Experimental measurement of scintillation index of vortex beams propagating in turbulent atmosphere*

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The scintillation indices (SIs) of Gaussian beams and vortex beams propagating in turbulent atmosphere are investigated experimentally. It is shown that with the increase of propagation distance, the SI of Gaussian beam around optical axis increases gradually, but the SI of vortex beam with topological charge of 4 increases, achieves the maximum value at a fixed distance, and then decreases as the continued increase of propagation distance. The SI of vortex beam can be smaller than that of Gaussian beam under certain conditions.

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The intensity of optical beams will fluctuate when they pass through random medium because of the distortions of the phase structure of wavefield by the medium[1-3]. The fluctuation in the intensity of beams can degrade the performance of free-space optical communication systems. It has been shown that the scintillation reduction can be realized by modulating the coherence, the polarization and the phase of input optical beams[4]. The scintillation index (SI) of partially coherent beam can be smaller than that of completely coherent beam[4-6]. The SI of optical beams on propagation in turbulence is influenced by the polarization state of beams as well. Gu et al[7] showed that an appropriately chosen non-uniformly polarized coherent optical field can have appreciably smaller scintillation than comparable beams of uniform polarization. Another option for scintillation reduction is the use of beam arrays[8].

Beams with spiral phase are known as vortex beams, and each photon of vortex beams carries orbital angular momentum (OAM)[9]. The interest in propagation of vortex beams through turbulent atmosphere has increased in recent years because of the potential applications in optical communications. Gibson et al[10] proposed that the orbital angular momentum of vortex beams can be used as information carrier. Such an application provides a possibility to increase the information density together with an inherent security enhancement. However, most of studies on propagation properties of vortex beams through atmosphere are limited to theoretical derivations. In this paper, we experimentally study the propagation of vortex beams in atmospheric turbulence. Particular interest is paid to the SI of vortex beams with different topological charges. It is found that in the certain situation, the SI of the vortex beams is smaller than that of Gaussian beams.

The schematic diagram of the experimental configuration is shown in Fig.1. The incident He-Ne laser beam with wavelength of 633 nm is expanded by a telescope system constructed by two lenses of L_1 and L_2, whose focal lengths are 5 cm and 30 cm, respectively. Vortex beams are generated by propagating the expanded laser beam through a spiral phase plate (SPP). The topological charge of the vortex beam is determined by the structure of the SPP. The generated vortex beam then propagates through the turbulent atmosphere. The intensity of laser beam fluctuates on propagation in turbulent atmosphere because of the distortions of the phase structure of wavefield by the turbulence. A detector (D) for measuring the scintillation is employed, which contains an opto-electron detector with aperture of 5 mm×5 mm. A personal computer (PC) is connected to the detector to record the magnitude of the SI.

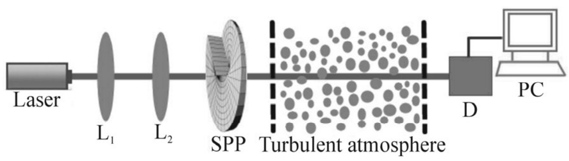

Fig.1 Experimental schematic diagram of vortex beams on propagation in turbulent atmosphere

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The experiments were carried out along an outdoor path during two different nights. Because of the environmental limitation, the maximum propagation distance of the path is limited to 400 m. The fluctuation of Gaussian beam intensity in one night is weaker than that in the other night. Hereafter, the turbulent atmosphere in which the Gaussian beam has a weaker fluctuation is denoted as “turbulent atmosphere I”, and that in which the Gaussian beam has a stronger fluctuation is denoted as “turbulent atmosphere II”.

According to previous study[1], the SI of the beam in a single location of the receiver plane is defined as

$$\sigma^2(x,y,z)=\frac{\left\langle I^2(x,y,z)\right\rangle-\left\langle I(x,y,z)\right\rangle^2}{\left\langle I(x,y,z)\right\rangle^2}. \tag{1}$$

SIs of a Gaussian beam and two vortex beams with topological charges of 1 and 4 passing through turbulent atmosphere are experimentally measured. We adjust the optical system and the receiving detector, so that the detector is located in the center of the beam. Owing to a limited size of the opto-electron detector, the obtained SI actually presents the fluctuation of light reaching a small area near optical axis of the detector, which means that the scintillation refers to area SI. Recently, the aperture averaged scintillation is proposed to study the scintillation of an area, which is defined as[11]

$$\sigma_a^{\,2}(z)=\frac{\left\langle P^2(z)\right\rangle-\left\langle P(z)\right\rangle^2}{\left\langle P(z)\right\rangle^2}, \tag{2}$$

where

$$P(z)=\int\int I(x,y,z)\mathrm{d}x\mathrm{d}y. \tag{3}$$

Fig.2 presents the evolution of SI with propagation distance in the “turbulent atmosphere I” for vortex beams with different topological charges. We find that the received light intensity across the detector fluctuates for the beam propagating through the turbulent atmosphere and finally reaches the detector. Therefore, the experimental data are changed during the measurements. The value of the SI at a certain distance is the average of SI during the measurements, and the upper and lower bars of the SI represent the maximum and minimum values of the scintillation at the distance. It is found that the SI of a Gaussian beam increases gradually as the propagation distance increases from 100 m to 400 m. The evolution of SI of the vortex beam with topological charge of m=1 is similar to that of a Gaussian beam, but the SI of the vortex beam with topological charge of m=4 increases and then decreases with increasing distance. In particular, it is interesting to notice that the SI at propagation distance of 400 m is smaller than that at propagation distance of 100 m for the vortex beam with m=4. It can be concluded from the experimental measurement that at the distance of 400 m, the larger the topological charge of a vortex beam, the larger the SI.

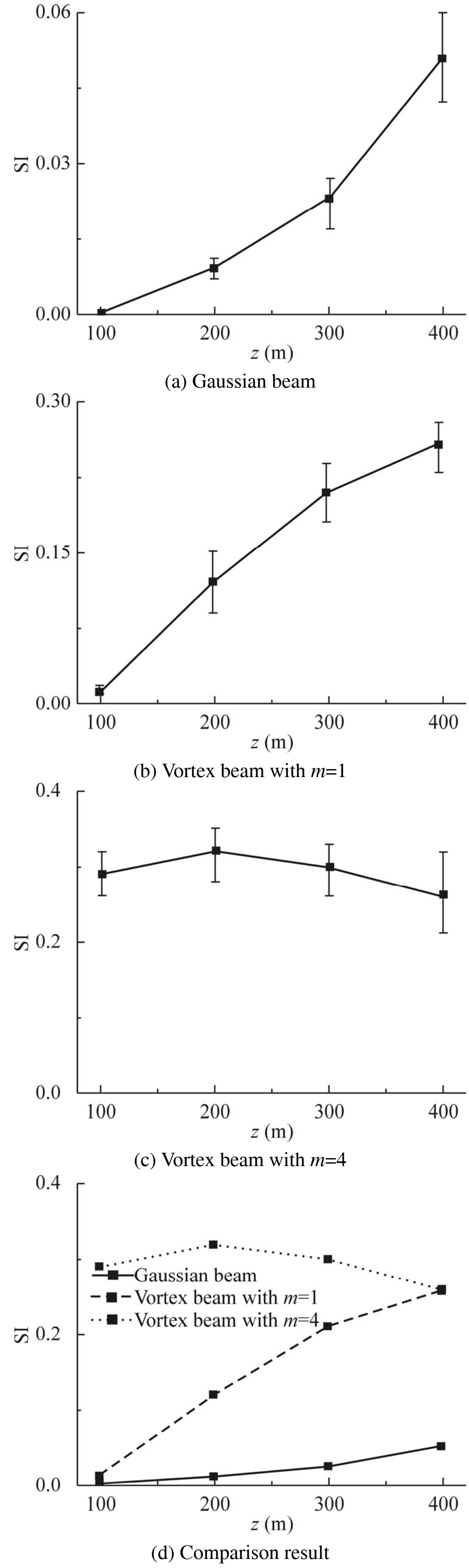
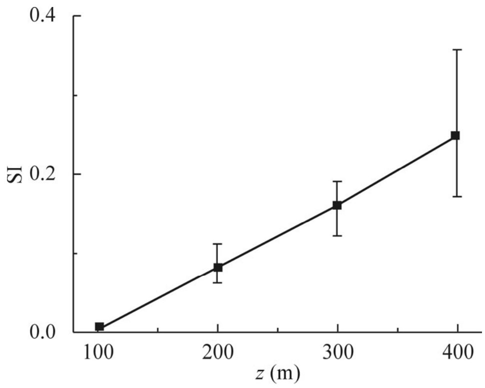
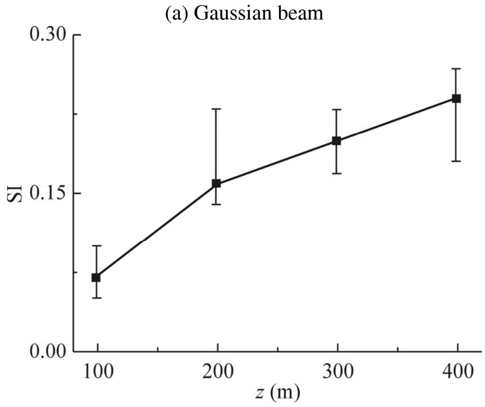


Fig.2 Scintillation indices of beams in “turbulent atmosphere I”

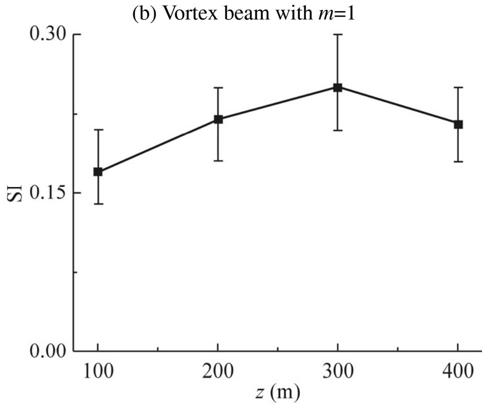
The SI of beams in the “turbulent atmosphere II” is presented in Fig.3. It can be found that at propagation distance of 400 m, the SI of the vortex beam with topological charge of 4 is smaller than those of the vortex beam with topological charge of 1 and the Gaussian beam. This conclusion is different from that obtained in "turbulent atmosphere I". It is known that the scintillation of a Gaussian beam increases with the increase of propagation distance in turbulence. According to the evolution tendency, the SI of vortex beam with m=4 in "turbulent atmosphere I" may also be smaller than that of a Gaussian beam at a longer propagation distance. However, because of the environmental limitation, the maximum propagation distance in the experiment is limited to 400 m. The experimental study carried out in a thermally induced turbulence shows that the SI of Gaussian-Schell model vortex (GSMV) beam with topological charge is smaller than that of Gaussian-Schell model (GSM) beam, and the SI decreases with the increase of topological charge. Moreover, the advantage of a GSMV beam over a GSM beam is enhanced with the increase of the strength of turbulence[12].



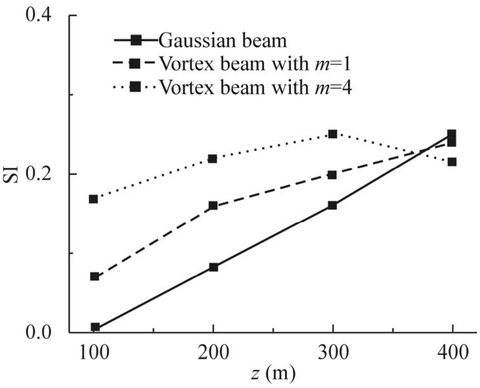
(a) Gaussian beam



(b) Vortex beam with m=1



(c) Vortex beam with m=4

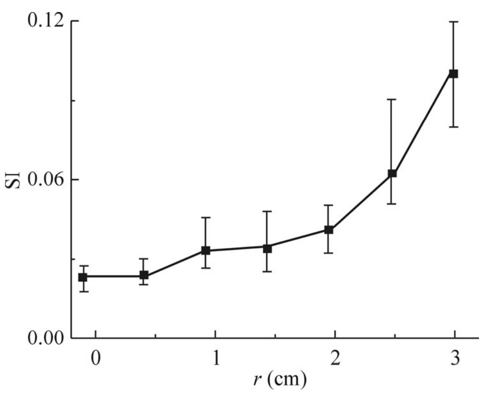


(d) Comparison result

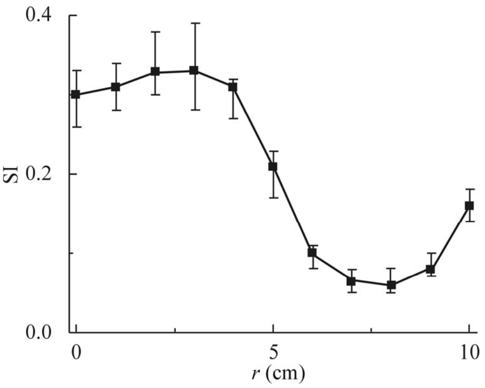
Fig.3 Scintillation index of beams in "turbulent atmosphere II"

It can be found by comparing the experimental measurement results in Figs.2 and 3 that the SI of the Gaussian beam in "turbulent atmosphere II" is larger than that in the "turbulent atmosphere I". However, the SI of the vortex beam with topological charge of 4 in the "turbulent atmosphere II" is smaller than that in the "turbulent atmosphere I". It is known that the vortex beam has donut shape irradiance distribution. The dark core is filled with light on propagation in turbulent atmosphere, and finally evolves into a Gaussian shape after a sufficiently long propagation distance. Clearly, this effect is stronger in a stronger turbulence. Therefore, the intensity in the central area of vortex beams in stronger turbulence can be stronger than that in weaker turbulence at a short propagation distance. In addition, it should be noticed that different from the theoretical study, the SI in the experiment is measured by the detector, and the noise of the detector influences the SI obtained by the detector. This influence is more serious in low intensity case. These features can explain why the SI of the vortex beam with topological charge of 4 is smaller in stronger turbulence.

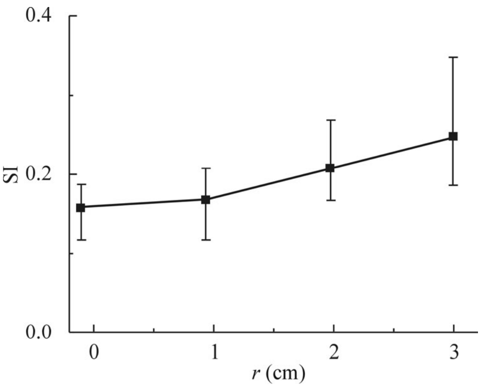
In Fig.4, we show the variation of SI value with the radial position at the observation plane with propagation distance of 300 m, in which the radial position denoted by "r" presents the distance between the center of the detector and the optical axis. It is shown that the SI of the



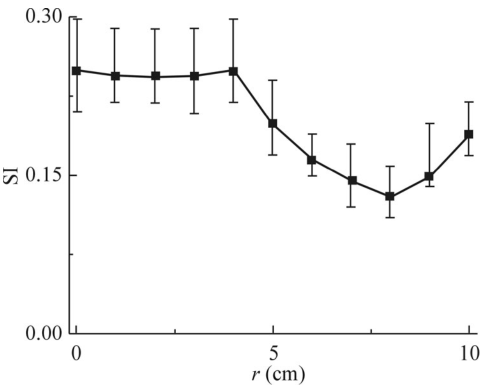
(a) Gaussian beam in "turbulent atmosphere I"



(b) Vortex beam with *m*=4 in “turbulent atmosphere I”



(c) Gaussian beam in “turbulent atmosphere II”



(d) Vortex beam with *m*=4 in “turbulent atmosphere II”

Fig.4 Scintillation indices of beams at propagation distance of 300 m

Gaussian beam increases with increasing *r*, but the SI of the vortex beam with topological charge of 4 is nearly invariant when *r* increases from 0 cm to 4 cm, then decreases and reaches minimum when *r*=8 cm, and then increases again. The experimental measurement results are consistent with the theoretical predictions of Ref.[13].

In conclusion, the SIs of a Gaussian beam and two vortex beams over a 400 m propagation path in turbulent atmosphere are experimentally measured. With the propagation distance increasing from 100 m to 400 m, the SI of the Gaussian beam increases gradually, and the SI of the vortex beam with topological charge of 4 increases first and then decreases. It is shown that the SI of vortex beam is larger than that of Gaussian beam in “turbulent atmosphere I”, but is smaller than that of Gaussian beam after propagating 400 m in the “turbulent atmosphere II”. Besides that, it is found that the SI of the Gaussian beam at distance of 400 m in “turbulent atmosphere II” is larger than that in “turbulent atmosphere I”, but the SI of the vortex beam with topological charge of 4 in “turbulent atmosphere II” is smaller than that in “turbulent atmosphere I”.

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