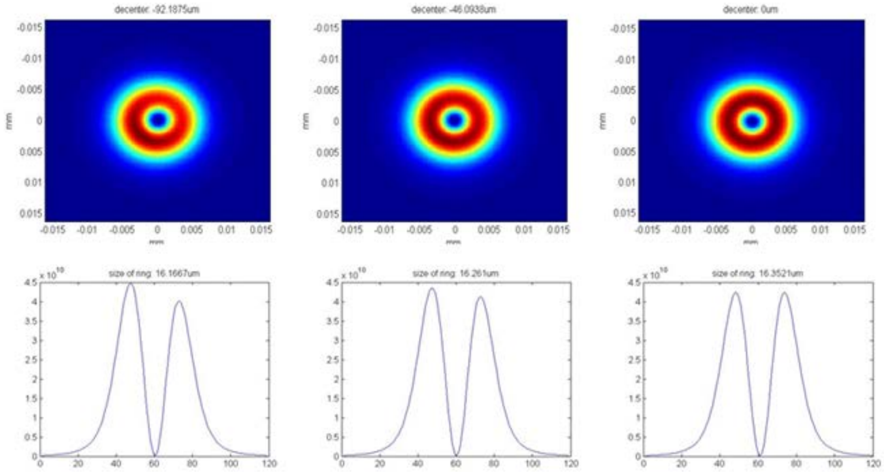


Fig. 5: Effect of x/y axis de-centering (92um, 46um, 0um) of 8mm input beam on Vortex

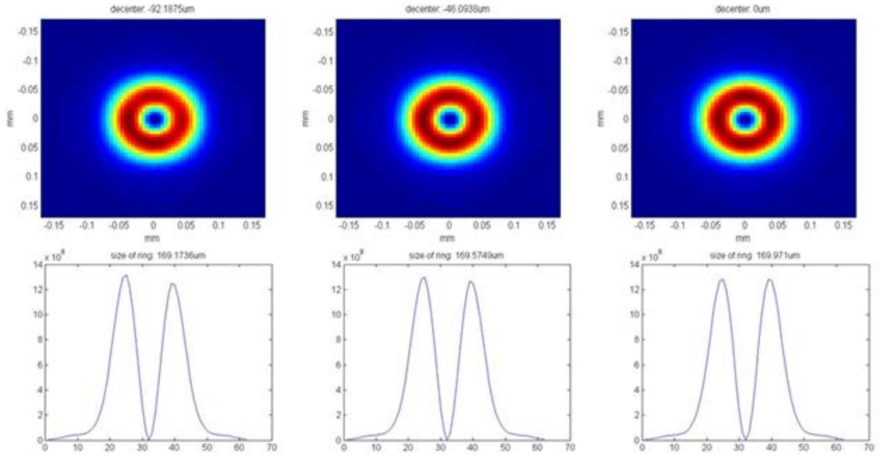
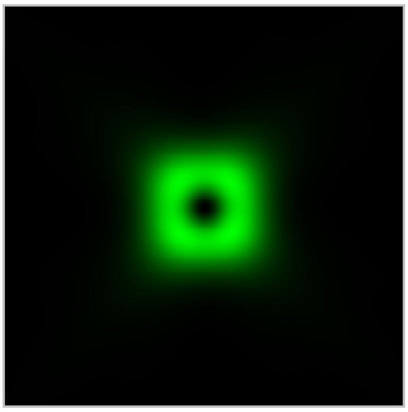


Fig. 6: Effect of x/y axis de-centering (92um, 46um, 0um) of 15mm input beam on Vortex

Square Donut Shape Vortex



- Not sensitive to beam size
- Very stable to defocusing
- Stable to decentering
- Available for different wavelengths
- Hig efficiency
- Good uniformity contrast

Technical specifications

- Spot size about 2 times diffraction limit
- Efficiency ≈ 90% ($\exp^{-2}$)
- Uniformity contrast 7% (corners vs. valleys)