Analysis of beam efficiency and accuracy of Gerchberg-Saxton method in multi-beam control of free space optical communication

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ABSTRACT

Free space laser communication has the characteristics of large bandwidth, high speed, high security and small size, and has become the preferred way of high-speed data transmission in space today. The realization of multi-beam control in free-space optical communication through optical phased array has obvious advantages in energy consumption and control accuracy. Gerchberg-Saxton (GS) is a commonly used modulation phase design method for optical phased arrays. This paper analyzes the relationship between the beam efficiency and accuracy and the number of iterations in the modulation phase of optical phased arrays designed by the GS algorithm. The results show that in the ideal case, the beam efficiency increases with the number of iterations of the GS algorithm, and eventually tends to be stable; the beam pointing accuracy increases with the number of iterations of the GS algorithm, and finally tends to be stable, and the speed of stable convergence is faster than the beam efficiency.

Keywords: Free space optical communication, beam control, Gerchberg-Saxton

1. INTRODUCTION

Free space optical communication has the advantages of large bandwidth and high speed. It is a very promising communication method in satellite communication, and it is also a research hotspot. With the maturity of laser communication technology, laser communication links are expected to become high-orbit relay satellites at home and abroad. Reliable way of data transmission[1, 2]. Beam control at the communication end is one of the key technologies of free-space optical communication. The current mainstream beam control method is mechanical beam control, but mechanical beam control has the problems of large volume and high-power consumption. Optical phased array[3] is a method to control the beam by controlling the wavefront distribution of the beam. It has the characteristics of all-solid-state, low power consumption, and no inertia, and can well meet the requirements of the spaceborne platform for beam control. The GS algorithm[4-6] is a commonly used method for the modulation phase design of the optical phased array[7-11]. In this paper, the relationship between the beam efficiency and accuracy and the number of iterations in the modulation phase of the optical phased array designed by the GS algorithm is analyzed. Provide theoretical reference for the design of phased beam method for free space optical communication.

2. PRINCIPLES OF OPTICAL PHASED ARRAYS

Optical phased array refers to the modulation of the complex amplitude distribution of the incident beam by controlling the phase relationship between the various elements on the two-dimensional phased array front, so that the co-phase interference occurs in the specified direction, so as to realize the manipulation of the beam propagation state. According to the Huygens-Fresnel principle, each point on the front is regarded as a wavelet source with the same frequency, and the complex amplitude of the light wave at any point in the space is the result of the interference superposition of all wavelets at that point. Under the conditions, the Fresnel diffraction formula can be obtained as shown in equation (1):

$$U_z(x_z, y_z) = \frac{e^{\frac{i2\pi z}{\lambda}} e^{\frac{i\pi}{\lambda z}(x_i^2+y_i^2)}}{i\lambda z} \iint_{-\infty}^{\infty} U_0(x_0, y_0) e^{\frac{i\pi}{\lambda z}(x_0^2+y_0^2)} e^{-\frac{i2\pi}{\lambda z}(x_0 x_i + y_0 y_i)} dx_0 dy_0 \tag{1}$$

in which $U_z(x_z, y_z)$ is the complex amplitude distribution of the light wave on the plane with a distance of z; $U_0(x_0, y_0)$

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is the complex amplitude distribution of the light wave on the $z=0$ plane, the spatial frequency corresponding to $U_z(x_i,y_i)$ is $(x_i/\lambda z, y_i/\lambda z)$, and the Fourier transform form corresponding to equation (1) is as equation (2) shown.

$$U_z(x_i,y_i)=\frac{e^{\frac{i2\pi z}{\lambda}}e^{\frac{i\pi}{\lambda z}(x_i^2+y_i^2)}}{i\lambda z}F\left\{U_0(x_0,y_0)e^{\frac{i\pi}{\lambda z}(x_0^2+y_0^2)}\right\} \tag{2}$$

When $z>>\pi(x_0^2+y_0^2)/\lambda$, the phase factor $e^{\frac{i\pi}{\lambda z}(x_0^2+y_0^2)}$ can be ignored, and the Fraunhofer diffraction formula is obtained as shown in equation (3):

$$U_z(x_i,y_i)=\frac{e^{\frac{i2\pi z}{\lambda}}e^{\frac{i\pi}{\lambda z}(x_i^2+y_i^2)}}{i\lambda z}F\left\{U_0(x_0,y_0)\right\} \tag{3}$$

Assuming that the complex amplitude distribution of the incident beam is $U_{\mathrm{in}}(x,y)$, and the modulation phase of the incident beam by the optical phased array is t_{OPA}, the complex amplitude distribution $U(x_0,y_0)$ of the outgoing beam modulated by the optical phased array is shown in equation (4):

$$U_0(x_0,y_0)=t_{\mathrm{OPA}}\cdot U_{\mathrm{in}}(x,y) \tag{4}$$

Combined with equation (2), it can be known that the complex amplitude distribution $U(x_z,y_z)$ of the optical phased array outgoing beam at the distance z is shown in equation (5).

$$U_z(x_z,y_z)=\frac{e^{\frac{i2\pi z}{\lambda}}e^{\frac{i\pi}{\lambda z}(x_1^2+y_1^2)}}{i\lambda z}F\left\{t_{\mathrm{A}}\cdot t_{\mathrm{OPA}}\cdot U_{\mathrm{in}}(x,y)\right\} \tag{5}$$

It can be known from equation (5) that the propagation state of the beam after passing through the finite aperture is determined by the complex amplitude distribution of the beam at the aperture. By modulating the complex amplitude distribution of the beam through the modulation phase of the optical phased array at a suitable position during the beam propagation process, the phase and amplitude of the beam at any position in the three-dimensional space after passing through the aperture can be controlled.

In the GS algorithm, the initial phase is first determined. The initial complex amplitude is formed by superimposing a random phase on the desired optical field amplitude according to the desired complex amplitude distribution. The obtained complex amplitude distribution is subjected to inverse Fourier transform, and the phase value is extracted as the phase value of the first iteration. The initial phase and the amplitude of the incident beam are combined as the input for this iteration. After the iteration starts, the initial complex amplitude is substituted into the Fourier transform to obtain the output of this iteration, that is, the complex amplitude distribution of the beam in the far field after the optical phased array modulation. The obtained far-field complex amplitude distribution is analyzed, if it is consistent with the expected light intensity amplitude and within the limited error threshold, the iteration is completed; otherwise the iteration is continued. That is, the obtained far-field complex amplitude is reserved for the phase distribution. The amplitude distribution in the desired complex amplitude distribution replaces its original amplitude until the iteration termination condition is satisfied. Among them, the number of iterations has a significant relationship with the final multi-beam control accuracy and efficiency. How to take into account the calculation cost and control effect needs to be analyzed.

3. ANALYSIS OF MULTI-BEAM POINTING CONTROL PERFORMANCE

3.1 Parameter definition

The energy efficiency is used to measure the utilization rate of the incident laser energy by the optical phased array beam control method, indicating how much of the incident laser power is used for multi-beam optical communication. The energy efficiency η is defined as shown in equation (6):

$$\eta = \frac{\sum_{i=1}^{n} I_i}{I_{\text{sum}}} \times 100\% \tag{6}$$

where I_i is the total energy intensity of the ith beam, n is the total number of beams, and I_{sum} is the total energy of the beam in the far field.

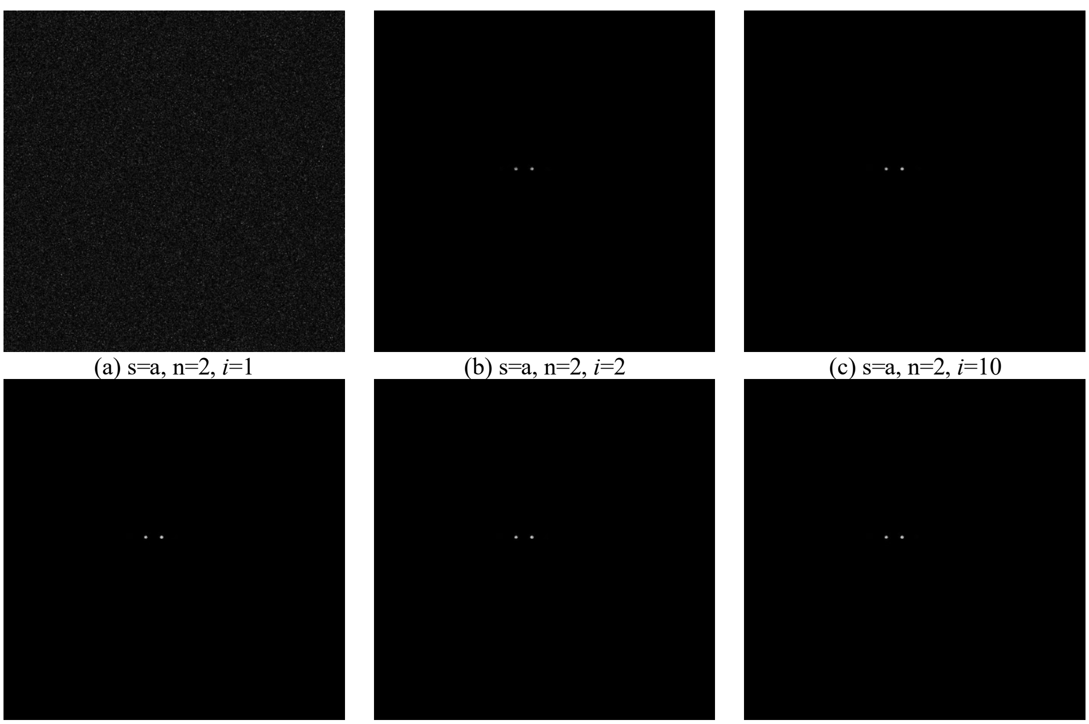
The pointing error is used to evaluate the control pointing accuracy of multiple beams, as shown in equation (7):

$$\begin{cases} x_e = \dfrac{\sum_{i=1}^{m}\sum_{j=1}^{n} x_i g_{ij}}{\sum_{i=1}^{m}\sum_{j=1}^{n} g_{ij}} - (m+1)/2 \\ y_e = \dfrac{\sum_{i=1}^{m}\sum_{j=1}^{n} y_i g_{ij}}{\sum_{i=1}^{m}\sum_{j=1}^{n} g_{ij}} - (n+1)/2 \end{cases} \tag{7}$$

Among them, x_e is the error in the x direction, y_e is the error in the y direction, g_{ij} is the gray value of the i-th row and the j-th column, and m and n are the ranges of the beam in the x and y directions, respectively.

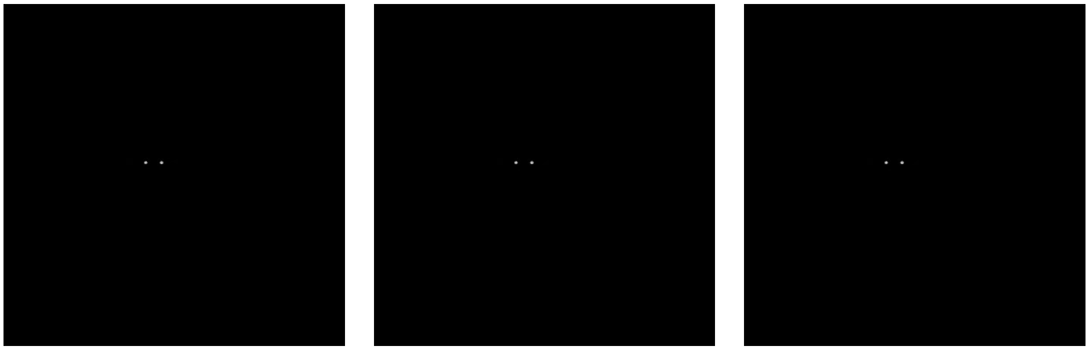
3.2 Performance parameter analysis

When the angle Seita=a and the number of beams n=2, the relationship between the energy efficiency and precision of beam control and the number of iterations is analyzed. The resulting optical phased array controls the far-field plane energy distribution of multiple beams at the same distance as shown in Figure 1.

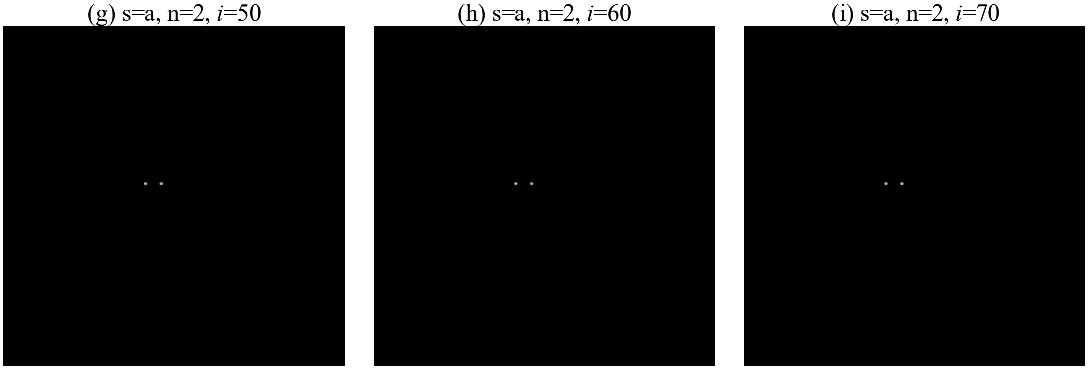


(a) s=a, n=2, *i*=1 (b) s=a, n=2, *i*=2 (c) s=a, n=2, *i*=10

(d) s=a, n=2, *i*=20 (e) s=a, n=2, *i*=30 (f) s=a, n=2, *i*=40



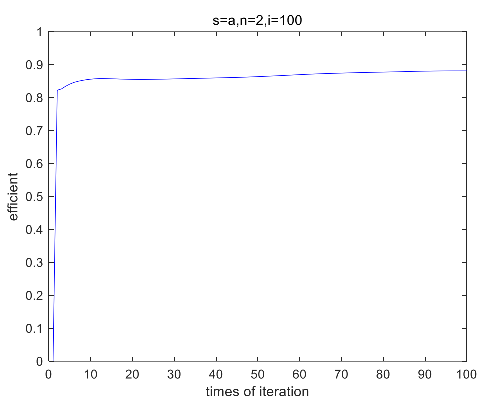
(g) s=a, n=2, *i*=50 (h) s=a, n=2, *i*=60 (i) s=a, n=2, *i*=70



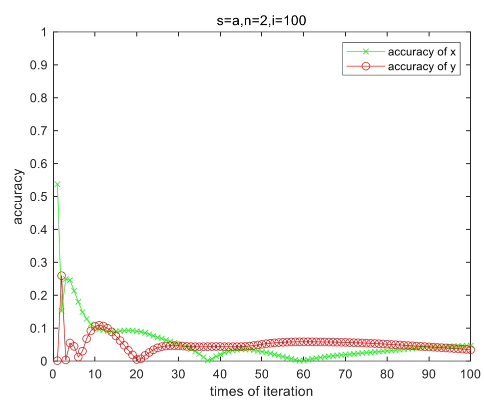
(j) s=a, n=2, *i*=80 (k) s=a, n=2, *i*=90 (l) s=a, n=2, *i*=100

Figure 1. The distribution of multiple beams in the far field. When the angle is a, the number of beams is 2, and the number of iterations *i* is 1, 2, 10, 20, 30, 40, 50, 60, 70, 80, 90, and 100.

The relationship between beam control efficiency and accuracy and the number of iterations is shown in Figure 2, respectively.



(a) Energy efficiency as a function of the number of iterations



(b) Variation of control accuracy with the number of iterations

Figure 2. Relationship between efficiency, accuracy, and number of iterations. When the angle is a and the number of beams is 2, the energy efficiency and control accuracy vary with the number of iterations.

As can be seen from Figure 2, when the angle is a and the number of beams is 2, the energy efficiency of the optical phased array control multi-beam control shows a gradually increasing trend with the increase of the number of iterations, and finally stabilizes at 0.88; the control accuracy increases with the number of iterations. It shows a trend of beating and then gradually stabilizing, and finally stabilizes at 0.047 pixels in the x direction and 0.034 pixels in the y direction.

4. CONCLUSION

Based on the above data analysis, it can be seen that the energy efficiency of optical phased array control multi-beam control shows a gradually increasing trend with the increase of the number of iterations, and is usually above 0.85 in the end; and the increase of the number of iterations does not significantly improve the control accuracy, the two are not. Monotonically increasing relationship, the control accuracy shows a trend of beating and then gradually stable as the number of iterations increases, and finally is usually below 0.1 pixel.

REFERENCES

[1] Arimoto, Y., Toyoshima, M., Toyoda, M., Takahashi, T. and Araki, K., "Preliminary result on laser communication experiment using (ETS-VI)," Free-Space Laser Communication Technologies VII, 2381, 151-158(1995).
[2] Salter, P. S. and Booth, M. J., "Adaptive optics in laser processing," Light: Science & Applications 8 (1) 1-16(2019).
[3] Bauchert, K. A., Serati, S. A. and Furman, A., "Advances in liquid crystal spatial light modulators," Proc. SPIE—The International Society for Optical Engineering, 35-43(2002).
[4] Yang, G. Z., Dong, B. Z., Gu, B. Y., Zhuang, J. Y. and Ersoy, O. K., "Gerchberg-saxton and Yang-Gu algorithms for phase retrieval in a nonunitary transform system: A comparison," Applied Optics, 33(2), 209-18(1994).
[5] Sinclair, G., Leach, J., Jordan, P., Gibson, G. and Courtial, J., "Interactive application in holographic optical tweezers of a multi-plane gerchberg-saxton algorithm for three-dimensional light shaping," Optics Express, 12(8), 1665-70(2004).
[6] Porfirev, A. P., "Modification of the Gerchberg-Saxton algorithm for the generation of specle-reduced intensity distributions of micrometer and submicrometer dimensions," Optik, 195, 163163(2019).
[7] Wang, S., Huayan, S. and Guo, H., "Application of dot-matrix illumination of liquid crystal phase space light modulator in 3D imaging of APD array," Conf. on Nanophotonics, (2018).
[8] Ren, Y., et al., "Development of terahertz two-dimensional phase gratings for multiple beam generation based on a high-accuracy phase retrieval algorithm," Optics Express, 29(12), 17951-17961(2021).
[9] Liu, Y., Hao, Z., Wang, L., Xiong, B. and Luo, Y. I., "A single-chip multi-beam steering optical phased array: Design rules and simulations," Optics Express, 29(5), 7049-7059(2021).
[10] Dev, V., Reddy, A. N. K. and Pal, V., Generation of uniform-intensity light beams with controllable spatial shapes, Optics Communications, 475, 126226(2020).
[11] Li, L., Zhao, H., Liu, C., Li, L. and Cui, T. J., "Intelligent metasurfaces: Control, communication and computing," eLight, 2(1), 1-24(2022).