Experimental Study of Large-amplitude Wavefront Correction in Free-space Coherent Optical Communication

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In a free-space coherent optical communication system, wavefront distortion is frequently beyond the correction range of the adaptive-optics system after the laser has propagated through the atmospheric turbulence. A method of residual wavefront correction is proposed, to improve the quality of coherent optical communication in free space. The relationship between the wavefront phase expanded by Zernike polynomials and the mixing efficiency is derived analytically. The influence of Zernike-polynomial distortion on the bit-error rate (BER) of a phase-modulation system is analyzed. From the theoretical analysis, the BER of the system changes periodically, due to the periodic extension of wavefront distortion. Experimental results show that the BER after correction is reduced from $10^{-1}$ to $10^{-4}$; however, when the closed-loop control algorithm with residual correction is used, the experimental results show that the BER is reduced from $10^{-1}$ to $10^{-7}$.

Keywords: Adaptive optics, Coherent optical communication, Large distortion, Residual correction
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I. INTRODUCTION

Adaptive optics (AO) is an optics-mechatronics technology that improves beam quality by correcting wavefront distortion. It has been extensively used in the field of free-space optical communications [1–3]. A deformable mirror (DM) corrects the wavefront distortion by changing its own surface distribution and optical-path difference [4]. Its resolution and stroke directly determine the accuracy and range of wavefront correction [5]. In the case of long-distance propagation, such as in free-space optical communication systems, the wavefront is distorted considerably when the laser is transmitted by a high-power output system and received by a large-aperture optical system, through an atmospheric environment with strong turbulence [6, 7]. Although the accuracy requirement for wavefront correction in the field of laser communication systems is not strict, the correction stroke of the DM is insufficient to compensate for large wavefront distortion [8]. If the uncorrected wavefront phase is applied to the actual free-space laser communication system, the communication link will suffer from reduced stability, and even interruption in serious cases [9, 10].

In 1953, Babcock first proposed AO correction technology. The basic principle is to generate an aberration conju-
gate with the distorted wavefront to offset the influence of atmospheric turbulence. In 1972, the United States developed the first set of real-time atmospheric compensation imaging experimental systems, which was used to detect and compensate 300-m horizontal atmospheric turbulence disturbance. The compensated image’s resolution was close to the diffraction limit [11]. In 1996, Tyson et al. [12] of the United States analyzed the influence of light-intensity fluctuation on communication bit-error rate in intensity modulation and direct detection (IM/DD) systems. Simulation results showed that adaptive optical correction can reduce the laser signal attenuation and light-intensity fluctuation caused by atmospheric turbulence in a satellite-ground link, and improve the communication performance of a space optical communication system. In 2004, the University of Maryland carried out an adaptive-correction experiment of horizontal laser communication using wavefront-free detection technology [13]. The system takes the received light intensity as the evaluation index, and uses a 132-unit microelectromechanical system (MEMS) DM to correct the distorted aberration. In 2008, the Johns Hopkins university applied physics laboratory (JHU/APL) and Aoptix Technology Co., Ltd. demonstrated a 147-km long-distance bidirectional RF and FSO communication experiment with OOK modulation and a transmission rate of 10 Gbps. Transmitter precorrection and receiver correction were used to improve the Strehl ratio and single-mode fiber coupling efficiency respectively [14]. In 2016, jet propulsion laboratory (JPL) of the United States tested the AO system at OPALS, the ground observation station of the optical communication telescope. The system realized downlink 50-Mpbs video transmission with the International Space Station, which proved that the beam energy received by the satellite increased from 3% to 66% [15]. However, the above AO technology is mainly used in the field of wireless optical communication for short-distance transmission near the ground, and satellite-ground link transmission. Compared to the near-ground surface, the long-distance turbulence intensity in a turbulent environment is weaker, and the surface shape generated by the DM cannot compensate for the wavefront distortion. However, there have been only a few reports on the application of long-distance large-amplitude distorted-wavefront correction in the field of wireless optical communication.

Using the Shark-Hartmann wavefront sensor (SH-WFS) to measure the distorted wavefront information, according to the principles of microlens-array imaging with a charge-coupled-device camera, large-scale numerical measurement will definitely reduce the detection accuracy of wavefront information [16]. Yoon et al. [17] used a commercial SH-WFS, which has a large dynamic range and resolves this problem by using a translatable plate with subapertures to improve the measurement range of the wavefront without sacrificing measurement accuracy. By dividing the image into two-frame storage areas during the data-reading period by the SH-WFS, a large binocular telescope system achieved a repetition rate of over 1000 frames per second to improve the wavefront measurement range [18]. The holographic SH-WFS can measure a wavefront aberration with a large dynamic range, by introducing a holographic optical element and a pattern-matching technique [19, 20].

To correct wavefront distortion with large amplitude and a large aperture, a large-aperture DM was reported to control the intensity profile of the laser beam (diameter 400 mm, thickness 8 mm, with 37 actuators glued hexagonally on the back surface of the mirror) [21]. By using a spherical mirror to design a novel optical system that provides two wavefront channels on the DM, the displacement of the DM (with a stroke of 6 μm) produced a wavefront phase compensation of 12 μm, so that a wavefront error of 24 μm could be corrected for fundus imaging [22]. A micromachined thin-film DM was designed to improve the shape of the surface [23]. A prediction method was also used to control the voltage of the surface shape of the MEMS of the DM, which was based on an elastic analysis model of the reflecting film and an empirical electromechanical model of the actuator [24, 25]. Similarly, the combination of multiple correctors was used to improve the correction of the large stroke of the wavefront [26–28]. By using two DMs composed of a woofer and tweeter to correct the distorted wavefront caused by atmospheric turbulence in the field of astronomical observation, the correction ability of the combined mirror could reach a Strehl ratio of 0.9, and its correction ability could meet the distortion requirements [29]. However, the wavefront-measurement method based on multiple correctors increases the complexity of the optical path, and thus reduces the utilization of optical energy, which is not conducive to a laser communication system. Based on the background of the application of AO in coherent optical communications, a residual correction method for large wavefront distortions is proposed in this paper.

This paper adopts AO to correct the wavefront distortion and proposes a residual correction method, by correcting the residual error of the optical path in the main range of values. According to the 2π-periodic continuation characteristic of wavefront phase distortion in a coherent optical communication system, the residual wavefront distortion is corrected by taking an integer multiple of 2π of the wavefront as the whole period. While ensuring that the DM has sufficient travel, according to the 2π-periodic property of trigonometric functions, the bit-error rate of a wireless coherent optical communication system can be significantly reduced, and thus the communication performance of the whole system is improved. The results show that the proposed method not only can expand the application range of wavefront correction, but also can improve the gain of a wireless coherent communication system.

II. THEORETICAL CALCULATIONS

The wavefront phase $\phi(r, \theta)$ distorted by atmospheric turbulence can be expanded using Zernike polynomials [30]:

$$
\phi(r, \theta) \approx \sum_{n=0}^{\infty} \sum_{m=-n}^{n} a_{nm} Z_n^m(r, \theta)
$$
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\[
\varphi(r, \theta) = \sum_{j=1}^{\infty} a_j \cdot Z_j(r, \theta),
\]

where \(a_j\) is the Zernike coefficient, \(Z_j(r, \theta)\) is the Zernike series, and \(r\) and \(\theta\) are respectively the radial and angular coordinates in the polar coordinate system. In total, Zernike polynomials of highest order 30 with \(j = 2\)–31 (where \(j = 1\) is the wavefront piston term, which does not participate in the calculation of wavefront reconstruction) are used. The expression for the signal optical field affected by atmospheric turbulence is

\[
E_s(r, \theta, t) = A_s \cdot \exp \left[ -i(\omega_s t + \varphi_s + \varphi_m(t) + \varphi(t, r, \theta)) \right],
\]

where \(A_s\) is the amplitude of the signal light, \(\omega_s\) is the angular frequency of the signal light, \(t\) is the time variable, \(\varphi_m\) is the initial phase of the signal light, \(\varphi_s\) is the modulated phase, and \(\varphi_{rad}\) is the wavefront phase affected by atmospheric turbulence. The expression for the local-oscillator light \(E_L\) is

\[
E_L(r, \theta, t) = A_L \cdot \exp \left[ -i(\omega_L t + \varphi_L) \right],
\]

where \(A_L\) is the amplitude of the local-oscillator light, \(\omega_L\) is the angular frequency of the local-oscillator light, and \(\varphi_L\) is the initial phase of the signal light.

There are several kinds of signal noise at intermediate frequencies, such as detector shot noise, local-oscillator relative intensity noise, and thermal detector noise. Given that the intensity of the local-oscillator light is much higher than that of the light signal, the shot noise of \(E_L\) plays a dominant role. For a homodyne coherent detection system, the expression for the signal-to-noise ratio (SNR) can be obtained as follows:

\[
\text{SNR} = \frac{e n \int_U |E_s|^2 dU}{h \nu B} \cdot \frac{\left[ \int_U A_s A_L \cos(\Delta \varphi) dU \right]^2 + \left[ \int_U A_s A_L \sin(\Delta \varphi) dU \right]^2}{\int_U |E_s|^2 dU \cdot \int_U |E_L|^2 dU},
\]

where \(e\) is the electronic charge, \(\eta\) is the quantum efficiency, \(U\) is the detector area, \(h\) is Planck’s constant, \(\nu\) is the carrier frequency, \(B\) is the detector bandwidth, and \(\Delta \varphi\) is the phase difference between \(E_s\) and \(E_L\). Generally, the mixing efficiency \(\eta_{\text{mixing}}\) in a coherent detection system can be defined from Eq. (4) as

\[
\eta_{\text{mixing}} = \frac{\left[ \int_U A_s A_L \cos(\Delta \varphi) dU \right]^2 + \left[ \int_U A_s A_L \sin(\Delta \varphi) dU \right]^2}{\int_U |E_s|^2 dU \cdot \int_U |E_L|^2 dU}.
\]

According to the theory of wavefront reconstruction, the peak-to-valley (PV) value of wavefront phase will exceed one complete wavelength range in the case of long-distance laser communication. If the collected wavefront phase is used for the actual calculation of a communication system, the wavefront phase \(\varphi_{\text{rad}}\) in micrometers collected by the SH-WFS usually needs to be converted to express radian \(\varphi_{\text{rad}}\) in radians:

\[
\varphi_{\text{rad}} = \frac{\varphi_{\text{rad}}}{\lambda} \cdot 2\pi.
\]

For a phase-modulation coherent detection system, without consideration of the flickering light intensity, the optical field of the modulated signal light with wavefront distortion caused by turbulence can be expressed as

\[
E_{s-\text{BPSK}}(r, \theta, t) = A_s \cdot \exp \left[ -i(\omega_s t + \varphi_s + \varphi_{s-\text{BPSK}}(t) + \varphi_{\text{rad}}(r, \theta, t)) \right] \quad \varphi_{s-\text{BPSK}}(t) = \begin{cases} 0 & \text{sending "0"}, \\ \pi & \text{sending "1"}. \end{cases}
\]
The bit-error rate (BER) of the system can be expressed as

\[ \text{BER}_{\text{QPSK}} = \frac{1}{2} \text{erfc} \left( \sqrt{\frac{\text{SNR}_{\text{QPSK}}}{2}} \right) \]

\[ = \frac{1}{2} \text{erfc} \left( \frac{\epsilon\eta}{\sqrt{2\nu B}} \right) \]

\[ \frac{\left[ \int_{E_{i} dU} \left( \cos \sum_{j=1}^{M} a_{j} \cdot Z_{j}(r, \theta) + \varphi_{\text{e-QPSK}}(t) \right) dU \right]^{2}}{\int_{E_{i} dU} dU} \]

\[ + \frac{\left[ \int_{E_{i} dU} \left( \sin \sum_{j=1}^{M} a_{j} \cdot Z_{j}(r, \theta) + \varphi_{\text{e-QPSK}}(t) \right) dU \right]^{2}}{\int_{E_{i} dU} dU} \] ,

where \( M \) is a positive integer. The wavefront distortion

\[
E_{\text{QPSK}}(r, \theta, t) = A_{5} \cdot \exp \left[ -i \left( \omega_{5} t + \varphi_{5} + \varphi_{\text{e-QPSK}}(t) + \varphi_{\text{ad}}(r, \theta, t) \right) \right]
\]

\[
\varphi_{\text{e-QPSK}}(t) = \begin{cases} 
0 & \text{sending "00"} \\
\pi/2 & \text{sending "01"} \\
\pi & \text{sending "10"} \\
3\pi/2 & \text{sending "11"} 
\end{cases}
\]

Therefore, introducing Eqs. (6)–(8) into Eq. (4), the initial phase of the signal light and local oscillator are ignored, so that

\[
\text{SNR}_{\text{QPSK}} = \frac{\epsilon\eta}{\nu B} \left\{ \frac{\left[ \int_{E_{i} dU} \left( \cos \sum_{j=1}^{M} a_{j} \cdot Z_{j}(r, \theta) + 2M\pi + \varphi_{\text{e-QPSK}}(t) \right) dU \right]^{2}}{\int_{E_{i} dU} dU} \right\}^{2}
\]

\[ = \frac{\epsilon\eta}{\nu B} \left\{ \frac{\left[ \int_{E_{i} dU} \left( \cos \sum_{j=1}^{M} a_{j} \cdot Z_{j}(r, \theta) + 2M\pi + \varphi_{\text{e-QPSK}}(t) \right) dU \right]^{2}}{\int_{E_{i} dU} dU} \right\}^{2}
\]
caused by atmospheric turbulence is composed of two parts, \( \sum a_i Z_i(r, \theta) \) and \( 2M \pi \). Only the part of \( \sum a_i Z_i(r, \theta) \) located from 0 to \( 2\pi \) has an impact on the SNR and BER of the system, while the other part of \( 2M \pi \) does not have a substantial impact on the system, according to the properties of the trigonometric functions in Eqs. (9)–(11). Therefore, for coherent optical communication in free space, wavefront correction is only needed for \( \sum a_i Z_i(r, \theta) \).

III. SIMULATION ANALYSIS

For a given level of distortion, the defocusing term has the most serious influence on communication performance, due to its influence on wavefront distortion. Therefore, the defocusing term is taken as the object of our analysis.

Figure 1 shows the influence of distorted wavefront phase (expanded by Zernike polynomials) on the mixing efficiency of the system. We can see from the simulation results that, for different Zernike orders with the same amount of distortion, the third defocusing term of the wavefront (represented by the red curve) has the most significant influence on the mixing efficiency of the system, and with increasing Zernike order, the influence of each Zernike coefficient on the mixing efficiency becomes less and less. When the Zernike order is constant, the mixing efficiency decreases with increasing distortion. Noll has shown that the tilt component of the wavefront in the Kolmogorov turbulence spectrum accounts for about 82% of the total distortion, so the tilt component of the wavefront distortion has the most significant effect on the mixing efficiency of the system.

Figure 2 shows the relationship between Zernike coefficients of different orders and mixing efficiency. Under the same distortion, the defocusing term of the wavefront has the most significant influence on the SNR of the system. With increasing Zernike order, the influence of the Zernike coefficient on the SNR is constantly weakened. For the same Zernike order, taking the defocusing term as an example, the SNR of the distorted wavefront decreases with increasing distortion. Therefore, the wavefront defocusing term is taken as an example in the simulation calculation.

Figure 3 shows the generated wavefronts with defocusing terms of \( 1\pi \) rad, \( 2\pi \) rad, \( 3\pi \) rad, and \( 4\pi \) rad respectively. The defocusing term of the wavefront produces a scoop-shaped structure with circumferential symmetry for the variation in wavefront distortion, and with the increase of the distortion variable of the defocusing term, the degree of wavefront distortion is also greater.

Roddier [31] constructed a statistically independent Karhunen-Loeve function, according to which the important function, namely the covariance of Zernike coefficients \( \sum D_{zz} j n n r \) can be obtained as follows:

\[
E(a, a') = \frac{K_{a' \cdot a'} \cdot \delta \cdot \Gamma \left[ \left( n - n' + \frac{17}{3} \right) / 2 \right] \Gamma \left[ \left( n' - n + \frac{17}{3} \right) / 2 \right] \Gamma \left[ \left( n + n' + \frac{23}{3} \right) / 2 \right]}{\Gamma \left[ \left( n - n' + \frac{17}{3} \right) / 2 \right] \Gamma \left[ \left( n' - n + \frac{17}{3} \right) / 2 \right] \Gamma \left[ \left( n + n' + \frac{23}{3} \right) / 2 \right]}, \tag{12}
\]

FIG. 1. Relationship of Zernike coefficient to mixing efficiency.

FIG. 2. Relationship diagram of Zernike coefficient to signal-to-noise ratio (SNR).
where \( n \) and \( n' \) represent the Zernike polynomial and angular frequency of coefficients \( a_j \) and \( a'_j \) respectively, and \( \delta_j \) is the Kronecker delta function. Furthermore, \( D \) is the aperture diameter of the optical system, and \( r_0 \) is the atmospheric coherence length (Fried constant). Taking aperture \( D = 300 \) mm, the range of the atmospheric coherence length \( r_0 \) is 1–30 cm, from a series of derivations to calculate the influence of atmospheric coherence length \( r_0 \) on the PV value, as shown in Fig. 4.

With decreasing atmospheric coherence length \( r_0 \) (that is, the enhancement of atmospheric turbulence), the PV value of wavefront distortion tends to increase, and inevitably exceeds the correction range of a DM.

Considering the defocusing term of the Zernike coefficient as an example, the number of simulation points is \( 10^6 \), the range of defocusing is 0–0.9 \( \mu \)m the SNR range is 2–20 dB, the wavelength \( \lambda \) is 1550 nm, the bandwidth is 40 GHz and the quantum efficiency is 1.4. The dependence of the wavefront distortion on BER for binary phase-shift keying (BPSK) and quadrature phase-shift keying (QPSK) are obtained, as shown in Fig. 5.

The wavefront distortion has a direct impact on the phase of the signal, and a QPSK signal is more sensitive to the phase than a BPSK signal. For a coherent detection communication system with phase modulation, the change of Zernike coefficient of the wavefront has a periodic effect

**FIG. 3.** Wavefront generated by different defocusing terms: (a) 1\( \pi \) rad, (b) 2\( \pi \) rad, (c) 3\( \pi \) rad, and (d) 4\( \pi \) rad.

**FIG. 4.** Dependence of the wavefront’s peak-to-valley (PV) value and the proportion of the tilt component on the atmospheric coherence length \( r_0 \).
on the BER of the system. A distortion of 0.33 μm generated by the Zernike defocusing term will contribute to a phase shift of \(2\pi\) for wavefront PV, so the BER of the system is characterized by \(2\pi\)-periodic continuation. The influence of wavefront on the BER of the system is only that its distortion variable is located in a complete \(2\pi\) period principal-value interval. Therefore, when the wavefront phase does not exceed a complete wavelength range, the BER of the system decreases with increasing SNR. As a result, for large-amplitude wavefront distortion the residual wavefront can be corrected to keep the whole-integer-multiple principal-value interval, to ensure that the communication system is in a low-error-rate state and thus improve communication performance.

Setting the atmospheric coherence length \(r_0 = 0.02\) m, the three-dimensional figure of the wavefront phase diagram and the direct-view diagram of the wavefront phase are obtained, as shown in Fig. 6.

The PV value of wavefront distortion in this state is 49.51 μm (76.17 × \(2\pi\) rad). According to the aforementioned theoretical analysis, it can be observed that 0.17 × \(2\pi\) rad (residual part) only affects the SNR and BER of the coherent detection system, while 76 × \(2\pi\) rad is an integer multiple of the \(2\pi\)-period and does not affect the system. Therefore, for the coherent detection system only the residual part of the wavefront phase, 0.17 × \(2\pi\) rad in Fig.

![FIG. 5. Bit-error rate (BER) of the system as a function of the Zernike coefficient (third-order mode): (a) binary phase-shift keying (BPSK), (b) quadrature phase-shift keying (QPSK).](image)

![FIG. 6. Wavefront phase diagram for atmospheric turbulence intensity \(r_0 = 0.02\) m: (a) three-dimensional diagram, and (b) direct-view diagram.](image)
4(b), needs to be modified in the regime of low BER, while ensuring that the DM has an adequate travel distance to correct a large wavefront distortion.

Figure 7 shows the curves for wavefront PV after full correction and residual correction. The wavefront distortion in the initial state is 52.21 μm. If the full correction is adopted, the corrected wavefront phase is 31.99 μm (49.21 × 2π rad), due to the insufficient travel distance of the DM, and the phase value is not an integer multiple of 2π. The distortion of 0.21 × 2π rad leaves the system not at the bottom of the BER curve in Fig. 3, and the BER is about 10^-3. However, with the residual correction method, the corrected wavefront phase is 52 μm (80 × 2π rad) and the corrected phase is an integer multiple of 2π, which satisfies the range of the DM, and this part does not contribute to the coherent detection system. At this point, the BER of the communication system is just at the bottom of the curve in Fig. 5, and the BER is 10^-6.

According to the above analysis, the influence of wavefront distortion on mixing efficiency and BER of a wireless coherent communication system is only in the main-value range of 0–2π. In a traditional AO system the corrected wavefront phase is a plane wave, but the phase of the distorted wavefront is beyond the correction range of the DM after long-distance laser transmission. From the above analysis, we can see that the influence of wavefront on communication performance is only in the main-value range of 0–2π. Therefore, for the correction of wavefront, only the 0–2π principal-value range of wavefront distortion needs to be corrected, and the integer-multiple range of distortion should be ignored. Communication performance can be improved by ensuring that the DM has enough travel distance.

IV. EXPERIMENTAL RESEARCH

4.1. Experimental Composition

The principle block diagram of the AO wavefront correction system is shown in Fig. 8. The beam emitted by the semiconductor laser is collimated by lenses, L1 and L2, and then vertically incident to the surface of the liquid-crystal spatial light modulator (SLM) through beam splitter, BS1. When the simulated large-distortion turbulence phase screen is loaded on the SLM, the distorted wavefront will be produced and then reflected. After DM correction, the reflected beam with residual phase passes through the BS2 and enters lenses L3 and L4 and the SH-WFS in the direction of the parallel optical axis, and enters the pupil plane of the SH-WFS. The AO system is composed of the WFS, DM, and a wavefront control module. In the experiment, the wavelength of the light source is 650 nm and the power is 5 mw. The focal lengths of L1, L2, L3, and L4 are 30, 200, 175, and 75 mm respectively. The high-speed continuous reflection DM DM69 (Alpao Co., Montbonnot-Saint-Martin, France) features 69 actuator units and a 10.5-mm diameter. The liquid-crystal SLM is RL-SLM-R2 (Anhui Ruiguang Electronics and Technology Co., Ltd., Beijing, China) and its reflectivity is more than 70%. The SH-WFS HASO4-first (Imagine Optics, Orsay, France) has a 400–1100 nm wavelength range and 32 × 40 subapertures. The HASO4-first wavefront sensor is used as the test light source with a red light of 650 nm. The measurement range of tilt is 260 μm and defocus is 227.5 μm. Table 1 shows the specific parameters of the HASO4-first wavefront sensor used in the experiment.

4.2. Algorithm Principle

The closed-loop control algorithm based on AO is usually realized by using the traditional integral control. The schematic diagram of the algorithm is shown in Fig. 9. First, the interaction matrix from Zernike coefficient to DM voltage is calculated by a push-pull method, and then closed-loop operation is realized by integral control. When the Zernike coefficient of the control object is 0, that is, the plane wavefront, this represents complete correction of the wavefront. When the control object is the remainder of the wavefront phase relative to the maximum integer wavelength, it represents the residual correction of the wavefront.

4.3. Experimental Results

For the large wavefront distortion generated by the SLM, the complete correction and the residual correction are adopted respectively. The Zernike coefficients after wavefront correction are shown in Fig. 10.

Figure 10 shows the Zernike-coefficient distribution of the wavefront before and after correction, in the cases of complete and residual corrections. Under the complete correction, since the first two orders of tilt-component account for a large proportion of the wavefront-distortion compo-
nents, the first two orders of tilt-component wavefront are mainly corrected. Only the residual distortion is corrected, and the reconstructed wavefront phase after correction is an integer multiple of the wavelength.

The voltage distribution of the DM driver after adopting the complete and residual corrections is shown in Fig. 11. It is obvious that the voltage distribution of the DM subject to the condition of complete correction is larger than that for residual correction.

The total voltage power of the DM driver can be defined as

$$\text{Power}_{\text{DM}} = \sum_{i=1}^{60} v_i^2. \quad (13)$$

In the case of actual measurement and collection, since the voltage of the deformation mirror is normalized, the maximum value of the default voltage is 1; that is, it is di-

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**TABLE 1.** HASO sensor specifications

<table>
<thead>
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<th>Configuration</th>
<th>Full Resolution</th>
<th>High Speed</th>
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</thead>
<tbody>
<tr>
<td>Aperture Dimension</td>
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<td>(18 \times 18 \text{ mm}^2)</td>
</tr>
<tr>
<td>Number of Subapertures Dedicated for Analysis</td>
<td>32 × 40</td>
<td>16 × 16</td>
</tr>
<tr>
<td>Tilt Dynamic Range</td>
<td>±3° (400(\lambda))</td>
<td>±3° (200(\lambda))</td>
</tr>
<tr>
<td>Focus Dynamic Range</td>
<td>±0.018 (\text{m(\lambda)}) ± inf (350(\lambda))</td>
<td>±0.018 (\text{m(\lambda)}) ± inf (70(\lambda))</td>
</tr>
<tr>
<td>Repeatability (rms)</td>
<td>&lt; (\lambda/200)</td>
<td>&lt; (\lambda/200)</td>
</tr>
</tbody>
</table>

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**FIG. 8.** Wavefront correction diagram of adaptive optics (AO) for coherent optical communication: (a) system diagram, (b) physical diagram.

**FIG. 9.** Schematic diagram of the algorithm.
In practice, the voltage sent in the correction process is treated with 1 as the normalized dimension, without actual units. When the DM completely corrects the wavefront phase, the total power is 10.40. When the residual correction is applied, the total power is 0.12. For large wavefront distortion, the service life of the actuator will be shortened if the distortion is completely corrected. Therefore, to achieve the best efficiency, residual correction can effectively alleviate the problems of high output power and excessive stroke of the DM driver.

The adaptive optical closed-loop control algorithm is used for complete correction and residual correction of the distorted wavefront, the PV value and root-mean-square (RMS) values of the wavefront correction are analyzed. The curves for the two wavefront closed-loop states are obtained, as shown in Fig. 12.

As shown in Fig. 12, with complete correction the PV of the corrected wavefront phase is reduced from 50 μm to 1.6 μm, the RMS is reduced from 13 μm to 0 μm, and the wavefront phase before full correction is tilted. After correction, the wavefront phase is flat and the correction effect is good. With residual correction, the PV of the corrected wavefront phase is reduced from 45 μm to 12 μm, the RMS value after correction is too large, and the wavefront phase before residual correction is tilted. Comparing Figs. 12(a) and 12(b), the PV of the wavefront after residual correction is larger than that after complete correction, while the RMS value does not change significantly.

Low-order aberration is corrected with a deflection mirror or a large-stroke deformation mirror, and high-order aberration is corrected with a small-stroke deformation mirror. Based on the orthogonality of Zernike polynomials, the correction-area space between the two is clearly divided. As a common multicorrector adaptive optical system, the adaptive optical system DM69 is composed of a piezoelectric tilt mirror (TM) based on two-dimensional motion and

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**FIG. 10.** Zernike coefficients after wavefront correction: (a) complete correction and (b) residual correction systems.

**FIG. 11.** Voltage distributions of deformable mirror (DM) after wavefront correction.
a deformation mirror with an independent unit, as shown in Fig. 13.

However, for the actual situation, compared to the wavefront correction system of a single DM69, the TM + DM69 wavefront correction system has an additional corrector, which increases the complexity of the optical path and leads to more optical-path error in the system. At the same time, more first-level correction systems are introduced, which reduces the utilization of light energy. As a result, the communication performance of the system is fundamentally reduced, and there is a correction range for the commonly used TM. For example, the TM model used is PT2M60-240s (Shanghai Nano Motions Technology CO., LTD, Shanghai, China) with a maximum stroke of 1.2 mrad. For a large-distortion wavefront, the inclined component usually occupies the major proportion. At this point, the TM cannot meet its necessary correction stroke. Therefore, residual correction is the simplest and most direct method to apply for AO correction of large distortion in the field of wireless coherent optical communication.

Mixing efficiency, as the key parameter of phase matching in a coherent detection system, directly determines the response of local-oscillator light and the compatibility of the phase of the signal light, so the mixing efficiency has a vital role in the coherent optical communication system. The higher the mixing efficiency, the better the coherent optical communication performance. Calculation of mixing efficiency is based on Eq. (5), and the mixing efficiency curves of the two wavefront closed-loop states are shown in Fig. 14.

Figure 14 shows that when the number of sampling points is 1000, the mixing efficiency of wavefront correction remains at 90%, while that of the residual correction closed-loop control algorithm approaches 100%. Therefore, the wavefront-matching degree of the residual correction algorithm is higher than that of the complete correction algorithm.

Figures 15(a) and 15(b) respectively show the change of SNR with the number of iterations of the complete correction AO algorithm and the residual correction AO algorithm. In the case of complete correction, the SNR of the communication system increases from 5 dB before correction to 13 dB after correction; in the case of residual correction, the SNR of the communication system increases from 5 dB before correction to 15 dB after correction, so the SNR after residual correction is higher than that after complete correction. The residual correction algorithm can better improve the communication environment.

Figures 16(a) and 16(b) respectively show the change in BER with the number of iterations of the complete correction AO algorithm and the residual correction AO algorithm. In the case of complete correction, the bit-error rate of the communication system decreases from $10^{-3}$ before correction to $10^{-10}$ after correction, and in the case of re-
sidual correction the bit error rate of the communication system decreases from $10^{-2}$ before correction to $10^{-11}$ after correction.

V. CONCLUSIONS

Based on the AO in free-space coherent optical communication system, this paper analyzes the relationship between the Zernike-polynomial wavefront phase and the mixing efficiency, and the influence of wavefront distortion on the BER of phase-modulation systems. The following conclusions can be drawn:

1. Due to the wavefront’s periodic extent, its distortion has a periodic effect on the BER of a free-space coherent optical communication system.

2. According to the characteristic that wavefront distortion has a periodic influence on the BER of free-space coherent optical communication, the experimental results show that the BER decreases from $10^{-1}$ to $10^{-7}$ after correction using an AO closed-loop control algorithm with residual correction. Compared to the complete correction algorithm, this method can reduce the stroke requirement and power output of the DM and achieve a low error rate of $10^{-7}$, which effectively improves the communication per-
formance of a free-space coherent optical communication system.

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