Gauss-Bessel Beam Shaper [Modulated Axicon]

Digital Twin Specification

Twin Code:	CF-BESM01
Twin Name:	Gauss-Bessel Beam Shaper [Modulated Axicon]
Category:	Component
Type:	Function-Based
Version:	1.0
Package:	Light Shaping
Last Updated:	2026-04-27

Description

This twin implements a phase-only transmission whose phase function consists of three parts:

- Standard axicon phase: $\Phi_{\text{axicon}}(\rho) = -k_0 \sin\theta \cdot \rho$
- Gaussian modulation: $\Phi_{\text{mod}}(\mathbf{r}) = -A \exp\left(-\frac{|\mathbf{r}-\mathbf{r}_c|^2}{(r_m w_0)^2}\right)$, where A is the modulation magnitude, $\mathbf{r}_c$ the modulation center, and r_m the relative modulation radius.
- Azimuthal vortex phase: $\exp(il\phi)$

Here $\mathbf{r} = (x, y)$ is the transverse position vector, and $\rho = |\mathbf{r}|$ is the radial coordinate. The Gaussian modulation reshapes the axial intensity distribution – for appropriate parameters, it produces a uniform axial profile or other targeted distributions. 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. Default: 1 degree.
- **Topological charge** (l): Integer vortex charge. Default: 0.
- **Quantization levels** (Q): Number of discrete phase levels (0 for continuous, or 2,4,8,...). Default: 0.
- **Sampling accuracy** (S): Multiplicative factor for base sampling grid. Default: 1.0.
- **Modulation magnitude** (A): Strength of the Gaussian phase modulation. Default: 0 (no modulation).
- **Modulation radius** (r_m): Effective radius of the Gaussian modulation, relative to the input beam waist radius w_0. Default: 1.0.
- **Modulation center** (x_c, y_c): Center of the modulation, relative to the input beam waist radius w_0. Default: (0,0).
- **Export Designed Phase**: When enabled, simulation pauses at the shaper plane to export the computed phase mask.

Simulation Model

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

$$\Phi_{\text{total}}(\mathbf{r}, \phi) = -k_0 \sin\theta \cdot \rho + l\phi - A \exp\left(-\frac{|\mathbf{r} - \mathbf{r}_c|^2}{(r_m w_0)^2} \right), \tag{1}$$

where:

- $k_0 = 2\pi/\lambda$ is the wavenumber,
- $\rho = \sqrt{x^2 + y^2}$ is the radial coordinate,
- $\mathbf{r}_c = (x_c w_0, y_c w_0)$ is the modulation center in physical units.

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

- **Base axicon phase:** Generates a standard Bessel beam with multiple concentric rings and an oscillatory axial intensity profile.
- **Gaussian modulation:** The negative Gaussian phase dip counteracts the natural axial intensity variations, allowing engineering of the axial profile. Parameters A, r_m, and (x_c, y_c) control the effect.
- **Bessel zone length:** The non-diffracting behaviour of the unmodulated part persists over the length
  $$L \approx \frac{w_0}{\tan\theta}. \tag{2}$$
  Modulation can shift and modify this length.
- **Effect of quantization (Q):** Higher Q yields a better approximation to the ideal continuous phase mask. Lower Q introduces higher diffraction orders and may introduce artefacts.
- **Effect of topological charge (l):** Introduces a phase singularity and dark core.
- **Sign of cone angle (θ):** Positive θ produces a Bessel–Gauss beam; negative θ produces a hollow Bessel beam.

Application Scenarios

1. **Long-depth laser processing**: Use the modulated Bessel beam to maintain a uniform intensity over extended depth, improving cut quality in thick materials or high-aspect-ratio drilling.
2. **Optical trapping with custom axial profile**: The tailored axial distribution enables stable trapping over a designed working range or creates multiple trapping zones.
3. **Microscopy with structured illumination**: Generate engineered axial intensity patterns for advanced imaging techniques such as light-sheet microscopy.
4. **Beam shaping research**: Investigate how Gaussian modulation parameters affect the axial intensity distribution and Bessel beam evolution.
5. **Fabrication of advanced phase masks**: Export the designed phase for implementation on spatial light modulators or diffractive optical elements.

Software Usage

This twin is available in the Digital Twin Hub.

System Setup

1. **Generate a Gaussian beam:** Place `SF-GAUS01` in your system.
2. **Collimate the beam (if needed):** Use `CF-ILCO01` or `CS-SLEN01` to achieve infinite radius of curvature at the shaper plane.
3. **Add the beam shaper:** Place `CF-BESM01` at the desired position.
4. **Configure the shaper:** Set θ, l, Q, S, A, r_m, x_c, y_c.
5. **Add field monitors:** Place `DF-FMON01` at various distances to observe the modulated Bessel beam.

> ⚠ **Important:**
>
> - 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-BESA01, CF-BESP01, CF-BESV01, CF-ILCO01