Spatial Interference: From Coherent To Incoherent

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Abstract

It is well known that direct observation of interference and diffraction pattern in the intensity distribution requires a spatially coherent source. Optical waves emitted from portions beyond the coherence area possess statistically independent phases, and will degrade the interference pattern. In this paper we show an optical interference experiment, which seems contrary to our common knowledge, that the formation of the interference pattern is related to a spatially incoherent light source. Our experimental scheme is very similar to Gabor's original proposal of holography[1], just with an incoherent source replacing the coherent one. In the statistical ensemble of the incoherent source, each sample field produces a sample interference pattern between object wave and reference wave. These patterns completely differ from each other due to the fluctuation of the source field distribution. Surprisingly, the sum of a great number of sample patterns exhibits explicitly an interference pattern, which contains all the information of the object and is equivalent to a hologram in the coherent light case. In this sense our approach would be valuable in holography and other interference techniques for the case where coherent source is unavailable, such as x-ray and electron sources.

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At the early time when coherent sources were unavailable, interference experiments were carried out by a thermal light source with the help of a pinhole aperture. Though it can improve spatial coherence of the source, the pinhole aperture, as a cost, eventually reduces the power of the source and thus restricts the potential application of optical interferometric techniques such as holography. The effort to realize interference with chaotic light has been developed since the landmark experiment reported by Hanbury-Brown and Twiss (HBT)[2]. They realized that light from different, completely uncorrelated portions of the star gives rise to an interference effect which is visible in intensity correlations but not in the intensities themselves, and proposed an intensity interferometer to measure the angular size of distant stars. The intensity correlation property of spatially incoherent light achieves significant development recently in ghost interference and subwavelength interference[3, 4, 5, 6, 7, 8]. The physics behind these effects is that each point of a spatially incoherent source produces coherence of the field at two separate positions, after having travelled different paths, and the coherent information can be acquired through the intensity correlation measurement of the two positions. Moreover, Ref. [9] reported that phase and amplitude of the field correlation function of two positions can be retrieved by a modified Young interferometer, instead of intensity correlation measurement. There is still a challenging question whether, by using an incoherent light source, the coherent information can be recorded through intensity distribution itself?

When Dennis Gabor accomplished the first holography experiment, he did not realized the fact that the requirment of spatial coherence can be avoided so long as his interferometric scheme is somewhat modified. In this paper, we propose such an interferometric scenario which is capable of carrying out interference and diffraction in intensity observation using a spatially incoherent source. The experimental setups of interferometer are sketched in Fig. 1, which is similar to Gabor's original proposal of holography[1]. The source field is divided into two sets: one illuminates an object, called object wave, and the other acts as a reference wave. The interference occurs at the outgoing beamsplitter BS_2 and can be recorded by either one of two CCD cameras. The interference parts at the two outgoing ports have a phase shift π due to the reflection of the field. In order to demonstrate primary principle simply, the object in the experiments is a double-slit of slit width $b = 125\mu m$ and spacing $d = 310\mu m$. As a proof-of-principle experiment, we first use a pseudo-thermal light source, which is formed by passing a He-Ne laser beam of wavelength 632.8 nm through a

slowly rotating ground glass disk G. A step-motor moves the ground glass each $80ms$ in which CCD camera can register a frame of interference pattern. The pattern fluctuates randomly by moving the ground glass. We first consider the scheme of Fig. 1(a) in which two waves travel different distances: $z_o = 16cm$ for the object wave and $z_r = 27cm$ for the reference wave, and $|z_o - z_r|/c$ is less than the coherent time of the laser beam. Experimental results of two-dimensional (2D) intensity patterns detected by CCD_1 are summarized in Fig. 2. We can see that two single frames in Figs. 2(a) and 2(b) show irregular patterns. With the increasing of number of frames to be averaged in Figs. 2(c)-2(g), the well-defined interference pattern has emerged gradually.

The above experimental results can be readily explained by the fundamental optics theory. Let $E_o(x)$ and $E_r(x)$ be the field distributions of the object wave and the reference wave at the recording plane, respectively. The interference term is given by $E_r^*(x)E_o(x) = \alpha_r^*\alpha_o \int h_r^*(x, x_0)T(x_0')h_o(x, x_0')E_s^*(x_0)E_s(x_0')dx_0dx_0'$, where $E_s(x_0)$ is the source field at beam-splitter BS_1; $h_j(x, x_0)$ and α_j are the impulse response functions between $E_s(x_0)$ and $E_j(x)$ $(j = o, r)$ and the attenuation constant in each path, respectively; x_0 and x are the transverse positions across the beam. A transmittance object $T(x)$ is located close to BS_1 in the object path of the interferometer. For a coherent source which wavefront $E_s(x_0)$ is stationary, the intensity pattern $I(x) = |E_r(x)|^2 + |E_o(x)|^2 + [E_r^*(x)E_o(x)+\text{c.c.}]$ is stable. However, if the source is a spatially incoherent field in which both the amplitude and phase distributions fluctuate randomly, the interference pattern $I(x)$ will fluctuate, too. This has been shown by the single frame in Figs. 2(a) and 2(b).

The incoherent source field $E_s(x)$ is assumed to be quasi-monochromatic and satisfies completely spatial incoherence $\langle E_s^*(x)E_s(x')\rangle = I_s\delta(x - x')$. The interference term in the statistical average can be obtained as

$$\langle E_r^*(x)E_o(x)\rangle = \alpha_r^*\alpha_o I_s \int T(x_0)h_r^*(x, x_0)h_o(x, x_0)dx_0. \tag{1}$$

The integration manifests that all portions of the source globally contribute to the interference term. If both the object and reference waves travel in exactly same configuration $(h_r = h_o)$ as, for example, in an usual interferometer, one immediately obtains a homogeneous distribution of Eq. (1). This used to be understood as an incoherent superposition effect which washes out the information of the object. We now modify the interferometer in an unbalanced way as shown in Fig. 1(a). For the moment we as-

sume that the source beam has temporal coherence. Hence Eq.(1) is still valid under such an appropriate path difference that $\langle E_s^*(x,t)E_s(x',t-|z_o-z_r|/c)\rangle \approx \langle E_s^*(x)E_s(x')\rangle$. In the paraxial propagation, the impulse response function for a free path z_j is given by $h_j(x,x_0) = \sqrt{k/(i2\pi z_j)}\exp[ikz_j+ik(x-x_0)^2/(2z_j)]$ where k is the wavenumber of the beam. Hence we obtain

$$\langle E_r^*(x)E_o(x)\rangle = \frac{\alpha_r^*\alpha_o I_s k}{2\pi\sqrt{z_o z_r}}\exp[ik(z_o-z_r)]\int T(x_0)\exp\left[\frac{ik}{2Z}(x-x_0)^2\right]dx_0 \qquad (2)$$
$$\approx (\alpha_r^*\alpha_o I_s k/\sqrt{2\pi z_o z_r})\exp[ik(z_o-z_r)]\exp[ikx^2/(2Z)]\widetilde{T}(kx/Z).$$

Equation (2) presents the Fresnel diffraction integral of an object under the paraxial condition, the same as a coherent source does but with an effective object distance $Z = z_o z_r/(z_r-z_o)$ replacing the real one z_o. The approximation in Eq. (2) is hold when the size of object is much less than the area of diffraction pattern, and the Fourier transform $\widetilde{T}$ of object T can be deduced, for instance, $\widetilde{T}(q) = (2b/\sqrt{2\pi})\operatorname{sinc}(qb/2)\cos(qd/2)$ for the double-slit.

In the above interference scheme, we have released the requirement of spatial coherence, but still demand a better temporal coherence for the source. This restriction can be relieved in the scheme of Fig. 1(b) in which the two arms of the interferometer have the same distance while a lens of the focal length f_o is set at the middle position of the object path of distance $2f_o$. In this configuration we obtain the interference term

$$\langle E_r^*(x)E_o(x)\rangle = \frac{\alpha_r^*\alpha_o I_s k}{2\sqrt{2}\pi f_o}\int T(x_0)\exp\left[-\frac{ik}{4f_o}(x+x_0)^2\right]dx_0 \qquad (3)$$
$$\approx [\alpha_r^*\alpha_o I_s k/(2\sqrt{\pi}f_o)]\exp[-ikx^2/(4f_o)]\widetilde{T}[kx/(2f_o)],$$

which is equivalent to Eq. (2). The experimental results of the present scheme with $f_o = 19cm$ are shown in Fig. 3, where (a) and (b) exhibit the average intensity patterns $\langle I_1(x)\rangle$ and $\langle I_2(x)\rangle$ registered by CCD_1 and CCD_2, respectively. We can see that the two interference patterns having a phase shift π are formed in the sum of 10,000 frames and match with the theoretical simulation of Eq. (3) in addition to an intensity background. Moreover, for a 50/50 beamsplitter BS_2, the difference and sum of the two patterns present the net interference pattern and the intensity background, as shown in Figs. 3(c) and 3(d), respectively. As a matter of fact, the homogeneous intensity background in Fig. 3(d) verifies the incoherence of the source. To further confirm whether the interference pattern is

related to the spatial incoherence, we may compare it with the result obtained in the same interferometer using coherent light. We simply remove the ground glass in Fig. 1(b). In this case, the interference pattern for the coherent field consists of two parts, $|\widetilde{T}(kx/f_o)|^2$ and $\widetilde{T}(kx/f_o)$+c.c.. The corresponding experimental results are plotted in Fig. 4, where (a) and (b) show the stable intensity patterns $I_1(x)$ and $I_2(x)$ registered by CCD_1 and CCD_2, respectively. After eliminating the intensity of each arm, the net interference pattern in Fig. 4(c) fits the formula $\widetilde{T}(kx/f_o)$, which has a doubled spatial frequency with respect to that in Eq. (3) for the incoherent source. Therefore, in the same interferometer, both the coherent and incoherent sources can perform Fourier transform of an object with different spatial frequency.

To further exploit the effect, we must consider a true thermal light source. An extended thermal light source can be regarded as spatially incoherent source with a short coherent time less than 0.1 nsec. Within the coherent time, the source may produce an instantaneous exposure of interference pattern in our schemes. Unlike the pseudothermal light source, each individual exposure cannot be registered directly by the slow CCD camera with the response time of order msec. Instead, an average intensity distribution of these exposures will appear on the CCD screen. We have indicated that the scheme of Fig. 1(b) is appropriate for observing interference using ture thermal light source, since both the object and reference waves travel the same distance and it thus releases the requirement of temporal coherence. We use a Na lamp of wavelength $589.3nm$ with the illumination area $10 \times 10 \ mm^2$ to replace the pseudothermal light source in Fig. 1(b) and find that the interference patterns directly appear on the CCD screen, as shown in Fig. 5(b). For comparison, Fig. 5(a) shows the 2D interference pattern corresponding to Fig. 3(a) for the pseudothermal light in the same interferometer. The two fringes are similar but with a slight different spacing, which displays different wavelength of the two sources. Then we set a pinhole of diameter $0.36mm$ after the lamp, and the spatial incoherence has been dispelled. With this point-like source, a different interference pattern, which has a half fringe spacing of that for the spatially incoherent source, is recorded on the CCD screen, as shown in Fig. 5(c).

We have both theoretically and experimentally demonstrated that a spatially incoherent light source is capable of performing interference in an unbalanced interferometer under certain configurations. Physically, each point in the spatially incoherent source may produce an interference pattern in the interferometer. A frame of sample pattern observed on the

screen is the incoherent superposition of those patterns corresponding to all illuminating points in the incoherent source, and thus fluctuates randomly due to the spatial incoherence. In most interferometric schemes so far, the statistical average of the sample patterns will present a homogeneous distribution. Our experimental results clarify that this obstacle can be surpassed under certain interferometric configurations. Unexpectedly, in the same interferometer the interference pattern for the spatially incoherent source is well defined and equivalent to that for the coherent source but with different spatial frequency. We note that, in the light of holography, our approach is in essence different from the previous method called "incoherent holography"[10, 11, 12] which aims at encoding an incoherent object, such as a fluorescence object. In the incoherent holography, each source point in the object produces, by interfering its wave fronts, a stationary two-dimensional intensity pattern (e.g. Fresnel zone plate) which uniquely encodes the position and intensity of the object point, and hence the method is limited to record intensity distribution for the fluorescence object. However, in our approach, the hologram formed in the statistical average of the patterns can be equivalent to that in the coherent holography, recording the complete information of the object. The present experiment can significantly refresh our intuition and experience: the irregular phase distribution of incoherent field does not always wash out the interference pattern. It is also interesting that photons emitted from uncorrelated portions of the source can be cooperatively involved in a well-defined interference pattern without photon spatial correlation. After releasing the spatial coherence requirement, we may expect a wide and potential application in the interference techniques especially for those sources the coherence is unavailable, such as x-ray and electron sources.

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Figure Captions

Fig. 1. Experimental schemes of unbalanced interferometer using an incoherent light source. P_1 and P_2 are two polarizers for modulating intensity; G is a rotating ground glass; CCD_1 and CCD_2, two CCD cameras. Two mirrors, M_1 and M_2, and two beamsplitters, BS_1 and BS_2, form an interferometer. T is a double-slit close to BS_1. (a) Two arms have different distances; (b) One lens L_o with the focal length f_o is set at the middle position of the object arm, and two arms have the equal distance $2f_o$.

Fig. 2. Experimental results of 2D interference patterns recorded by CCD_1 in the scheme of Fig. 1(a). (a) and (b) are individual single frames; (c), (d), (e), (f) and (g) are averaged over 10, 40, 400, 6400 and 10,000 frames, respectively.

Fig. 3. Experimental results of 1D interference patterns in the scheme of Fig. 1(b). (a) and (b) are interference patterns (averaged over 10,000 frames) registered by CCD_1 and CCD_2, respectively; (c) and (d) are their difference and summation, respectively. Experimental data and theoretical simulation are given by open circles and solid lines, respectively.

Fig. 4. Same as in Fig. 3 but removing the ground glass in Fig. 1(b). All the interference patterns are stable.

Fig. 5. 2D interference patterns registered by CCD_1 in the scheme of Fig. 1(b). (a) with the original pseudothermal light source in Fig. 1(b); (b) with a Na lamp of extended illumination area replacing the pseudothermal light source; (c) with a Na lamp followed by a pinhole replacing the pseudothermal light source.

a

Laser

P₁ P₂ G BS₁ T

M₁ M₂

BS₂ CCD₁

CCD₂

b

Laser

P₁ P₂ G BS₁ T L₀ M₂

M₁

BS₂

CCD₁

CCD₂