Two-photon interference of multimode two-photon pairs with an unbalanced interferometer

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(Dated: September 10, 2018)

Two-photon interference of multimode two-photon pairs produced by an optical parametric oscillator has been observed for the first time with an unbalanced interferometer. The time correlation between the multimode two photons has a multi-peaked structure. This property of the multimode two-photon state induces two-photon interference depending on delay time. The nonclassicality of this interference is also discussed.

PACS numbers: 42.50.St, 42.50.Ar, 42.65.Lm

Quantum interference is one of the most interesting phenomena in quantum physics. Since the observation of nonclassical effects in the interference of two photons by Ghosh and Mandel [1], several types of quantum interference experiments have been demonstrated using correlated two-photon pairs generated by spontaneous parametric down-conversion (SPDC) [2, 3, 4, 5, 6, 7, 8, 9]. In Refs. [1, 2, 3, 4, 5, 6, 7, 8, 9], higher visibility of quantum interference has been demonstrated using correlated two-photon pairs generated by SPDC [10]. Quantum lithography has been proposed by Boto et al. in order to surpass classical diffraction limit utilizing this feature of quantum interference [11]. D’Angelo et al. have reported a proof-of-principle quantum lithography [12]. This feature of quantum interference has also been confirmed using a conventional Mach-Zehnder interferometer [13].

In these quantum interference experiments, SPDC process has been used to prepare correlated two photons. Ou et al. have succeeded in generating correlated two photons with new property by using an optical parametric oscillator (OPO) [14, 15]. The bandwidth of the two photons is narrow and the correlation time is long (≈10 ns). This property of the two photons produced by an OPO has enabled to directly observe their correlation function by coincidence counting. These narrow-band two-photon state have been used to observe nonclassical photon statistics [16]. Goto et al. have recently reported the observation of another type of correlated two photons, that is, multimode two photons produced by an OPO [17]. The correlation function of the multimode two-photon pairs has a multi-peaked structure. In this Brief Report, we report the first observation of two-photon interference of the multimode two-photon pairs with an unbalanced interferometer. Our experiment is shown in Fig. 1. The output beam from an OPO is incident at one of the input ports of an unbalanced interferometer. The correlation function of one of the outputs of the interferometer is observed with two photodetectors and a coincidence counter. First, we discuss briefly what happens in this experiment. Next, we explain our experimental setup and show our experimental results. Finally, we discuss our results with theoretical calculation of the correlation function of the output from the interferometer. The nonclassical feature of the two-photon interference is also discussed.

FIG. 1: Block diagram of our experiment. The output beam from an OPO is incident at one of the input ports of an unbalanced interferometer. The correlation function of one of the outputs of the interferometer is observed with two photodetectors and a coincidence counter. BS: 50/50 beam splitter; PD: photodetector; CC: coincidence counter.

The distance between multimode two photons produced by an OPO is \( n\tau_c c \), where \( \tau_c \) is the round-trip time of the OPO cavity, \( c \) is the speed of light in the vacuum, and \( n \) is an integer [17]. We assume that the propagation time difference, \( T \), between the short and long paths in the interferometer is nearly equal to \( \tau_c /2 \). There are two cases, Case1 and Case2: in Case 1, both the photons are reflected or transmitted at the first beam splitter of the interferometer; in Case 2, one of the two photons is reflected and the other is transmitted there. The distance between two photons in the output of the interferometer is \( n\tau_c c \) in Case 1 and \((n+1/2)\tau_c c \) in Case 2. Therefore, the two-photon pairs in Case 1 and Case 2 will induce the peaks of coincidence counts at delay times \( n\tau_c \) and \((n+1/2)\tau_c \), respectively. This enables to distinguish Case 1 and Case 2 through delay time. The height of the peaks of coincidence counts at delay times \((n+1/2)\tau_c \) will...
be constant with regard to the path-length difference of the interferometer because two photons in Case 2 do not interfere with each other. On the other hand, in Case 1, the two-photon pairs provide two-photon interference because we can not say which path a two-photon pair propagate on. Therefore, the height of the peaks of coincidence counts at delay times $n\tau$ will change with regard to the path-length difference of the interferometer. Thus, it is expected that two-photon interference depending on delay time will be observed.

The schematic of the experimental setup is shown in Fig. 2. The differences between this setup and that used in our previous work [17] are an unbalanced interferometer between the OPO and detectors, and a locking beam for the phase lock of the interferometer. The light source is a single-mode cw Ti:Sapphire laser of wavelength 860 nm. The round-trip length of the OPO is set long (560 mm) in order to time resolve the oscillatory structure in the correlation function. The output beam from the OPO (see Fig. 2). One of the two outputs of the interferometer is split into two with a 50/50 beam splitter. The two beams are coupled to optical fibers and detected with avalanche photodiodes (APD, EG&G SPCM-AQR-14). The coincidence counts of the signals from the two APDs are measured with a time-to-amplitude converter (TAC, ORTEC 567) and a multichannel analyzer (MCA, NAIG E-562).

We measured the coincidence counts at $\theta = (\pi/8) \times j$ ($j = 0, 1, \ldots, 8$), where $\theta$ is the phase difference of the interferometer defined as the intensity of the output of the interferometer is proportional to $(1 + \cos \theta)$ when classical light of wavelength 860 nm is incident to the interferometer. The experimental results at $\theta = (\pi/8) \times j$ ($j = 0, 1, \ldots, 8$) are shown in Fig. 3(a)-(i).

From now, we discuss our experimental results. First, we derive the correlation function of the output from the interferometer. The output operator, $\hat{a}(t)$, from one of the output ports of the interferometer is expressed as

$$\hat{a}(t) = \frac{\hat{a}_{\text{out}}(t - T_S) + \hat{c}_\text{in}(t - T_S)}{2} - \frac{\hat{c}_\text{in}(t - T_L) - \hat{a}_{\text{out}}(t - T_L)}{2}.$$  \hspace{1cm} (1)

Here $\hat{a}(t)$ denotes a Fourier transform of a field operator, $a(\Omega)$, of frequency $\omega_0 + \Omega$ ($\omega_0$ is the degenerate frequency of the OPO). That is, it is defined as

$$\hat{a}(t) = \frac{1}{\sqrt{2\pi}} \int d\Omega a(\Omega) e^{-i(\omega_0 + \Omega)t}.$$  \hspace{1cm} (2)

$\hat{a}_{\text{out}}$ is the output operator of the OPO far below threshold [14] and $\hat{c}_\text{in}$ is an annihilation operator of the vacuum entering the interferometer from the other of the input ports (see Fig. 4). $cT_S$ and $cT_L$ are the short and long path lengths of the interferometer, respectively. The intensity correlation function is derived as follows [13, 17]:

$$\Gamma(\tau) = \langle \hat{a}^\dagger(t)\hat{a}^\dagger(t + \tau)\hat{a}(t + \tau)\hat{a}(t) \rangle$$

$$= \left[ 2\sqrt{\Gamma_0(\tau)\cos \theta + \sqrt{\Gamma_0(\tau - T) + \sqrt{\Gamma_0(\tau + T)}}} \right]^2 + \left[ 2\sqrt{\delta\Gamma_0(0) + e^{i\theta} \sqrt{\delta\Gamma_0(-T) + e^{-i\theta} \sqrt{\delta\Gamma_0(T)}}} \right]^2$$

$$+ \left[ 2\sqrt{\delta\Gamma_0(\tau) + e^{i\theta} \sqrt{\delta\Gamma_0(\tau - T) + e^{-i\theta} \sqrt{\delta\Gamma_0(\tau + T)}}} \right]^2,$$  \hspace{1cm} (3)
FIG. 3: Experimental results. The phase, $\theta$, increases stepwise by $\pi/8$ from (a) to (i) ($\theta = (\pi/8) \times j$; $j = 0, 1, \cdots, 8$). The circles represent the measured coincidence counts. The lines are fits to Eq. (3), where fitting parameters are $C_1$, $C_2$, and $\theta$. The fitting result of $\theta$ is shown in Fig. 4. The range of the data used for the fitting is from 18 ns to 77 ns.

with

$$\Gamma_0(\tau) = |\epsilon|^2 \left( \frac{F}{F_0} \right)^2 e^{-\Omega_\tau} \frac{\sin^2[(2N + 1)\Omega_F \tau/2]}{\sin^2(\Omega_F \tau/2)}, \quad (4)$$

$$\delta = \frac{4|\epsilon|^2}{\Omega_\epsilon^2}. \quad (5)$$

Here $\epsilon$ is the single-pass parametric amplitude gain; $F$ and $F_0$ are the finesse of the OPO with and without loss, respectively; $\Omega_c$ and $\Omega_F$ are the bandwidth and free spectral range of the OPO, respectively; $2N+1$ is the number of the longitudinal modes in the OPO output. $\Gamma_0(\tau)$ is a multi-peaked function of delay time $\tau$. The width of the peaks is about $\tau_r/(2N+1)$. We assume that $T$ is nearly equal to $\tau_r/2$ but the difference between $T$ and $\tau_r/2$ is longer than the width of the peaks. This assumption is feasible in our experiment. This results in the following approximations:

$$\Gamma_0(\tau)\Gamma_0(\tau \pm T) \approx 0, \Gamma_0(\tau - T)\Gamma_0(\tau + T) \approx 0, \Gamma_0(\pm T) \approx 0. \quad (6)$$

In addition, $\delta$ is much smaller than one when the OPO is operated far below threshold. Therefore, Eq. (3) can be approximated as follows:

$$\Gamma(\tau) \approx \frac{\Gamma_0(\tau) \cos^2 \theta}{4} + \frac{\Gamma_0(\tau - T) + \Gamma_0(\tau + T)}{16} + \frac{\delta \Gamma_0(0)}{4}. \quad (7)$$

The first term in the right-hand side of Eq. (7) corresponds to two-photon interference in Case 1. This is a periodic function of $\theta$ with a period $\pi$, which is a half of that of classical interference. It means that two-photon interference in Case 1 is nonclassical. The second term in the right-hand side of Eq. (7) is constant with regard to $\theta$, corresponds to coincidence counts in Case 2. These two terms are due to correlated two photons. The last term in the right-hand side of Eq. (7) corresponds to the contribution from higher photon-number states than two. This term is not negligible when the pump power of the OPO is relatively high. As discussed in Ref. [17], the coincidence rate measured in experiments is an average of the correlation function over the resolving time, $T_R$, of detectors. According to Ref. [17], the coincidence counts measured in this experiment will become
\[ \Gamma_c(\tau) = C_1 \left[ 4\Gamma_c^{(0)}(\tau) \cos^2 \theta + \Gamma_c^{(0)}(\tau - T) + \Gamma_c^{(0)}(\tau + T) \right] + C_2, \]

with

\[ \Gamma_c^{(0)}(\tau) = e^{-\Omega_c |\tau - \tau_0|} \sum_n \left( 1 + \frac{2|\tau - n\tau_r - \tau_0| \ln 2}{T_R} \right) \exp \left( -\frac{2|\tau - n\tau_r - \tau_0| \ln 2}{T_R} \right). \]

Here \( C_1 \) and \( C_2 \) are constants and \( \tau_0 \) is an electric delay. The lines in Fig. 3 are fits to Eq. (8). Fitting parameters are two constants, \( C_1 \) and \( C_2 \), and the phase difference \( \theta \). Constant parameters are set as follows: \( \tau_0 = 47.5 \) ns; \( \tau_r = 2.07 \) ns; \( T_R = 280 \) ns; \( \Omega_c/(2\pi) = 11 \) MHz. The range of the data used for the fitting is from 18 ns to 77 ns, while the range plotted in Fig. 3 is from 41 ns to 54 ns. The fitting in Fig. 3 is good. The term, \( C_2 \), independent of the delay time, \( \tau \), is mainly due to the last term in the right-hand side of Eq. (7). In our experiment, \( C_2 \) is comparable to \( C_1 \). It means that the pump power of the OPO is relatively high and the contribution from higher photon-number states than two is not negligible. The phase determined from the fitting is plotted in Fig. 4.

In conclusion, we have observed two-photon interference of multimode two-photon pairs produced by an OPO for the first time with an unbalanced interferometer. This two-photon interference has been dependent on delay time. The experimental results have been explained theoretically. Nonclassical feature of the two-photon interference has been also discussed.

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