Scintillation of nonuniformly polarized beams in atmospheric turbulence

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We demonstrate, through numerical simulations, that an appropriately chosen nonuniformly polarized coherent optical field can have appreciably smaller scintillation than comparable beams of uniform polarization. This results from the fact that a nonuniformly polarized field acts as an effective two-mode partially coherent field. The results described here are of direct relevance to the development of free-space optical communication systems. © 2009 Optical Society of America

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One of the fundamental limitations in the development of free-space optical communication systems is the intensity fluctuations induced in an optical wavefield by atmospheric turbulence [1]. These optical scintillations result from the distortions of the phase structure of the wavefield by the turbulence, in effect causing the wave to interfere with itself.

However, it was demonstrated some time ago (see, for instance, [2,3]) that the scintillation of a partially coherent field can be lower than that of its fully coherent counterpart. This has become a topic of renewed interest in recent years [4–8], and can be roughly understood as follows. A partially coherent beam carries its energy in multiple, mutually incoherent, spatial modes, with a larger number of modes corresponding to a lower degree of coherence, and each mode produces its own distinct interference pattern on propagation through turbulence. Because these modes are mutually incoherent, however, their interference patterns add *by intensity* and on average will produce a more uniform intensity spot at the detector. Incorporating partial coherence into an optical communications system, however, requires a source whose statistical properties can be easily controlled, and it is natural to ask whether easier methods exist to reduce scintillation.

It is generally supposed that polarization effects are not significant in clear-air turbulence. Indeed, it has been shown that optical turbulence has a negligible effect on the direction of polarization of a uniformly polarized field ([9], chapter 11). It is well known, however, that fields that are generated by partially coherent and partially polarized sources can have a significant change in their degree and state of polarization on propagation through turbulence [10,11]. Furthermore, recent research has demonstrated that a partially coherent and partially polarized field will have lower scintillation than a comparable, linearly polarized field [12].

The previously mentioned research considered fields that possessed a spatially uniform state of polarization. In this Letter we demonstrate via numerical example that similar reductions in scintillation can occur even for a spatially coherent field, provided it is *nonuniformly polarized*. Nonuniformly polarized beams such as radially and azimuthally polarized beams have been shown to be extremely useful in focusing applications [13], and recently the polarization behavior of such beams in turbulence has been studied [14,15].

One can understand the reduction in scintillation by analogy with a two-mode partially coherent beam. A nonuniformly polarized beam can be expressed as the coherent superposition of a pair of orthogonally polarized spatial modes. As noted above, because the polarization of coherent beams does not change significantly in turbulence, the modes remain orthogonal over appreciable propagation distances. Just like a pair of partially coherent modes, the orthogonally polarized modes do not interfere with one another, and their respective interference patterns add by intensity. A nonuniformly polarized beam acts effectively as a two-mode partially coherent beam, and one would expect similar improvements in its scintillation index.

We consider the scintillation of a monochromatic, nonuniformly polarized beam consisting of a coherent superposition of an x-polarized Laguerre–Gauss (LG) beam of order $n=0$, $m=0$ (LG_{00}), which has the following form in the plane $L=0$:

$$U_{00}(x,y) = \sqrt{\frac{2}{\pi w_0^2}} \exp\left(-\frac{x^2+y^2}{w_0^2}\right), \qquad (1)$$

and a y-polarized LG beam of order $n=0$, $m=1$ (LG_{01}) ([16], Section 4.6), which in the plane $L=0$ takes on the form

$$U_{01}(x,y) = \frac{2}{\sqrt{\pi}w_0^2}(x+iy)\exp\left(-\frac{x^2+y^2}{w_0^2}\right). \qquad (2)$$

(Simulations with radially and azimuthally polarized fields showed higher scintillation than that for an ordinary Gaussian mode, likely in part owing to the intensity null in their centers.) The modes are normalized such that
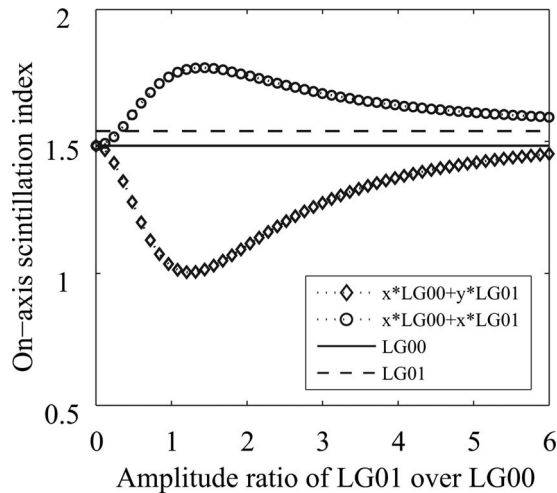
Fig. 1. Simulation of the scintillation index of beams of different structure on propagation through 5 km of turbulence. Here the wavelength is taken to be $\lambda = 1.55$ μm, the turbulence strength is $C_n^2 = 10^{-14}$ m$^{-2/3}$, and the width of the beam is taken to be $w_0 = 0.05$ m.
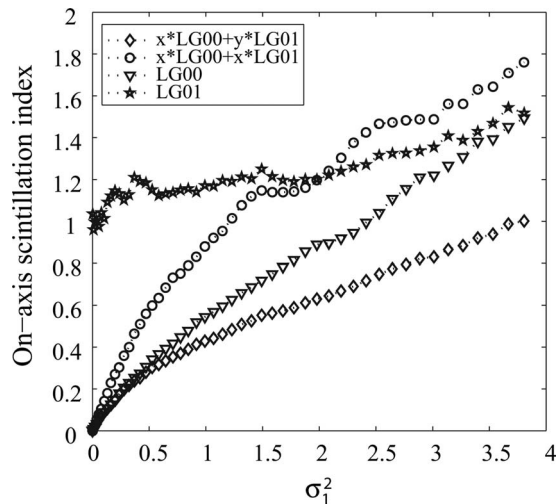

Fig. 2. Scintillation of beams of different mode structure as a function of the Rytov variance $\sigma_1^2 = 1.23 C_n^2 k^{7/6} L^{11/6}$. For the simulations, the wavelength is taken to be $\lambda = 1.55$ μm, the turbulence strength is $C_n^2 = 10^{-14}$ m$^{-2/3}$, and the width of the beam is taken to be $w_0 = 0.05$ m.

$$\int\int |U_{nm}(x,y)|^2 \mathrm{d}x\mathrm{d}y = 1, \tag{3}$$

where the integration extends over the entire source plane.

We simulate the propagation of such beams using a multiple-phase screen method [17]. The two modes are propagated through the same realization of turbulence, and their intensities are added at the detector plane.

In Fig. 1, we consider the on-axis scintillation index of such beams as a function of the ratio of the amplitudes of the two modes. The wavelength is taken to be $\lambda = 1.55$ μm, the turbulence strength is $C_n^2 = 10^{-14}$ m$^{-2/3}$, the propagation distance $L = 5$ km, and the width of the beam is taken to be $w_0 = 0.05$ m. For comparison, the scintillation index is also shown for the modes individually and for the modes superimposed with the same polarization. It can be seen that a minimum of the scintillation occurs when the amplitude of the LG_{01} mode is about unity, providing a 33% reduction as compared to the scintillation of the Gaussian beam alone.

Figure 2 illustrates the scintillation index of the same four beams, as a function of the Rytov variance [16],

$$\sigma_1^2 = 1.23 C_n^2 k^{7/6} L^{11/6}. \tag{4}$$

It can be seen that the nonuniformly polarized field outperforms the individual modes as well as the combination of the modes with the same polarization.

Over significant propagation distances the LG_{01} mode takes on a Gaussian shape. In Fig. 3, an analytic calculation of the average intensity of the LG_{01} mode and the LG_{00} mode is plotted using the extended Huygens–Fresnel principle ([16], Chapter 12) with a quadratic phase approximation for the turbulence fluctuation. In Fig. 3(a), it is seen that the average on-axis intensity for the LG_{01} mode increases as the on-axis intensity for the LG_{00} mode decreases; the intensity node in the center of the LG_{01} mode fills in as it propagates. As $L \to 5$ km, the two intensities become nearly equal and, as shown in Fig. 3(b), the LG_{01} mode has, on average, a nearly Gaussian form.
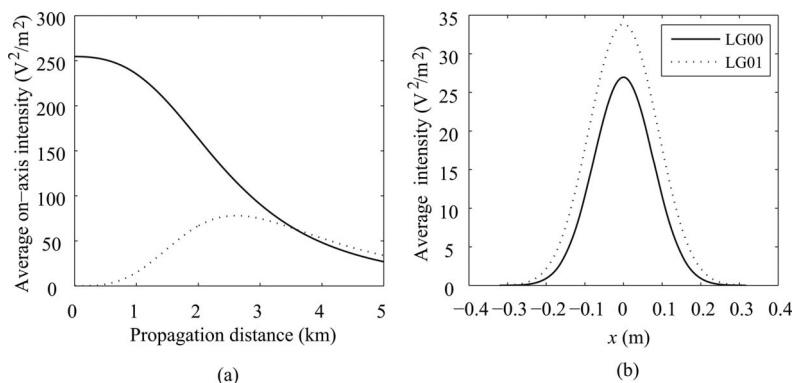

(a)

(b)

Fig. 3. Calculations of the mean intensity using the extended Huygens–Fresnel principle with quadratic approximation for the turbulence, with $\lambda = 1.55$ μm, $C_n^2 = 10^{-14}$ m$^{-2/3}$, and $w_0 = 0.05$ m. (a) Evolution of the on-axis intensity of an LG_{00} and LG_{01} beam on propagation, for the optimal ratio of intensities given in Fig. 1. It can be seen that the intensities become nearly equal after 5 km. (b) Transverse profile of the LG_{00} and LG_{01} beams at $L = 5$ km.

The net effect is that this mode, combined with the LG_{00} mode, looks like an unpolarized Gaussian beam.

This effect is possible because the LG_{01} mode propagates through the turbulence in a different manner from the LG_{00} mode. The interference pattern produced by the LG_{01} mode is therefore different from that of the LG_{00} mode. Instead of the two modes producing a mutual interference pattern, the polarization of the field is scrambled; a realization of this, determined by numerical simulation, is shown in Fig. 4. The independence of the two polarized modes is crucial; this reduction of scintillation index would not happen if two Gaussian beams, identical save for

their direction of polarization, were coherently superimposed and propagated through turbulence.

It is worth noting that, over time scales small compared to the turbulence fluctuations, the field remains essentially fully polarized. Over time scales long compared with the turbulence fluctuations, those fluctuations result in polarization changes and an overall decrease in the degree of polarization.

This nonuniform polarization effect suggests a relatively easy and inexpensive way to reduce the scintillation of a coherent optical beam, as optical elements to convert linear to nonuniform polarization are now common. For instance, a radially polarized beam can be generated by use of a conical Brewster prism [18]. Though we have used a simple superposition of LG_{00} and LG_{01} modes for this Letter, simulations with other LG mode combinations suggest that the optimal choice may depend upon the specific propagation conditions. In addition, it seems likely that nonuniform polarization might be used in conjunction with partially coherent effects such as described in [7,8].

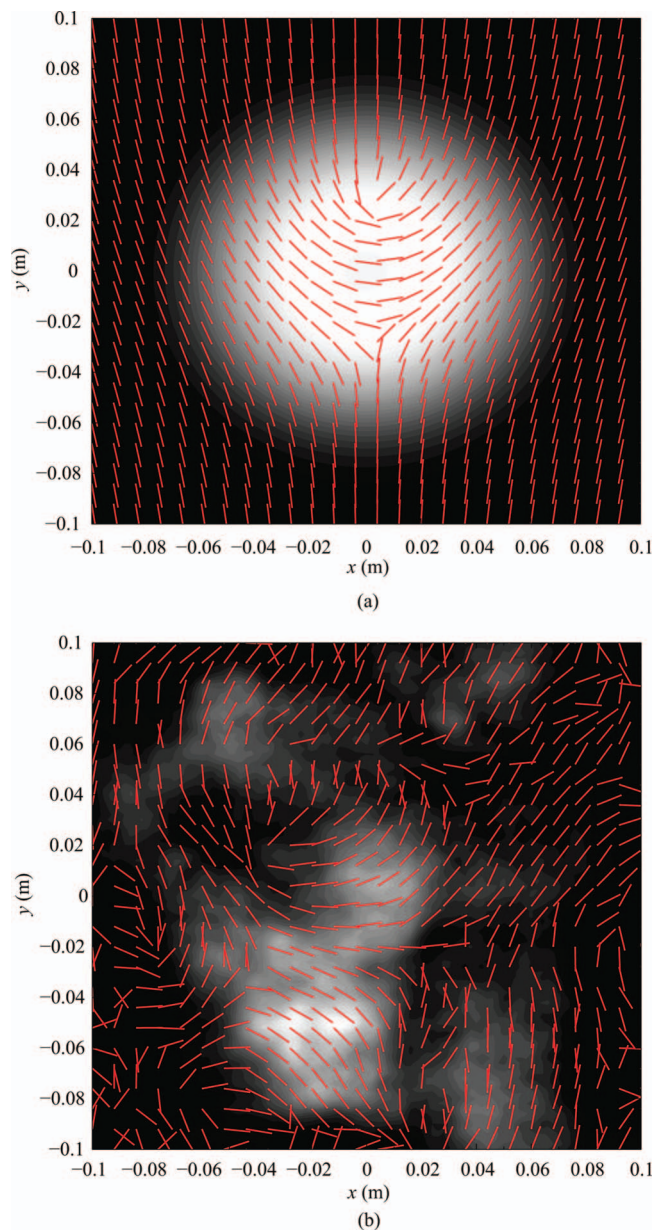Fig. 4.   Major axis of polarization of the field in (a) the source plane, $L=0$, and (b) the detector plane, $L=5$ km. In the detector plane, interference between the two modes is replaced with an effective scrambling of the state of polarization. The beam and turbulence parameters are the same as the ones in Figs. 1–3.

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