Enhancing Photoluminescence of Silicon Quantum Dots Using a Computationally Designed Nanolens

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BACKGROUND

- Si quantum dots (Si QD) in fused silica emit photoluminescence over a broad angular range, limiting forward collection.
- A computationally designed 3D nanolens can redirect this emission into the objective collection cone.
- Adjoint FDTD optimization and a tandem neural network are used to design fabrication-ready nanolenses.

OBJECTIVE

Enhance Si-QD photoluminescence (PL) collected by camera imaging through objective lenses by integrating 3D-printed computational nanolenses.

Nanolens Design, Fabrication and Characterization

- Nanolens geometries were generated with MEEP (FDTD) using adjoint topology optimization and a tandem neural network.
- 3D nanolenses were fabricated by two-photon lithography using the optical setup shown in Fig. 3.
- Scanning Electron Microscopy (SEM) inspection confirms that the printed nanolenses reproduce the design with good fidelity (Fig. 4).
- PL enhancement was measured using objective lens as nanolens-region intensity divided by uncoupled Si-QD background intensity.

QD Fabrication and Characterization

Si QDs were formed by Si-ion implantation into fused silica at Western's Tandetron facility, followed by annealing for QD nucleation. Steady-state PL was measured (Fig. 2).

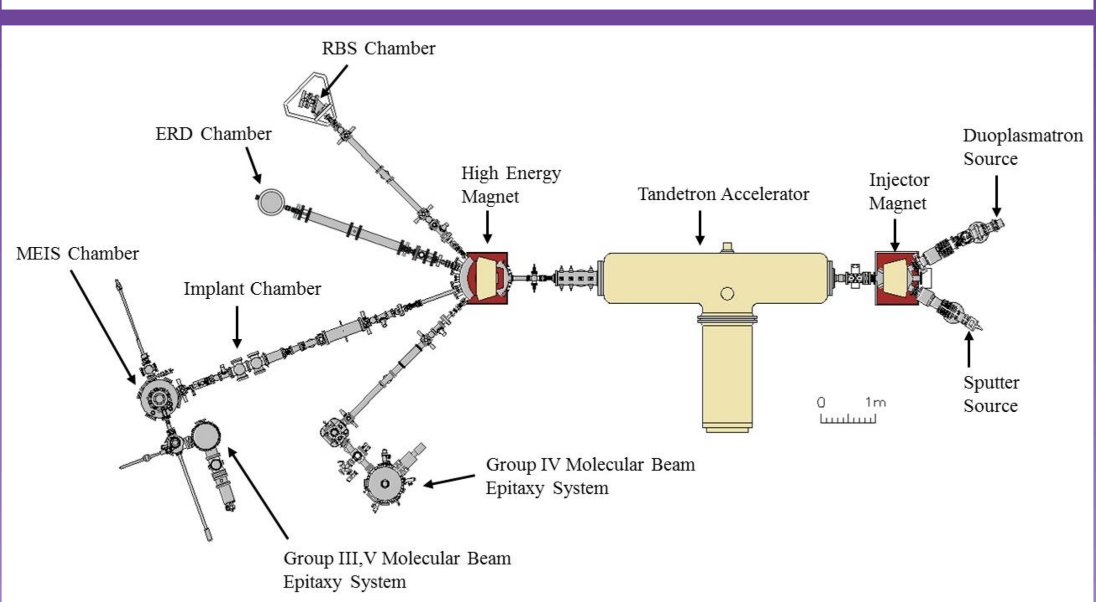

Figure 1: Schematic of Western University's Tandetron accelerator facility. Si-ion implantation for Si-QD fabrication is performed at the implant chamber/beamline.

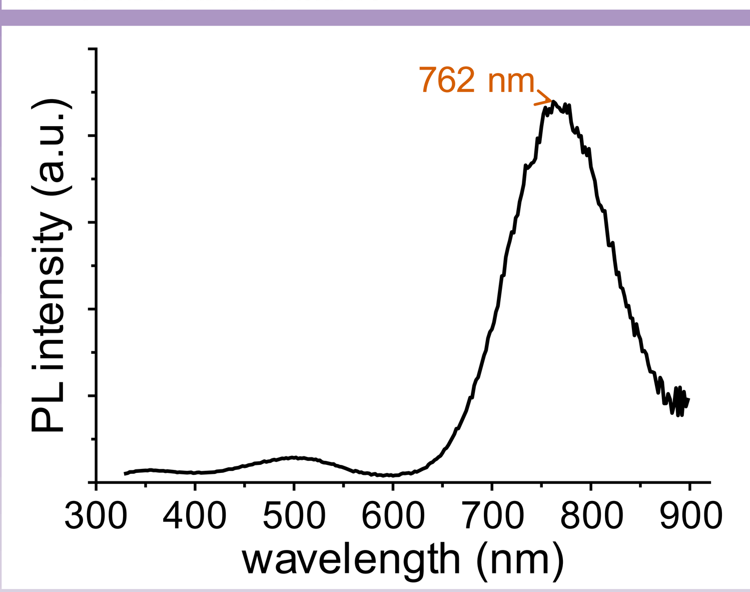

Figure 2: Steady-state Si-QD PL spectrum under 270 nm excitation (40 keV, 1 x 10^{16} atoms/cm^2 Si implant in fused silica).

REFERENCES

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4. Johlin et al., Nat. Commun. 9, 4742 (2018).

RESULTS

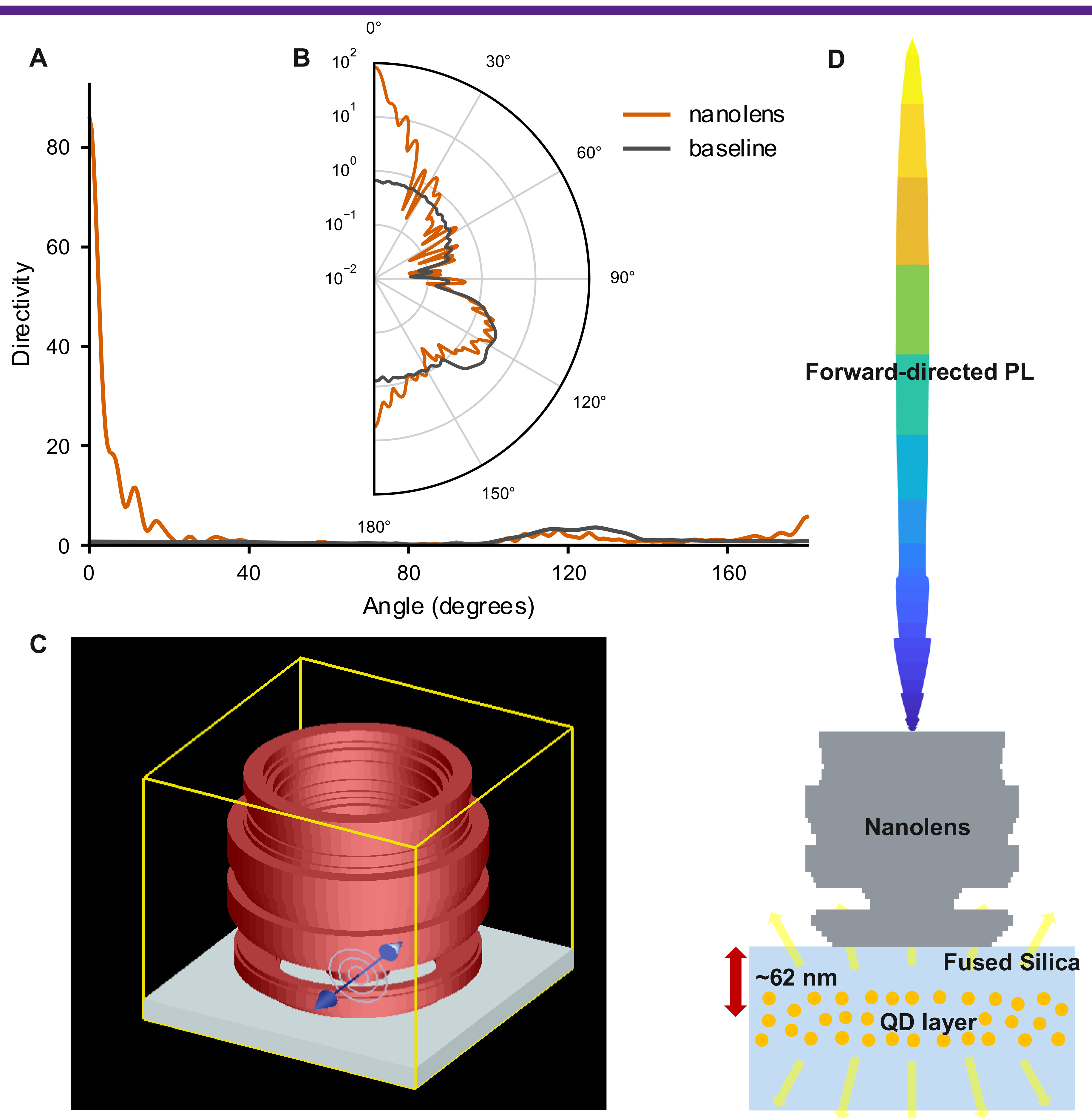

Figure 5: Simulated forward directivity and Si-QD–nanolens coupling. (A,B) Cartesian and polar directivity plots compare emission with the nanolens case to the baseline case without the nanolens. The nanolens case shows strong beaming near 0°, indicating that the nanolens redirects emission along the optical axis and enhances forward collection. (C) FDTD simulation geometry. (D) Schematic of the Si-QD layer ~62 nm below the fused-silica surface coupled to the nanolens for enhanced forward PL collection.

3D-printed nanolenses enhance forward-collected Si-QD PL.

- Printed nanolens arrays produce localized PL brightening relative to uncoupled Si-QD background.
- Peak measured enhancement reaches ~4.5× at Numerical Aperture (NA) 0.92 and ~9.5× at NA 0.46.
- Simulated collection enhancement predicts the same NA-dependent trend, with ideal values of 5.9× at NA 0.92 and 21.0× at NA 0.46.

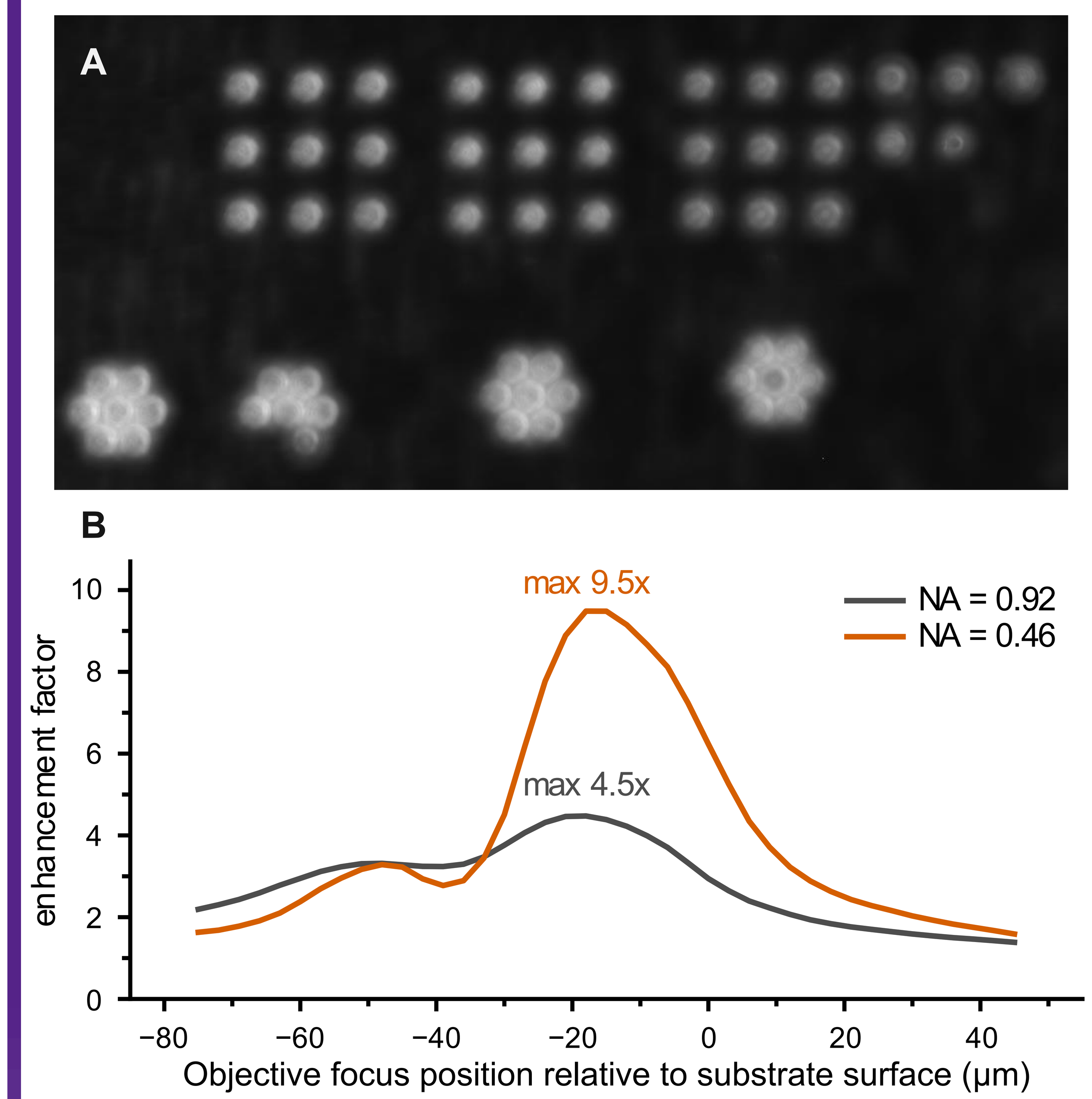

Figure 6: Measured Si-QD PL collection enhancement from printed nanolens arrays. (A) PL image acquired with a 20× objective. (B) Enhancement factor versus lateral position for NA 0.92 and NA 0.46. Peak measured enhancement reaches ~4.5× and ~9.5×, respectively, following the simulated trend of stronger enhancement at lower NA.

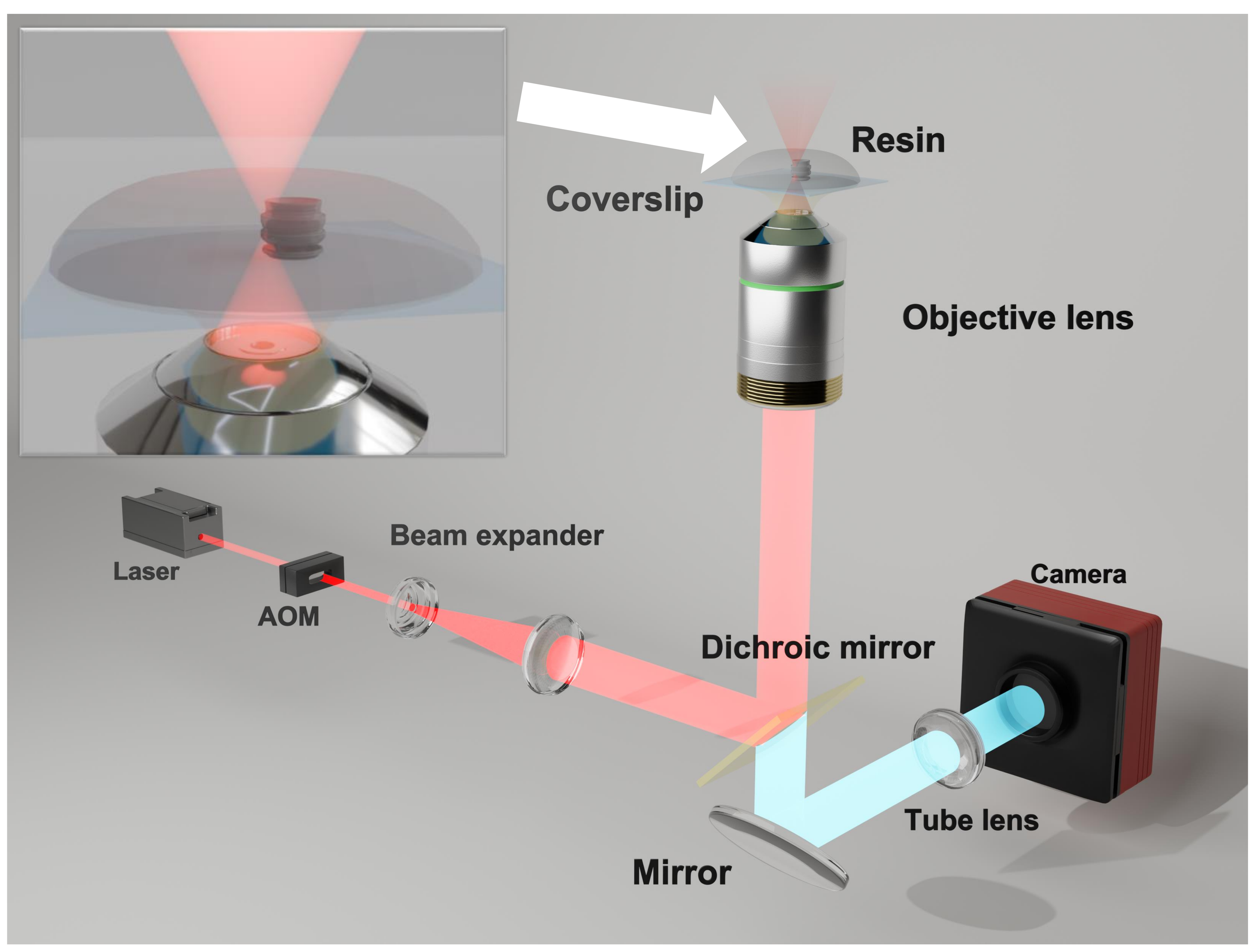

Figure 3: Optical setup for two-photon lithography nanolens fabrication. A modulated and expanded femtosecond laser is focused through the objective into resin beneath the coverslip, while the camera path enables alignment and monitoring during printing.

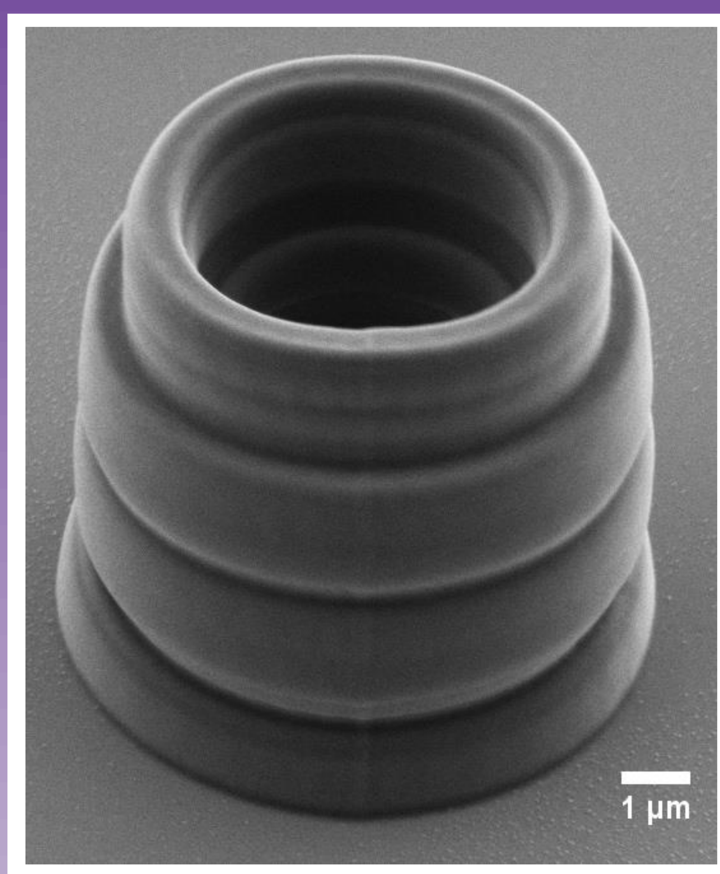

Figure 4: SEM image of a two-photon-lithography printed nanolens with stacked annular features and smooth sidewalls. Scale bar: 1 μm.

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DISCUSSION

- 3D nanolens coupling redistributes Si-QD photoluminescence toward the objective collection direction rather than relying on increased emitter density.
- The stronger response under smaller collection cones is consistent with emission concentrated near the optical axis.
- Simulated far-field directivity supports a beaming mechanism produced by the computationally designed annular nanolens geometry.
- Differences between ideal simulation and experiment likely arise from emitter-position averaging, fabrication tolerances, surface roughness, and nanolens–QD alignment.
- These results demonstrate a compact route toward improved optical readout from Si-compatible quantum-dot emitters.