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Enhancing phase measurement by a factor of two in the stokes correlation

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Abstract: Phase loss is a typical problem in the optical domain and optical detectors measure only the amplitude distribution of the signal without a phase. However, phase is desired in a variety of practical applications such as optical metrology, nondestructive testing, and quantitative microscopy, etc. Several methods have been proposed to quantitatively measure the phase and among them, interferometry is a commonly used technique. An intensity interferometer has also been used to recover the phase and enhance the phase difference measurement by the intensity correlation. In this paper, we present and examine another technique based on the Stokes correlation for enhancing the phase measurement by a factor of two. Enhancement in phase measurement is accomplished by the evaluation of the correlation between two points of Stokes fluctuations of the randomly scattered light and recovering the enhanced phase of the object by using three steps phase- shifting along with the Stokes correlations. This technique is expected to be useful in the experimental measurement of the phase of a weak signal and in imaging.

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1. Introduction

Among the most active areas of research in contemporary physics is optical metrology [1], which aims to increase measurement accuracy. This encourages the study of novel phenomena and the advancement of fundamental research. Phase measurement is important in metrology for measuring length, speed and rotation vibration etc. Phase loss is a typical problem in the optical domain and optical detectors measure only the amplitude distribution of the signal without a phase. Several methods have been proposed to quantitatively measure the phase [2] and among them, interferometry is a commonly used technique. However, the majority of these methods are capable to detect the phase profile of phase object in free space or homogeneous media. Intensity interferometer has also been used to recover the phase and enhance the phase difference measurement by the intensity correlation [3,4]. Measuring the weak phase information is a common problem in the present scenario. It was suggested that enhancement of phase in measurement might increase the precision and phase resolution.

In this paper, we present and examine a highly stable noninterferometric technique to recover and enhance the phase measurement by a factor of two through scattering media. This is realized by a two-point Stokes correlation along with three-step phase shifting[5]. Our method acquires the complex polarization correlation function (CPCF) which provides a complex Fourier coefficient and enhanced phase measurement. The complex Fourier coefficient renders the information of the complex amplitude and utilize to extract enhanced phase information. Pilot assisted strategy, which loads phase object into one of the orthogonal polarization states, is employed to design a compact highly stable, and robust noninterferometric setup. The two stokes parameters S_2, and S_3 are used as the theoretical basis of our method.

2. Theory

Consider a polarized coherent light source that is traveling along the z-axis and has two orthogonal polarization states x and y. A phase object is loaded on one polarization state of the beam and the other without it. At the transverse plane z=0, the complex field of coherent-polarized light is given as,

$$E(\hat{r}) = E_x(\hat{r})\hat{e}_x + E_y(\hat{r})\,\hat{e}_y \qquad (1)$$

where $E_x(\hat{r}) and\ E_y(\hat{r})$ represent the x and y polarization component of the beam respectively. A light beam given in Eq. (1) passes through the random scattering media and travels to the detection plane which is located at any random distance z by the Fresnel diffraction formula. At the arbitrary distance z, the scattered field is given as,

$$E_d(r) = \int E_d\,(\hat{r})e^{i\delta(\hat{r})}g(r,\hat{r})d\hat{r}\ , \qquad \mathrm{d} = (\mathrm{x}\ ,\mathrm{y}) \qquad (2)$$

Where $g(r,\hat{r}) = \frac{-ik}{2\pi z}\exp\{\frac{ik}{2}[\frac{(r-\hat{r})^2}{z}]\}$ is a propagation kernel and k is a wavenumber. The position vector at the detector plane and source are denoted by r and r̂ respectively and the diffuser introduces a random phase $\delta(\hat{r})$. Pauli spin matrices are used to define the Stokes parameter of the scattered field as

$$S_n = E^T(\hat{r})\sigma^n E^*(\hat{r}),\quad \mathrm{n} \in (0,..3) \qquad (3)$$

σ^0 is the identity matrix and σ^1, σ^2, σ^3 are the Pauli spin matrices of 2x2 order. The Stokes fluctuation around the mean value of SPs are given as

$$\Delta S_n(r) = S_n(r) - < S_n(r) > \qquad (4)$$

where bracket < > represents the ensemble average. Let us consider that the random light follows Gaussian statistics, the Gaussian moment theorem is used to illustrate the SPs fluctuations as

$$C_{pq}(r_1, r_2) =< \Delta S_p(r_1)\Delta S_q(r_2) > \quad \text{where } p, q \in (0,\ldots,3) \qquad (5)$$

From the above equation, we calculate $C_{22}(r_1, r_2)$ and $C_{33}(r_1, r_2)$.The real part of the CPCF are obtained by subtracting $C_{33}(r_1,r_2)$ from $C_{22}(r_1,r_2)$ as

$$C_{Re}(r_1, r_2) = C_{22}(r_1, r_2) - C_{33}(r_1, r_2)$$
$$\propto \mathrm{Re}\big[W_{xy}(r_1, r_2)W^*_{yx}(r_1, r_2)\big] \qquad (6)$$

where $W_{xy}(r_1, r_2)W^*_{yx}(r_1, r_2) = < E^*_x(r_1)E_y(r_2) > [< E^*_y(r_1)E_x(r_2) >]^*$

Now we use Eqn. of (6) in the development of phase recovery and enhancement method through scattering media. Here, a phase object named vortex beam i.e. $E_x(\hat{r}) = A\exp(il\varphi)$ with topological charge l and azimuthal index φ is loaded into the x polarized state and y polarized state is researved as a reference beam i.e. $E_y(\hat{r}) = B$ where A and B represent the amplitude distribution of vortex beam and plane beam respectively.Substituting the value of $W_{xy}(r_1, r_2)$, $W^*_{yx}(r_1, r_2)$, into Eq. (6).Therefore, Eq. (6) transform [6] to

$$C_{Re}(r_1, r_2) \propto Re[< E^*_x(r_1)E_y(r_2) > \{< E^*_y(r_1)E_x(r_2) >\}^*] \qquad (7)$$

now combined Eq. (7) with three steps- phase shifting method [7] to obtain CPCF which is given below

$$C(\Delta r) = 2C^0_{Re}(\Delta r) - C^{2\pi/3}_{Re}(\Delta r) - C^{4\pi/3}_{Re}(\Delta r) + \sqrt{3}i[C^{2\pi/3}_{Re}(\Delta r) - C^{4\pi/3}_{Re}(\Delta r)]\ , \qquad (8)$$

where $C^{4\pi/3}_{Re}(\Delta r)$, $C^{2\pi/3}_{Re}(\ \Delta r)$ and $C^0_{Re}(\Delta r)$ indicate the real component of the CPCF with phase shift of $\frac{4\pi}{3}, \frac{2\pi}{3}, 0$ respectively. $C(\Delta \mathrm{r})$ is our required quantity and is utilized to recovered and enhanced the phase measurement of the phase object.

The schematic diagram of our experiment is shown in figure 1 given below.

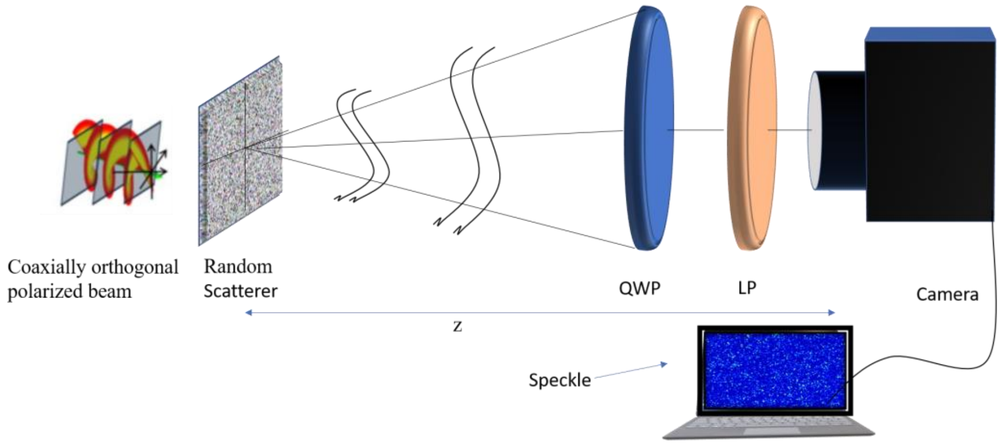

Figure 1. Schematic representation of proposed method. QWP: quarter wave plate, LP: linear polarizer. The CCD records intensity speckle patterns at the observation plane. These speckle patterns are used to determine two SPs.

3. Result and Discussion

We load a vortex beam of topological charge *l*= -1 in x polarization component of beam and y polarization as a guide. The vortex beam is considered as a phase object to test the enhancement in the phase measurement. Around the singularity, the vortex beam's phase change on the order of $2l\pi$. For the topological charge l = -1, the phase variation is one times on the order of 2π around the singularity. However, reconstructed results from the polarization correlations based on Eq. (7) show topological charge l=-2 instead on 1. These results highlight two times enhancement in the phase measurement. The simulation and experimental results of our proposed method are shown in figure 2

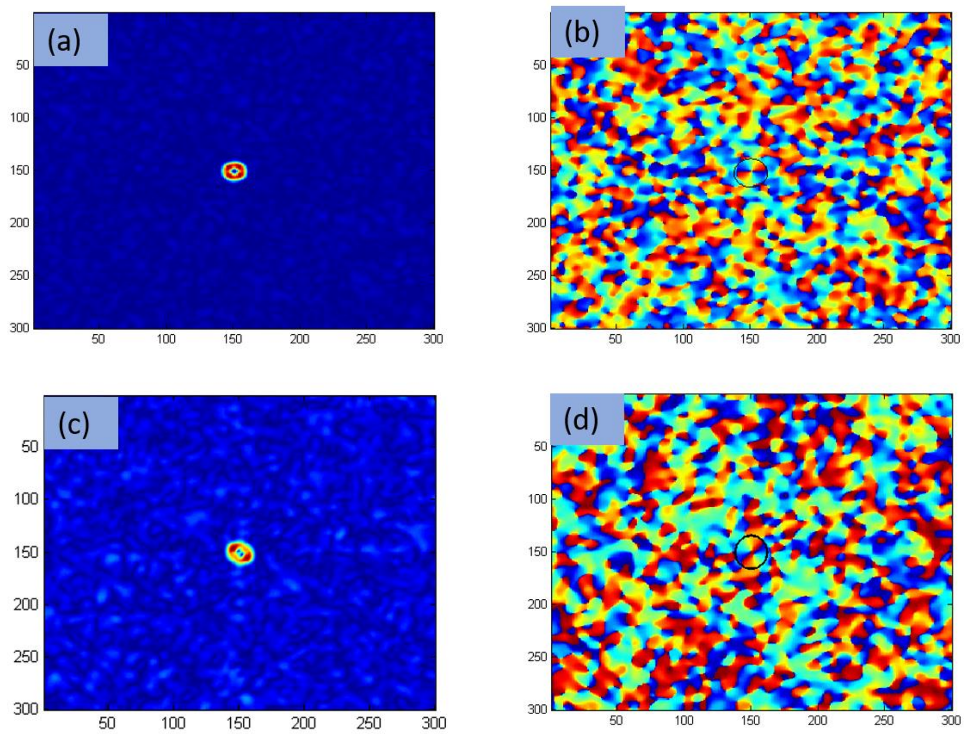

Figure 2. Simulation results: (a) amplitude distribution and (b) corresponding phase distribution for vortex beam of charge *l*= -1; **Experimental results:** (c) amplitude distribution (d) corresponding phase distribution for the vortex beam with *l*= -1.

Conclusions

We present a method to enhance the phase measurement by using higher order stokes fluctuations correlation. This method is expected to be helpful in optical metrology and in measuring weak phase information. The proposed method's viability is assessed by numerical simulation, which is followed by an experimental demonstration to gain enhanced phase information.

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Conflicts of Interest: The authors declare no conflict of interest.

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