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Generation and 3D Regulation of Optical Needle Beams via Caustic Engineering

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Abstract

This paper summarizes the generation and regulation of optical needle beams based on caustic engineering and angular-spectrum control. An optical needle beam can be regarded as a specially truncated Bessel-type beam with a narrow full width at half maximum, an extended depth of focus, and a strong non-diffracting core. Compared with traditional needle-beam generation methods that rely on bulky axicons, binary optical elements, or high-numerical-aperture systems, the reported approach uses a programmable phase modulation strategy to produce and regulate the beam more flexibly. The method first interprets the central focus of a Bessel beam as a degenerate caustic point, then suppresses peripheral rings to form a highly localized needle-like main lobe. By establishing the relation between the modulated angular spectrum and the desired on-axis intensity distribution, the axial intensity can be made nearly uniform, linearly increasing, or linearly decreasing over a designed propagation interval. The source material also extends the caustic-point concept from a single focal point to a sequence of focal points, providing a route for trajectory control in space. The study indicates that caustic-based optical needle beams are promising for particle manipulation, light-sheet microscopy, deep imaging, laser manufacturing, and other photonic applications requiring compact and reconfigurable beam shaping.

Keywords

Optical Needle Beam; Caustic Engineering; Bessel Beam; Longitudinal Regulation; Angular Spectrum; Beam Shaping

1. Introduction

Propagation-invariant non-diffracting optical fields have long been a research hotspot in modern optics, as they can maintain a stable transverse intensity profile over a long propagation distance, far beyond the Rayleigh range of conventional Gaussian beams. Among various non-diffracting beams, optical needle beams stand out due to their unique combination of an ultra-narrow central focal spot, an extended depth of focus, and high energy concentration. These characteristics make them ideal for applications demanding high spatial resolution and long working distances, such as optical trapping, high-precision micromachining, light-sheet fluorescence microscopy, and wavefront sensing.

Traditional methods for generating optical needle beams usually adopt radial polarization modulation, multi-ring binary phase elements, axicon lenses, high-NA focusing systems, or micro-nano metasurfaces. Although these techniques can produce sub-wavelength focusing and long DOF, most suffer from bulky system volume, fixed optical functions, poor reconfigurability, and high fabrication costs. To overcome these limitations, this paper introduces a caustic-driven angular-spectrum modulation method, which interprets the formation of optical needle beams from the perspective of geometric optical caustics and realizes flexible beam control through programmable phase masks.

The core objective of this study is to elaborate the physical mechanism of converting a circular caustic into a degenerate caustic point for needle-beam generation, establish the quantitative relationship between angular-spectrum phase modulation and longitudinal intensity distribution, and extend the method to realize spatial trajectory regulation. This work provides a compact, reconfigurable, and theoretically intuitive solution for designing high-performance optical needle beams.

2. Physical Basis of Optical Needle Beams

2.1. From Circular Caustics to a Needle-Like Focus

The theoretical starting point is the same angular-spectrum framework used for structured non-diffracting beams. When the prescribed transverse caustic is a finite circle, the resulting field corresponds to a high-order Bessel-like structure. As the radius of the target caustic tends toward zero, the circular caustic degenerates into a focal point. In this limit, the beam approaches a zero-order Bessel-type core concentrated on the optical axis.

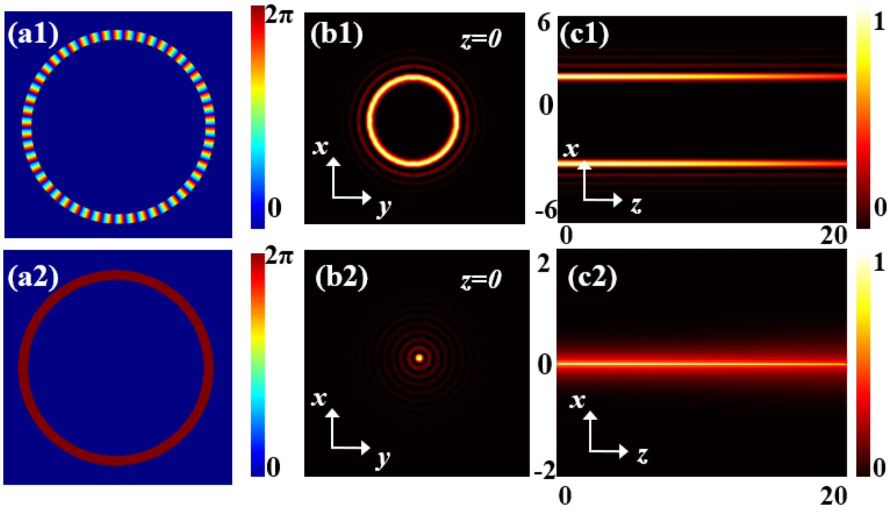

Figure 1. Comparison between a higher-order annular caustic beam and the degenerated central-focus case associated with a needle-like beam.

As the radius R of the target circular caustic approaches zero, the circular caustic gradually degenerates into a single focal point on the optical axis. In this limit, the light field reduces to a zero-order Bessel beam, where most energy is concentrated in the central main lobe, forming the basic skeleton of an optical needle beam. Mathematically, the optical field of the zero-order Bessel beam can be expressed as:

$$U(\rho, z) = e^{ik_z z} J_0(k_t \rho)$$

where J0 is the zero-order Bessel function, kt=k0sin$\alpha$is the transverse wave number, kz=k0cosα is the axial wave number, k0=2 π / λ is the wave number in vacuum, andα is the half-cone angle of the wavevector cone.

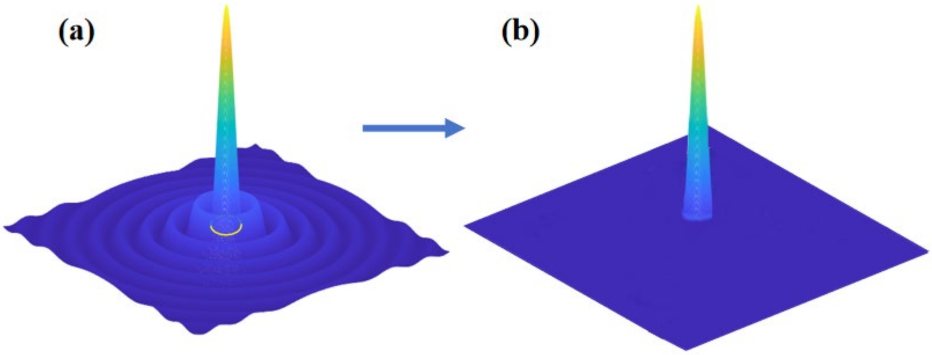

Figure 2. Transformation from a ring-rich Bessel distribution to a concentrated optical needle beam.

2.2. Gaussian Truncation for Pure Needle-Beam Formation

A standard zero-order Bessel beam inherently contains infinite concentric side lobes, which limit energy utilization and introduce background interference in practical applications. To obtain a clean optical needle beam, Gaussian truncation filtering is applied to retain only the central main lobe within the first zero of J0(ktρ) and suppress all high-order rings. The truncated field is written as:

$$U_{\text{needle}}(\rho, z) = e^{ik_z z} J_0(k_t \rho) \cdot \text{rect}\left(\frac{\rho}{\rho_0}\right)$$

where rect(•) is the rectangular filter function and $\rho 0$ is the radius of the first zero of J0(ktρ). After truncation, the beam becomes a pure needle-like field with a single central lobe, no side lobes, and finite energy, fully satisfying the characteristics of an optical needle beam.

2.3. Performance Comparison: Needle Beam vs. Bessel vs. Gaussian Beam

Numerical comparisons reveal significant advantages of the optical needle beam:

- Transverse profile: The needle beam has a narrower FWHM than the Gaussian beam and eliminates the side lobes of the Bessel beam.
- Axial propagation: The needle beam maintains a stable central lobe over a long range, with a much flatter intensity distribution than the rapidly diffracting Gaussian beam and the ring-distributed Bessel beam.
- Energy concentration: Most energy is confined in the central needle core, greatly improving energy efficiency.

These features confirm that the caustic-based optical needle beam outperforms conventional beams in scenarios requiring long-range, high-resolution, and low-background focusing.

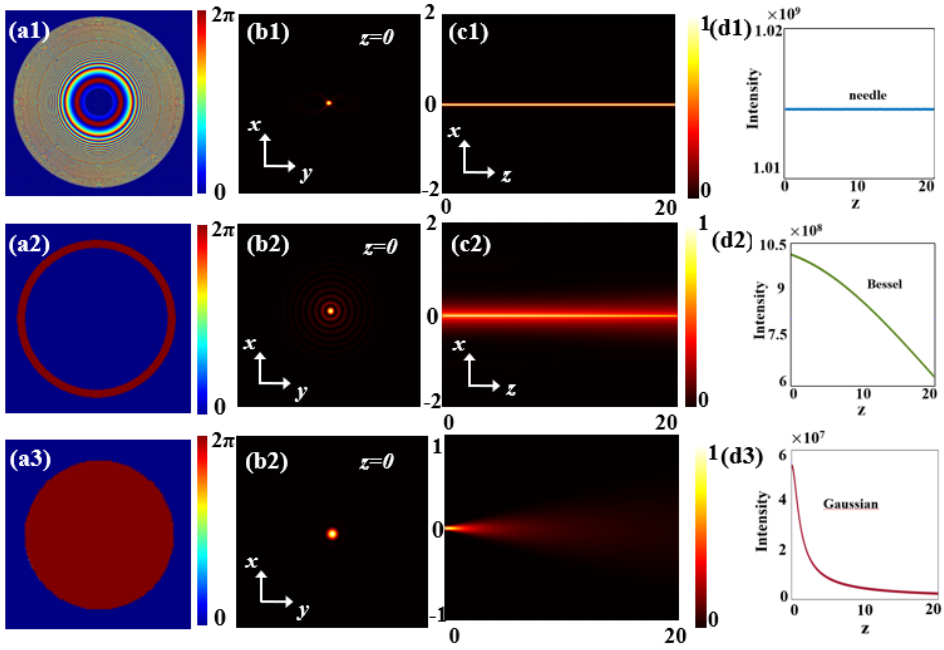

Figure 3. Numerical comparison of angular spectra, transverse intensity, side-view propagation, and axial intensity for needle, Bessel, and Gaussian beams.

This comparison highlights the physical advantage of the approach. Instead of merely maximizing peak intensity at one focal plane, the design seeks to create a confined beam that remains useful over a finite axial range. That property is important for microscopy, micro-fabrication, and trapping tasks in which the target does not remain at a single exact focal position.

3. Longitudinal Regulation by Angular-Spectrum Engineering

3.1. Hankel-Transform Relation between Phase Mask and Axial Intensity

For azimuthally symmetric optical fields, the angular-spectrum integral can be converted into a Hankel transform, which directly links the phase modulation on the spatial light modulator (SLM) to the axial intensity distribution:

$$U(0,z)=\int_0^\infty \tilde{U}(k_t)e^{ik_z z}k_t J_0(k_t\rho)dk_t$$

where $\tilde{U}$(kt) is the radial angular spectrum modulated by the SLM phase mask. This equation indicates that the on-axis optical field is a superposition of ideal Bessel components with different radial wavevectors kt.

By dividing the SLM phase mask into multiple concentric annular zones, each zone introduces a specific phase delay that corresponds to a caustic point at a certain axial position zi. The total optical needle beam is the coherent superposition of all these caustic points. By designing the phase delay of each annular zone, we can precisely control the density and distribution of caustic points along the z-axis, thus shaping the axial intensity profile.

3.2. Arbitrary Longitudinal Intensity Control

Based on the superposition principle of caustic points, we realize three typical longitudinal intensity distributions:

Uniform intensity (I(z)=1): Phase delays are optimized so that caustic points are evenly distributed along the axis, resulting in nearly constant intensity over a designed range.

Linearly increasing intensity (I(z)=2z/zmax): Caustic-point density gradually increases with propagation distance.

Linearly decreasing intensity (I(z)=2(1−z/zmax)): Caustic-point density gradually decreases with propagation distance.

This arbitrary longitudinal regulation cannot be achieved by traditional passive optical elements and provides unique flexibility for application-specific beam design.

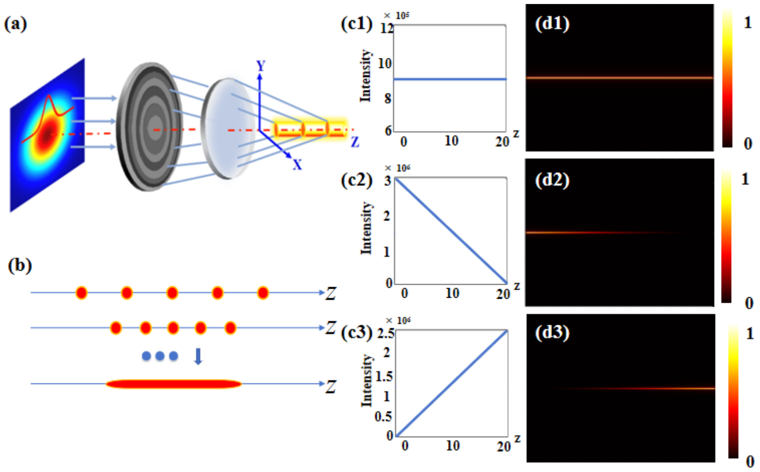

Figure 4. Principle of optical needle generation by superposing controlled focal points,

enabling uniform, decreasing, or increasing axial intensity.

The source material demonstrates three representative longitudinal profiles: nearly uniform intensity, linearly decreasing intensity, and linearly increasing intensity. This ability to prescribe how energy is distributed along the axis is a strong advantage over passive focusing methods, because it allows the same optical platform to be adapted to different tasks simply by updating the phase mask.

3.3. Extension to Trajectory Control

The same caustic-point logic can be generalized from an axial sequence to a spatial trajectory. If one focal point corresponds to one annular spectral contribution, then a desired focal path corresponds to a family of annular contributions distributed in k-space. In this way, the beam can be regulated not only in length and on-axis intensity, but also in position, making the method relevant to directed energy delivery and dynamic beam steering.

Although the second paper focuses mainly on optical needle formation and axial regulation, this extension shows that the proposed framework is part of a larger programmable caustic toolbox rather than an isolated beam-design trick.

3.4. Representative Trajectory-Regulated Needle Beams

The source chapter further shows that a phase mask derived from caustic-point superposition can steer the focal core along prescribed paths rather than keeping it on a straight axis. Representative simulations include a parabolic bending path and a sinusoidal oscillating path. In both cases, the optical energy remains highly concentrated near the moving focal position, which indicates that the needle-like confinement can be preserved while the beam trajectory is deliberately changed.

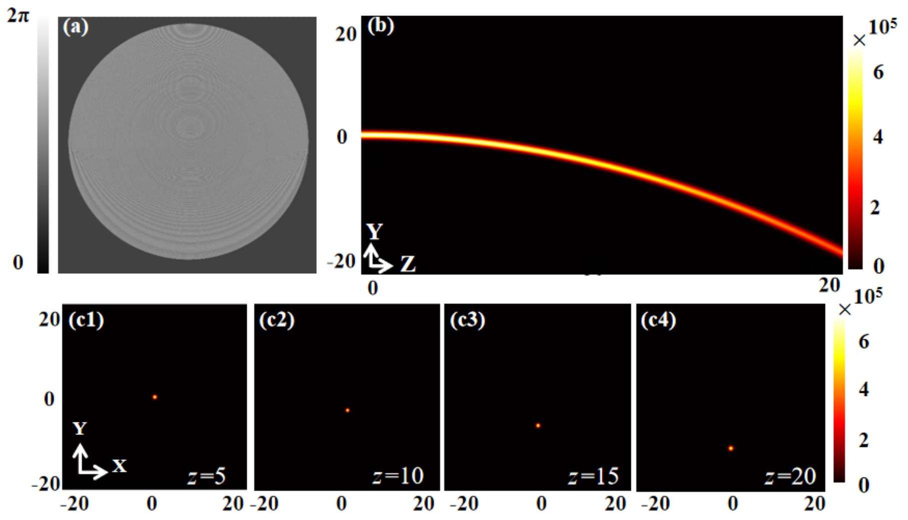

Figure 5. Example of a parabolically guided needle-like focus obtained by caustic-point trajectory regulation.

This result is conceptually important because it bridges two goals that are often treated separately: long-depth focusing and spatial steering. Once these two capabilities are unified in one programmable phase design, the beam can be adapted to curved-surface processing, non-contact delivery around obstacles, and three-dimensional illumination tasks.

4. Experimental Verification

The experimental setup consists of a He－Ne laser, beam expander, SLM, Fourier lens, and CCD camera. The pre-calculated annular phase masks are loaded onto the SLM to modulate the incident Gaussian beam. After Fourier transformation, the generated optical needle beams are recorded at different propagation planes.

Experimental results show that:

- The generated needle beams have an ultra-narrow central lobe and long DOF, consistent with numerical simulations.
- The axial intensity can be stably controlled to be uniform, increasing, or decreasing.
- The needle beam can propagate along preset curved trajectories without obvious distortion or diffraction.

The high agreement between experimental and simulated results fully validates the reliability and practicability of the caustic-based method.

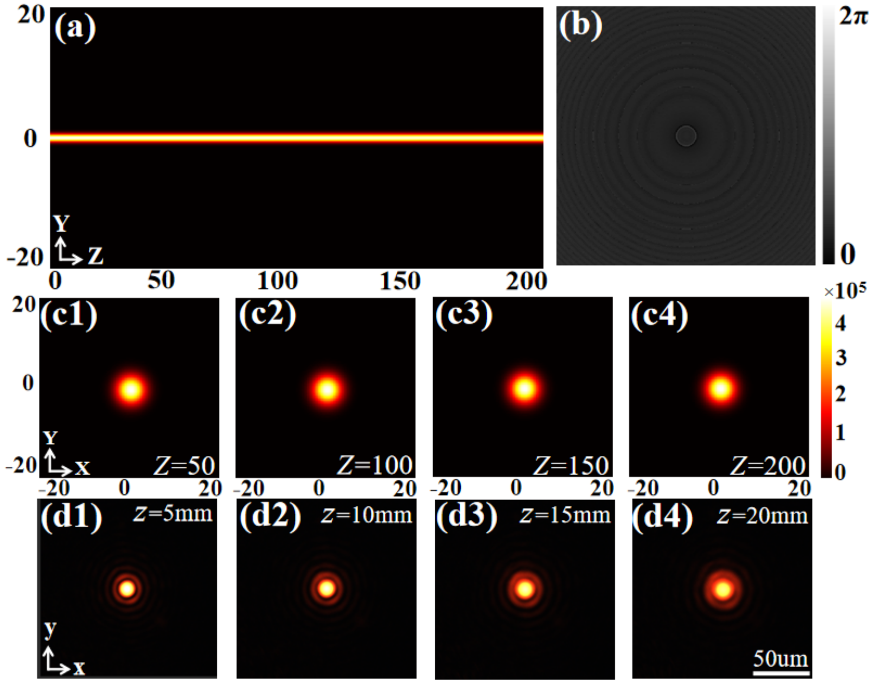

Figure 6. Experimental results of the laser beam

5. Advantages and Potential Applications

The caustic-based needle-beam strategy offers several clear advantages. First, it uses a programmable phase-only modulation platform, which simplifies reconfiguration and avoids dependence on a single fixed optical component. Second, it provides high axial flexibility, allowing the beam to maintain, increase, or decrease intensity over a chosen propagation interval. Third, it preserves the non-diffracting character needed for extended working distances.

These properties make the beam suitable for optical trapping and manipulation, where particles may need to remain confined over an extended depth. They are also relevant to light-sheet and deep imaging, because a long narrow focus can improve sectioning and penetration performance. In laser manufacturing and micro-processing, an optical needle beam can deposit energy along an elongated region instead of at a single point, which may improve processing efficiency and tolerance.

From an engineering perspective, the approach is also attractive because it can be implemented with a spatial light modulator and updated digitally. That means the beam can be redesigned in real time without replacing hardware.

6. Conclusion

In conclusion, the source work provides a coherent caustic-based explanation for the generation and regulation of optical needle beams. By interpreting the beam core as a degenerate caustic point derived from annular angular-spectrum control, the method connects non-diffracting-beam theory with practical programmable focusing. It further shows that the axial intensity of the beam can be prescribed through the superposition of multiple focal contributions, enabling uniform or deliberately varying longitudinal profiles. This combination of high localization, extended depth of focus, and digital reconfigurability makes caustic-engineered optical needle beams a promising tool for advanced photonic applications.

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