Optical Engineering

RESEARCH PAPER

Multichannel dual-fiber optical traps on chip

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ABSTRACT. Building on conventional dual-fiber optical trap systems, we have developed a multichannel dual-fiber optical trap chip that is simple and low-cost. This chip features three channels, enabling simultaneous capture of three individual microspheres within a liquid environment. With each microsphere being captured by opposing optical fibers at 45-mW power, the measured axial optical trap stiffnesses of each channel were 0.4626, 0.7184, and 0.6467 pN/μm, respectively, whereas the transverse optical trap stiffnesses were 1.7794, 1.6885, and 1.4560 pN/μm. This chip may have various applications in the field of microfluidics, such as optical stretching, viscosity coefficient measurements, cell analysis, and micromixing.

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1 Introduction

In 1905, Einstein pioneered the explanation of photoelectric effect through quantum optics, thereby establishing wave–particle duality.[1] This discovery revealed that light possesses both momentum and energy, enabling it to exert pressure on irradiated objects.[2] In 1960, Theodore Maiman, an American physicist, developed the world's first ruby laser.[3] The laser's intense and collimated light advanced research on photon momentum and contributed to the development of optical tweezers.[4,5] In 1986, Arthur Ashkin utilized a single, highly focused laser beam to trap micron-sized particles successfully in the liquid environment, thus creating optical tweezers technology,[4,6] which has since been refined and expanded continuously.[7–10] In fact, as early as 1970, Ashkin had successfully trapped silica microspheres using two opposing Gaussian beams.[4] Compared with single-beam optical tweezers, dual-fiber optical traps exhibit distinct force balance characteristics.[11] The combined effects of perpendicular and horizontal forces significantly contribute to the capture of the microsphere, making dual-fiber optical traps more stable while requiring less force.[12,13]

Most dual-fiber optical trap chips are single-channel,[13] typically manufactured using planar optical waveguide or polydimethylsiloxane (PDMS) processes.[14] However, these designs tend to be complex and expensive. In addition, chips manufactured with planar optical waveguide technology often face poor mode field matching,[15] whereas PDMS chips struggle with maintaining precise alignment.[16] Furthermore, Wang et al.[17] discovered that high reflectivity and the associated scattering forces of conventional optical tweezers have limitations in capturing microspheres.

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In our experiment, two pieces of optical fiber arrays were directly used to fabricate the multichannel dual-beam optical trap chip. It is characterized by its simple structure and exhibits excellent mode field characteristics, high alignment precision, and ease of use. Owing to its unique design, the chip was able to capture three individual microspheres simultaneously on-chip. By analyzing and fitting their respective Brownian motions, we determined the axial and transverse optical trap stiffnesses across various channels. The integrated chip holds potential applications in microfluidics, encompassing tasks such as optical stretching, viscosity coefficient measurements, cell analysis, and micromixing.[18–25]

2 Experiment

The experimental setup for the multichannel dual-fiber optical traps is depicted in Fig. 1(a). In this system, the 1550-nm capturing laser is divided into six optical paths by a 1×6 coupler. Each optical path incorporates a variable optical attenuator (VOA) to finely adjust the power of each capturing laser. Subsequently, the six laser beams are individually directed onto both sides of the multichannel dual-fiber optical trap chip. A light-emitting diode positioned beneath the chip functions as the illumination source for the optical trap, whereas the trapped microspheres in the chip are collectively observed through a 4× microscopic objective lens. A real-time complementary metal oxide semiconductor (CMOS) camera captures the images, which are then transmitted to a connected personal computer for further recording and analysis.

Figure 1(b) illustrates the specific structure of the multichannel dual-fiber optical trap chip. It consists of two three-channel fiber arrays, with a separation of 150 μm in the x-direction. This spacing was selected after careful consideration. If it were too large, the axial and transverse optical trapping forces would be too weak to effectively capture the microspheres. Conversely, if too small, the microsphere's motion would be significantly affected by the end face of the fiber array (FA). Thus, a spacing of 150 μm was determined to be optimal for achieving stable capture without significant interference from the FA end face. Each fiber array featured a channel spacing of 500 μm, with SMF28-e optical fibers positioned within the channels, ensuring that each fiber operated independently. Microspheres were introduced into the rectangular area at the center of the chip and were successfully trapped.

In our experiment, to achieve high-precision alignment of the optical fiber arrays, we secured one optical FA on the quartz slide. Then, we performed coupling loss measurements every 0.2 μm as we adjusted the position of the movable FA. Our experiments showed that the coupling loss increased when the movable fiber was displaced from the fixed one, indicating misalignment. Then, we used epoxy glue to secure the movable FA, and the coupling loss did

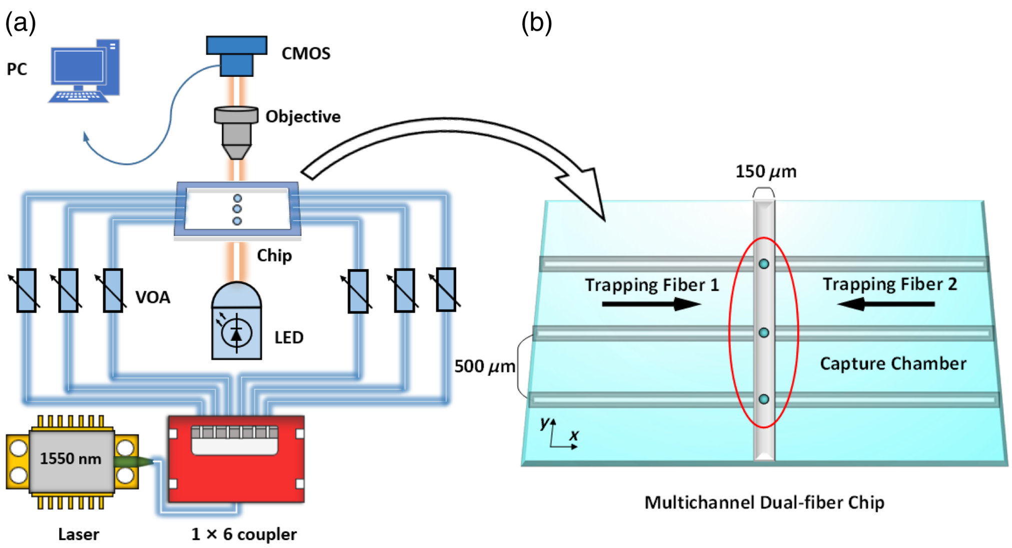

Fig. 1 (a) Experimental optical layout of multichannel dual-fiber optical traps. (b) Specific structure of the multichannel dual-fiber chip for the optical trap.

not change during the curing process of the epoxy glue. The alignment accuracy of this method is better than 0.2 μm. The point at which the coupling loss was minimal indicated the optimal alignment of the fibers, as shown in Fig. 2.

To ensure that individual microspheres can be captured in their respective channel, the microsphere solution was appropriately diluted with distilled water to achieve a moderate concentration of microspheres within the observation field.

The microspheres used in our experiment were silica microspheres. The surface morphology of the silica microspheres was analyzed using scanning electron microscopy (SEM). To account for the inherent variability among individual microspheres, three samples from the same batch were analyzed (Fig. 3). The average size of these samples accurately represents the dimension of the microsphere. The three tested silica microspheres are all standard spherical, with diameters of 9.80, 9.72, and 9.74 μm, respectively. Thus, the average diameter of the microsphere was 9.75 μm.

In addition, our experiments demonstrated the superior mode field properties of our on-chip multichannel dual-fiber optical traps. To assess the modal field characteristics of the fiber, we selected one fiber and measured its spatial intensity distribution. As shown in Fig. 4, the fitting results show that the output of the fiber array is a standard Gaussian beam, which is superior to that of the planar optical waveguides.[26,27]

In the experiment, by adjusting the VOAs, the powers of the six capturing lasers were set at 45 mW each, resulting in the simultaneous capture of three independent microspheres across three channels. As shown in Fig. 5.

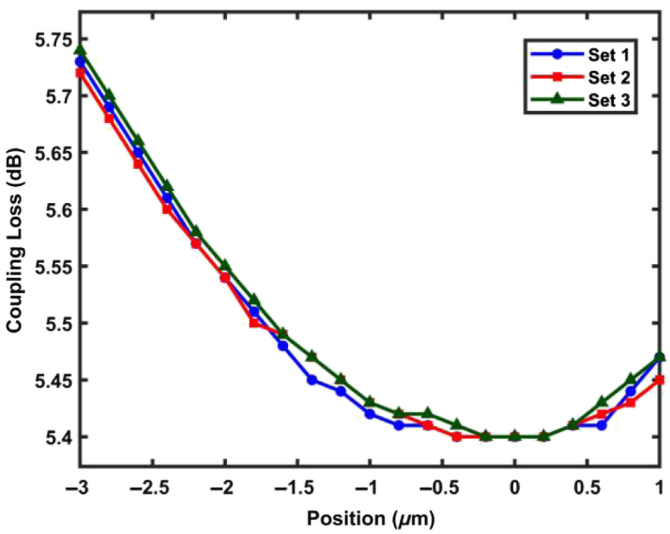

Fig. 2 Coupling loss across three channels during fiber array movement.

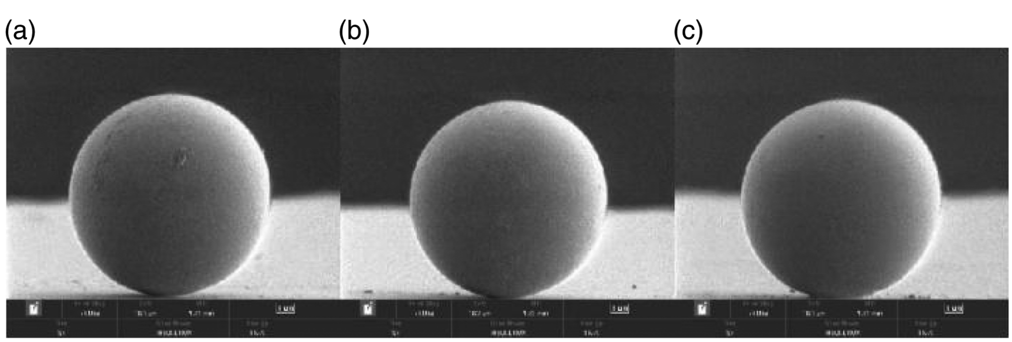

Fig. 3 SEM images of three silica microspheres.

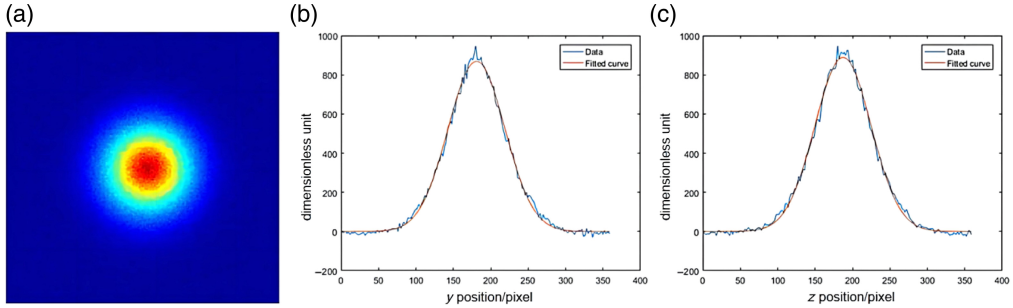

Fig. 4 (a) Intensity distribution in the y–z plane. Gaussian fitting of intensity distribution along the (b) y direction and (c) z direction.

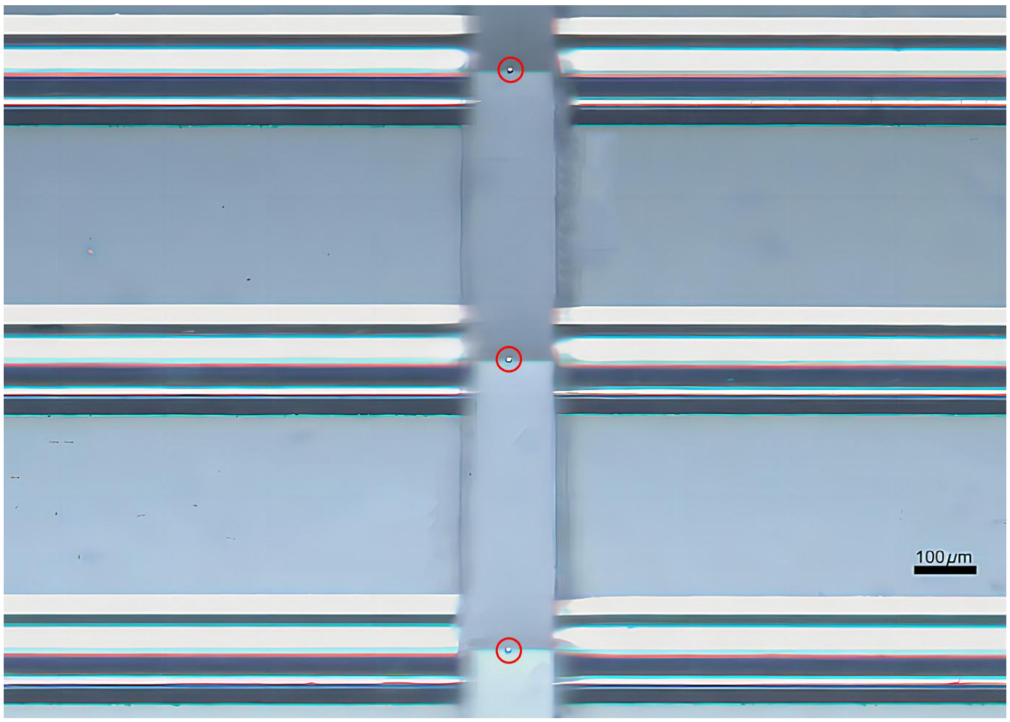

Fig. 5 Simultaneous trapping of three microspheres in the capture chamber.

3 Results and Discussions

Optical trap stiffness is a pivotal parameter in optical capture,[28] influencing trapping stability, precision, and the ability to apply controlled forces on trapped particles.[29–32] To determine optical trap stiffness, various methods have been developed, including mean-square displacement analysis,[33] fluid dynamics modeling, and power spectral density measurements.[34] In our experiment, we utilize the mean-square displacement method to measure the stiffness of the optical trap.

The mean-square displacement method is widely used in the analysis of thermal motion and particle dynamics.[35] In the optical trap's potential field, a particle has limited Brownian motion near the equilibrium point.[36–38] The displacement of the particle in each direction follows a normal distribution. For example, the mean-square error along the x-axis is[35]

$$\sigma^2 = \frac{k_b T}{k_x}, \tag{1}$$

where k_b represents the Boltzmann constant, T represents the absolute temperature, and k_x represents the optical trap stiffness along the x-axis. Thus, optical trap stiffness could be obtained through mean-square displacement of the microsphere.

The centroid method relies on determining the centroid positions of microsphere images to represent their locations.[39] Through continuously tracking these centroids, the displacement of the microspheres can be effectively analyzed.

In the experiment, the frame rate of the CMOS camera was 110 Hz. Through the centroid algorithm, axial and transverse displacements over time of the three captured microspheres were recorded. Scatter plots were constructed to illustrate the position distribution of each captured microsphere, as shown in Fig. 6. Probability distribution fittings were performed separately for the axial and transverse directions. For clarity, the axial direction is represented by the x-axis and the transverse direction by the y-axis in Fig. 6.

The measured temperature in the capture chamber was 310 K. Using Eq. (1), it was calculated that the respective axial optical trap stiffnesses for the three channels were 0.4626, 0.7184, and 0.6467 pN/μm. Meanwhile, the transverse stiffnesses were 1.7794, 1.6885, and 1.4560 pN/μm.

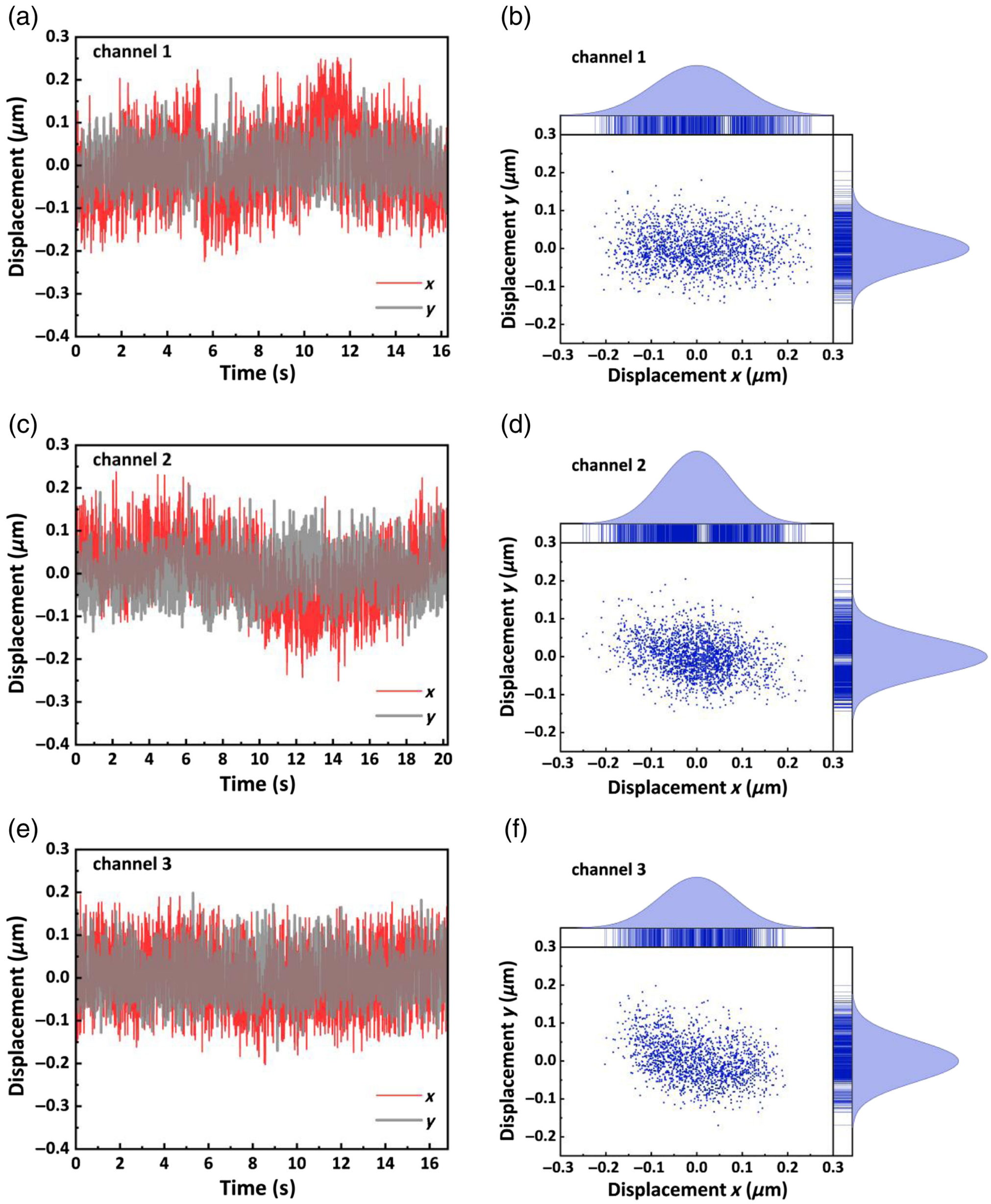

Fig. 6 (a)–(c) Time history plot of the x (axial) and y (transverse) displacements of the three captured microspheres. (d)–(f) Position change of the captured microspheres around their displacement center.

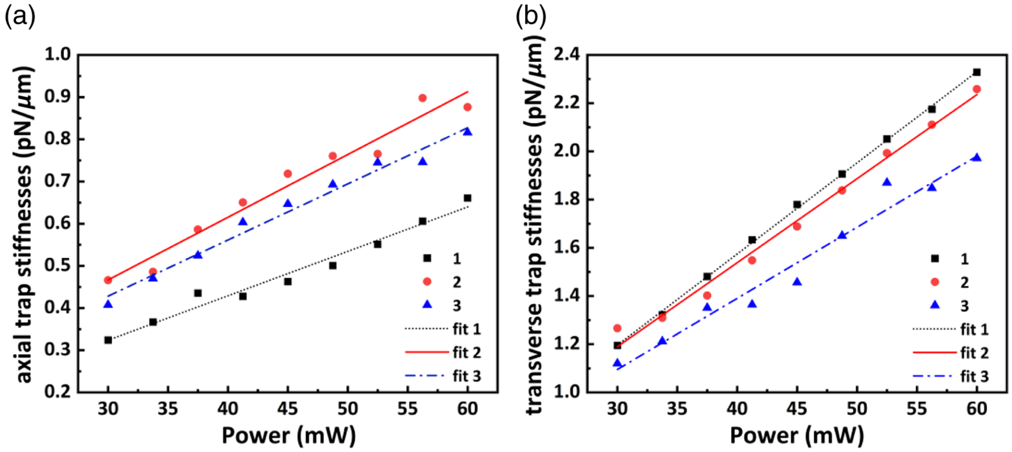

Fig. 7 (a) Axial and (b) transverse trap stiffnesses of each dual-fiber optical trap as a function of trapping power.

In Fig. 7, we analyzed the influence of trapping power on optical trap stiffness, with trapping powers ranging from 30 to 60 mW. The figure revealed a linear correlation between trapping power and optical trap stiffness in both axial and transverse directions. However, we found variations in the trap stiffness across the different channels. These variations can be attributed to factors such as manufacturing tolerances, fiber positioning misalignments, and differences in the size of the trapped microspheres and in the trapping beam quality. All these factors contribute to the variability in the microspheres' displacement, which leads to differences in the calculated optical trap stiffness. In addition, environmental factors, including viscosity and refractive index variations in the liquid medium, also contribute to the slight discrepancies observed in the slopes of the linear relationship fits at different positions.

4 Conclusions

In summary, we achieved simultaneous capture of three individual microspheres using on-chip multichannel dual-fiber optical traps and measured their respective optical trap stiffnesses. The optical trap stiffnesses demonstrated a linear increase in response to increasing trapping powers.

Compared with conventional optical tweezers, this system offers advantages including reduced fabrication costs, superior mode field characteristics, and operational simplicity. Moreover, the chip's fiber array design enables the precise alignment of multiple optical fibers in a single plane. In addition, it facilitates the simultaneous capture of multiple microspheres, allowing for a more comprehensive evaluation of the liquid's properties. In the future, on-chip multichannel dual-fiber optical traps are expected to find diverse applications in microfluidics, including optical stretching, viscosity coefficient measurements, cell analysis, micromixing, and beyond.

Disclosures

The authors declare no conflicts of interest.

Code and Data Availability

All data in support of the findings of this paper are available within the article.

Acknowledgments

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