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Fourth-order interference of quasi-thermal light beams generated in an acoustic cell

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Abstract

A new source of light with quasi-thermal statistics is suggested using light scattering by quasi-thermal acoustic waves. With the help of this source, fourth-order interference between two independent quasi-thermal beams is obtained.

1. Introduction

In the flow of works on quantum optics a great proportion of papers is devoted to the effects of second-order intensity interference, or, in Glauber's notation, fourth-order interference (see, for instance, Refs. [1-3]). These effects are studied using nonclassical sources of light such as parametric down-converters generating correlated photon pairs. The correlated photons are fed to various optic interferometers, and fourth-order interference patterns are observed, often in the absence of the second-order interference. This is sometimes referred to as a demonstration of the quantum nature of light and a phenomenon that cannot be understood from classical view point. It has been shown, however, that classical and quantum theories can both describe fourth-order interference, and the only difference in their predictions is that the classical calculation gives smaller interference visibilities [4,5]. Our paper demonstrates this fact experimentally: for two independent purely classical (quasi-thermal) sources of light we observe fourth-order interference, while the intensity distribution contains no second-order interference effects. The quasi-thermal source is constructed using a HeNe laser beam scattered in an acoustic cell where the propagating acoustic wave has thermal statistics. This source has certain advantages over the ground-glass rotating disc [6], which is commonly used as a model quasi-thermal source.

2. Experimental

The experimental setup is shown in Fig. 1. A single-mode HeNe laser beam is split in two parallel beams separated by a distance of 8 mm. Pinholes P1, P2 diaphragm both beams to the diameters 0.75 mm, and the beams are directed into a block of fused silica FS. In the silica the beams are scattered by an acoustic wave propagating normally to their direction. The acoustic wave has quasi-thermal statistics, for it is excited in the following way. A PMT (PMT0) operating in photon counting regime is illuminated by the radiation of a stabilized light-emitting diode (LD), and its amplified pulses form a continuous spectral distribution in the frequency range from 10 to 100 MHz. This "white noise" is sent to a narrow-band active filter AF, which amplifies the signal within the band of $\Delta f = 2.5$

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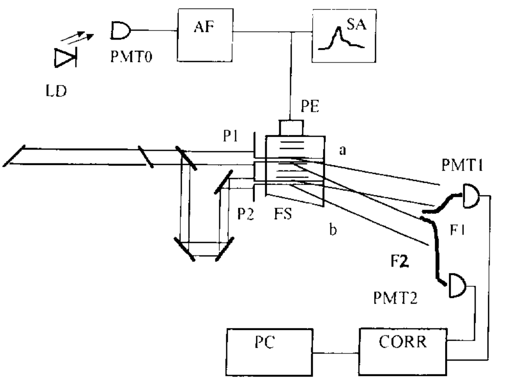

Fig. 1. Experimental setup. P1, P2, pinholes; FS, fused silica sample; *a*, *b*, two scattered beams; F1, F2, fibers transmitting the scattered light to photomultipliers PMT1, PMT2, respectively; CORR, correlator measuring the photon counting rates and the coincidence rate; PC, computer. Excitation of the acoustic wave: LD, stabilized light emitting diode; PMT0, photomultiplier; AF, active filter; SA, spectrum analyzer; PE, piezoelectric element generating the acoustic wave.

MHz with central frequency $f = \Omega/2\pi = 50$ MHz. According to the principles of statistical radiophysics, such a procedure forms a random signal with Gaussian (thermal) statistics. The spectrum of the electric signal is controlled by means of a spectrum analyser (SA). This signal is fed to a piezoelectric element (PE) generating the acoustic wave in the silica. Thus, we obtain a quasi-thermal acoustic wave with coherence length of 1.8 mm. Light scattered by this quasi-thermal source must also possess thermal statistics. This fact, maybe obvious enough, is to be discussed in detail in Ref. [7]; for its theoretical proof, see Ref. [8]. This way we obtain a quasi-thermal source that has the same frequency width as the laser and very narrow angular divergence (less than 10^{-3}) determined by the size of the scattering volume.

It is quite easy to "switch" the statistics of the scattered light into coherent one. This is done by replacing the quasi-Gaussian electric signal, which excites the acoustic wave, by the amplified harmonic voltage from a generator. In this case, there are no amplitude fluctuations of the electric signal, and hence, the acoustic wave also has no amplitude fluctuations. This means that the acoustic wave has coherent statistics, and it follows that the scattered light is also coherent [7]. We have confirmed this fact experimentally by measuring the normalized second-order intensity correlation function $g^{(2)} = \langle I^2\rangle/\langle I\rangle^2$. This measurement was carried out for the setup shown in Fig. 1, with the pinhole P2 closed and the beam '*a*' scattered by the acoustic wave. When the acoustic wave was excited by a quasi-Gaussian electric signal, the correlation function $g^{(2)}$ of the scattered light was equal to 2 in its maximum. When the acoustic wave was excited by a harmonic electric signal, the correlation function for the scattered beam was equal to 1, which is typical for coherent light.

The beams of the HeNe laser are scattered at a distance of 8 mm from each other, so that they interact with "independent fragments" of the acoustic wave. Due to the angular divergence, the scattered beams overlap in the far field zone (at a distance of 14 m from the sample) over an area with transverse diameter of 30 mm. Putting a screen into this area, we observed no interference between the two quasi-thermal scattered beams, although the spot formed by the two intersecting pump beams contained an evident interference picture. Changing the statistics of the acoustic wave to a coherent one, we also observed interference between the two scattered beams.

Light formed by the two intersecting scattered beams is fed, by means of two fibers F1, F2, to a pair of photon counting photomultipliers PMT1 and PMT2. Both fibers have diameters of 200 μm. One of the fibers can be moved in the plane of the beams, the other is fixed. The output pulses of the PMTs are sent to a digital correlator CORR that provides the coincidence counting rate R_c and the counting rates of both detectors R_1, R_2. An IBM PC calculates the normalized second-order intensity correlation function $g^{(2)}$, which is related to R_c as $g^{(2)} = R_c/R_1R_2\tau$, the time parameter τ being determined by the resolution of the correlator. Scanning the position of F2, $g^{(2)}$ is measured and the fourth-order interference fringes are observed.

3. Results

It is quite natural that a superposition of two independent light beams with thermal statistics must manifest fourth-order interference. Indeed, let us label the beams by indices '*a*' and '*b*'. The intensity measured by each detector is

$$I_i(t) = \left|E_a(t)\,e^{i\phi_{ai}} + E_b(t)\,e^{i\phi_{bi}}\right|^2, \quad i = 1,2, \qquad (1)$$

where $E_a(t)$ and $E_b(t)$ are analytic signals for both beams at the output of the sample. The phases ϕ_{ai} and ϕ_{bi}, $i = 1, 2$, are determined by the path lengths of the beams from the sample to the detectors. Since the beams are independent, there will be no interference fringes observed in the intensity distribution in the far field zone: the interference terms in Eq. (1) vanish as a result of time averaging:

$$2\,\mathrm{Re}\left\{\left\langle E_a(t)\, \mathrm{e}^{\mathrm{i}\phi_{ai}} E_b^*(t)\, \mathrm{e}^{-\mathrm{i}\phi_{bi}} \right\rangle\right\} = 2\,\mathrm{Re}\left\{\left\langle E_a(t)\right\rangle \left\langle E_b^*(t)\right\rangle \mathrm{e}^{\mathrm{i}(\phi_{ai}-\phi_{bi})}\right\} = 0.$$

However, there will be interference of intensities. Indeed, using Eq. (1) for the intensities I_1, I_2 and calculating their correlation function we obtain:

$$\langle I_1 I_2 \rangle = \left\langle I_a^2 \right\rangle + \left\langle I_b^2 \right\rangle + 4\,\langle I_a\rangle \langle I_b\rangle \cos^2(\phi/2), \qquad (2)$$

where $\phi \equiv \phi_{a1} - \phi_{a2} + \phi_{b2} - \phi_{b1}$ and I_a, I_b are intensities of both beams at the output of the sample. For thermal beams, we have $\left\langle I_i^2 \right\rangle = 2\,\langle I_i\rangle^2$, and the expression for the normalized correlation function is

$$g^{(2)} \equiv \frac{\langle I_1 I_2\rangle}{\langle I_1\rangle \langle I_2\rangle} = 1 + \cos^2(\phi/2). \qquad (3)$$

(We assume $\langle I_a\rangle = \langle I_b\rangle$.)

In principle, there is nothing new in this result. The fact that two independent thermal sources can form a fourth-order interference pattern was pointed out in several theoretical works on the Brown-Twiss interferometry and related problems. (See, for instance, the survey in Ref. [9].) However, it seems that at present this statement is sometimes forgotten, for the very fact of the fourth-order interference existing between two independent sources is often thought to demonstrate some quantum phenomenon.

The experimental results are presented in Fig. 2, where the normalized coincidence rate (normalized correlation function) is plotted against the displacement of the fiber leading to PMT2. The largest achieved visibility of the fringes is 27%. This is close to the classical limit for the visibility $V^{\mathrm{class}} = (g^{(2)}_{\mathrm{max}} - g^{(2)}_{\mathrm{min}})/(g^{(2)}_{\mathrm{max}} + g^{(2)}_{\mathrm{min}}) = \frac{1}{3}$. There is an agreement between the experimental and theoretical values of the interference period (1.15 ± 0.05 mm and 1.1 ± 0.1 mm, respectively).

It should be noted that the fourth-order interference of two independent thermal sources has been already

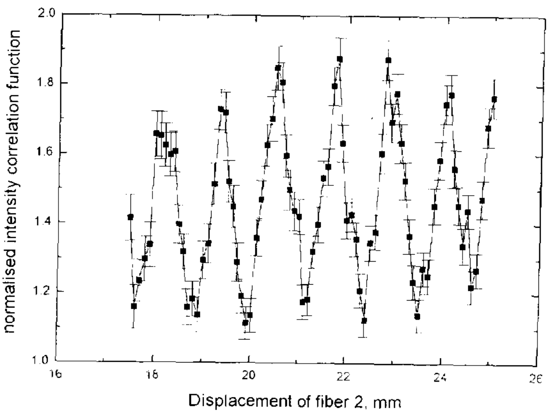

Fig. 2. Fourth-order interference fringes. The normalized second-order intensity correlation function $g^{(2)}$ depending on the displacement of fiber F2.

demonstrated experimentally in Ref. [10], where a thermal source was simulated by a rotating ground glass disc. The two sources, however, were separated by a rather small distance, so that the interference pattern contained only three peaks inside the envelope.

In fact, this experiment is a classical analogue of the quantum interference experiment described in Ref. [1].

4. Conclusions

The observed fourth-order interference (intensity interference) has an obvious classical character. This fact leaves no room for claims that the existence of the fourth-order interference for independent light beams (in the absence of the second-order interference) demonstrates "quantum entanglement" or "quantum nonlocality". Only visibility of the interference fringes or some other quantitative parameters enable one to distinguish between the quantum and classical effects. The experiment demonstrates the abilities of the new quasi-thermal source suggested in the present paper. Along with the high intensity and narrow frequency band, it also has low angular divergence, which is determined by the diameter of the scattered beam.

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