Influence of the Degree of Polarization on Beam Wander of Partially Coherent Laguerre-Gaussian-Schell Model Beam

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Abstract Influence of the degree of polarization on beam wander of partially coherent Laguerre-Gaussian-Schell model (LGSM) beams propagating in a turbulence atmosphere is investigated. Based on the cross-spectral density function and the extended Huygens-Fresnel integral principle, the expression for beam width and beam wander of partially coherent LGSM beams in theory is developed. In different transmission distances, turbulence strength and coherence length, influence of the degree of polarization on beam wander of partially coherent LGSM beams is illustrated numerically. The numerical results show that beam wander of a LGSM beam with larger degree of polarization and less coherent length is smaller. Therefore, in free-space optical (FSO) communication, we can choose beams with larger degree of polarization and smaller coherent length to reduce the beam wander.

Key words coherence optics; degree of polarization; beam wander; coherence; atmosphere turbulence

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偏振度对部分相干拉盖尔-高斯谢尔模型光束漂移的影响

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摘要 研究了当部分相干拉盖尔-高斯谢尔模型(LGSM)光束在大气湍流中传输时,偏振度对光束漂移的影响。依据交叉谱密度函数和广义惠更斯积分原理,理论上推导出了部分相干 LGSM 光束的长期束宽和光束漂移表达式。通过仿真不同偏振度的 LGSM 光束随着传输距离、湍流强度和相干长度变化的光束漂移,研究偏振度对光束漂移的影响。仿真结果表明,部分相干 LGSM 光束的偏振度越大,相干长度越小,产生的光束漂移越小。这对自由空间光通信(FSO)中,有效降低光束漂移有重要意义。

关键词 相干光学;偏振度;光束漂移;相干长度;大气湍流

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1 Introduction

In recent years, the interest in free-space optical (FSO) communication has increased due to its high security, high bandwidth, potential high-rate data capacity, high ability of resistant to electromagnetic interference, and low power requirements[1,2]. However, the transmission of laser beam in atmosphere is affected by atmospheric turbulence, which generates a series of turbulence effects, such as intensity scintillation, beam spreading, beam wander and spot shake[1,3-7]. These turbulence effects influence the transmission of optical signal, especially the transmission of optical signals can be interrupted by beam

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wander, which limits the performance of FSO communication system. Since Wu *et al.*[8-15] demonstrated that the effect of atmospheric turbulence on partially coherent beam is less than that on the completely coherent beam, more and more attention is being paid to partially coherent beams. This paper presents the analysis of the beam wander of partially coherent Laguerre-Gaussian-Schell model (LGSM) beams.

Beam wander refers to the random displacement of the center of a laser beam in the receiver plane, and it can be represented statistically by the variance of transverse displacement[1]. In the past years, beam wander has been studied widely. Yu *et al.*[16] studied the beam wander of electromagnetic Gaussian-Schell model beams propagating in atmospheric turbulence. Wen *et al.*[17] studied the beam wander of airy beam with a spiral phase. Ke *et al.*[18] investrgated spreading and wander of partially coherent beam propagating along a horizontal-path in the atmospheric turbulence. Aksenov *et al.*[19] reported random wandering of laser beams with orbital angular momentum during propagation through atmospheric turbulence. They found that LGSM beam has less beam wander than modified Bessel-Gaussian beam and hypergeometric Gaussian beam. So far, the research of beam wander of LGSM beams is relatively less. Therefore, we study the beam wander of LGSM beams, and mainly focus on the influence of the degree of polarization on beam wander of partially coherent LGSM beam.

We consider the effect of degree of polarization on beam wander under different transmission distances, turbulence strength and coherence length conditions, give the theoretical derivation and numerical simulation of the beam wander of partially coherent LGSM beams, and summarize the achievements in this paper.

2 Theoretical description and numerical simulation of beam wander

We derive the formula of beam wander of partially coherent LGSM beams in theory, and illustrate the effect of degree of polarization on beam wander by simulating.

2.1 Formulation calculation

The second-order coherence and polarization properties of the beam propagating through atmospheric turbulence can be characterized by the 2×2 cross-spectral density matrix[20]. The cross-spectral density matrix of a LGSM beam at the source plane $z=0$ is expressed as

$$W(\boldsymbol{s}_1,\boldsymbol{s}_2,0,\omega)=\begin{bmatrix} W_{xx}(\boldsymbol{s}_1,\boldsymbol{s}_2,0,\omega) & W_{xy}(\boldsymbol{s}_1,\boldsymbol{s}_2,0,\omega) \\ W_{yx}(\boldsymbol{s}_1,\boldsymbol{s}_2,0,\omega) & W_{yy}(\boldsymbol{s}_1,\boldsymbol{s}_2,0,\omega) \end{bmatrix}, \tag{1}$$

where

$$W_{ij}(\boldsymbol{s}_1,\boldsymbol{s}_2,0,\omega)=\langle E_i^*(\boldsymbol{s}_1,0,\omega)E_j(\boldsymbol{s}_2,0,\omega)\rangle(i,j=x,y), \tag{2}$$

where E_x and E_y are two electric-field components, $*$ and $\langle\cdot\rangle$ denote the complex conjugate and ensemble average, respectively, $\boldsymbol{s}_1$ and $\boldsymbol{s}_2$ are the position vectors at the source plane $z=0$, ω is the frequency and can be omitted for brevity in the following. In order to simplify the analysis, we assume that the electric fields E_x and E_y are perpendicular to each other, namely $W_{xy}=W_{yx}=0$, Eq. (1) can be rewritten as[16]

$$W(\boldsymbol{s}_1,\boldsymbol{s}_2,0)=\begin{bmatrix} W_{xx}(\boldsymbol{s}_1,\boldsymbol{s}_2,0) & 0 \\ 0 & W_{yy}(\boldsymbol{s}_1,\boldsymbol{s}_2,0) \end{bmatrix}. \tag{3}$$

The element of a LGSM beam in Eq. (3) is expressed as[21]

$$W_{ij}(\boldsymbol{s}_1,\boldsymbol{s}_2,0)=A_iA_jB_{ij}\times\exp\left[-\frac{\boldsymbol{s}_1^2+\boldsymbol{s}_2^2}{w_0^2}-\frac{(\boldsymbol{s}_1-\boldsymbol{s}_2)^2}{2\delta_{ij}^2}\right]\times L_n^0\left[\frac{(\boldsymbol{s}_1-\boldsymbol{s}_2)^2}{2\delta_{ij}^2}\right], \tag{4}$$

where A_x and A_y are the amplitudes of the electric field-vector component, w_0 is the transverse beam width, δ_{ij} is the coherent length, n is the radial index, L_n^0 represents the Laguerre polynomial of mode n

and 0, B_{ij} denotes correlation coefficient, and $B_{ij}=\begin{cases}0 & i\neq j\\ 1 & i=j\end{cases}$.

Based on the extended Huygens-Fresnel integral principle, the cross-spectral density function $W_{ij}(\boldsymbol{r}_1,\boldsymbol{r}_2,z)$ at the receiver plane can be expressed as[1]

$$W_{ij}(\boldsymbol{r}_1,\boldsymbol{r}_2,z)=A_iA_jB_{ij}\left(\frac{k}{2\pi z}\right)^2\times\iint\mathrm{d}^2\boldsymbol{s}_1\iint\mathrm{d}^2\boldsymbol{s}_2\times W_{ij}(\boldsymbol{s}_1,\boldsymbol{s}_2,0)\times \exp\left[-\frac{\mathrm{i}k}{2z}(\boldsymbol{s}_1-\boldsymbol{r}_1)^2+\frac{\mathrm{i}k}{2z}(\boldsymbol{s}_2-\boldsymbol{r}_2)^2\right]\times\langle\exp[\psi(\boldsymbol{s}_1,\boldsymbol{r}_1)+\psi^*(\boldsymbol{s}_2,\boldsymbol{r}_2)]\rangle, \tag{5}$$

where $k=2\pi/\lambda$ is the wavenumber, λ is the wavelength, $\boldsymbol{r}_1$ and $\boldsymbol{r}_2$ are the position vectors at the receiver plane, the expression in the angular brackets is

$$\langle\exp[\psi(\boldsymbol{s}_1,\boldsymbol{r}_1)+\psi^*(\boldsymbol{s}_2,\boldsymbol{r}_2)]\rangle=\exp\left[-\frac{(\boldsymbol{s}_1-\boldsymbol{s}_2)^2}{\rho_0^2}-\frac{(\boldsymbol{s}_1-\boldsymbol{s}_2)\cdot(\boldsymbol{r}_1-\boldsymbol{r}_2)}{\rho_0^2}-\frac{(\boldsymbol{r}_1-\boldsymbol{r}_2)^2}{\rho_0^2}\right], \tag{6}$$

where $\rho_0(z)=(0.55C_n^2k^2z)^{(-\frac{3}{5})}$ is the coherence length of a spherical wave propagating through turbulence, C_n^2 represents the refractive index structure parameter describing the strength of atmospheric turbulence. Substituting Eqs. (4) and (6) into Eq. (5), we can obtain

$$W_{ij}(\boldsymbol{r}_1,\boldsymbol{r}_2,z)=\frac{A_iA_jB_{ij}k^2}{4\pi^2z^2}\times\exp\left[-\frac{\mathrm{i}k}{2z}(\boldsymbol{r}_1^2-\boldsymbol{r}_2^2)-\frac{(\boldsymbol{r}_1-\boldsymbol{r}_2)^2}{\rho_0^2}\right]\times \iint\mathrm{d}^2\boldsymbol{s}_1\iint\mathrm{d}^2\boldsymbol{s}_2\times L_n^0\left[\frac{(\boldsymbol{s}_1-\boldsymbol{s}_2)^2}{2\delta_{ij}^2}\right]\times\exp\left[\left(-\frac{\mathrm{i}k}{2z}-\frac{1}{w_0^2}\right)\boldsymbol{s}_1^2+\left(\frac{\mathrm{i}k}{2z}-\frac{1}{w_0^2}\right)\boldsymbol{s}_2^2+\boldsymbol{s}_1\left(\frac{\mathrm{i}k}{z}\boldsymbol{r}_1-\frac{\boldsymbol{r}_1-\boldsymbol{r}_2}{\rho_0^2}\right)\right]\times \exp\left[-\boldsymbol{s}_2\left(\frac{\mathrm{i}k}{z}\boldsymbol{r}_2-\frac{\boldsymbol{r}_1-\boldsymbol{r}_2}{\rho_0^2}\right)-\left(\frac{1}{2\delta_{ij}^2}+\frac{1}{\rho_0^2}\right)(\boldsymbol{s}_1-\boldsymbol{s}_2)^2\right]. \tag{7}$$

For the convenience of integration, we set

$$\boldsymbol{s}=\frac{\boldsymbol{s}_1+\boldsymbol{s}_2}{2},\boldsymbol{s}_\mathrm{d}=\boldsymbol{s}_1-\boldsymbol{s}_2. \tag{8}$$

Equation (7) is reduced to

$$W_{ij}(\boldsymbol{r}_1,\boldsymbol{r}_2,z)=\frac{A_iA_jB_{ij}k^2}{4\pi^2z^2}\times\exp\left[-\frac{\mathrm{i}k}{2z}(\boldsymbol{r}_1^2-\boldsymbol{r}_2^2)-\frac{(\boldsymbol{r}_1-\boldsymbol{r}_2)^2}{\rho_0^2}\right]\times \iint\exp\left[-\left(\frac{1}{2\delta_{ij}^2}+\frac{1}{\rho_0^2}+\frac{1}{2w_0^2}\right)\boldsymbol{s}_\mathrm{d}^2\right]\times L_n^0\left(\frac{\boldsymbol{s}_\mathrm{d}^2}{2\delta_{ij}^2}\right)\times\exp\left\{\left[\frac{\mathrm{i}k}{2z}(\boldsymbol{r}_1+\boldsymbol{r}_2)-\frac{\boldsymbol{r}_1-\boldsymbol{r}_2}{\rho_0^2}\right]\boldsymbol{s}_\mathrm{d}\right\}\mathrm{d}^2\boldsymbol{s}_\mathrm{d}\times \iint\exp\left\{-\frac{\boldsymbol{s}^2}{2w_0^2}+\boldsymbol{s}\left[-\frac{\mathrm{i}k}{z}\boldsymbol{s}_\mathrm{d}+\frac{\mathrm{i}k}{z}(\boldsymbol{r}_1-\boldsymbol{r}_2)\right]\right\}\mathrm{d}^2\boldsymbol{s}. \tag{9}$$

After integrationover $\boldsymbol{s}$, we find

$$W_{ij}(\boldsymbol{r}_1,\boldsymbol{r}_2,z)=\frac{A_iA_jB_{ij}k^2}{8\pi z^2}\times\exp\left[-\frac{\mathrm{i}k}{2z}(\boldsymbol{r}_1^2-\boldsymbol{r}_2^2)-\left(\frac{k^2w_0^2}{8z^2}+\frac{1}{\rho_0^2}\right)(\boldsymbol{r}_1-\boldsymbol{r}_2)^2\right]\times \iint\exp\left[-\left(\frac{1}{2\delta_{ij}^2}+\frac{1}{\rho_0^2}+\frac{1}{2\omega_0^2}+\frac{k^2w_0^2}{8z^2}\right)\boldsymbol{s}_\mathrm{d}^2\right]\times L_n^0\left(\frac{\boldsymbol{s}_\mathrm{d}^2}{2\delta_{ij}^2}\right)\times \exp\left\{\left[\frac{\mathrm{i}k}{2z}(\boldsymbol{r}_1+\boldsymbol{r}_2)-\frac{\boldsymbol{r}_1-\boldsymbol{r}_2}{\rho_0^2}+\frac{k^2w_0^2}{4z^2}(\boldsymbol{r}_1-\boldsymbol{r}_2)\right]\boldsymbol{s}_\mathrm{d}\right\}\mathrm{d}^2\boldsymbol{s}_\mathrm{d}. \tag{10}$$

If we set $a_{ij}=\frac{1}{2\delta_{ij}^2}+\frac{1}{\rho_0^2}+\frac{1}{2w_0^2}+\frac{k^2w_0^2}{8z^2}$, when $\boldsymbol{r}_1=\boldsymbol{r}_2=\boldsymbol{r}=\sqrt{r_x^2+r_y^2}$, Eq. (10) is reduced to

$$W_{ij}(\boldsymbol{r},z)=\frac{A_iA_jB_{ij}k^2}{8\pi z^2}\times\iint\exp\left(-a_{ij}\boldsymbol{s}_\mathrm{d}^2+\frac{\mathrm{i}k}{z}\boldsymbol{r}\cdot\boldsymbol{s}_\mathrm{d}\right)\times L_n^0\left(\frac{\boldsymbol{s}_\mathrm{d}^2}{2\delta_{ij}^2}\right)\mathrm{d}^2\boldsymbol{s}_\mathrm{d}. \tag{11}$$

Taking $n=2$, through calculation, we can find

$$W_{ij}(\boldsymbol{r},z)=\frac{A_iA_jB_{ij}k^2w_0^2}{8a_{ij}z^2}\times\exp\left(-\frac{k^2\boldsymbol{r}^2}{4a_{ij}z^2}\right)\times \left[\frac{k^4\boldsymbol{r}^4}{128a_{ij}^4z^4\delta_{ij}^4}+\left(\frac{k^2}{4a_{ij}^2z^2\delta_{ij}^2}-\frac{k^2}{8a_{ij}^3z^2\delta_{ij}^4}\right)\boldsymbol{r}^2+\left(1-\frac{1}{a_{ij}\delta_{ij}^2}+\frac{1}{4a_{ij}^2\delta_{ij}^4}\right)\right]. \tag{12}$$

Therefore, we obtain the average intensity of a LGSM beam in the out plane:

$$I(\boldsymbol{r},z)=W_{xx}(\boldsymbol{r},z)+W_{yy}(\boldsymbol{r},z)=\frac{k^2w_0^2A_x^2}{8a_{xx}z^2}\times\exp\left(-\frac{k^2\boldsymbol{r}^2}{4a_{xx}z^2}\right)\times\left[\frac{k^4\boldsymbol{r}^4}{128a_{xx}^4z^4\delta_{xx}^4}+\left(\frac{k^2}{4a_{xx}^2z^2\delta_{xx}^2}-\frac{k^2}{8a_{xx}^3z^2\delta_{xx}^4}\right)\boldsymbol{r}^2+\left(1-\frac{1}{a_{xx}\delta_{xx}^2}+\frac{1}{4a_{xx}^2\delta_{xx}^4}\right)\right]+\frac{k^2w_0^2A_y^2}{8a_{yy}z^2}\times\exp\left(-\frac{k^2\boldsymbol{r}^2}{4a_{yy}z^2}\right)\times\left[\frac{k^4\boldsymbol{r}^4}{128a_{yy}^4z^4\delta_{yy}^4}+\left(\frac{k^2}{4a_{yy}^2z^2\delta_{yy}^2}-\frac{k^2}{8a_{yy}^3z^2\delta_{yy}^4}\right)\boldsymbol{r}^2+\left(1-\frac{1}{a_{yy}\delta_{yy}^2}+\frac{1}{4a_{yy}^2\delta_{yy}^4}\right)\right].\tag{13}$$

We obtain the long-term beam width $W_{\mathrm{LT}}(z)$ in the presence of turbulence, which is the radius of the long term spot caused by the movement of the short-term beam over a long time period,

$$W_{\mathrm{LT}}(z)=\left[\frac{2\iint\boldsymbol{r}^2I(\boldsymbol{r},z)\mathrm{d}^2\boldsymbol{r}}{\iint I(\boldsymbol{r},z)\mathrm{d}^2\boldsymbol{r}}\right]^{\frac{1}{2}}.\tag{14}$$

Substituting Eq. (14) into Eq. (15), we obtain

$$W_{\mathrm{LT}}(z)=\left[\frac{8z^2A_x^2(\delta_{xx}^2a_{xx}+1)+8z^2A_y^2(\delta_{yy}^2a_{yy}+1)}{k^2\delta_{xx}^2A_x^2+k^2\delta_{yy}^2A_y^2}\right]^{\frac{1}{2}}.\tag{15}$$

The degree of polarization P of the sources can be expressed as

$$P=\frac{|A_x^2-A_y^2|}{A_x^2+A_y^2}.\tag{16}$$

The beam wander of LGSM beams can be expressed as

$$\langle\boldsymbol{r}_c^2\rangle=7.25L^2C_n^2\int_0^L\left(1-\frac{z}{L}\right)^2W_{\mathrm{LT}}(z)^{(-\frac{1}{3})}\mathrm{d}z,\tag{17}$$

where L is the total propagation path length, z is the distance of an intercept point from the input plane at $z=0$. It is shown that the beam wander of LGSM beams varies with changes in refractive index structure constant, long-term beam width, and the propagation distance.

2.2 Numerical simulation

According to Eq. (17), we simulate the beam wander of partially coherent LGSM beams under some different conditions. We focus on the normalized and dimensionless quantity $B_w=\langle\boldsymbol{r}_c^2\rangle/W_{\mathrm{LT}}^2$, which is more informative than merely $\langle\boldsymbol{r}_c^2\rangle$ about the practical significance of the wandering.

The normalized and dimensionless quantity B_w of partially coherent LGSM beams as a function of C_n^2 for different degrees of polarization is plotted in Fig. 1. The parameters are $L=10$ km, $w_0=0.02$ m, $\delta_{xx}=0.02$ m, $\delta_{yy}=0.05$ m, and $\lambda=632$ nm. On the one hand, it is shown that the beam wander decreases with increasing the degree of polarization. The effective coherent length δ_p^2 meets the formula $\frac{1}{\delta_P^2}=\frac{1+P}{2\delta_{xx}^2}+\frac{1-P}{2\delta_{yy}^2}$, when $\delta_{xx}<\delta_{yy}$, the increase of P would give rise to a larger beam width[16]. From Eq. (17), we can know that the beam wander is inversely proportional to the beam width. Consequently, the beam wander decreases with increasing P.

On the other hand, one can find that the beam wander increases with increasing the turbulence strength when the turbulence is weak. But the beam wander decreases with increasing the turbulence strength when the turbulence is strong, and it reaches the maximum value at the moderate turbulence. Because in the region of weak turbulence, the beam broadening is almost unaffected by turbulence, the probability of the beam deflected by large-scale turbulence eddies increases with increasing turbulence strength. While in the region of strong turbulence, the scattering effect of turbulence greatly aggravates the beam broadening, which reduces the probability of thebeam refraction[22].

Figure 2 plots the beam wander of partially coherent LGSM beams as a function of the degree of polarization P under three different coherent conditions. Here, $\delta_{xx}=0.01$ m, $C_n^2=10^{-14}$ $\mathrm{m}^{-2/3}$ and the rest of the parameters are the same as those in Fig. 1. It is shown that the partially coherent LGSM beam with smaller coherence length generates less beam wander. Because beam width increases with decreasing the coherence length when the beam propagates in the atmospheric turbulence[10], the beam wander decreases with decreasing coherent length. When $\delta_{xx}=\delta_{yy}$, the effective coherent length δ_P^2 has nothing with the degree of polarization, then beam wander is no longer affected by the degree of polarization. In addition, one can find that beam wander decreases with increasing the degree of polarization P.

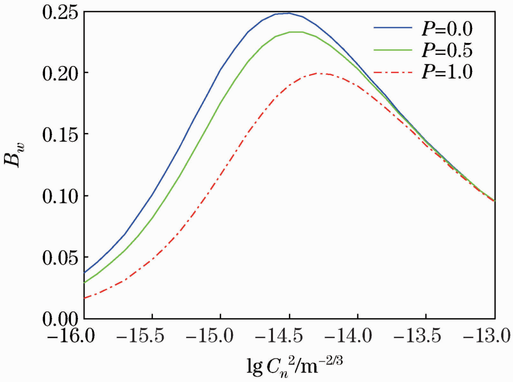

Fig. 1 Dimensionless quantity B_w as a function of C_n^2 for different degrees of polarization P

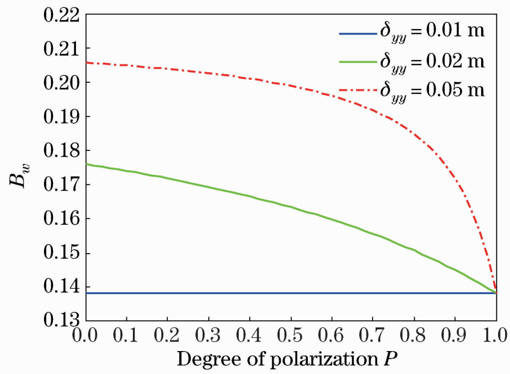

Fig. 2 Dimensionless quantity B_w as a function of the degree of polarization P for different coherent lengths δ_{yy}

Beam wander of partially coherent LGSM beams as a function of propagation distance under three different degrees of polarization conditions is plotted in Fig. 3. The parameters are the same as those in Fig. 1. It is shown that the beam wander increases with increasing the propagation distance, whatever the values of the degree of polarization. Because, for a certain beam divergence angle, the width between the two lines would increase as the distance increases. We can also find that the degree of polarization is larger, the beam wander is smaller.

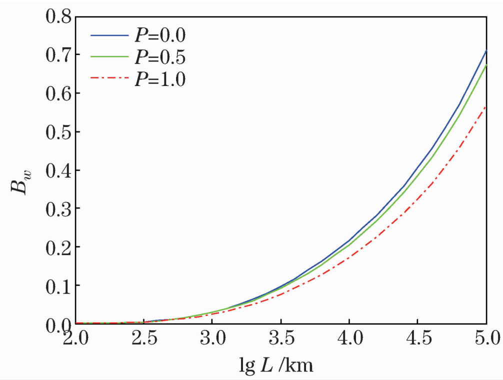

Fig. 3 Dimensionless quantity B_w as a function of propagation distance L for different degrees of polarization P

3 Conclusion

We derive the expression of beam wander for the partially coherent LGSM beams in theory, and study the effect of degree of polarization on beam wander under different transmission distances, turbulence strength and coherence length conditions by simulating. It is found that the beam wander can be reduced by increasing degree of polarization and decreasing coherence length, which will be useful in FSO communication.

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