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Numerical simulation of super-continuum laser propagation in turbulent atmosphere*

Ya-Qian Li(李雅倩)[1,2,3], Wen-Yue Zhu (朱文越)[1,3], and Xian-Mei Qian(钱仙妹)[1,3,†]

[1] *Key Laboratory of Atmospheric Optics, Anhui Institute of Optics and Fine Mechanics, HFIPS, Chinese Academy of Sciences, Hefei* 230031, *China*
[2] *Science Island Branch of Graduate School, University of Science and Technology of China, Hefei* 230026, *China*
[3] *Advanced Laser Technology Laboratory of Anhui Province, Hefei* 230037, *China*

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Considering the atmospheric extinction and turbulence effects, we investigate the propagation performances of super-continuum laser sources in atmospheric turbulence statistically by using the numerical simulation method, and the differences in propagation properties between the super-continuum (SC) laser and its pump laser are also analyzed. It is found that the propagation characteristics of super-continuum laser are almost similar to those of the pump laser. The degradation of source coherence degree may cause the relative beam spreading and scintillation indexes to decrease at different propagation distances or different turbulence strengths. The root-mean-square value of beam wandering is insensitive to the variation of source correlation length, and less aperture averaging occurs when the laser source becomes less coherent. Additionally, from the point of view of beam wandering, the SC laser has no advantage over the pump laser. Although the pump laser can bring about a bigger aperture average, the SC laser has a lower scintillation which may be due to the multiple wavelength homogenization effects on intensity fluctuations. This would be the most important virtue of the SC laser that can be utilized to improve the performance of laser engineering.

Keywords: super-continuum laser source, pump laser source, numerical simulation, atmospheric propagation properties

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1. Introduction

High brightness and wide spectrum are the advantages of super-continuum laser sources,[1–6] which are widely used in laser engineering applications, such as laser remote sensing, free-space optical communication, hyper-spectral light detection and ranging (LIDAR) and laser guidance.[7–10] It is believed that the distortions of atmospheric turbulence can lead beam spreading, beam wandering, and scintillation to have significant negative influence on practical applications due to random variation in the refractive index of the atmosphere. Therefore, comprehensive researches of the propagation characteristics of super-continuum (SC) laser sources in atmospheric turbulence are most important for the practical applications of super-continuum.

So far, the more mature technology is based on the spectral absorption characteristics of SC laser to study its applications in the detection of atmospheric composition.[11–13] Nevertheless, the characteristics of SC laser propagating through the atmosphere are rarely studied. On the assumption that the beam qualities of different wavelength components of SC laser are identical, Li *et al.* (2010)[14] numerically studied the influence of turbulence on the Strehl ratio of SC laser. The results showed that the Strehl ratio of SC laser is greatly affected by atmospheric turbulence. The effect, especially, on its short-wave components is more serious. Four years later, taking into account the atmospheric refraction, extinction, and turbulence, Wu *et al.* (2014)[15] numerically calculated the beam width and propagation efficiency of SC laser source in a slant path through the turbulent atmosphere. Then, Kang (2015)[16] experimentally measured the centroid drift of SC laser source after propagating for 1 km. The results revealed that beam wandering of the SC laser is the same as that of the monochromatic laser, in other words, the horizontal drift is smaller than the vertical one. However, to the best of our knowledge, theoretical analysis or experimental studies on other turbulent effects of SC laser sources (*e.g.*, instantaneous scintillation effects) has not been conducted before. Furthermore, the universal law of the influence of turbulence on propagation characteristics of SC laser is not clear at all.

On the one hand, most of theoretical researches on the propagation of laser sources in turbulence are only applicable to weak turbulence conditions because of the assumption of small perturbations. On the other hand, uncontrollable experimental conditions make it so difficult to obtain an ensemble average. Recently, numerical simulation method has become an important way to investigate the laser propagation in turbulent atmosphere. In this paper, according to the propagation theory of partially coherent beams, based on

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†Corresponding author. E-mail: qianxianmei@aiofm.ac.cn
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the Maxwell equation and atmospheric radiance transfer equations, the characteristics of beam spreading, beam wander and intensity scintillation of SC laser sources are analyzed by using the multiple phase screen method. Difference in propagation property between SC laser source and their pump laser source is also discussed.

2. Numerical simulation approach

We use a superposition of narrow-band spectral components to simulate the super-continuum spectrum.[17] According to the atmospheric radiation transmission theories of partially coherent beams, the superposition of propagation results of each narrowband spectral component is taken as the ultimate total value of SC laser at the receiver.

Based on the parabolic approximation and the Maxwell equation, the optical field E in turbulence satisfies

$$\frac{\partial E}{\partial z}+\frac{1}{2\mathrm{i}k}\nabla_{\perp}^{2}E+\mathrm{i}k(1-n)E=0, \tag{1}$$

where n is the variation of the refractive index, $k=2\pi/\lambda$ is the wave number, λ is the wavelength, and ∇^2 is called the Laplacian operator. The multiple phase screen and Fourier transform method[18–20] is widely used to solve Eq. (1) and to realize the dynamic propagation of an optical wave beam. The laser propagation distance L is divided into N segments, each with a thickness of Δz. For a homogeneous atmospheric path, the medium may be modeled by identical spaced phase screens, so the distance between two phase screens is $\Delta z = L/N$. The phase variation due to the turbulence of each phase screen is $s(\boldsymbol{r},\Delta z)=k\int_{z_{i-1}}^{z_i} n_1(\boldsymbol{r},\boldsymbol{z}')\,\mathrm{d}\boldsymbol{z}'$ $(\Delta z=z_i-z_{i-1})$ and the phase spectrum can be described by

$$\boldsymbol{\Phi}_S(\kappa_x,\kappa_y)=2\pi k^2\Delta z\boldsymbol{\Phi}_n(\kappa_x,\kappa_y,0), \tag{2}$$

where $\boldsymbol{\Phi}_n$ is the spectrum of the refractive index of the atmosphere, κ_x and κ_y are the wave numbers. For a Kolmogorov turbulence $\boldsymbol{\Phi}_n=0.33C_n^2\boldsymbol{\kappa}^{-11/3}$, where $\boldsymbol{\kappa}=\sqrt{\kappa_x^2+\kappa_y^2+\kappa_z^2}$ and C_n^2 is the construct constant of atmospheric refractive index. The optical field at position z_i can be expressed as[21]

$$\begin{aligned}\boldsymbol{E}(r,z_i,\lambda) &= F^{-1}\Big\{F\{\boldsymbol{E}(\boldsymbol{r},z_{i-1},\lambda)\exp[\mathrm{i}s(\boldsymbol{r},\Delta z)]\}\\ &\quad\times\exp\left\{-\mathrm{i}\frac{\lambda\left(\kappa_x^2+\kappa_y^2\right)}{4\pi}\Delta z\right\}\Big\},\end{aligned} \tag{3}$$

where F and F^{-1} are the Fourier transform and the inverse Fourier transform, respectively, and $\boldsymbol{r}$ is the position vector on the phase screen. By using the phase screen transfer method, we can obtain the final optical field $\boldsymbol{E}(\boldsymbol{r},L,\lambda)$ on the objective plane. Thus, the total intensity distribution of SC laser at propagation distance $z=L$ can be written as

$$\begin{aligned}I(\boldsymbol{r},L) &= \int_{\lambda_1}^{\lambda_2} I(\boldsymbol{r},L,\lambda)\,\mathrm{d}\lambda\\ &= \int_{\lambda_1}^{\lambda_2} T(\lambda,L)\,|\boldsymbol{E}(\boldsymbol{r},L,\lambda)|^2\,\mathrm{d}\lambda\\ &= \int_{\lambda_1}^{\lambda_2}\left[\exp-\int_0^L \nu(\lambda,z)\,\mathrm{d}z\right]|\boldsymbol{E}(\boldsymbol{r},L,\lambda)|^2\,\mathrm{d}\lambda,\end{aligned} \tag{4}$$

where $I(\boldsymbol{r},L,\lambda)$ is the intensity distribution of each spectral component at propagation distance $z=L$, $T(\lambda,L)$ is the transmittance, $\nu(\lambda z)$ is the attenuation factor, and $[\lambda_1,\lambda_2]$ is the spectral range of SC laser source.

The SC laser is a special kind of partially coherent beam. Analytically, its partial coherence can be described by the coherence parameter of a partially coherent beam. As proposed in many publications, the partial coherence can be modeled by the random phase screen assumed to be $\zeta(x,y;t)$, which changes randomly with time. Thus, the initial optical field of a partially coherent beam can be expressed as

$$\boldsymbol{E}(x,y,0;t)=\boldsymbol{E}_0(x,y,0)\exp[\mathrm{i}\varsigma(x,y;t)], \tag{5}$$

where $\boldsymbol{E}_0(x,y,0)$ is the initial optical field of a homologous fully coherent beam. For illustration purpose, we discuss the spatially partially coherent GSM beam which is an analytically tractable model where the spatial coherence function is Gaussian.[22]

The random phase can be modeled as[23]

$$\varsigma(x,y;t)=r(x,y;t)\otimes n(x,y), \tag{6}$$

where $\otimes$ indicates a spatial convolution, $r(x,y;t)$ is the spatially uncorrelated random signal with an average 0 and a standard deviation σ_r, $n(x,y)$ is a Gaussian distribution function with standard deviation σ_n

$$n(x,y)=\frac{1}{2\pi\sigma_n^2}\exp\left(-\frac{x^2+y^2}{2\sigma_n^2}\right), \tag{7}$$

thus from Eqs. (6) and (7), the transmittance auto-correlation function can be obtained to be

$$R(\boldsymbol{r}_1,\boldsymbol{r}_2)\approx\langle\exp[\mathrm{i}\varsigma(\boldsymbol{r}_1;t)]\exp[-\mathrm{i}\varsigma(\boldsymbol{r}_2;t)]\rangle_t, \tag{8}$$

under the condition of $\sigma_r^2/\left(4\pi\sigma_n^2\right)\gg 1$, equation (8) can be approximated as

$$R(\boldsymbol{r}_1,\boldsymbol{r}_2)\approx\exp\left(\frac{-\rho^2\sigma_r^2}{16\pi\sigma_n^4}\right), \tag{9}$$

lateral correlation radius l_{c} determines the spectral degree of source coherence and it can be expressed as

$$l_{\mathrm{c}}=\sqrt{\frac{16\pi\sigma_n^4}{\sigma_r^2}}. \tag{10}$$

For a completely coherent beam, l_c tends to infinity, and with the degradation of l_c, the degree of source coherence degrades. In our study, we assume that the coherent degree of each wavelength component of the whole super-continuum spectrum is identical.

3. Numerical simulation results and analysis

The normalization spectrum distribution of the SC laser is shown in Fig. 1, and its spectrum covers the range from 450 nm to 2000 nm. The pump laser we choose is a monochromatic partially (spatial) coherent beam, and its emission aperture is the same as that of the SC laser, *i.e.*, $D_0 = 50$ mm. The wavelength of the pump laser is 1064 nm. The atmospheric model used here is the mid-latitude summer and a rural aerosol model with 23-km visibility.

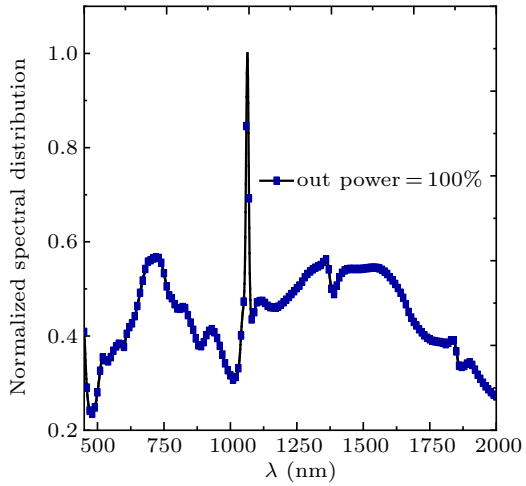


Fig. 1. Normalization spectrum distribution of super-continuum source (450 nm–200 nm).

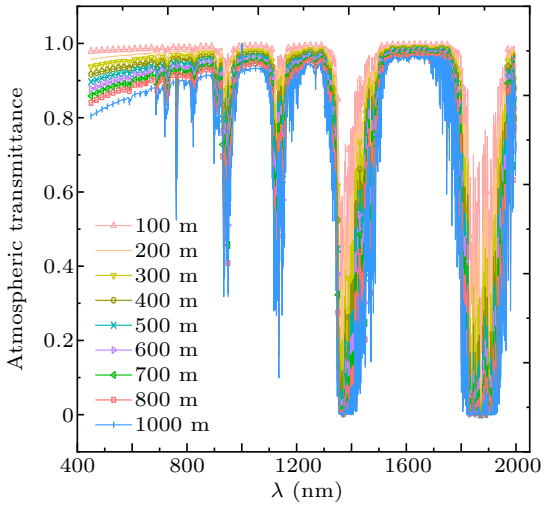


Fig. 2. Variations of atmospheric transmittance with wavelength for different propagation distances in turbulence.

Figure 2 shows the curves of atmospheric transmittance *versus* wavelength λ at different propagation distances. In this paper, we use the wavelength segmentation method to simulate the super-continuum spectrum. Considering these factors such as the spectral distribution of SC laser, the atmospheric transmittance of each spectral segment, and the influences of different wavelengths on the propagation characteristics of a laser beam. For the band with stable transmittance, we set the wavelength interval $\Delta\lambda = 20$ nm, while in the band with the unstable change, we set $\Delta\lambda = 1$ nm. In a turbulent atmosphere, we assume that during the period that atmospheric turbulence has changed once, the random phase screen $\zeta(x,y;t)$ has changed K times, where K is the relative modulation frequency of random phase screen to turbulence frequency, in this paper, the relative modulation frequency is chosen to be $K = 10$. A kolmogorov power-law spectrum is assumed, and the propagation paths involved in this paper are all horizontal paths. Every calculated point in the following figures is the statistic average result of 300 simulation realizations.

3.1. Beam spreading effect

The beam spreading of the SC laser is different from that of a monochromatic partially (spatial) coherent laser. In this part, we study the characteristics of beam spreading of SC laser source propagation in turbulent atmosphere, and discuss the differences in beam spreading between SC laser source and their pump laser source.

The effective beam radius in a particular z plane can be written as[24]

$$\begin{aligned} W^2 &= 2\iint \left[\sqrt{(x-x_c)^2+(y-y_c)^2}\right]^2 I(x,y,z)\,\mathrm{d}x\mathrm{d}y \\ &\quad \times \left[\iint I(x,y,z)\,\mathrm{d}x\mathrm{d}y\right]^{-1} \\ &= 2\iint \rho^2 I(x,y,z)\,\mathrm{d}x\mathrm{d}y \left[\iint I(x,y,z)\,\mathrm{d}x\mathrm{d}y\right]^{-1}, \end{aligned} \tag{11}$$

where $I(x,y,z) = |\boldsymbol{E}(x,y,z)|^2$ is the total intensity distribution, (x_c, y_c) is the position coordinate of the beam centroid, and ρ is the distance far from the beam centroid at plane z.

The structure constant of refractive index is set to be $C_n^2 = 10^{-13}$ m$^{-2/3}$, and the source correlation length l_c is set to be 1 cm and 5 cm, separately. Figure 3 shows the curves of effective beam radius of SC laser source and pump laser source *versus* propagation distance L in turbulence for different cases. It can be noticed that as the source correlation length decreases, the effective beam radius increases more rapidly along the whole propagation path, which may be due to the enhancement of the diffraction effect. At small value of l_c, the effective beam radius of the SC laser is always larger than that of the pump laser along the whole propagation path. As the source correlation length increases, the difference tends to disappear. When l_c grows to 5 cm, the effective beam radius of the SC laser is almost equal to that of its pump laser. It

means that under the same turbulence condition, the effective beam radius of the SC laser is more sensitive to the source correlation length than that of the pump laser, especially at a long-distance propagation.

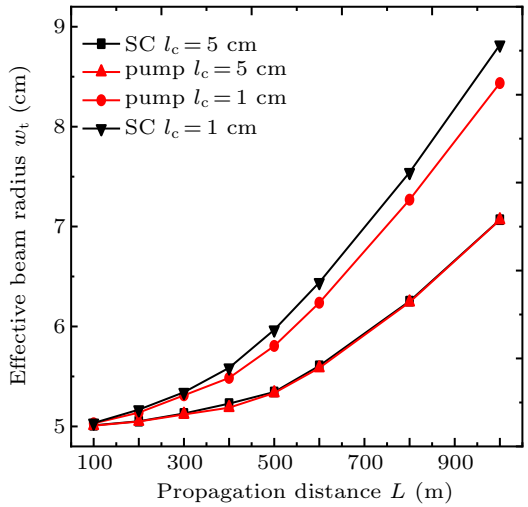


Fig. 3. Variations of effective beam radius with propagation distance of SC laser sources and pump laser sources for different source correlation lengths.

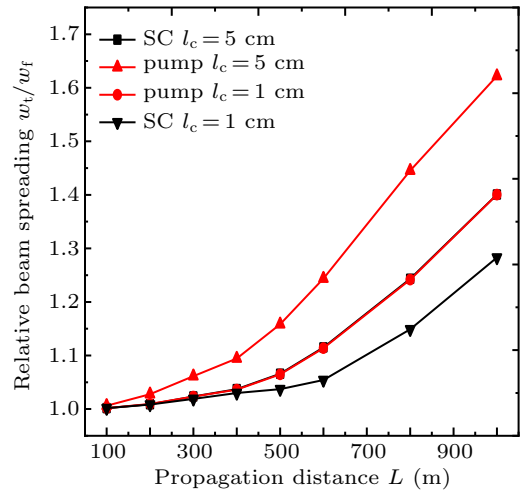


Fig. 4. Variations of relative beam spreading *versus* propagation distance of SC laser sources and pump laser sources for different source correlation lengths.

In some sense, relative beam spreading is an appropriate parameter to reflect to what extent a beam is affected by atmospheric turbulence. We divide the effective beam radius in turbulence w_t by the effective beam radius in free space w_f to obtain the relative beam spreading w_t/w_f. Figure 4 shows the curves of relative beam spreading of SC laser source to pump laser source versus propagation distance L for different source correlation lengths. It can be observed that as the source correlation length increases, relative beam spreading increases along the whole propagation path. Under the same condition of source correlation length, the relative beam spreading of the SC laser is a little lower than that of the pump laser at small value of L. As the propagation distance increases, the difference tends to be obvious. It means that the relative beam spreading of the SC laser is more insensitive to the turbulence atmosphere than that of the pump laser. Therefore, the optical field of the SC laser is less distorted than that of the pump laser due to turbulent effects, and SC laser sources can be utilized to improve the performance of laser engineering.

The C_n^2 is set to be 10^{-16} m$^{-2/3}$, 10^{-14} m$^{-2/3}$, 2×10^{-14} m$^{-2/3}$, 5×10^{-14} m$^{-2/3}$, and 10^{-13} m$^{-2/3}$ separately, and the propagation distance is chosen to be $L = 1$ km. Figure 5(a) shows the curves of effective beam radius w_t *versus* C_n^2 of SC laser source and pump laser source, and figure 5(b) shows the curves of relative beam spreading, which is defined by w_t/w_f, *versus* C_n^2 of SC laser source and pump laser source. It can be seen that as the turbulence strength grows, the effective beam radius and the relative beam spreading increase gradually, and there is a quick decline of effective beam radius as beam source becomes more coherent. But the relative beam spreading maintains a noticeable rise, which indicates that the influence of turbulent atmosphere on the beam spreading may decrease by reducing the degree of source coherence.

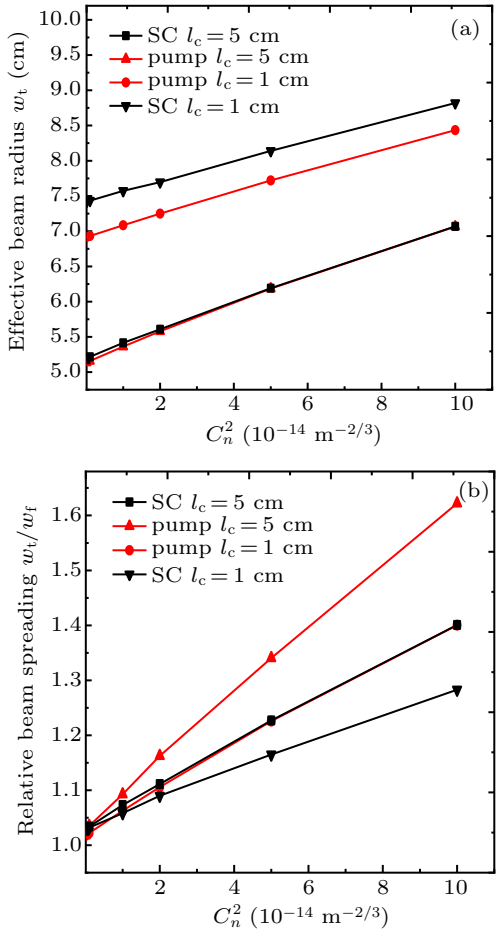


Fig. 5. Curves of (a) effective beam radius and (b) relative beam spreading *versus* C_n^2 of SC laser sources and pump laser sources over 1-km-propagation distance in turbulence.

From Figs. 5(a) and 5(b), we can also notice that at small value of l_c, the effective beam radius of the SC laser is significantly larger than that of the pump laser at any turbulence

strength. As the source correlation length increases, the difference tends to disappear. This indicates that under the same turbulence condition, the effective beam radius of the SC laser is less sensitive to the degree of source coherence than that of the pump laser. Besides, the relative beam spreading of the pump laser is much larger than that of the SC laser, especially at higher C_n^2. Even when $C_n^2 = 10^{-13}$ m$^{-2/3}$, l_c rises up to 5 cm, the relative beam spreading of the SC laser is only 1.40, while the relative beam spreading of the pump laser grows to 1.62. Combining Fig. 3 with Fig. 4, it can be concluded that the beam spreading of the SC laser is less affected by turbulence than that of its pump laser, which is an advantage of the SC laser over the pump laser.

3.2. Beam wandering effect

To the best of our knowledge, the beam wander reflects the change in spatial position with time. Turbulence scales that are much large with respect to the beam size cause the beam to tilt and thereby to deflect, resulting in beam wandering. In general, we use the variation of beam centroid position to describe the beam wandering effect, and the beam centroid can be expressed as[25]

$$\rho_c = \iint \rho I(\rho)\,\mathrm{d}\rho \Big/ \iint I(\rho)\,\mathrm{d}\rho, \tag{12}$$

where $I(\rho)$ is the intensity distribution. Then we can obtain the root-mean-square (RMS) value of σ_ρ of the wandering of beam centroid to be

$$\begin{aligned}\sigma_\rho &= \sqrt{\langle \rho_c^2 \rangle} \\ &= \left[\iint\iint (\rho_1 \cdot \rho_2) I(\rho_1) I(\rho_2)\,\mathrm{d}\rho_1\,\mathrm{d}\rho_2\right]^{1/2} \Big/ \iint I(\rho)\,\mathrm{d}\rho.\end{aligned} \tag{13}$$

In order to analyze the beam wander of SC laser sources in turbulent atmosphere, and discuss the difference in beam wander between SC laser source and their pump laser source, we set $C_n^2 = 10^{-13}$ m$^{-2/3}$. Figure 6 shows the plots of RMS of beam wandering of the SC laser and the pump laser *versus* propagation distance L with different source correlation lengths. We can see that for an SC laser, the change of source correlation length does not lead the beam wandering to vary evidently. The average relative variation is less than 3%. It indicates that the behavior of beam wandering of the SC laser is almost independent of the degree of source coherence. Furthermore, under the same condition of source correlation length, the RMS value of beam wandering of the SC laser is approximately equal to that of the pump laser along the whole propagation path.

Figure 7 shows the dependence of RMS of beam wandering of the SC laser and the pump laser on turbulence strength C_n^2 for different source correlation lengths when the propagation distance $L = 1$ km. It can be noticed that as turbulence strength grows, the beam wandering of SC laser becomes more pronounced. The degradation of the degree of source coherence of SC laser has no evident influence on beam wandering. Under the same condition of source correlation length, the RMS value of beam wandering of the pump laser is nearly equal to that of the SC laser, which is consistent with the results in Fig. 6. Therefore, there is no need to consider the beam wandering seriously for selecting an optimal laser source from between an SC laser and its pump laser.

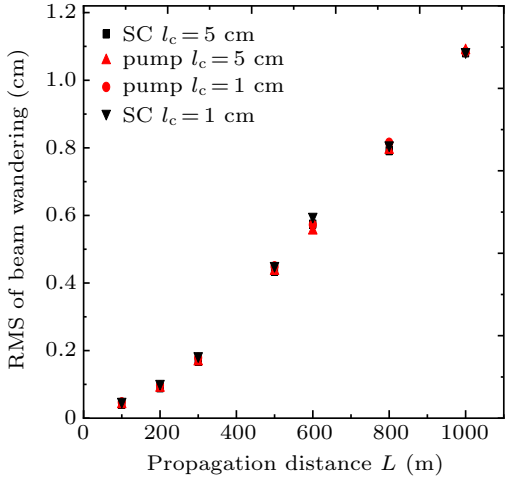


Fig. 6. RMS values of beam wandering σ_ρ *versus* propagation distance L of SC laser sources and pump laser sources *versus* propagation distance L for different cases.

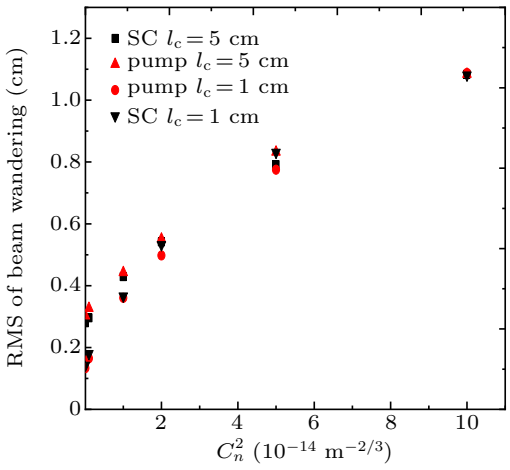


Fig. 7. RMS values of beam wandering σ_ρ *versus* C_n^2 of SC laser sources and pump laser sources for different cases.

3.3. Intensity scintillation effect

The intensity scintillation index β_I^2 defined as $\langle I^2 \rangle - \langle I \rangle^2 / \langle I \rangle^2$ is usually used to describe the normalized variance of intensity fluctuations, where $\langle \cdot \rangle$ denotes the ensemble average.

Here we set the off-axis distance from the point receiver to be $r = 4$ cm, and all other parameters involved are the same as those in Fig. 3. Figure 8 shows the variations of scintillation

index $\beta_{\rm I}^2$ with propagation distance L. It can be noticed that as the source correlation length decreases, the scintillation index decreases evidently. This means that the degradation of beam coherent degree may bring about less intensity fluctuation. Besides, under the same condition of source correlation length, the scintillation index of the SC laser is obviously lower than that of the pump laser, especially at larger propagation distance. At $l_{\rm c} = 5$ cm, the scintillation index of the pump laser can be seen clearly: when beam propagates for about 1 km, the maximum value is nearly 1.8. However, the scintillation index of the SC laser keeps lower than 1.32 along the whole propagation path. It indicates that the SC laser is generally more resistant to the distortions caused by atmospheric turbulence than the pump laser.

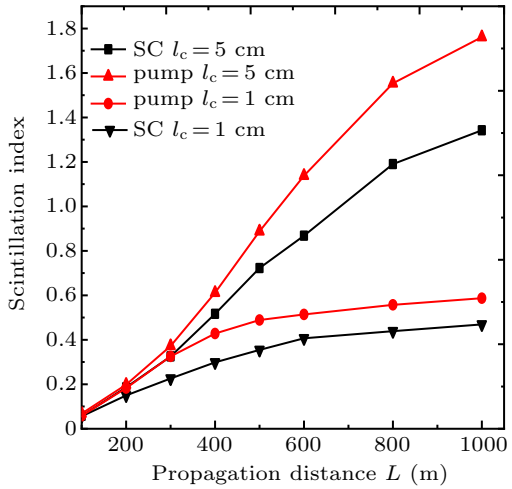


Fig. 8. Variations of scintillation index $\beta_{\rm I}^2$ with propagation distance L of SC laser sources and pump laser sources at off-axis distance $r = 4$ cm.

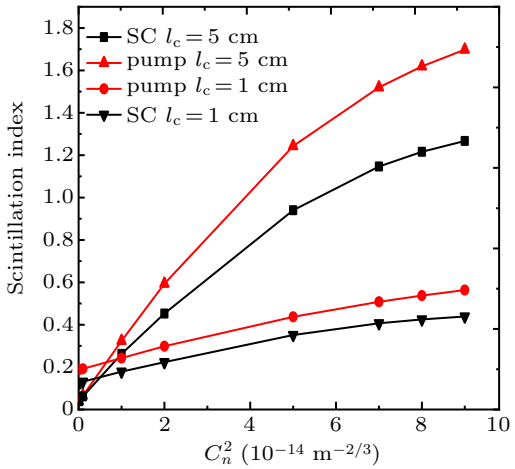


Fig. 9. Variations of scintillation index $\beta_{\rm I}^2$ with turbulence strength C_n^2 of SC laser sources and pump laser sources at off-axis distance $r = 4$ cm.

For the propagation distance $L = 1$ km, all the other parameters are kept the same as those in Fig. 8. Figure 9 shows the variations of $\beta_{\rm I}^2$ with C_n^2 of the SC laser and the pump laser for different source correlation lengths. It can be seen clearly that at low value of C_n^2, the degradation of the degree of source coherence may make the scintillation index $\beta_{\rm I}^2$ increase, this happens because in weak turbulence, the random phase screen $\zeta(x, y; t)$ is the dominant contribution to the intensity fluctuations, and the influence of turbulence is negligible. However, as the turbulence strength becomes strong, the intensity fluctuation caused by the turbulence turns more serious. When C_n^2 grows to a certain high level, with the degradation of the degree of source coherence, the scintillation index tends to decline. Besides, under the same condition of source correlation length, the scintillation index of the SC laser is always lower than that of the pump laser at different propagation distances or different turbulence strengths. It may be because of the additional influence of multiple wavelength homogenization effect of the SC laser. Thus, the SC laser sources have potential advantages in laser engineering because of lower scintillation and thus lower communication bit error rate.

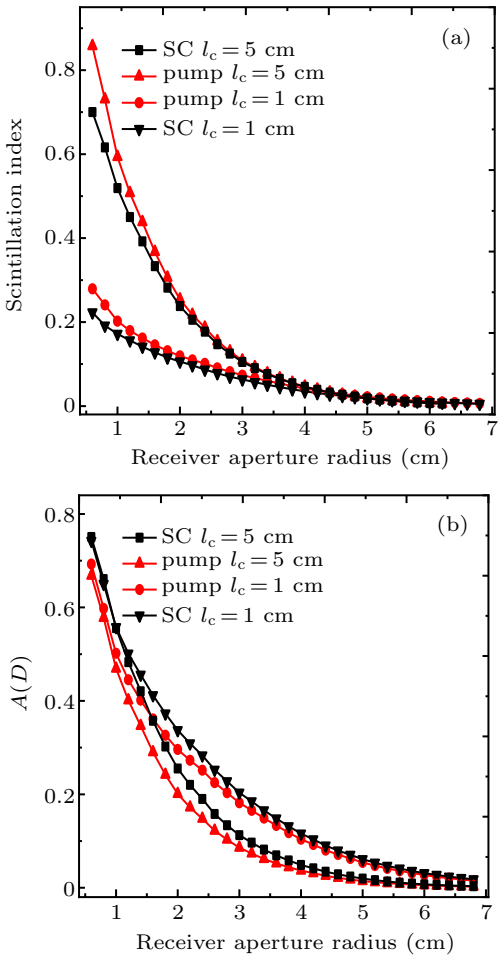


Fig. 10. Variations of (a) scintillation index and (b) aperture smoothing factor $A(D)$ with aperture radius of receiver of SC laser sources and pump laser sources at $r = 0$ cm.

In order to compare the difference in aperture averaging effect between the SC laser and its pump laser, we analyze the scintillation index and the aperture smoothing factor $A(D)$ of a receiver with different receiver aperture radii. The aperture smoothing factor $A(D)$ is defined as $\beta_{\rm I}^2(D)/\beta_{\rm I}^2(0)$, and the smaller the aperture smoothing factor, the stronger the aperture averaging effect is. Figure 10(a) shows the variations of

scintillation index of SC laser sources and their pump laser sources with receiver aperture radius for different source correlation lengths, and figure 10(b) shows the variations of aperture smoothing factor $A(D)$ with receiver aperture radius for different source correlation lengths. Here the receiver plane is fixed at 1 km far from the transmitter, off-axis distance $r = 0$ cm, and $C_n^2 = 10^{-13}$ m$^{-2/3}$. From Figs. 10(a) and 10(b), it is easy to see that under the same condition of source correlation length, with the increase of receiver aperture radius, the scintillation index of the pump laser tends to drop more rapidly than that of the SC laser. This may be because the ratio of receiver aperture radius to the beam radius of the pump laser is larger than the ratio of receiver aperture radius to the beam radius of the SC laser. When D changes from 6 mm to 20 mm, the scintillation index of the pump laser is always larger than that of the SC laser, and its aperture smoothing factor is always smaller than that of the SC laser. Thus, to some extent, it can be said that although pump laser source can bring about more aperture average, the SC laser source has lower scintillation index for $D < 20$ mm. It may be due to the multiple wavelength homogenization effects on intensity fluctuations.

4. Conclusions and perspectives

In this paper, we study the characteristics of beam spreading, beam wandering, and intensity scintillation of supercontinuum laser sources in turbulent atmosphere by using numerical simulation method, and analyze the difference in propagation property between the SC laser and its pump laser. The results show that the propagation characteristics of the SC laser are similar to those of the pump laser. The degradation of source coherence degree may cause the relative beam spreading and scintillation index to decrease at different propagation distances or different turbulence strengths. The beam wandering is insensitive to the variation of the degree of source coherence. Additionally, the beam wandering of the SC laser is almost the same as that of the pump laser. Therefore, from the point of view of beam wandering, the SC laser has no advantage over the pump laser. There is no need to consider the beam wandering seriously for selecting a laser source from between the SC laser and its pump laser. Unlike beam wandering, under the same condition of source correlation length, the beam spreading and intensity scintillation of the SC laser are less affected by the turbulence than those of the pump laser. This may be one of the most important properties of the SC laser which could be utilized to improve the performance of laser engineering. This property can be used to improve the signal-to-noise ratio and reduce the bit error rate of light communication.

Finally, we analyze the difference in intensity scintillation aperture averaging effect between SC laser and pump laser. It is found that under the same condition, although the pump laser can bring about a bigger aperture average, the SC laser has a lower scintillation index, which may be caused by the additional influence of the multiple wavelength homogenization effects of the SC laser.

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