A simple technique for measuring the spatial correlation of photon pairs for complete interference in the Michelson interferometer

K Boonkham1,* and P Limsuwan2
1 Division of Physics, Mahidol Wittayanusorn School, Nakhon Pathom 73170, Thailand
2 Department of Physics, Faculty of Science, King Mongkut's University of Technology Thonburi, Bangkok 10140, Thailand

*kitisak.bnk@mwit.ac.th

Abstract. In this research, a simple technique for measuring the spatial correlation or angular correlation of photon pairs was developed. The system consisted of two aluminium rails which had the same pivot at the position of a nonlinear crystal. The rails were manually moved to find the position of the correlated photon pairs. At this position, the photon pairs were collected by the collimators attached at the end of the rails. The pairs were produced by type I spontaneous parametric down-conversion process using a 405 nm diode laser and a BBO crystal. The crystal was specifically cut for emitting the photon pairs at an angle of 3° with respect to the direction of the pump laser. These pairing photons were correlated and interfered in the Michelson interferometer, then, the correlated photons were demonstrated. It was found that the visibilities in the case of perfect alignment, near perfect alignment and misalignment were $V = 1.0000 \pm 0.0004$, $0.869 \pm 0.002$, $0.591 \pm 0.002$ and $0.168 \pm 0.002$, respectively.

1. Introduction
The correlated photon pairs (twin photons) have been widely studied for fundamental quantum mechanics by using quantum information protocol for several decades. There is a very significant new class of instructional laboratory experiment to demonstrate quantum mechanics in undergraduate curriculum e.g., demonstrating the existence of photons [1-3], single-photon interference [4], two photon interference [5-7], quantum eraser [3,8,9], entanglement and tests of Bell’s inequalities [10-13].

In this paper, the experiments were performed with the simple techniques for measuring the spatial correlation or angular correlation of photon pairs. The techniques used consisted of two aluminium rails which had the same pivot at the position of nonlinear crystal. The rails were manually moved to find the location of the correlated photon pairs in which the photons were collected into collimators attached at the end of the rails. Before taking the data for interference of photon pairs in the coincidence counts, the Michelson interferometer was set using the white light source and the white light interference fringes were observed by the CMOS camera. If two mirrors in the interferometer are adjusted to be perpendicular, then the circular interference fringes (zero order maxima) appear on the monitor. This case is called the perfect alignment and the completeness of the interference was obtained.
2. Experimental Setup

2.1. The first technique: the spatial correlation measurement

A 50 mW diode laser with a wavelength of 405 nm was used as a pump beam. The horizontal polarization pump beam was sent through a Glan-Thompson calcite polarizer. Then, it was reflected on the 400 - 750 nm broadband dielectric mirror and reached the beta barium borate (BBO) crystal. It was attached to the high-precision rotation mount for fine tuning of the phase-matching angle \( \theta_m = 29.2^\circ \). The BBO holder was mounted on the translation stage. The BBO crystal was cut for type I down-conversion of 405 nm pump light. When the pump beam pass through the crystal, the vertically polarized signal and idler photons with a wavelength of 810 nm spontaneously decays into pairs of photons making an angle of \( \theta_l = 3^\circ \) with respect to the pump beam outside the crystal and the pump beam was blocked by the beam trap. However, the polarization of photon pairs was monitored with the polarizers placed in front of the fiber collimators as shown in figure 1. The collimators were used to transmit the light into the single photon counting modules (SPCM’s) and the 780 nm long-pass colored glass filters were inserted in front of these collimators. The filter allowed only the light with a wavelength longer than 780 nm to pass through it. Then, the 810 nm photon pairs were sent to the detectors \( A \) and \( B \) on the SPCM via multimode fiber path cables. The signal and idler photons that produced by the spontaneous parametric down-conversion process in the crystal were identified by the coincidence detection using a simple coincidence circuit from fast logic chips [13]. The coincidence counts from the coincidence detection between detectors \( A \) and \( B \) \( (N_{AB}) \) were recorded with LABVIEW program in the personal computer. The iris diaphragms in the setup were employed in the alignment allowing the optical elements to have the same height on the table.

![Figure 1](image-url)  
**Figure 1.** Schematic of experimental setup for spatial (angular) correlation measurement.

The aluminum rails \( A \) and \( B \) with 1.20 meter in length were adjusted to set the angle of fiber collimators which were used to collect the photons and the photons were sent to the SPCM (the distance
from collimator to BBO crystal on the aluminum rail was 1 meter). The two aluminum rails have the same pivot at the position of BBO crystal. The angle of rail $A$ and $B$ was 3º with respect to the pump beam by using the ruler in setting up the angle. In the alignment of fiber collimator, the red light from laser diode was beamed into the fiber collimator without a long-pass colored glass filter. After that, the alignment laser travels backwards through the iris diaphragms on both $A$ and $B$ rails allowing the beam to hit the center of the BBO crystal. Since the room was darkened, the fiber collimators were fine adjusted so that the highest single count rate in each detector were nearly the same. The 780 nm long-pass colored glass filter must be placed before the measurement were carried out. Finally, the plane of optic axis of the BBO was horizontally adjusted by high-precision rotation mount until the maximum coincidence counts were observed. In this experiment, the spatial correlation of photon pairs could be determined by measuring the coincidence counts in 1 second, by setting rail $A$ ($\theta_A$) at 1º and adjusting rail $B$ ($\theta_B$) step by step with 0.5º until it reached 6º. Repeating the same adjustment by changing rail $A$ to 2º, 3º and 4º, respectively.

2.2. The second technique: the photons interference measurement in the Michelson interferometer

In this section, the Michelson interferometer as shown in figure 2 was used to investigate the interference fringes of the single photons (signal photons). The signal photons were reflected by the prism into the interferometer, consist of two broadband dielectric mirrors (750 - 1100 nm) as shown in number 5, piezo electric translation stage (number 6) and a beam splitter (number 4). While another beam splitter (number 8) was used to beam the signal photons into the detector $A$ by the fiber collimator (number 10), and transmitted the visible interference fringes to the CMOS camera. The 780 nm long-pass colored glass filter (number 9) was inserted in front of the fiber collimator. Another parts, the half wave plates ($\lambda/2$) as shown in number 1 and 7 were used to change the vertical polarization state of signal photons in the horizontal polarization state (and vice versa). The polarizing beam splitter as shown in number 2 was used to beam the signal photons and white light beam into the beam-splitter of the interferometer. The source of white light was the broadband (470 - 850 nm) fiber - coupled LED.

![Figure 2. Schematic of experimental setup of the photons interference measurement in the Michelson interferometer.](image-url)
The high visibility of interference was obtained when the interferometer path length difference was zero. For the visible light parts, the white light source and CMOS camera were conveniently used to set the same path length difference of the interferometer arms. Then, the zero-order fringe of the interference was observed at the CMOS camera. Furthermore, the important key to obtain the high visibility of the interference was the coincidence detection between signal and idler photons, i.e. the coincidence counts of the pairs \(N_{ab}\). The measurement of the coincidence counts in the down-conversion pairs was carried out to confirm that the interference patterns produced by individual (signal) photons if the detection at the detector \(A\) of a signal photon was recorded, and an idler photon was detected at detector \(B\). The interference fringes of photons occurred by adjusting the length of any arm of the interferometer by backward or forward of the mirror mounted on the translation stage and applying the voltage to the piezo electric transducer (PZT) mounted on the translation stage (0.1 volt will change the distance of translation stage by 10 nm). The interference fringes which results from the measurement of coincidence count between down-conversion pairs was a function dependence on the difference in path length between two arms of interferometer. After that, the imperfect alignment (mirrors in two arms were not perpendicular) was taken into consideration.

In conventional interference measurements, a single-photon detector was used to measure the probability of finding a photon as a function of the phase difference between the interferometer arms \[5\]. The rate of photons reach to the detector is called single count. However, the coincidence counting is important for measuring a photon pair (down-converted photons), because a photon pair emitted simultaneously from a photon pump and reach to the two detectors at almost the same time. Since the detectors were connected to an electronic coincidence circuit, the output pulses of the pairs from the circuit are called coincidence counts. This technique is useful in rejecting photons that do not originate from the photon source (background photons).

3. Results and Discussion

3.1. The spatial (angular) correlation measurement
The spatial correlation of photon pairs is illustrated in figure 3. The coincidence counts in 1 second between detector \(A\) and \(B\) (collimators on the rails) were recorded. The coincidence counts as a function of the rail \(B\) angles \(\theta_B\) is shown on the left axis. While, the single counts in 1 second of detector \(B\) (collimator on the rail \(B\)) as a function of the rail \(B\) angles is shown on the right axis. The closed triangle, open triangle, open square and closed circle show coincidence count rates for \(\theta_B = 1^\circ, 2^\circ, 3^\circ, 4^\circ\), respectively, on left scale. Crosses show rail \(B\) detection rate on right scale. However, the very low coincidence counts were observed at \(\theta_B = 1^\circ, 2^\circ, 4^\circ\) as shown in figure 2. The region in grey shade indicates that photons with a wavelength of longer than 780 nm can pass through 780 nm long-pass colored glass filter. This is because the filter allows the beams with a wavelength longer than 780 nm to pass through. When the rail \(B\) was at 0° – 2°, the light beams hardly pass through it. Consequently, the single counts rate was very low because the wavelength of light beam (< 780 nm) does not match with the filter. However, when the rail \(B\) was at 2.5°, the single counts rate was highest because the wavelength of photon at this angle was longer than 780 nm. But, the coincidence count rate was highest when the rail \(B\) was at 3° even though the single count rate was highest at 2.5°. This results refer to as the correlation between the pairs which are the result from the photon energy and momentum conservation. Therefore, the measurement of a photon in one arm corresponded with the existence of the photon in the other arm at the similar distance from the crystal. It can be referred to as the twin photons (correlated photons).
Figure 3. Spatial correlation of photon pairs (momentum conservation). The coincidence and single count rates are functions of collimator on the rail B angle at different rail A angles.

3.2. The photons interference measurement in the Michelson interferometer
The high visibility interference of the signal photons as shown in figure 4 was obtained when the interferometer arms have the same lengths and two mirrors of the interferometer are perpendicular to each other. In this situation, the interfering beams between two paths of the interferometer are completely overlap, refer to as the perfect alignment. The signal photons from the interferometer showed interference at the detector A. The single counts \( N_A \) in 1 second was a function of the path length difference as shown in figure 4(a). The fringe visibility of \( V = 0.850 \pm 0.002 \) was observed even without any correction for background photons. The same fringe pattern, with a visibility of \( V = 1.0000 \pm 0.0004 \) (complete interference) was obtained when the signal photons were measured in coincidence with the photons in the idler path \( N_{AB} \) as shown in figure 4(b). The coincidence counts in 1 second was a function of path length difference.

Figure 4. Interference fringes of single (individual) photons were obtained in the single counts (a) and the coincidence counts (b)
Furthermore, the figure 5(a) shows the interference fringe in which the coincidence counts in 1 second was a function of path length difference. The complete interference was obtained in case of the perfect alignment. The error bars are proportional ($N_{ph}$)$^{1/2}$ due to Poisson static. The right hand side of the figure 5(a) are the photo of the zero-order fringe of the interference taken by the CMOS camera. The camera was used to easily set up the perfect alignment of the interferometer by observing the visible interference fringes before taking the data of interference fringes with single photon detector in the coincidence counts. But, the near perfect alignment (the interfering beams are almost overlap) the reduced visibilities of $V = 0.869 \pm 0.002$ and $0.591 \pm 0.002$ were observed as shown in figure 5(b) and (c), respectively. The bright and dark bands of the interference pattern on the right hand side of figure 5(b) and (c) were observed when the interfering beams were near completely overlap. In case of the misalignment as shown in figure 5(d), the interfering fields are slightly overlap and a very low visibility of $V = 0.168 \pm 0.002$ was obtained.

![Figure 5](image)

**Figure 5.** Interference fringes of single (individual) photon were obtained in the coincidence counts. The photos on the right are the visible interference fringes with CMOS camera.

4. Conclusion
In this work, one of a photon pair from spontaneous parametric down-conversion process (correspond to the energy and momentum conservation), interfere with itself in the Michelson interferometer. The coincidence detection between the photon pairs allowed the complete interference.

Acknowledgement
We wish to acknowledge valuable discussion with Associate Professor Surasak Chaingga. We also thank Department of Physics, Kasetsart University for supporting facility used in this work.

References
[1] Thorn J J, Neel M S, Donato V W, Bergreen G S, Davies R E and Beck M 2004 *Am. J. Phys.* 72(9) 1210–19
[2] Beck M 2007 *J. Opt. Soc. Am. A* 24 2972–8
[3] Galvez E J, Holbrow C H, Pysher M J, Martin J W, Courtemanche N, Heilig L and Spencer J 2005 Am. J. Phys. 73(2) 127–40
[4] Brett J P and David P J 2010 Am. J. Phys. 73(2) 471–84
[5] Lopez-Mago D and Novotny L 2012 Phys. Rev. A 86(2) 023820
[6] Kawabe Y, Fujiwara H, Okamoto R, Sasaki K and Takeuchi S 2007 Opt. Express 15(21) 14244–50
[7] Kwiat P G, Vareka W A, Hong C K, Nathel H and Chiao R Y 1990 Phys. Rev. A 41(5) 2910–13
[8] Gogo A, Snyder W D and Beck M 2005 Phys. Rev. A 71(5) 052103
[9] Schneider M B and LaPuma I A 2002 Am. J. Phys. 70(3) 266–71
[10] Dehlinger D and Mitchell M W 2002 Am. J. Phys. 70(9) 903–10
[11] Kwiat P G, Waks E, White AG, Appelbaum I and Eberhard P H 1999 Phys. Rev. A 60(2) R773–6
[12] Kwiat P G, Mattle K, Weinfurter H, Zeilinger A, Sergienko A V and Shih Y 1995 Phys. Rev. Lett. 75(24) 4337–41
[13] Dehlinger D and Mitchell M W 2002 Am. J. Phys. 70(9) 898–902