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Scintillation reduction in pseudo Multi-Gaussian Schell Model beams in the maritime environment

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ABSTRACT

Irradiance fluctuations of a pseudo Multi-Gaussian Schell Model beam propagating in the maritime environment is explored as a function of spatial light modulator cycling rate and estimated atmospheric turnover rate. Analysis of the data demonstrates a strong negative correlation between the scintillation index of received optical intensity and cycling speed for the estimated atmospheric turnover rate.

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1. Introduction

Free-space optical (FSO) communication offers a natural complement and extension to current RF infrastructure and capabilities of the US Navy with the advantage of high bandwidth, low probability of detection and interception, and resistance to jamming [1,2]. FSO communications have drawbacks as well. Specifically, a propagating laser beam in the maritime environment faces challenges from optical turbulence in the atmospheric channel. One widely accepted method for potential mitigation of the optical turbulence effects on a propagating optical beam is based on modifying the spatial partial coherence of the source and use of spatially partially coherent beams (PCB) [3–9].

While PCBs have been the focus of much recent research, very little has been done in the area of pseudo-partially coherent beams (PPCB); and what has been done has primarily focused on in-laboratory results and numerical simulations [10–15]. This paper is motivated by studies carried out in Refs. [10] and [15]. Ref. [10] first proposed and coined the term ‘pseudo’ in order to describe and distinguish the effect of more experimentally realistic PPCBs from the more common analytic PCBs. Specifically, the PPCB is an experimental realization of a partially coherent beam (PCB) in that the beam is physically limited in how fast individual source realizations are produced as compared with the detection rate as well as atmospheric turnover time. Ref. [15] proposed and numerically investigated the effect of the relative changing frequency of random phase screens to the atmospheric rate, or K value, on scintillation index for spatially pseudo-partially coherent GSM beams in atmospheric turbulence. The current paper extends the body of literature to include the experimental exploration of PPCBs through atmospheric turbulence in the maritime environment, the investigation of the effects of a varying K value on the scintillation index, and the pseudo Multi-Gaussian Schell Model (MGSM) beam class. To generate the PPCBs in the experiments, we used a liquid crystal spatial light modulator (SLM) with fully controllable phase modulation capabilities. While the SLM is an efficient method of modulating the phase spatially, it has drawbacks associated with cycling speed limitations. Other methods to produce PPCBs include a rotating grounded glass plate [10,11] and a coupled output of a superluminescent diode to a multi-mode fiber that allows for generation of the PPCBs with a high phase fluctuation rate [12].

Analysis of the data demonstrates a strong negative correlation between the scintillation index of the received optical intensity and the SLM cycling rates for a given atmospheric turnover rate.

2. Generation of pseudo Multi-Gaussian Schell Model beams

A recently developed model for the MGSM (flattop) beams, gives the following spectral (scalar) degree of coherence at the source [16,17]:

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$$\mu^{(0)}(\rho_1, \rho_2) = \frac{1}{C_0} \sum_{m=1}^{M} \binom{M}{m} \frac{(-1)^{m-1}}{m} \exp\left[-\frac{|\rho_2 - \rho_1|^2}{2m\delta^2} \right] \tag{1}$$

where ρ_1 and ρ_2 are position distances and superscript (0) refers to the source plane,

$$C_0 = \sum_{m=1}^{M} \binom{M}{m} \frac{(-1)^{m-1}}{m} \tag{2}$$

is the normalization factor used for obtaining the same maximum intensity level for any number of terms M in the summation, and $\binom{M}{m}$ is the binomial coefficient. In Eq. (1), δ is the r.m.s. width of the degree of coherence which describes the degree of coherence of the beam; where a value of $\delta=0$ gives a spatially incoherent beam and a value of $\delta \to \infty$ gives a spatially coherent beam. Additionally, the upper index M relates to the flatness of the intensity profile formed in the far field: $M=1$ corresponds to the classical Gaussian Schell-Model source and $M \to \infty$ corresponds to sources producing far fields with flat centers and abrupt decays at the edges.

In our experiment, we generated the pseudo MGSM beams with phase screen realizations on an SLM with resolution of 256×256 pixels. Reference [9] describes the general process that we used for generating the SLM phase screens. To summarize the method: a 256×256 random matrix with Gaussian statistics and zero mean is convolved with a Multi-Gaussian window function of the form of Eq. (1), the result is then optimized for a 256 (8 bit) gray-scale bitmap (phase screen, see Fig. 1a) and sent to the SLM. Note, when these phase screens are used with an SLM, there is a zeroth order spot, which is a common artifact to the SLMs [18] and is caused by pixelation of the SLM. To eliminate the effect of the zeroth order 'hot' spot we generated 'shifted' beams by multiplying the window function by a cosine function with prescribed periodicity and then convolved the result and optimized it as before. The cosine multiplication serves to generate additional spatially shifted copies of the beam, which with an experimentally prescribed periodicity closely overlap into shifted off-axis quadrants. Fig. 1 illustrates the effects of representative phase screens with and without the cosine shift. Specifically, Fig. 1a shows a representative non-cosine shifted MGSM phase screen, Fig. 1b shows the graphical simulation of the stationary phase screen in Fig. 1a, and Fig. 1c shows the 'smoothed' experimental realization of Fig. 1a with a 333 Hz cycling rate. Fig. 1d shows a representative cosine shifted MGSM phase screen, Fig. 1e shows the graphical simulation of the phase screen in Fig. 1d, and Fig. 1f shows the experimental realization of Fig. 1d with the beam shifted into quadrants and isolation of the first order mode (upper left) with a mechanical iris. The 'cross' pattern seen on the mechanical iris (Fig. 1f) is due to the square shape of the SLM used in the experiment. All experimental evaluations in this paper were performed using the shifted beams.

3. Experimental description

Fig. 2a illustrates the over-the-water (College Creek) link at the United States Naval Academy. The field trials were conducted in July and were performed during the night in relatively calm (0–1 m/s crosswind speeds) weather conditions over a maritime link

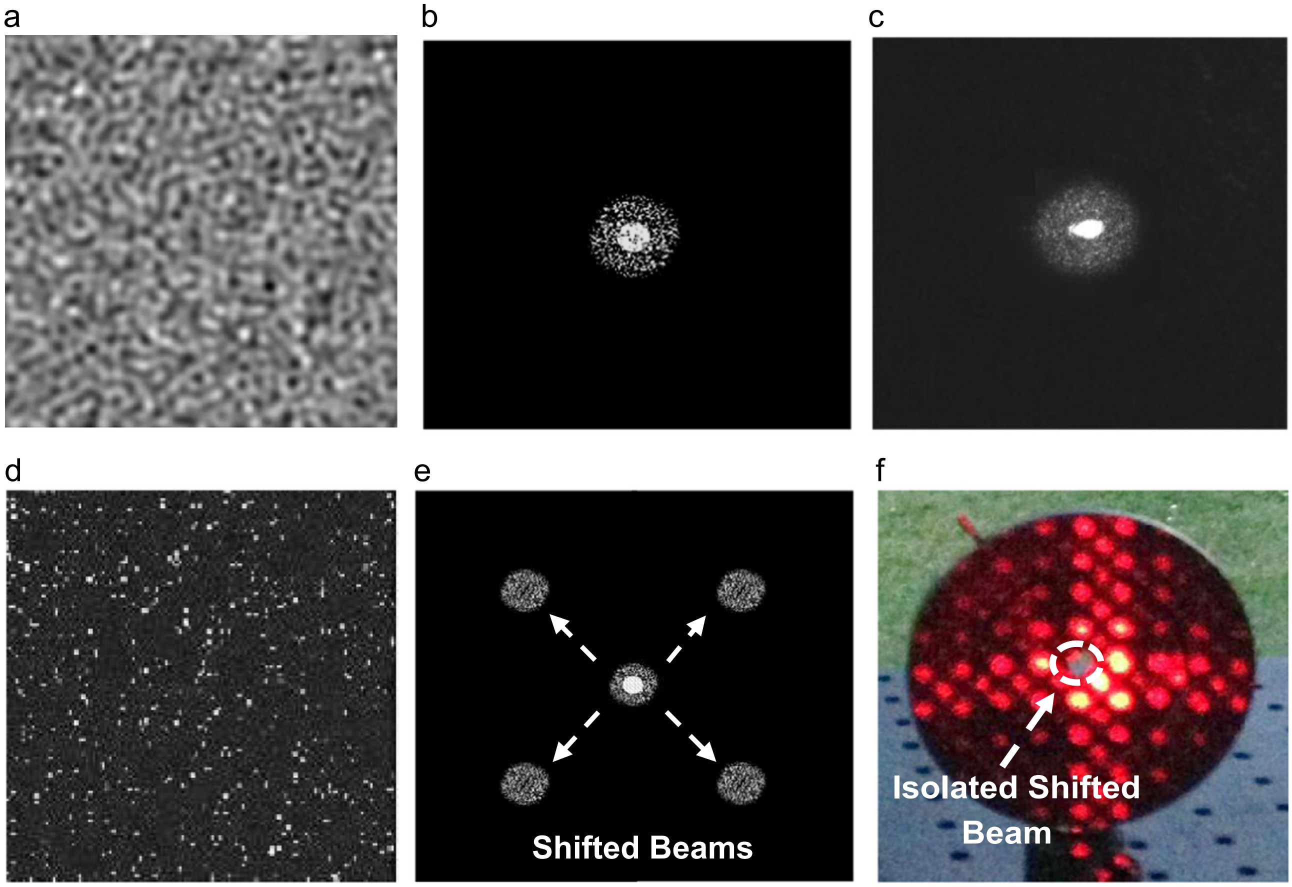

Fig. 1. Typical phase screens with and without a prescribed cosine shift, simulations of the far-field, and experimental realizations: (a) phase screen without cosine shift, (b) simulation of phase screen in far-field, (c) experimental realization with 333 Hz cycling, (d) phase screen with cosine shift, (e) simulation of far-field showing effect of the cosine shift, (f) experimental realization (as used in field test).