Optics and Laser Technology 100 (2018) 332–341

Contents lists available at ScienceDirect

Optics and Laser Technology

journal homepage: www.elsevier.com/locate/optlastec

Full length article

Performance analysis of coherent free space optical communications with sequential pyramid wavefront sensor

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ARTICLE INFO

Article history:
Received 28 October 2016
Accepted 18 September 2017
Available online 16 October 2017

Keywords:
Sequential pyramid wavefront sensor
Fiber optics and optical communications
Active or adaptive optics
Atmospheric turbulence
Coherent communications

ABSTRACT

Based-on the previous study on the theory of the sequential pyramid wavefront sensor (SPWFS), in this paper, the SPWFS is first applied to the coherent free space optical communications (FSOC) with more flexible spatial resolution and higher sensitivity than the Shack-Hartmann wavefront sensor, and with higher uniformity of intensity distribution and much simpler than the pyramid wavefront sensor. Then, the mixing efficiency (ME) and the bit error rate (BER) of the coherent FSOC are analyzed during the aberrations correction through numerical simulation with binary phase shift keying (BPSK) modulation. Finally, an experimental AO system based-on SPWFS is setup, and the experimental data is used to analyze the ME and BER of homodyne detection with BPSK modulation. The results show that the AO system based-on SPWFS can increase ME and decrease BER effectively. The conclusions of this paper provide a new method of wavefront sensing for designing the AO system for a coherent FSOC system.

1. Introduction

With higher spectral efficiencies and data rates, a greater ability to decrease both background and thermal noise, and more sensitive coherent receivers, the performance of the coherent detection scheme is better than that of the intensity modulation direct detection in the free space optical communication (FSOC) systems [1–4]. Unfortunately, the atmospheric turbulence greatly degrades the performance of the coherent FSOC links [5]. The effects of laser beam propagation through turbulent atmosphere such as wavefront distortion, scintillation, beam wandering and spreading will not only degrade the entrance efficiency of receiving antenna but also cause the mismatch of the field of signal beam and local oscillator [6].

Adaptive optics (AO) system is successfully used to compensate atmospheric turbulence in coherent FSOC [7,8]. And as the main components of AO system, wavefront sensor is attracting extensive attention [9]. Generally, the Shack–Hartmann wavefront sensor (SHWFS) is widely used as an effective wavefront sensor in coherent FSOC [10]. Belmonte paid attention to elucidate how the addition of AO to the transmitter or receiver can reduce the effects of atmospheric propagation and to quantify the improvement on the performance of optical communications systems regarding coherent detection [11,12]. Zuo investigated the bit error rate (BER) performance of FSOC links in weak non-Kolmogorov turbulence and showed that BER decreased sharply as more Zernike modes were corrected by AO. Considering the influence of both the amplitude fluctuation and spatial phase aberrations, the Zernike mode was accurate when the ratio of receiving aperture diameter D to the coherent length r0 (D/r0) was large enough [13,14]. Ming Li evaluated the performance of the coherent FSOC employing quadrature array phase-shift keying modulation over the maritime atmosphere with atmospheric turbulence compensated by AO system based-on SHWFS [15]. Chao Liu and Jian Huang analyzed the mixing efficiency (ME) and BER performance improvement of the coherent FSOC with AO system based-on SHWFS by numerical simulation and experimental data of a 1.8 m telescope with AO system based-on a 127-subaperture SHWFS, under different D/r0 [16–19]. However, SHWFS was so sensitive to laser scintillation that the performance was limited in coherent FSO system. The focal plane wavefront sensor solved this problem, it had higher power usage ratio, but it was much more time cost [20]. In 1996, the pyramid wavefront sensor (PWFS) was proposed by Ragazzoni [21], and it was high sensitive in closed-loop operation, good characteristics of variable gain, and adjustable sampling in real time [22]. The PWFS had higher sensitivity and flexibility of sampling over established SHWFS. However, PWFS is difficult to

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https://doi.org/10.1016/j.optlastec.2017.09.030
0030-3992/

manufacture and expensive, and the PWFS has not been used for FSO system. The reflective pyramid sensor is proposed by Wang utilizing a reflective pyramid mirror instead of a refractive pyramid prism [23]. Its working principle was identical to that of the PWFS. In addition, four charge-coupled devices and four relay lenses were required in a reflective pyramid sensor. Sequential operation of the micromirror array could instead of PWFS to measure wavefront aberrations, which was proposed in our previous work [24,25]. And it offered some advantages. First, comparing with the SHWFS, the spatial resolution was arbitrary adjustment and the sensitivity is higher than the SHWFS; Second, the SPWFS utilized the one-fourth pixels of detection element to realize the same wavefront resolution as PWFS, which meant higher uniformity of sensitivity and lower cost, especially for the avalanche photon diode (APD) array receiver of the coherent FSOC system. Third, the design of relay system could be more simplified than PWFS. Forth, SPWFS had weaker diffraction effect and smoother light intensity distribution. Thus, the goal of this paper is to evaluate the performance improvement of the coherent FSOC system with the AO system based-on SPWFS.

In this paper, the sequential operation approach of PWFS (SPWFS) which proposed in our previous work is first used in coherent FSOC to measure the wavefront aberrations. And the ME and the BER are analyzed to evaluate the performance of the coherent FSO communication. The numerical simulation is used to verify the feasible of the SPWFS for the coherent FSOC, and the experimental system of the SPWFS is designed to evaluate the improvement of the coherent FSOC performance with the SPWFS.

2. System model

The schematic diagram of coherent FSO system with AO to compensate atmospheric turbulence is shown in Fig. 1 [3]. As transmitting terminal, the laser beam is modulated into laser carrier signal and transmited through atmospheric channel. At the receiving terminal, the laser carrier frequency is mixed with a laser signal from local oscillation (LO signal) to generate the intermediate frequency signal. Then, according to the intermediate frequency signal, proper demodulator is used in order to be processed by digital signal processor. However, during the transmitting through the atmospheric channel, the laser carrier signal is distorted by atmospheric turbulence, and its wavefront and amplitude are disturbed. Accordingly, atmospheric compensation is indispensable in the coherent FSO system. In this paper, we introduce the AO unit in the coherent FSO system which consists of the wavefront corrector, the wavefront controller and the wavefront sensor. Firstly, the wavefront sensor measures the wavefront aberrations of the laser carrier signal. Secondly, according to the measured aberrations, wavefront controller controls the wavefront corrector. Finally, the wavefront corrector corrects the wavefront aberrations in real time. Thus, atmospheric turbulence is compensated and the quality of the received laser carrier signal is improved.

3. Theoretical analysis

3.1. The theory of SPWFS

The basic configuration of the PWFS is shown in Fig. 2. It consists of three fundamental parts: a tip-tilt mirror conjugated to the pupil is used to modulation, a square-based glass pyramid with its vertex at the nominal focal plane of the system and a relay lens that forms four images of the exit pupil on a detector plane. Where the role of modulation is to increase the linearity and dynamic range of the sensor [21].

Fig. 2 shows that the pupil re-imager is used to form images of the pupil relayed by the four facets of the pyramid on the detector. For each beam, it can be seen as being masked 3 quadrants on the focus plane. The signal is computed for each sub-aperture with the following formula (similar to a quad-cell signal):

$$S_x(x,y) = \frac{[I_1(x,y) + I_4(x,y)] - [I_2(x,y) + I_3(x,y)]}{I_1(x,y) + I_2(x,y) + I_3(x,y) + I_4(x,y)} \tag{1}$$

$$S_y(x,y) = \frac{[I_1(x,y) + I_2(x,y)] - [I_3(x,y) + I_4(x,y)]}{I_1(x,y) + I_2(x,y) + I_3(x,y) + I_4(x,y)} \tag{2}$$

where $I_n(x,y)$ is the image intensity of the position (x,y) of the nth quartile. In the case of a circular tip-tilt modulation having amplitude bigger than the local tilt of the aberrated wavefront $w(x,y)$, geometrical optics calculations show that [21]:

$$\frac{\partial_w(x,y)}{\partial x} \propto \sin\left[\frac{\pi}{2} S_x(x,y)\right] \tag{3}$$

$$\frac{\partial_w(x,y)}{\partial y} \propto \sin\left[\frac{\pi}{2} S_y(x,y)\right] \tag{4}$$

The Eq. (3) and the Eq. (4) show that the local tilt of wavefront is in proportion to the output signal of the PWFS when the wavefront aberrations are low enough.

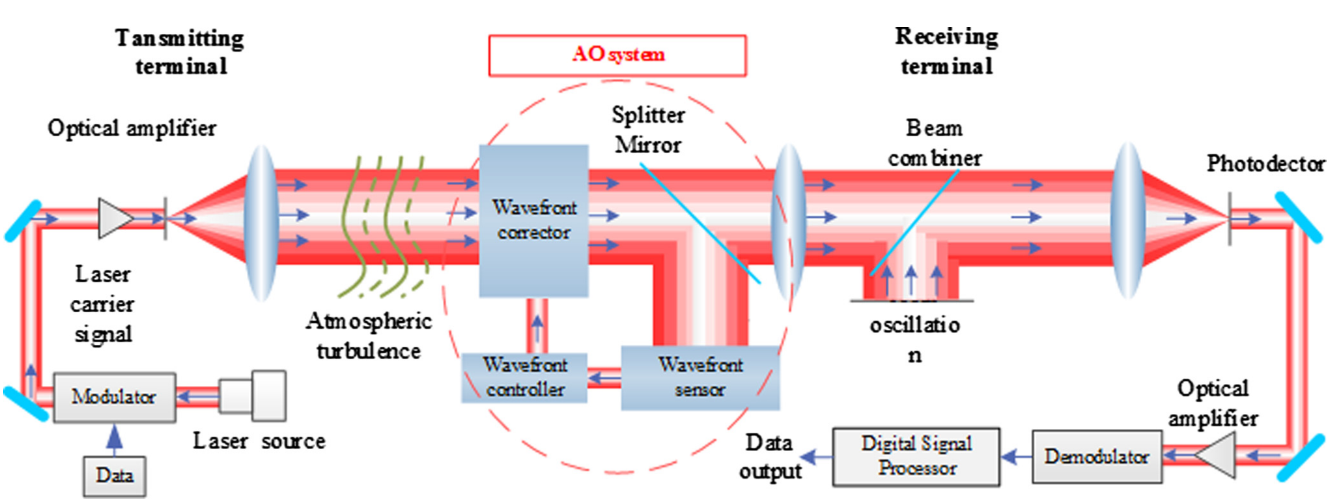

Fig. 1. The schematic diagram of FSO communication system.