Diffractive Axicon application note

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Introduction

A Diffractive Axicon (DA) is a kind of Diffractive Optical Element (DOE) that transforms a laser beam into a ring shape (a Bessel intensity profile). An Axicon also images a point source into a line along the optical axis and increases the Depth of Focus (DOF). Each Diffractive Axicon product is defined by its ring propagation angle.

The calculated ring’s width (RW) is equal to \(~1.75\times\text{Diffraction Limit (DL}_{SM}\) at \(1/e^2\) size of the input for Single Mode laser beam.

For multimode beam the Ring width will equal to:

\[
RW = \sim_{DL_{SM}} \cdot (M^2 + 0.75) = \sim \frac{4\lambda \cdot EFL}{\pi D} \cdot (M^2 + 0.75)
\]

Where:
- EFL - effective focal length
- \(\lambda\) - Wavelength
- D - Input Beam Size
- \(M^2\) - \(M^2\) value of input laser beam

Definitions of sizes for Diffractive Axicon

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General specifications of Diffractive Axicons

<table>
<thead>
<tr>
<th>Materials:</th>
<th>Fused Silica, Sapphire, ZnSe, Plastic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength range:</td>
<td>193 [nm] to 10.6 [um]</td>
</tr>
<tr>
<td>DOE design:</td>
<td>2-level (binary) to 16-level</td>
</tr>
<tr>
<td>Diffraction efficiency:</td>
<td>75% - 96%</td>
</tr>
<tr>
<td>Element size:</td>
<td>Few mm to 100 [mm]</td>
</tr>
<tr>
<td>Damage threshold:</td>
<td>&gt;3 [J/cm^2] in 7 [nS] pulse @ 1064 [nm]</td>
</tr>
<tr>
<td>Coating (optional):</td>
<td>AR/AR Coating</td>
</tr>
<tr>
<td>Custom Design:</td>
<td>Almost any ring diameter</td>
</tr>
</tbody>
</table>

Typical applications

<table>
<thead>
<tr>
<th>Atomic traps</th>
<th>Generating plasma in linear accelerators</th>
</tr>
</thead>
<tbody>
<tr>
<td>Axicon resonators in lasers</td>
<td>Laser Corneal Surgery</td>
</tr>
<tr>
<td>Optical Coherence Tomography (OCT)</td>
<td>Laser Drilling/Optical Trep Manning</td>
</tr>
<tr>
<td>Telescopes</td>
<td>Solar concentrators</td>
</tr>
</tbody>
</table>

Advantages of the Diffractive Axicon

<table>
<thead>
<tr>
<th>Allows very small angles</th>
<th>Aberration free</th>
</tr>
</thead>
<tbody>
<tr>
<td>Positive and negative configurations</td>
<td>Compact solution for larger angles – (fab. on thin window)</td>
</tr>
<tr>
<td>Exceptionally precise shape and angle</td>
<td>Plastic available for low power applications in low price</td>
</tr>
<tr>
<td>Fab. on Fused Silica or ZnSe (for infrared app.)</td>
<td>Arrays of micro Axicons</td>
</tr>
<tr>
<td>Can accept very small incident beams</td>
<td></td>
</tr>
</tbody>
</table>

Principle of operation and design considerations

The principal of operation is similar as for basic focus lens.

Unlike a Refractive Axicon (RA), which is defined with an apex angle or a cone angle, a Diffractive Axicon (DA) is defined by its divergence angle. The divergence angle defines ring diameter in specific distance.

The divergence angle \( \beta \) can be calculated from the diffraction grating equation:

\[
\beta = 2 \cdot \sin^{-1} \left( \frac{\lambda}{\Lambda} \right)
\]

The ring diameter can be calculated from a geometrical point of view:

\[
D = 2 \cdot WD \cdot \tan \frac{\beta}{2}
\]

\( \lambda \)  Wavelength
\( \Lambda \)  Diffraction period
\( WD \)  Working distance
\( D \)  Ring Diameter
Example for finding the divergence angle:

- Wavelength: 355 [nm]
- EFL: 50 [mm]
- Desired Ring Diameter: 0.2 [mm]

\[
\beta = 2 \cdot \tan^{-1}\left( \frac{0.2}{50} \right) = 0.2292 \text{ [deg]}
\]

Relation between Divergence Angle, and Cone Angle or Apex Angle of a Refractive Axicon:

\[
D = 2 \cdot WD \cdot \tan[(n - 1) \cdot \alpha]
\]

\[
\beta = 2 \cdot [\sin^{-1}(n \sin \alpha) - \alpha] \approx 2 \alpha \cdot (n - 1)
\]

\[
\theta = 180 - 2\alpha
\]

- \( n \): Refractive index
- \( \alpha \): Cone angle
- \( \theta \): Apex angle

Another example for finding the divergence angle (\( \beta = ? \)):

- Cone angle: 0.25 [deg]
- Material: Fused Silica
- Wavelength: 355 [nm]

\[
\beta = 2 \cdot [\sin^{-1}(1.4761 \cdot \sin 0.25) - 0.25] = 0.238 \text{ [deg]}
\]

**Key parameters for Refractive and Diffractive Axicons:**

<table>
<thead>
<tr>
<th>Diffractive Axicon</th>
<th>Refractive Axicon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Divergence angle</td>
<td>Cone angle or Apex angle</td>
</tr>
<tr>
<td>Wavelength</td>
<td>Refractive index</td>
</tr>
<tr>
<td>Working distance</td>
<td>Working distance</td>
</tr>
</tbody>
</table>
Comparison between binary and multilevel Diffractive Axicon

A binary (or two levels) Diffractive Axicon can be an affordable alternative to a multilevel model or to a refractive element.

In the table below, we show simulation results corresponding to a specific example, with the following parameters:

- Wavelength: 1064 [nm]
- Beam diameter: 6 [mm]
- Laser: TEM\textsubscript{00} Gaussian
- DOE clear aperture: 9.2 [mm]
- Ideal lens f=100 [mm]
Superposition of profiles:

<table>
<thead>
<tr>
<th>Tolerance</th>
<th>Value</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tilt X,Y</td>
<td>&lt; 5 deg.</td>
<td>Small amount of energy goes to Zero Order</td>
</tr>
<tr>
<td>Shift X,Y</td>
<td>Sensitive</td>
<td>Uniformity along ring</td>
</tr>
<tr>
<td>Tilt Z</td>
<td>No effect</td>
<td></td>
</tr>
<tr>
<td>Shift Z</td>
<td>Yes</td>
<td>Depends on optical setup</td>
</tr>
<tr>
<td>Beam size</td>
<td>No effect</td>
<td></td>
</tr>
<tr>
<td>$M^2$</td>
<td>No effect</td>
<td></td>
</tr>
<tr>
<td>Polarization</td>
<td>No Effect</td>
<td></td>
</tr>
</tbody>
</table>
Typical optical setups TBD

1) Controlling ring width by placing Variable Beam Expander before Diffractive Axicon.

   The diameter of the ring remains constant.

2) Controlling Ring diameter by placing DA after focusing lens.

   Ring diameter will reduce linearly with distance between diffractive pattern and image plane/ focal plane.
   Ring width will remain constant.