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Mitigating effect on turbulent scintillation using non-coherent multi-beam overlapped illumination

Lu Zhou [a], Yuzhen Tian [b,*], Rui Wang [b], Tingfeng Wang [b], Tao Sun [b], Canjin Wang [b], Xiaotian Yang [a]

[a] Jilin Provincial Key Laboratory of Architectural Electricity & Comprehensive Energy Saving, School of Electrical Engineering and Computer, Jilin Jianzhu University, Changchun 130118, China

[b] State Key Laboratory of Laser Interaction with Matter, Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Science, Changchun 130033, China

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ABSTRACT

In order to find an effective method to mitigate the turbulent scintillation for applications involved laser propagation through atmosphere, we demonstrated one model using non-coherent multi-beam overlapped illumination. Based on lognormal distribution and the statistical moments of overlapped field, the reduction effect on turbulent scintillation of this method was discussed and tested against numerical wave optics simulation and laboratory experiments with phase plates. Our analysis showed that the best mitigating effect, the scintillation index of overlapped field reduced to 1/N of that when using single beam illuminating, could be obtained using this method when the intensity of N emitting beams equaled to each other.

1. Introduction

Laser played an important role in applications such as active imaging, laser communication and ladar [1,2], because of the characteristics of laser, far operation range, small divergence angle and high brightness. However, when laser transmitted long path through atmospheric turbulence, the irradiance fluctuation affected these applications seriously [3–9]. Therefore, if we could reduce the irradiance fluctuation, the performance of these applications could be enhanced.

In this paper, we introduced a simple non-coherent multi-beam illumination model to reduce irradiance fluctuation at the observation plane, under weak turbulence conditions, when the probability distribution function (PDF) of irradiance was modeled as lognormal distribution. This model could be used in active imaging and laser communication system, and was useful for designing optical system and laboratory experiments with phase plates, which the performance is prior to purchasing equipment and conducting experiments. The model of Tellez and Schmidt [10] introduced the theory results of multi-beam model under moderate and strong turbulence, and many others also did some theoretical [5] or experiments [11] research of multi-beam scintillation models under different conditions, but the model developed here just focus on weak turbulence situation for laser active imaging and laser communication, and we treated this model as a simple statistical problem, which did not consider the complexity physical process. The multi-beam scintillation index verified that the non-coherent multi-beam illumination model was useful for mitigating the irradiance fluctuation. Especially when each beam illuminated with equal intensity, the index reduced to 1/N of that of individual beam. In order to test this model, we simulated 4 non-coherent beams propagation through numerical random phase screen and overlapped at the observation plane, and conducted laboratory experiments with phase plates, in the end compared the irradiance fluctuation with individual beam. Both wave optics simulation and laboratory experiments showed the mitigating effect of our model on irradiance fluctuation.

2. Theory analysis

2.1. Non-coherent multi-beam emitting model

In order to obtain non-coherent multi-beam from one laser, firstly, we split one beam into several beams, meanwhile increased the optical path difference (OPD) of each beam, which should be longer than laser coherence length. Then overlapped these beams at the observation plane. Here, we took advantage of the property that with the reduction of laser temporal coherence, the laser spatial coherence reduced. This method could guarantee both the highly coherence of individual beam and lowly coherence of overlapped illumination field.

* Corresponding author.
E-mail address: tianyz@ciomp.ac.cn (Y. Tian).

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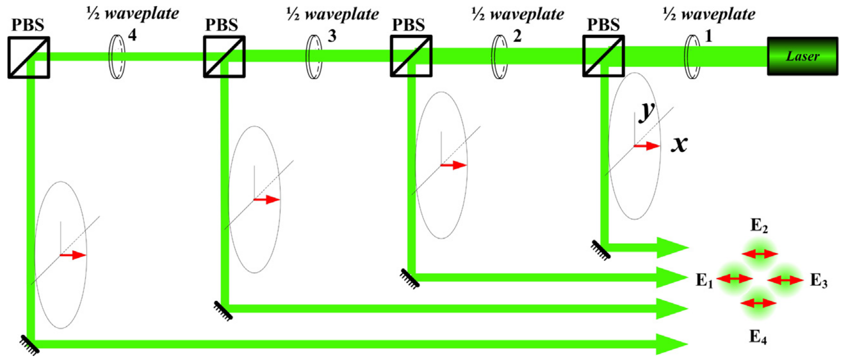

Fig. 1. Non-coherent multi-beam emitting model with changeable intensity of each beam.

According to this idea, we established the non-coherent multi-beam emitting model, as shown in Fig. 1, which 4 beams were generated here. Four groups ½ wave plates, controlling laser polarization angle, and polarization beam splitters (PBS), making sure emitting laser with the same polarization state, were used to split beams and adjust emitting power of each beam. In order to make sure emitting beams were not coherent, 4 beams should divide far enough to ensure the OPD greater than coherent length.

2.2. The mitigating effect on turbulent scintillation of non-coherent multi-beam overlapped illumination

The scintillation index [5], normalized irradiance variation of illumination field, was always used to evaluate the irradiance uniformity and fluctuation when laser propagation through atmosphere, and in this paper we didn't consider the spatial uniformity which could be ignored for laser active imaging and laser communication. If we could deduce the relationship between the scintillation index of single beam and that of non-coherent multi-beam, the mitigating effect on turbulent scintillation of the model, as shown in Fig. 1, could be evaluated. In this section, we studied the relationship of scintillation index only using statistical method but avoided the complexity physical process.

Assuming emitting intensity was I at source, and it split into N non-coherent beams with field U_i, intensity I_i, thus:

$$\langle I\rangle = \sum_{i=1}^{N}\langle I_i\rangle, \tag{1}$$

where $\langle\rangle$ denoted the ensemble average. The irradiance PDF of illumination field of each beam followed lognormal distribution under weak turbulence [5,12]:

$$p_{I_i}(I_i) = \frac{1}{2\sqrt{2\pi\sigma_{\chi_i}^2}I_i}\exp\left\{-\frac{[\ln(I_i/I_0)-2\langle\chi_i\rangle]^2}{8\sigma_{\chi_i}^2}\right\} \quad (I_i \geqslant 0), \tag{2}$$

where $\langle\chi_i\rangle$ and ${\sigma_{\chi i}}^2$ were the mean and variance of lognormal amplitude $\chi = \ln(A/A_0)$ of the i^{th} beam.

Because N beams were non-coherent which meant independent with each other [13] from the point of statistical property, the PDF of N overlapped beams was considered as the PDF of the sum of N independent random variables. Generally, the PDF of the sum of N independent variables was the convolution of their PDFs, or the Fourier transformation of characteristic function (CF) of the sum of variables, was the product of CFs of all these variables. For normal distribution, this operation was easily carried out by their CFs, and the sum distribution was another normal distribution. For lognormal distribution, however, it was known that the CF of log-normal distribution had not been found yet [14]. Fortunately, we could use statistical moments, which could be solved accurately, of the sum distribution to estimate the irradiance fluctuation of multi-beam model.

The sum distribution of N lognormal variables could also be approximated to lognormal model, which was verified using numerical convolution [15], therefore, we could utilize this approximation under appropriate assumption. And the PDF of overlapped multi-beam could be obtained using its moments, which were easy to get, according to the fact that the approximated mean $\langle\chi\rangle$ and variance σ_χ^2 were equal to the first and second moments of the real sum PDF of N independent lognormal variables [15].

Assuming the mean and variance of the amplitude of U_i were $\langle A_i\rangle$ and ${\sigma_{Ai}}^2$, respectively, and the n^{th} moments of A were:

$$\langle A^n\rangle = \int_0^\infty z^n \frac{1}{\sqrt{2\pi}\sigma_\chi^2 z}\exp\left[-\frac{(\ln z - \langle\chi\rangle)^2}{2\sigma_\chi^2}\right]dz. \tag{3}$$

Based on the CF of normal distribution, we could obtain $\langle A^n\rangle$:

$$\begin{aligned}\langle A^n\rangle &= e^{n\langle\chi\rangle}\int_0^\infty e^{it\upsilon}\frac{1}{\sqrt{2\pi}}\exp\left(-\frac{\upsilon^2}{2}\right)d\upsilon \\ &= \exp(n\langle\chi\rangle + \sigma_\chi^2 n^2/2).\end{aligned} \tag{4}$$

Also the n^{th} moments of irradiance I were expressed as:

$$\langle I^n\rangle = \exp(2n\langle\chi\rangle + 2n^2\sigma_\chi^2). \tag{5}$$

Based on Eq. (4) and (5), the 1st and 2nd moments could be obtained:

$$\begin{aligned}&\langle A_i\rangle = e^{\langle\chi_i\rangle+\sigma_{\chi_i}^2/2}; \quad \langle A_i^2\rangle = e^{2\langle\chi_i\rangle+2\sigma_{\chi_i}^2} \\ &\langle I_i\rangle = e^{2\langle\chi_i\rangle+2\sigma_{\chi_i}^2}; \quad \langle I_i^2\rangle = e^{4\langle\chi_i\rangle+8\sigma_{\chi_i}^2}.\end{aligned} \tag{6}$$

The amplitude mean $\langle A\rangle$ and variance ${\sigma_A}^2$ of overlapped field, and the irradiance mean $\langle I\rangle$ and variance D^2 of overlapped field were:

$$\begin{aligned}&\langle A\rangle = \sum_{i=1}^{N}\langle A_i\rangle = \sum_{i=1}^{N}e^{\langle\chi_i\rangle+\sigma_{\chi_i}^2/2}; \\ &\sigma_A^2 = \sum_{i=1}^{N}\sigma_{A_i}^2 = \sum_{i=1}^{N}\langle A_i\rangle^2(e^{\sigma_{\chi_i}^2}-1) \\ &\langle I\rangle = \sum_{i=1}^{N}\langle I_i\rangle = \sum_{i=1}^{N}e^{2\langle\chi_i\rangle+2\sigma_{\chi_i}^2} \\ &D^2 = \sum_{i=1}^{N}D_i^2 = \sum_{i=1}^{N}\langle I_i\rangle^2(e^{4\sigma_{\chi_i}^2}-1),\end{aligned} \tag{7}$$

where ${D_i}^2$ was irradiance variance of the i^{th} beam, it should be noticed that beams were independent with each other, so the cross-terms were eliminated on the right side of Eq. (7). Thus the