Scintillation of Airy beam arrays in atmospheric turbulence

Yalong Gu* and Greg Gbur

Department of Physics and Optical Science, University of North Carolina at Charlotte, Charlotte, North Carolina 28223, USA
Corresponding author: ygu4@uncc.edu

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We investigate the scintillation properties of Airy beam arrays in atmospheric turbulence. By utilizing the "self-bending" propagation property of Airy beams, the constituent beamlets propagate through relatively independent regions of turbulence but still largely overlap at the on-axis detector. Through numeric simulations, it is shown that the scintillation of an Airy beam array is significantly reduced and close to the theoretical minimum. © 2010 Optical Society of America

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Scintillations are intensity fluctuations arising from the random phase modulation induced when an optical beam propagates through the turbulent atmosphere [1]. They are detrimental to the performance of free-space optical communication systems, and scintillation reduction is, therefore, one of the primary concerns in the development of such systems [2].

The propagation of partially coherent beams in the atmosphere has become a topic of renewed interest in recent years. It is now well known that partially coherent beams have, in general, a lower scintillation than their fully coherent counterparts [3–8]. However, a partially coherent beam has a larger angular spread and forms a relatively large spot in the receiver plane [9], which results in a small fraction of the transmitted energy being received by the detector. In addition, it is still relatively difficult to generate a partially coherent beam of controllable coherence properties. Beam arrays, which are composed of spatially separated beamlets, have been suggested as another solution for scintillation reduction. It has been shown that the scintillation of a beam array can be reduced by carefully adjusting the spatial separation of beamlets [10–12]. However, a beam array suffers significant scintillation increase if the spatial separation of beamlets deviates from the optimal value. Also, the problem of low received energy exists in beam arrays unless the constituent beamlets are inclined to overlap at the receiver plane, and an optimal inclination could be difficult to achieve over long propagation distances.

By examining the scintillation reduction mechanism of partially coherent beams and beam arrays, both may be interpreted as delivering energy through mutually independent coherent modes or beamlets that propagate through statistically independent regions of turbulence. As a result, turbulence-induced intensity fluctuations of the modes are relatively uncorrelated and, on average, the scintillation of partially coherent beams or beam arrays is reduced. However, the coherent modes or beamlets studied so far belong to conventional beam classes whose average propagation paths in turbulence are straight lines. They partially overlap and produce a relatively large spot in the receiver plane. Therefore, a question naturally arises: can we develop a special beam array whose spatially separated beamlets can self-bend on propagation and finally overlap at the receiver plane?

Airy wave packets were initially reported as a nondiffracting solution of the free-space Schrödinger equation within the context of quantum mechanics [13]. By the mathematical analogy between the free-space Schrödinger equation and the paraxial wave equation, Airy beams were recently theoretically predicted and experimentally observed within the context of optics [14,15]. The most exotic feature of Airy beams is their ability to transversely accelerate, i.e., to propagate along parabolic trajectories in free space [16]. This "self-bending" phenomenon can still be observed when the phase of an Airy beam is prerandomized [17]. It is also shown that Airy beams can self-reconstruct after propagating through obstacles and retain their intensity profiles under turbulent conditions [18]. These intriguing properties suggest that Airy beams could serve as constituent beamlets for beam arrays in turbulence applications.

In this Letter, we show through numeric simulations that the constituent beamlets of Airy beam arrays can be made to propagate through relatively independent regions of turbulence and to greatly overlap at the on-axis detector. The scintillation of Airy beam arrays is significantly reduced in consequence.

We consider an Airy beam represented as a scalar wave field $U(x,y,L)$ propagating primarily in the L direction, which has the following form in the transmitter plane $L=0$ [14]:

$$U(x,y)=\mathrm{Ai}\left(\frac{x}{x_0}\right)\exp\left(a\frac{x}{x_0}\right)\mathrm{Ai}\left(\frac{y}{y_0}\right)\exp\left(a\frac{y}{y_0}\right), \quad (1)$$

where Ai represents the Airy function. The parameters x_0 and y_0 are transverse scales, and a is the exponential truncation factor; they characterize the width and curvature of the beam. In this Letter, x_0 and y_0 are taken to be 0.012 m and $a=0.1$.

The propagation of an Airy beam in turbulence is simulated by using a multiple-phase-screen method [19]. The average intensity of an Airy beam in the transmitter and receiver planes is shown in Fig. 1. The wavelength is $\lambda=1.55\ \mu$m, and the refractive index structure constant C_n^2, which characterizes the turbulence strength ([1], Chap. 3), is $10^{-14}\ \mathrm{m}^{-2/3}$. After propagating in turbulence for 3 km, the location of the simulated average intensity peak is at $(0.058, 0.062\ \mathrm{m})$, while the corresponding

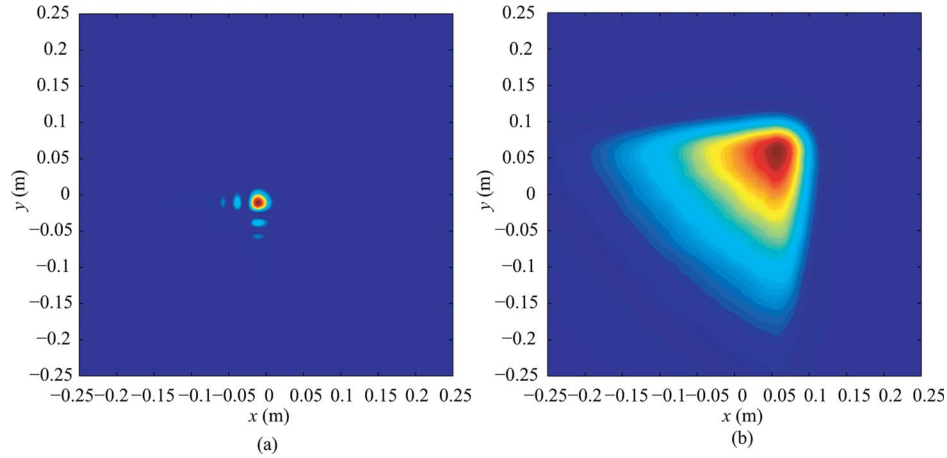

Fig. 1. (Color online) Illustration of the intensity patterns of an Airy beam in the (a) transmitter plane and (b) receiver plane. The wavelength is $\lambda = 1.55\ \mu$m, the turbulence strength is $C_n^2 = 10^{-14}\ \mathrm{m}^{-2/3}$, and the propagation distance is $L = 3$ km.

location of the intensity peak in free space is at (0.066, 0.066 m). The simulated intensity at (0.066, 0.066 m) is 96% of the simulated intensity at (0.058, 0.062 m). However, the random phase screens are generated by an FFT-based method in which turbulence spectrum is discretely sampled [19]. This discrepancy is on the order of 1–2 pixels in the simulation (2 mm pixel separation) and is readily explained by discrete sampling of the turbulence spectrum and possibly the finite number of realizations. Accounting for this small discrepancy, it can be seen that, on average, Airy beams move along the 45° axis in the x–y plane and the transverse displacement is approximately the same as in free space. Figure 2 illustrates the average propagation dynamics of the same Airy beam. It can be seen that the average propagation path in turbulence is also a parabolic trajectory.

Now we define a four-beamlet Airy beam array whose beamlet wave fields take on the following form in the transmitter plane $L = 0$:

$$U_m(s_{xm}, s_{ym}) = \mathrm{Ai}(s_{xm}) \exp(a s_{xm}) \mathrm{Ai}(s_{ym}) \exp(a s_{ym}), \tag{2}$$

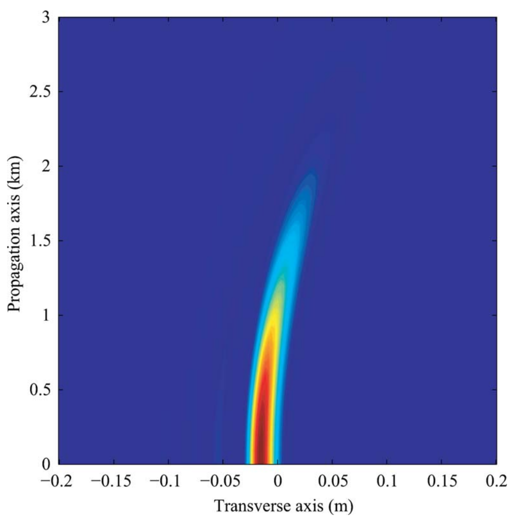

Fig. 2. (Color online) Illustration of the average propagation dynamics of an Airy beam as a function of distance on propagation in turbulence. The transverse axis is the 45° axis in the x–y plane. The parameters are the same as in Fig. 1.

where

$$\begin{cases} s_{xm} = \left[\sqrt{2}\cos\left(\frac{3+2\,m}{4}\pi\right)x + d\right]/x_0, \\ s_{ym} = \left[\sqrt{2}\sin\left(\frac{3+2\,m}{4}\pi\right)y + d\right]/y_0, \end{cases} \tag{3}$$

where d is the transverse displacement parameter and $m = 1, 2, 3, 4$ labels the mth beamlet. Figure 3 illustrates the intensity pattern of the array in the receiver plane $L = 3$ km when $d = 0.066$ m. Compared to the corresponding intensity pattern in the transmitter plane $L = 0$, it can be seen that the four initially separated beamlets meet in the receiver plane and their intensity peaks fully overlap at the on-axis detector.

The scintillation of an optical beam at the receiver plane is characterized by the scintillation index [1]:

$$\sigma^2(x, y, L) = \frac{\langle I^2(x, y, L)\rangle}{\langle I(x, y, L)\rangle^2} - 1, \tag{4}$$

where I is the instantaneous intensity and the angle brackets stand for the average of the realizations of turbulence. The correlation of intensity fluctuations between two optical beams is characterized by the cross-scintillation index

$$\sigma_{mn}^2(x, y, L) = \frac{\langle I_m(x, y, L) I_n(x, y, L)\rangle}{\langle I_m(x, y, L)\rangle\langle I_n(x, y, L)\rangle} - 1. \tag{5}$$

When the subscript $m = n$, Eq. (5) reduces to Eq. (4) and represents the self-scintillation index of the mth beam. The simulated on-axis self- and cross-scintillation indices of the four beamlets of an Airy beam array are shown in Table 1. The self-scintillation indices are roughly the same, about 0.80. The cross-scintillation indices are nearly zero. It is shown that the four beamlets propagate through relatively independent regions of turbulence and their own turbulence-induced intensity fluctuations are mutually uncorrelated. As a result, the on-axis scintillation index of the beam array is 0.2135, roughly one-fourth of the on-axis scintillation indices of the individual beamlets. This is very close to the theoretical limit of the maximum scintillation reduction of beam arrays, i.e.,

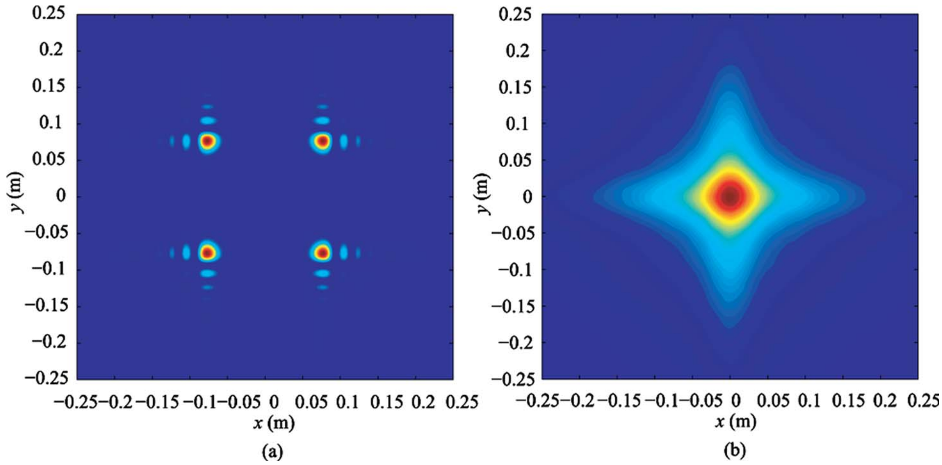

Fig. 3. (Color online) Illustration of the intensity patterns of a four-beamlet Airy beam array in the (a) transmitter plane and (b) receiver plane. The transverse displacement parameter d is taken to be 0.066 m. The rest of the parameters are the same as in Fig. 1.

Table 1. On-Axis Self- and Cross-Scintillation Indices of the Four Constituent Beamlets of an Airy Beam Array at the Receiver Plane $L = 3$ km[a]

σ_{mn}^2	$n = 1$	$n = 2$	$n = 3$	$n = 4$
$m = 1$	0.8052	0.0372	−0.0192	0.0121
$m = 2$	0.0372	0.8030	0.0315	0.0074
$m = 3$	−0.0192	0.0315	0.7716	0.0349
$m = 4$	0.0121	0.0074	0.0349	0.8274

[a]The transverse displacement parameter d is 0.066 m. The rest of the parameters are the same as in Fig. 1.

$\sigma_{\min}^2 = \sigma_{\mathrm{ind}}^2/N$, where σ_{ind}^2 is the scintillation index of the individual beamlet and N is the number of beamlets. It is to be noted from Table 1 that a two or three-beamlet array will produce a one-half or two-thirds reduction, respectively.

We have also considered the beam propagation for fixed values of x_0, y_0, and a with varying L. To keep maximum intensity overlap at the detector, d must be varied as well. At 2.5 km and 3.5 km, scintillation reduction was 72% and 74%, respectively. The reduction was only 55% at the shorter distance 1.5 km, which is due to the relatively small separation of beamlets and the resultant correlated propagation in turbulence. A sufficient initial separation between the beamlets of an Airy beam array is crucial for their mutually independent propagation through turbulence. It requires large transverse displacements of the beamlet intensity peaks so that they can overlap at the receiver plane. However, a practical Airy beam can only keep its free transverse acceleration feature up to a certain propagation distance [14]. Considering the long-range propagation of optical beams in free-space optical communications, the transverse scale and truncation parameters of Airy beams should be appropriately chosen so that they can retain adequate transverse displacements of intensity peaks.

In conclusion, we have demonstrated, through numeric simulations, that the appropriately chosen constituent beamlets of an Airy beam array can propagate through relatively independent regions of turbulence but still largely overlap at the on-axis detector. The scintillation of the beam array is significantly reduced compared to a single Airy beam and near the theoretical minimum.

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References

1. L. C. Andrews and R. L. Phillips, *Laser Beam Propagation through Random Media*, 2nd ed. (SPIE, 2005).
2. L. C. Andrews, R. L. Phillips, and C. Y. Hopen, *Laser Beam Scintillation with Applications* (SPIE, 2001).
3. J. C. Leader, J. Opt. Soc. Am. **69**, 73 (1979).
4. V. A. Banakh, V. M. Buldakov, and V. L. Mironov, Opt. Spectrosk. **54**, 1054 (1983).
5. Y. Baykal, M. A. Plonus, and S. J. Wang, Radio Sci. **18**, 551 (1983).
6. J. C. Ricklin and F. M. Davidson, J. Opt. Soc. Am. A **19**, 1794 (2002).
7. O. Korotkova, L. C. Andrews, and R. L. Phillips, Opt. Eng. **43**, 330 (2004).
8. T. J. Schulz, Opt. Lett. **30**, 1093 (2005).
9. G. Gbur and E. Wolf, J. Opt. Soc. Am. A **19**, 1592 (2002).
10. A. Peleg and J. V. Moloney, J. Opt. Soc. Am. A **23**, 3114 (2006).
11. P. Polynkin, A. Peleg, L. Klein, T. Rhoadarmer, and J. V. Moloney, Opt. Lett. **32**, 885 (2007).
12. A. Peleg and J. V. Moloney, IEEE Photon. Technol. Lett. **19**, 883 (2007).
13. M. V. Berry and N. L. Balazs, Am. J. Phys. **47**, 264 (1979).
14. G. A. Siviloglou and D. N. Christodoulides, Opt. Lett. **32**, 979 (2007).
15. G. A. Siviloglou, J. Broky, A. Dogariu, and D. N. Christodoulides, Phys. Rev. Lett. **99**, 213901 (2007).
16. G. A. Siviloglou, J. Broky, A. Dogariu, and D. N. Christodoulides, Opt. Lett. **33**, 207 (2008).
17. J. E. Morris, M. Mazilu, J. Baumgartl, T. Čižmár, and K. Dholakia, Opt. Express **17**, 13236 (2009).
18. J. Broky, G. A. Siviloglou, A. Dogariu, and D. N. Christodoulides, Opt. Express **16**, 12880 (2008).
19. J. M. Martin and S. M. Flatté, Appl. Opt. **27**, 2111 (1988).