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Toward defeating diffraction and randomness for laser beam propagation in turbulent atmosphere

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Laser beam propagation though turbulent atmosphere results in disintegration of laser beam into speckles at the distances exceeding several kilometers (strong irradiance fluctuation regime) [1], see Fig. 1 with examples of such propagation. At smaller distances (weak irradiance fluctuation regime) classic perturbative approaches well describe modification of laser beam propagation due to turbulence [2, 3], while statistically averaged beam propagation in strong scintillation regimes is addressed through semi-heuristic theory [4]. The strength of the fluctuations of the irradiance I (laser beam intensity) at the target plane is characterized by the scintillation index $\sigma_I^2 \equiv \langle I^2\rangle/\langle I\rangle^2 - 1$, where by $\langle\ldots\rangle$ we denote an the average over the ensemble of atmospheric turbulence realizations. It was shown in [5] that a significant fraction of deviation between theoretical value of σ_I^2 [4] and simulations is due to rare large fluctuations of laser beam intensity. Such giant fluctuations were first observed in experiments of [6, 7]. Here we study the structure of large fluctuations and propose to use them for the efficient delivery of laser energy over long distances by triggering the pulse laser operations only during the times of such rare fluctuations. For instance, in atmospheric conditions of Fig. 1, 0.1 % realizations carry $\gtrsim 28\,\%$ of initial power after 7 km of laser beam propagation. A temporal rate of change in atmospheric realizations is affected by atmosphere conditions. Typically new atmospheric realization could occur each ~ 10 ms [5]. Thus waiting for the optimal realization might take several seconds. We find that the most intense speckle approximately preserves both the Gaussian shape and the diameter of the initial collimated beam while loosing energy during propagation. Such optimal realizations create effective extended lenses focusing the intense speckle beyond the diffraction limit of vacuum propagation. Atmospheric realizations change every several milliseconds. A triggering the pulsed laser operations only at times of optimal realizations results in power delivery and laser irradiance at the intense speckles to well exceed both intensity of diffraction-limited beam and intensity averaged over typical realizations.

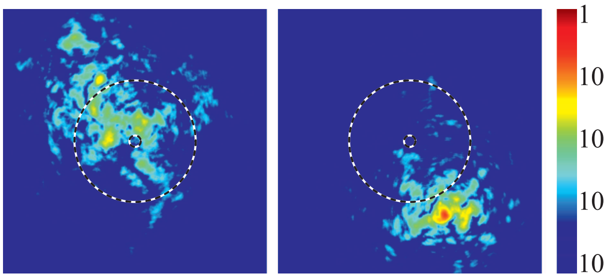

Fig. 1. (Color online) Distribution of laser irradiance I in transverse plane (69×69 cm central part of target screen is shown) after $L = 7$ km propagation of the collimated Gaussian beam with the waist $w_0 = 1.5$ cm and the maximal intensity $I_{\max} = 1$ (the maximum in the transverse plane) through the turbulent atmosphere in the strong scintillation regime $\sigma_I^2 = 3.3$ and the turbulence strength $C_n^2 = 10^{-14}\,\mathrm{m}^{-2/3}$ [2, 3]. Left panel: a typical atmospheric turbulence realization with $I_{\max} = 0.04$ (61 % realizations produce higher $I_{\max}$). Right panel: a rare realization with $I_{\max} = 0.19$ (0.16 % realizations produce higher $I_{\max}$). Dashed circles show w_0 and the waist of diffraction limited beam propagated in vacuum. The initial beam disintegrates into several speckles with the width of the most intense speckle being $\sim w_0$. The intense speckles on left and right panels carry 4.7 % and 30 % of the total laser power, calculated based on $\sqrt{2}w_0$ radius cross section around the intensity maximum. Diffraction-limited and ensemble-averaged beams carry 3.5 % and 1.1 % in $\sqrt{2}w_0$ radius, respectively. Also the ensemble-averaged $\langle I_{\max}\rangle = 5.10433 \cdot 10^{-2}$ and $\langle I_{\text{center}}\rangle = 2.86788 \cdot 10^{-3}$ (the averaged irradiance at the center of the target plane)

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1. J. W. Strohbehn, *Laser Beam Propagation in the Atmosphere*, ed. by J. W. Strohbehn, Springer, N.Y. (1978).
2. V.I. Tatarskii, *Wave Propagation in a Turbulent Medium*, McGraw-Hill Series in Electrical Engineering, N.Y. (1961).
3. V.I. Tatarskii, *The Effects of the Turbulence Atmosphere on Wave Propagation, Jerusalem: Israel Program for Scientific Translations*, Jerusalem (1971).
4. L. C. Andrews and R. L. Phillips, *Laser Beam Propagation Through Random Media. Press Monograph Series vol PM53*, SPIE – The International Society for Optical Engeneering (1998).
5. S. L. Lachinova and M. A. Vorontsov, J. Opt. **18**, 025608 (2016).
6. M. A. Vorontsov, G. W. Carhart, V. S. R. Gudimetla, T. Weyrauch, E. Stevenson, S. L. Lachinova, L. A. Beresnev, J. Liu, K. Rehder, and J. F. Riker, Characterization of atmospheric turbulence effects over 149 km propagation path using multi-wavelength laser beacons, in *Proc. 2010 AMOS Conf.*, Maui, Hawaii (2010).
7. M. A. Vorontsov, V. R. Gudimetla, G. W. Carhart, T. Weyrauch, S. L. Lachinova, E. Polnau, J. R. L. A. Beresnev, J. Liu, and J. F. Riker, Comparison of turbulence-induced scintillations for multi-wavelength laser beacons over tactical (7 km) and long (149 km) atmospheric propagation paths, in *Proc. 2011 AMOS Conf.*, Maui, Hawaii (2011).
8. A. Hasegawa and F. Tappert, Appl. Phys. Lett. **23**, 142 (1973).
9. J. A. Fleck, J. R. Morris, and M. D. Feit, Appl. Phys. **10**, 129 (1976).
10. M. S. Rytov, Y. A. Kravtsov, and V. I. Tatarskii, *Principles of Statistical Radiophysics 4: Wave Propagation through Random Media*, Springer-Verlag, Berlin (1989).
11. I. M. Lifshitz, Usp. Fiz. Nauk **83**, 617 (1964) [Sov. Phys. Uspehi **7**(4), 549 (1965)].
12. L. N. Lipatov, ZhETF **72**, 411 (1977) [Sov. Phys. JETP **45**, 216 (1977)].
13. G. Falkovich, I. Kolokolov, V. Lebedev, and A. Migdal, Phys. Rev. E **54**, 4896 (1996).
14. M. Chertkov, Phys. Rev. E **55**, 2722 (1997).
15. T. Grafke, R. Grauer, and T. Schafer, J. Phys. A: Math. Theor. **48**, 333001 (2015).
16. G. E. Falkovich, I. Kolokolov, V. Lebedev, and S. K. Turitsyn, Phys. Rev. E **63**, 025601(R) (2001).
17. P. M. Lushnikov and N. Vladimirova, Opt. Lett. **35**, 1965 (2010).
18. Y. Chung and P. M. Lushnikov, Phys. Rev. E **84**, 036602 (2011).
19. A. E. Siegman, *Lasers*, University Science Books, Mill Valley, California (1986).
20. M. A. Vorontsov, V. V. Kolosov, and A. Kohnle, J. Opt. Soc. Am. A **24**, 1975 (2007).
21. A.I. Khizhnyak, and V.B. Markov, *Turbulence-corrected adaptive laser beam focusing on a remote image-resolved target*, in *Proc. SPIE 8238, 82380K*, San Francisco, USA (2012).
22. S. L. Lachinova, M. A. Vorontsov, G. A. Filimonov, D. A. LeMaster, and M. E. Trippel, Opt. Eng. **56**, 071509 (2017).
23. A. P. Godlevsky, Y. D. Kopytin, and V. P. Aksenov, USSR patent 950016 (1981).
24. I. A. Vaseva, M. P. Fedoruk, A. M. Rubenchik, and S. K. Turitsyn, Sci. Rep. **6**, 30697 (2016).
25. S. N. Vlasov, V. A. Petrishchev, and V. I. Talanov, Izv. Vys. Uchebn. Zaved. Radiofizika **14**, 1353 (1971).
26. P. M. Lushnikov, S. A. Dyachenko, and N. Vladimirova, Phys. Rev. A **88**, 013845 (2013).
27. P. M. Lushnikov and N. Vladimirova, Opt. Lett. **39**, 3429 (2014).
28. P. M. Lushnikov and N. Vladimirova, Opt. Express **23**, 31120 (2015).
29. T. Weyrauch, M. Vorontsov, J. Mangano, V. Ovchinnikov, D. Bricker, E. Polnau, and A. Rostov, Opt. Lett. **41**, 840 (2016).