# Reduction of turbulence-induced scintillation by nonuniformly polarized beam arrays

**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*

Received February 7, 2012; revised March 12, 2012; accepted March 17, 2012;
posted March 19, 2012 (Doc. ID 162648); published May 1, 2012

We have explored a method to reduce turbulence-induced scintillation by using an incoherent beam array composed of beamlets with nonuniform polarization. It is shown that significant scintillation reduction of such an incoherent beam array can be obtained by using nonuniformly polarized beamlets whose scintillation properties are optimized. 

*OCIS codes:* 010.1300, 260.5430.

When optical beams propagate through the atmosphere, they suffer from turbulence-induced intensity fluctuations, known as scintillations, that can severely degrade the performance of free-space optical communication systems. Therefore, understanding and reducing scintillation is one of the primary concerns in the development of such systems [1]. One viable option for scintillation reduction is the use of partially coherent beams. It has been shown by numerous researchers that scintillation of a partially coherent beam can be lower than that of a comparable fully coherent beam (see Ref. [2] for a review). In 2005, Schulz theoretically showed that beams that minimize scintillation are in general partially coherent [3]. These results have inspired investigations of the use of partially coherent beams in free-space communication systems. A number of optimization schemes for partially coherent beams in free-space optical communications have been proposed [4–6].

However, the generation of partially coherent beams with controllable coherence properties is still challenging. With this in mind, a number of researchers have turned to incoherent beam arrays as a readily realizable partially coherent source. Their usefulness in scintillation reduction has been theoretically and experimentally demonstrated [7,8]. A recent study further showed that scintillation properties of a general partially coherent beam can be well-approximated by an appropriately designed incoherent beam array [9]. These results suggest that incoherent beam arrays are a promising class of partially coherent sources for turbulence applications.

In general, the scintillation properties of an incoherent beam array strongly depend on the scintillation properties of its constituent beamlets. Therefore, a straightforward consideration in reducing scintillation of an incoherent beam array is whether it can be achieved by selecting a type of beamlet with small inherent scintillation. Scintillation properties of various beam types have been studied in recent years (see Ref. [10] for a review). It is shown that scintillations strongly depend on the initial beam properties, such as phase and intensity profile. In general, due to the complicated nature of turbulence-induced beam scintillation, it is difficult to find general guidelines for scintillation reduction by manipulating initial beam parameters. However, the beam types investigated so far are scalar. The vectorial nature of optical beams and noninterference of orthogonal polarizations suggest that a beam of complex polarization can act effectively as a two-mode partially coherent beam. Our recent study demonstrated that an appropriately chosen nonuniformly polarized beam (NPB) can have appreciably smaller scintillation than comparable beams of uniform polarization [11]. This result suggests the use of NPBs in incoherent beam arrays for scintillation reduction. In this Letter, we demonstrate that the scintillation of an incoherent beam array can be significantly reduced by using NPBs with optimized self-scintillation properties.

We consider an NPB generated by a simple orthogonal superposition of an $x$-polarized Laguerre–Gauss (LG) mode of order $n=0$, $m=0$ ($\mathrm{LG}_{00}$) and a $y$-polarized LG mode of order $n=0$, $m=1$ ($\mathrm{LG}_{01}$) [11], namely

$$E_x(x,y,z=0)=A_{0x}\sqrt{\frac{2}{\pi w_{0x}^2}}\exp\left(-\frac{x^2+y^2}{w_{0x}^2}\right), \quad (1a)$$

$$E_y(x,y,z=0)=A_{0y}\frac{2}{\sqrt{\pi}w_{0y}^2}(x+iy)\exp\left(-\frac{x^2+y^2}{w_{0y}^2}\right). \quad (1b)$$

From calculations of the scintillation index of an electromagnetic beam [12], it can be shown that an NPB has a minimum scintillation index

$$\sigma_{\min}^2=\begin{cases}\frac{\sigma_{xx}^2\sigma_{yy}^2-(\sigma_{xy}^2)^2}{\sigma_{xx}^2+\sigma_{yy}^2-2\sigma_{xy}^2} & \text{if } \sigma_{xy}^2<\min[\sigma_{xx}^2,\sigma_{yy}^2] \\ \min[\sigma_{xx}^2,\sigma_{yy}^2] & \text{otherwise}\end{cases}, \quad (2)$$

when the ratio of their amplitudes takes an optimal value

$$\frac{A_{0y}}{A_{0x}}=\sqrt{\frac{\langle I_x\rangle(\sigma_{xx}^2-\sigma_{xy}^2)}{\langle I_y\rangle(\sigma_{yy}^2-\sigma_{xy}^2)}} \text{ if } \sigma_{xy}^2<\min[\sigma_{xx}^2,\sigma_{yy}^2]. \quad (3)$$

$\langle I_x\rangle$ and $\langle I_y\rangle$ in Eq. (3) are the average intensities of the two orthogonally polarized modes when their amplitudes $A_{0x}$ and $A_{0y}$ are unity. Here, $\sigma_{xx}^2$ and $\sigma_{yy}^2$ are the self-scintillation indices of the $x$ or $y$ polarized modes and $\sigma_{xy}^2$ is the cross scintillation index.

Equation (2) suggests that scintillation reduction by an NPB arises from the different scintillation properties of its two orthogonally polarized modes on propagation through the atmosphere. We use a multiple random phase screen method [13] to numerically study the on-axis scintillations of such a beam. In this Letter, the wavelength is $\lambda = 1.55\ \mu$m and turbulence strength is $C_n^2 = 10^{-14}\ \mathrm{m}^{-2/3}$. For an NPB whose mode widths are $w_{0x} = w_{0y} = 0.05$ m, the simulated on-axis self-scintillation indices of $\mathrm{LG}_{00}$ and $\mathrm{LG}_{01}$ are $\sigma_{xx}^2 = 0.57$ and $\sigma_{yy}^2 = 1.25$ after it propagates through the turbulence for 2.5 km. The on-axis cross scintillation index is $\sigma_{xy}^2 = 0.19$. From Eq. (2), the minimum on-axis scintillation index of the NPB is 0.47. The simulated scintillation index of a uniformly polarized beam (UPB), where $\mathrm{LG}_{00}$ and $\mathrm{LG}_{01}$ superpose with the same linear polarization state, is 0.88. These results indicate that the NPB's small scintillation is the result of its nonuniform polarization. This 18% reduction as compared to the scintillation of the Gaussian beam ($\mathrm{LG}_{00}$) alone is due to the low correlation between the intensity fluctuations of the two orthogonally polarized modes. Even though they have the same width and propagate through a similar region of turbulence, the corresponding correlation coefficient between their on-axis intensity fluctuations is small, namely $\rho_{I_x,I_y} = \sigma_{xy}^2/\sqrt{\sigma_{xx}^2\sigma_{yy}^2} = 0.23$. This effect is possible because the $\mathrm{LG}_{00}$ and $\mathrm{LG}_{01}$ modes have different transverse profiles at the source, consequently have different propagation characteristics in both free space and turbulence, and therefore produce statistically low correlated intensity patterns at the detector.

As the turbulence propagation of a mode depends on its initial profile parameters, the scintillation properties of an NPB could be further optimized by varying the width of its modes. Figure 1 illustrates the minimum on-axis scintillation index of an NPB as a function of the initial width of the $\mathrm{LG}_{01}$ mode. It can be seen that the on-axis scintillation could be further reduced from 18% to 38% when the width of the $\mathrm{LG}_{01}$ mode decreases from 5 cm to 2.2 cm. The variation of the intensity correlation coefficient $\rho_{I_x,I_y}$ is illustrated in Fig. 2, which clearly shows that the correlation between the intensity fluctuations of these two modes strongly depends on the initial beam profiles and can even be nearly zero when the width of the $\mathrm{LG}_{01}$ mode is around 1.5 cm.

Now we use this optimized NPB as the fundamental component of an incoherent beam array. As the $\mathrm{LG}_{01}$

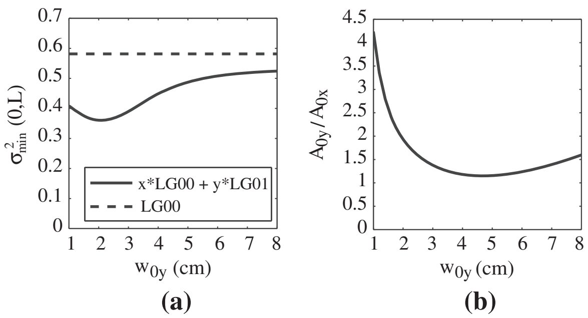


Fig. 1. (a) Minimum on-axis scintillation of an NPB [$\sigma_{\min}^2(0, L)$] as a function of the initial width of the $\mathrm{LG}_{01}$ mode. (b) The optimal amplitude ratio $A_{0y}/A_{0x}$. Here the propagation distance is 2.5 km and width of the $\mathrm{LG}_{00}$ mode is $w_{0x} = 0.05$ m.

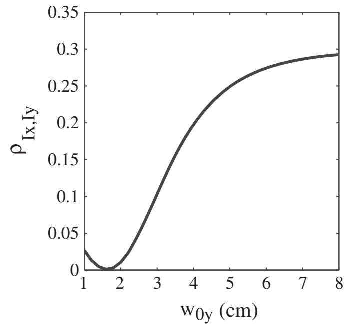


Fig. 2. Intensity correlation coefficient $\rho_{I_x,I_y}$ as a function of the initial width of the $\mathrm{LG}_{01}$ mode. The parameters are the same as in Fig. 1.

mode gradually evolves to a Gaussian profile on propagation in turbulence, an NPB propagates along a straight line. Therefore, the constituent beamlets of this NPB array are mutually inclined to an on-axis detector on the receiver plane so that the received intensity can be maximized. A 4-beamlet array takes the following form in the plane $z = 0$;

$$E_{mx}(x, y) = A_{0x}\sqrt{\frac{2}{\pi w_{0x}^2}}\exp[-i(k_{mx}x + k_{my}y)] \times \exp\left[-\frac{(x - d_{mx})^2 + (y - d_{my})^2}{w_{0x}^2}\right], \tag{4a}$$

$$E_{my}(x, y) = A_{0y}\frac{2}{\sqrt{\pi}w_{0y}^2}[(x - d_{mx}) + i(y - d_{my})] \times \exp\left[-\frac{(x - d_{mx})^2 + (y - d_{my})^2}{w_{0y}^2}\right] \times \exp[-i(k_{mx}x + k_{my}y)], \tag{4b}$$

where $m = 1, 2, 3, 4$ labels the $m$th beamlet. The configuration of this beam array is illustrated in Fig. 3. Each beamlet is located at $(d_{mx}, d_{my})$ on the source plane. The corresponding off-axis distance is $d = \sqrt{d_{mx}^2 + d_{my}^2}$. $(k_{mx}, k_{my})$ is the transverse wave vector. In order to make all beamlets overlap at the receiver plane $z = L$, $k_{mx} = kd_{mx}/L$ and $k_{my} = kd_{my}/L$.

Figure 4 illustrates the on-axis scintillation index of this 4-beamlet NPB array as a function of the off-axis distance $d$ after propagating in turbulence for 2.5 km. The on-axis scintillations of 4-beamlet Gaussian beam (GB) and UPB arrays are also shown for comparison, whose

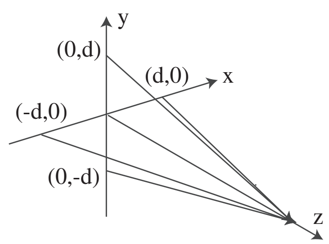


Fig. 3. Geometry of incoherent beam array.

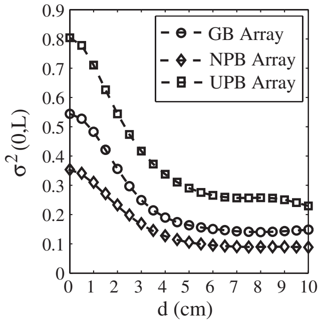


Fig. 4. On-axis scintillations of NPB, GB, and UPB arrays $[\sigma^2(0, L)]$ as a function of the off-axis distance $d$. $w_{0x} = 5$ cm, $w_{0y} = 2.2$ cm, $E_{0x} = 1$ V/m, and $E_{0y} = 1.8$V/m. The rest of the parameters are the same as in Fig. 1.

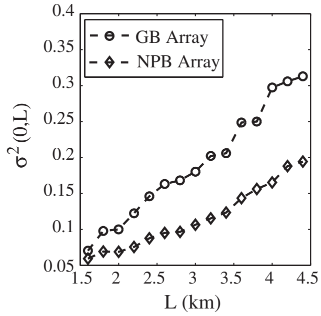


Fig. 5. On-axis scintillation of an NPB array $[\sigma^2(0, L)]$ as a function of propagation distance. Here, $d = 10$ cm and the rest of the parameters are the same as in Fig. 4.

beamlets are generated in a way similar to the NPB array. It can be seen that the NPB array has lower scintillation than a comparable GB array and UPB array as its beamlets have small scintillation due to a nonuniform polarization effect. When $d = 10$ cm, the on-axis scintillation of the NPB array is 61% of the scintillation index of the GB array. In addition, as the beamlets' propagation paths in the atmosphere become more independent as the off-axis distance $d$ increases, the scintillation of the NPB array has a 75% reduction as compared to the scintillation of the NPB array when $d = 0$. This value is the theoretical maximum reduction of a 4-beamlet incoherent beam array [14].

The on-axis scintillation index of this NPB array over a range of propagation distances is shown in Fig. 5. It outperforms the corresponding GB array beyond the propagation distance of $L = 1.5$ km. It is worth noting that the initial beam width and amplitude parameters used in Fig. 5 are selected to optimize the on-axis scintillation of the NPB array under particular propagation conditions, which are $L = 2.5$ km and $C_n^2 = 10^{-14}$ m$^{-2/3}$. For another propagation scenario, such as different propagation distance or turbulence strength, the optimal choice of the initial beam parameters will in general be different, but can be obtained by Eqs. (2) and (3).

In conclusion, we have demonstrated significant reduction of turbulence-induced scintillation by using an incoherent beam array whose constituent beamlets are NPBs with optimized scintillation properties. This result suggests a relatively easy method to improve scintillation reduction by utilizing polarization effects. The key factor for this reduction is the low correlation between the two orthogonally polarized modes on propagation in the atmosphere. An observation from Eq. (2), which is that $\sigma^2_{\min}$ decreases monotonically as $\sigma^2_{xy}$ decreases, also suggests that scintillation of an NPB as well as the corresponding incoherent beam array might be further reduced by exploring methods to make orthogonally polarized modes low or even negatively correlated on propagation in the atmosphere.

This research was supported by the United Sates Air Force Office of Scientific Research (USAFOSR) under grant FA9550-12-1-0007.

**References**


1. L. C. Andrews, R. L. Phillips, and C. Y. Hopen, *Laser Beam Scintillation with Applications* (SPIE Press, 2001).
2. G. Gbur and T. D. Visser, Prog. Opt. **55**, 285 (2010).
3. T. J. Schulz, Opt. Lett. **30**, 1093 (2005).
4. C. Chen, H. Yang, X. Feng, and H. Wang, Opt. Lett. **34**, 419 (2009).
5. D. G. Voelz and X. Xiao, Opt. Eng. **48**, 036001 (2009).
6. D. K. Borah and D. G. Voelz, Opt. Express **18**, 20746 (2010).
7. A. Peleg and J. V. Moloney, J. Opt. Soc. Am. A **23**, 3114 (2006).
8. P. Polynkin, A. Peleg, L. Klein, T. Rhoadarmer, and J. V. Moloney, Opt. Lett. **32**, 885 (2007).
9. Y. Gu and G. Gbur, J. Opt. Soc. Am. A **27**, 2621 (2010).
10. Y. Baykal, H. T. Eyyuboğlu, and Y. Cai, Proc. SPIE **7200**, 720002 (2009).
11. Y. Gu, O. Korotkova, and G. Gbur, Opt. Lett. **34**, 2621 (2009).
12. O. Korotkova, Opt. Commun. **281**, 2342 (2008).
13. J. M. Martin and S. M. Flatté, Appl. Opt. **27**, 2111 (1988).
14. L. C. Andrews and R. L. Phillips, Proc. SPIE **5338**, 265 (2004).