Study on the Influence of Random Phase Interference on the Positioning Performance of a Four-Quadrant Detector

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***Abstract*—Random phase interference is the main factor leading to uneven optical power distribution, which will affect the positioning accuracy of the four-quadrant detector. This paper uses the power spectrum inversion method to simulate the light spot power distribution affected by random phase interference, and studies the subdivision capability characteristics of the four-quadrant detector under different random phase interference. The simulation experiment results show that when the radius of the light spot received by the detector is 1/2 the radius of the detector, both detection range and positioning accuracy can be taken into account. When the random phase interference is enhanced, the detector's subdivision capability decreases. When the random phase interference is small, the detector can achieve more than 100 subdivisions. When the random phase interference is large, the light spot can only achieve 3 subdivision at the edge of the detector target surface. An experimental system was built to test the subdivision capability of the four-quadrant detector, the experimental test results were basically consistent with the simulation results. The research results provide a technical reference for the application of four-quadrant detector. in free space environments.**

***Index Terms*—Four-quadrant detector, random phase interference, power spectrum inversion method, subdivision capability.**

I. Introduction

As a position sensitive device, the four-quadrant detector (4-QD) has many advantages, such as high sensitivity, wide dynamic range and fast response speed [1], [2]. It has been widely used in laser communication [3], laser guidance [4], and laser navigation. There are many factors that affect the positioning performance of 4-QD. Reference [5] analyzes different light spot position detection algorithms and considers the impact of the gap size of the 4-QD in the model on positioning accuracy. Reference [6] in an angle measurement system based on a 4-QD, phase error caused by lens distortion affects the 4-QD positioning performance. Reference [7] studied the effects of inherent errors and random errors on 4-QD performance, reduces the impact of random errors such as background photocurrent and dark current on spot positioning accuracy. Reference [8] establishes the mathematical model of azimuth standard deviation based on Gaussian light spot, and studied the influence of light spot position,the light spot radius, and signal-to-noise ratio on 4-QD positioning accuracy. Reference [9] investigating the difference in localization effects on 4-QD between Gaussian-distributed spot energies and ideally uniformly distributed spot energies. The current research status indicates that the spot size, spot shape, and signal-to-noise ratio received by the detector all have an impact on the performance of the 4-QD device. When laser light is transmitted in free space, its phase will change randomly due to the influence of the external environment, For example, platform vibration, changes in atmospheric characteristics [10], this random change in phase will also affect the positioning performance of the detector.

In order to meet the application requirements of 4-QD in free space positioning and automatic tracking, this paper conducts a study on the impact of random phase interference on the positioning performance of 4-QD. Taking the random phase changes of light caused by turbulent channels as the research background, simulating spot power distributions subject to random phase interference using the power spectrum inversion method, study the working performance of 4-QD under different random phase interference intensities, establish the corresponding simulation model and test system, and complete simulation and experimental tests, and useful conclusions are obtained to provide reference and basis for its application in the field of spot detection, localization and tracking.

II. Working Principle of Four-Quadrant Detector

A. Four-Quadrant Detector Positioning Principle

When 4-QD detects the light spot position, it relies on the phase or power of the optical signal received in its four quadrants. When position detection is performed based on the phase difference of the received light signal in the four quadrants, using the principle of interference between the he local oscillator light and the incident light., the phase difference between the two is detected to realize the position detection and localization. Due to the use of coherent detection principle, so that the 4-QD device detector sensitivity has been significantly improved, this method is mostly used in the field of technology with less external interference and higher requirements for localization

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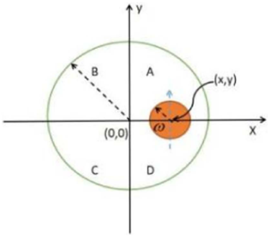

Fig. 1. Principle of the four-quadrant detector spot positioning.

segmentation capability, such as the field of gravitational wave detector technology [11].

The light spot detection based on optical power difference has lower detection accuracy than phase detection, but its application field is wider. The basic positioning principle is shown in Fig. 1.

When light shines on the 4-QD surface, each quadrant generates a corresponding photocurrent whose magnitude corresponds to the optical power incident on each quadrant. The optical power of the light spot in each quadrant produces corresponding photocurrents $\mathrm{I_A}$, $\mathrm{I_B}$, $\mathrm{I_C}$, and $\mathrm{I_D}$. According to the photocurrent generated in each quadrant, the position coordinates of the light spot on the 4-QD surface can be calculated [12].

$$\sigma_{\mathrm{x}} = \frac{(\mathrm{I_A} + \mathrm{I_D}) - (\mathrm{I_B} + \mathrm{I_C})}{\mathrm{I_A} + \mathrm{I_D} + \mathrm{I_B} + \mathrm{I_C}} \tag{1}$$

$$\sigma_{\mathrm{y}} = \frac{(\mathrm{I_A} + \mathrm{I_D}) - (\mathrm{I_B} + \mathrm{I_C})}{\mathrm{I_A} + \mathrm{I_D} + \mathrm{I_B} + \mathrm{I_C}} \tag{2}$$

In the formula, σ_{x}, σ_y is the coordinate of the centroid of the light spot in the x-direction and y-direction. When the size of the incident light spot is known, taking the x-direction as an example, its position coordinates can be expressed as:

$$\sigma_{\mathrm{x}} = \frac{2}{\pi\omega}\left[x\sqrt{1-\left(\frac{x}{\omega}\right)^2} + w \arcsin\left(\frac{x}{\omega}\right)\right] \tag{3}$$

where ω represents the size of the light spot. The light spot location x are far less than the radius of the spot. In the above formulas, respectively, apply an approximation, (3) can be approximated as:

$$\sigma_{\mathrm{x}} \approx \frac{2\mathrm{x}}{\pi\omega} \tag{4}$$

From this, the relationship between the light spot coordinates and the measured values can be obtained:

$$\mathrm{x} = \frac{\pi\omega\sigma_{\mathrm{x}}}{2} \tag{5}$$

Let Δ be the minimum variation and $\Delta\mathrm{x}$ be the spatial resolution in the x-direction, which can be expressed by the following equation:

$$\Delta\mathrm{x} = \frac{\pi\omega\Delta\sigma_x}{2} \tag{6}$$

The above positioning analysis is based on the fact that the optical power distribution form on the 4-QD surface is uniform or Gaussian, and its spot position detection characteristics are related to factors such as incident spot size, signal-to-noise ratio, spot shape, spot position, etc. When the optical power distribution on the 4-QD surface is random, the spot position detection characteristics will be closely related to the random phase changes of the optical power.

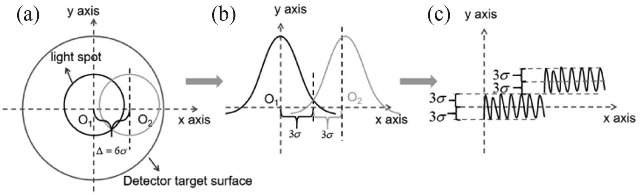

Fig. 2. Schematic diagram of the minimum distance that the spot moves on the 4-QD target surface. (a) Schematic of spot movement. (b) The detector recognizes the minimum spacing. (c) Corresponds to subdivision capability.

B. Four-Quadrant Detector Subdivision Capability

When 4-QD device are used in the field of precision tracking technology, not only the light spot detection accuracy must be studied, but its subdivision characteristics must also be studied. The subdivision characteristics are related to the detection minimum resolution distance. The so-called minimum resolution distance refers to the minimum distance that the detector can identify when the light spot moves on the detector target surface. Assuming that the instantaneously received optical power distribution on the 4-QD surface is Gaussian,

$$f\left(x\right) = \frac{1}{\sigma\sqrt{2\pi}} e^{\frac{(x-\mu)^2}{2\sigma^2}} \tag{7}$$

In the formula, x is the spot center position, σ is the optical power variance, and μ is the optical power average value. The minimum distance for this light spot to move on the 4-QD surface is shown in Fig. 2 below.

Assume that when the light spot moves from position 1 ($\mathrm{O_1}$) to position 2 ($\mathrm{O_2}$) on the detector target surface (shown in Fig. 2(a)), its power distribution form remains unchanged. To ensure that changes in position are reliably recognized, the distance between position 1 and position 2 is required to be at least 6σ, which is the minimum distance that the detector can identify (shown in Fig. 2(b)). When the detector target surface is normalized, the entire radius of the target surface is normalized to a distance of 1, and the subdivision capability of the 4-QD detector is defined as $1/3\sigma$ (shown in Fig. 2(c)). This parameter can be used as an important parameter to evaluate the performance of the 4-QD detector.

The above analysis is obtained when the light spot moves on the 4-QD surface and the optical power distribution remains unchanged. In actual situations, due to the influence of random phase changes, when the light spot moves on the 4-QD surface, its optical power changes randomly. It is more reasonable to use subdivision characteristic parameters to evaluate the random phase variations on 4-QD performance.

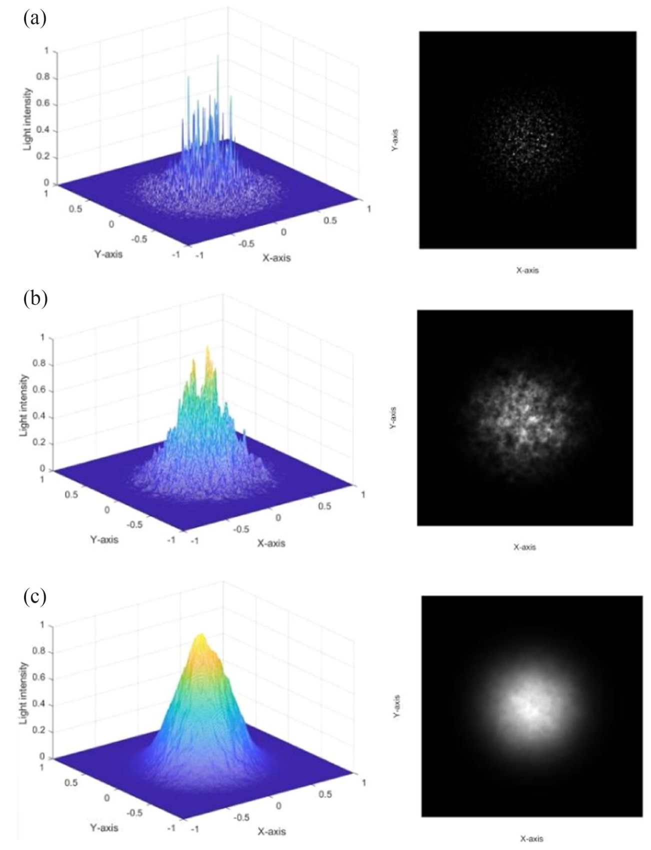

Fig. 3. Simulation of light intensity of the spot received by the detector at different random interference intensities. (a) $C_n^2 = 1 \times 10^{-13}$, (b) $C_n^2 = 1 \times 10^{-15}$, (c) $C_n^2 = 1 \times 10^{-17}$.

III. SIMULATION ANALYSIS OF THE EFFECT OF RANDOM PHASE INTERFERENCE ON THE PERFORMANCE OF FOUR-QUADRANT DETECTOR

A. *Random Phase Interference Simulation*

When 4-QD is applied in free space localization and automatic tracking, random phase interference mainly comes from the random undulation of the link channel on the beam, and the study takes the turbulent channel as the application background, The power spectrum inversion method is used to simulate the random phase changes of turbulence of different intensities, and random phase screens of different intensities are introduced in the path of laser transmission, respectively. The laser wavelength is 1064 nm, and the initial waist radius is $\omega = 0.5$ mm. Strong turbulence is taken as $C_n^2 = 1 \times 10^{-13}$, medium turbulence is taken as $C_n^2 = 1 \times 10^{-15}$, and weak turbulence is taken as $C_n^2 = 1 \times 10^{-17}$. The intensity distribution characteristics of the received light spot through simulation are shown in Fig. 3.

The figure consists of a three-dimensional view of a Gaussian spot with different random interference intensities and the corresponding top view. The z-axis in the figure is the light intensity. It can be seen that the random interference in the transmission path causes the detector to receive a change in the optical power distribution, and the degree of phase distortion increases with the strengthening of the turbulence intensity. When the turbulence intensity reaches a certain level, even phenomena such as spot splitting will occur, resulting in an imbalance of the received optical power in each quadrant, which will have an important impact on the operating performance of the 4-QD device and reduce its spot detection accuracy and subdivision capability.

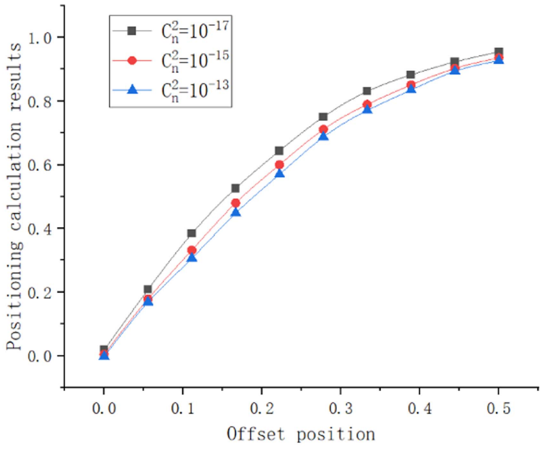

Fig. 4. Simulation of the four-quadrant detector positioning under different intensity phase interference.

B. *Positioning Accuracy of the Four-Quadrant Detector Under Random Interference*

The simulation results of Fig. 3 are applied to 4-QD for center coordinate solving to analyze the influence of phase interference of different intensities on the positioning performance of 4-QD. Make the light spot of each group move along the horizontal direction (x-axis) of the detector, and the positioning calculation (σ_x) is completed every 0.05 mm, and the simulation results of 4-QD positioning of phase interference of different intensities are shown in Fig. 4.

The x-axis of the graph indicates the distance of the spot from the center of the detector, and the y-axis is the positioning result (σ_x) calculated by (1) and (2). Fig. 4 shows the trend of 4-QD performance with atmospheric turbulence intensity, when the atmospheric turbulence is weak, the position and shape of the light spot is relatively stable, and the positioning accuracy near the center of the 4-QD is higher, and when the light spot is far away from the center of the detector, the detection accuracy of the device decreases. Under the same conditions, the increase in turbulence leads to a decrease in the accuracy of 4-QD detection.

C. *Optimal Light Spot Size Under Random Interference*

Different light spot sizes affect the detection accuracy and detection range. Let the radius of the light spot received by the detector be ω and the radius of the detector target surface R = 1 mm. Under $C_n^2 = 1 \times 10^{-17}$ weak turbulence conditions, the light spot moves along the x-axis positive direction on the detector. When the light spot radius is selected $\omega < \mathrm{R}/2$ ($\omega = 2/10\mathrm{R}$, $\omega = 3/10\mathrm{R}$, $\omega = 4/10\mathrm{R}$), $\omega = \mathrm{R}/2$($\omega = 5/10\mathrm{R}$), $\omega > \mathrm{R}/2$($\omega = 6/10\mathrm{R}$, $\omega = 7/10\mathrm{R}$, $\omega = 8/10\mathrm{R}$, $\omega = 9/10\mathrm{R}$, $\omega = \mathrm{R}$), respectively, the output simulation results of the 4-QD device are shown in Fig. 5.

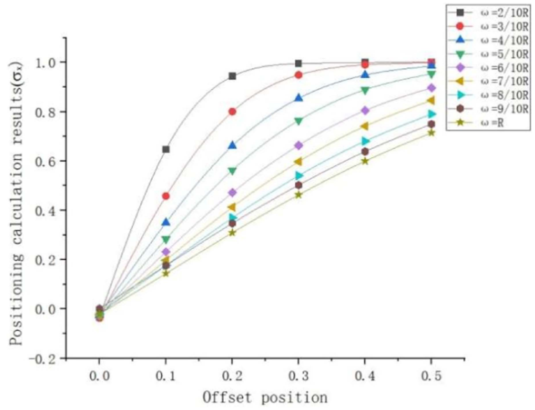

Fig. 5. Calculation results of different light spot radius positioning.

The x-axis of the graph indicates the the distance of the spot from the center of the detector, and the y-axis is the positioning result (σ_{x}). As can be seen from Fig. 5, when the spot radius (ω) is small, the corresponding detection accuracy is high, but the detection range is small. On the contrary, when the radius of the light spot is larger, it has a large range of movement in the x-axis direction, the detection range is large, but its detection accuracy is relatively low. Therefore, to synthesize the constraints between the detection accuracy and the detection range, the light spot radius can be set to 1/2 of the radius of the target surface.

D. *Impact of Random Phase Interference on Subdivision Capability*

The above analysis assumes that the light spot phase interference is a specific value, and the corresponding input and output are smooth curves. When the phase interference is randomly varying, the turbulence intensity is randomly varying, the 4-QD output exhibits the characteristic of subdivision capability. When the light spot is at the center of the detector coordinates,the weak turbulence varies randomly from $\mathrm{C}_n^2 = 1 \times 10^{-16}$ to $\mathrm{C}_n^2 = 1 \times 10^{-17}$ (Fig. 6(a)), the medium turbulence varies randomly from $\mathrm{C}_n^2 = 1 \times 10^{-15}$ to $\mathrm{C}_n^2 = 1 \times 10^{-16}$ (Fig. 6(b)), and the strong turbulence varies randomly from $\mathrm{C}_n^2 = 1 \times 10^{-13}$ to $\mathrm{C}_n^2 = 1 \times 10^{-14}$ (Fig. 6(c)). Simulations are performed for each of these three cases and the simulation results are shown in Fig. 6.

The x-axis of the graph is the range of variation of C_n^2, and the y-axis is the positioning result (σ_{x}). It can be seen that random phase interference has a great impact on the performance of 4-QD detection. The variance of the data in Fig. 6(a) is calculated to be 0.0161 (1σ), In order to be able to distinguish the position between the two spots, a minimum distance of 6σ between the two spots is required, the subdivision capability $1/3\sigma \approx 20$, When turbulence intensity is weak $\mathrm{C}_{\mathrm{n}}^2 = 10^{-17}$, 4-QD can achieve more than 100 subdivision capability. In the same way that the subdivision capability of Fig. 6(b) is 7, and the subdivision capability of Fig. 6(c) is 6. The results indicate that as the intensity of the random phase interference increases, the minimum resolution of 4-QD device detection decreases.

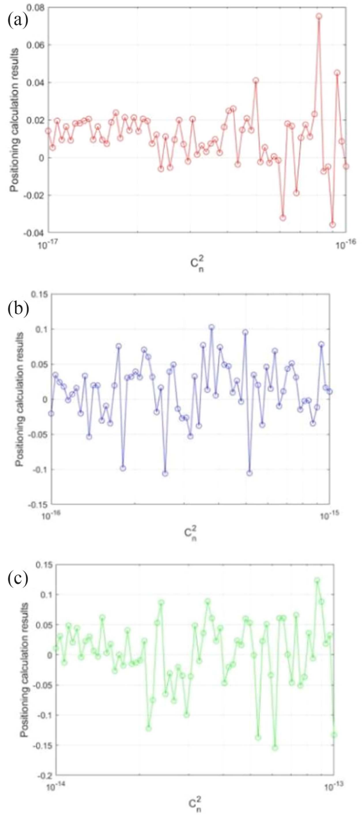

Fig. 6. Simulation of 4-QD output results under random changes in phase interference. (a) Weak turbulence varies randomly from $\mathrm{C}_n^2 = 1 \times 10^{-16}$ to $\mathrm{C}_n^2 = 1 \times 10^{-17}$. (b) Medium turbulence varies randomly from $\mathrm{C}_n^2 = 1 \times 10^{-15}$ to $\mathrm{C}_n^2 = 1 \times 10^{-16}$. (c) Strong turbulence varies randomly from $\mathrm{C}_n^2 = 1 \times 10^{-13}$ to $\mathrm{C}_n^2 = 1 \times 10^{-14}$.

When the light spot moves along the positive direction of x-axis at 0.1 intervals on the detector coordinate axis, the phase random interference is taken as $\mathrm{C}_n^2 = 1 \times 10^{-15}$ to $\mathrm{C}_n^2 = 1 \times 10^{-17}$ variation (Fig. 7(a)) and$\mathrm{C}_n^2 = 1 \times 10^{-13}$ to $\mathrm{C}_n^2 = 1 \times 10^{-15}$ variation (Fig. 7(b)), respectively, and the output results of the corresponding 4-QD devices are simulated as shown in Fig. 7.

The x-axis of the graph indicates the distance of the spot from the center of the detector, and the y-axis is the positioning result (σ_{x}). It can be seen that the subdivision capability is higher when the light spot is located in the center of the detector, and the subdivision capability decreases when the light spot is away from the center of the detector. Fig. 7(a) the subdivision capability decreases from 12 at the center to 4 at the edge; Fig. 7(b) the subdivision capability decreases from 6 at the center to 3 at the edge, and the detection accuracy decreases significantly. Therefore, when the 4-QD device is used in a random phase interference environment, the detection light spot should be kept at its center position as much as possible.

IV. EXPERIMENTAL TESTING OF THE IMPACT OF RANDOM PHASE INTERFERENCE ON THE PERFORMANCE OF THE FOUR-QUADRANT DETECTOR

An experimental system was built to complete the 4-QD performance test in the atmospheric channel, and the experimental principle is shown in Fig. 8 below, providing a practical basis

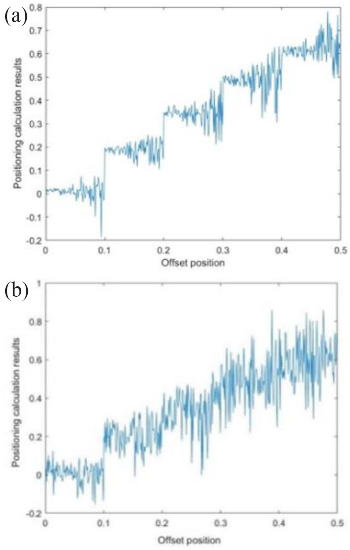

Fig. 7. Simulation of 4-QD output during forward movement of light spot in x-axis with random phase interference variation. (a) Random phase interference changes from $C_n^2 = 1 \times 10^{-15}$ to $C_n^2 = 1 \times 10^{-17}$. (b) Random phase interference changes from $C_n^2 = 1 \times 10^{-13}$ to $C_n^2 = 1 \times 10^{-15}$.

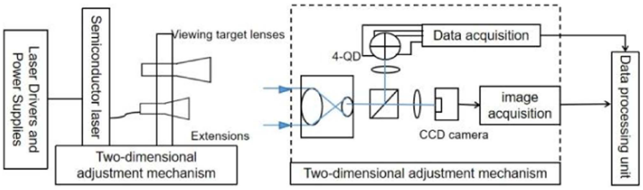

Fig. 8. Schematic diagram of 4-QD performance testing experiment.

Fig. 9. Transmission and reception experimental terminal.

for spot detection, localization, and tracking. Transmission and reception experimental terminal in Fig. 9.

The experimental system consists of two parts, the launch and reception. Due to the long distance of the experiment, rough alignment was first achieved at the launching end by viewing the target mirror, design of the same optical axis for 4-QD and CCD cameras at the receiving end, the incident light spot will be adjusted to the center of the CCD to ensure that the light spot at the same time incident experiments to the center of the 4-QD. A high-frame-frequency CCD camera was also used to statistically process the optical power and obtain the light intensity scintillation variance:

$$\sigma_I^2 = \frac{< I^2 > - < I >^2}{< I >^2} \tag{8}$$

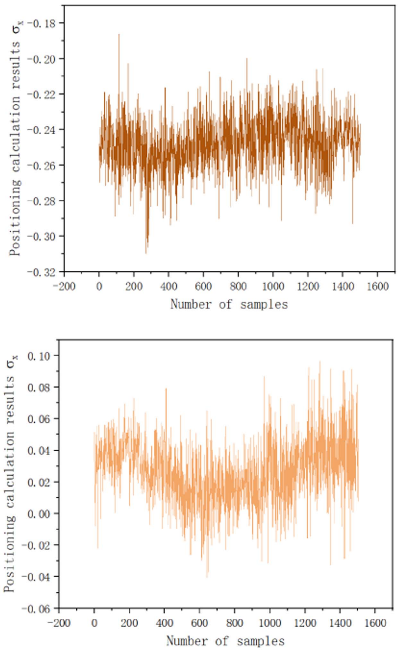

Fig. 10. Experimental results.

Where I is the intensity of the CCD received light spot, $< \cdot >$ represents the averaging operation. Combined with $C_n^2 = \frac{\sigma_I^2}{1.23K^{7/6}L^{11/6}}$, the C_n^2 value is calculated in real time. where $K = 2\pi/\lambda$ is the wave vector and L is the link distance.

The output of the experiment, which measured the range of C_n^2 variation in $0.6 \times 10^{-15} \sim 1.2 \times 10^{-17}$ variation when the incident light spot was located near the center of 4-QD, its output is shown in Fig. 10 below.

The x-axis of the graph is the number of samples sampled, and the y-axis is the positioning result (σ_x). As a result, the experimentally measured subdivision capability varies between 10 and 6, and the experimental test results are basically consistent with the simulation results.

V. CONCLUSION

In this paper, for the impact of random phase interference on 4-QD performance, the power spectrum inversion method is used to simulate the spot power distribution subject to random phase interference, and the 4-QD positioning and subdivision characteristics are studied.The simulation results show that the random phase interference has a large impact on the 4-QD performance, and the detector can balance the detection range and localization accuracy when the spot radius received by the detector is 1/2 of the detector radius. When the random phase interference is small, the detector can realize more than 100 subdivision, and the subdivision capability decreases with the increase of phase interference intensity, and only 3 subdivision can be realized at the edge of the target surface at the minimum.The experimental system is built to complete the 4-QD subdivision capability test in an outdoor environment, and the phase random undulation intensity is measured at the same time during the experiment as the basis for the evaluation of subdivision capability, and the experimental results are basically consistent with the simulation results when the random phase interference intensity is medium.The research results provide a reference for 4-QD devices in free space localization and auto-tracking applications, especially in technical fields involving the light spot detection, localization, and tracking.

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