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偏振部分相干激光波束在湍流大气中传输的扩展和漂移

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摘　要:基于广义 Huygens-Fresnel 原理,利用 Collins 公式,讨论了偏振部分相干激光波束在湍流大气中传输的交叉谱密度函数,推导出经过偏振后的高斯-谢尔模型光束在外场不同距离水平传输时,光谱强度、束腰宽度及重心位置漂移的解析表达式.对偏振激光在大气湍流中传输时光束扩展和漂移进行数值仿真,得到相同传输距离下,偏振角、初始束腰及波长取不同值时,激光波束的扩展和漂移的变化情况.分析了相同偏振角度下,不同传输距离对光束扩展和漂移的影响.研究结果表明:大气湍流中偏振激光波束的扩展和漂移依赖于波束的波长、初始光束的偏振角和初始束腰;随着偏振角的变化,偏振部分相干激光波束的扩展和漂移关于 45°呈现对称变化,当波束初始束腰小于或等于 0.5 mm 时,大气湍流对波束扩展和漂移的影响明显.

关键词:大气湍流;偏振部分相干激光;交叉谱密度函数;光束扩展;光束漂移

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Spread and Wander Characteristics of Polarized and Partially Coherent Laser Beam Propagated in Turbulent Atmosphere

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Abstract: Cross-spectral density function of polarized and partially coherent laser propagated in turbulent atmosphere was determined based on the extended Huygens-Fresnel principle and Collins Formula. Analytical expressions for spectral intensity, expansion radius and barycentric position wander of polarized Gaussian-shell model beam were obtained under horizontal transmission at different distances of external fields. The beam extension and drift of the polarized laser polarized laser propagated in turbulent atmosphere were simulated, and the changing information of laser beam's extension and drift in the same propagating distance with different polarizing angle, initial waist widths, and wave length were got. Similar simulation was also done using the different wavelengths and the same polarization angle but with different propagation distances. The results indicated that the spread and wander of polarized and partially coherent laser propagated in turbulent atmosphere are dependent on the polarization angle and initial waist width. The spread and wander of polarized laser beam at 45° show symmetry as polarization angle varies. With initial waist width less than or equal to 0.5 mm, the spread and wander were increasingly affected by atmospheric turbulence.

Key words: Atmospheric turbulence; Polarized and partially coherent laser beam; Cross-spectral density

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0 Introduction

Laser propagation properties in turbulent atmosphere have been extensively investigated both theoretically and through practical applications. Currently, majority of studies are focused on spread and wander characteristics[1-3] of laser propagation in horizontal and oblique turbulence. Wolf[4] proposed a unified coherence and polarized theory, making it possible to unify studies on beams spectrum, coherence, and polarization properties. Hema[5] used this theory to investigate the spectral intensity, coherence, and polarization of Gaussian-shell Model (GSM) beams, as well as the changes in polarization angle as Electromagnetic Gaussian-shell Model (EGSM) beam propagates through turbulent atmosphere.

At present, most studies investigate spread and wander of GSM beam propagated in turbulent atmosphere. However, there are few theories on how polarized laser beams are affected as they propagate in a turbulent medium. In terms of polarization, only coherence[6] and polarization of EGSM beam have been investigated. Atmospheric turbulence affects polarized laser beams by causing beams to spread and wander. This phenomenon should be considered to improve the efficiency of a free space optical communication system, a laser radar system, and a laser ranging technique, or the accuracy of laser alignment and laser positioning. Therefore, the study of spread and wander characteristics of polarized laser propagated in turbulent atmosphere has a vital significance in the field of practical application of laser guidance, laser tracking, and so on. It also provides a theoretical basis for improving the propagation quality of laser beams.

In the present study, a partially coherent source, GSM with a Gaussian intensity distribution, and the distribution of coherence were investigated. Based on the extended Huygens-Fresnel Principle diffraction integral formulas, spread and wander characteristics of polarized laser[7] in turbulent atmosphere, and together with expressions of spectral intensity[8], waist width and deflection of gravity center, were determined by combining the diffraction integral with optical system matrix. Spread and wander of beams under different polarized angles, different wavelengths, and different initial waist widths are also discussed.

1 Spread and wander of polarized and partially coherent laser beam

When $z=0$, spectral intensity and spectral coherent degree function of partially coherent GSM are expressed as follows

$$S(\boldsymbol{x}_{10},\boldsymbol{x}_{20},0)=S_0\exp\left[-\frac{\boldsymbol{x}_{10}^2+\boldsymbol{x}_{20}^2}{w_0^2}\right] \tag{1}$$

$$\mu(\boldsymbol{x}_{10},\boldsymbol{x}_{20},0)=\exp\left[-\frac{\boldsymbol{x}_{10}^2-\boldsymbol{x}_{20}^2}{2\sigma_0^2}\right] \tag{2}$$

where S_0 is constant, w_0 is waist width of GSM beam, σ_0 is spatial correlation length in light source, $\boldsymbol{x}_{10}$ and $\boldsymbol{x}_{20}$ are two different radial coordinate vectors at $z=0$, respectively.

Based on cross-spectral density function, the cross-spectral density function of GSM beams in the incident plane $z=0$ can be written as

$$W(\boldsymbol{x}_{10},\boldsymbol{x}_{20},0,\omega)=\sqrt{S(\boldsymbol{x}_{10},\boldsymbol{x}_{10},0)}\cdot \sqrt{S(\boldsymbol{x}_{20},\boldsymbol{x}_{20},0)}\,\mu(\boldsymbol{x}_{10},\boldsymbol{x}_{20},0) \tag{3}$$

Combining Eq. (1) and (2), Eq. (3) can be written as

$$W(\boldsymbol{x}_{10},\boldsymbol{x}_{20},0,\omega)=\frac{1}{2}S_0\exp\left[-\frac{\boldsymbol{x}_{10}^2+\boldsymbol{x}_{20}^2}{w_0^2}\right]\cdot \exp\left[-\frac{(\boldsymbol{x}_{10}-\boldsymbol{x}_{20})^2}{2\sigma_0^2}\right] \tag{4}$$

As beams propagate through paraxial ABCD optical system, a two-dimensional distribution of the optical field can be obtained using Collins Formula in $z=L$.

$$E(x,y,z)=\left(\frac{\mathrm{i}}{\lambda B}\right)\exp(-\mathrm{i}kL)\iint E(x',y')\cdot \exp\left\{-\frac{\mathrm{i}k}{2B}\left[A(x'+y')^2+D(x+y)^2-2(xx'+yy')\right]\right\}\mathrm{d}x'\mathrm{d}y' \tag{5}$$

A one-dimensional formula is expressed as

$$E(x,y)=\sqrt{\frac{\mathrm{i}}{\lambda B}}\int E(x_0,z=0)\exp\left\{-\frac{\mathrm{i}\pi}{\lambda B}\cdot \left[Ax_0^2-2x_0x+Dx^2\right]+\varphi(x_0,x)\right\}\mathrm{d}x_0 \tag{6}$$

where $\varphi(x_0,x)$ is the random phase factor caused by spherical wave in turbulent atmosphere.

With an angle between the penetrate vibration direction of the linear polarizing device and the x axis shown as θ, the Jones Matrix of the polarizing device is

$$\begin{bmatrix}\cos^2\theta & \frac{1}{2}\sin 2\theta\\ \frac{1}{2}\sin 2\theta & \sin^2\theta\end{bmatrix}$$

The optical system containing a linear polarizing device in ABCD matrix format can be expressed as

$$\begin{bmatrix}A & B\\ C & D\end{bmatrix}=\begin{bmatrix}1 & z\\ 0 & 1\end{bmatrix}\begin{bmatrix}\cos^2\theta & \frac{1}{2}\sin 2\theta\\ \frac{1}{2}\sin 2\theta & \sin^2\theta\end{bmatrix}=$$

$$\begin{bmatrix} \cos^2\theta+\frac{z}{2}\sin 2\theta & \frac{1}{2}\sin 2\theta+z\sin^2\theta \\ \frac{1}{2}\sin 2\theta & \sin^2\theta \end{bmatrix} \tag{7}$$

Combining Eq. (6) and (7), the field distribution as a GSM beam propagates through the paraxial ABCD optical system of a linear polarizing device is expressed as

$$E(x,z)=\sqrt{\frac{\mathrm{i}}{\lambda\left(\frac{1}{2}\sin 2\theta+z\sin^2\theta\right)}}\int E(x_0,z=0)\cdot \exp\left\{-\frac{\mathrm{i}\pi}{\lambda\left(\frac{1}{2}\sin 2\theta+z\sin^2\theta\right)}\left[\left(\cos^2\theta+\frac{z}{2}\sin 2\theta\right)\cdot x_0^2-2x_0x+\sin^2\theta x^2\right]+\varphi(x_0,x)\right\}\mathrm{d}x_0 \tag{8}$$

When the beam propagates from $z=0$ to $z=L$ along the direction of propagation, the cross-spectral density function expressed in a paraxial ABCD optical system transmission formula can be derived from the extended Huygens-Fresnel Principle[9-10]

$$W(\boldsymbol{x},\boldsymbol{y},z,\omega)=\langle E(\boldsymbol{x},z)\cdot E^*(\boldsymbol{y},z)\rangle=\langle\sqrt{\frac{\mathrm{i}}{\lambda B}}\int E(x_0,0)\cdot \exp\left\{-\frac{\mathrm{i}\pi}{\lambda B}[Ax_0^2-2x_0\boldsymbol{x}+D\boldsymbol{x}^2]+\varphi(x_0,\boldsymbol{x})\right\}\mathrm{d}x_0\cdot \sqrt{\frac{-\mathrm{i}}{\lambda B}}\int E^*(y_0,0)\exp\left\{\frac{\mathrm{i}\pi}{\lambda B}[Ay_0^2-2y_0\boldsymbol{y}+D\boldsymbol{y}^2]+\varphi(y_0,\boldsymbol{y})\right\}\mathrm{d}y_0\rangle=\frac{1}{\lambda B}\iint\langle E(x_0,0)\cdot E^*(y_0,y)\rangle\cdot \exp\left\{-\frac{\mathrm{i}\pi}{\lambda B}[A(x_0^2-y_0^2)-2(x_0\boldsymbol{x}-y_0\boldsymbol{y})+D(\boldsymbol{x}^2-\boldsymbol{y}^2]\right\}\langle\exp[\varphi(x_0,\boldsymbol{x})+\varphi^*(y_0,\boldsymbol{y})]\rangle_m\mathrm{d}x_0\mathrm{d}y_0 \tag{9}$$

where x and y are radial coordinate vectors at different points along $z=L, k=2\pi/L$, is a wave number, and $\langle\exp\varphi(r_1',r_1)+\varphi^*(r_2',r_2)\rangle_m$ is ensemble average[4]. The quadratic approximation of the Rytov phase structure function is

$$\langle\exp[\varphi(\boldsymbol{x}_{10},x_1)+\varphi^*(\boldsymbol{x}_{20},x_2)]\rangle_m=\exp[-[(\boldsymbol{x}_{10}-\boldsymbol{x}_{20})^2+(\boldsymbol{x}_{10}-\boldsymbol{x}_{20})(x_1-x_2)+(x_1-x_2)^2]/\rho_0^2] \tag{10}$$

where ρ_0 is coherence length of spherical waves through atmospheric turbulence, $\rho_0=(0.545C_n^2k^2z)^{-3/5}$, and c_n^2 is the refractive index structure constant.

Eq. (9) can be solved by integral formulas

$$\int_{-\infty}^{+\infty}\exp[-(x-y)^2]\mathrm{d}x=\pi^{1/2}$$

$$\int_{-\infty}^{+\infty}\exp[-px^2\pm 2qx]\mathrm{d}x=\sqrt{\frac{\pi}{p}}\exp\left[\frac{q^2}{p}\right] \tag{11}$$

The spectral intensity of polarized GSM beams through atmospheric turbulence when $x_1=x_2=x$, which is the same as the spectral density function at a field point, is

$$I=S(x,z)=W(x,x,z)=S_0\frac{\pi}{\lambda B}\times\frac{1}{\sqrt{p_1m_1}}\times \exp\left[\left(\frac{q_1^2}{p_1}+\frac{m_2^2}{m_1}\right)x^2\right] \tag{12}$$

where

$$\begin{cases} p_1=\dfrac{1}{w_0^2}+\dfrac{1}{2\delta_0^2}+\dfrac{\mathrm{i}\pi}{\lambda B}A+\dfrac{1}{\rho_0^2} \\ p_2=\dfrac{1}{w_0^2}+\dfrac{1}{2\delta_0^2}-\dfrac{\mathrm{i}\pi}{\lambda B}A+\dfrac{1}{\rho_0^2} \\ q_1=\dfrac{\mathrm{i}\pi}{\lambda B} \\ m_1=p_2-\left(\dfrac{1}{2\delta_0^2}+\dfrac{1}{\rho_0^2}\right)^2/p_1 \\ m_2=-\dfrac{\mathrm{i}\pi}{\lambda B}+\dfrac{q_1}{p_1}\left(\dfrac{1}{2\delta_0^2}+\dfrac{1}{\rho_0^2}\right) \end{cases} \tag{13}$$

Based on the definition of second moment width[11], the second moment width of spectral intensity (x direction) can be expressed as[15]

$$W_i^2=\frac{4\int_{-\infty}^{\infty}x^2S(x,z,\omega)\mathrm{d}x}{\int_{-\infty}^{\infty}S(x,z,\omega)\mathrm{d}x} \tag{14}$$

Replacing the spectral intensity in Eq. (12), Eq. (14) can be rearranged as

$$W_i^2=\frac{\lambda^2B^2}{2\pi^2}\left(\frac{1}{cw_0^4}-\frac{2}{w_0^2}+\frac{\pi^2A^2}{c\lambda^2B^2}\right)=\frac{\lambda^2\left(\frac{1}{2}\sin 2\theta+z\sin^2\theta\right)^2}{2\pi^2}\cdot \left[\frac{1}{cw_0^4}-\frac{2}{w_0^2}+\frac{\pi^2\left(\cos^2\theta+\frac{z}{2}\sin 2\theta\right)^2}{c\lambda^2\left(\frac{1}{2}\sin 2\theta+z\sin^2\theta\right)^2}\right] \tag{15}$$

where

$$c=\frac{1}{2\delta_0^2}+\frac{1}{\rho_0^2}$$

Therefore, the waist width of the polarized laser beam can be expressed as

$$W_i^2=\frac{\lambda B^2}{\sqrt{2}\pi}\sqrt{\frac{1}{cw_0^4}-\frac{2}{w_0^2}+\frac{\pi^2A^2}{c\lambda^2B^2}}=\frac{\lambda^2\left(\frac{1}{2}\sin 2\theta+z\sin^2\theta\right)}{\sqrt{2}\pi^2}\cdot \sqrt{\frac{1}{cw_0^4}-\frac{2}{w_0^2}+\frac{\pi^2\left(\cos^2\theta+\frac{z}{2}\sin 2\theta\right)^2}{c\lambda^2\left(\frac{1}{2}\sin 2\theta+z\sin^2\theta\right)^2}} \tag{16}$$

Using the position of the barycentric coordinates of a beam to represent beam wander, based on the definition of the first moment width[12], the coordinates of the beam's barycentric position is expressed as

$$\bar{x}=\frac{\int xS(x,z)\mathrm{d}x}{\int S(x,z)\mathrm{d}x} \tag{17}$$

Combined with Eq. (12), Eq. (17) can be written as

$$\bar{x}=\frac{\lambda^2\left(\frac{1}{2}\sin 2\theta+z\sin^2\theta\right)}{2\sqrt{2}(\pi)^{3/2}}\cdot \sqrt{\frac{1}{cw_0^4}-\frac{2}{w_0^2}+\frac{\pi^2\left(\cos^2\theta+\frac{z}{2}\sin 2\theta\right)^2}{c\lambda^2\left(\frac{1}{2}\sin 2\theta+z\sin^2\theta\right)^2}} \tag{18}$$

where

$c=1/2\delta_0^2+1/\rho_0^2$

2 Numerical analysis

The atmospheric refractive index structure constant, C_n^2 is 1.7×10^{-14} ($\mathrm{m}^{-2/3}$) along a horizontal path. This value is based on the structure constant model used by I. T. U. in studying ITU-R in turbulent atmosphere[13]. The depolarization effect of laser beams through atmospheric turbulence is not considered.

Fig. 1 and Fig. 2 show the relationship of a beam′s spread and wander variation with the distance of laser propagation at different polarization angles but with constant initial waist width, when $\lambda=1.06$ μm, $\omega_0=5$ mm, $\delta_0=5$ mm. Based on the results, low polarization angle leads to an increased extent of spread and wander as propagation distance increases at $0°<\theta\leqslant45°$. At $45°\leqslant\theta<90°$, lower polarized angle leads to lower expansion radius and the barycentric position deflection. It shows that when polarized laser beams propagate in turbulent atmosphere along a horizontal direction within a given propagation distance and within the range of $0°<\theta\leqslant45°$, atmospheric turbulence has an increased effect over the expansion radius and barycentric position deflection. On the other hand, within the range of $45°<\theta\leqslant90°$, the expansion radius and barycentric position deflection caused by turbulent atmosphere have lower values with lower polarizing angles. Based on the figure, the simulation results also indicate that the relationship between spread and wander′s variation for the polarization angles of 30° and 60° is coincidental, similar to 15° and 75°, as opposed to 45°, which shows complete symmetry pattern. This is because the 45° angle is the main partial linear polarization direction. At this direction, the transmittance is at its maximum value. For values greater is less than 45°, the power of transmitted light is less than that along the main partial direction. This results to the symmetry by the main partial direction, with either side showing decreased transmitting power.

Fig. 3 and Fig. 4 demonstrate the relationship between spread and wander variation with distance of propagation at constant polarized angle ($\theta=45°$) and with initial waist width set at $w_0=5$ mm and $w_0=10$ mm, respectively, when $\lambda=1.06$ μm, $\omega_0=5$ mm, $\delta_0=5$ mm. Based on the figure, when initial waist width is greater than or equal to 5 mm ($w_0\geqslant5$ mm) and with polarization angle at 45°, the initial beam waist width does not have an impact on the beam′s expansion radius and barycentric position deflection. This simply means that the different initial waist width of polarized and partially coherent laser beams do not affect the beam′s spread and wander with propagation

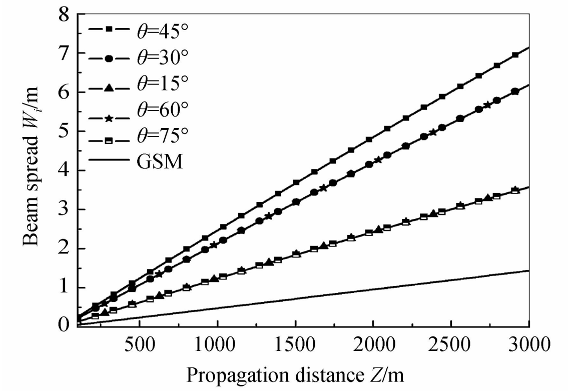

Fig. 1 Spread changes with the same propagation distance under different polarization angles

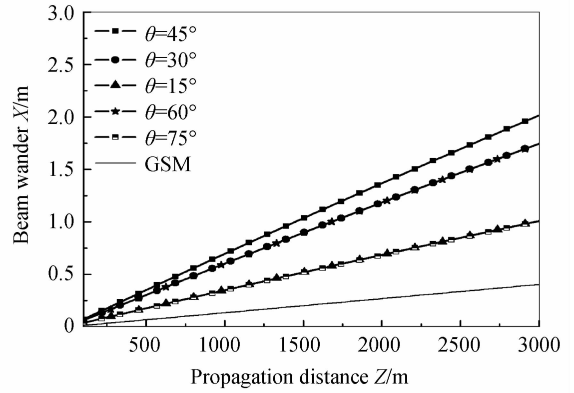

Fig. 2 Wander changes with the same propagation distance the different polarization angles

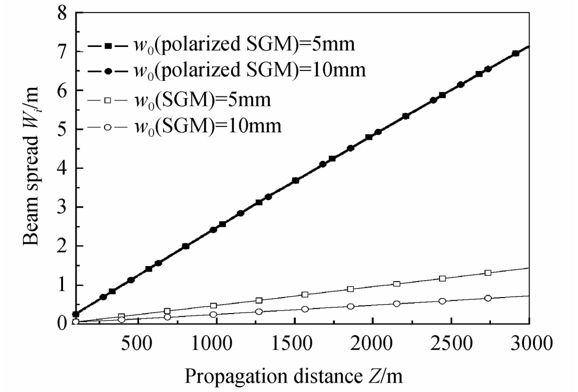

Fig. 3 Spread variation with propagation distance under different initial waist width

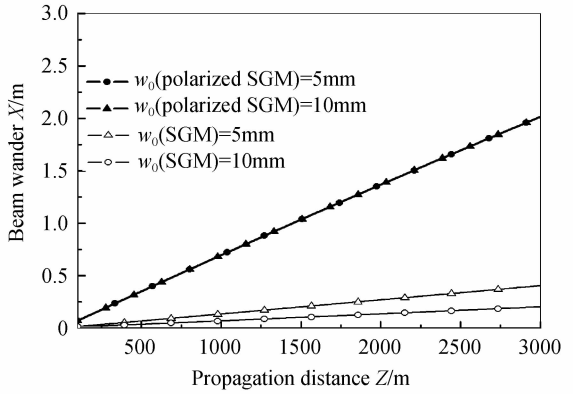

Fig. 4 Wander variation with propagation distance under different initial waist widths

distance at $w_0 \geqslant 5$ mm. With an increasing in initial waist width of the GSM beam, spread and wander under different initial waist width gradually decrease with an increase in distance.

Overall, when the polarization angle is at 45°, the power of transmitted light reaches its maximum value as the incident polarizing angle of linear polarization. At this point, the polarization of a beam is at its maximum value, and spread and wander of the beam are also at its strongest. Fig. 5 and Fig. 6 show variations in the beam′s expansion radius and the barycentric position deflection with changes in initial waist width at different propagation distances when $\lambda = 1.06\ \mu$m, $\delta_0 = 5$ mm, $\theta = 45^\circ$, and $w_0 < 5$ mm. The graph shows that expansion radius and barycentric position deflection decreases significantly as initial waist width increases at 45° and $w_0 \leqslant 0.5$ mm. At $w_0 \geqslant 0.5$ mm, expansion radius and barycentric position deflection remain virtually constant as initial waist width increases. Compared with the GSM beam, at 45° and $w_0 \leqslant 0.5$ mm, the beam′s expansion radius and barycentric position deflection clearly decrease when initial waist width increases. Further at $w_0 \geqslant 0.5$ mm, with an increase in initial waist width, at the same propagation distance, the beam′s expansion radius and barycentric position deflection continue to decrease slowly, indicating that polarized GSM is more stable than GSM beam on spread and wander.

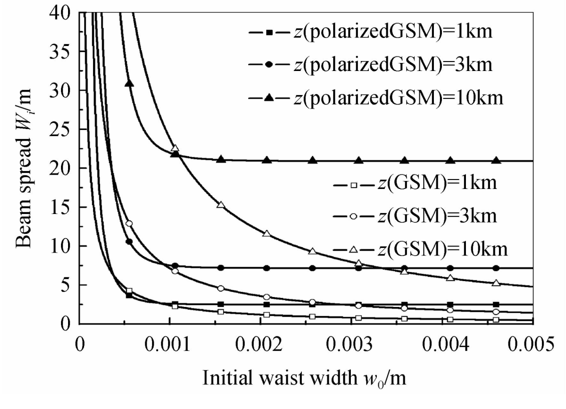

Fig. 5 Spread variation with initial waist width at given propagation distances

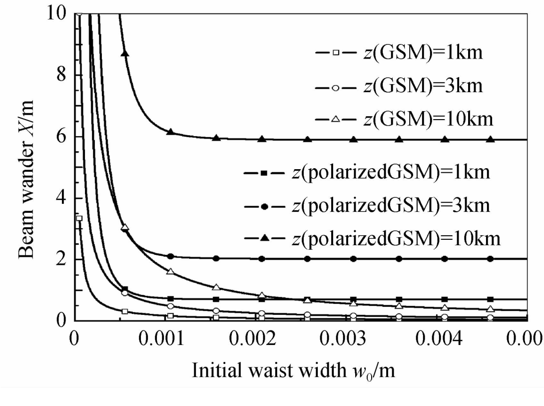

Fig. 6 Wander variation with initial waist width at given propagation distances

Fig. 7 and Fig. 8 show the spread and the wander of a beam at different laser wavelengths with changing distances when $\omega_0 = 5$ mm, $\delta_0 = 5$ mm. In contrast with GSM at different wavelengths, the beam′s expansion radius and barycentric position deflection of polarized GSM at different wavelengths are smaller.

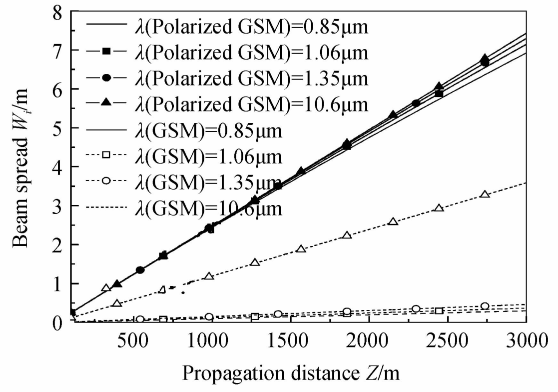

Fig. 7 Spread variation with propagating distance

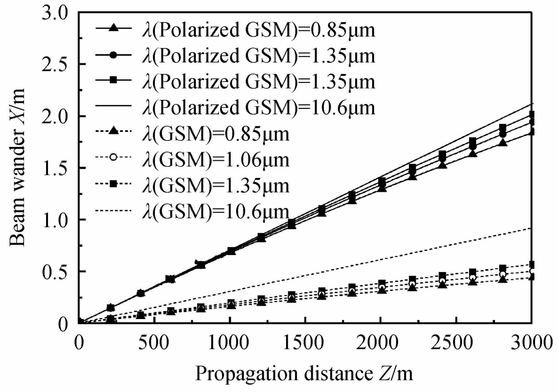

Fig. 8 Wander variation with propagating distance

3 Conclusion

Based on the extended Huygens-Fresnel Principle and Collins Formula, the analytical expression of the polarized GSM′s spectral intensity, expansion radius, and barycentric position deflection in turbulent atmosphere along horizontal propagation were determined using partially coherent GSM. The present study was conducted to investigate spread and wander characteristics of polarized and partially coherent laser in turbulent atmosphere. The main conclusions are as follows

1) With a given initial waist width and polarization angle in the range of $0^\circ < \theta \leqslant 45^\circ$, the expansion radius and the barycentric position deflection increase as the polarized angle decreases. Within the range of $45^\circ < \theta \leqslant 90$, the expansion radius and the barycentric position deflection decrease as the polarized angle decreases.

2) For a given polarization angle and with different initial waist widths, the expansion radius and the

barycentric position deflection do not change significantly as the propagation distance increases when $w_0 \geqslant 5$ mm.

3) At $w_0 < 5$ mm, with the different propagation distances and at a given polarization angle, the expansion radius and the barycentric position deflection apparently decrease as the initial waist width increases when the initial waist width is less than $w_0 \leqslant 0.5$ mm. When the initial waist width $w_0 \geqslant 0.5$ mm, the expansion radius and the barycentric position deflection remain virtually unchanged as the initial waist width changes.

4) As opposed to GSM at different wavelengths, spread and wander of a beam at different wavelengths of polarized GSM are lower.

Through analyzing the spread and wander phenomena of the polarized and partially coherent laser beams in turbulent atmosphere, it can be concluded that changes in characteristics of the polarization of partially coherent laser as beams propagate in the turbulent atmosphere do not affect spread and wander of a beam at $w_0 < 5$ mm. For polarized GSM at different wavelengths, spread and wander of beams are lower. Compared with general Gauss beams, this type of laser beams has a strong advantage in terms of the quality of spread and wander of beams during propagation. This study could provide theoretical basis to improve propagation quality of polarized laser in an external field of turbulent atmosphere, and play an important role in optical communication and in target recognition. Spread and wander caused by depolarization in turbulent atmosphere will be the next major discussion.

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