Reconstruction of the nonstationary optical picture from two-photon correlations, and stellar interferometry

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We demonstrate the possibility of observing an optical picture that moves randomly over a screen and is too weak for the usual instantaneous photography. By using a correlation method of registration in a Michelson stellar interferometer one can expect an increase of the resolving power of the interferometer.

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In a number of physical problems it is necessary to register an optical image that is very weak and is furthermore nonstationary. The usual method of instantaneous photography (even with the aid of an electron-optical converter) will not do in this case, for in the case of a short time exposure the screen will show individual flashes, and when the exposure is increased, the shift of the image will result in uniform illumination. We shall show that in this case the optical picture can be reconstructed by using the technique of photocount coincidence, which was first used in other problems by Brown and Twiss[1] to measure the so-called intensity correlation function.

We consider first a one-dimensional optical picture, in which the brightness depends on the coordinate x like $f(x-\Delta(t))$, where the arbitrary function $\Delta(t)$ characterizes the shift of the picture as a unit at the instant of time t. By locating at the points x_1 and x_2 on the screen electron multipliers that operate in the photon-counting regime, and by connecting their outputs to counters connected for coincidence with a resolution time τ, we can measure over an arbitrary time $T(T\gg\tau)$ the number of the photocounts N_1 and N_2 and the number N_{12} of their coincidences. If the displacement of the picture in each time interval τ can be neglected, then the values of N_1, N_2, and N_{12} can be used to determine the parameter

$$R=\frac{N_{12}T}{N_1N_2}=2\tau T\frac{\int_0^T f(x_1-\Delta(t))\,f(x_2-\Delta(t))\,dt}{\int_0^T f(x_1-\Delta(t))\,dt\int_0^T f(x_2-\Delta(t))\,dt}. \tag{1}$$

Repeating the measurements at different photomultiplier positions, we obtain a function $R(\xi)$, where $\xi=x_2-x_1$, which enables us in many cases to reconstruct the image of $f(x)$, or at least its main characteristics.

In the case of uniform illumination $[f(x)\equiv\text{const}]$, it follows from (1) that $R(\xi)$

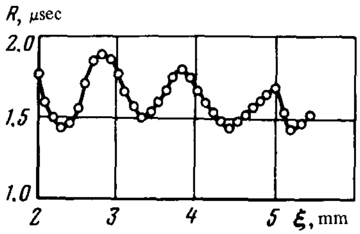

FIG. 1. Interference pattern.

$\cong 2\tau$, but when an image is present on the screen, then the brightness modulation due to the image motion leads to a difference between R and 2τ. If the displacement velocity for each passage of the image over the screen can be regarded as constant (this is the case, for example, when the image-oscillation amplitude is large; the velocity can vary from oscillation to oscillation), then

$$R(\xi) \sim \int_{-\infty}^{\infty} f(x) f(x+\xi)\, dx, \tag{2}$$

i.e., the function $R(\xi)$ has formally the same form as the correlation function used in the theory of random functions.

The fact that $f(x)$ is a determined function different from zero over a bounded interval x leads to two features. First, both positive correlation ($R(\xi) > 2\tau$) and anticorrelation $R(\xi) < 2\tau$ are observed, i.e., the number of coincidences is smaller than the number of random coincidences, whereas the intensity correlation function, which characterizes the random temporal modulation of the light, always corresponds to positive correlation. Second, knowing $R(\xi)$ we can reconstruct $f(x)$ either uniquely (if $f(x)$ is symmetric), or accurate to mirror symmetry ($\tilde{f}(x) = f(x_0 - x)$, see, e.g., [2]), whereas no such unique reconstruc-

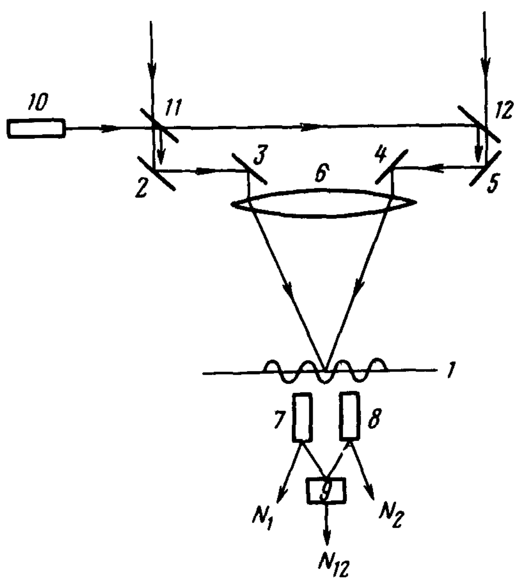

FIG. 2. Stellar interferometer.

tion is possible for an arbitrary function, and one can assess only the width of the spectrum (the coefficients of the expansion of $R(\xi)$ in a Fourier integral are the squares of the moduli of the Fourier coefficients of the function $f(x)$). In many cases of practical importance (a Gaussian function, a harmonic function, etc.,) it is possible to reconstruct $f(x)$ from $R(\xi)$ directly, by calculating the integral (2) and bypassing the expansion of $R(\xi)$ in a Fourier integral.

By way of an example of the use of the method described above, we demonstrate the possibility of recording an interference pattern in a Michelson interferometer in the case when thermal effects and vibration make it impossible to obtain a stationary interference pattern. To this end, an additional temporal phase shift was introduced in one of the arms of the interferometer (the angle of inclination of the plane-parallel plate was changed slightly). The light source was an LG-56 helium-neon laser. The plate vibration frequency corresponded to a displacement of the interference pattern by one period in a time $\sim 10^{-4}$ sec. At a counting rate $N_1 \approx N_2 \sim 10^4$ sec^{-1} and $\tau = 1.7$ μsec we obtained a distinct interference pattern (Fig. 1).

Using the described results, we can extend the capabilities of stellar interferometry, which is used to determine the angular diameters of stars. It is known that in a Michelsom interferometer the maximum base, which determines the angular resolution, is ~ 15 m,[3] and is limited by the phase shifts introduced by the fluctuations of the refractive index of the atmosphere. The Brown-Twiss interferometer, in which one measures the correlation of the light-intensity fluctuations, is free of this shortcoming, and the distance between the light receivers is increased in it to 180 m.[4] This type of interferometer, however, can measure the angular diameter of only very bright stars, since the light intensity fluctuates quite rapidly, and in view of the limited bandwidth of the recording system ($\sim 10^8$ Hz) the fluctuation correlation can be measured only after a prolonged signal accumulation under conditions of large brightness.

The shortcomings of both interferometers can be eliminated by combining them by the method shown in Fig. 2. The interferences pattern is formed in plane 1 by mirrors 2—5 and by lens 6 (or by a concave mirror), as in an ordinary Michelson interferometer. If the base is long, this picture will be randomly displaced by thermal drifts of the interferometer arms, by vibrations, and by the influence of atmospheric fluctuations. It must therefore be registered by the above-described correlation method, using photon counters 7 and 8 and the coincidence circuit 9, i.e., by a scheme formally analogous to that of the Brown-Twiss interfereometer. In this case, however, the fast fluctuations of the light are averaged out and are immaterial, while the frequency at which the pattern is scanned under the influence of atmospheric fluctuations is low ($< 10^3$ Hz), and therefore no large brightness is necessary to register the picture, as explained in the experiment described above. Slow thermal drifts can introduce an interference-arm length difference exceeding the coherence length, and must therefore be compensated for. It is proposed for this purpose to produce in the focal plane, with the aid of laser 10 and semitransparent mirrors 11 and 12, an auxiliary interference pattern and fix its position by introducing in one of the interferometer arms an alternating phase shift and using a negative feedback system (cf. [5]).

We point out in conclusion that the described correlation method of reconstructing an image admits of various modifications. In particular, by using a mosaic of immobile photon counters and a multichannel registration system, it is possible to reconstruct, after one pass over the screen, not only a one-dimensional but also a two-dimensional image. The method can be used not only in visible light but also in the shorter-wavelength regions of the spectrum, so that one can expect to use it to study the structure of accelerated electron clusters (by means of their synchrotron radiation) or a high-frequency plasma pinch,[6] and for many other applications.

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