Intensity correlation imaging with sunlight-like source

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ABSTRACT

We show a method of intensity correlation imaging of targets illuminated by a sunlight-like source both theoretically and experimentally. With a Faraday anomalous dispersion optical filter (FADOF), we have modulated the coherence time of a thermal source up to 0.167 ns. And we carried out measurements of temporal and spatial correlations, respectively, with an intensity interferometer setup. By skillfully using the even Fourier fit on the very sparse sampling data, the images of targets are successfully reconstructed from the low signal-to-noise-ratio (SNR) interference pattern by applying an iterative phase retrieval algorithm. The resulting imaging quality is as well as the one obtained by the theoretical fitting. The realization of such a case will bring this technique closer to geostationary satellite imaging illuminated by sunlight.

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1. Introduction

Intensity interferometer (II) was first carried out by Hanbury Brown and Twiss, in 1950s, who measured the apparent diameter of discrete radio wave sources [1]. This technique was applied to measure the angular diameter of Sirius with an excellent resolution (microarcsecond) in the visible spectrum [2–4]. Differing from the Michelson-style amplitude interferometer used to measure the first-order correlation of the source, the intensity interferometer is an outcome of second-order correlation of statistical intensity fluctuation of thermal light. This effect invoked a hot debate about the correlation nature of thermal light, which consequently leads to numbers of researches on the quantum nature of thermal light [5–7], such as quantum interpretations of HBT effect [8–10], photon bunching and Nth-order classical correlation [11–13].

HBT effect has been of vital importance in the development of quantum optics, even motivated plenty of studies of higher-order correlation on ghost imaging, condensed matter and particle physics [14–19].

Furthermore, they constructed an optical stellar intensity interferometer named Narrabri, in New South Wales, Australia and measured the angular diameter of 32 stars from 1965 to 1972. While photon detectors were only blue-sensitive at that time and the signal noise ratio (SNR) is very low, it usually took much more time to obtain the experimental result. Then the proposed plan for VLNSII (Very Large Narrabri Stellar Intensity Interferometer) was standstill in the next few years and gradually abandoned and forgotten. In recent years, astronomy has again pursued the intensity interferometry with the great developing of single photon detectors [20–22], especially in intensity correlation imaging [23]. By means of the intensity interferometer, the autocorrelation function of the object is reconstructed based on van Cittert–Zernike theorem [24]. Since the light intensity is the square of the wave amplitude, it is insensitive to the phase difference coming from the defects of the optical system or turbulence. Besides of the astronomy, such advantages of the II have attracted researchers’ attention who want to apply this technique in the geostationary satellite imaging. For this purpose, many preparatory works have already been done recently. Intensity correlation imaging of second-order and third-order is achieved by using the pseudothermal light [25]. P.K. Tan has modulated the power spectrum of sunlight to obtain the second-order temporal correlation by the Fabry–Perot interferometer [26]. However, more useful intensity correlation imaging with sunlight has not been realized experimentally.

In this paper, we show the intensity correlation imaging of targets illuminated by sunlight-like source both theoretically and experimentally. Firstly, with mimic sunlight (Xe lamp) filtered by a Faraday...
anomalous dispersion optical filter (FADOF), the second-order temporal correlation function is measured by HBT interferometer, which agrees with the theory prediction well. Then, by changing the relative position of two detectors, second-order spatial correlation functions of objects are obtained. Faced with the low SNR, we provide the solution of the even Fourier fitting to reconstruct the image. Eventually, based on these fitting data, object information recovery is done by phase-retrieval algorithm. And the information is consistent with the objects in the experiment.

2. Theory

A typical intensity interferometer schematic diagram is shown in Fig. 1. Two detectors placed in one coherent area measure the light intensities from the same source. The correlation between these two detection is an ensemble average of the product of two intensities from the same source. The correlation between these two intensities is measured by HBT interferometer, which agrees with the theory prediction well. Then, by changing the relative position of two detectors, second-order spatial correlation functions of objects are obtained. Faced with the low SNR, we provide the solution of the even Fourier fitting to reconstruct the image. Eventually, based on these fitting data, object information recovery is done by phase-retrieval algorithm. And the information is consistent with the objects in the experiment.

2. Theory

A typical intensity interferometer schematic diagram is shown in Fig. 1. Two detectors placed in one coherent area measure the light intensities from the same source. The correlation between these two detection is an ensemble average of the product of two intensities $I_1$ and $I_2$, which is represented as blow [24]

$$
\langle I_1(t_1, x_1)I_2(t_2, x_2) \rangle = \langle E_1(t_1, x_1)E_2^*(t_2, x_2) \rangle \langle E_1^*(t_2, x_2)E_2(t_1, x_1) \rangle
$$

where $E_1(t_1, x_1)$ and $E_2^*(t_1, x_1)$ are a pair of conjugate electronic field variables, $I(t_i, x_i)$ is the instantaneous intensity at time $t_i$ at detector $d_i$, $\gamma_{12}$ is the autocorrelation function of light field between points $x_1$ and $x_2$, and $\langle \rangle$ denotes time ensemble average. According to the van Cittert–Zernike theorem, autocorrelation function $\gamma_{12}$ is the Fourier transform of intensity distribution function $I(\alpha, \beta)$ of the object,

$$
\gamma(\Delta x, \Delta y) = \frac{\int I(\alpha, \beta)w(x, y)\frac{1}{\sqrt{2\pi}} e^{-i\alpha \Delta x + i\beta \Delta y} d\alpha d\beta}{\int I(\alpha, \beta) d\alpha d\beta}.
$$

By Eqs. (1) and (2), the correlation function of two detectors can be written as:

$$
\langle I_1(t_1, x_1)I_2(t_2, x_2) \rangle = \langle I_1(t_1, x_1) \rangle \langle I_2(t_2, x_2) \rangle (1 + |\gamma_{12}|^2)
$$

$$
= \langle I_1(t_1, x_1) \rangle \langle I_2(t_2, x_2) \rangle \ast
$$

$$
(1 + \frac{\int I(\alpha, \beta)w(x, y)\frac{1}{\sqrt{2\pi}} e^{-i\alpha \Delta x + i\beta \Delta y} d\alpha d\beta}{\int I(\alpha, \beta) d\alpha d\beta} )^2,
$$

where $\Delta x$ and $\Delta y$ are the relative position of the two detectors, $\phi$ is the phase difference induced by different optical length and $z$ is the distance between object and observer surface. From Eq. (3), autocorrelation function is obtained by coincidence counts at different relative positions. However, what we measured is the square of the autocorrelation function, losing the phase information, which could not to recover the object by means of direct inverse-Fourier transform of Eq. (2). Hence, phase retrieval algorithm is necessary to obtain the image of the object. The main approaches that generally applied in phase-retrieval algorithm are Cauchy–Riemann [27] and iterative Fourier phase recovery [26]. In this paper, hybrid input–output (HIO) algorithm is adopted as one of the iterative Fourier phase recovery [28]. After phase retrieval process, the intensity distribution in Eq. (2) can be reconstructed. Finally the image of object can be recovered.

3. Experimental setup and results

The experimental arrangement is schematically shown in Fig. 2. The sunlight-like source employed in experiment is Xe lamp (Sirius-300P-300W) and illuminates the objects as shown in the inset of Fig. 2(b): (a) a circular hole with diameter 8 mm, and a double-slits with width $b = 1 \text{ mm of each slit and distance } d = 2 \text{ mm between two slits, respectively}).

Then, the transmitted light goes through a narrow-bandpass filter system composed of a 1 nm narrow-bandpass interference filter (IF) and a 6 GHz FADOF, shown in Fig. 3. The distance between lens and object is 400 mm. Since the coherence area ($\sim \mu m$) is too small to place two bulk detectors inside one area, the intensity correlation measurement system is special design as shown in Fig. 2. Namely, the filtered light is collimated by a lens, and then splitted into two same parts by a beamsplitter (BS), detected by two single-photon detectors with single mode fibers (SMFs). Especially, one SMF (D1) is kept in a fixed position inside a coherence area, the other (D2) placed inside the corresponding area is fixed on the 1-D motorized stage which can automatically move for the spatial correlation measurements. Two signals of D1 and D2 are counted by a coincidence circuit for the joint-detection events. By scanning the fiber in the transverse plane, one can observe interference pattern.

The source here applied is Xe lamp, which is a specialized type of gas discharged lamp, working by passing electricity through ionized xenon gas at both high frequency and pressure, the lamp is usually used to mimic the natural sunlight because of its similar spectrum in the visible range [29], as shown in Fig. 2(c). The lamp, whose diameter is about 2 mm, is supplied by a direct current of 21A and its Color Temperature is 5600 K. The sunlight is natural and has a great value in the practical application. Obviously, intensity correlation imaging with sunlight is
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