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High-dimensional free-space optical communications based on orbital angular momentum coding

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ABSTRACT

In this paper, we propose a high-dimensional free-space optical communication scheme using orbital angular momentum (OAM) coding. In the scheme, the transmitter encodes N-bits information by using a spatial light modulator to convert a Gaussian beam to a superposition mode of N OAM modes and a Gaussian mode; The receiver decodes the information through an OAM mode analyser which consists of a MZ interferometer with a rotating Dove prism, a photoelectric detector and a computer carrying out the fast Fourier transform. The scheme could realize a high-dimensional free-space optical communication, and decodes the information much fast and accurately. We have verified the feasibility of the scheme by exploiting 8 (4) OAM modes and a Gaussian mode to implement a 256-ary (16-ary) coding free-space optical communication to transmit a 256-gray-scale (16-gray-scale) picture. The results show that a zero bit error rate performance has been achieved.

1. Introduction

A free-space optical communication is a high data rate and secure communication technique which has been shown to be an attractive solution for the "last mile" problems to bridge the gap between the terminal user and the fiber optic infrastructure already in place [1]. Most of free-space optical communication systems rely on modulations of amplitude, phase, wavelength, time, and polarization of the light. An alternate way to encode the information is in the degree of freedom of orbital angular momentum (OAM) which corresponds to the helical spatial phase distribution of the photon [2]. Theoretically, there are infinite OAM modes, a single-photon can carry an OAM with arbitrary magnitude, and different OAM modes are mutually orthogonal. Hence, these outstanding properties make OAM modes to have been extensively studied to increase the channel capacity for both quantum [3–7] and classical [8–11] communications. Moreover, it is possible to use multiple OAM modes to realize high-dimensional coding for free-space optical communications. In 2004, Gibson et al. [12] demonstrated information transferring using OAM coding. In 2013, Jia et al. [13] reported a free-space communication scheme based on sidelobe-modulated OAM coding. In 2014, Krenn et al. [14] proposed high-dimensional communications using OAM superposition modes with the incoherent detection. In 2015, Du et al. [15] used Bessel beams carrying OAM to realize the high-dimensional coding for the free-space optical communications free of obstructions.

In this paper, we propose a high-dimensional free-space optical communication scheme using OAM coding. In the scheme, the transmitter encodes N-bits information by using a spatial light modulator (SLM) to convert a Gaussian beam to a superposition mode of N OAM modes and a Gaussian mode; The receiver decodes the information through an OAM mode analyser which consists of a MZ interferometer [16,17] with a rotating Dove prism, a photoelectric detector and a computer. The information could be decoded fast and accurately by only performing the fast Fourier transform (FFT) on the voltage signals sampling by the photoelectric detector.

The advantages of the proposed scheme are the following. Firstly, the proposed scheme could realize a 2^N-ary coding free-space optical communication by using a superposition mode of N OAM modes and a Gaussian mode, which greatly increases the channel capacity comparing with the existed schemes [12–15] where they could realize N-ary coding communications by using at least N OAM modes. Secondly, the scheme decodes the information more fast than that of the existed schemes [12–15] which capture the intensity patterns by cameras and then decode the information from the patterns by time consuming techniques, such as an digital imaging process and an artificial neuronal network [14].

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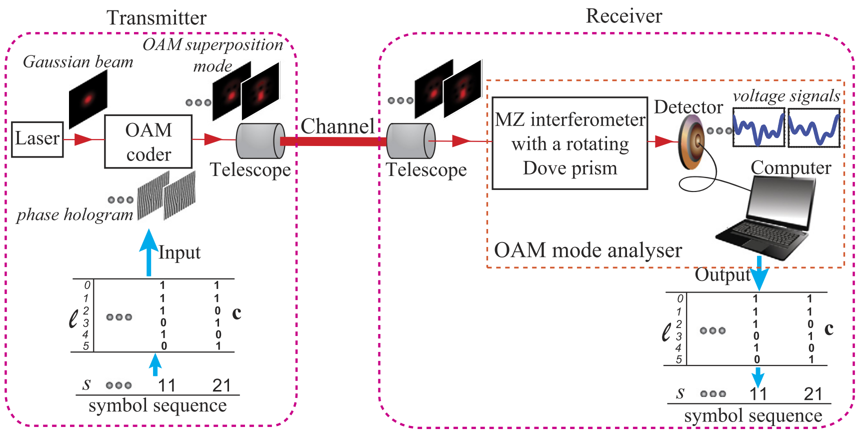

Fig. 1. (Color online) A schematic diagram of the high-dimensional free-space optical communication scheme based on OAM coding. MZ: Mach-Zhender.

The organization of the paper is as follows. In Section 2, the high-dimensional free-space optical communication scheme based on OAM coding is presented. In Section 3, the performance of the scheme is discussed. Finally, Section 4 concludes the paper.

2. High-dimensional free-space optical communications based on orbital angular momentum coding

Fig. 1 shows the schematic diagram of the high-dimensional free-space optical communication scheme based on OAM coding. At the transmitter side, an OAM coder uses a computer-controlled phase hologram displayed on the SLM to convert a Gaussian beam from a laser to an OAM superposition mode of N OAM modes and a Gaussian mode. Each phase hologram is produced by superposing N phase holograms with N different OAM modes $\ell_i, i = 1,2,\ldots,N$, each mode carrying an encoding bit $c_i, i = 1,2,\ldots,N$ and a Gaussian mode ($\ell = 0$ and $c_0 = 1$) together. The encoding bits $c_i, i = 0,1,2,\ldots,N$, which could construct a vector $\mathbf{c}$, depend on a symbol s to be sent (For example, when 5 OAM modes with $\ell = 1,2,3,4,5$ are used, $s = 21 \to \mathbf{c} = [c_0, c_1, c_2, c_3, c_4, c_5] = [1,1,0,1,0,1]$ and $s = 11 \to \mathbf{c} = [c_0, c_1, c_2, c_3, c_4, c_5] = [1,1,1,0,1,0]$). Then after expanded by a telescope, the OAM superposition mode propagates through a free-space channel. At the receiver side, the OAM superposition mode is captured by a telescope, and is decoded into a set of encoding bits $\mathbf{c}$ by using an OAM mode analyser which consists of a Mach–Zhender interferometer with a rotating Dove prism, a photoelectric detector and a computer. The interference intensity out of the Mach-Zhender interferometer varies with the rotations of the Dove prism. The Dove prism rotates a half of one circle during the period of a symbol. Then the varied intensities are collected by the photoelectric detector and converted to the voltage signals. At last the computer carries out the FFT to transform the voltage signals to a set of encoding bits $\mathbf{c}$ for OAM topological charges. The sets of encoding bits $\mathbf{c}$ could be mapped to a symbol sequence. (For example, $\mathbf{c} = [1,1,0,1,0,1] \to s = 21$ and $\mathbf{c} = [1,1,1,0,1,0] \to s = 11$.)

The OAM superposition mode of N OAM modes and a Gaussian mode is defined as

$$\Psi(r,\theta) = \sum_{i=0}^{N} c_i R_{\ell_i}(r) \exp(j\ell_i\theta), \tag{1}$$

where $R_{\ell_i}(r)$ and $\exp(j\ell_i\theta)$ denotes the amplitude and the spatial phase of the beam associated with ℓ_i, respectively. $R_{\ell_i}(r)$ could be different mode structures, such as Laguerre-Gaussian modes or Bessel beams. r and θ are the radial and azimuthal coordinates respectively, and ℓ_i is the OAM topological charge, which is a positive integer. The $i \neq 0$ terms of Eq. (1) represent the OAM modes, which are employed to encode N-bits information by setting the encoding bit $c_i, i = 1,2,\ldots,N$, which can be taken an integer index from the set $\{0,1\}$. Hence, we could realize a 2^N-ary coding communication, and the symbol s could be determined as

$$s = \sum_{i=1}^{N} c_i 2^{i-1}. \tag{2}$$

The $i = 0$ term of Eq. (1) represents a Gaussian mode (defining $c_0 = 1$, and $\ell_0 = 0$), which is used as a reference signal to monitor the states of link of the communication.

After $\Psi(r,\theta)$ travels z-distances of a free-space channel,

$$\Psi(r,\theta,z) = \sum_{i=0}^{N} c_i R_{\ell_i}(r,z) \exp(j(\ell_i\theta + \varphi_i(z))), \tag{3}$$

where $\varphi_i(z)$ is the phase caused by transmission.

On the receiver side, the OAM mode analyser is used to obtain a set of encoding bits $c_i, i = 1,2,\ldots,N$ for OAM topological charges $\ell_i, i = 1,2,\ldots,N$ from $\Psi(r,\theta,z)$. At first, the interferogram of $\Psi(r,\theta,z)$ from the Mach-Zhender interferometer with a rotating Dove prism is

$$\begin{aligned}\Psi(r,\theta,z) \to\ & \frac{1}{2}\Bigg[\sum_{i=0}^{N} c_i R_{\ell_i}(r,z)\exp(j(\ell_i\theta + \varphi_i(z))) \\ &+ \sum_{i=0}^{N} c_i R_{\ell_i}(r,z)\exp(j(\ell_i(\theta + 2\alpha) + \varphi_i(z)))\Bigg] \\ =\ & \frac{1}{2}\sum_{i=0}^{N} c_i R_{\ell_i}(r,z)\exp(j(\ell_i\theta + \varphi_i(z)))\left[1 + \exp(j2\ell_i\alpha)\right]\end{aligned} \tag{4}$$

where α is the rotating angle of the Dove prism. The Dove prism rotates a half of one circle during the period of a symbol, so $0 \le \alpha < \pi$. Then the intensity of the interferogram is collected by the photoelectric detector and converted to the electrical voltage signal I,

$$\begin{aligned} I\ =\ & \eta\int_0^{D/2} rdr \int_0^{2\pi} d\theta \Bigg|\frac{1}{2}\sum_{i=0}^{N} c_i R_{\ell_i}(r,z)\exp(j(\ell_i\theta + \varphi_i(z))) \\ & \left[1 + \exp(j2\ell_i\alpha)\right]\Bigg|^2 \\ =\ & \frac{\eta}{4}\int_0^{D/2} rdr \int_0^{2\pi} d\theta \Bigg[\sum_{i=0}^{N} c_i R_{\ell_i}(r,z)\exp(j(\ell_i\theta + \varphi_i(z))) \\ & \left[1 + \exp(j2\ell_i\alpha)\right]\Bigg] \\ & \Bigg[\sum_{i'=0}^{N} c_{i'} R_{\ell_{i'}}(r,z)\exp(-j(\ell_{i'}\theta + \varphi_{i'}(z)))\left[1 + \exp(-j2\ell_{i'}\alpha)\right]\Bigg] \\ =\ & \frac{\eta}{4}\int_0^{D/2} rdr \int_0^{2\pi} d\theta \Bigg[\sum_{i=0}^{N} c_i^2 R_{\ell_i}^2(r,z)\left[1 + \exp(j2\ell_i\alpha)\right] \\ & \left[1 + \exp(-j2\ell_i\alpha)\right]\end{aligned}$$