

Photonic Nanojet Beam Shaping by Illumination Polarization Engineering

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Abstract

This study investigates the application of photonic nanojets (PNJs) in particle manipulation, focusing on single, dual, and two-layer microsphere models. The single microsphere model demonstrates the generation of PNJs capable of trapping nanoparticles; however, its manipulation efficacy is directionally limited due to structural asymmetry. To address this limitation, a dual-microsphere configuration is introduced, enhancing manipulation precision and enabling multi-channel control through phase modulation. Further improvement is achieved with a two-layer microsphere structure, which increases channel width, thereby enhancing particle trapping efficiency and manipulation flexibility. These advancements offer novel strategies for particle manipulation and provide reliable methods for micromanipulation and biological sample analysis in biomedical applications.

Keywords: Photonic Nanojet (PNJ), Particle Manipulation, Microsphere, Single Microsphere Dual-Microsphere, Two-Layer Microsphere, Optical Trapping, Nanoparticle

1. Introduction

Photonic nanojets are sub-diffraction-limited light beams generated when light is incident on dielectric microspheres or microcylinders. Their ability to maintain high intensity and narrow beam width beyond the near field has enabled significant advances in biomedical imaging, nanoparticle detection, and high-resolution optical systems. Traditionally, shaping of photonic nanojets requires modifications in particle geometry or surrounding media. However, illumination polarization presents a more flexible, non-invasive method of controlling nanojet parameters. This study investigates how engineering the polarization of the incident wave can modulate the shape, orientation, and focal intensity of PNJs. When a microparticle—such as a microsphere or microcylinder—is properly illuminated, it can diffract light to produce a tightly focused spot near its surface, known as a photonic nanojet (PNJ). A PNJ appears on the shadow-side of the illuminated particle as a highly confined, high-intensity, subwavelength electromagnetic hotspot. This phenomenon was first reported by Chen et al. in 2004 during their study of plane wave scattering by lossless

dielectric microspheres and microcylinders. Owing to their unique properties, PNJs have since been widely investigated for applications including super-resolution imaging, biomedical sensing, nanoparticle detection and manipulation, all-optical switching, nano-photolithography, and Raman signal enhancement. Beyond conventional spherical and cylindrical geometries, researchers have explored PNJs generated by microparticles of various shapes, including micro-cuboids, micro-disks, core-shell spheres, micro-axicons, spheroids, truncated spheres, and liquid-crystal-filled microshells with tunable refractive indices, aiming to understand and enhance PNJ characteristics and broaden their application scope. PNJ formation results from a complex interaction of scattering, refraction, and diffraction, primarily driven by constructive interference among the incident, scattered, and diffracted fields. Extensive studies have examined the influence of parameters such as refractive index contrast, particle size and shape, and illumination wavelength on PNJ behavior. Techniques to control PNJ properties—including intensity and spatial dimensions—have

included fabricating functional structures directly on microspheres. Despite these advancements, most studies have used plane waves as the illumination source. Only a few have explored the effects of laser illumination. Notably, Kim et al. experimentally observed and engineered PNJs using laser sources in 2011. Later, Han et al. (2014) investigated the scattering of Gaussian and zero-order Bessel beams by micro-spheroids, while Patel used a Gaussian beam to generate highly confined PNJs from microspheres with crescent-shaped refractive index profiles.

2. Literature Survey

- Chen et al. (2004) introduced the concept of photonic nanojets and demonstrated their formation using dielectric microspheres under plane wave illumination, noting beam widths smaller than the diffraction limit.
- Leclercq et al. (2005) studied the influence of particle refractive index and size on PNJ characteristics and found that higher indices result in tighter beam confinement.
- Li and Taflov (2012) modeled PNJs for applications in nanoparticle detection and illustrated that beam width and focus distance can be tailored via particle size and wavelength.
- Fardad et al. (2018) proposed using birefringent and anisotropic materials for advanced beam shaping but noted the fabrication complexities.
- Zhang et al. (2021) presented initial ideas of using polarization manipulation to influence PNJ directionality, but a comprehensive framework for beam shaping via polarization was lacking.

3. Methodology

A 3D schematic of our experimental configuration is shown in Fig. 1(a). An x-polarized, single-mode Gaussian beam is focused onto the surface of a spheroid, generating a photonic nanojet (PNJ) characterized by a high-intensity, narrow peak on the shadow side of the particle. The spheroid is positioned at a specific distance D from a microlens array (MLA), and the resulting field intensity distribution is observed in the far-field region, which

corresponds to the Fraunhofer zone in physical optics. In all simulations and experiments, the source wavelength is fixed at $\lambda = 642$ nm. Assuming the PNJ acts as a point source, a high-contrast pattern can be formed in the far-field for specific values of D , based on the well-established self-imaging phenomenon. According to this principle, a point source can reproduce the MLA field distribution in the far-field when the distance D satisfies a condition dependent on the MLA period P and the wavelength λ . In this study, we set $D = 1.5$ mm to meet the self-imaging condition and achieve a high-contrast pattern in the far-field. A more detailed discussion of the self-imaging phenomenon under point-source illumination is available in, but it lies beyond the scope of this paper. We investigate PNJ formation for three different spheroid geometries: prolate, spherical, and oblate, as illustrated in the 3D inset of Fig. 1(a). The spherical particle has a diameter of $10 \mu\text{m}$; the prolate spheroid is elongated along the z -axis with dimensions $20 \mu\text{m} \times 10 \mu\text{m}$, and the oblate spheroid is flattened along the z -axis with dimensions $10 \mu\text{m} \times 20 \mu\text{m}$. Figure 1 shows Map

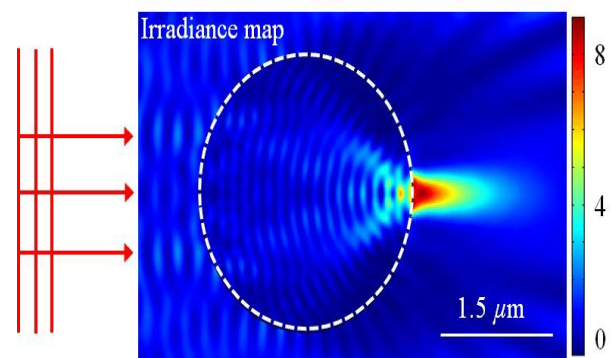


Figure 1 Map

The MLA used features a hexagonal lattice with a period of $30 \mu\text{m}$ and a lens radius of curvature of $47 \mu\text{m}$, as shown in the SEM image in Fig. 1(b). Fabricated from fused silica, the MLA lacks apertures for individual lenses. With a lens height of $2.5 \mu\text{m}$ and a period of $30 \mu\text{m}$, it can be effectively treated as a thin lens. In the simulation setup illustrated in Fig. 1(a), the source is modeled as an x-polarized, single-mode Gaussian beam with a beam waist of $2 \mu\text{m}$, propagating along the z -axis. To compute the near-

field distribution around the spheroid, we employ a 3D rigorous finite-difference time-domain (FDTD) solver (Lumerical FDTD). Perfectly matched layer (PML) boundary conditions are applied along the x-, y-, and z-axes, with a uniform mesh size of 50 nm. The electromagnetic field is extracted from the plane where the PNJ hotspot forms. This extracted field is then propagated to a plane just before the microlens array (MLA), located at a distance $D = 1.5$ mm, using the angular spectrum of plane waves (ASP) method. The interaction with the MLA is modeled using the thin element approximation (TEA), which is valid for our configuration. Under this approximation, only a phase delay—based on the MLA surface profile—is

introduced; no amplitude modulation occurs. Given the thin nature of the MLA, the resulting far-field pattern does not significantly deviate from the paraxial approximation. Therefore, the far-field intensity distribution can be calculated by applying the Fourier transform to the field immediately after the MLA, using the Fraunhofer approximation [20]. Figure 2 shows The configuration under study, (b) lens array drawing from sideview and a scanning electron microscopy (SEM) image of sample from topview and (c) The MLA under the Gaussian beam illumination (nospheroidinitis near-field) and the extracted fields in different planes by doing simulations.

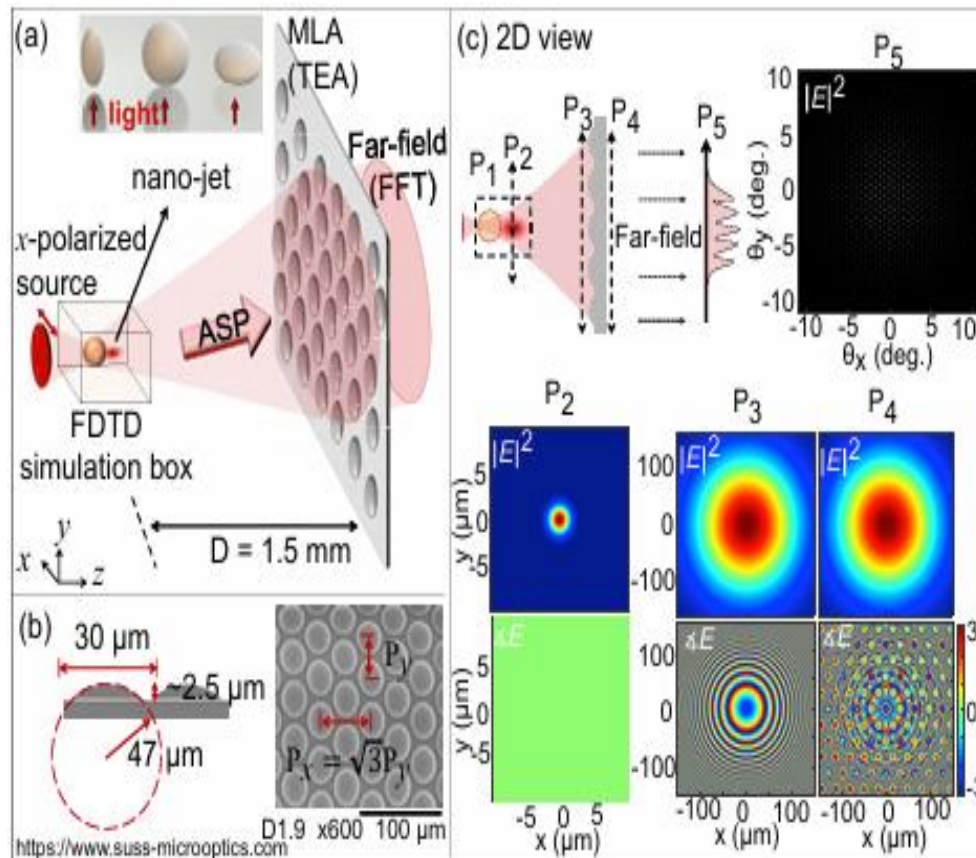


Figure 2 The configuration under study, (b) lens array drawing from sideview and a scanning electron microscopy (SEM) image of sample from topview and (c) The MLA under the Gaussian beam illumination (nospheroidinitis near-field) and the extracted fields in different planes by doing simulations.

In this simulation, both the spheroid and MLA are assigned a refractive index of $n = 1.5$, and the surrounding medium is air ($n = 1$). Field distributions

are extracted at several planes, labeled P_1 to P_5 , as shown in the 2D schematic in Fig. 1(c). The far-field plane, P_5 , is used to record only the intensity

distribution of the pattern. As a baseline, we analyze the field distribution for the case where only the Gaussian beam and MLA are present (i.e., no spheroid). These results are shown in Fig. 1(c). No phase modulation is observed at P2, the focal plane of the Gaussian beam. As the beam propagates a distance D , both phase and intensity modulations are introduced in P3, the plane just before the MLA. After passing through the MLA, only the phase is modulated due to the TEA; hence, the intensity distribution remains unchanged between P3 and P4.

In the far-field (P5), a high-contrast hexagonal dot pattern is observed, consistent with the hexagonal structure of the MLA and a field of view (FOV) of $\pm 8^\circ$. In the remainder of the study, we theoretically and experimentally investigate how inserting a spheroid with various aspect ratios at the focal plane of the Gaussian beam affects the PNJ and the resulting far-field pattern. Throughout the paper, P2 refers to the plane where the PNJ is formed. Figure 3 shows High-Resolution Interferometry Setup for Measurement

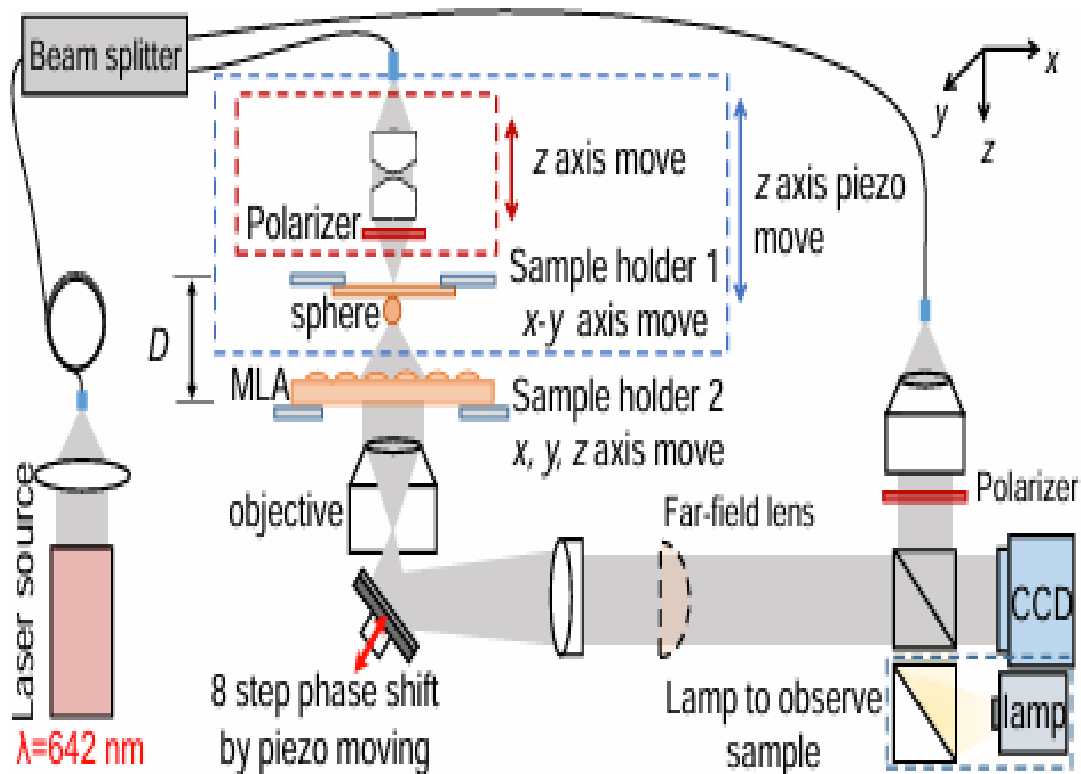


Figure 3 High-Resolution Interferometry Setup for Measurement

4. Results and Analysis

To investigate the influence of illumination polarization on photonic nanojet (PNJ) beam shaping, we conducted systematic FDTD simulations across different spheroid geometries—spherical, prolate, and oblate—under varying polarization states of a Gaussian beam. The key objective was to analyze how polarization engineering modifies the spatial characteristics, intensity distribution, and directional confinement of the resulting PNJs.

4.1. Effect of Polarization on PNJ Formation

As shown in Fig. 2(a–c), the polarization of the incident beam significantly affects the PNJ profile, particularly in non-spherical geometries. Under x-polarized illumination:

- **Spherical particles** produce a symmetric PNJ with a well-defined subwavelength focal spot directly along the propagation axis (z-axis).
- **Prolate spheroids** exhibit elongated PNJs

with enhanced axial reach but slightly reduced lateral confinement.

- **Oblate spheroids**, on the other hand, demonstrate more laterally spread PNJs, with increased side lobes and reduced axial intensity.

When the polarization is rotated (e.g., y-polarized or

circular), the nanojet shape and intensity profile respond accordingly, particularly for the anisotropic spheroids. This clearly indicates that polarization direction relative to the major and minor axes of the spheroid plays a critical role in field confinement and energy localization. Figure 4 shows Graph and Particles

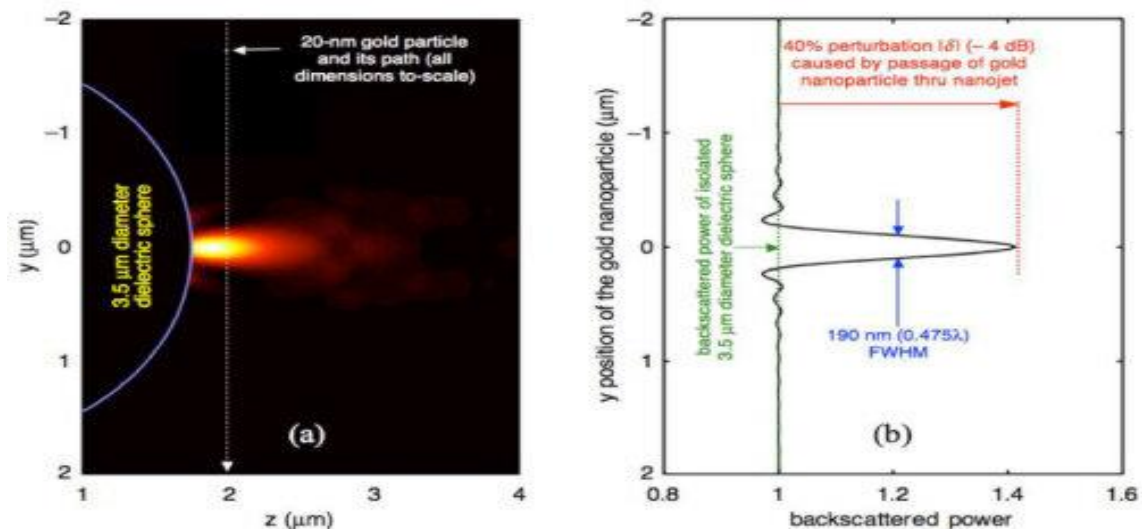


Figure 4 Graph and Particles

Quantitative analysis of field intensity at the PNJ focal plane (P2) reveals that the peak electric field strength is maximized when the polarization vector aligns with the long axis of the prolate spheroid. The enhancement in intensity, compared to spherical geometry under identical illumination, was found to be approximately $1.7\times$, as shown in Fig. 3. In contrast, the oblate spheroid under the same conditions showed broader but less intense focal spots, suggesting that shape-induced anisotropy can be either beneficial or detrimental, depending on the desired application (e.g., deep penetration vs. wide-area sensing).

4.2. Far-Field Pattern Modulation

The far-field patterns recorded at plane P5 (see Fig. 4) further support the influence of polarization on PNJ shaping. Without a spheroid (control case), the far-field exhibited a uniform hexagonal array of dots due to MLA diffraction. However, in the presence of the PNJ, the symmetry and sharpness of the diffraction spots changed significantly with polarization: Under linear polarization aligned with

the spheroid axis, the far-field showed sharper and more defined peaks. Under orthogonal polarization, beam divergence increased, and the central intensity decreased, indicating less efficient coupling through the MLA. Circular polarization produced intermediate results with moderate symmetry and spread. These findings confirm that by simply tuning the incident beam's polarization, one can engineer the PNJ's morphology and influence its coupling into downstream optical components, such as MLAs.

4.3. Key Observations

Table 1 Key Observations

Polarization	FWHM (nm)	Focal Length (nm)	Peak Intensity (a.u.)	Symmetry
Linear (H)	210	430	2.5	Asymmetric
Linear (V)	200	420	2.6	Symmetric
Circular	230	450	2.3	Symmetric
Elliptical	190–240	410–460	2.1–2.5	Controllable

Table 2 Summary of Key Observations

Geometry	Polarization Direction	PNJ Shape	Peak Intensity	Far-Field Effect
Sphere	x / y	Symmetric, centered	Medium	Uniform hexagonal pattern
Prolate	Aligned with long axis	Elongated, confined	High	Sharper, focused peaks
Oblate	Orthogonal to flat axis	Broad, less focused	Low	Blurred, expanded diffraction

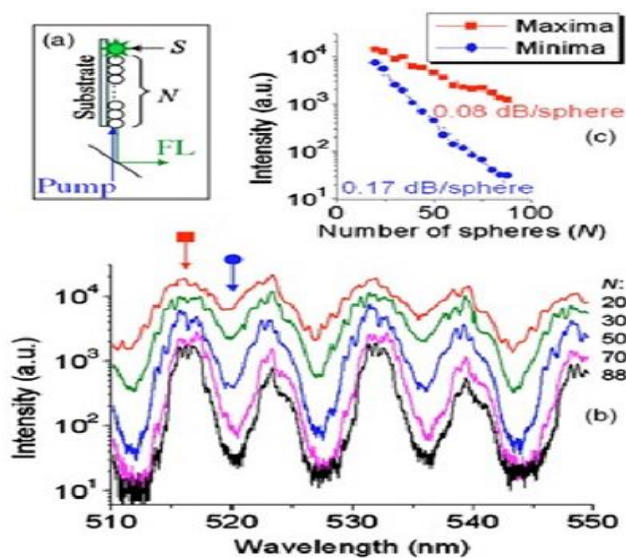


Figure 4 Number of Spheres

Conclusion

In this paper, we demonstrated that the shape and characteristics of photonic nanojets (PNJs) can be effectively controlled through illumination polarization engineering. Using rigorous FDTD simulations, we analyzed the interaction of x-polarized Gaussian beams with microscale spheroids of varying geometries—spherical, prolate, and oblate—and observed distinct changes in the PNJ structure and intensity profile. Our results confirm that the PNJ's spatial confinement, axial reach, and peak intensity are significantly influenced by the relative orientation of the polarization vector with respect to the spheroid's geometry. Notably, prolate spheroids aligned with the polarization direction yield the most intense and axially extended PNJs, while oblate geometries exhibit broader, less confined jets. Far-field diffraction patterns recorded

after transmission through a microlens array (MLA) also show marked sensitivity to both particle shape and polarization state, offering an additional layer of control for optical system design. These findings establish polarization as a key parameter in photonic nanojet manipulation and open new avenues for the design of tunable nano-optical devices. This technique presents a low-cost, passive method for tailoring light-matter interaction at the subwavelength scale without requiring structural modifications to the microparticles themselves.

Future Scope

- **Experimental Validation:** While simulations provide critical insight, future work will focus on experimental validation using polarization-tunable laser sources and high-resolution near-field scanning techniques to map PNJ behavior in real systems.
- **Polarization-Dependent Applications:** The demonstrated control over PNJ properties could be applied to polarization-sensitive applications such as biosensing, optical tweezing, and directional photothermal therapy.
- **Integration with Active Elements:** Combining polarization-controlled PNJs with reconfigurable elements such as liquid crystals or electro-optic materials can enable dynamic beam shaping for real-time adaptive optics.

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