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Coherent receiving efficiency in satellite-ground coherent laser communication system based on analysis of polarization

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ABSTRACT

Aimed at analyzing the coherent receiving efficiency of a satellite-ground coherent laser communication system, polarization state of the received light is analyzed. We choose the circularly polarized, partially coherent laser as transmitted light source. The analysis process includes 3 parts. Firstly, an theoretical model to analyze received light's polarization state is constructed based on Gaussian-Schell model (GSM) and cross spectral density function matrix. Then, analytic formulas to calculate coherent receiving efficiency are derived in which both initial ellipticity modification and deflection angle between polarization axes of the received light and the intrinsic light are considered. At last, numerical simulations are operated based on our study. The research findings investigate variations of polarization state and obtain analytic formulas to calculate the coherent receiving efficiency. Our study has theoretical guiding significances in construction and optimization of satellite-ground coherent laser communication system.

1. Introduction

In the domain of satellite-ground communication system, the traditional system of intensity modulation/directly detection (IM/DD) is developing slowly owning to the power loss caused by atmospheric attenuation [1]. At the same time, the coherent laser communication system could make the detection threshold lower by set an intrinsic light to carry on coherent receiving, thus raise the practicability of laser communication propagating though the atmosphere [2,3].

The coherent laser communication technology has been used widely in the optical fiber communication system. The difficulties will be unavoidable when used in free space especially in the atmosphere environment [4–7].

Firstly, although the coherent laser communication system has a low detection threshold, it unavoidably has great power loss when propagating through atmosphere because of the beam broadening and intensity scintillation effect. To solve this problem, the partially coherent light has been analyzed to apply in laser communication system, and the existing research shows that the partially coherent laser has lower attenuation compared with the completely coherent light when propagating in atmosphere [8,9]. Recently, Wu et al. had investigated the effects of coherence and polarization on beam spreading and directionality in atmospheric turbulence [10,11]. More recently, Avramov-Zamurovic et al. took an experiment to analyze the scintillation index in the case of propagating Bessel-Gaussian Schell Model (BGSM) electromagnetic beams in weak atmospheric turbulence, and verified the demonstration of scintillation index reduction by up to 50% when scalar spatially pseudo-partially coherent beams were compared to electromagnetic beams with uncorrelated field components [4].

In a satellite-ground coherent laser communication system (Fig. 1), take heterodyne detection for example, there are several requirements to be met, in which the polarization state is required to be same between the received light and the intrinsic light [12,13]. However, the light beam's polarization state is greatly related with its initial coherent parameters and will be influenced and changed in the propagation process [14,15], thus will cause lose in coherent receiving efficiency in a communication system.

As stated before, coherent receiving efficiency from the aspect of polarization is particularly worthy of academic investigation. We will analyze the polarization state of received light and construct an analytic model of coherent receiving efficiency of satellite-ground coherent laser communication system in our study.

2. Analysis of polarization state

The partially coherent light beam has advantages for its good performance in coping with beam broadening and light scintillation in atmospheric turbulence, but it also has backwards in a coherent laser

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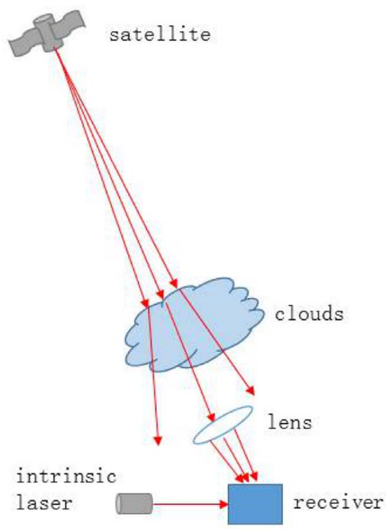

Fig. 1. A simplified satellite-ground coherent laser communication system.

communication system for the reason that coherent receiving efficiency is greatly affected by received light's polarization state. To estimate the coherent receiving efficiency caused by the difference of polarization state between received light and intrinsic light, our study will firstly analyze the polarization change model in propagation, and our model is based on partially coherent Gaussian Schell-model (GSM) beams [8].

A coherent laser communication system requires that the received light and intrinsic light should have the same polarization state. However, because of the relative motion between satellite transmitter and ground receiver, there will be a real-time rotation of polarization axis between received light and intrinsic light [16–19]. Even if an adaptive polarization control system is used in receiving process, the receiver still couldn't get a high receiving efficiency. As previously reported, the utilization of circularly polarized light beam could effectively avoid the above problem [20]. So, it is selected as the polarization mold in our study. For a circularly polarized GSM beam, its polarization state can be characterized by a normalized Stokes vector as [20]:

$$\boldsymbol{S} = [S_0 \quad S_1 \quad S_2 \quad S_3]^{\mathrm{T}} = [1 \quad 0 \quad 0 \quad 1]^{\mathrm{T}} \tag{1}$$

A rectangular coordinate system (Fig. 2) is built to depict position and direction of vectors in the wave surface along light's propagation path. Assuming that the transmitted light beam is monochromatic, the cross spectral density function matrix $\mathbf{W}(\mathbf{r}, \mathbf{r}, 0, \omega_0)$ of any vector in the source plane(z=0) will have the following relationship with beam's initial stokes vectors [5]:

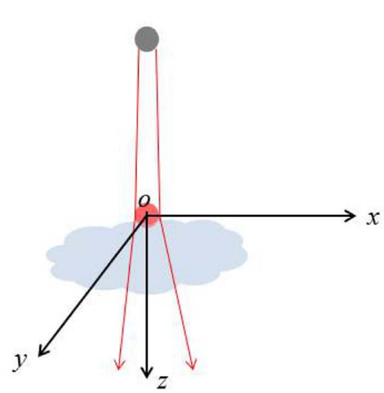

Fig. 2. Rectangular coordinate system of transmitted light beam.

$$\boldsymbol{W}(\mathrm{r}, \boldsymbol{r}, 0, \omega_0) = \begin{bmatrix} W_{xx}(\mathrm{r}, \boldsymbol{r}, 0, \omega_0) & W_{xy}(\mathrm{r}, \boldsymbol{r}, 0, \omega_0) \\ W_{yx}(\mathrm{r}, \boldsymbol{r}, 0, \omega_0) & W_{yy}(\mathrm{r}, \boldsymbol{r}, 0, \omega_0) \end{bmatrix} \tag{2}$$

$$\begin{cases} S_0 = W_{xx}(\mathrm{r}, \boldsymbol{r}, 0, \omega_0) + W_{yy}(\boldsymbol{r}, \boldsymbol{r}, 0, \omega_0) \\ S_1 = W_{xx}(\mathrm{r}, \boldsymbol{r}, 0, \omega_0) - W_{yy}(\boldsymbol{r}, \boldsymbol{r}, 0, \omega_0) \\ S_2 = W_{xy}(\mathrm{r}, \boldsymbol{r}, 0, \omega_0) + W_{yx}(\boldsymbol{r}, \boldsymbol{r}, 0, \omega_0) \\ S_3 = i(W_{yx}(\mathrm{r}, \boldsymbol{r}, 0, \omega_0) - W_{xy}(\boldsymbol{r}, \boldsymbol{r}, 0, \omega_0)) \end{cases} \tag{3}$$

In the above equation, "i" denotes the sign of imaginary part. By comprehensively analyzing Eqs. (1)–(3), the cross spectral density function matrix of any vector in the source plane(z=0) is written as:

$$\boldsymbol{W}(\mathrm{r}, \boldsymbol{r}, 0, \omega_0) = \begin{bmatrix} 1/2 & i/2 \\ -i/2 & 1/2 \end{bmatrix} \tag{4}$$

When beam's spatial coherence only considered and time coherence ignored, the cross spectral density function component of a partially coherent GSM light beam is expressed as [8]:

$$W_{ab}(\boldsymbol{r}_1, \boldsymbol{r}_2, z, \omega_0) = \left(\frac{\omega_0}{2\pi cz}\right)^2 \cdot \iint W_{ab}(\boldsymbol{r}_1, \boldsymbol{r}_2, 0)\exp\{\frac{i}{2cz}\omega_0[(\boldsymbol{r}_2 - \boldsymbol{\rho}_2)^2 - (\boldsymbol{r}_1 - \boldsymbol{\rho}_1)^2]\} \cdot K_2(\boldsymbol{r}_1, \boldsymbol{r}_2, \boldsymbol{\rho}_1, \boldsymbol{\rho}_2, z, \omega_0)d\boldsymbol{\rho}_1 d\boldsymbol{\rho}_2 \tag{5}$$

In the above equation, a and b denote components of x and y axis, ω_0 denotes the initial angular frequency of the light beam and c denotes the speed of light. $K_2(\mathbf{r}_1, \mathbf{r}_2, \boldsymbol{\rho}_1, \boldsymbol{\rho}_2, z, \omega_0)$ denotes the random phase fluctuation caused by atmospheric turbulence. Under the condition of monochromaticity, it would be written as:

$$K_2(\boldsymbol{r}_1, \boldsymbol{r}_2, \boldsymbol{\rho}_1, \boldsymbol{\rho}_2, z, \omega_0) = \exp\left[\frac{(\boldsymbol{r}_1 - \boldsymbol{r}_2)^2 + (\boldsymbol{r}_1 - \boldsymbol{r}_2)(\boldsymbol{\rho}_1 - \boldsymbol{\rho}_2)^{\mathrm{T}} + (\boldsymbol{\rho}_1 - \boldsymbol{\rho}_2)^2}{\rho_0^2}\right] \tag{6}$$

In Eq. (6), $\rho_0 = (0.55\widetilde{C_n^2}k_c^2 z)^{-3/5}$ denotes the spatial coherence radius of a light beam propagating in atmospheric turbulence. $k_c = 2\pi/\lambda$ denotes the wavenumber. l_0 denotes the inner scale of turbulence. $\widetilde{C_n^2}$ denotes the mean refractive index structure function on the light beam propagation path and it can be calculated as:

$$\widetilde{C_n^2} = (1/H)\int_0^H C_n^2(h)dh \tag{7}$$

According to the ITU-R P.1621 recommended atmospheric refractive index structure constant model, the level of atmospheric turbulence can be described [8]:

$$C_n^2(h) = 8.148 \times 10^{-56}v_{rms}^2 h^{10}e^{-h/1000} + 2.7 \times 10^{-16}e^{-h/1500} + C_0 e^{-h/100} \tag{8}$$

where h is the height above the ground, v_{rms} is the wind speed on vertical path and is often approximate to 21 m/s. C_0 is the refractive-index structure constant near the ground. Assuming that the light beam's initial spatial coherence length matrix is $\boldsymbol{\sigma} = \begin{bmatrix} \sigma_{xx} & \sigma_{xy} \\ \sigma_{yx} & \sigma_{yy} \end{bmatrix}$, then there is

$$W_{ab}(\boldsymbol{r}_1, \boldsymbol{r}_2, 0, \omega_0) = W_{ab}(\boldsymbol{r}_1, \boldsymbol{r}_1, 0, \omega_0)\cdot\exp\left[-\frac{(\boldsymbol{r}_1 - \boldsymbol{r}_2)^2}{2\sigma_{ab}{}^2}\right], (a, b = x, y) \tag{9}$$

However, in the practical application of satellite-ground coherent laser communication system, especially for laser transmitter on satellite, it is difficult to make the transmitted light beam always circularly polarized [14]. To be close to the practical application, a modification of $\triangle\varepsilon$ to the ellipticity of transmitted light is considered in the light beam model we built. The modified light beam's polarization state on the source plane is then written as:

$$\boldsymbol{S}' = [S_0' \quad S_1' \quad S_2' \quad S_3']^{\mathrm{T}} = [1 \quad \Delta\varepsilon \quad -\Delta\varepsilon \quad \sqrt{1 - 2\Delta\varepsilon^2}]^{\mathrm{T}} \tag{10}$$

Based on the relationship between stokes vector and cross spectral density function matrix in Eq. (3), the modified cross spectral density function matrix $\mathbf{W}'(\mathbf{r}, \mathbf{r}, 0, \omega_0)$ is calculated as: