Optimized multiemitter beams for free-space optical communications through turbulent atmosphere

Pavel Polynkin
College of Optical Sciences, The University of Arizona, Tucson, Arizona 85721, USA

Avner Peleg
Arizona Center for Mathematical Sciences, The University of Arizona, Tucson, Arizona 85721, USA

Laura Klein and Troy Rhoadarmer
Starfire Optical Range, Air Force Research Laboratory, Kirtland Air Force Base, New Mexico 87117, USA

Jerome Moloney
Arizona Center for Mathematical Sciences, The University of Arizona, Tucson, Arizona 85721, USA

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Using laser beams with less than perfect spatial coherence is an effective way of reducing scintillations in free-space optical communication links. We report a proof-of-principle experiment that quantifies this concept for a particular type of a partially coherent beam. In our scaled model of a free-space optical communication link, the beam is composed of several partially overlapping fundamental Gaussian beams that are mutually incoherent. The turbulent atmosphere is simulated by a random phase screen imprinted with Kolmogorov turbulence. Our experiments show that for both weak-to-intermediate and strong turbulence an optimum separation between the constituent beams exists such that the scintillation index of the optical signal at the detector is minimized. At the minimum, the scintillation reduction factor compared with the case of a single Gaussian beam is substantial, and it is found to grow with the number of constituent beams. For weak-to-intermediate turbulence, our experimental results are in reasonable agreement with calculations based on the Rytov approximation. © 2007 Optical Society of America

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Propagation of laser light through turbid media has recently attracted renewed attention due to the emergence of high-capacity free-space optical communication systems[1] (Lasercom). Various techniques developed to reduce signal scintillations due to turbulence typically utilize several redundant communication channels for simultaneous transmission of data. Such alternative channels can be established in either wavelength or spatial domain. The wavelength-diversity approach has been recently analyzed in detail.[2] Since the dependence of atmospheric turbulence on wavelength is relatively weak, using this approach results in a modest reduction of scintillation index values by ~10%.

In contrast, the spatial diversity techniques are more powerful and can result in multifold reduction of the scintillation index. They utilize statistical independence of fluctuations along physically distinct optical paths through turbulence, which can be taken advantage of either in the detector plane by using a multiaperture receiver[3] or in the transmitter plane by employing optical beams with low spatial coherence. In fact, this concept has been known in astronomy for quite some time: reduced spatial coherence of planets compared with that of stars, which are essentially perfectly coherent point sources, is precisely the reason why stars twinkle but planets do not.

Effects of turbulence on propagation of low-spatial-coherence beams in the context of Lasercom have been extensively studied both theoretically[4–7] and experimentally.[8] In the theoretical studies, considering the so-called Gaussian Shell-model beams is common because in some cases this model allows for analytical results to be derived in a closed form.

We here consider a different kind of low-coherence beam that is composed of several partially overlapping, mutually incoherent fundamental Gaussian beams generated by independent laser sources. All constituent beams are assumed to be collinear and identical in size, and the degree of spatial coherence of the compound beam can be varied by either changing the number of constituent beams or overlap between them. Considering this kind of multiemitter beam is important for practical reasons because it can be straightforwardly generated by an appropriately configured multiwavelength vertical external-cavity surface-emitting laser diode source.[9]

A recent publication[10] reported a detailed theoretical study of a short-range propagation of multiemitter beams through weakly turbulent atmosphere. It has been shown that for various compound-beam configurations, an optimum separation between constituent beams exists such that the scintillation index of the optical signal at the detector is minimized. For such a minimum to occur, it is important that the constituent beams overlap in the detector plane. Then the optimum beam separation is of the order of the expanded beam size at the detector. At the minimum, the scintillation reduction factor can be substantial. For example, by using a nine-emitter beam with optimized separation between emitters, the signal scintillation can be reduced by more than an order of magnitude compared with the case when a single fundamental Gaussian beam is used.

The existence of the optimum separation between emitters in the transmitter plane can be explained by the interplay between two effects: on the one hand, the emitters have to be sufficiently separated to take advantage of the statistical independence of fluctuations along physically distinct paths through turbulence. On the other hand, the scintillations independently produced by each constituent emitter grow with distance from the beam axis.[1]

In this Letter we report an experiment that confirms and quantifies this concept. The minimum of the scintillation index with respect to the beam separation is observed for multiemitter beams composed of two and four identical fundamental Gaussian beams, for both weak-to-moderate and strong turbulence. Although the reduction of scintillations using multiemitter beams has been studied previously,[11] to our knowledge no attempt to optimize transmitter configuration with respect to the separation between constituent beams has been reported.

A scaled model of a free-space optical data link used in our experiments is shown schematically in Fig. 1. The multiemitter beam is constructed by spatially combining collimated outputs of several single-mode fiber-coupled diode lasers operating at around 1.55 μm, by using beam-splitter cubes. The beam diameter of the individual emitter is 0.42 mm. Two lasers combined with a single beam splitter are shown in the figure; by cascading such two-beam combiners, more lasers can be straightforwardly added to the beam. In the setup, the separation between constituent beams is varied by moving the collimators that are mounted on translation stages. Two- and four-beam configurations with linear and square intensity patterns are used in the experiments, as is also shown in Fig. 1.

The combined multiemitter beam diverges in free space. The effects of turbulence are simulated by a thin transparent phase screen that is mounted on a

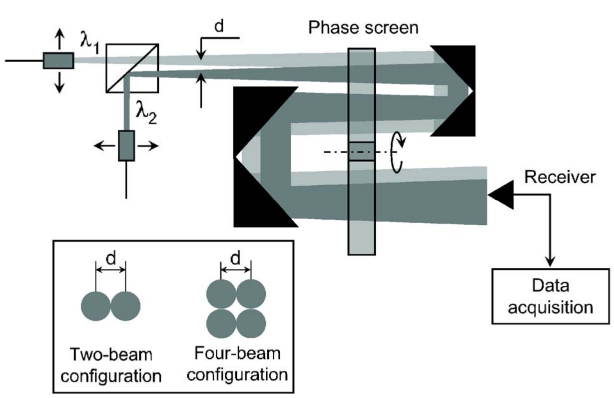

Fig. 1. Experimental setup.

rotation stage and placed in the optical path. The pseudorandom phase distribution was machined into the screen according to a pattern generated by using standard Fourier transform techniques filtered with a Kolmogorov spectrum.[12] The phase distribution is characterized by a single parameter, the effective Fried coherence length r_0, which in this case equals 0.8 mm, and the strength of the simulated turbulence can be varied by changing the location of the screen along the optical path, the total propagation distance, and the number of passes through the screen.

As the phase screen is rotated, passing through successive uncorrelated representations of turbulence, the varying intensity of the signal is measured by a small-area photodetector placed on the optical axis of the system. The detected signal is digitized and recorded by a data acquisition system. The data are subsequently processed to calculate the mean intensity and the scintillation index.

Since the thickness of the screen is negligible compared with the total optical path length, we use the following relation between the Fried coherence length r_0 and the effective structure constant $\tilde{C}_n^2$ for the screen[13]:

$$\tilde{C}_n^2 = C_n^2 d = 2.36(\lambda/2\pi)^2 (r_0)^{-5/3} \approx 2.1 \times 10^{-8} \mathrm{m}^{1/3}, \tag{1}$$

where C_n^2 is the actual structure constant, d is the thickness of the phase screen, and $\lambda = 1.55\ \mu$m is the optical wavelength.

To simulate weak-to-intermediate turbulence, we place the detector at a distance of 1 m from the emitter plane and use a single pass through the phase screen, which is located midway between the emitter and the detector. The Rytov variance σ_χ^2 for this setup can be estimated by using the formula[1,13]

$$\sigma_\chi^2 = 0.56(2\pi/\lambda)^{7/6} \tilde{C}_n^2 (L/4)^{5/6} \approx 0.19. \tag{2}$$

Formula (2) is valid for the case of a spherical wave and also approximately holds for the multiemitter beams used in the experiments.

The strongly turbulent case is simulated by using the setup with a total optical path length of 2 m and three passes through the phase screen. In this case the optical path is folded in such a way that the beam passes through the screen after propagating distances of 0.5 m, 1.0 m, and 1.5 m from the emitter plane, and the three successive interceptions occur in physically different locations on the screen. In this case, the effects of a turbulent atmosphere are lumped into three discrete points along the beam path. Using a generalization of Eq. (2) for the case of multiple phase screens,[1] we estimate the effective Rytov variance in this case at 0.87.

The experimental results for the scintillation index on the optical axis (the longitudinal scintillation) as a function of the beam separation are summarized in Fig. 2 for the cases of weak-to-intermediate and strong turbulence described above. In the plots the separation between Gaussian components of the multiemitter beam is scaled by D_{out}, the beam size at the

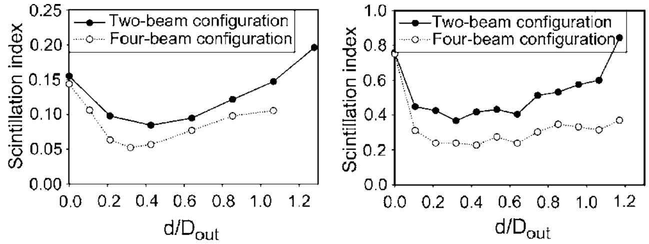

Fig. 2. Measured scintillation index as a function of beam separation for weak-to-intermediate (left) and strong (right) turbulence as described in the text. The beam separation is scaled by the individual beam diameter in the detector plane in the absence of turbulence.

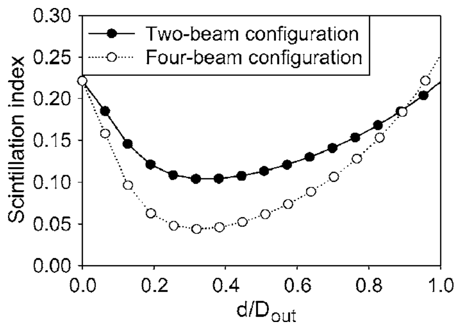

Fig. 3. Calculated scintillation index for a short-range optical communication link in the presence of weak turbulence. Parameters of the link are such that the link is simulated by the experimental setup.

detector in the absence of turbulence, which equals 4.7 and 9.4 mm for the weak-to-intermediate (1 m path length) and strong (2 m path length) turbulence cases, respectively. In both cases the beams strongly overlap in the detector plane, and the scintillation index at the detector has a minimum at a particular beam separation that is of the order of the expanded beam size in the detector plane in the absence of turbulence. Zero beam separation corresponds to perfectly overlapping beams. Relative to that point, the scintillation reduction factor at the minimum is 2.1 and 3.3 for the two- and four-beam configuration, respectively, for the strongly turbulent case. For the case of weak-to-intermediate turbulence, the reduction factor is slightly lower, 1.8 and 2.7 for the two- and four-beam configuration, respectively.

The experimental results for the case of weak-to-intermediate turbulence are modeled by using Rytov theory. The calculation procedure used is described in detail elsewhere.[10] In this analysis, we model a short-range optical communication link with a total optical path length of 1 km and a beam diameter of the individual Gaussian component of the multiemitter beam of 1.33 cm. Then the individual Gaussian beams in the simulated atmospheric link, and those in our experimental setup have the same Fresnel number. Further, the structure constant of the distributed atmosphere is chosen to be equal to 3.8 $\times 10^{-14}$ $m^{-2/3}$, such that the corresponding value of Rytov variance equals the estimated value for the phase screen, Eq. (2). With these parameters, the link is adequately represented by the experimental setup. Results of the modeling are shown in Fig. 3. As before, the separation between individual emitters is scaled by the beam diameter at the detector in the absence of turbulence, which in this case equals 14.9 cm. The scintillation reduction factor predicted for the two- and four-beam configuration is 2.1 and 5.1, respectively, in good qualitative agreement with the experimental results.

In conclusion, we have experimentally studied scintillations produced by a multiemitter beam in the presence of turbulence. We have shown that the scintillation index can be substantially reduced if the constituent beams overlap at the detector and are properly separated in the transmitter plane. In the case of weak-to-intermediate turbulence, the experimental results are in qualitative agreement with calculations based on Rytov theory.

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