

Gauss-Bessel Beam Shaper [Axicon]

Digital Twin Specification

Twin Code:	CF-BESA01
Twin Name:	Gauss-Bessel Beam Shaper [Axicon]
Category:	Component
Type:	Function-Based
Version:	1.0
Package:	Light Shaping
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Description

This twin implements a phase-only axicon: a conical phase mask that transforms a collimated Gaussian input beam into a Bessel-like beam with extended depth of focus.

The phase function consists of a radial part (linear in the radial coordinate) and an optional azimuthal part (vortex):

- **Radial phase:** linear with slope proportional to $\sin \theta$, where θ is the cone angle. Positive θ produces a convergent conical phase; negative θ produces a divergent conical phase.
- **Azimuthal phase:** $\exp(il\phi)$ with integer topological charge l , creating a phase singularity and a dark core.

The twin supports phase quantization and export of the designed phase data.

Model Parameters

Design parameters:

- **Cone angle (θ):** Slope of the radial phase. Positive for convergent (beam converges toward axis), negative for divergent (beam diverges from axis). The magnitude determines the transverse spatial frequency of the resulting Bessel beam. Default: 1 degree.
- **Topological charge (l):** Integer vortex charge. Non-zero values produce a dark core in the beam. Default: 0.
- **Quantization levels (Q):** Number of discrete phase levels (0 for continuous phase, or a positive integer such as 2, 4, 8). Default: 0 (continuous).
- **Sampling accuracy (S):** Multiplicative factor for the base sampling grid. The base sampling distance is determined from the Nyquist criterion for the maximum phase slope; increasing S improves resolution for quantized masks or large cone angles. Default: 1.0.
- **Export Designed Phase:** When enabled, simulation pauses at the shaper plane and opens a dialog to export the computed phase mask. The user can specify the output grid size; resampling is performed automatically.

Simulation Model

The twin applies a phase mask with transmission $t(\rho, \phi) = \exp(i\Phi_{\text{total}})$, where:

$$\Phi_{\text{total}}(\rho, \phi) = -k_0 \sin \theta \cdot \rho + l\phi, \quad (1)$$

with $k_0 = 2\pi/\lambda$, θ the cone angle (positive for convergent), and $\rho = \sqrt{x^2 + y^2}$ the radial coordinate. For quantized masks ($Q > 0$), the total phase is quantized to Q equally spaced levels before forming the transmission.

The input must be a collimated Gaussian beam (wavelength λ , waist radius w_0 at the mask plane).

Key Physical Principles

- **Conical phase and Bessel beam formation:** The axicon applies a linear radial phase $\Phi(\rho) = -k_0 \sin \theta \cdot \rho$, creating a conical phase. Behind the mask, constructive interference of conical waves generates a Bessel beam with a central core surrounded by multiple concentric rings. The transverse intensity follows $J_0^2(k_\rho r)$ for $l = 0$. The Bessel-like rings become clearly visible after a certain propagation distance.
- **Bessel zone length:** The non-diffracting behaviour persists over the Bessel zone length

$$L \approx \frac{w_0}{\tan \theta}. \quad (2)$$

Beyond L the beam rapidly spreads.

- **Effect of quantization (Q):** Higher quantization levels produce a better approximation to the ideal Bessel beam. Lower Q deviates from the ideal phase profile, introducing higher-order conical waves and modifying the ring structure.
- **Effect of topological charge (l):** A non-zero vortex phase $\exp(il\phi)$ creates a phase singularity and a dark core (doughnut profile). The radial intensity distribution follows $J_l^2(k_\rho r)$.
- **Sign of cone angle (θ):** Positive θ (convergent) produces a Bessel-Gauss beam: the field has on-axis intensity that first converges, then forms rings. Negative θ (divergent) produces a Bessel beam with a hollow center (dark on axis) because the conical waves diverge immediately.

Application Scenarios

1. **Tunable laser processing:** Adjust θ to control the ring radius and depth of focus for drilling or cutting.
2. **Optical trapping with variable confinement:** Use the ring or donut pattern (with $l > 0$) for multi-particle trapping or low-damage trapping in the dark core.
3. **Microscopy with structured illumination:** Generate ring patterns for super-resolution techniques.
4. **Material processing with extended depth of focus:** Leverage the non-diffracting nature of the Bessel beam for processing thick samples or high-aspect-ratio holes.
5. **Beam shaping research:** Study how the cone angle and quantization affect the Bessel beam formation and propagation.
6. **Educational demonstrations:** Visually demonstrate the transition from Gaussian to Bessel beam as a function of propagation distance.

Software Usage

This twin is available in the Digital Twin Hub. For correct operation, follow the setup steps below.

System Setup

1. **Generate a Gaussian beam:** Place a Gaussian Beam Mode twin (SF-GAUS01) in your system.
2. **Collimate the beam (if needed):** If the source is not collimated, add a collimation element:
 - Use an Ideal Lens [Collimation] twin (CF-ILC001) for aberration-free collimation, OR
 - Use a Spherical Lens twin (CS-SLEN01) with appropriate curvature to achieve collimation
3. **Add the beam shaper:** Place the Gauss-Bessel Beam Shaper [Axicon] twin (CF-BESA01) at the desired position.
4. **Configure the shaper:** Set the design parameters (θ , l , Q , Sampling accuracy S).
5. **Add field monitors:** Place field monitors (DF-FMON01) at various distances behind the shaper to observe the evolution of the Bessel beam.

⚠ Note:

- Input beam must be collimated at the shaper plane.
- For proper operation, the input field must be a Gaussian beam; other input fields produce unspecified results.

Exporting the designed phase for fabrication:

- Check the **Export Designed Phase** option in the shaper's dialogue.
- When enabled, system simulation pauses at the shaper plane and an export dialogue opens.
- The dialogue displays the current number of sampling points used internally for the mask. The user can specify the desired number of sampling points for the exported mask. The minimum allowed number of points corresponds to the current internal grid size (derived from the sampling rule). Larger grid sizes increase resolution but also file size.
- Users can adjust the number of points based on fabrication constraints; the software automatically resamples the phase data accordingly. Reducing the number of points below the minimum would degrade the mask and is not permitted.
- After closing the export dialogue, the simulation continues normally.

⚠ Note: The Export Designed Phase option must be disabled during parameter runs or parametric optimizations, as it pauses the simulation and opens an export dialogue, which interrupts automated sweeps.

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Related Twins: SF-GBES01, SF-GAUS01, CF-BESP01, CF-BESV01, CF-BESM01, CF-ILCO01