Propagation of partially coherent beams: turbulence-induced degradation

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We show that, when a partially coherent beam propagates through an inhomogeneous medium such as atmospheric turbulence, the phase randomization that is induced is less effective in degrading the spatial coherence properties. By evaluating the final beam widths we report what is to our knowledge the first experimental demonstration that, on propagation through thermally induced turbulence, a partially coherent beam is less affected than a spatially coherent beam.

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One of the most appealing characteristics of laser beams is their directionality, a property often associated with their high degree of spatial coherence. However, it is now well understood that this directionality is not always necessary and that certain types of partially coherent beam can also have rather similar properties of directionality and spatial confinement.[1,2]

In general, it is anticipated that the spatial coherence properties of optical beams will change on propagation through inhomogeneous media when the phase front is randomized. Experiments indicate that, when initially coherent, optical waves propagate through turbid media, the wave front's phase uniformity degrades much faster with increasing propagation distance than the wave's intensity decays. For a variety of applications such as guiding and tracking as well as active remote sensing through turbulent atmospheres it is also instructive to know how an initially partially coherent beam (PCB) changes its properties when it propagates through a random medium. Imaging through random media that are specific to biomedical applications is yet another situation in which resolution can be improved if beam distortions are controlled. Recent studies addressed the evolution of the statistical properties and the global shapes of specific types of PCB for free-space propagation[3,4] and through a certain kind of weak atmospheric turbulence.[5,6]

We present experimental evidence of the better performance of a PCB than a coherent beam on propagation through thermally induced turbulence. We conducted systematic experiments to assess the effect of phase turbulence on the intensity profiles of beams with different degrees of spatial coherence and to compare this effect with the distortion of a spatially coherent beam propagating in the same conditions. We report what is to our knowledge the first experimental demonstration that, when the phase front of the incident beam is already distorted, further phase randomization will not significantly affect certain spatial coherence properties and that, in general, the turbulence-induced spread of a PCB is less than that of an initially coherent beam.

The properties of a PCB can be quantitatively described by the correlation between the field fluctuations at two different points, P_1 and P_2. For a quasi-monochromatic field U, the usual procedure is to evaluate the cross-spectral density, which is defined as the following statistical average over the ensembles of realizations: $W_{12} = \langle U^*(P_1)U(P_2)\rangle$.[2] For a beam of light, i.e., a sufficiently directional field such that the paraxial approximation can be used, the result of free-space propagation of cross-spectral density ${W_{12}}^{(z)}$ can be evaluated for any distance z in terms of cross-spectral density ${W_{12}}^{(0)}$ in origin. One can immediately calculate the intensity distribution in a plane situated at a distance z along the direction of propagation:

$$I(\rho, z) = \frac{1}{\lambda z} \iint {W_{12}}^{(0)} \times \exp\left\{i \frac{\pi}{\lambda z} [{\xi_1}^2 - {\xi_2}^2 - 2\rho(\xi_1 - \xi_2)]\right\} \mathrm{d}\xi_1 \mathrm{d}\xi_2 . \quad (1)$$

As can be seen, the propagation generates a certain beam degradation, and one way to quantify the width of the propagating beam is in terms of the intensity variance across the beam:

$$\overline{\rho^2(z)} = \frac{\int \rho^2 I(\rho, z) \mathrm{d}^2\rho}{\int I(\rho, z) \mathrm{d}^2\rho} , \quad (2)$$

a quantity that can be directly measured. When the beam propagates through an inhomogeneous medium, one must take into account both the field's and the medium's randomness to evaluate the intensity distribution in a certain plane z. For weak atmospheric turbulence, specific stochastic models have been used to describe the power spectrum of the atmospheric fluctuations, and analytical results have been obtained for PCB spreading.[6]

In the present series of experiments we evaluated the relative degradation f_{PCB} of a PCB by measuring the ratio between the mean-squared width of the

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beam at a distance z through the turbulence and the mean-squared width at the same distance in free-space propagation (in the absence of turbulence). Using the same conditions of propagation (distance z and turbulence characteristics), we also determined a similar ratio f_{CB} for a spatially coherent beam. It is worth mentioning that Ref. 6 reported that the mean-squared width of a partially coherent beam propagating through weak turbulence depends on the propagation distance as

$$\overline{\rho^2(z)} = {\sigma_I}^2 + {\sigma_J}^2 z^2 + Tz^3, \tag{3}$$

where σ_I is the width of the intensity distribution in the plane $z = 0$ and σ_J is a measure of the far-zone angular spread of the beam in free space. In Eq. (3) the initial state of coherence is described entirely by σ_J, whereas the beam spread that is due to turbulence is quantified by the parameter T. Using the dependence suggested in Eq. (3), one can evaluate the factors that describe the relative degradation introduced by the turbulence. In the case of a spatially coherent beam for which σ_J reaches its minimum (and which for short propagation distances may be neglected), this factor is

$$f_{\mathrm{CB}} = \frac{{\sigma_I}^2 + Tz^3}{{\sigma_I}^2}, \tag{4}$$

whereas for the general case of a partially coherent beam it becomes

$$f_{\mathrm{PCB}} = \frac{{\sigma_I}^2 + {\sigma_J}^2 z^2 + Tz^3}{{\sigma_I}^2 + {\sigma_J}^2 z^2}. \tag{5}$$

It follows immediately that a partially coherent beam will always be less affected by propagation through random inhomogenities of the refractive index:

$$f = \frac{f_{\mathrm{CB}} - 1}{f_{\mathrm{PCB}} - 1} = 1 + \frac{{\sigma_J}^2}{{\sigma_I}^2} z^2 > 1. \tag{6}$$

Note that this behavior has been predicted for partially coherent beams propagating through atmospheric turbulence.[3]

The experiment is presented schematically in Fig. 1. We achieved the partially coherent beam generator by focusing a laser beam on a rotating random phase screen and recollimating the scattered field. By adjusting the position of the phase screen between the lenses we were able to obtain partially coherent beams with variable transverse coherence lengths. This procedure introduces an additional small divergence of as much as 0.4 mrad in a PCB, which, however, cancels out in f_{PCB}. According to the van Cittert–Zernike theorem, the degree of spatial coherence in the plane of the second lens is merely the Fourier transform of the intensity distribution in the plane of the phase screen. Our calculations show that this length was practically varied from 30λ to 2500λ. We obtained the corresponding spatially coherent beam by simply removing the phase screen from the setup. The beams with adjustable coherence properties were subsequently propagated through a 40-cm-long region where fluctuations of the refractive index were induced thermally. After passing through the turbulence, the beams were focused by a lens with a focal length of 50 cm, and the intensity distribution in the focal plane was recorded with a 16-bit high-resolution CCD array. The intensity distributions were averaged over times much longer that the characteristic time scale of the thermal turbulence, and the corresponding beam widths were determined from Eq. (2) by use of the measured intensity profiles.

A number of intensity distributions have been recorded for various PCBs as well as for spatially coherent beams. As expected, one observes in all the situations that the thermally induced turbulence degrades the beams. The quantitative effect of this degradation is shown in Fig. 2, where the beam waists as obtained from Eq. (2) are plotted against the transversal coherence length of the beam entering the turbulent region. Remarkably, one can see that the additional degradation introduced by the turbulence is less significant when the spatial coherence of the beam is reduced. In fact, it can be concluded that the coherent beam is the beam that is most affected by passing through the turbulence.

One should perform a systematic study of the beam degradation effect by controlling the propagation distance as well as the detailed characteristics of the turbulence. In these experiments, however, we kept the conditions of propagation constant, and we focused on

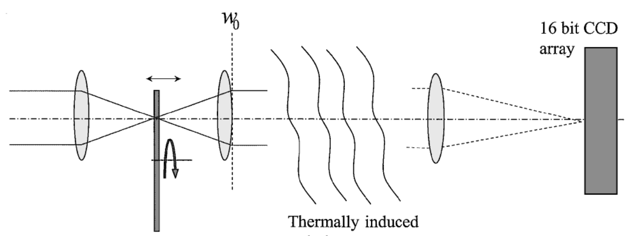

Fig. 1. Experimental setup used to generate a PCB with adjustable coherence properties and to record the width of the beam in the far field.

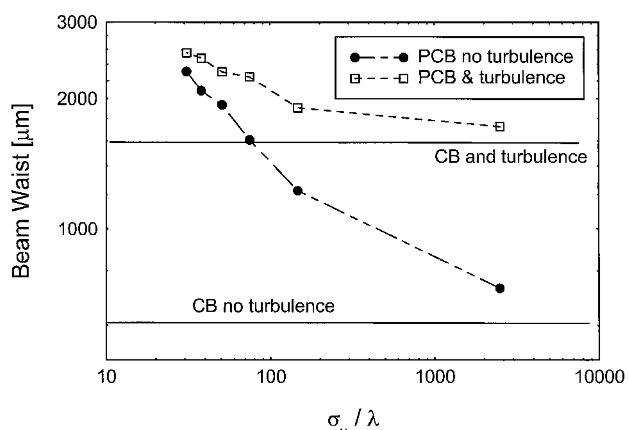

Fig. 2. Waist of a PCB with different coherence properties after propagation in free space and through a 40-cm layer of thermally induced turbulence. Also shown are the corresponding waists of the partially coherent beam.

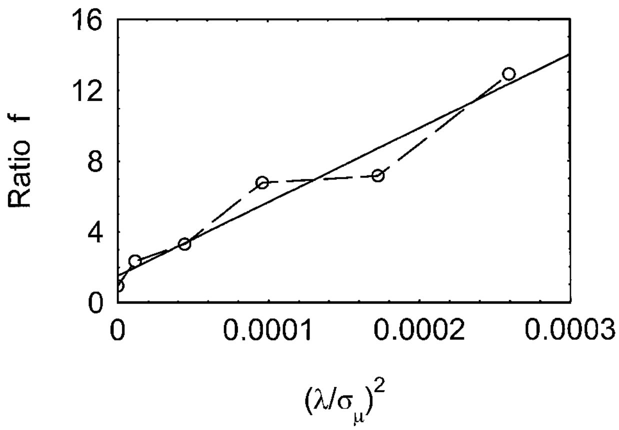

Fig. 3. Relative spreading factor f calculated from beam widths of the several PCBs indicated in Fig. 2. The solid line is a fit with dependence indicated in expression (7).

comparing relative effects on beams with different initial states of coherence. When the ratio f defined in inequality (6) is calculated for the particular case of a beam generated by a Gaussian–Schell-model source at $z = 0$ for which the intensity distribution is $I(\rho) = A \exp(-2\rho^2/{w_0}^2)$ and the degree of coherence is $\mu(\rho) = A \exp(-\rho^2/{\sigma_\mu}^2)$, the following result is obtained.

$$f = 1 + \frac{\lambda^2}{\pi^2}\frac{1}{{w_0}^4}\left(1 + \frac{{w_0}^2}{{\sigma_\mu}^2}\right)z^2 \approx 1 + \frac{1}{\pi^2}\frac{\lambda^2}{{\sigma_\mu}^2}\frac{z^2}{{w_0}^2}\,. \tag{7}$$

We evaluated f for our experimental data, and the results are plotted in Fig. 3 together with a fit with the dependence indicated in expression (7). As can be seen, we recovered the expected linear dependence of f on $\lambda^2/{\sigma_\mu}^2$, indicating that the source of our PCB is well described by a Gaussian–Schell model. Notably, the slope of the linear fit determines a width of 670 μm, very close to the value of 620 μm measured directly in the focal plane of the lens. It is worth mentioning that Gaussian–Schell-model beams have also been used in the context of planar scattering experiments.[7]

In conclusion, we conducted a proof-of-concept experiment to assess the effect of phase turbulence on the intensity profiles of beams with different degrees of spatial coherence. Our results suggest that laser beams with special coherence properties can exhibit better performance under adverse conditions of propagation. More specifically, we have shown that partially coherent beams are less sensitive to propagation through turbulence and, therefore, can perform an energy transfer that is superior to that of fully coherent laser beams. In addition, the possibility of designing and controlling specific coherence properties could lead to developing efficient techniques to mitigate the degradation associated with beam propagation in adverse environments.

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References

1. E. Wolf and E. Collett, Opt. Commun. **25,** 293 (1978).
2. L. Mandel and E. Wolf, *Optical Coherence and Quantum Optics* (Cambridge U., Cambridge, 1995).
3. J. Wu and A. D. Boardman, J. Mod. Opt. **38,** 1355 (1991).
4. M. Santarsiero, F. Gori, R. Borghi, G. Cincotti, and P. Vahimaa, J. Opt. Soc. Am. A **16,** 106 (1999).
5. G. Gbur and E. Wolf, Opt. Commun. **199,** 295 (2001).
6. G. Gbur and E. Wolf, J. Opt. Soc. Am. A, **19,** 1592 (2002).
7. F. Gori, C. Palma, and M. Santarsiero, Opt. Commun. **74,** 353 (1990).