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Single and double passage interferometric analysis of Pseudo-Random-Phase-Plates

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ABSTRACT

In this paper, we analyze the phase introduced by two Pseudo-Random-Phase-Plates (PRPPs) in the path of a propagating beam, when the PRPPs are inserted as objects (either *individually* or *in-a-combination*) in one of the arms of well-known Mach–Zehnder and Michelson's interferometers. A He–Ne laser lasing at 633 nm is used as a source for this purpose. We find that both the PRPPs under consideration behave like non-Kolmogorov turbulence simulators, when introduced individually or jointly. We also notice an interesting phenomenon that the nature of turbulence depends upon the number of passages the beam travels through these PRPPs. More specifically, we witness the tendency of *approaching towards Kolmogorov* turbulence regime *on increasing the number of passages* through the given PRPP or PRPPs-in-a-combination.

1. Introduction

Characterization of random media is a subject of great interest in various research fields including bio-medical optics, imaging optics, optical communication, adaptive optics, and interferometry [1–6]. One performs such characterization by analyzing the alterations in intensity, phase, coherence, and polarization of the electromagnetic waves propagating through these media [1,2,7]. Atmospheric turbulence, which is one such random medium, has been studied extensively in the existing literature [1,8–11].

Attempts on understanding the nature of turbulence and its statistical properties have resulted in some seminal contributions in this area. Kolmogorov in his work [12] derives an expression for the *velocity structure function* in the turbulent flow, which is further extended by Tatarskii [7] to formulate *refractive index structure function*. From these expressions, the strength of turbulence is understood as the structure constant. Another useful parameter, known as the Fried's parameter, given by Fried [13], relates the statistics of wave distortion in a turbulent medium to optical resolution of the detecting system. Also, Greenwood's frequency, named after its inventor Greenwood, gives a simplified expression for the frequency or bandwidth of an adaptive optics system [14] required for an effective wavefront correction of distorted wavefronts traveling through a turbulent medium. Furthermore, Zernike polynomials [15,16] are used towards describing aberrations introduced in a wavefront traveling through turbulence.

It is evident that the most widely explored turbulence regimes are either Kolmogorov or non-Kolmogorov [7,12–20], with *structure function* being one of the important parameters for their characterization [7,12,18].

For accurate validation of new generation systems in areas such as adaptive optics [21], optical communication [22] and optical imaging [5] through free-space, one requires a realistic, well-defined and repeatable turbulence at laboratory level. To generate such artificial laboratory-level turbulence, several methods have been proposed in the literature which include near index matching [23], hot air chambers [24], liquid filled chambers [25], spatial light modulators [26], hair sprays [27], paints [28], ion-exchange phase screens [29] and surface etching [30,31]. The primary focus of these methods remains on experimentally achieving a Kolmogorov turbulence regime in the sense of both spatial and temporal characteristics.

Such a well-defined turbulence mimicking capacity in an experimental laboratory can prove to be very useful in observing the effects of turbulence on a propagating beam by measuring the changes introduced in some quantities of physical relevance as has been recently reported in [32,33]. Further, a turbulence mimicking medium has also been used in [34] as a mediating medium to demonstrate the possibility of sharing a secret key between two observing ends separated by a realistic atmosphere. The effects of turbulence on beam coherence and polarization are another area of exploration wherein such media can prove to be helpful.

Motivated from the above works, our paper considers Pseudo-

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Random-Phase-Plates (PRPPs), which are claimed to be such turbulence mimicking media [35] and characterizes them at 633 nm wavelength, by using phase extracted from interference fringe patterns in two interferometric geometries. We subsequently draw a robust conclusion on the nature of these media. We also witness an interesting phenomenon that the nature of turbulence depends upon the number of passages the beam travels through this medium. In fact, there is an observed tendency of approaching towards Kolmogorov turbulence regime on increasing the number of passages through the PRPP or PRPPs-in-a-combination.

The paper is organized in the following manner: In Section 2, we provide the details of the experiment which include a description of the two PRPPs used, the Mach–Zehnder and Michelson's interferometric geometries. Section 3 explains the phase retrieval algorithm in detail. Section 4 gives the theoretical background for an analysis of the retrieved phases (from the experimental data) by means of phase structure functions. Further, it explains the steps involved in the calculations of phase structure functions for determining the Kolmogorov/Non-Kolmogorov nature of the PRPPs supported with various images. And finally it ends with a discussion on the obtained results via tables, plots and comments. Section 5 draws the concluding remarks.

2. Details of the experiment

In this section, we explain the details of our experiment with single and double passage interferometric geometries for calculating phase structure function. Later, we utilize it for checking the possible Kolmogorov/non-Kolmogorov model behavior of PRPP or PRPPs-in-a-combination under consideration.

An interferometric arrangement when modified by inserting an unknown transmissive medium as object in one of its arms, can be used to extract the phase added due to this object from the acquired fringe pattern images. Such an arrangement, if modified by the insertion of a 4*f* imaging system, placed strategically in the interferometric geometries such that its first focal plane coincides with the exit plane of the object (when present) and the detecting system (CCD) with the second focal plane, can measure phase added to the propagating beam at the exit plane of the object-in-question rather than after some propagation in free space behind it.

This method of including a 4*f* imaging system in the interferometric geometry is advantageous in the sense that, since the beam traversing through the object is captured right its exit plane, there is no inclusion of any other effects because of its propagation through another medium (i.e. free space). In other words, we can compute the phase added *purely* due to a propagation inside the object. Thus, while analyzing the phase added to the propagating beam due to the said object, we achieve the results which are purely for wave propagation through it.

With the above set-up, the interference pattern can be recorded in the interferometer in the following two situations:

1. When the unknown medium has not been inserted.
2. When the unknown medium has been inserted in the object arm.

In situation 1, straight line fringes tilted with respect to the horizontal axis at an angle of about 45° (obtained by suitably tilting mirrors M1 and M2) are captured. In situation 2, the fringes seen in situation 1 shift or get distorted in accordance with the properties of the medium in question. This additional phase introduced due to the medium can be retrieved and analyzed by subtracting the phase retrieved from fringes in situation 1 from those retrieved in situation 2.

In our case, the unknown mediums are two PRPPs (Pseudo-Random-Phase-Plates), both of them are transparent five layer packed systems consisting of two outer layers of BK-7 glass, two inner layers of near index matching (NIM) polymer and one layer of acrylic with a turbulence profile written onto it on one side. It has been claimed in [35], that the turbulence strength of the phase plates is such that the phase plates would result in aberrated wavefronts having a known Fried coherence length, of either 16 or 32 samples, allowing varying levels of turbulence to be simulated. The phase screens (to be machined on the PRPPs) were generated using standard Fourier transform techniques filtered with the desired spectrum. Each phase screen had 4096 sample phase points across a side. The turbulence phase profiles were machined into the acrylic and eventually turbulence was written on a 3.28” acrylic annulus, with a 1.35” diameter obscuration in the middle, so that the sample spacing is, 20 μm in both the phase plates. The two PRPPs are different in the sense of Fried's coherence length, and have been shown to mimic atmospheric turbulence like conditions at a wavelength of 1550 nm [35]. The PRPPs are mounted on two separate computer controlled stepper motors with a single driver, so that these can be rotated with a given range of velocities, for creating a time varying phase profile (Fig. 1).

We intend to understand the behavior of these two PRPPs at a wavelength of 633 nm using a low power (12 mW) He–Ne laser which is most commonly used in optics laboratories. In order to completely understand their phase adding properties to a propagating beam, we create three different cases:

1. Only PRPP1 inserted as object in the Object arm of the interferometer (Figs. 2(a) and 3(a)).
2. Only PRPP2 inserted as object in the Object arm of the interferometer (Figs. 2(a) and 3(a)).
3. A combination of both the PRPPs 1 and 2 inserted together as an object in the Object arm of the interferometer (Figs. 2(b) and 3(b)).

The interferometric geometries for, (1) The Mach–Zehnder interferometer and (2) Michelson's interferometer are used for retrieving the phase added due to these phase plates to a 633 nm wavelength laser beam and its phase structure function is subsequently analyzed in the above three cases.

In Mach–Zehnder interferometer, the object beam traverses through the unknown medium kept in the Object arm ‘only once’

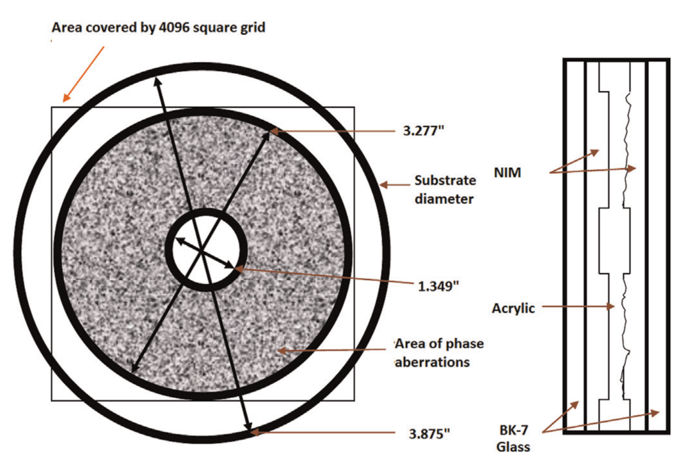

Fig. 1. The above is a diagram showing schematic representation of a Pseudo-Random-Phase-Plate (PRPP). The varying refractive index profile lies only in the middle of the annular region and the whole phase plate has been divided into 4096 sample phase points. The diameters of various regions have been indicated and a section showing layers the involved in the manufacture of this phase plate has been shown towards the right. (Figure courtesy [35]).