Dirac-Comb Convolution Detector [Ring]

Digital Twin Specification

Twin Code:	DF-CONV02
Twin Name:	Dirac-Comb Convolution Detector [Ring]
Category:	Detector
Type:	Function-Based
Version:	1.0
Package:	Platform
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Description

Modeling sources with rotational symmetry—such as ring-shaped emitters or certain types of multi-mode fibers — may require superimposing many laterally shifted modes arranged in a circular pattern. Propagating each mode individually is computationally expensive. This detector twin provides an efficient alternative: propagate only the central mode, then perform a convolution with a Dirac-comb arranged on a ring. The detector superimposes laterally shifted copies of the propagated field at positions defined by the ring geometry. This technique dramatically reduces simulation time while accurately representing rotationally symmetric sources, provided the optical system is laterally invariant.

Measured Quantity

The detector outputs the convolved field or derived quantity (depending on the position of the add-on in the detector channel), typically:

- **Electromagnetic field**: When placed after the "Electromagnetic Field Quantities" add-on (coherent superposition).

- **Irradiance**: When placed after the "Irradiance" add-on (incoherent superposition).

The result represents the superposition of all ring-positioned source copies.

Model Parameters

The Dirac-Comb Convolution Detector itself has no configurable parameters. Its behavior is controlled exclusively through its associated **Convolution with Delta Ring** add-on:

- **Show Ring**: Toggle to visualize the Dirac-comb ring as an output overlay (helpful for verification).

- **Number of Modes**: Specifies the number of Dirac delta functions equally spaced around the ring circumference. This determines the angular sampling of the ring.

- **Ring Size**: Defines the radial distance from the center at which all Dirac delta functions are positioned. All copies are shifted by this distance from the origin, at equally spaced angles.

Simulation Model

The fundamental principle is based on the convolution theorem for laterally invariant systems, but applied to a ring geometry. Instead of propagating each shifted copy individually through the system, we propagate only the central field $U(\boldsymbol{\rho})$ and then perform the convolution with a Dirac-comb on a ring at the detector side.

For a ring of N equally spaced Dirac delta functions at radius R, with angular positions $\phi_m = 2\pi m/N$ for $m = 0, 1, \ldots, N - 1$, the lateral shift vectors are:

$$\boldsymbol{\rho}_m = (R \cos \phi_m, R \sin \phi_m). \tag{1}$$

The output field $U_{\text{out}}(\boldsymbol{\rho})$ is given by the superposition:

$$U_{\text{out}}(\boldsymbol{\rho}) = \sum_{m=0}^{N-1} U_{\text{prop}}(\boldsymbol{\rho} - \boldsymbol{\rho}_m), \tag{2}$$

where $U_{\text{prop}}(\boldsymbol{\rho})$ is the propagated field from the central source mode.

Key Physical Principle: Rotational Symmetry and Lateral Invariance

This technique is valid when the optical system is **laterally invariant**—meaning its impulse response is shift-invariant. This holds for many systems consisting of lenses, free-space propagation, and apertures, provided there are no laterally varying elements. For ring geometries, this allows us to treat each shifted copy identically, with only the position of the copy changing.

The ring arrangement is particularly useful for modeling:

- **Annular sources**: Laser modes with donut-shaped intensity profiles (e.g., Laguerre-Gaussian modes with $\ell \neq 0$ approximated by a ring of point sources).

- **Ring illuminators**: LED or fiber arrays arranged in a circular pattern.

- **Multi-mode fiber outputs**: Fibers supporting modes that concentrate energy in a ring-shaped region.

Typical Application Scenarios

1. **Annular Laser Modes**: Approximate a donut-mode laser (e.g., LG_{01} mode) by distributing point sources around a ring. Use the Ring Radius to match the mode's intensity peak radius and Number of Modes to achieve sufficient angular sampling.

2. **Ring-Shaped LED Illuminators**: Model circular LED arrays used in machine vision or microscopy for dark-field illumination. The Ring Radius corresponds to the physical radius of the LED ring.

3. **Fiber Optic Ring Sources**: Simulate specialized fiber optics that emit light from a circular ring (e.g., certain endoscopic imaging systems or ring lighting for medical devices).

4. **Annular Aperture Illumination**: Model the effect of illuminating an annular aperture with a coherent source by representing the illumination as a ring of coherent point sources.

5. **Optical Trapping with Ring Beams**: Simulate the field distribution produced by holographic optical tweezers generating ring-shaped traps for particle manipulation.

Software Usage

1. **Adding the Detector**: From the Digital Twin Hub, add the "Dirac-Comb Convolution Detector [Ring]" (DF-CONV02) to your optical system. Position it at the plane where you want to observe the superimposed field.

2. **Configuring the Detector Channel**: Open the detector's properties and navigate to the Add-ons tab. Add and configure the **Convolution with Delta Ring** add-on:

   - Set "Number of Modes" (e.g., 12 for a ring with 12 equally spaced points).
   - Set "Ring Radius" (e.g., 0.5 mm).
   - Enable "Show Ring" for visualization.

3. **Choosing Coherent or Incoherent Superposition**: The position of the add-on in the channel determines the type of superposition:

   - **Incoherent superposition** (e.g., for LED rings): Place the "Convolution with Delta Ring" add-on **after** the "Irradiance" add-on. The detector will first compute irradiance from the propagated field, then convolve it with the ring Dirac comb (adding intensities).
   - **Coherent superposition** (e.g., for laser ring modes): Place the "Convolution with Delta Ring" add-on **directly after** the "Electromagnetic Field Quantities" add-on. The detector will convolve the complex electromagnetic field with the ring Dirac comb, preserving phase information and allowing interference between the shifted copies.

4. **Running the Simulation**: Execute the field tracing. Only the central mode is propagated through the system; the ring convolution is applied numerically within the detector.

5. **Interpreting Results**:

   - If "Show Ring" was enabled, you will see an overlay indicating the ring positions.
   - The resulting field/irradiance distribution shows the superposition of all ring-positioned copies.
   - For coherent superposition with sufficient Number of Modes, you may observe interference patterns characteristic of the ring geometry.
   - Use the detector's data export to analyze the combined profile.

6. **Choosing the Number of Modes**: A rule of thumb is to ensure the angular spacing between points is small enough to resolve the desired ring features. For a ring of radius R, the arc spacing is $\Delta s = 2\pi R/N$. For most applications, $N = 12$ to 36 provides good angular sampling.