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Novel Modulation Scheme of 6-PolSK for Atmospheric Laser Communication

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Abstract A modulation scheme of 6-PolSK for atmospheric laser communication is proposed. Theoretical analysis result demonstrates that the states of polarization (SOPs) and degree of polarization (DOP) of light wave can be well maintained after long distance propagation in the atmospheric channel with different turbulence models. Simulation results show that the transmission performance and the bandwidth efficiency are improved considerably. 6-PolSK modulation is an attractive approach to meet the criteria about data rate and bandwidth efficiency of the atmospheric laser communication system.

Key words optical communications; free-space optical communication; polarization; modulation; polarization shift-keying

OCIS codes 060.4510; 060.2605; 260.5430; 060.4080

新型的用于大气激光通信的 6 偏振键控调制方式

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摘要 提出了一种新型的用于大气激光通信的 6 偏振键控调制方式，理论分析和仿真结果表明，光信号的偏振态和偏振度在不同大气信道模型中经过长距离传输后保持不变，因此在大气激光通信中可以采用偏振键控的调制方式。多级调制方式可以提高系统频谱效率，利用光信号的 6 种偏振态来传输信息将大大提高系统的带宽效率，6 偏振键控调制是适合大气激光通信系统传输速率和带宽效率的一种具有吸引力的调制方式。

关键词 光通信；自由空间光通信；偏振；调制；偏振键控调制

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1 Introduction

Over the past few years, atmospheric laser communication technology has attracted more and more attention. With potential high bit rate capacity, excellent security, fast link installation and particularly wide bandwidth on an unregulated spectrum, atmospheric laser communication has been considered as a solution to the last mile problem[1-2]. In atmospheric laser communication systems, the optical signal transmits directly through the air, so the received signal is inevitably affected by atmospheric turbulence and experiences random amplitude and phase fluctuations, i.e., signal fading, also known as scintillation. Scintillation seriously degrades the system performance. To improve the performance of atmospheric laser communication system, many schemes have been proposed[3-5], such as coherent communication systems, adaptive optical technology, time or spatial diversity, etc. However, the system complexity or cost is increased dramatically in these schemes.

In this paper, a novel modulation scheme which uses the vector characteristics of the light wave and codes digital bits as different states of polarization (SOPs) is proposed. Theoretical analysis and simulation results show that the SOPs and the degree of polarization (DOP) can be well maintained after long distance propagation in the atmospheric channel with different turbulence models. Multilevel modulation schemes are attractive as they allow for reductions in the bandwidths of the electronic transmitter and receiver circuitry for a

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作者简介: 袁学光(1981—)，男，博士，讲师，主要从事光通信系统方面的研究。E-mail: yuanxg@bupt.edu.cn given information rate. Consequently, 6-PolSK (polarization shift keying) modulation is an attractive approach to improve the reliability of the atmospheric laser communication system.

2 Modulation principle and analysis

Polarization state of light wave can be conveniently described using Stokes parameters. But only three of the four Stokes parameters are independent. Using the three degrees of freedom provided by the state of polarization, 6-PolSK modulation can be achieved. Six SOPs of horizontal linearity polarization (HLP), vertical linearity polarization (VLP), 45° linearity polarization (45°LP), −45° linearity polarization (−45°LP), right circle polarization (RCP) and left circle polarization (LCP) are selected and the information is encoded and transferred in 6-PolSK modulation system. In Fig.1, the change of SOP on the Poincare sphere is shown. The six points are located respectively in the two ends of the $\bar{s}_1$-axis, $\bar{s}_2$-axis and $\bar{s}_3$-axis in 6-PolSK system.

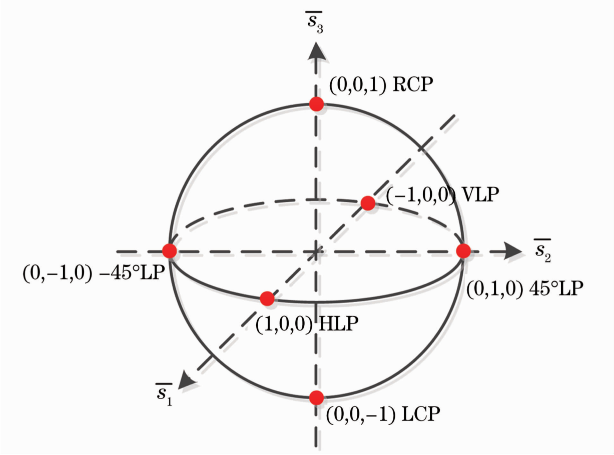

Fig.1 6-PolSK modulation signal expression on the Poincare sphere

Assuming the light wave from the laser as Gaussian-Schell model (GSM) beam, the coherence and polarization properties of this GSM beam can be characterized by the 2 × 2 cross-spectral density matrix (CSDM)[6] as

$$\boldsymbol{W}(\boldsymbol{r}_1,\boldsymbol{r}_2,z,\omega) \equiv \begin{bmatrix} W_{xx}(\boldsymbol{r}_1,\boldsymbol{r}_2,z,\omega) & W_{xy}(\boldsymbol{r}_1,\boldsymbol{r}_2,z,\omega) \\ W_{yx}(\boldsymbol{r}_1,\boldsymbol{r}_2,z,\omega) & W_{yy}(\boldsymbol{r}_1,\boldsymbol{r}_2,z,\omega) \end{bmatrix}, \tag{1}$$

$$W_{ij}(\boldsymbol{r}_1,\boldsymbol{r}_2,z,\omega) = \langle E_i^*(\boldsymbol{r}_1,z,\omega)E_j(\boldsymbol{r}_2,z,\omega)\rangle, \quad i=x,y,\ j=x,y, \tag{2}$$

where W is the cross-spectral density matrix, z is the propagation distance, ω is the angular frequency, E is intensity of electric field, $*$ denotes the complex conjugate and the angular brackets mean the ensemble average, $\boldsymbol{r}_1$ and $\boldsymbol{r}_2$ are two position vectors in the plane perpendicular to the propagation direction, x and y are two mutually orthogonal directions perpendicular to the beam axis.

The CSDM in the source plane $z=0$ has the following elements[7]:

$$W_{ij}(\boldsymbol{r}_1,\boldsymbol{r}_2,z=0,\omega) = A_iA_jB_{ij} \times \exp\left[-\left(\frac{\boldsymbol{r}_1^2}{4\sigma_i^2}+\frac{\boldsymbol{r}_2^2}{4\sigma_j^2}\right)\right] \times \exp\left[-\frac{(\boldsymbol{r}_2-\boldsymbol{r}_1)^2}{2\delta_{ij}^2}\right], \quad i=x,y,\ j=x,y \tag{3}$$

where, A_i, A_j are the electric field amplitudes of the two mutually orthogonal directions, B_{ij} is the correlation factor of the two electric fields, σ_i, σ_j are the half widths of the light beam waist respectively, δ_{ij} is the spectrum correlation line width. The parameters $A_i, A_j, B_{ij}, \sigma_i, \sigma_j, \delta_{ij}$ are independent of position, but they depend on the frequency ω. They satisfy the expressions $B_{ij}=1$, when $i=j$, $|B_{ij}| \leqslant 1$, when $i \neq j$, $B_{ij}=B_{ji}^*$ and $\delta_{ij}=\delta_{ji}$.

It's assumed as axial symmetry GSM beam. Assuming $\sigma_x=\sigma_y=\sigma$ and $\delta_{xx}=\delta_{yy}$, when $\boldsymbol{r}_1$ coincides with $\boldsymbol{r}_2$, the normalized Stokes parameters and the DOP (D_{OP}) in the source plane can be expressed as

$$\bar{s}_1(\boldsymbol{r},z=0,\omega) = \frac{A_x^2-A_y^2}{A_x^2+A_y^2}, \quad \bar{s}_2(\boldsymbol{r},z=0,\omega) = \frac{2A_xA_y\mathrm{Re}(B_{xy})}{A_x^2+A_y^2}, \quad \bar{s}_3(\boldsymbol{r},z=0,\omega) = \frac{2A_xA_y\mathrm{Im}(B_{xy})}{A_x^2+A_y^2},$$

$$D_{\mathrm{OP}}(\boldsymbol{r},z=0,\omega) = \sqrt{\frac{(A_x^2-A_y^2)^2+4\,|B_{xy}|^2A_x^2A_y^2}{(A_x^2+A_y^2)^2}}, \tag{4}$$

where Re and Im denote the real and the imaginary parts, respectively.

Based on generalized Huygens-Fresnel diffraction integral formula, after the propagation in the turbulent atmosphere, when $\boldsymbol{r}_1$ coincides with $\boldsymbol{r}_2$, the elements of CSDM in plane $z=c>0$ (c is a constant) are given as

$$W_{ij}(\boldsymbol{r},\boldsymbol{r},z,\omega) = \frac{A_iA_jB_{ij}}{\Delta_{ij}^2(z)} \times \exp\left[-\frac{\boldsymbol{r}^2}{2\sigma^2\Delta_{ij}^2(z)}\right], \tag{5}$$

where

$$\frac{1}{\Omega_{ij}^2} = \frac{1}{4\sigma^2}+\frac{1}{\delta_{ij}^2}, \quad \Delta_{ij}^2(z) = 1+\left(\frac{z}{k\sigma\Omega_{ij}}\right)^2+\frac{2Mz^2}{k^2\sigma^2}, \tag{6}$$

$k=2\pi/\lambda$ is the wave number of the light beam, M is the model of the spectrum of atmospheric fluctuations. There are two models[8], one is Tatarskii model

$$M = 0.5465C_n^2 l_0^{-1/3} k^2 z, \tag{7}$$

and another is Kolmogorov model[9] as

$$M = 0.49(C_n^2)^{6/5} k^{12/5} z^{6/5}, \tag{8}$$

where, C_n^2 is the refractive index structure parameter and l_0 is the inner scale of turbulence.

Substituting the parameters of the GSM beam into Eq. (5) and it's obtained that the SOP and the DOP in the receiver plane are

$$\begin{aligned}
\bar{s}_1(\boldsymbol{r},z,\omega) &= \frac{A_x^2 - A_y^2}{A_x^2 + A_y^2}\\
\bar{s}_2(\boldsymbol{r},z,\omega) &= \frac{2A_xA_y\mathrm{Re}(B_{xy})}{A_x^2 + A_y^2}\frac{\Delta_{xx}^2}{\Delta_{xy}^2}\exp\left[\frac{r^2}{2\sigma^2}\left(\frac{1}{\Delta_{xx}^2}-\frac{1}{\Delta_{xy}^2}\right)\right],\\
\bar{s}_3(\boldsymbol{r},z,\omega) &= \frac{2A_xA_y\mathrm{Im}(B_{xy})}{A_x^2 + A_y^2}\frac{\Delta_{xx}^2}{\Delta_{xy}^2}\exp\left[\frac{r^2}{2\sigma^2}\left(\frac{1}{\Delta_{xx}^2}-\frac{1}{\Delta_{xy}^2}\right)\right],\\
D_{\mathrm{OP}}(\boldsymbol{r},z,\omega) &= \sqrt{\left\{(A_x^2 - A_y^2)^2 + 4\mid B_{xy}\mid^2 A_x^2A_y^2\frac{\Delta_{xx}^4}{\Delta_{xy}^4}\exp\left[\frac{r^2}{\sigma^2}\frac{1}{\Delta_{xx}^2}-\frac{1}{\Delta_{xy}^2}\right]\right\}\Big/(A_x^2 + A_y^2)^2}.
\end{aligned} \quad (9)$$

There are six SOPs for 6-PolSK modulation. The change of every SOP after propagation in atmospheric turbulence can be investigated respectively. For the SOP of HLP or VLP, it should satisfy the expressions: $A_x = 0$ or $A_y = 0$. The SOP and the DOP can be simplified as

$$\begin{aligned}
&\bar{s}_1(\boldsymbol{r},z,\omega) = 1 \text{ or } \bar{s}_1(\boldsymbol{r},z,\omega) = -1,\\
&\bar{s}_2(\boldsymbol{r},z,\omega) = 0,\\
&\bar{s}_3(\boldsymbol{r},z,\omega) = 0,\\
&D_{\mathrm{OP}}(\boldsymbol{r},z,\omega) = 1.
\end{aligned} \quad (10)$$

It is obtained that the SOP and the DOP of the completely polarized GSM beam remain unchanged upon propagation in a turbulent atmosphere.

For the SOP of 45°LP or −45°LP, it should satisfy $A_x = A_y$. The SOP and the DOP can be simplified as

$$\begin{aligned}
&\bar{s}_1(\boldsymbol{r},z,\omega) = 0,\\
&\bar{s}_2(\boldsymbol{r},z,\omega) = \mathrm{Re}(B_{xy})\frac{\Delta_{xx}^2}{\Delta_{xy}^2}\exp\left[\frac{r^2}{2\sigma^2}\left(\frac{1}{\Delta_{xx}^2}-\frac{1}{\Delta_{xy}^2}\right)\right],\\
&\bar{s}_3(\boldsymbol{r},z,\omega) = 0,\\
&D_{\mathrm{OP}}(\boldsymbol{r},z,\omega) = \mid B_{xy}\mid\frac{\Delta_{xx}^2}{\Delta_{xy}^2}\exp\left[\frac{\boldsymbol{r}^2}{2\sigma^2}\left(\frac{1}{\Delta_{xx}^2}-\frac{1}{\Delta_{xy}^2}\right)\right].
\end{aligned} \quad (11)$$

For a completely polarized GSM source, the DOP in the source plane $D_{\mathrm{OP}}(\boldsymbol{r}, z = 0, \omega) = 1$. The equation $|B_{xy}| = 1$ is derived. But the DOP of a practical laser beam is always slightly less than 1. Considering the realizable conditions of the GSM beam[4]

$$\max\{\delta_{xx},\delta_{yy}\} \leqslant \delta_{xy} \leqslant \min\left\{\frac{\delta_{xx}}{\sqrt{|B_{xy}|}},\frac{\delta_{yy}}{\sqrt{|B_{xy}|}}\right\}. \quad (12)$$

when $\delta_{xx} = \delta_{yy} = \delta_{xy}$, it is obtained that the SOP and the DOP of the completely polarized GSM beam remain unchanged upon propagation in an atmosphere turbulence.

When $\delta_{xx} = \delta_{yy} < \delta_{xy}$, the propagation features of SOP and DOP are calculated and the results are shown in Fig. 2 and Fig. 3. The parameters of the GSM source are $\lambda = 1550$ nm, $\delta_{xx} = \delta_{yy} = 0.2$ mm, $\delta_{xy} = 0.2005$ mm, $A_x = A_y = 1$, $\sigma = 5$ cm, $B_{xy} = \pm 0.99$. The characterizing parameters of the atmosphere turbulence are chosen to be $C_n^2 = 10^{-13}$ m$^{2/3}$, $l_0 = 5$ mm[10]. It is obtained that the SOP and DOP decrease quickly along the propagation distance at the first. After more than approximate 50 m propagation in atmospheric turbulence, the SOP and DOP gradually increase along the propagation distance, and it reaches a relatively stable value within 1 km. The operating distances of most atmospheric laser communication systems in use are more than 1 km. At this distance, the SOP and DOP remain similar to its initial value.

For the SOP of LCP and RCP, the similar conclusion can be got. The SOP and DOP remain a relatively stable value upon propagation in a turbulent atmosphere. This is beneficial to polarization modulation systems. The six polarization states of optical signal will be hardly changed after propagation in atmosphere turbulence channel, so 6-PolSK modulation is ideally suited for atmospheric laser communication system.

3 Simulation and results

Figure 4 presents the employed architecture of atmospheric laser communication system with 6-PolSK

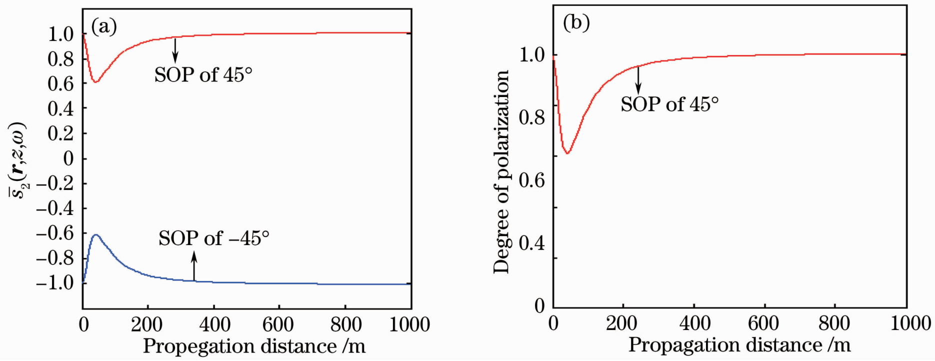

Fig. 2 Propagation features of SOP and DOP with Tatarskii model

modulation. A laser with the wavelength of 1550 nm is followed by a polarization beam splitter (PBS). Linearly polarized lights of two mutually orthogonal directions are modulated by Mach-Zehnder modulators (MZMs). The polarized lights amplitudes of two mutually orthogonal directions are modulated. Then a branch of the polarized lights is modulated by a phase modulator (PM), and various phase difference between x direction and y direction is generated. Six SOPs are generated after a polarization beam combiner (PBC).

The generating process of six SOPs is shown in Fig. 5. The input data are precoded by the serial to parallel conversion. The amplitudes and phases of the two mutually orthogonal lights are modulated by MZMs and PM. Six SOPs are generated.

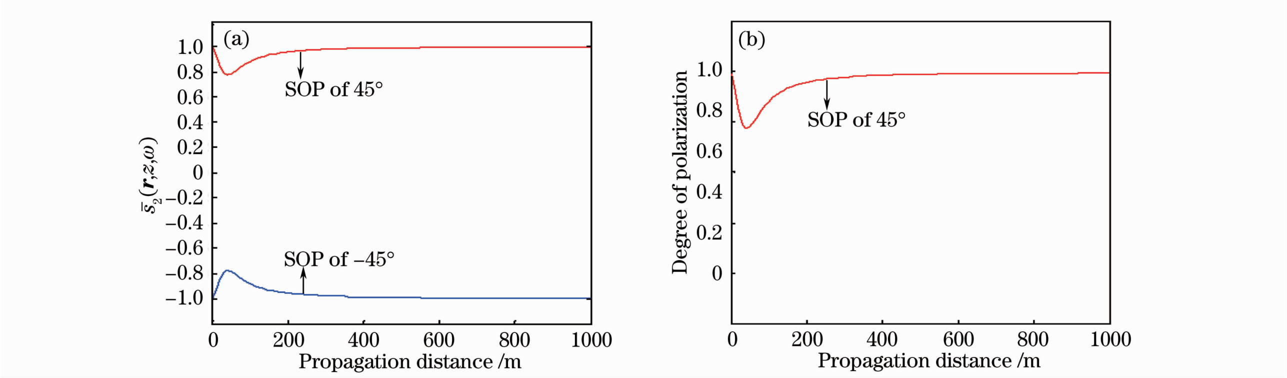

Fig. 3 Propagation features of SOP and DOP with Kolmogorov model

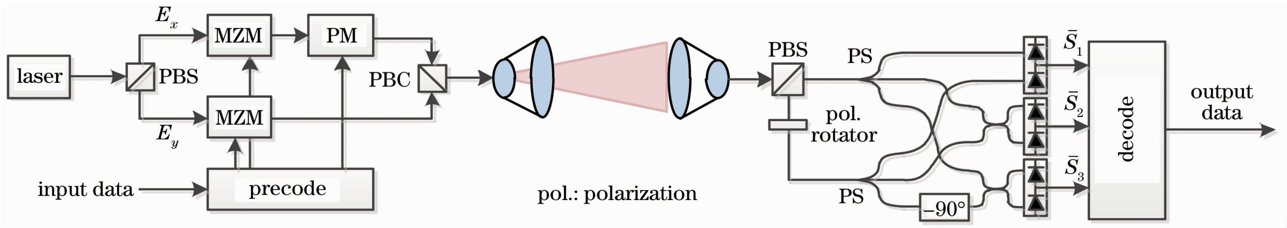

Fig. 4 Architecture of atmospheric laser communication system with 6-PolSK modulation

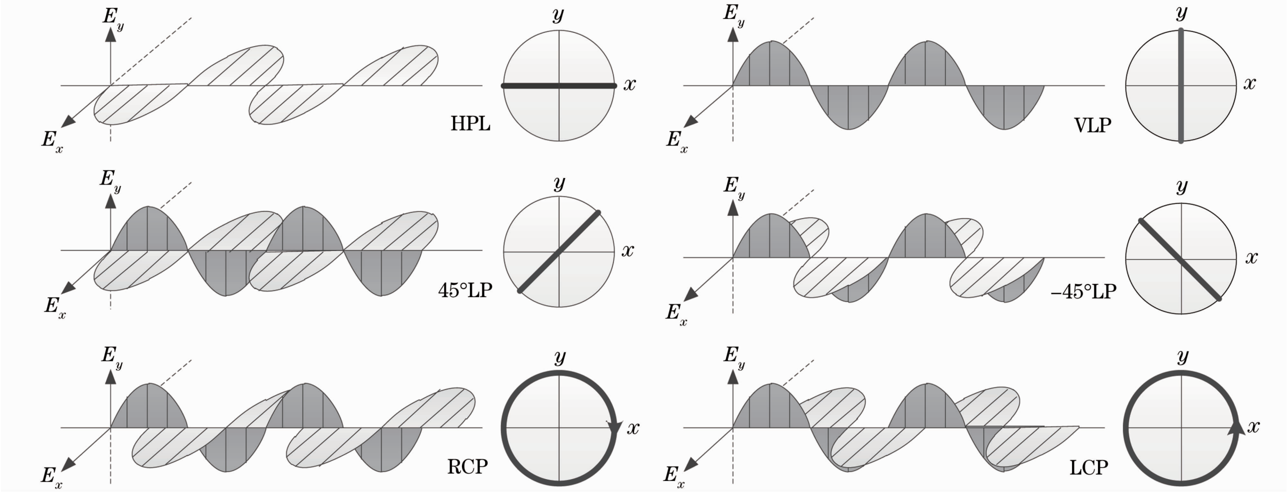

Fig. 5 Generating process of six SOPs

Then, the light signal is launched into the atmospheric turbulence channel. The model of atmospheric turbulence is Kolmogorov model. The architecture of the receiver is shown in Fig. 4, the received light is divided to two mutually orthogonal directions by a PBS. One of the polarized directions can be adjusted by polarization rotator. The light power is evenly divided to three parts by the power splitter (PS). One part of the light is detected by photoelectric detector and balance receiving circuit. Based on the detected information, the normalized Stokes parameter values of $\bar{s}_1$ can be obtained. Through a coupler, another part of the light is detected by photoelectric detector and balance receiving circuit. The normalized Stokes parameter values of $\bar{s}_2$ can be obtained. The phase of a branch of light is 90° delayed. Through a coupler, the other part of the light is detected by photoelectric detector and balance receiving circuit. The normalized Stokes parameter values of $\bar{s}_3$ can be obtained. Output data are regained after decoding based on various SOPs obtained. Different normalized Stokes parameters and corresponding polarization states are shown in Table 1.

Table 1 Normalized Stokes parameters and SOPs

$\begin{pmatrix}\bar{s}_1\\\bar{s}_2\\\bar{s}_3\end{pmatrix}$	$\begin{pmatrix}1\\0\\0\end{pmatrix}$	$\begin{pmatrix}-1\\0\\0\end{pmatrix}$	$\begin{pmatrix}0\\1\\0\end{pmatrix}$	$\begin{pmatrix}0\\-1\\0\end{pmatrix}$	$\begin{pmatrix}0\\0\\1\end{pmatrix}$	$\begin{pmatrix}0\\0\\-1\end{pmatrix}$
SOP	↔	↕	⤢	⤡	↻	↺

6-PolSK modulation is a multilevel modulation format, and it has higher spectral efficiency (SE) than on off keying (OOK) and PolSK modulation. It means that 6-PolSK modulation can transmit more bit informations using the same symbol rate.

Bit error rate (RER, R_{BE}) performances of OOK and 6-PolSK under weak turbulence conditions are shown in Fig. 6. The results indicate that strong fluctuations lead to significant BER and the values of the BER decrease with the increment of the optical signal-to-noise ratio (OSNR). For a given BER criterion, the required OSNR value of 6-PolSK is much lower than that of OOK.

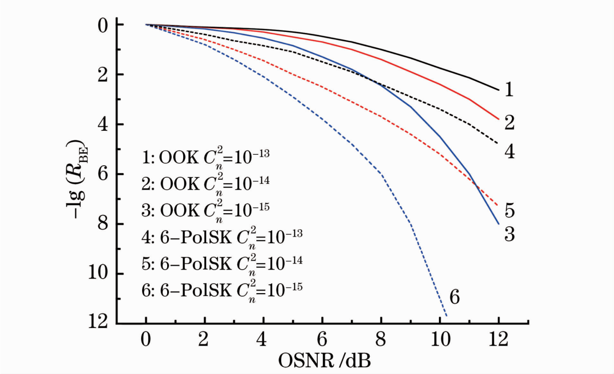

Fig. 6 BER performances of OOK and 6-PolSK modulation in atmospheric laser communication system

Because the photoelectric detector responds only to the optical intensity, the detection of SOP is accomplished by converting polarization informations into the differences of intensities. The performance of 6-PolSK modulation is influenced by atmosphere turbulent, although it has a significant improvement over intensity modulation.

4 Conclusion

A novel modulation scheme is proposed. Compared to the OOK scheme and PolSK scheme based on the linear polarizations, 6-PolSK modulation has higher spectral efficiency. The propagation of the polarized GSM beam in a turbulent atmosphere is studied based on the cross-spectral density matrix. The results show that the six SOPs and DOP keep hardly change along the propagation distance. Simulation results show that the BER performance of 6-PolSK modulation is much better than OOK scheme under weak turbulence conditions. 6-PolSK modulation is a practical approach to improve the reliability of the atmospheric laser communication system.

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