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# Two-Photon Interference Experiment in a Mach-Zehnder Interferometer

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A two-photon interference experiment is presented in which an entangled pair of photons generated from a parametric down-conversion was incident on two input ports of a Mach-Zehnder interferometer. The experiment was carried out using two photon coincidence detection with two detectors at the two output ports of the interferometer. The measured coincidence counts exhibit an interference effect with visibility of 0.75 at simultaneous inputs and 0.38 at inputs with different arrival times according to the degree of photon number entanglement.

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## I. INTRODUCTION

Quantum entanglement has recently attracted a great deal of attention because it has many potential applications in quantum information processing and transmission, such as quantum computation [1–3], teleportation [4], dense coding [5], cryptography [6], and communication. [7] Entanglement is one of the distinguished properties of quantum mechanics, whose state cannot be written as a direct product of individual states in any basis. Two-particle entangled states have been used as a means for the experimental study of the fundamental issues of quantum mechanics, for example, the Einstein-Podolsky-Rosen (EPR) correlation [8] and a quantitative test of Bell's inequalities. [9]

During the last two decades, a number of two-photon interference experiments have been done with the light source generated by the nonlinear optical process of the spontaneous parametric down-conversion (SPDC). [10] In this process one photon of the pump laser with high frequency is converted into a pair of photons with lower frequencies, conventionally called the signal and the idler. A pioneering study associated with pair detection has been performed by Franson [11], who proposed a new experimental test based on optical interference, with an interesting feature that the predicted interference occurs for optical path-length differences much larger than the first-order coherence length. The experimental realizations related to this type of interference effect(large path-length difference) have been carried out with three types of interferometers: the Michelson type [12–14], the Mach-Zehnder type [15–19], and the original Franson type. [20–24] For the case of large path-length difference compared with the coherence length, one of the most interesting features is that no second-order interference effect is observed but there exists fourth-order interference. This effect cannot be described with classical optics.

The Mach-Zehnder interferometer (MZI) has been shown to exhibit nonclassical fourth-order interference effects when entangled photon pairs are used as input beams. [15–19] They have been used to explore the entangled-state properties of the photons generated by SPDC. In the two-photon interference experiment with an MZI, in which the photon pairs from the SPDC are employed there is a main parameter which determines the visibility of the fourth-order interference. The factor limiting the visibility is the degree of entanglement of photon pairs after the first beam splitter of the interferometer. The more probability the two photons have to be split at the beam splitter, the less visibility of the fourth-order interference pattern is expected.

In this paper, we wish to report a two-photon interference experiment in which entangled state photons generated from the SPDC were incident on the input ports of an MZI. The pump photons with the wavelength of 325 nm by a He-Cd laser were employed to generate the entangled photons of 650 nm from a

BBO crystal. The experiment is based on two photon coincidence detection with two detectors at the two output ports of the interferometer. The fourth-order interference effects in an MZI are investigated for photon arrival time difference shorter and longer than the coherence time of the down converted photons. In the former case, the two photons from the SPDC are coincident at the input ports of the MZI, and in the latter case, the two photons arrive at the input ports with a relative time difference that is much greater than the coherence time of the down-converted beam.

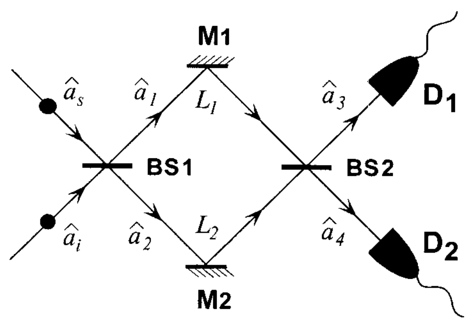


FIG. 1. A Mach-Zehnder interferometer with two detectors, which is employs the two photons(signal and idler photons) generated by parametric down-conversion process. The BS1 and BS2 are lossless 50/50 beam splitters, $M1, M2$ mirrors, $D_1, D_2$ detectors. $M2$ served as a device controlling the optical path-length difference between two paths $L_1$ and $L_2$.

## II. TWO-PHOTON INTERFERENCE IN A MACH-ZEHNDER INTERFEROMETER

Many theoretical studies for achieving high phase-sensitivity have been done with the Mach-Zehnder interferometer such as Fock-state inputs. [25] The interferometer consists of two lossless 50/50 beam splitters (BS1 , BS2), and two mirrors (M1 , M2). The two photodetectors $(D_1, D_2)$ are installed in each of the output ports as shown in Fig. 1 to measure the single count and the coincidence count simultaneously. The photon annihilation operators of the outputs, $\hat{a}_3$ and $\hat{a}_4$ are given by

$$\begin{aligned}\hat{a}_3 &= \frac{1}{2}\left[(-\hat{a}_s + i\hat{a}_i)e^{i\theta_1} + (\hat{a}_s + i\hat{a}_i)e^{i\theta_2}\right],\\ \hat{a}_4 &= \frac{1}{2}\left[(i\hat{a}_s + \hat{a}_i)e^{i\theta_1} + (i\hat{a}_s - \hat{a}_i)e^{i\theta_2}\right], \end{aligned} \quad (1)$$

where $\theta_j = kL_j (j = 1, 2)$ are the overall phases of the two paths of the interferometer.

For general Fock-state $|n_s, n_i\rangle$ inputs for the interferometer, the single photon counting rate is

$$\begin{aligned}R_s &\propto \langle n_s, n_i|\hat{n}_3|n_s, n_i\rangle = \langle n_s, n_i|\hat{n}_4|n_s, n_i\rangle\\ &= \frac{1}{2}n_s(1 - \cos\theta) + \frac{1}{2}n_i(1 + \cos\theta),\end{aligned} \quad (2)$$

while the coincidence counting rate is given by

$$\begin{aligned}R_c &\propto \langle n_s, n_i| : \hat{n}_3\hat{n}_4 : |n_s, n_i\rangle\\ &= \frac{1}{4}(n_s + n_i)^2 - \frac{1}{4}\left[n_s(n_i + 1) + n_i(n_s + 1)\right]\sin^2\theta - \frac{1}{4}(n_s - n_i)^2\cos^2\theta,\end{aligned} \quad (3)$$

where $n_3 = \hat{a}_3^\dagger\hat{a}_3$, $n_4 = \hat{a}_4^\dagger\hat{a}_4$.

Let's consider the entangled photon pairs from a SPDC process as two inputs for the interferometer. In this case, the inputs are described as two-photon Fock-states $|1, 1\rangle$, where $n_s = 1, n_i = 1$ in photon numbers. It is easily seen that there is no modulation in the single counting rate $R_s$ for the $|1, 1\rangle$ inputs, because $\langle\hat{n}_3\rangle$ is independent of the phase difference $\theta = k\Delta L$ of the two arms, where $\Delta L = |L_2 - L_1|$. On the other hand, the coincidence counting rate for the $|1, 1\rangle$ inputs is given by

$$R_c = A(1 + \cos 2\theta), \quad (4)$$

where $A$ is a constant. Therefore, the interference pattern in the coincidence counting rate is expected with the period of $\Delta L = \lambda/2$, for the wavelength $\lambda$ of the down-converted beams. As seen in Eq. (4), the visibility of the interference pattern can be 1 in the ideal case, in which two input photons go along the same path of the interferometer. In a practical case the visibility is reduced to less than 1 due to a lack of perfect entanglement in the two paths of an MZI, which is affected by alignment or defects of the optical components, and also because of the time difference between two input photons.

If the two photons arrive at the input ports of the MZI with a time difference that is larger than the coherence time of the input beams, then the two photons can be split into the two arms of the interferometer, which means that the signal photon travels along the path $L_1$ and the idler photon travels along the path $L_2$, or vice versa. So Eq. (4) is modified to

$$R_c = A(1 + B\cos 2\theta), \quad (5)$$

where $B$ is a constant for the visibility of the pattern.

## III. EXPERIMENT

The schematic diagram of the experimental setup is shown in Fig. 2. In the process of parametric down-conversion a nonlinear crystal (BBO) is pumped by a cw He-Cd laser line of 325nm(Liconix 3207N) that generates two photons in an entangled state. Simultaneous signal and idler photons of about 650 nm wavelength are incident on the nonpolarizing beam splitter (BS1) which has about 50/50 reflectivity and transmissivity. The beam splitter BS1 is mounted on a micrometer which has a resolution of 0.5$\mu$m that allows the control of the time difference between the input photons. When the BS1 is in the symmetric position, the signal and idler photons always appear together on one path and never on both paths simultaneously, because of the destructive interference between the two two-photon probability amplitudes in the Hong-Ou-Mandel (HOM) interferometer. [26]

The photon pairs emerging from the BS1 pass through one of the paths of the interferometer and arrive at the BS2, whose output photons are directed to the two detectors $D_1$ and $D_2$. The photodetectors are electronically cooled avalanche photodiodes (EG&G model SPCM-141-FC) with a single photon timing resolution of 300ps. Narrow bandwidth interference spectral filters (IF), with the center wavelength of 650 nm and the bandwidth of 10 nm, are placed in front of each of the detectors. Lenses with a 10 cm focal length are located in front of small apertures(not shown in the schematic diagram), which are used to focus the beam onto the active areas (180$\mu$m diameter) of these detectors. The output pulses of the photon detectors are then sent to single-channel counters and to a coincidence counter with a 6.38ns time resolution (LeCroy Model 1434A). Pulses arriving together at the coincidence counter within the resolving time are measured to be coincident.

The phase shifts $c\delta\tau_{\rm MZI}$ of the interferometer are varied by mounting the mirror $M4$ on a piezoelectric transducer and making a displacement smaller than the optical wavelength. In the experiment, we have performed two kinds of interference experiments, the first being the case of two photons coincident on the BS1, and the other being the two photons which are incident with a time difference (from down-converter to the interferometer inputs) greater than the single-photon coherence time. The MZI is controlled over the small path-length difference of the interferometer $c\delta\tau_{\rm MZI}$ which is shorter than the single-photon coherence length ($c\delta\tau_{\rm MZI} \ll c\tau_{\rm coh}$).

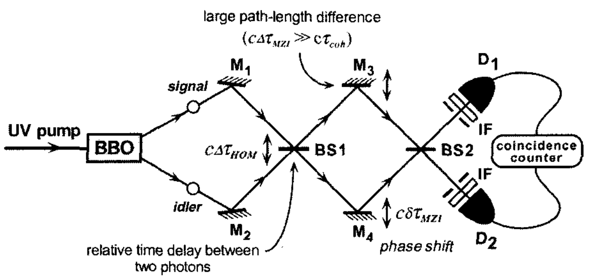


FIG. 2. Schematic diagram of the experimental setup. The noncollinear, degenerate type-I phase matched SPDC provides entangled state photon pairs. The UV pump is a cw He-Cd laser, the BBO a nonlinear crystal, the IFs, interference filters. The $c\delta\tau_{\rm MZI}$ introduces an optical path-length difference (or phase shift) between two paths, and $c\Delta\tau_{\rm HOM}$ controls the arrival time delay between two photons at the input port (BS1).

## IV. RESULTS AND DISCUSSION

The behavior of photon pairs from the SPDC has been extensively analyzed in the context of the Hong-Ou-Mandel type interferometer. [26] Fig. 3 shows the measured coincidence counts as a function of the BS1 position, which is a typical HOM's coincidence dip pattern. When two photons from the SPDC are incident on the two input ports of the BS1 without a time difference, the two photons exit the BS1 together from the same output port. The rate of coincidence counts is, therefore, found to be minimized for zero time difference between two input photons when two detectors are placed at each of the output ports of the BS1 (see Fig. 2).

To be certain of the pairing behavior at the output port of the BS1, additional experimentation is needed. This is performed with two detectors placed at the two output ports of the BS2 rather than the BS1 when one

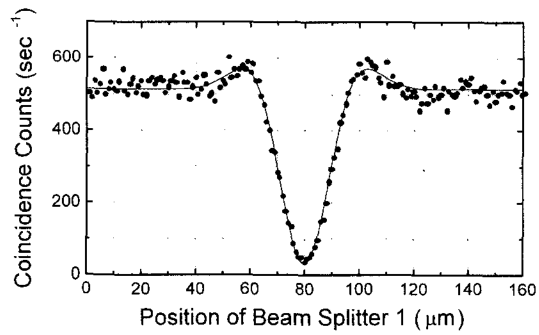


FIG. 3. Coincidence counts at the two output ports of the BS1 as a function of the BS1 position (or relative time delay between signal and idler photons at BS1) which is detected with two detectors after the two output ports of BS1.

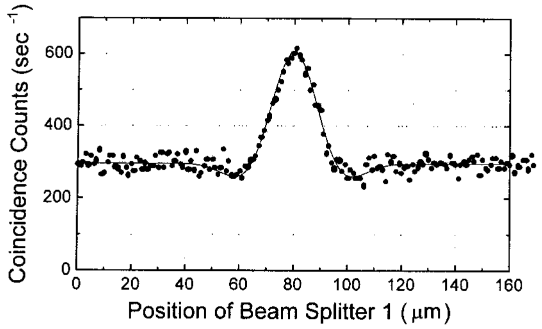


FIG. 4. Coincidence counts at the two output ports of BS2 as a function of the BS1 position (or relative time delay between signal and idler photons at BS1) which is detected with two detectors after the two output ports of the BS2 when one of the paths of the MZI is blocked.

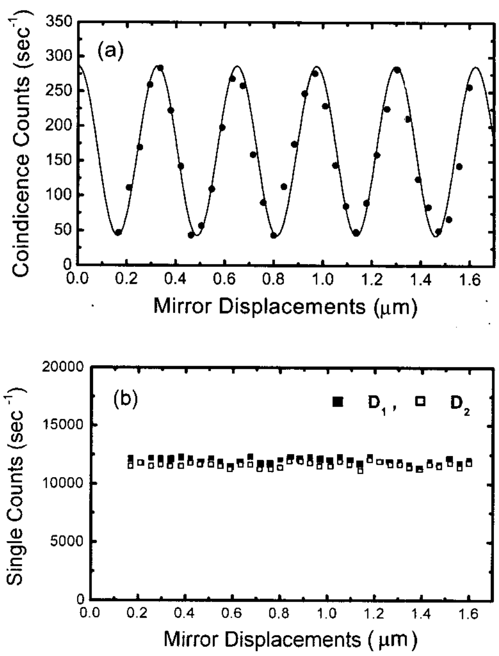


FIG. 5. The measured fourth-order and second-order interference effects as a function of the mirror ($M4$) displacements or of the optical path-length difference between two paths ($c\delta\tau_{\mathrm{MZI}}$) when the photons are coincident on the inputs of the interferometer ($c\Delta\tau_{\mathrm{HOM}} = 0$). (a) Coincidence counts with two detectors $D_1$ and $D_2$, and (b) Single counts with each detector. The solid circles represent experimental results, and the curve stands for the theoretical results based on the probability for joint detection by the two detectors.

of the paths of the MZI is blocked. Fig. 4 shows the coincidence count, at the two output ports of the BS2, as a function of the BS1 position (or time difference between the signal and idler photons at the BS1). The peak corresponds to the balanced position of the BS1. The pairing behavior shows a clear enhancement of the coincidence counts, which is almost twice the predicted value with the same width as the dip.

The width(FWHM) of the interference dip [Fig. 3] and peak [Fig. 4] in the coincidence counts is related to the bandwidth of the down-converted beams, and thus provides a measure of coherence time(or coherence length) of the input beams. In practice, this time can be predicted from the passband of the interference filters (IF) in front of the detectors. The measured coherence length by a displacement of the BS1 corresponds to twice the width of the dip due to the mirror effect. It is found to be about 42.3 $\mu m$ at FWHM, corresponding to a coherence time of about 141 $fs$, from the bandwidth of the interference filters ($\Delta\nu = 7.1 \times 10^{12}$ Hz).

The results of the two-photon interference experiment in an MZI are given in Fig. 5 for the coincident input ($c\Delta\tau_{\mathrm{HOM}} = 0$) and Fig. 6 for the input with time difference ($c\Delta\tau_{\mathrm{HOM}} \gg c\tau_{\mathrm{coh}}$). Fig. 5(a) reveals the measured two-photon coincidence counts with two detectors $D_1$ and $D_2$, and Fig. 5(b) shows the single counts with each detector, as a function of the very small optical path-length difference ($c\delta\tau_{\mathrm{MZI}}$) between two paths by scanning mirror $M4$. The solid circles represent the experimental results, and the curve stands for the theoretical results based on the probability of joint detection by the two detectors. In accordance with Eq. (3), the fourth-order interference pattern in the coincidence counts is seen to occur with a spatial period equal to the pump wavelength, rather than that of the down-conversion photons. This result is closely related not only to a measure of photonic de Broglie wavelength of entangled two-photon states [27], but also to a proof-of-principle experiment in quantum lithography. [28] The visibility is found to be about 0.75, while quantum theory predicts that the visibility of the two-photon interference should be 1.0. In this scheme the reduction of the visibility mainly arises from the imperfection in the alignment.

The results shown in Fig. 6(a) correspond to two-photon coincidence counts with two detectors $D_1$ and $D_2$, and Fig. 6(b) shows single counts with each detector, as a function of the path-length difference between the two paths. In this case the two photons arrive at the input ports of the MZI with a time difference that is larger than the coherence time $\tau_{\mathrm{coh}}$ of the down-converted photon beams ($c\Delta\tau_{\mathrm{HOM}} \gg c\tau_{\mathrm{coh}}$). When the arrival time difference exceeds the coherence time, the input photons behave in a more independent way in the interferometer. In this case, the two photons can be split at the input port of the interferometer. The signal photon travels through the

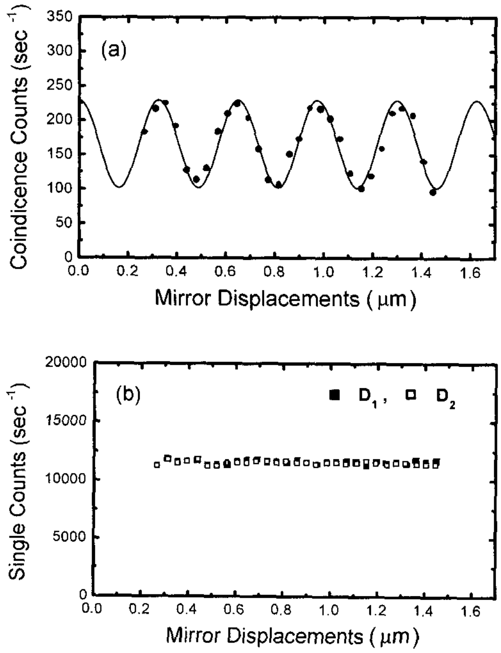


FIG. 6. The measured fourth-order and second-order interference effects as a function of the optical path-length difference between two paths when the relative time delay between two photons exceeds the coherence time of the beams ($c\Delta\tau_{\rm HOM} \gg c\tau_{\rm coh}$). (a) Coincidence counts with two detectors $D_1$ and $D_2$, and (b) Single counts with each detector.

one path and the idler photon travels through the other path, or vice versa. Therefore the visibility of the fourth-order interference pattern is reduced because the split photon contributes to the constant coincidence counts. The measured fourth-order interference effect in our experiment is observed with visibility $B$ of about 0.38.

To understand the experimental results, we have to take into account the quantum nature of the two-photon state in an MZI. When the two photons enter the input beam splitter BS1 of the interferometer simultaneously, the two photons always emerge together either at path $L_1$ or at path $L_2$, so that paths 1 and 2 are in the superposition state. In quantum theory this state is represented by the form

$$|\Psi_{\rm MZI}\rangle = \frac{1}{\sqrt{2}}\left(|2\rangle_1|0\rangle_2 + e^{i\theta}|0\rangle_1|2\rangle_2\right), \qquad (6)$$

where $\theta = k\Delta L$, and the phase factor $e^{i\theta}$ depends upon the phase shift(or optical path-length difference) by a small displacement of the mirror. The state $|\Psi_{\rm MZI}\rangle$ is in a linear superposition of a two-photon state and the vacuum state. The two photons are either in the path $L_1$ or in the other path $L_2$, but they cannot be in these two paths simultaneously. This is the photon-number entangled state.

## V. CONCLUSION

In this experiment we examined the two-photon interference effects in a Mach-Zehnder interferometer with entangled photon pairs generated by the parametric down-conversion. Under the condition of coincident input, no second-order interference is observed, but there is fourth-order interference with a visibility of 0.75. The interference pattern in the coincidence counts is seen to occur with a spatial period equal to half of the wavelength, which is considered not only as a measure of photonic de Broglie wavelength of entangled photon pairs, but also as a potential application of entangled state photons on the quantum lithography . In the case of the input photons with a time difference larger than the coherence time $\tau_{\rm coh}$, the visibility is reduced to 0.38. In conclusion, this experiment has found that the visibility of the two-photon interference effects indicates the degree of photon number entanglement in the interferometer.

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