

In-situ aberration correction for far-detuned laser systems via a trapped ion probe

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High-fidelity focused spots, achieving the diffraction limit and ultra-low crosstalk, are critical for manipulating trapped atoms and ions. Despite the existence of various aberration compensation techniques, obtaining such high-quality focused spots remains challenging for far-detuned laser systems. Here, we demonstrate a universal *in-situ* aberration correction technique for far-detuned-laser-based individual addressing systems. Our approach utilizes a trapped ion as a probe and a spatial light modulator for optical aberration compensation, demonstrating 17-fold suppression of crosstalk and achieving a low Rabi crosstalk of 0.031(4)%, nearly a four-fold improvement over previous state-of-the-art results. This method establishes an effective tool for high-fidelity quantum operations in trapped ion and atom systems, pivotal for quantum computing.

Keywords: aberration correction; optical tweezer; trapped ion probe; far-detuned laser.

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1. Introduction

Optical aberrations, arising from imperfections in optical systems, degrade focal intensity and beam quality, thereby exerting detrimental effects on optical imaging. To address this issue, various aberration correction methods have been proposed, including the employment of adaptive optical components^[1,2]. Such demands for aberration correction extend beyond optical imaging to quantum optics research^[3,4]. In systems with trapped atoms and ions, for instance, lasers are utilized for trapping and manipulation, where high-quality focused spots are essential for the precise operation of individual atoms or ions—specifically, they must meet the requirements of diffraction-limited focusing and ultra-low crosstalk^[5–7].

Currently, in trapped ion and atom systems, optical aberrations are *in-situ* characterized using the ions or atoms themselves as probes, with compensation achieved via spatial light modulators (SLMs) or digital micromirror devices (DMDs)^[8,9]. In trapped ion systems, for instance, lasers with wavelengths near resonance with ionic energy levels exhibit a direct relationship between laser intensity and ion fluorescence counts. This enables *in-situ* characterization and compensation

of optical path aberrations through fluorescence measurement, with demonstrations of addressing beams featuring low crosstalk^[10]. However, this approach constrains the selection of operational laser wavelengths. Notably, the employment of far-detuned lasers carries significant importance in optical tweezers and Raman operations^[11–13]. Smaller detunings lead to enhanced photon scattering, which imposes an upper limit on the fidelity of operations^[14]. Yet, *in-situ* aberration correction for far-detuned laser systems remains a formidable challenge. This difficulty arises primarily because far-detuned lasers interact weakly with ions due to their large frequency offset from resonance. Consequently, the optical signals (changes of fluorescence) generated by these interactions are extremely faint, making it difficult to accurately characterize aberrations.

In this paper, we present a method for evaluating and optimizing optical tweezers generated by far-detuned lasers. By modulating the optical tweezers laser and using the clock state levels of $^{171}\text{Yb}^+$ ions as probes, we generate an optical tweezer with a beam waist radius of 0.58(2) μm , approaching the diffraction limit. Subsequently, we measured the crosstalk of the optical tweezers light, achieving crosstalk as low as 0.031(4)% (and 0.065(2)%) between adjacent ions, which corresponds to a

maximum 17-fold crosstalk suppression. Our work provides a feasible scheme for evaluating and optimizing optical tweezers, offering a reference for experimental studies combining ion trap systems and optical tweezers.

2. Experimental Setup

In this work, $^{171}\text{Yb}^+$ is used to demonstrate our approach, as it possesses clock states that are insensitive to external noise, making it a commonly used ion species in quantum computing and simulation. The relevant energy levels are shown in Fig. 1. The ions are confined in a high-optical-access ion trap^[15]. Doppler cooling, initialization, and state detection are achieved using a 369 nm light generated through a tripling process^[16]. A static magnetic field is applied along the horizontal direction to lift the Zeeman levels' degeneracy. We select the clock states $|0\rangle \equiv |F=0, m_F=0\rangle$ and $|1\rangle \equiv |F=1, m_F=0\rangle$ within the $^2S_{1/2}$ manifold as the probe, which are insensitive to external magnetic and optical fields, enabling high-sensitivity measurements. Fluorescence collection is facilitated by a 0.6 numerical aperture (NA) objective lens, and quantum state measurement is conducted using a photomultiplier tube through state-dependent fluorescence techniques.

For ion manipulations by lasers, photon scattering is an inevitable source of infidelity. Increasing the detuning can effectively reduce this effect. However, longer wavelengths make it difficult to achieve smaller focus spots. Therefore, in our system, we have chosen to use a 532 nm laser to generate optical tweezers. To characterize the distant detuned laser using ions, we designed a laser modulation scheme that allows the 532 nm laser to drive stimulated Raman transitions (SRTs) between clock states, as shown in Fig. 2.

We generate the required 532 nm light via a second-harmonic generation (SHG) process. A fiber electro-optic modulator (EOM) is employed to modulate the 1064 nm seed light,

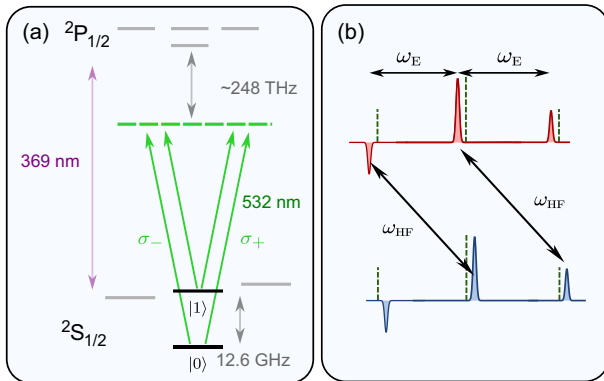


Fig. 1. (a) Relevant levels of $^{171}\text{Yb}^+$. Detection is performed using the noise-insensitive hyperfine levels $|0\rangle$ and $|1\rangle$, with an energy level difference of $\omega_{\text{HF}} = 12.6$ GHz. The green line illustrates how the 532 nm laser drives the transitions between $|0\rangle$ and $|1\rangle$ via SRT. (b) Schematic diagram of SRT driven by the optical frequency comb generated through the EOM. Frequency shifting is achieved through a pair of AOMs.

producing sidebands at $\omega_E = 12.24$ GHz. If the modulation index is β , the laser electric field after modulation can be written as

$$E_1 = \frac{E_0}{2} \exp[i(kx - \omega t)] \sum_{n=-\infty}^{\infty} J_n(\beta) \times \exp\{in[(\delta k)x - \omega_E t]\} + \text{c.c.}, \quad (1)$$

where E_0 is the unmodulated field amplitude, $J_n(\beta)$ is the n -th order Bessel function, and $\delta k = \omega_E/c$. After frequency conversion through a periodically poled lithium niobate (PPLN) crystal, a 532 nm frequency comb is generated. Considering the crystal's bandwidth and $\beta < 1$, in reality, we only need to consider the sum-frequency process involving the carrier and the first-order sideband. Thus, the electric field representation of the 532 nm laser is expressed as

$$E_2 = \eta \frac{E_0^2}{4} \exp[2i(kx - \omega t)] J_0(\beta) \times \sum_{n=-1}^1 J_n(\beta) \exp\{in[(\delta k)x - \omega_E t]\} + \text{c.c.}, \quad (2)$$

where η represents the conversion efficiency.

In the optical frequency comb produced by phase modulation, multiple pairs of laser frequencies are typically present simultaneously to drive SRT; however, these transitions will destructively interfere with one another, leading to a small net Rabi frequency^[17]. To address this issue, we designed a compact unequal-arm Mach-Zehnder interferometer (MZI), introducing an appropriate delay in one arm to enable SRT driven by far-detuned lasers, as shown in Fig. 2(c). The electric field after the acoustic-optic modulators (AOMs) can be expressed as $E_3 = E_{3-1} + E_{3-2}$, and

$$E_{3-1} = \frac{\eta E_0^2}{2} \frac{1}{4} \exp[2i(kx - \omega t)] J_0(\beta) \exp(-i\omega_A t) \times \sum_{n=-1}^1 J_n(\beta) \exp\{in[(\delta k)x - \omega_E t]\} + \text{c.c.},$$

$$E_{3-2} = \frac{\eta E_0^2}{2} \frac{1}{4} \exp[2i(k(x + \Delta x) - \omega t)] J_0(\beta) \exp(i\omega_A t) \times \sum_{n=-1}^1 J_n(\beta) \exp\{in[(\delta k)(x + \Delta x) - \omega_E t]\} + \text{c.c.}, \quad (3)$$

where $2\omega_A = \omega_{\text{HF}} - \omega_E$ and Δx represents the optical path difference between the two arms of the MZI. The diffraction efficiencies of the AOMs are set to 50%, enabling them to function as beam splitters and frequency shifters.

The effective Rabi frequency could be expressed as

$$\Omega_R = \frac{\mu_1 \mu_2 \langle E_3 E_3^* \exp(i\omega_{\text{HF}} t) \rangle}{\hbar^2 \Delta} \propto I \times [\exp(i\delta k \Delta x) - 1], \quad (4)$$

where μ_1 and μ_2 are the matrix elements of the electric dipole moment for a transition between the respective hyperfine states

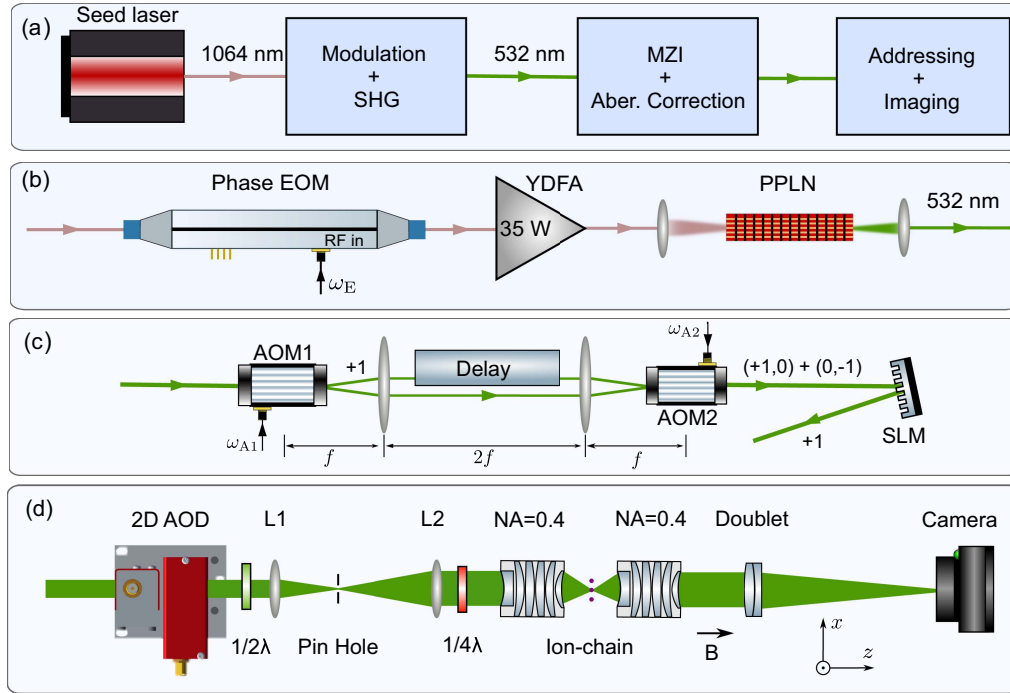


Fig. 2. Far-detuned laser system for SRT. (a) Functional schematic of the optical setup. (b) The 1064 nm seed laser is modulated by a fiber-EOM to generate multiple frequency components. The frequency of the radio-frequency (RF) signal driving the EOM is $\omega_E = 12.242$ GHz. Subsequently, a PPLN crystal converts the 1064 nm laser into 532 nm, containing multiple frequency components. The functionality of optical tweezers and qubit operations can be switched by toggling the RF signal that drives the EOM. (c) Two AOMs are used to form a compact unequal-arm MZI. The +1 order diffracted light from the first AOM and the -1 order diffracted light from the second AOM propagate along the same straight line. The drive frequency for the AOMs is set to 200 MHz, allowing both beams to drive SRT. Introducing an appropriate length of delay in one arm can introduce an additional phase between different frequency components, thereby avoiding cancellation of the Rabi frequency. Subsequently, the laser beam undergoes aberration correction through an SLM and then enters the addressing module through a 4f system (not shown). (d) Individual addressing module. The 2D AOD is used for scanning the position of the focused spot. After beam expansion, the Raman laser beam is focused onto ions through a 0.4 NA objective. For alignment ease, an achromatic objective is used to image both the ions and the 532 nm laser spots onto a camera simultaneously.

and the excited states, I indicates the intensity of a 532 nm laser, and $\Delta \approx 248$ THz. Therefore, the intensity of the 532 nm laser can be characterized by measuring the Rabi frequency Ω_R of SRT.

To generate high-quality optical tweezers, after the laser passes through the MZI, an SLM is used to compensate for beam aberrations. We load a grating onto the SLM to avoid interference from the zero-order reflected light. Subsequently, the laser goes through a 4f optical system and is transmitted via a spatial optical path to the platform where the ion trap is located.

Two apochromatic objective lenses with NA = 0.4 are placed on both sides of the ion trap. The 532 nm laser is directed through a 2D acousto-optic deflector (AOD) that is used for scanning beam position, and is subsequently focused onto the ions using the left-side objective lens. The polarization of the laser is adjusted to circular polarization via a set of wave plates, with the propagation direction aligned with the magnetic field orientation, thereby enabling the driving of clock states, as illustrated in the energy level diagram. The right-side objective lens simultaneously captures images of the ions and the attenuated 532 nm laser onto a camera, thereby facilitating the initial alignment of the ions with the optical tweezers.

3. Aberration Correction

Figures 3(a) and 3(b) illustrate the algorithm we utilized for *in-situ* characterization of aberrations in the optical system^[18]. The patterns on the SLM are divided into several small patches, using the central patch as the reference patch and any other patch is called a sample patch. When a sample patch and the reference patch are activated simultaneously, the two beams of light will interfere. Ideally, any sample patch should constructively interfere with the reference patch at the focal point. However, due to the presence of aberrations in the optical path, there are additional phase deviations between sample patches and the reference patch. Using the SLM to scan the global phase ϕ of the sample patch, we can obtain the intensity variations at the focal point as shown in Fig. 3(c), which allows us to fit and determine the phase deviations.

In the experiment, we use a single trapped ion as a probe for *in-situ* characterization of aberrations. This work employs the Rabi frequency of SRT to measure the intensity of the far-detuned laser. In principle, smaller patches allow for a more accurate characterization of aberrations, thereby achieving better correction results. However, the Rabi frequency is inversely

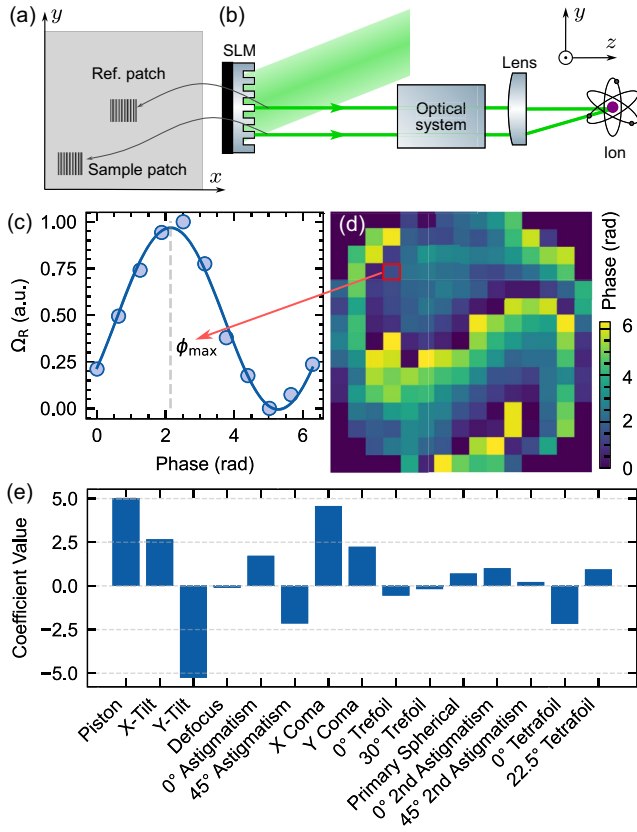


Fig. 3. (a), (b) Schematic diagram for measuring aberrations in the optical system. When only two patches are activated, the two beams of light interfere at the focal point. Using ions to detect the light intensity, changes in the global phase ϕ on the sample patch result in variations in the light intensity detected by the ions. (c) A typical experimental result. The Rabi frequency is proportional to the light intensity. (d) Aberration correction patterns. (e) Coefficients of the Zernike polynomial fit. "Piston", "X-Tilt", and "Y-Tilt" do not affect the focusing effect.

proportional to the square of the patch area; reducing the patch size leads to an increase in experimental time. To balance the correction effect and experimental time, a patch size of 70 pixel $\times$ 60 pixel was chosen in the experiment, where the Rabi frequency generated by the reference patch is approximately 0.4 kHz. The measured phase is normalized to the range of 0 to 2π , as shown in Fig. 3(d). Furthermore, based on the continuity of the phase variations, we perform an unwrapping of the results and utilize Zernike polynomials for fitting, revealing that the primary sources of the aberrations are coma, which arise from slight misalignments between the optical components in the beam path, such as the off-center positioning of the objective lens relative to the laser propagation axis.

4. Results

4.1. Beamshape

For a typical two-level system (simplified here, as interactions with the $^2P_{3/2}$ levels are neglected), with an energy level

difference of ω_0 and linewidth Γ , the expression for the AC Stark shift produced by a far-detuned laser is given by

$$\delta_{ac}(r) = \pm \frac{3\pi c^2 \Gamma}{2\omega_0^3 \Delta} I(r), \quad (5)$$

where $I(r)$ and Δ are the intensity and detuning of the laser. The positive and negative signs correspond to the upper and lower levels, respectively. For red-detuned lasers, this means that the energy level splitting increases, leading to a reduction in the fluorescence counting rate during the Doppler cooling process. Within a certain range of light intensity, the reduction in fluorescence counting rate can be approximately linearly related to the light intensity, which can assist us in characterizing the beam profile, as illustrated in Figs. 4(a) and 4(b).

Figures 4(c) and 4(d) show the beam profiles before and after compensation, indicating that after correction, the focused light

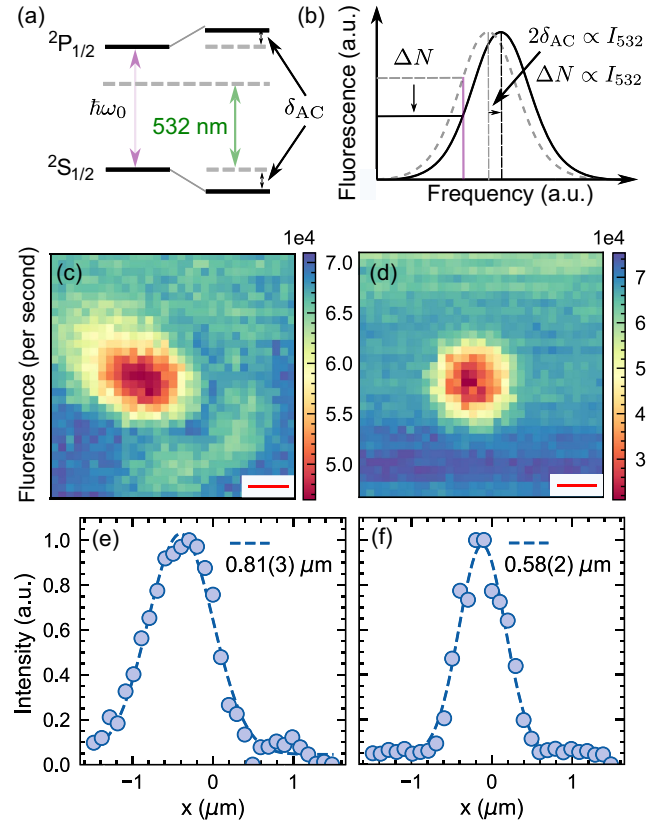


Fig. 4. Characterization of the beam profile through fluorescence counts (per second). (a), (b) Schematic diagram of measuring light intensity through AC Stark shifts. The variation in fluorescence counts per unit time ΔN is proportional to the light intensity due to AC Stark shifts, illustrated as (b). (c), (d) Ion fluorescence counts at different beam positions before (c) and after (d) aberration correction. Beam position scanning is achieved using a 2D acousto-optic deflector (AOD). The scalebar corresponds to 0.5 μm . The long-term drift of the 369 nm laser intensity result in a slight alteration of the background. (e), (f) The peak normalized light intensity distribution is obtained from the fluorescence counts. The beam waists w_0 in the x -direction before (e) and after (f) aberration correction are 0.81(3) and 0.58(2) μm , respectively.

closely resembles an ideal Gaussian beam. The result is consistent with that obtained from Zernike fitting, indicating that the original focused light spot exhibits significant coma aberration. To derive the light intensity distribution, we subtracted the fluorescence count data from the maximum fluorescence count and then performed normalization. The resulting light intensity distribution is shown in Figs. 4(e) and 4(f). Based on the fitting, the beam waist radius after correction is $0.58(2) \mu\text{m}$.

4.2. Crosstalk

When applying optical tweezers to an ion, significant crosstalk may affect the manipulation of adjacent ions, such as the operation between the S state manifold and the D state manifold. In addition, the configurations we mentioned before achieve functional reuse of optical tweezers and quantum bit operations in our systems. Therefore, evaluating the crosstalk on neighboring ions is essential.

To evaluate this crosstalk, we load three ions with an axial phonon frequency of 428 kHz, resulting in an inter-ion spacing of $5.2 \mu\text{m}$. We focus the beam onto the target (middle) ion and measure the Rabi frequencies of the three ions separately. Throughout the entire measurement duration, the power incident into the objective lens is maintained at a constant level

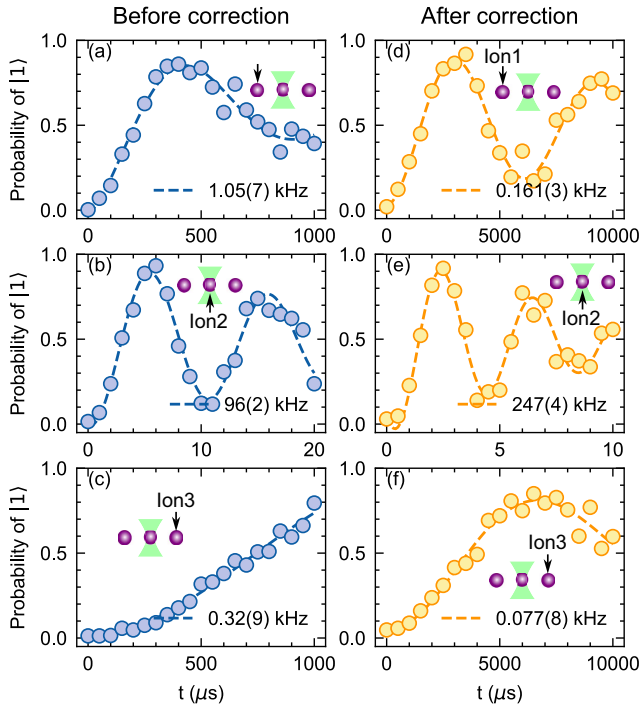


Fig. 5. Evaluation of crosstalk before and after aberration correction. We focus the laser on the target ion [Ion2] of a three-ion chain and measure the Rabi frequencies of all three ions. All data were measured with the same laser power. (a)–(c) Before aberration correction, the crosstalk are 1.1(1)% [Ion1] and 0.33(10)% [Ion3]. (d)–(f) After aberration correction, the crosstalk are reduced to 0.065(2)% [Ion1] and 0.031(4)% [Ion3]. The crosstalk on Ion1 after correction is still higher than that on Ion3, indicating that there are still residual aberrations.

Table 1. Rabi Crosstalk Comparison in Various Trapped Ion Systems.

Method	NA	Rabi crosstalk (%)	Wavelength (nm)
MCAOM ^[19]	0.63	<2.5	355
AODs ^[7]	0.4	0.12	532
MEMS ^[20]	0.6	0.2–0.6	355
This work	0.4	0.03–0.07	532

Note: MCAOM indicates the multichannel acousto-optic modulator; MEMS indicates the microelectromechanical systems. All the work listed here is based on optically addressed Raman operations.

Table 2. Crosstalk at Off-Center Positions^a.

Position [Ion2] (μm)	Crosstalk [Ion1] (%)	Crosstalk [Ion3] (%)
−22.5	0.080(5)	0.039(8)
0	0.065(2)	0.031(4)
+20.0	0.075(11)	0.034(11)

^aThe position is calculated based on the frequency offset loaded on the AOD, approximately $5.5 \mu\text{m}/\text{MHz}$.

to ensure the consistency and comparability of the experimental data. Figure 5 demonstrates the maximum Rabi frequency and crosstalk to adjacent ions under identical optical power before and after aberration correction. After aberration correction, the optical intensity crosstalk to adjacent ions was reduced to as low as 0.031(4)% (and 0.065(2)%). Table 1 provides the data from previous works for comparison.

Although it has been proven that good aberration compensation can be achieved at the position of the probe ion, it is still necessary to evaluate other positions within the field of view. To achieve this goal, we adjusted the DC voltage to move the ion position along the x -axis and measured the crosstalk at different positions. The crosstalk data are shown in Table 2, which demonstrates the effectiveness of this method over a relatively large field of view. In addition, we recorded the variation of the Rabi frequency over time, with a standard deviation of less than 3% within 12 h, demonstrating the long-term stability of the correction.

5. Conclusion

This work demonstrates a method for compensating and evaluating aberrations in far-detuned optical tweezers. We built a laser system capable of driving stimulated Raman transitions between the hyperfine levels of $^{171}\text{Yb}^+$ ions. Using this system along with an SLM, we employed ions as probes to implement aberration correction in the optical system. With this setup, we generated optical tweezers with a beam waist of $0.58(2) \mu\text{m}$ and achieved optical intensity crosstalk to adjacent ions as low as

0.031(4)% (and 0.065(2)%), representing an 11× (and 17×) improvement from the uncorrected crosstalk of 0.33(10)% (and 1.1(1)%).

Unlike previous works that require near resonance with atomic transitions^[8,10], the method proposed in this study is suitable for a relatively wide wavelength range. This characteristic enables it to be widely applied to the *in-situ* aberration characterization and compensation of optical paths in trapped atom and ion systems. It is worth noting that, in addition to driving Raman transitions of hyperfine energy levels, there is another effective alternative method for measuring the laser intensities, namely, using narrow-linewidth transitions to measure AC Stark shifts (e.g., the $^2S_{1/2}$ to $^2D_{3/2}$ transition of $^{171}\text{Yb}^+$).

Our design offers sufficient flexibility and versatility. By toggling the RF drive signal of the EOM, the laser beam can be adaptively configured for either addressable single-qubit operations or as optical tweezers. The SLM provides the capability to flexibly shape addressable optical tweezers into structured optical fields, enabling more versatile control of ions^[21–26]. For example, the use of Hermite–Gaussian (HG) modes has been demonstrated to implement axial multi-ion entangling gates^[27,28].

In this work, although the crosstalk has been reduced to 0.031(4)%, it has not yet reached the theoretical limit. By further reducing the patch size and optimizing the algorithms, we expect to achieve crosstalk below 1×10^{-4} to demonstrate high-fidelity operations^[10,29].

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