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Emerging fiber-end multi-beams manipulation platform

Tingting Yuan¹, Xiaotong Zhang² and Libo Yuan^{3*}

Abstract: By examining the development and recent advancements of fiber-optic tweezers, the article emphasizes that microfabrication techniques for multi-core optical fibers and their tapered fiber ends constitute a critical technical foundation for realizing multi-beam optical tweezers and enabling multifunctional integration. A key advantage of these advanced optical tweezers system lies in its significant reduction of the bulky size and complex optical configurations of conventional setups. This innovation not only facilitates remote operation but also enables seamless integration with microscale devices, such as microfluidic chips. It offers a novel approach for constructing photonic lattices at fiber terminations. The method of controlling beams with multiple polarization states serves as an emerging platform for optical manipulation, presenting promising prospects for future applications in atomic chip fabrication, cold molecule generation, and the development of microstructures cavity optomechanical quantum systems. These advancements open new pathways for the engineering design and practical deployment of next-generation quantum chips.

Keywords: optical tweezers; optical fiber device; multi beams manipulation at the fiber end

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1 Introduction

The essence of optical tweezers technology is the interaction between light and matter, and the pico-Newton forces generated during this interaction can be used to move and capture micro-objects. In 1970, Ashkin's research on the trapping and acceleration of micro particles by optical radiation pressure laid the foundation for modern optical tweezers technology¹. In 1985, Chu et al. used three-dimensional optical radiation pressure to achieve the viscous confinement and cooling of atoms², and successfully realized the laser manipulation of atoms³, for which Chu won the Nobel Prize in Physics in 1997. In 1986, Ashkin et al. proposed the current form of optical tweezers, which uses a tightly focused laser beam to stably trap particles with a diameter between 25nm and 10μm in three-dimensional space⁴, and then applied the optical tweezers technology to capture and manipulate viruses, bacteria and single cells^{5,6}. It was the first time that optical tweezers were widely used in the field of biology^{7,8}, and provided an effective tool for elastic measure-

ment of DNA molecules and in-depth systematic study of living single cells, enabling biological research to reach the level of single cells to single molecules. This groundbreaking work laid the foundation for Ashkin's Nobel Prize in Physics in 1986. A large part of this biological single-molecule study involves the exploration of the activity of individual driver proteins. The forces and movements generated by the movement of these proteins can be measured and controlled by optical tweezers to reveal their dynamics and energetics⁷. Another important area of research is DNA. In these studies, DNA molecules adhere to one or more light-captured small beads, which allows the molecules to be stretched and their mechanical properties studied by mechanical spectroscopy⁸.

It has been 50 years since optical tweezers were first proposed, although there have been several remarkable results in the fields of physics and life sciences. However, optical tweezers previously relied on microscope systems or spatial light modulators to generate optical force, and the equipment was relatively large and inconvenient to operate. Therefore, the idea of using optical fibers to make optical

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tweezers was conceived^{9,10}. The adoption of optical fiber technology has enabled precise optical manipulation of microscopic particles at the fiber end, effectively addressing challenges related to miniaturization, optical path simplicity, and remote controllability. This advancement has significantly facilitated the development of optical tweezers technology. A concise overview of the evolutionary milestones in fiber-based optical tweezers, along with representative landmark studies, is illustrated in Fig. 1. In 1993, a pioneering approach was proposed involving the integration of two optical fibers, enabling particle trapping and rotational control at the fiber tip⁹. However, it was not until 2006 that fiber end-tapering techniques were employed, achieving a breakthrough in establishing a three-dimensional gradient potential well at the tip of a single fiber and enabling stable particle trapping¹⁰. In 2007, Libérale et al. introduced a four-fiber configuration combined with focused ion beam (FIB) technology to fabricate micro-reflectors with specific reflection angles at each fiber core, thereby realizing a four-beam diagonal trapping system¹¹. In 2008, tapered dual-core optical fibers were utilized to achieve single-fiber optical tweezers with tunable field orientation at the fiber end, laying the groundwork for the concept of "micro-optical hands"¹². The formal proposal of the multi-core fiber-based micro-optical hand emerged in 2012, demonstrating that four-core fibers could not only trap particles but also perform orientation control, thus exhibiting rudimentary hand-like functionalities^{13,14}. In 2017, coaxial dual-waveguide fibers were developed, enabling both particle trapping and the controlled ejection of trapped particles—functionally analogous to an "optical gun"¹⁵. Multi-core fibers with high-density randomly distributed discrete cores have been used as devices for lensless microscopic imaging and image trans-

mission¹⁶. In 2024, J. Sun et al. realized rotational manipulation of living cells by combining a section of such multi-core fiber with a spatial light modulator (SLM) system¹⁷. Although the multi-core fiber in the system only provided cell trapping and rotational driving, this work fully demonstrated the potential of multi-core fiber-based optical manipulation techniques to cooperate with other optical systems (e.g., lensless single-fiber micro-endoscopy¹⁶, high-resolution cell tomography¹⁷) to accomplish more complex tasks. In 2025, by employing a seven-core fiber and using a precision grinding method for the fiber-end cone, our group successfully achieved multi-functional particle manipulation with a seven-beam micro-optical tweezer¹⁸.

These foundational studies have provided critical technical insights and paved the way for functional advancements in fiber-optic tweezers. After many years of efforts, with the help of multi-core fiber and coaxial double-waveguide fiber, multi-beam control at the cone end of multi-waveguide integration is realized¹⁹.

2 Results and discussion

There are various structural configurations of optical fiber tweezers, such as tweezers composed of multiple fibers⁹ and tapered fiber optical tweezers¹⁰. To discuss the multifunctionality and scalability of optical manipulation, in this paper we only focus on the multi-beam cone-frustum type. The multi-beam control platform with cone multi-core fiber end is a scheme with low waveguide loss and very wide operating wavelength. The most important thing is that based on this scheme, it is easy to manipulate the light beam at the end of the fiber, such as controlling the propagation direction and intensity distribution of each beam. If it is regarded

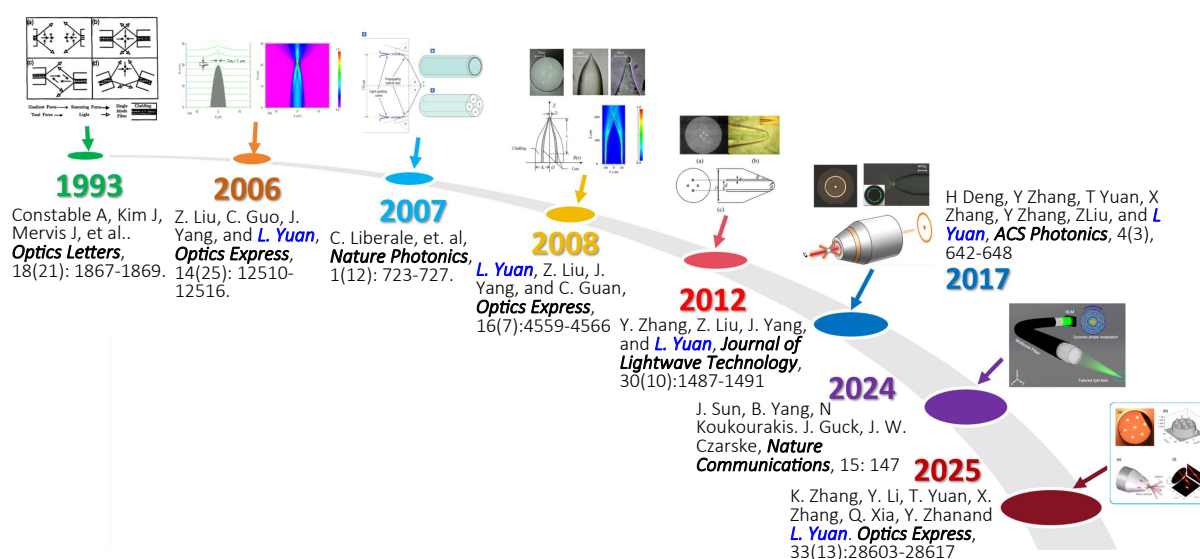


Fig. 1 | A concise overview of the development history of optical fiber tweezers and representative milestone achievements. Figure reproduced with permission from: (a) ref. ^{9,10,12,18}, Optica of American; (b) ref. ^{11,17}, Springer Nature; (c) ref. ¹³, IEEE of American; (d) ref. ¹⁵, American Chemical Society.

as an "optical control platform", the cone multi-core fiber end provides a more general and ideal multi-beam field control method. Figure 2 illustrates an optical tweezers cluster formed by multiple beams at the tip of a conical multi-core optical fiber. Figure 2(a) presents a photograph of a human hand grasping an egg, which serves as a vivid analogy for the particle manipulation mechanism of the multi-beam optical tweezers system: it demonstrates both trapping capability and the ability to control the orientation and position of particles¹⁸. Figure 2(b) displays a typical 7-core optical fiber along with its three-dimensional refractive index distribution, as detailed in Fig. 2(c). At the tapered end of the 7-core optical fiber, seven light beams converge at a focal point after reflection from the conical surface, thereby generating multiple optical traps for particle manipulation.

The central core emits a light field that exerts optical radiation pressure on the particles, while the gradient force traps formed by the six surrounding circumferentially arranged beams generate counteracting forces. This configuration enables push-pull control, realizing a "micro-optical hand" capable of dexterous, three-dimensional manipulation analogous to the human hand.

To enhance the ratio of optical gradient force to total optical power and minimize photothermal effects on captured biological specimens such as cells, we designed a ring-shaped core fiber, as illustrated in Fig. 3(a), and developed a fiber-based optical tweezers system with relatively high trapping efficiency²⁰, designated herein as "Hercules." This device exhibits strong trapping capability, enabling the capture of polystyrene microspheres with diameters ranging

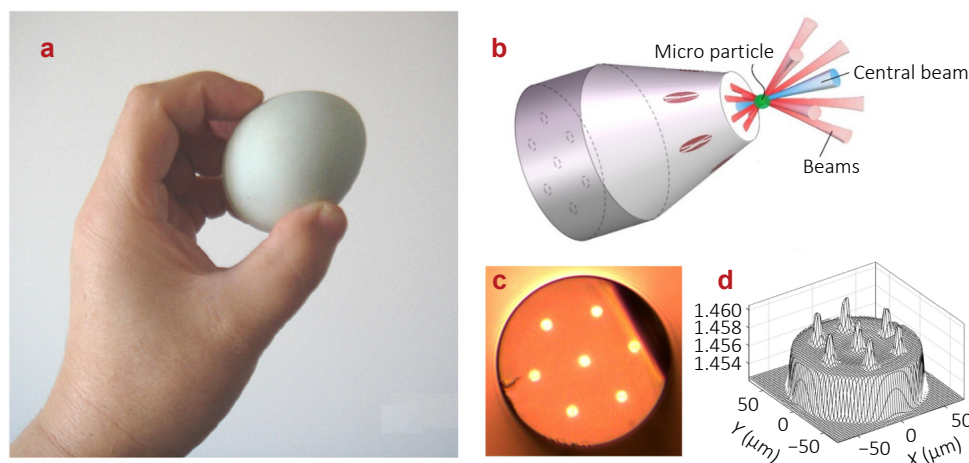


Fig. 2 | Push-pull multi-beam optical tweezers cluster: (a) Photo of a human hand grasping an egg; (b) 7-beams manipulation fiber end in which cross beams combination and micro particle position adjusted by central beam of the central core beam of the seven-core fiber; (c) Cross-section of the seven-core fiber; (d) 3-D refractive index distribution of 7-core fiber.

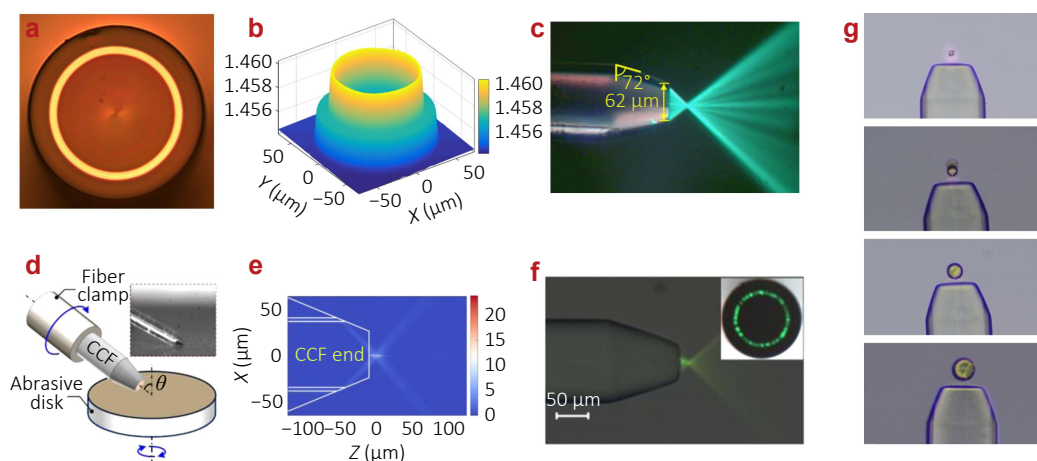


Fig. 3 | Illustration of the "Hercules" optical tweezers based on an annular core tapered fiber end: (a) cross-sectional image of the annular core fiber; (b) three-dimensional refractive index distribution of the annular core fiber; (c) schematic of the fiber tip polished into a 36° conical angle, forming a tightly focused conical shell-shaped light field that generates a large gradient force; (d) illustration of the fiber polishing process; (e) simulation model for optical field convergence at the fiber end; (f) experimental observation of the annular light field emitted from the fiber tip; (g) experimental images showing polystyrene particles with diameters of 5, 10, 20, and 30 μm successfully trapped by the annular core optical tweezers.

from 2 μm to 30 μm , as demonstrated in Fig. 3(g).

The functional expansion of the annular core optical fiber involves incorporating a single-mode fiber core at the center of the annular structure, thereby forming a novel coaxial dual-waveguide optical fiber. This central core serves multiple functions. One key function is enabling the propulsion of microparticles trapped by the annular conical light field. By delivering forward-directed optical radiation pressure through the central core, these microparticles can be accelerated and ejected along the propagation direction of the Gaussian output beam—akin to a bullet propelled by gunpowder within the confines of a gun barrel¹⁵. This mechanism is illustrated in Fig. 4(a–d).

Another promising fiber configuration for optical tweezers applications is the annular core capillary fiber. This fiber features a large central air channel, which facilitates the transport of cell-laden microfluidic streams, thereby enabling integration with microfluidic chips for cell manipulation and analysis. Consequently, it supports both cell trapping and downstream analytical functions. Figure 4(e–k) presents two micro-manipulation tools enabled by this fiber platform. The first is referred to as the "optical machine gun," capable of sequentially ejecting microparticles²¹. In biomedical applications, particularly in targeted drug delivery, this system can be utilized for controlled release of nanoparticles, making it a highly effective tool for precision cell therapy. The second is termed an "optical funnel"²², which achieves single-cell alignment technique commonly employed in flow cytometry and related analytical systems.

3 Key technologies

Reviewing the above fiber-based multi-beam optical manipulation platforms, they mainly include two key technologies: First, optical fibers with multi-core or ring-core structures, as shown in Fig. 5(a–f). Various core structures enable the generation of multiple independent beams, which provides fundamental elements for multi-functional optical manipulation. Second, fiber-end cone fabrication technology, as shown in Fig. 6(a–c). This technology not only makes it possible to construct optical fields with an equivalent large numerical aperture (NA) for multi-beams, but also provides the necessary conditions for achieving optical trapping forces to manipulate micro-particles.

During the fabrication of the fiber-end cone, the numerical aperture of the output optical field is closely related to the gradient force of the optical potential well. Taking a ring-core fiber as an example, Fig. 6(d–f) show the relationship between the cone angle μ of the output optical field and the numerical aperture, corresponding to the grinding cone angle μ' of the fiber end, as shown in Fig. 6(g–i).

Besides the tapered frustum-shaped fiber optical tweezers we have focused on above, other representative fiber optical tweezers technologies have also achieved considerable progress. For instance, Professor Baojun Li's group has

achieved great success in the research on photonic nanojets at fiber tips²³. They applied fiber optical tweezers to the precise optical regulation of neurons, proposed a novel strategy for the precise manipulation of neural cells based on optomechanical forces, and constructed optomechanically controlled biological darts capable of precisely stimulating neuronal subcellular structures. This work realized the accurate stimulation, activation, and growth direction regulation of neuronal subcellular structures, providing a new approach for in-depth understanding of neuronal dysfunction, neural signal transmission, and neural circuit reconstruction²⁴. Professor Shangran Xie's group realized long-distance transport of micro-nano particles using hollow-core photonic crystal fibers²⁵, which paved the way for hollow-core photonic crystal fiber optical tweezers in particle manipulation and high-precision measurement²⁶.

In contrast, the multi-beam tapered fiber tip proposed in this work possesses a central microfluidic channel, thus offering distinct comparative advantages in terms of both the functional extension of optical manipulation and the integration with microfluidic chips.

4 Summary and comparison

Optical tweezers utilize optical radiation pressure to achieve non-contact and non-damaging manipulation of micro/nanoparticles, serving as a key technique in the fields of life science and precision physical measurement. The mainstream technologies can be divided into two categories: conventional optical tweezers and fiber-based optical tweezers, which are highly complementary in terms of technical performance, physical structure, and application scenarios. To demonstrate the respective advantages and applicable scenarios of these two types of optical tweezers, we compare conventional optical tweezers with fiber-based optical tweezers, as listed in Table 1.

As can be seen from the comparison in Table 1, conventional optical tweezers, which are centered on high-numerical-aperture microscope objectives and precision microscope systems, exhibit outstanding advantages: high optical trap stiffness, optical force measurement precision down to the femtonewton level, and a mature and complete quantitative measurement system. They serve as important tools for investigating extreme physical phenomena, precision biophysical measurements, and atomic and quantum technologies. Meanwhile, they are naturally compatible with high-resolution microscopic imaging, offering excellent observation convenience and superior long-term stability after a single alignment. However, their bulky and complex system structure hinders miniaturization and integration. The extremely high equipment procurement and maintenance costs also restrict their application scenarios to laboratory environments.

Fiber-based optical tweezers are centered on micro-nano structured fiber probes, with greatly simplified optical

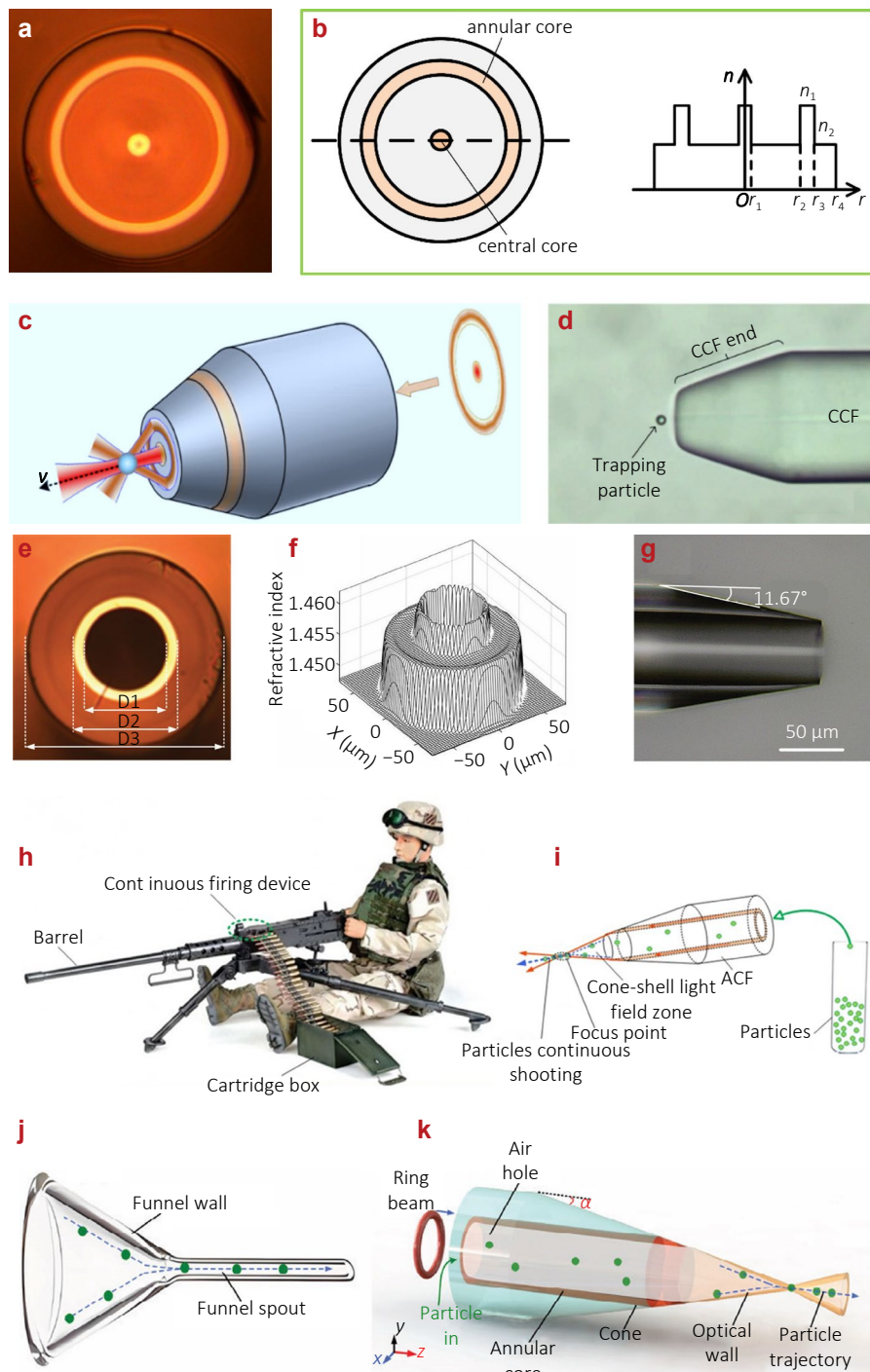


Fig. 4 | Illustration of the coaxial dual-waveguide fiber and hollow capillary fiber-based optical tweezers system featuring the "optical gun", "optical machine gun" and "optical funnel": (a) Cross-sectional image of the coaxial dual-waveguide fiber; (b) the annular core and intermediate core structure of the coaxial dual-waveguide optical fiber; (c) the trapped light field and the radiated scattering force field acting on microparticles at the tapered fiber end call as "optical gun"; (d) experimental demonstration of conical fiber-based optical tweezers capturing microparticles; (e) cross-sectional image of the capillary fiber with an inner-wall annular waveguide; (f) three-dimensional refractive index profile of the inner-wall waveguide structure; (g) capillary fiber with its tip polished to an 11.67° angle; (h) conceptual analogy between a military machine gun and the optical counterpart; (i) schematic illustration of the operational principle of a "optical machine gun" device capable of continuous emission of microscopic particles; (j) conventional funnel used for visual analogy; (k) alignment of microparticles passing through the optical funnel into a single-file stream. Figure reproduced with permission from: (a) ref.¹⁵, American Chemicla Society; (b) ref.^{21,22}, Optica of American

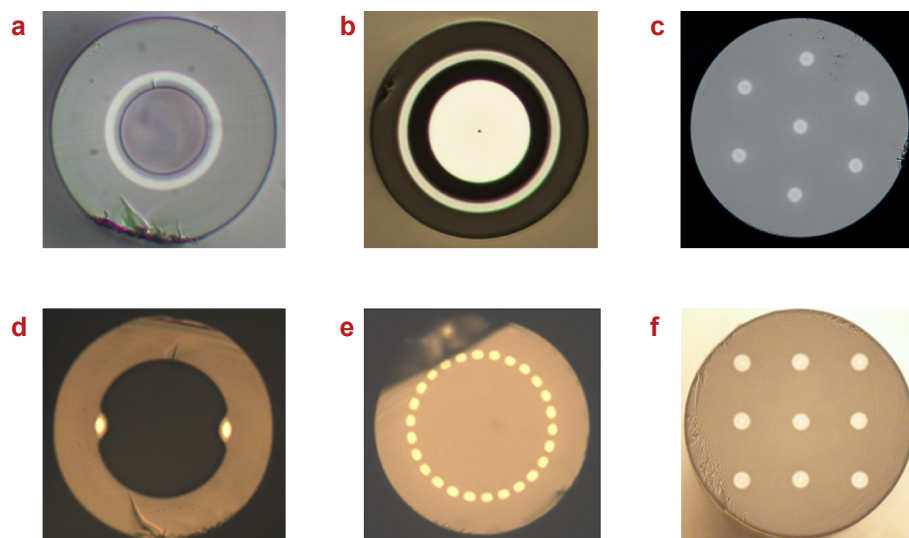


Fig. 5 | Cross-sectional images of several typical multi-core and ring-core fibers: (a) hollow ring-core fiber; (b) coaxial dual-waveguide fiber; (c) seven-core fiber; (d) hollow fiber with two suspended elliptical cores on the inner wall; (e) 26-core fiber with a ring-shaped core distribution; (f) nine-core fiber with a square core distribution.

paths. Their core strengths include compact size, flexible manipulation, easy integration, and strong cost-effectiveness potential. They are naturally suited for multi-beam and multi-dimensional manipulation and can be conveniently integrated into microfluidic chips, extreme-environment chambers, and other platforms, thus breaking through the spatial limitations of conventional optical tweezers. Nevertheless, their trapping stability and quantitative measurement accuracy are still inferior to those of conventional optical tweezers, and the corresponding quantitative measurement techniques are still under development.

The core positioning of the two technologies can be summarized as follows:

- Conventional optical tweezers are essentially laboratory-grade platforms for ultra-high-precision quantitative measurement and manipulation. Their core advantages lie in ultimate measurement accuracy, system stability, and a mature quantitative metrology system, making them indispensable tools for cutting-edge basic research in life sciences, soft matter physics, and related fields.

- Fiber-based optical tweezers are scenario-oriented, miniaturized, and multifunctional manipulation tools. Their core competitiveness stems from miniaturization, high flexibility, and strong integration adaptability. They possess irreplaceable value in applications requiring embedded integration of optical tweezers, such as lab-on-a-chip systems, in vivo manipulation, and industrial on-line detection.

The core technical advantages of fiber-based optical tweezers are as follows:

1. They decouple the optical tweezers system from the microscopic imaging platform, breaking the strong dependence of conventional optical tweezers on large-scale microscopes and enabling the miniaturization and high flexibility

of the manipulation unit.

2. They support long-distance transmission of optical power and remote control of optical traps, making them suitable for enclosed chambers, extreme environments, and other special applications inaccessible to conventional optical tweezers.

3. Micro-nano structures and multifunctional designs can be integrated on the fiber endface, enabling the combination of optical imaging, fluorescence excitation, photoacoustic detection, electrochemical sensing, and other functions to achieve integrated manipulation and detection.

In this paper, we use vivid metaphors such as micro-optical hand, optical gun, optical machine gun, and optical funnel to describe their operating principles. These metaphors not only help readers understand complex mechanisms more intuitively but also inspire associative thinking, thus providing insights for the functional expansion and application innovation of this technology. Table 2 summarizes the corresponding fiber and optical field structures as well as the relevant optical manipulation principles based on these functional metaphors.

As shown in the table above, these metaphors effectively lower the cognitive barrier and make abstract principles easier to understand. The microscopic manipulation mechanism of optical tweezers is rather abstract and difficult to perceive directly. However, the metaphors we adopted precisely convert the intangible optical field interactions into familiar daily scenes: the micro-optical hand vividly reflects its ability to grip and flexibly move micro-particles with high precision; the optical gun and optical machine gun clearly demonstrate the intensity and efficiency of pulsed optical manipulation; and the optical funnel intuitively presents the core function of particle focusing by the optical field.

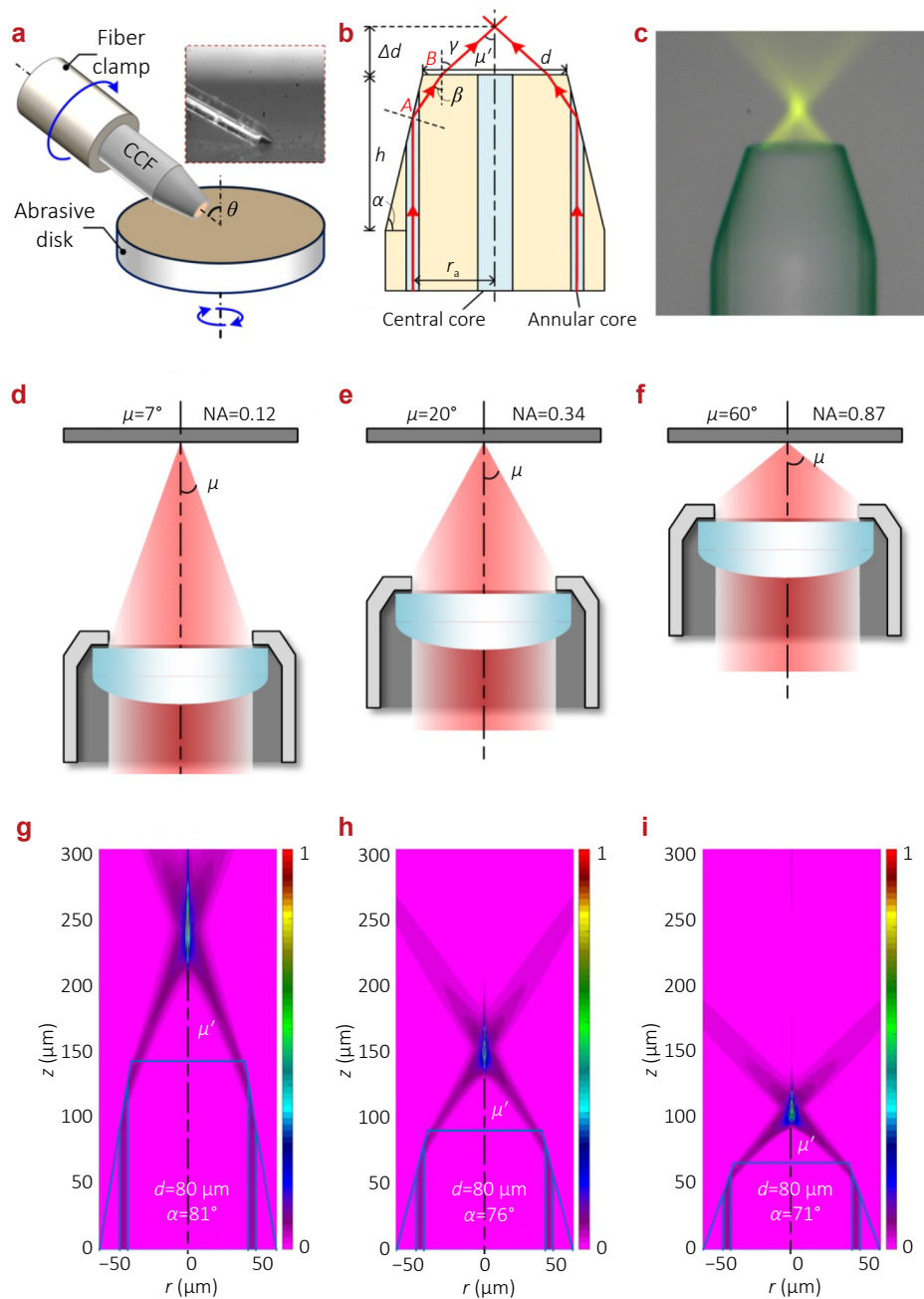


Fig. 6 | Relationship between the cone angle and the numerical aperture of the output optical field during the fabrication of the fiber-end cone: (a) Schematic of the precision grinding principle for the frustum of the fiber-end cone; (b) Schematic of light emission from the fiber end after polishing, where the ring-core or multiple cores are distributed on a concentric circle at the fiber end; (c) Experimental image of the cone shape and output light beam after the ring-core fiber is ground into a frustum cone; (d) Corresponding to a half-cone angle $\mu = 7^\circ$ with $NA = 0.12$ for the circularly distributed optical field focused by a lens; (e) Corresponding to a half-cone angle $\mu = 20^\circ$ with $NA = 0.34$; (f) Corresponding to a half-cone angle $\mu = 60^\circ$ with $NA = 0.87$; (g) For the ring-core fiber with a core ring diameter $d = 80 \mu\text{m}$, the base angle of the ground frustum $\alpha = 81^\circ$, corresponding approximately to $NA \approx 0.12$, and the equivalent half-cone angle of the output light field is μ' (which depends on the ambient refractive index of the output optical field); (h) The base angle of the ground frustum $\alpha = 76^\circ$, corresponding approximately to $NA \approx 0.34$; (i) The base angle of the ground frustum $\alpha = 71^\circ$, corresponding approximately to $NA \approx 0.87$.

These metaphors act as a bridge connecting macroscopic cognition with microscopic principles, allowing researchers and readers to quickly grasp the core working logic of optical tweezers without extensive theoretical background. In

addition, the extensibility of these metaphors stimulates associative thinking and helps break through the limitations of conventional understanding. From the flexible manipulation of the micro-optical hand, one can further envision its

Table 1 | conventional optical tweezers vs. fiber-based optical tweezers.

Comparison items	Conventional optical tweezers	Fiber-based optical tweezers
Core components	High-numerical-aperture (NA) microscope objectives, high-precision optical microscope systems, nanometer-resolution 3D displacement stages	Micro-nanofabricated tapered/microstructured fiber probes; laser coupling and beam delivery paths are highly simplified
System size & integration	Bulky structure, complicated optical paths, strongly dependent on large optical platforms; difficult for miniaturization and on-chip integration	Compact structure, small size, flexible manipulation; can be readily integrated into miniaturized platforms such as microfluidic chips and endoscopic systems
Manipulation dimensions	Mainly single-point static optical traps; multi-dimensional dynamic manipulation and multi-particle parallel trapping require complex scanning optics or SLMs	Naturally compatible with multi-beam optical trap configurations; enables 3D trapping, stretching, rotation and other multi-dimensional manipulations without complex optical paths
Trapping stiffness & stability	High optical trap stiffness, optical force measurement precision down to femtoNewton (fN) level; strong immunity to environmental disturbances, excellent long-term trapping stability	Relatively lower trapping stiffness and long-term stability; performance significantly affected by fiber NA, tip fabrication accuracy and beam alignment; vulnerable to environmental vibrations and fluid disturbances
Alignment difficulty	Core optical paths pre-calibrated at factory; stable long-term operation after single setup and alignment	For multi-core or ring-core fibers with tapered end-faces, only end-fabrication accuracy matters; no assembly or alignment issues
Thermal effect & photodamage	Low photothermal effect, high optical transmittance of objectives, uniform beam energy distribution, mature thermal management; low risk of photothermal damage to biological samples	Significant local photothermal effect; laser absorption and scattering at fiber tapers and microstructures induce local temperature rise; higher damage risk for thermally sensitive biological samples
Quantitative measurement ability	Mature and high-precision quantitative measurement; key tool for single-molecule/single-cell biomechanics; enables accurate quantitative measurement and metrology of optical forces from piconewton to femtoNewton levels	Quantitative measurement still under development; complex optical force calibration procedures; inferior measurement precision, long-term repeatability and usability compared with conventional optical tweezers
Observation & manipulation convenience	Excellent compatibility with imaging; natively integrated with high-resolution fluorescence microscopes, phase-contrast microscopes, etc.; simultaneous sample trapping/manipulation and high-resolution real-time imaging	Poor compatibility with direct imaging; requires an additional microscopic imaging system; separates trapping/manipulation from imaging observation, which is beneficial for extending optical manipulation functions
Cost	Extremely high purchase and maintenance costs; strongly dependent on high-precision microscopes, high-NA objectives and nanometer displacement stages; entry-level systems cost hundreds of thousands of RMB, high-end systems millions	Remarkable cost advantage; core devices are commercial semiconductor lasers and specialty multi-core or ring-core microstructured fibers; low fabrication and assembly cost; potential for mass production and low-cost popularization
Main application scenarios	Ultra-high-precision quantitative measurement and fundamental research, e.g., single-molecule biophysics, single-cell mechanical characterization, molecular motor dynamics, colloid and soft matter physics	Cell/particle sorting and manipulation in microfluidic chips; sample operation in extreme environments (low temperature, high pressure, strong electromagnetic fields); endoscopic in vivo biological manipulation; multi-trap parallel high-throughput processing

application potential in micro-assembly, precise cell manipulation, and similar scenarios. Inspired by the particle ejection mechanism of the optical gun and optical machine gun, one can extend the value of pulsed optical manipulation to targeted drug delivery, rapid particle sorting, and other fields. Based on the focusing function of the optical funnel, new applications in particle enrichment and trace sample detection can be explored. Such associative thinking helps researchers step outside the framework of traditional principles and explore more diverse applications of optical tweezers. Finally, these metaphors transform inspiration into innovative motivation and promote further expansion of technical functions. Relying on the flexibility of the micro-optical hand, new functions can be explored in single-cell sequencing, nanomaterial assembly, and other areas. Taking advantage of the pulsed nature of the optical machine gun, more efficient micro-particle manipulation technologies can be developed. Based on the focusing capability of the optical funnel, the sensitivity of trace sample detection can be

improved. These metaphors provide important intellectual support for accelerating technological iteration and expanding application boundaries.

5 Challenges and prospects

The question arises as to how the application of multi-beam control platforms at the fiber end can be further extended. In recent years, research on atomic and ionic chips for quantum computing has garnered increasing attention. Since Steven Chu was awarded the Nobel Prize in Physics in 1997^{2,27}, studies involving atom and ion manipulation using optical tweezers technology have become highly active in the field of atomic trapping. In 2020, the research team led by J. M. Sage and J. Chiaverini focused on developing ion trap arrays to investigate the feasibility of practical quantum computers based on optical tweezers array technology²⁸. Six distinct laser wavelengths are required to fulfill the essential functions in quantum computing: ion preparation, cooling,

Table 2 | Brief summary of functional metaphors for fiber-based optical tweezers.

Functional metaphor	Fiber geometry	Output optical field structure at fiber end	Principle of optical manipulation
Single optical tweezer	Single-mode fiber tapered into a conical structure	An equivalent steep Gaussian beam with large numerical aperture (NA) is formed at the fiber output	Particle trapping via the gradient force of the optical potential well
Micro-optical hand	Multi-core fiber with a micro-machined conical end	Multiple beams intersect and converge to form multiple optical potential wells	Particle translation, rotation, and other manipulations by independently adjusting the optical power of each core
Optical gun	Coaxial dual-waveguide fiber with a rotationally ground conical frustum end	The ring-core output is reflected and refracted by the conical frustum to form a hollow cone-shell field; the central core outputs a quasi-Gaussian beam	The tip of the ring-shaped cone-shell field traps particles (like loading a bullet); the central Gaussian beam provides a pushing force to accelerate and eject particles (like firing a bullet)
Optical machine gun	Hollow fiber with a ring core, whose end is processed into a cone; the central air hole is used for transporting particle streams	The ring-core output is reflected and refracted by the conical frustum to form a cone-shell field	With an appropriate cone angle or when the optical power is below a certain threshold, the cone-shell field only focuses and continuously emits particles from the particle stream
Optical funnel	Fiber with a ring-core structure (solid or hollow central region)	The ring-core output is reflected and refracted by the conical frustum to form a cone-shell field	Particles near the cone-shell field at the fiber end are automatically converged into a single particle stream via gradient forces and sequentially injected into designated microfluidic channels

state readout, and quantum gate operations. Yu et al. proposed a novel fabrication method enabling on-chip manipulation of multiple optical tweezers arrays^{29,30}. As an example of ultracold molecule applications, ref.²⁸ demonstrates an optical tweezers array for laser-cooled monocalcium fluoride molecules, allowing individual particle control and establishing a platform for harnessing the quantum device's potential. Quantum control of large-scale, massive, and complex systems opens new opportunities for precision sensing and fundamental physics tests. However, achieving such extreme quantum states remains a significant challenge. Ref.³¹ integrates solid-state optical trapping with cavity-mediated light-matter interactions. By precisely controlling the frequency and spatial alignment of the trapping laser relative to the optical cavity, dielectric nanoparticles can be cooled from room temperature to their quantum ground state of motion. These nanoparticles, consisting of approximately 10^8 atoms, exhibit densities comparable to bulk solids and represent macroscopic quantum systems akin to current Bose-Einstein condensates. This cooling approach, combined with advanced optical trapping techniques, provides a promising pathway toward generating quantum superposition states in massive objects that were previously inaccessible.

The successful execution of this task —manipulating a large number of atoms or ions via multi-beam control at fiber terminations —critically depends on the ability to establish an optical lattice at the tapered end of the fiber. Such a lattice enables the precise manipulation of numerous cold atoms or cold ions. Figure 7(a–c) illustrates experimental results demonstrating the trapping of a large ensemble of cold atoms using photonic lattices³². Furthermore, photonic

lattice-based manipulation serves as an effective approach for achieving quantum control between atoms through Floquet engineering^{33–35}. To support this objective, we have designed and fabricated polarization-maintaining multi-core optical fibers. As a proof-of-concept, an eight-core elliptical-core fiber with orthogonal symmetry has been developed, in which each core exhibits polarization state preservation, as depicted in Fig. 7. Realizing multiple polarization-preserving cores within a single optical fiber presents significant technical challenges. To address this, we employed waveguide geometric birefringence—a relatively feasible method for polarization control—and successfully developed an eight-core polarization-maintaining multi-core fiber, shown in Fig. 7(e). In addition to its eight radially arranged elliptical polarization-maintaining cores, the fiber incorporates a central air channel, which offers a potential pathway for delivering cold atomic gases.

We acknowledge that, on one hand, ultracold atoms, ions, and molecules — being highly controllable quantum systems — hold significant promise for a wide range of applications, including quantum simulation, quantum computation, and high-precision physical measurements. On the other hand, optical tweezers enable the trapping of atoms and ions, as well as the cooling of molecules, thereby forming an integrated platform for the preparation, manipulation, and readout of their quantum states. Recent advances in research^{27–29} have demonstrated that the miniaturization and micro-miniaturization of optical tweezer arrays are key enablers toward the practical realization of optical tweezer array chips. Viewing the fiber end as a multi-beam control "chip" offers not only inherent flexibility and convenience in multi-wavelength and multi-beam operation but also

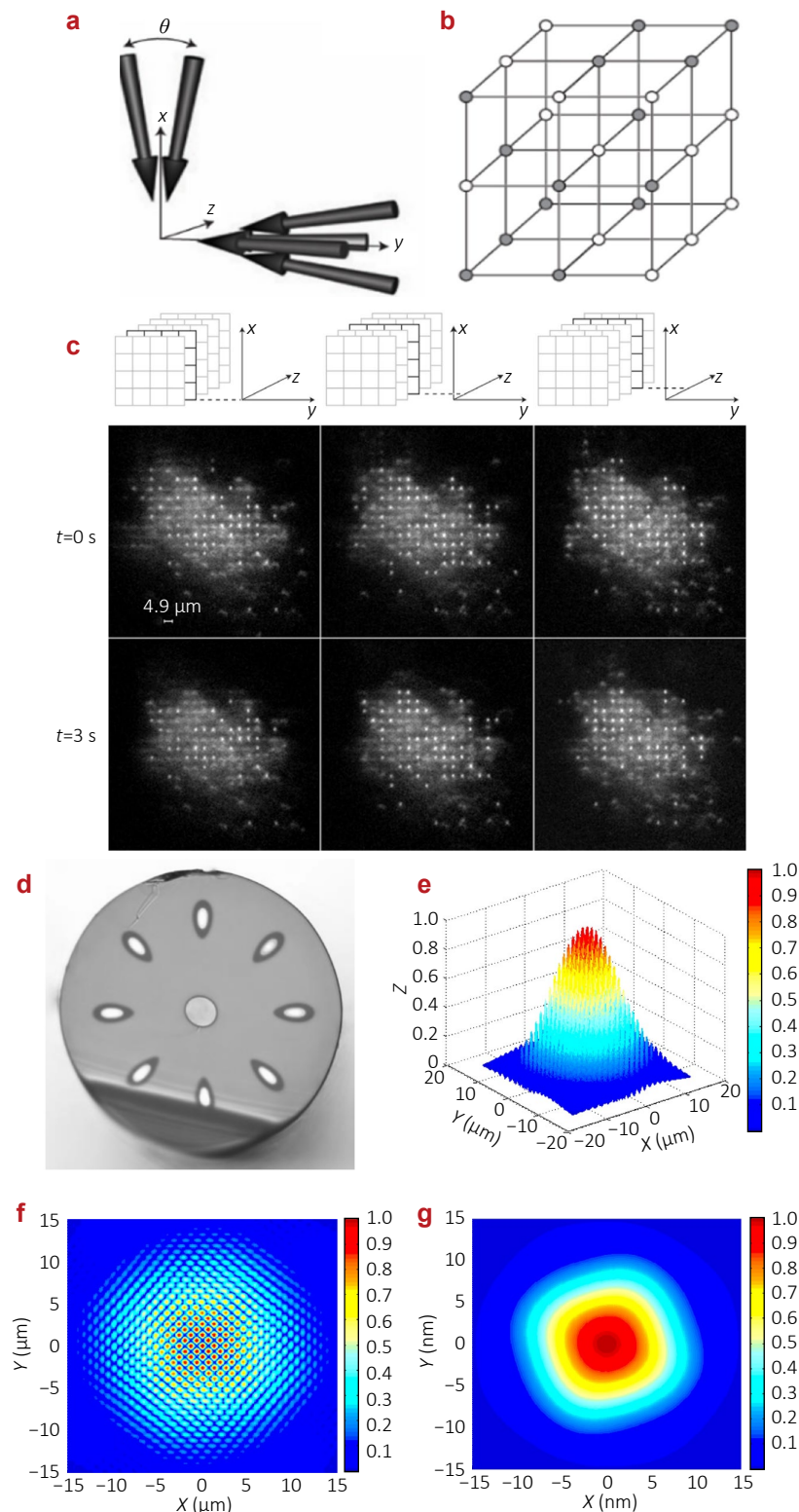


Fig. 7 | Preparation technology of photonic lattices at the fiber end. (a) Multiple beam interference generates a three-dimensional intensity distribution pattern at the intersection region, enabling the formation of a three-dimensional photonic lattice; (b) Each lattice site can trap individual atoms, analogous to the construction of a three-dimensional atomic array; (c) Fluorescence images from experiments demonstrating a three-dimensional photonic lattice trapping numerous atoms; (d) Cross-sectional image of a polarization-maintaining multi-core optical fiber containing eight elliptical cores; (e) Light intensity distribution map of the photonic lattice in the beam overlap region; (f) Two-dimensional schematic of a square photonic lattice formed by the interference of four orthogonally arranged laser beams; (g) Optical power distribution profile of the potential well at a single lattice site. Figure reproduced permission from: ref.²⁶, Springer Nature.

eliminates the need for coupling between waveguides and external chips. This mitigates coupling losses and reduces the overall power consumption of the system, thereby opening new pathways for the engineering development and real-world deployment of quantum chip technologies.

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Author contributions

Tingting Yuan and Xiaotong Zhang contributed equally to this work. They jointly established the research framework, independently compiled research materials, and collaboratively completed manuscript composition and figure preparation. Libo Yuan provided resource support, offered academic guidance, and revised the full version of the manuscript.

Competing interests

The authors declare no competing financial interests.



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