Optics Communications 392 (2017) 258–262

Contents lists available at ScienceDirect

Optics Communications

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

Simulation method of spatial laser field for arbitrary distance optical transmission with carbon nanotube

Jianmin Wang*, Rumeng Bai, Ye Zhou, Guang Zhao

Institute of Quantum Electronics, Department of Electronics, Peking University, Beijing 100871, China

ARTICLE INFO

Keywords:
Free space optical communication
Optical transmission
Carbon
Nanotube

ABSTRACT

In this paper, an arbitrary distance optical transmission simulation method for free-space optical communication system is presented. Based on this method, direct point-to-point performance tests between two optical terminals can be realized in the laboratory, and the test results are equivalent to those on-orbit. A theoretical analysis of this method is presented in this paper. Verification experiments showed that there is a good linearity between the incoming power density and output photocurrent of the carbon nanotube (CNT); the relative power difference between the CNT and the charge-coupled device (CCD) camera is 4.75%, which can be ignored compared with the link redundancy.

1. Introduction

For a free-space optical (FSO) communication system, prelaunch ground tests on pointing, acquisition, tracking, and communications are necessary, all of which are influenced by the received optical power of the receiver on-orbit [1–4]. These kinds of technologies mentioned above are known as optical communication ground validation and detection technologies (GVDT). If point-to-point direct detection between two optical terminals, also known as a system-level test, is realized at a short distance and the results are equivalent to those on-orbit, this will undoubtedly be a very appealing method in GVDT. As the distance of FSO communication is very long, the receiver receives the far-field pattern (FFP) of the transmitter. In the process of ground validation and detection, directly placing the FSO terminals over the far-field distance of at least tens of kilometers will decrease the simulating accuracy. The reason for this is that the receiving wavefront is distorted by the atmosphere; hence, methods of optical transmission simulation at a short distance are required. In other words, by simulating an optical beam propagating within a channel at a relatively short distance, we can create a receiver that will receive optical signals of the same power as those received on-orbit during actual FSO communication. However, the on-orbit received power changes over time; this is due to mis-pointing of the transmitting beam, which is caused by factors such as satellite platform vibration, orbital errors, and mechanical pointing errors. Therefore, the simulation device should synchronously output signal in the pointing direction of the transmitting beam.

Several methods of optical transmission simulation have been developed. In the method used by the Semiconductor Inter Satellite Link Experiment (SILEX) of the European Space Agency (ESA), the FSO terminal antenna is removed so that far field conditions can be realized at a relatively short distance [2]. However, this is a partial instead of a whole-terminal test; hence, computer simulations are necessary to evaluate the on-orbit performance of the receiver. Another method, known as the compact range method, utilizes a long focal lens to transform the transmitted beam, obtaining the FFP spot in the focal plane. Then, a scaled sampling aperture is used to sample the focal plane spot, and the same optical signals as those received on-orbit are obtained. The simulated link distance of this method has a positive correlation with the focal length and a negative correlation with the sampling aperture size. Normal sampling apertures, such as a fiber and micropore, have areas that are generally several square micrometers, and the simulated link distance is hundreds of kilometers [5]. With the development of laser communication and deep-space exploration technology, the link distances have been improved; accordingly, methods for simulating longer distances are necessary. For example, lunar-earth FSO communication at a rate of 622 Mbps has been accomplished for a distance of 380,000 km [6], and a communication link between the Earth and Mars is planned. Finally, a recently proposed method utilizes several cascade magnifiers to magnify the FFP spot of the incident beam by 64,000-fold, and has a maximum simulated distance of 160,000 km [7]. However, this method introduces magnification errors, optical aberrations, and distortions, which affects the simulation accuracy.

In short, the simulated distance of all the optical transmission simulation methods at present is limited, and these methods are unable

---

* Corresponding author.
E-mail address: digitaltech@pku.edu.cn (J. Wang).

http://dx.doi.org/10.1016/j.optcom.2017.02.009
Received 26 September 2016; Received in revised form 2 February 2017; Accepted 4 February 2017

to meet the continually increasing distance required for FSO communication. They also cannot be adjusted flexibly according to actual needs. As no further report has yet been published on interrelated research achievements, we think that the exploration of a new simulation method is necessary.

In this paper, we propose and experimentally demonstrate an optical transmission simulation scheme applied to an arbitrary distance for FSO communication using a CNT as a wavefront sampling and power output control element. Contrary to the traditional optical-optical method, we adopted the optical-electrical-optical method, which allows to simulate transmission within any distance over a broad spectral range, making it more flexible and widely applicable. The typical receiving area of a CNT is four orders of magnitude smaller than that of a normal aperture; therefore, the simulation distance can be improved by two orders of magnitude; with subsequent signal attenuation, the optical transmission simulation of an arbitrary distance can be realized. In addition, CNTs have a relatively high infrared photoelectric conversion efficiency in a wide band, which can meet the demands of FSO communications (approximately 800–1600 nm), and exhibit a fast-light response up to the picosecond range [8,9].

2. Method and theoretical model

The FSO transmission ground-simulation system is presented in Fig. 1. In this figure, TL stands for transform lens, OTSS for optical transmission simulation system, EOM for electro-optic modulator, AS for aperture stop, RM for reflective mirror, BS for beam splitter, and CE for collimator and expander. The upper part of Fig. 1 shows the actual transmission of the laser beam on-orbit, where L represents the communication distance; the lower part is the ground simulation scheme of optical transmission, and the simulation results should reflect similar behaviors as those on-orbit. In the simulation system, the optical beam from the transmitter is firstly split into two sub-beams: one is for the input laser of the EOM and the other propagates through the transform lens and produces an FFP in the focal plane where the CNT is initially mounted in the direction of the maximum point of the FFP (mostly in the center of the FFP spot). This represents the pointing direction of the transmitted beam. There exists a pointing error in the ground tests, similar to that in the on-orbit situation, and the received power of the CNT is decreased accordingly. The CNT translates the received optical signals into proportional electrical signals. These electrical signals are amplified and used to drive an EOM for amplitude modulation. The light emitted from the EOM is collimated and expanded, and the wide beam – with its power is equal to that for the on-orbit situation received by the receiver – enters the receiver. Of course, a power calibration process is still required.

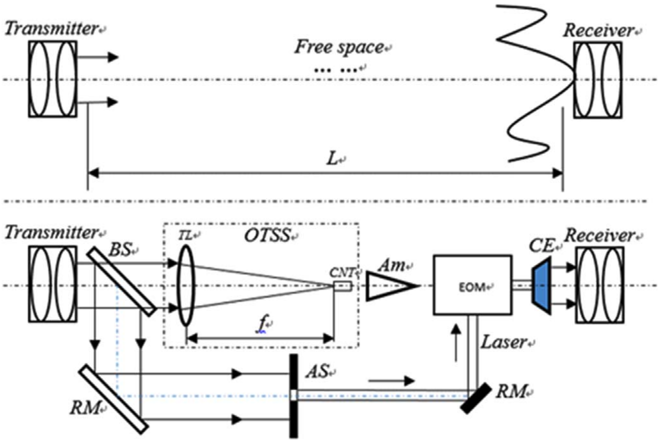

Fig. 1. Arbitrary -distance optical transmission simulation.

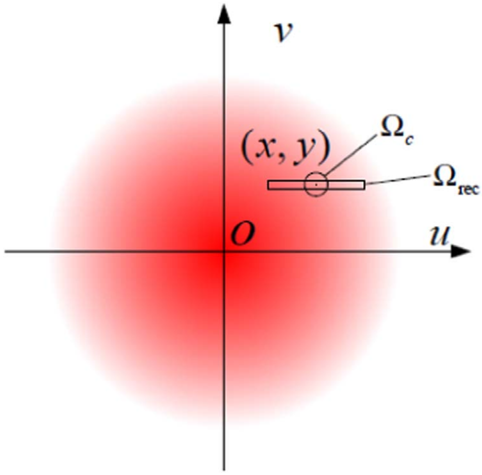

Fig. 2. Schematic of rectangular and circular apertures sampling the FFP spot.

According to the above description, we can see that the CNT just acts as a controller.

The theoretical analysis of the simulation method is elaborated below. In Fig. 1, although the sampling area of a CNT is rectangular, we can consider it as an equivalent circular shape with diameter d under the same photosensitive area conditions. The CNT's receiving optical power is Pc and that of an antenna on-orbit with diameter D is PR. The transform lens causes a spherical phase shift of the impinged beam and produces a L=f ratio compression of the on-orbit FFP in the focal plane [10]. When

$$\frac{d}{f}=\frac{D}{L}. \tag{1}$$

and ignoring the lens energy loss, the receiving powers, PR and Pc, are equal.

Eq. (1) requires that the sampling aperture is the proportional contraction of the receiving antenna, which has a circular shape, whereas the sampling area of a CNT is rectangular. To compare the received power difference between a rectangle and a circle, we assign u, v coordinates for the FFP spot in the focal plane, as shown in Fig. 2. A rectangle of length l and width b and a circle of diameter d sample the FFP spot at the same position, (x, y). Both shapes have identical areas, i.e., (area $S = lb = \pi d^2/4$). We define the power density distribution of the FFP as $I\,(u, v)$, which can be calculated from the Fresnel-Kirchhoff diffraction formula. However, this calculation is overly complex. As another approach, note that the laser beam of the FSO system is an approximately ideal Gaussian beam and its FFP is approximately Gaussian. Therefore, we can set

$$I\,(u,\,v)\propto\frac{8}{\pi d_{spot}^2}\exp\left(-\frac{8(u^2+v^2)}{d_{spot}^2}\right). \tag{2}$$

where d_{spot} is the spot diameter, measured when the power intensity decreases to $1/e^2$ times its value at the center. According to the compact range method, the spot diameter is $d_{spot} = f\,\theta,\ \theta\approx\lambda/D'$, where θ is the transmitted beam divergence angle, λ is working wavelength, and D' is the diameter of the transmitting antenna. Hence, the difference between the received powers is expressed as:

$$\begin{aligned}P_{\rm dif}\,(x,\,y) &= \left|\int_{\Omega_{rec}} I\,(u,\,v)dudv-\int_{\Omega_c} I\,(u,\,v)dudv\right|,\\ &\approx\left|b\int_{x-\frac{1}{2}}^{x+\frac{1}{2}} I\,(u,\,v)du-I\,(x,\,y)S\right|,\\ &\approx\left|b\int_{x-\frac{1}{2}}^{x+\frac{1}{2}} I\,(x,\,y)+\frac{\partial}{\partial x}I\,(x,\,y)(u-x)\right.\\ &\quad\left.+\frac{\partial^2}{\partial x^2}I\,(x,\,y)(u-x)^2du-I\,(x,\,y)S\right|,\end{aligned} \tag{3}$$