Evolutions of polarization of quasi-homogeneous beams propagating in Kolmogorov and non-Kolmogorov atmosphere turbulence

Feinan Chen (陈斐楠)[1], Qi Zhao (赵 琦)[1*], Jingjing Chen (陈晶晶)[1], Yanru Chen (陈延如)[1], Yu Xin (辛 煜)[1] , Jia Li (李 伽)[2], and Yanming Shao (邵艳明)[1]

[1]*Department of Optical Engineering, Nanjing University of Science and Technology, Nanjing 210094, China*

[2]*Institute of Fiber Optic Communication & Information Engineering, College of Information Engineering, Zhejiang University of Technology, Hangzhou 310014, China*

[*]*Corresponding author: zhaoqi@njust.edu.cn*

Received March 3, 2013; accepted March 27, 2013; posted online July 17, 2013

In the letter the polarization properties of quasi-homogenous (QH) beam propagating in Kolmogorov and non-Kolmogorov turbulence are studied. The results show that the polarization properties of QH beam undergoes three stages during the propagation in turbulence: in the "near field", the degree of polarization (Dop) and the state of polarization (Sop) fluctuate with source parameters and transverse position; after that the beam come to the "middle field" where its properties are affected by source parameters and turbulence perturbation; in the final "far field", the values come to constants which dependent only on source parameters.

OCIS codes: 010.1290, 010.1300, 030.7060, 260.2710.

doi: 10.3788/COL201311.S20101.

The beams generated by quasi-homogenous (QH) sources[1] are important models which have been studied and used widely today. The coherence and polarization properties of QH beam have been solved by Korotkova *et al.*[2]. Roychowdhury *et al.* found the invariance of spectrum of light generated by QH sources[3]. On the other hand, more and more work has been carried out on the beam propagation in turbulence recently. For example, the spreading and changes of the degree of coherence of partially coherent electromagnetic Gaussian Schell-model (EGSM) beam in atmosphere turbulence have been studied by Gbur*et al.*[4,5]. Not long ago, Wolf[6]pointed out the uniform theory of coherence and polarization, and the Stokes parameters were generalized from on-point quantities to two-point counterparts by Korotkova *et al.*[7]. After that it is more convenient to study the polarization properties of the beam propagation in random media[8−10]. In this letter, we find the "fluctuation" region and "stable" region of polarization properties of QH beams during the propagation. The variations of ellipses of the state of polarization (SOP) of such beams along the z-axis under different turbulence conditions are plotted and analyzed.

The beams generated by QH sources mean the spectral density $S^0(\mathbf{r})$ varies much more slowly with the position vector $\mathbf{r}$ than the correlation coefficients $\mu_{ij}^{(0)}(\mathbf{r},\omega)$ change with the difference of position vectors $\mathbf{r_1}-\mathbf{r_2}$[1,2]. So the cross spectral density of QH beams can be expressed as

$$\begin{aligned}\mathbf{W}^{(0)} &= W_{ij}^{(0)}(\mathbf{r_1},\mathbf{r_2},\omega)\\ &= \alpha_{ij}S^{(0)}\left[(\mathbf{r_1}+\mathbf{r_2})/2,\omega\right]\mu_{ij}^{(0)}(\mathbf{r_1}-\mathbf{r_2},\omega),\end{aligned} \quad (1)$$

where the superscript (0) denotes quantities pertaining to the incident field. The spectral density can be expressed as the trace of cross spectral density matrix: $S^{(0)}(\mathbf{r},\omega) = Tr\mathbf{W}^{(0)}(\mathbf{r_1},\mathbf{r_2},\omega)$, and α_{ij} depends only on frequency:

$$\alpha_{ij}=\begin{cases}\dfrac{1}{1+\alpha} & \text{when } i=j=x\\ \dfrac{\alpha}{1+\alpha} & \text{when } i=j=y\\ \dfrac{\sqrt{\alpha}}{1+\alpha} & \text{when } i\neq j\end{cases}. \quad (2)$$

Without loss of generality, Gaussian-Schell model is used to describe the spectral density and correlation coefficients:

$$S^{(0)}(\mathbf{r},\omega)=A\exp\left(-\mathbf{r}^2/2\sigma^2\right), \quad (3)$$

$$\mu(\mathbf{r_1},\mathbf{r_2},\omega)=B_{ij}\exp\left[\frac{(\mathbf{r_1}-\mathbf{r_2})^2}{2\delta_{ij}^2}\right], \quad (4)$$

where $A, B_{ij}, \sigma, \delta_{ij}$ are parameters independent of position but depend on frequency, B_{ij} represents the width of the source, and δ_{ij} represents the coherent width of source. Several conditions of the source must be satisfied in order to produce physical reliable QH beam[2,11].

The cross-spectral density matrix of beam propagation through turbulence can be derived by the extended Huygens-Fresnel principle:

$$\begin{aligned}&W_{ij}(\boldsymbol{\rho_1},\boldsymbol{\rho_2},z;\omega)=\frac{k^2}{4\pi^2z^2}\iint \mathrm{d}^2r_1\iint \mathrm{d}^2r_2W_{ij}^{(0)}\\ &(\mathbf{r_1},\mathbf{r_2},\omega)\exp\left[-\mathrm{i}k\frac{(\boldsymbol{\rho_1}-\mathbf{r_1})^2-(\boldsymbol{\rho_2}-\mathbf{r}_2)^2}{2z}\right]\\ &\langle\exp[\psi^*(\rho_1,\mathbf{r_1})+\psi(\boldsymbol{\rho_2},\mathbf{r_2})]\rangle_m,\end{aligned} \quad (5)$$

where $\mathbf{r_1}$, $\mathbf{r_2}$ are the position vectors of two points on the source plane, $\boldsymbol{\rho_1}$, $\boldsymbol{\rho_2}$ are two position vectors observation points on the receive plane, z is the propagation distance, and $k = \frac{2\pi}{\lambda}$ is the wave number of the beam. The last term describes the correlation function of complex phase perturbed by random media. The subscript m denotes the average over medium realization. $\Phi_n(\kappa)$ is the spatial spectral degree of refractive index fluctuations which traditionally described by Kolmogorov model, but the data from recent experiments in some portions of atmosphere such as free troposphere and stratosphere has shown significant deviations from this model, so non-Kolmogorov model was established to describe the turbulence in these parts of atmosphere.

$$\langle \exp[\psi^*(\boldsymbol{\rho_1}, \mathbf{r_1}) + \psi(\boldsymbol{\rho_2}, \mathbf{r_2})]\rangle_m = \exp\left\{-\frac{1}{3}\pi^2 k^2 z \int_0^\infty \kappa^3 \Phi_n(\kappa)\mathrm{d}\kappa[(\boldsymbol{\rho_1}-\boldsymbol{\rho_2})^2 + (\mathbf{r_1}-\mathbf{r_2})(\rho_1-\rho_2) + (\mathbf{r_1}-\mathbf{r_2})^2]\right\}. \quad (6)$$

For Kolmogorov model, the power spectrum is the function of refractive-index structure parameter C_n^2:

$$\Phi_n(\kappa) = 0.033 C_n^2 \kappa^{-11/3}. \quad (7)$$

For non-Kolmogorov model:

$$\Phi_n(\kappa,\alpha) = A(\alpha)\widetilde{C}_n^2 \frac{1}{(\kappa^2+\kappa_0^2)^{\frac{\alpha}{2}}} \exp\left(-\frac{\kappa^2}{\kappa_m^2}\right)$$
$$(0<\kappa<\infty, 3<\alpha<4), \quad (8)$$

where α is the power law, and $\widetilde{C}_n^2$ is the generalized refractive-index structure parameter which has the unit of $m^{3-\alpha}$; $\kappa_0 = \frac{2\pi}{L_0}, \kappa_m = \frac{c(\alpha)}{l_0}$, L_0 and l_0 are the out scale and inner scale of turbulence. $A(\alpha)$ and $c(\alpha)$ are defined as

$$A(\alpha) = \frac{1}{4\pi^2}\Gamma(\alpha-1)\cos\left(\frac{\alpha\pi}{2}\right),$$

$$c(\alpha) = \left[\Gamma\left(\frac{5-\alpha}{2}\right)A(\alpha)\frac{2\pi}{3}\right]^{\frac{1}{\alpha-5}}. \quad (9)$$

From Eq. (6), we set $H = \frac{1}{3}\pi^2 k^2 z \int_0^\infty \kappa^3 \Phi_n(\kappa)\mathrm{d}\kappa$ as a quantity to describe the strength of turbulence perturbation:

$$H = 0.49\left(C_n^2\right)^{6/5} k^{12/5} z^{6/5} \quad \text{(Kolmogorov model)}, \quad (10)$$

$$H = \frac{\pi^2 k^2 z}{6(\alpha-2)}A(\alpha)\widetilde{C}_n^2 \Gamma\left(2-\frac{\alpha}{2}, \frac{\kappa_0^2}{\kappa_m^2}\right)$$
$$\times\left\{-2\kappa_0^{(4-\alpha)} + \exp\left(\frac{\kappa_0^2}{\kappa_m^2}\right)\kappa_m^{(2-\alpha)}[(\alpha-2)\kappa_m^2 + 2\kappa_0^2]\right\}$$
$$\text{(non-Kolmogorov model)} \quad (11)$$

In the letter, we set the $C_n^2 = 10^{-13}m^{-2/3}$ for Kolmogorov turbulence and $\widetilde{C}_n^2 = 10^{-13}m^{3-\alpha}$ for non-Kolmogorov model.

It has been known that the spectral density, the degree of coherence and the degree of polarization (DOP) of a random electromagnetic beam may change on propagation. The polarization invariant properties of beam propagation were studied in 2007[16]. The far-zone behavior of DOP of electromagnetic beams in turbulence has been explored[17]. Since the non-Kolmogorov turbulence model has been introduced, some papers worked on the properties of beams propagating through this turbulence[18,19]. However, the change of the SOP, i.e., the size, the shape, and the orientation of the polarization ellipse of the polarized portion of the QH beam on propagation has not been investigated up to now. In the letter we study such changes of QH beams travel through different turbulence models. From Eq. (3) the cross spectral density matrix of the electromagnetic field on the receive plane can be written as

$$W_{ij}(\boldsymbol{\rho_1},\boldsymbol{\rho_2},z;\omega) = \frac{k^2}{4\pi^2 z^2}\iint \mathrm{d}^2\mathbf{r}_1 \iint \mathrm{d}^2\mathbf{r}_2$$
$$S^{(0)}\left[(\mathbf{r_1}+\mathbf{r_2})/2,\omega\right]\mu_{ij}^{(0)}(\mathbf{r_1}-\mathbf{r_2},\omega)$$
$$\exp\left\{-H(\alpha,z)[(\boldsymbol{\rho_1}-\boldsymbol{\rho_2})^2 + (\mathbf{r_1}-\mathbf{r_2})(\boldsymbol{\rho_1}-\boldsymbol{\rho_2}) + (\mathbf{r_1}-\mathbf{r_2})^2]\right\}$$
$$\exp\left[-\mathrm{i}k\frac{(\boldsymbol{\rho_1}-\mathbf{r_1})^2 - (\boldsymbol{\rho_2}-\mathbf{r}2)^2}{2z}\right]. \quad (12)$$

As a matter of convenience, we make changes of the spatial arguments:

$$\mathbf{r}^+ = (\mathbf{r_1}+\mathbf{r_2})/2, \quad \boldsymbol{\rho}^+ = (\boldsymbol{\rho_1}+\boldsymbol{\rho_2})/2,$$
$$\mathbf{r}^- = \mathbf{r_1}-\mathbf{r_2}, \quad \boldsymbol{\rho}^- = \boldsymbol{\rho_1}-\boldsymbol{\rho_2}. \quad (13)$$

With the help of Eq. (13), the cross spectral density matrix on the receive plane is derived as

$$W_{ij}(\boldsymbol{\rho_1},\boldsymbol{\rho_2},z;\omega) = \frac{k^2\sigma^2\alpha_{ij}AB_{ij}}{2z^2 M_{ij}}\exp\left[\left(\frac{N}{M_{ij}}-1\right)\frac{k\mathrm{i}}{z}\boldsymbol{\rho}^-\boldsymbol{\rho}^+\right]$$
$$\exp\left\{\left[\frac{N^2}{M_{ij}} - \frac{k^2\sigma^2}{2z^2} - H(\alpha,z)\right]\boldsymbol{\rho}^{-2} - \frac{k^2}{4z^2 M_{ij}}\boldsymbol{\rho}^{+}2\right\}, \quad (14)$$

where $M_{ij} = \frac{1}{2\delta_{ij}^2} + H(\alpha,z) + \frac{k^2\sigma^2}{2z^2}$; $N = (\frac{k^2\sigma^2}{2z^2} - \frac{H(\alpha,z)}{2})$.

The general stokes parameters are introduced to study the changes of polarization changes. They also can determine other coherence properties of the beam propagation in any linear medium:

$$S_0(\boldsymbol{\rho}_1,\boldsymbol{\rho}_2,\omega) = W_{xx}(\boldsymbol{\rho}_1,\boldsymbol{\rho}_2,\omega) + W_{yy}(\boldsymbol{\rho}_1,\boldsymbol{\rho}_2,\omega);$$
$$S_1(\boldsymbol{\rho}_1,\boldsymbol{\rho}_2,\omega) = W_{xx}(\boldsymbol{\rho}_1,\boldsymbol{\rho}_2,\omega) - W_{yy}(\boldsymbol{\rho}_1,\boldsymbol{\rho}_2,\omega);$$
$$S_2(\boldsymbol{\rho}_1,\boldsymbol{\rho}_2,\omega) = W_{xy}(\boldsymbol{\rho}_1,\boldsymbol{\rho}_2,\omega) + W_{yx}(\boldsymbol{\rho}_1,\boldsymbol{\rho}_2,\omega);$$
$$S_3(\boldsymbol{\rho}_1,\boldsymbol{\rho}_2,\omega) = -\mathrm{i}[W_{yx}(\boldsymbol{\rho}_1,\boldsymbol{\rho}_2,\omega) - W_{xy}(\boldsymbol{\rho}_1,\boldsymbol{\rho}_2,\omega)]. \quad (15)$$

If we only considered polarization properties of one point, *ie.*, $\boldsymbol{\rho}_1 = \boldsymbol{\rho}_2 = \boldsymbol{\rho}$, Eq. (14) is simplified to

$$W_{ij}(\boldsymbol{\rho}, z, \omega) = \frac{k^2\sigma^2\alpha_{ij}AB_{ij}}{2z^2M_{ij}} \exp\Big\{ -\frac{k^2}{4z^2M_{ij}}\boldsymbol{\rho}^2\Big\}. \quad (16)$$

Substituting Eq. (16) into Eq. (15), the analytical expressions of four generalized stokes parameters could be expressed as

$$\begin{aligned}
&S_0(\boldsymbol{\rho}, z, \omega) = \frac{Ak^2\sigma^2}{2z^2}\left[\frac{\alpha_{xx}}{M_{xx}}\exp\left(-\frac{k^2}{4z^2M_{xx}}\boldsymbol{\rho}^2\right)\right.\\
&\left.+\frac{\alpha_{yy}}{M_{yy}}\exp\left(-\frac{k^2}{4z^2M_{yy}}\boldsymbol{\rho}^2\right)\right];\\
&S_1(\boldsymbol{\rho}, z, \omega) = \frac{Ak^2\sigma^2}{2z^2}\left[\frac{\alpha_{xx}}{M_{xx}}\exp\left(-\frac{k^2}{4z^2M_{xx}}\boldsymbol{\rho}^2\right)\right.\\
&\left.-\frac{\alpha_{yy}}{M_{yy}}\exp\left(-\frac{k^2}{4z^2M_{yy}}\boldsymbol{\rho}^2\right)\right];\\
&S_2(\boldsymbol{\rho}, z, \omega) = \frac{Ak^2\sigma^2\alpha_{xy}}{2z^2M_{xy}}\\
&\left[\exp\left(-\frac{k^2}{4z^2M_{xx}}\boldsymbol{\rho}^2\right)(B_{xy}+B_{yx})\right];\\
&S_3(\boldsymbol{\rho}, z, \omega) = \frac{-\mathrm{i}^*Ak^2\sigma^2\alpha_{xy}}{2z^2M_{xy}}\\
&\left[\exp\left(-\frac{k^2}{4z^2M_{xy}}\boldsymbol{\rho}^2\right)(B_{xy}-B_{yx})\right].
\end{aligned} \quad (17)$$

From the conditions what we have mentioned above, we set $A = 1.5$, other parameters of the source are set as: $B_{xy} = 0.25\exp(\mathrm{i}\frac{\pi}{6})$, $B_{yx} = 0.25\exp(-\mathrm{i}\frac{\pi}{6})$, $\lambda = 0.6328$ μm, $\sigma = 1$ cm, $\delta_{xx} = 0.4$ mm, $\delta_{xy} = 0.2$ mm, $\delta_{xy} = \delta_{yx} = 0.2$ mm.

The first parameter we cared about is the DOP which used to describe the portion of an electromagnetic wave which is polarized. DOP=1 means perfectly polarized beam while DOP=0 means unpolarized beam.

$$P(\boldsymbol{\rho}, z, \omega) = \frac{\sqrt{S_1^2(\boldsymbol{\rho}, z, \omega) + S_2^2(\boldsymbol{\rho}, z, \omega) + S_3^2(\boldsymbol{\rho}, z, \omega)}}{S_0^{(\boldsymbol{\rho}, z, \omega)}}. \quad (18)$$

For different transverse points the changes of DOP with the propagation distance z under different turbulence conditions have shown in Fig. 1.

Figure 1 intimates that the turbulence effect on variations of DOP is similar to each other. The transverse coordinate $\boldsymbol{\rho}$ influence the DOP obviously when $z < 0.1$ km, but the affection will become weakness when $z > 0.1$ km.

In order to find out the influence of the source parameters on DOP changes, different δ_{xx}, δ_{yy} of QH beams are chosen, and the turbulence condition in each sub graph is set to be same: $L_0 = 10$ m , $l_0 = 1$ mm. The results are revealed in Fig. 2.

It can be easily found in Fig. 2 that the correlation widths δ_{xx}, δ_{yy} play crucial part in determining the change of DOP in turbulence. The value becomes a constant smaller or larger than initial value when $z > 10^6$ m in free space. However, in turbulence, the final value is equal to initial value. The phenomenon is so called "self-reconstructed" of polarization properties of QH beams propagating in turbulence.

The polarization ellipse describes the SOP of the fully polarized portion of the beam. The azimuth angle θ is defined by the smallest angle formed by the positive x-direction and the direction of major semi-axis of the ellipse and the value ε is the ratio of major semi-axis and the minor semi-axis which determines the shape of the ellipse.

$$\begin{aligned}
&\theta(\boldsymbol{\rho}, z, \omega) = \frac{1}{2}\arctan\left[\frac{S_2(\boldsymbol{\rho}, z, \omega)}{S_1(\boldsymbol{\rho}, z, \omega)}\right],\\
&\varepsilon(\boldsymbol{\rho}, z, \omega) =\\
&\frac{1}{2}\arcsin\left[\frac{S_3(\boldsymbol{\rho}, z, \omega)}{\sqrt{S_1^2(\boldsymbol{\rho}, z, \omega) + S_2^2(\boldsymbol{\rho}, z, \omega) + S_3^2(\boldsymbol{\rho}, z, \omega)}}\right].
\end{aligned} \quad (19)$$

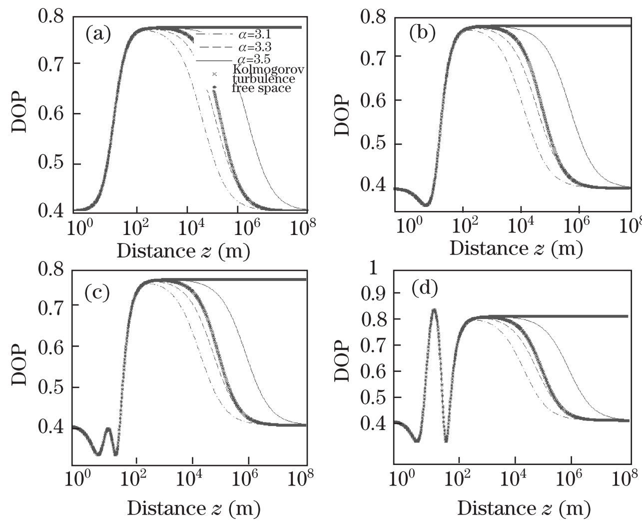

Fig. 1. DOP changes with distance of different transverse points: (a) $\boldsymbol{\rho} = 0$; (b) 0.02; (c) 0.03; (d) 0.04 m.

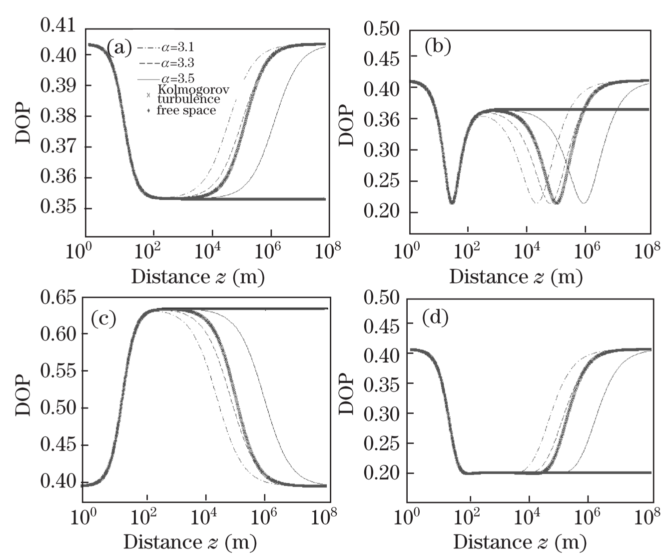

Fig. 2. On-axis DOP changes of QH beam with different source parameters. (a) $\delta_{xx} = 0.3$ mm, $\delta_{yy} = 0.3$ mm; (b) $\delta_{xx} = 0.2$ mm, $\delta_{yy} = 0.4$ mm; (c) $\delta_{xx} = 0.3$ mm, $\delta_{yy} = 0.2$ mm; (d) $\delta_{xx} = 0.2$ mm, $\delta_{yy} = 0.3$ mm.

The changes of θ and ε were plotted in Fig. 3. According to the results that we have obtained above, we only considered three turbulence conditions. Just like the changes of DOP, the changes of transverse SOP with different turbulence conditions are different for each transverse position when $z < 0.1$ km, but it become same to each other when 0.1 km$< z < 10$ km, at last it will become constant when $z > 10^3$ km.

The variations of polarization ellipses on-axis are shown in Fig. 3. The difference is very small at $z = 1$ km but it becomes obviously when the distance increase to 10 km.

The azimuth angle of polarization ellipses come to two values: one is in turbulence, the other is in free space. The length of semi-axis also shows discrimination: the length of semi-axis decreases much more in turbulence than free space. We have plotted the polarization ellipses affected by different turbulence perturbations in Fig. 4.

The source parameters were chosen as: $\delta_{xx} = 0.4$ mm, $\delta_{yy} = 0.2$ mm and $\delta_{xx} = 0.2$ mm, $\delta_{yy} = 0.4$ mm. Because what we cared about are polarization fluctuations of QH beams so we neglected the energy attenuation so the length of semi-axis has been normalized in order to display SOP variations clearly.

From Fig. 4 we can see that the ellipses vary in atmosphere turbulence and free space. The polarization ellipses under different turbulence conditions get obviously discrimination in the region of $z = 10^4$ to 10^6 m, but they will be closer to each other when $z > 10^6$ m. The parameters of source effect the variation importantly in the region 10^4 m$< z < 10^6$ m and determine the final ellipses when $z > 10^6$ m. Compared Figs. 4(a) and (b), we can find that the evolution of ellipses are obviously different because the difference of δ_{xx} and δ_{yy}. And the ellipses in Fig. 4(a) seem more stable than the ellipses in Fig. 4(b) So the ellipses of SOP of QH beams can be controlled by the choice of source parameters.

In conclusion, we study the changes of the DOP and the SOP for several source parameters of QH beams propagating through atmosphere turbulence. Generally, the DOP and SOP of QH beams are affected by two

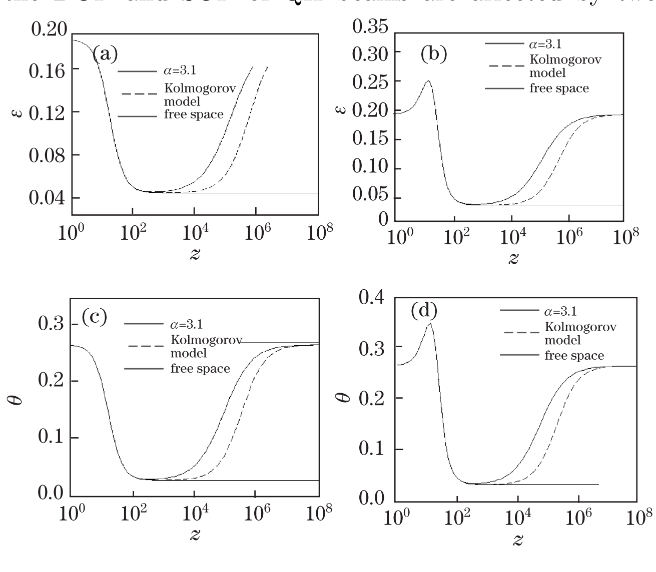

Fig. 3. Changes of SOP at different transverse points with distance $\boldsymbol{\rho}$ of (a) 0; (b) 0.02; (c) 0; (d) 0.02 m.

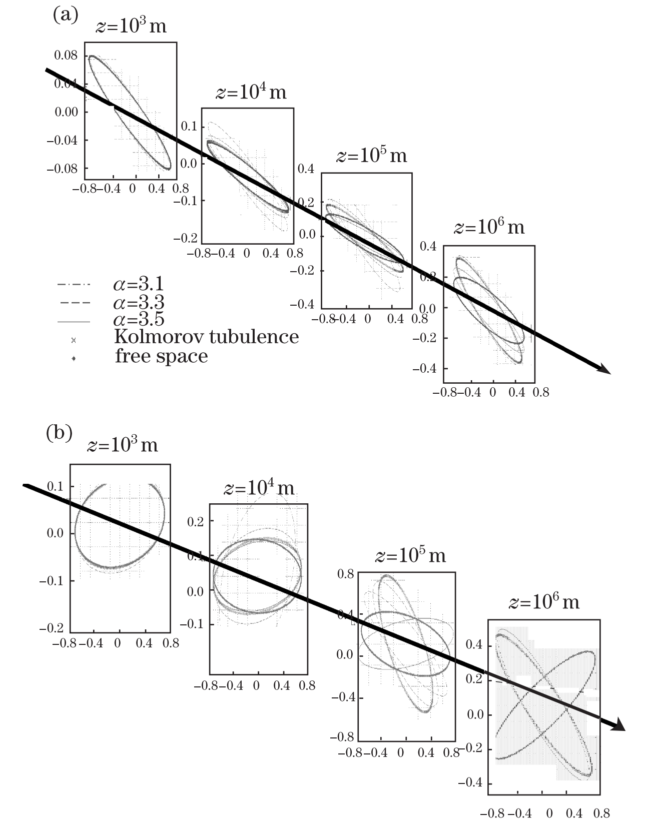

Fig. 4. Variation of polarization ellipses with distance in different turbulence models. (a) $\delta_{xx} = 0.4$ mm, $\delta_{yy} = 0.2$ mm, $\delta_{xy} = \delta_{yx} = 0.2$ mm; (b) $\delta_{xx} = 0.2$ mm, $\delta_{yy} = 0.4$ mm, $\delta_{xy} = \delta_{yx} = 0.2$ mm.

mechanisms: one is the transverse position which affect the changes in the near field; the other is turbulence perturbation which affect the polarization properties in the middle field, but both SOP and DOP "self-reconstructed" to initial value when the beam have propagated a sufficient long distance. Different turbulence model or turbulence condition has similar affection of variation. However, in free space, the final values of these quantities are not same to initial values. At last, the correlation lengths of QH beams play important rule in the variations of polarization properties of QH beam through the propagation. Our work domonstrates the chosen of source parameters is important in the control of polarization characteristics of the beam propagation in turbulence. The results of the letter will help us to use polarization optical communication or imaging system in atmosphere.

The work was supported by the National Natural Science Foundations of China under Grant Nos. 61077012, 61107011, 61205121.

References

1. L. Mandel and E. Wolf, *Optical Coherence and Quantum Optics* (Cambridge University Press, Cambridge, 1995) pp. 190.
2. O. Korotkova, B. G. Hoover, V. L. Gamiz, and E. Wolf, J. Opt. Soc. Am. A **22,** 2547 (2005).
3. H. Roychowdhury and E. Wolf, Opt. Comm. **241,** 11 (2004).

4. G. Gbur and E. Wolf, J. Opt. Soc. Am. A **19,** 1592 (2002).
5. W. Lu, L. Liu, J. Sun, Q. Yang, and Y. Zhu, Opt. Commun. **271,** 1 (2007).
6. E. Wolf, Phys. Lett. A **312,** 263 (2003).
7. O. Korotkova and E. Wolf, Opt. Lett. **30,** 198 (2005).
8. M. Salem, O. Korotkova, A. Dogariu, and E. Wolf, Waves Random Media **14,** 513 (2004).
9. X. Y. Du and D. M. Zhao, Opt. Comm. **281,** 5968 (2008).
10. J. Li, C. Ding, and B. Lü, Appl. Phys. B **103,** 245 (2011).
11. O. Korotkova, M. Salem, and E. Wolf, Opt. Lett. **29,** 1173 (2004).
12. B. E. Stribling, B. M. Welsh, and M. C. Roggemann, Proc. SPIE **2471,** 181 (1995).
13. G. Wu, H. Guo, S. Yu, and B. Luo, Opt. Lett. **35,** 715 (2010).
14. A. Zilberman, E. Golbraikh, and N. S. Kopeika, Appl. Opt. **47,** 6385 (2008).
15. N. S. Kopeika, A. Zilberman, and E. Golbraikh, Proc. SPIE **7463,** 746307 (2009).
16. E. Wolf, Opt. Lett. **32,** 3400 (2007).
17. I. Toselli, B. Agrawal, and S. Restaino, J. Opt. Soc. Am. A **28,** 483 (2011).
18. E. Shchepakina and O. Korotkova, Opt. Express **18,** 10650 (2010).
19. A. Zilberman, E. Golbraikh, and N. S. Kopeika, Opt. Commun. **283,** 1229 (2010).