Transient first-order interference of two independent thermal light beams

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Abstract

By analyzing the first-order interference of two independent thermal light beams in Feynman's path integral theory, we conclude that it is impossible to observe the transient first-order interference pattern by superposing two independent thermal light beams if the initial phases of the photons in thermal light are random. The result suggests that the classical model of thermal light field within the coherence time may not be the same as the one of laser light field within the coherence time.

1. Introduction

It is usually thought there is no difference between laser and thermal light fields within the coherence time in classical electromagnetic theory, in which the amplitude and phase are approximately constant within the coherence time [1-3]. This conclusion is drawn from the analysis of the first-order interference of laser and thermal light in the usual Young's double-slit interferometer and Michelson interferometer. However, this conclusion is questionable if the transient first-order of two independent light beams is taken into consideration. Magyar and Mandel observed spatial transient first-order interference pattern by superposing two independent ruby laser light beams [4]. Transient first-order interference pattern is the first-order interference pattern obtained in a short time interval, which is usually shorter than the coherence time of the field. The transient first-order interference of two independent thermal light beams has never been reported. Most physicists attribute the reason to that the degeneracy parameter of thermal light is usually much less than one [2,5]. On the other hand, if the degeneracy parameter of thermal light is much greater than one, the transient first-order interference pattern of two independent thermal light beams can be observed. Is this prediction true? Our answer is no. In the following part, we will show that it is impossible to observe the transient first-order interference pattern by superposing two independent thermal light beams even if the degeneracy parameter of thermal light is much greater than one on the condition that the initial phases of photons in thermal light are random. Our result suggests that thermal and laser light fields are different within the coherence time, which will change long existed classical model for thermal light field within the coherence time [1-3] and be helpful to understand the physics of light.

2. Theory and Numerical Simulations

The scheme for the interference of two independent thermal light beams is shown in Fig. 1. S1 and S2 are two identical but independent point sources emitting polarized quasi-monochromatic thermal light. For simplicity, we assume the light beams emitted by these two sources have equal intensities and consider one-dimension case only. There are two different ways for a photon to be detected at space-time coordinate (x,t) on the observation plane. One is the detected photon is emitted by S1 and the other one is the photon is emitted by S2. In classical picture, one can always figure out the detected photon comes from S1 or S2, for the measurement accuracy can be arbitrarily high without influencing the system. However, it is not the case in quantum mechanics. Based on the conclusion that all the photons within the coherence volume are intrinsically indistinguishable from each other [5], it is straightforward to judge whether these two different ways are distinguishable or not. In the scheme shown in Fig. 1, the effective transverse coherence length of the field emitted by these two point sources can be treated as the same as the coherence length of the field emitted by a thermal source with dimension of d. If the uncertainty in the position detection is not greater than the transverse coherence length, $\lambda_0 L / d$, these two different ways are indistinguishable. Where λ_0 is the mean wavelength of the photon. In fact, the position uncertainty in the usual photon detection is much less than $\lambda_0 L / d$, which means these two different ways are usually indistinguishable if other properties of photons emitted by these two sources are identical.

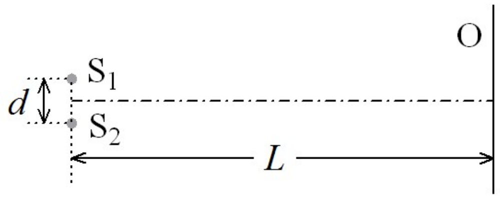

Fig. 1 Two source interferometer

When these two different ways to trigger a photon detection event on the observing plane are indistinguishable, the probability distribution for the jth detected photon is [6]

$$P_j(x) = | e^{i\varphi_{j1}} K_1(x) + e^{i\varphi_{j2}} K_2(x) |^2 \quad (1)$$

Where $K_1(x)$ and $K_2(x)$ are the Feynman's photon propagator for the photons emitted by S_1 and S_2 going to x on the observing plane, respectively. φ_{j1} and φ_{j2} are the initial phases of the jth detected photon emitted by S_1 and S_2, respectively. The finally observed first-order interference pattern is proportional to the ensemble average of all these single photon probability distributions. Feynman's photon propagator is the same as the Green function in classical optics [1,6]. Hence the results are the same in both quantum and classical calculations. The only difference is the interpretation. We will directly employ the results in classical optics in the following discussions. Equation (1) can be simplified as [1]

$$P_j(x) \propto 1 + \cos\left(\frac{2\pi d}{\lambda_0 L} x + \varphi_{j1} - \varphi_{j2}\right) \quad (2)$$

in which periodic modulation of the probability distribution is obvious. However, it is impossible to observe interference pattern with only one photon. One has to collect certain number of photons to observe interference pattern. Since the initial phases of photons in thermal light are random and uniformly distributed between 0 and 2π . The relative phase, $\varphi_{j1} - \varphi_{j2}$, changes randomly for every detected photon. This conclusion is true even if all the photons are detected in a time interval shorter than the coherence time.

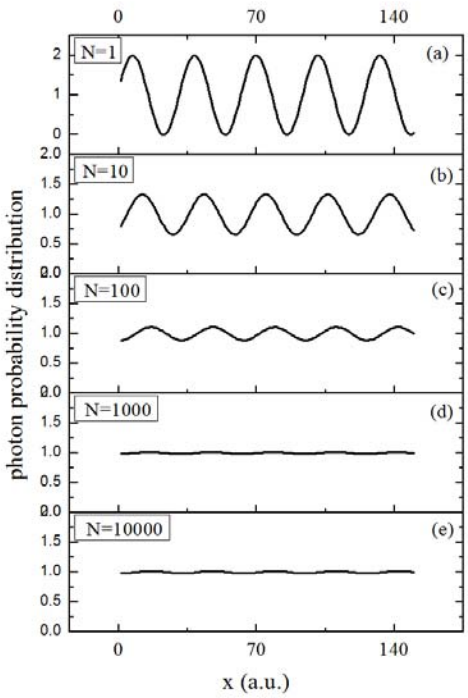

Fig.2 Photon probability distribution for different number of detected photons in the first-order interference of two independent thermal light beams

The probability distribution for a finite number of photons is given by the sum of N different single-photon probability distributions. Since the relative phase is random for every detected photon, it is straightforward to get the probability distribution for different number of photons as

$$P_N(x) \propto 1 + \frac{1}{\sqrt{N}} \cos\left(\frac{2\pi d}{\lambda_0 L} x + \varphi\right) \quad (3)$$

where φ is a random phase determined by the sum of all N different relative phases. Figure 2 shows the theoretical simulation of the photon probability distribution for different number of photons in a single run.

Based on Eq. (3), the visibility of the photon probability distribution is given by

$$V_N = \frac{1}{\sqrt{N}}. \quad (4)$$

Figure 3 shows the theoretical simulated visibility for different number of photons, in which each dot is an average of 50 independent numerical trials and the red line is the theoretical curve of Eq. (4). The theoretical result is consistent with the numerical simulations within the errors. One should not confuse the conclusion here with the one of thermal light in a

Young's double-slit interferometer, in which, the visibility of first-order interference pattern is independent of the number of detected photons.

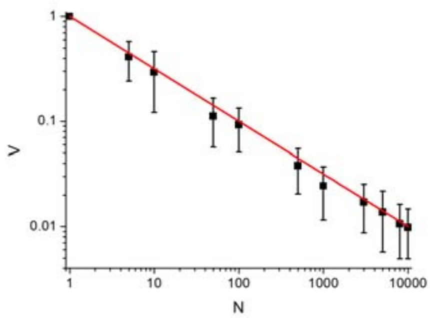

Fig. 3 Visibility vs. number of detected photons

When the number of detected photons is small, the visibility of the photon probability distribution is high. However, there may not be enough photons to retrieve the probability distribution. On the other hand, when the number of photons is large enough to retrieve the probability distribution, the visibility may be too low to show the interference pattern. This is similar as the first-order interference pattern of two independent laser light beams disappears for long measurement time. Hence we may conclude that, in the model that the initial phases of all photons in thermal light are random and uniformly distributed between 0 and 2π , it is impossible to observe the first-order interference pattern by superposing two independent thermal light beams. The conclusion is true for both short and long measurement time compared to the coherence time of the thermal light.

3. Discussions

The difference between the transient first-order interference by superposing two independent thermal and laser light beams is more obvious if we analyze both of them in Feynman's path integral theory. The initial phases of photons in a single-mode continuous wave laser light are identical within the coherence time. The probability distribution for the jth detected photon by superposing two independent laser light beams is also given by Eq. (2). Unlike in the thermal light case, the relative phase in the laser light case will not change for different detected photons during the coherence time. The probability distribution function for a finite number of photons is the same as single-photon probability distribution, Eq. (2). Hence there will be transient interference pattern by superposing two independent laser light beams [4].

Due to the degeneracy parameter of thermal light is much less than one, it is impossible to receive enough photons within the coherence time to experimentally testify our conclusion. Pseudothermal light can not be employed to test the conclusion either, for the initial phases of photons are not random during the coherence time for pseudothermal light. However, there is an alternative way to testify the conclusion, which is by employing the cold atoms just above the threshold temperature of Bose-Einstein Condensate (BEC). It has been proved that there is first-order interference pattern by superposing two independent BECs [7], which is just the same as the transient interference pattern by superposing two independent laser light beams [4]. If there is a way to superpose two independent cold atomic beams within the coherence time, one could judge whether there is interference pattern or not, which is an analogy of superposing two independent thermal light beams.

4. Conclusions

In conclusion, we have proved that there is no transient first-order interference pattern by superposing two independent thermal light beams if all the photons in thermal light have random initial phases within the coherence time. The reason is not the degeneracy parameter of thermal light is much less than one, but the initial phases of the photons in thermal light are random. The transient first-order interference pattern by superposing two independent thermal light beams can not be observed even if there is large number of photons within the coherence volume. Our results suggest that the classical models for thermal and laser light field within the coherence time are different.

5. References

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