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Active wavefront shaping for multimode fiber optical tweezers with structured light

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ABSTRACT

Optical fiber tweezers have proven highly effective in precisely manipulating and trapping microscopic particles. Most existing demonstrations use single-mode fibers, which require tapered ends and are limited to single-particle control. Although multimode fibers (MMFs) can generate arbitrary structured light fields by transmitting multiple spatial modes simultaneously, inherent mode crosstalk renders the transmitted light field uncontrollable. In this study, we demonstrate MMF optical tweezers capable of manipulating and trapping multiple microspheres by projecting structured light, achieving performance comparable to that of holographic optical tweezers. By employing neural networks to guide active wavefront shaping and mitigate mode crosstalk, we achieved precise projection of structured light fields. Our experimental setup, which includes a green laser and a digital micromirror device, enabled the generation of focused and structured light through the MMF. We successfully manipulated single microspheres along a defined path and trapped multiple microspheres simultaneously using ring-shaped structured light. These results highlight the versatility and potential of MMF optical tweezers for advanced optical manipulation applications.

1. Introduction

The optical tweezer, first developed in the 1970s [1,2], is a versatile tool that uses a highly focused laser beam to trap and manipulate microscopic particles, including atoms, molecules, and cellular components. This innovative approach allows scientists to investigate the mechanical properties of particles and enables numerous applications in biology, physics, and chemistry [3]. Since their inception, optical tweezers have revolutionized micromanipulation, leading to Arthur Ashkin receiving the Nobel Prize in Physics in 2018 for their development. A notable advancement within this technology is the optical fiber tweezer, which is distinguished by its compact size and cost-effectiveness [4,5]. These features are particularly advantageous in settings where space is limited and budget considerations are crucial. Optical fiber tweezers are widely employed across various disciplines. In biomedical research, they are instrumental for tasks such as cell sorting, manipulation of individual cells, and in vivo experiments [6-8]. Additionally, in materials science, optical fiber tweezers are utilized for constructing microstructures and assembling nanomaterials with high precision. Their versatility and efficiency have made them an invaluable tool in advancing research and development across multiple scientific fields.

Optical fiber tweezers, widely utilized today, primarily employ single-mode fibers (SMFs) for trapping, manipulating, arranging, and assembling microscopic objects [4,5]. While dual-fiber tweezers are often considered complex, single-fiber tweezers offer greater

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convenience but still face significant limitations [9]. One major drawback is the small core of the fiber, which restricts the diameter of the tapered tip that can be created at the fiber end. This restriction further reduces the trapping distance due to the short focal length. Additionally, to enhance convergence capability and increase the gradient force, the tapered tip requires a specific shape, complicating the manufacturing process. Another issue is the potential for imperfections or roughness at the fiber tip, which can cause light confined within the fiber core to scatter more readily in SMFs compared to multimode fibers (MMFs). This scattering effect can adversely affect the efficiency and reliability of the optical tweezers. These challenges underscore the need for further advancements in fiber design and manufacturing techniques to optimize the performance and applicability of optical fiber tweezers in various scientific and industrial applications.

The use of MMFs in optical tweezers offers a potential solution to mitigate the drawbacks associated with SMFs [9]. By employing combinations of SMFs and MMFs or few-mode fibers with MMFs, a more robust trapping effect has been achieved, as demonstrated in various studies [10-13]. MMFs have also been utilized to generate structured light, such as Bessel beams, which are beneficial for extended depth of field in trapping [12,14,15]. Although the excitation of different modes often requires mechanical adjustment, which can be somewhat inconvenient, the capability to generate structured light in optical fiber tweezers is a significant advantage. Despite these benefits, MMFs inherently act as scattering media in practical applications where bending, twisting, and translating MMFs are inevitable. These issues result in speckle patterns caused by mode crosstalk. While speckles generated by MMFs have been proven effective for particle trapping [16], the performance is often limited by the contrast of the speckles. Consequently, most MMF-based optical tweezers currently use very short lengths of MMFs, typically ranging from micrometers to millimeters [9,13-15], to maintain control over the focal spot and enhance efficiency. Alternatively, using longer MMFs [17,18] requires tapering at the fiber's end to effectively confine the focal spot size. However, this approach can diminish the ability to generate structured light and reduce the efficiency of energy utilization.

Recent developments in wavefront shaping, which actively modulate the wavefront of the illumination light, have the potential to greatly enhance the capabilities of optical tweezers. This technique enables the regeneration of optical focus or structured light from speckle patterns, offering a promising solution to overcome the scattering effects typically encountered in optical systems [19-25]. Recently, demonstrations of optical tweezers operating through a piece of scattering media have been achieved by forming a bright focus using either a feedback-based approach or a transmission matrix approach [26-28]. Incorporating active wavefront shaping into MMF optical tweezers could effectively resolve the problem of inherent mode crosstalk, allowing for the creation of structured light for particle manipulation. The capability of projecting multiple optical foci or structured light through MMFs has already been demonstrated [22,29-37], laying the foundation for the development of MMF optical tweezers. Using wavefront shaping to generate multiple focal spots, the manipulation and trapping of multiple discrete particles have been demonstrated through MMFs [38]. These advancements suggest that integrating active wavefront shaping with MMFs can significantly improve control and precision in optical trapping applications.

In this work, we further demonstrated MMF optical tweezers with structured light illumination using active wavefront shaping. This innovative approach eliminates the need for fiber tapering and, by integrating active wavefront shaping, facilitates the generation of any desired structured light at the fiber tip, enhancing the system's versatility. Specifically, we developed a neural network tailored to address the mode crosstalk inherent in the MMF. Compared to the traditional approach of directly measuring the transmission matrix and then projecting the structure, neural networks eliminate pixelation effects, making them more effective for projecting continuous patterns. This network efficiently generates the necessary phase maps to produce desired structured light patterns through the MMF, such as optical foci, ring-shaped patterns with different radii, and elliptical-shaped patterns with varying orientations. These structured lights can be conveniently switched by simply changing the loaded phase maps, enriching the techniques and functionalities available for trapping particles without any mechanical movement. This advanced capability for the dynamic alteration of structured light mirrors the functionalities of holographic optical tweezers, which can trap multiple particles simultaneously [39]. It also allows for multidimensional control of particles through structured light [40,41]. The introduction of active wavefront shaping in MMF optical tweezers not only bridges the functionality gap but also establishes a new benchmark in the versatility and functionality of optical tweezer technology. This advancement paves the way for pioneering applications in microscopic manipulation, significantly expanding the potential uses and effectiveness of optical tweezers in various scientific and industrial fields.

2. Operational principle and simulation results

The schematic representation of the MMF optical tweezers is detailed in Fig. 1. This setup employs active wavefront shaping to project structured light through an MMF, enabling particle trapping and manipulation, as shown in Fig. 1a. A photograph of the MMF used in the experiment is presented in Fig. 1b, featuring FC/PC connectors instead of tapered tips to highlight the general applicability. The primary challenge in the proposed MMF optical tweezers is mitigating the mode crosstalk inherent in MMFs. To address this, we utilized neural networks, building on the pioneering work referenced in Ref. [22] and further adapting it to generate highly structured light with complex patterns [36]. The advantage of using neural networks in this context is that they do not rely on interferometric arms; instead, they are trained through direct intensity detection.

Our approach utilizes two sub-networks: the Model network and the Actor network, to simulate the forward and backward propagation of light in the MMF, respectively. The Model network is designed to learn the forward propagation of light through the fiber, predicting the output field from a given input. Initially, the two-dimensional (2D) phase map of the input is transformed into a one-dimensional (1D) column vector, which is then split into real and imaginary components. For each component, two fully connected blocks, each containing two layers of neurons, simulate the forward propagation. To reduce overfitting and limit the number of training parameters, a dropout layer with a ratio of 0.2 is included in each block, excluding 20% of the parameters. The outputs from these dropout layers are combined and processed through two tanh activation functions to constrain the output range. Finally, a reshape layer converts the 1D vector back into a 2D intensity image. Once the Model network is trained, the Actor network learns the inverse propagation path, determining the necessary input to project the desired structured light field. The architecture of the Actor network closely mirrors that of the Model network but includes two additional fully connected blocks to separate the output fringes into real and imaginary components, each containing two layers. Following these are four more fully connected blocks, each with two layers. Unlike the Model network, the Actor network does not include dropout layers. During the training of the Model network, we used a dataset comprising 20,000 pairs of input and output images. The inputs are complex optical fields containing both intensity and phase information, with intensity values ranging from 0 to 1 and phase values from 0 to 2π, spanning 40×40 modes. The outputs are resultant speckle images after transmitting these optical fields, with dimensions of 120×120, calculated using a linear transmission matrix model (blind to the network). The paired input and output images are then fed into the Model network for training. Upon completion of training, the predicted intensity images from the Model network are compared with the ground truth intensity images, achieving an average Pearson correlation coefficient of approximately 81.7%.

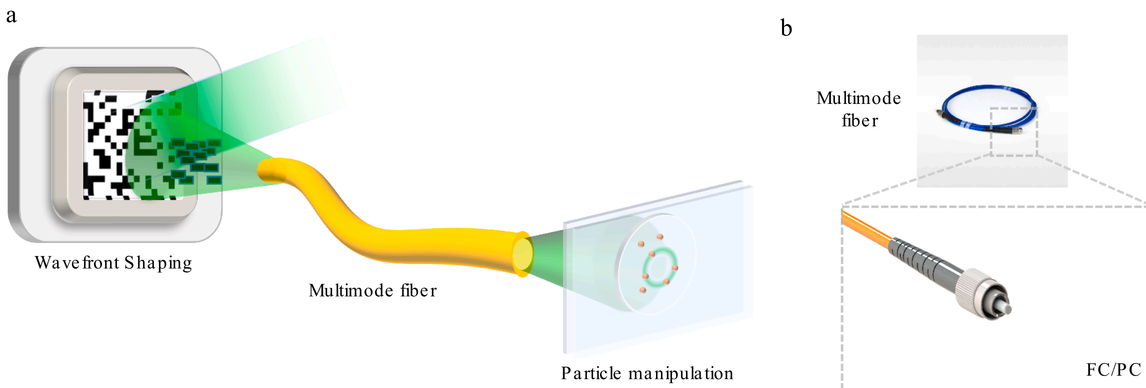

Fig. 1. A schematic illustration of active wavefront shaping enabled MMF optical tweezers. a. The modulated wavefront pre-compensates for mode crosstalk inherent in the MMF, effectively generating structured light through the MMF, which can be further utilized for particle manipulation and trapping. **b**. A photograph of the MMF used in the experiment, featuring an FC/PC connector.

Subsequently, the Actor network is trained to determine the required input optical fields that correspond to the desired projected structured light. The training set for the Actor network consists of 1,000 images, designed specifically for projection tasks that do not require generalization [36]. These images are composed of repeated patterns of 40 ring-shaped images, consisting of different circles and ellipses with varying diameters and orientations, sized with a dimension of 120 × 120. Post-training, the Actor network's predicted ring-shaped images are compared to the target images, resulting in an average Pearson correlation coefficient of 77.2%. This parameter quantifies the similarity between the system's projected pattern and the target pattern, thus measuring the accuracy of the projection. A Pearson coefficient closer to 1 indicates a higher similarity between the projected and target optical fields, resulting in a particle formation pattern that more closely matches expectations.

The simulation results on the effectiveness of the neural network in projecting ring-shaped structured light are illustrated in Fig. 2. Representative target intensity distributions are shown in Fig. 2a. The first row depicts circles of different diameters, the second row shows ellipses with horizontally oriented main axes and an eccentricity of 0.78, and the third row presents ellipses with vertically oriented main axes and an eccentricity of 0.53. By synthesizing the neural network-predicted wavefront as the input field, the corresponding results through the MMF are displayed in Fig. 2b. Each subfigure in Fig. 2b corresponds to its counterpart in Fig. 2a, with the Pearson correlation coefficients between the projected and target images displayed in the lower right corner of each subfigure. The average Pearson correlation coefficient across these projections is 77.5%, validating the accuracy of the neural network. These simulation results demonstrate that active wavefront shaping can successfully project ring-shaped structured light through an MMF to its output end, despite mode crosstalk. This lays the groundwork for subsequent optical tweezer applications.

3. Experimental setup and results

Having validated the effectiveness of the neural networks in projecting structured light, we proceeded to build an experimental setup for the MMF optical tweezers, illustrated in Fig. 3. The light source used was a green laser (MSL-R-532, CNI) with a wavelength of 532 nm and a maximum output power of 1 W. The beam was expanded using a compound expansion system (L1, MCX10607-A, LBTEK, f = 30 mm; L2, MCX10615-A, LBTEK, f = 150 mm). After passing through a polarizer for polarization control, the beam was directed at an angle onto the Digital Micromirror Device (DMD, ViALUX, V-7001). By adjusting the incidence angle to satisfy the conditions for grating diffraction, we maximized the modulation efficiency [42]. For complex field modulation on the DMD, we adopted the superpixel scheme from Ref. [43], which achieves intensity and phase modulation by applying low-pass filtering in the Fourier plane of the DMD and calculating the corresponding binary hologram. The ability to modulate complex fields enables the generation of more intricate patterns to probe the transmission characteristics of MMFs, which in turn reduces the required size of the training dataset. Using a 4f system with a spatial filter, we achieved complex field modulation at the MMF input facet. This spatial filtering system included components (L3, MCX10619-A, LBTEK, f = 300 mm; L4, MCX10619-A, LBTEK, f = 300 mm; Iris, DP25, LBTEK). The modulated

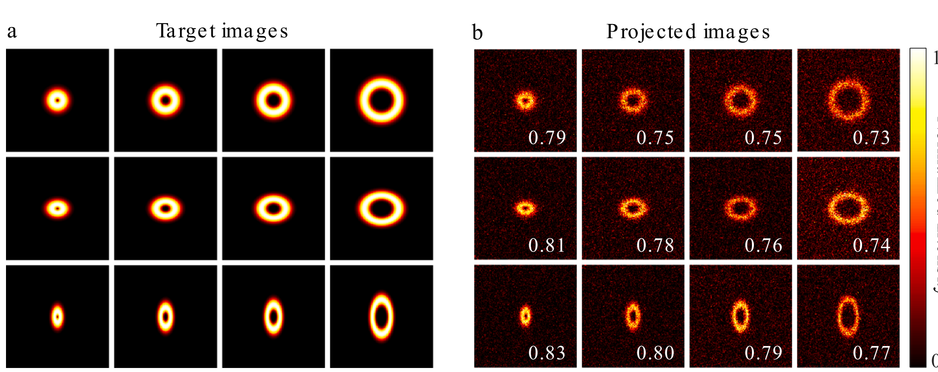

Fig. 2. Numerical simulations of projecting structured light through the MMF. a. The representative target images to be projected, which correspond to the ground truth images. These target images include circles of varying diameters in the first row, ellipses with the main axis horizontally oriented and an eccentricity of 0.78 in the second row, and ellipses with the main axis vertically oriented and an eccentricity of 0.53 in the third row. **b.** The corresponding projected images generated using the input optical wavefront provided by the neural networks. The Pearson correlation coefficients relative to the ground truth images are displayed in the lower right corner of each subfigure, indicating the accuracy of the projection.

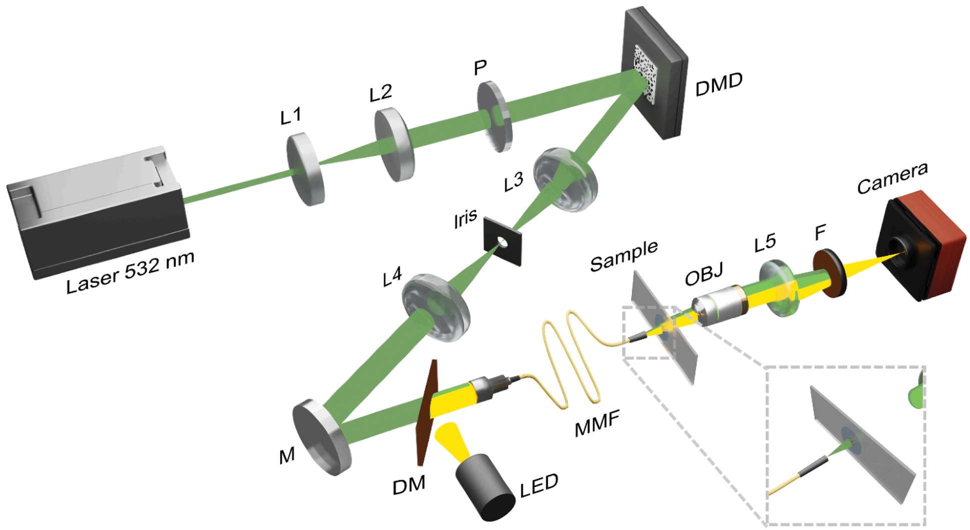

Fig. 3. Experimental setup for realizing MMF optical tweezers. L: lens; P: polarizer; DMD: digital micromirror device; M: mirror; DM: dichroic mirror; MMF: multimode fiber; LED: light-emitting diode; OBJ: objective lens; F: spectral filter. The optical path for generating structured light fields is marked in green, and the optical path for observing and validating the optical tweezers is marked in yellow.

light was then coupled into a 1 m long, 50 μm core, 0.22 numerical aperture MMF (MMC50L-0.22-PC-1, LBTEK). This fiber supports the simultaneous transmission of several thousand spatial modes in the green wavelength band. To obtain the training set for the neural networks, a combination of an objective lens (MPLAN APO 50x, Mitutoyo), a lens (L5, AC254-200-A, Thorlabs, f = 200 mm), and a camera (MER2-502-79U3M, DAHENG IMAGING) was used as the observation module to monitor the intensity distribution in the target region. The captured information was then fed into the network for training to overcome the mode crosstalk in the MMF.

For particle manipulation and trapping, we prepared 1 μm diameter polystyrene particles (M122067-5ml, Aladdin) diluted in water and placed them in a sample chamber made of a glass slide and a coverslip. The sample chamber is mounted on the manual stage for position adjustment. To observe the trapping process, a light-emitting diode (LED) provided side illumination, creating bright-field images captured by the observation module containing the camera mentioned above. The LED illumination was coupled into the system through a dichroic mirror (DMR-550SP, LBTEK). To avoid interference from the green laser during trapping experiments, a spectral filter (MEFH10-550LP, LBTEK) with a cutoff wavelength of 550 nm was added in front of the camera to filter out the 532 nm green light. For visualization purposes, an enlarged schematic of the optical tweezer capturing particles is provided in the inset at the bottom right.

We first demonstrated the capability of MMF optical tweezers in manipulating a single microsphere. Generating a single focus is essentially creating a ring-shaped structure with zero diameter. Initially, we generated a single focus through the MMF, with a size of approximately 3 μm. The power at the focus was around 1.6 mW. The low light energy utilization is attributed to the DMD causing diffraction, where the first-order light is filtered out instead of the zero-order. The input mode number during the focusing experiment was 12 × 12, with each mode segment occupying a size of 32 × 32 pixels on the DMD. Due to the diffraction-limited size of the focal spot being larger than $\lambda/2NA = 0.532/(2 \times 0.22) = 1.21$ μm, the single focus size exceeded the diffraction limit, indicating that the focal point had diffracted over a certain distance in free space. In terms of power efficiency, a significant amount of energy is lost due to the use of the DMD's superpixel method to achieve faster switching speeds [44]. However, employing a phase-only spatial light modulator could greatly improve efficiency, making it comparable to that of conventional holographic optical tweezer systems. The only additional energy loss in our system occurs during fiber coupling, a limitation that holographic systems do not encounter. Regarding particle manipulation range, holographic systems are ultimately limited by the field of view of the objective lens, whereas MMF-based systems are constrained by the diameter of the MMF.

To generate this focus, we encoded the amplitude and phase distribution of the optical field at the MMF input end using the DMD and superpixel scheme, as shown in Fig. 4b and 4c. After achieving the single optical focus, we successfully trapped a single microsphere. The trapped particles are confined and positioned at the interface between the liquid sample medium and the coverslip, approximately 200 μm from the fiber end face. By adjusting the position of the sample chamber, we were able to manipulate the single microsphere, as illustrated in Fig. 4d. At four different time intervals, we controlled the microsphere (indicated by the white bright spot) to move along a square trajectory (red dashed box). In contrast, two uncontrolled microspheres (indicated by white arrows) remained stationary throughout the observation period. This result demonstrates the effectiveness of the MMF optical tweezers in particle manipulation.

Dragging a single microsphere can also be achieved using SMF optical tweezers. To further demonstrate the superior capabilities of MMF optical tweezers, we performed multiple microsphere trapping experiments. As shown in Fig. 5a, we generated a structured intensity distribution at the output end of the MMF. Each image corresponds to a projected ring-shaped structured light, with the Pearson correlation coefficient listed in the lower right corner of each subfigure, achieving an average value of 95.9%. Note that this value is slightly higher than that obtained through numerical simulation. This discrepancy is likely due to the mode crosstalk of the MMF not fully randomizing the output speckles during experiments, a phenomenon observed in previous studies [35,36,45]. In this experiment, the input mode number was 16 × 16, with each mode segment occupying a size of 24 × 24 pixels on the DMD. The average power of the ring-shaped structured light was approximately 1 mW. Using this structured light, we successfully trapped multiple microspheres simultaneously. Fig. 5b illustrates that microspheres were firmly confined within the high-intensity regions of the structured light, including circular and eccentric ring-shaped structures. The diameter of the ring used to trap the particles is approximately 5 μm. These results showcase the ability of MMF optical tweezers to capture multiple microspheres simultaneously, comparable to traditional holographic optical tweezers. The capability to trap multiple particles simultaneously with high precision demonstrates the versatility and effectiveness of MMF optical tweezers, highlighting their potential for

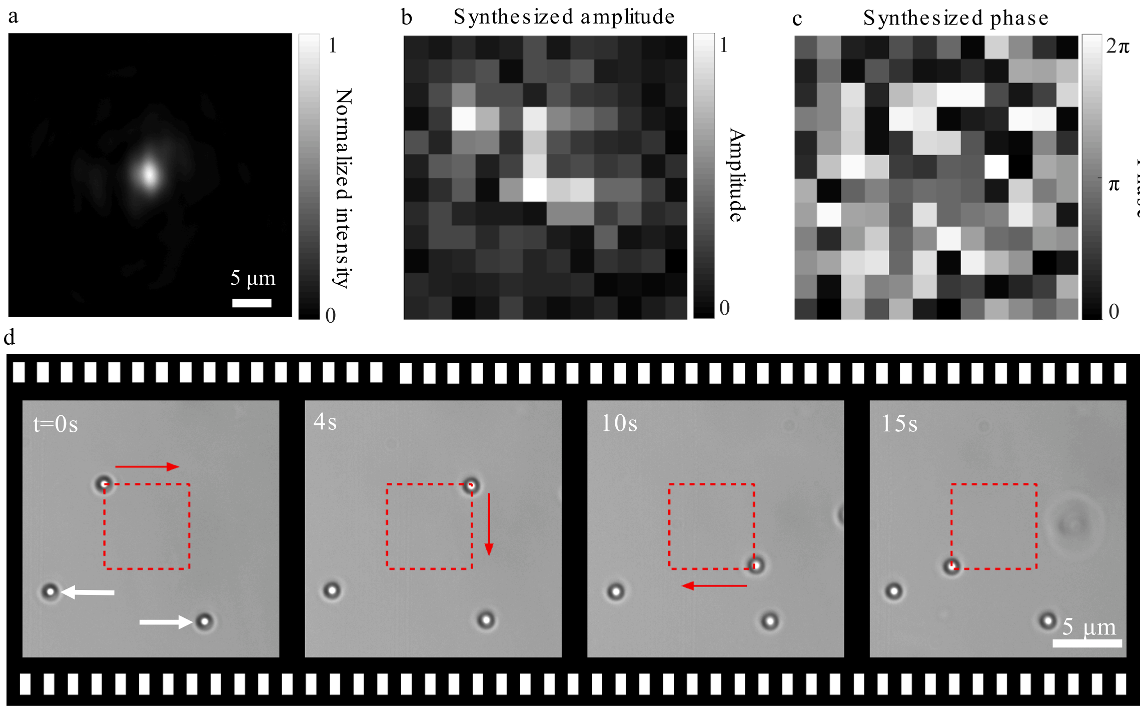

Fig. 4. Experimental results of employing MMF optical tweezers to manipulate a single microsphere. a. Experimentally achieved single-speckle focusing through the MMF. **b.** Corresponding synthesized amplitude distribution. **c.** Corresponding synthesized amplitude distribution. **d.** Time-resolved process of particle manipulation, showing the controlled movement of the microsphere along a square trajectory. White arrows indicate static reference particles, red arrows show the direction of particle movement, and the red dashed box represents the particle's movement trajectory. Scale bar: 5 μm.

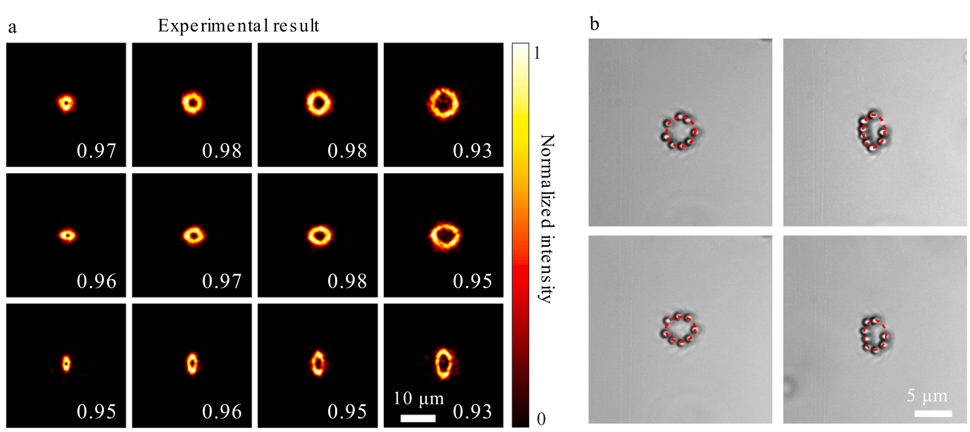

Fig. 5. Experimental results of employing MMF optical tweezers to trap multiple microspheres simultaneously. a. Experimentally generated structured intensity distributions with ring-shaped patterns. The Pearson correlation coefficient for each structured light compared to the target is provided in the lower right corner of each subfigure. Scale bar: 10 μm. **b.** Experimental results of simultaneous trapping of multiple microspheres using the ring-shaped structured light. Microspheres are confined within the high-intensity regions of the structured light. Scale bar: 5 μm.

advanced optical manipulation applications.

4. Discussion and conclusions

There is considerable potential for future improvements in the application of MMF optical tweezers. Firstly, active wavefront shaping has been theoretically and experimentally proven to enable focusing and structured light projection at distances far from the fiber end face. Although in this experiment the distance was limited to a few hundred micrometers due to the limited magnitude of the optical force, MMF optical tweezers, in principle, can achieve far-field particle manipulation and trapping. Additionally, recent work has utilized active wavefront shaping to realize photon-efficient optical tweezers with confined volumes [46]. Integrating this approach into MMF optical tweezers could enable particle manipulation and trapping at lower power levels and longer distances. Furthermore, the currently generated ring-shaped structured light has no phase variation along the ring's direction, so the trapped microspheres remain stationary. In our future work, we plan to introduce vortex beams [37], adding a phase gradient along the ring's direction to achieve particle rotation around the ring [47].

Moreover, the MMF used in the experiment has a small numerical aperture (NA), resulting in insufficient gradient force along the optical axis, which prevents true three-dimensional (3D) trapping. This limitation restricts the ability to manipulate particles effectively in 3D space. As demonstrated in Ref. [48], the NA of the fiber can be enhanced by optimizing the core and cladding materials, enabling 3D trapping. Furthermore, increasing the core diameter also increases the NA. However, in practical experiments, efficiently coupling more high-order modes into the fiber presents a challenge, and these high-order modes tend to be more sensitive to environmental disturbances. Nevertheless, enhancing the NA of MMFs for 3D trapping would enable precise control and manipulation of particles, not only in the lateral plane but also along the depth axis. Such a capability cannot be achieved with optical tweezers based on SMFs, which lack the necessary mode diversity and flexibility. Integrating these advancements would significantly enhance the functionality and application scope of MMF optical tweezers, making them a powerful tool for complex optical manipulation tasks.

When using MMFs for optical field projection, even slight disturbances to the fiber can result in significant variations in the projected optical field. Since training the neural network requires thousands of images, the extended time needed to collect the training dataset introduces system errors due to changes in the MMF's transmission characteristics, causing minor discrepancies between the projected and desired patterns. Our current setup makes significant efforts to keep the fiber stationary to mitigate these issues. However, future applications, particularly in more complex or dynamic environments, are likely to encounter unavoidable fiber disturbances. These disturbances could impact the stability and accuracy of the projected optical field. Fortunately, neural networks have demonstrated potential in adapting to such dynamic changes within MMFs [49,50]. This study aims to equip optical fiber tweezers with functionalities comparable to holographic optical tweezers, including the simultaneous manipulation of multiple particles and structured light control, while maintaining the inherent flexibility of the fiber-based system. However, the current implementation has certain limitations. The first limitation is the relatively low energy efficiency of the modulation technique, primarily due to fiber coupling. Secondly, the beam quality of the structured light generated in the MMF-based system is inferior to that of conventional holographic optical tweezers in free space, as reflected by non-unity Pearson correlation coefficients. These factors limit the overall performance of MMF-based optical tweezers. Nonetheless, we are confident that these challenges can be addressed with further technological advancements, particularly in developing more efficient modulation methods.

In summary, we have demonstrated the capability of MMF optical tweezers in manipulating and trapping microspheres. Initially, we addressed the challenge of mode crosstalk in MMFs by employing neural networks trained to project structured light effectively. Our neural network approach, consisting of Model and Actor networks, achieved high Pearson correlation coefficients, indicating accurate projection of target intensity distributions. We built an experimental setup for MMF optical tweezers using a green laser source and a DMD-based system for complex field modulation. This setup enabled the generation of focused light spots and structured light through the MMF. We successfully manipulated a single microsphere, demonstrating the precision and effectiveness of our method. Additionally, we extended the capability to trap multiple microspheres simultaneously using structured ring-shaped light, showcasing the versatility of MMF optical tweezers. These advancements significantly enhance the potential of MMF optical tweezers for a wide range of scientific and technological applications.

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CRediT authorship contribution statement

Zhiling Zhang: Investigation. **Yuecheng Shen:** Conceptualization. **Shile Yang:** Software. **Jiawei Luo:** Resources. **Zhengyang Wang:** Methodology. **Daixuan Wu:** Methodology. **Xiaodie Hu:** Investigation. **Zhengqi Huang:** Resources. **Yu He:** Software. **Mengdi Guo:** Resources. **Huajie Chen:** Resources. **Dalong Qi:** Supervision. **Yunhua Yao:** Supervision. **Lianzhong Deng:** Resources. **Zhenrong Sun:** Resources. **Shian Zhang:** Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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