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Bending motion of photons in Young's double-slit

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Abstract

The investigation of the interference phenomenon of Young's double-slit using a single photon is an epoch-making experiment demonstrating the mystery of quantum mechanics, but the details have not yet been clarified. We have developed a method for observing the behavior of photons near the double-slit using a multimode optical fiber to obtain a two-dimensional map of photon motion. Quantitative analysis of the directional motion revealed that the directional change was related to the derivative of the electric field and was uniquely determined by the direction of photon motion.

***Keywords*: photon trajectory, photon behavior, interference phenomenon, double-slit experiment**

1. Introduction

Quantum interference experiments using double-slits best show the strange behavior of particles in the quantum world. This mysterious quantum phenomenon is demonstrated using a single photon [1] and explained by standard interpretations (i.e., the Copenhagen interpretation), including particle-wave duality and superposition principles [2] and the collapse of wave-function [3]. On the other hand, deterministic views represented by the interpretation of the de Broglie-Bohm theory [4,5] are an attempt to explain the quantum interference while emphasizing the well-defined trajectory of the photon [6]. The de Broglie–Bohm theory is a method of calculating trajectories using two main equations, the continuity equation and the quantum Hamilton–Jacobi equation [7]. In the de Broglie–Bohm interpretation, the number of measured particles is proportional to the probability density of standard quantum mechanics, so simply measuring the particle distribution cannot distinguish it from standard quantum mechanics. Recently, Kocsis et al. have measured the "average trajectories" of photons using weak-measurements and showed that they were similar to those predicted by the de Broglie–Bohm theory [8]. However, despite various interpretations and experiments, photon behavior in double-slit experiments remains ambiguous.

We conducted an experiment to determine which slit of the double-slit the photon passes through using the characteristics of multimode optical fiber [9]. This apparatus was modified to measure the two-dimensional map of the moving direction of photons emitted from the double-slit. We found that the photons formed interference fringes while changing their direction of movement so that they gathered on the bright line of the interference fringes. We also found that photons proceed while intersecting, unlike the interpretation of the de Broglie–Bohm [10]. In this paper, we introduce the outline of the apparatus we have developed for observing photon behavior using an optical fiber, show at which position on the interference fringe the photon changes its direction, and report the change is related to the second derivative of the electric field.

2. Observation of photon movement

In the multimode optical fiber (numerical aperture = 0.22, diameter = 50μm) used in this experiment, light waves with various incident angles can propagate through the fiber, but light waves with different incident angles spread in different cone angles when exiting of the fiber. Figure 1 shows an apparatus for observing the movement of a light wave utilizing this characteristic of multimode fibers. Laser light (635nm, 1mW) passes through a polarizing plate (45° direction) and a double-slit (slit width = 20μm, interval = 100μm) and forms interference fringes. The interfering light waves are observed by the multimode optical fiber tilted to about 9° with respect to the optical axis of the laser. The light wave propagating through the fiber is detected by a charge coupled device (CCD). The circle shown in Fig. 1 is observed, and the radius of the circle changes when the incident angle is changed [10]. At the same time, when light waves are incident from two directions, double concentric circles are obtained. It has been confirmed that the angle of incidence and the radius of the circle are proportional [10]. Therefore, from the radius of the circle, the direction of the light wave (the direction of photon motion) at each measurement point can be measured. The obtained two-dimensional map of photon motion is shown in Fig. 2. In the previous paper [10], two vectors were displayed when two circles were observed, but in Fig. 2, only the vector with the maximum intensity is displayed (for details, see reference [10]). The interference fringes are formed while the vector direction gradually changes in direction along the bright line of the interference fringes.

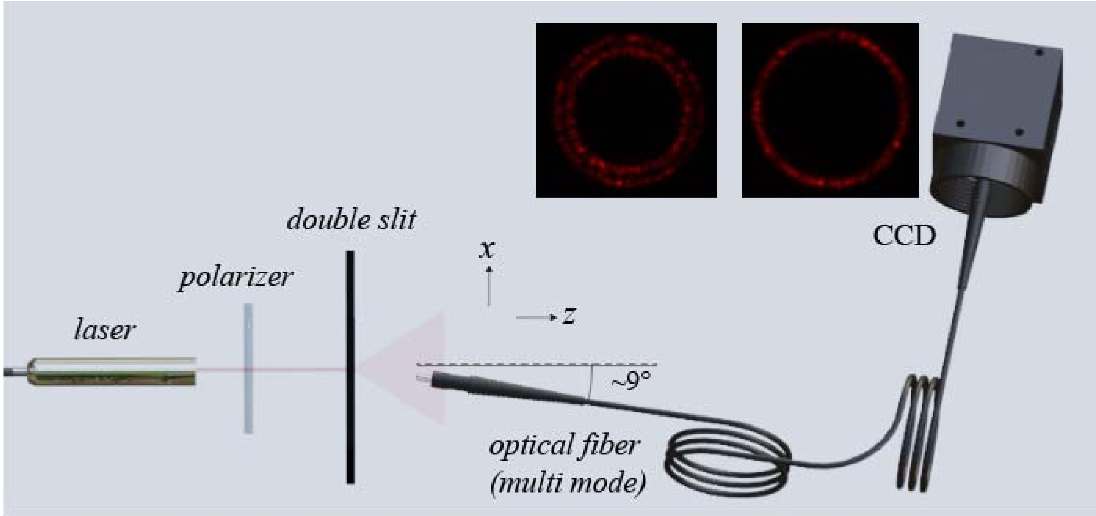

Fig. 1 Apparatus for observing photon motion using fiber. Laser beam (635nm) passes through a polarizing plate (45°) and a double-slit (slit width = 20μm, interval = 100μm) to form interference fringes. The interference light enters the optical fiber (inclination is 9°, diameter = 50μm) and is detected by the CCD placed at the tip. A motorized stage scans the optical fiber in the *x* and *z* directions to obtain a distribution of photon movement.

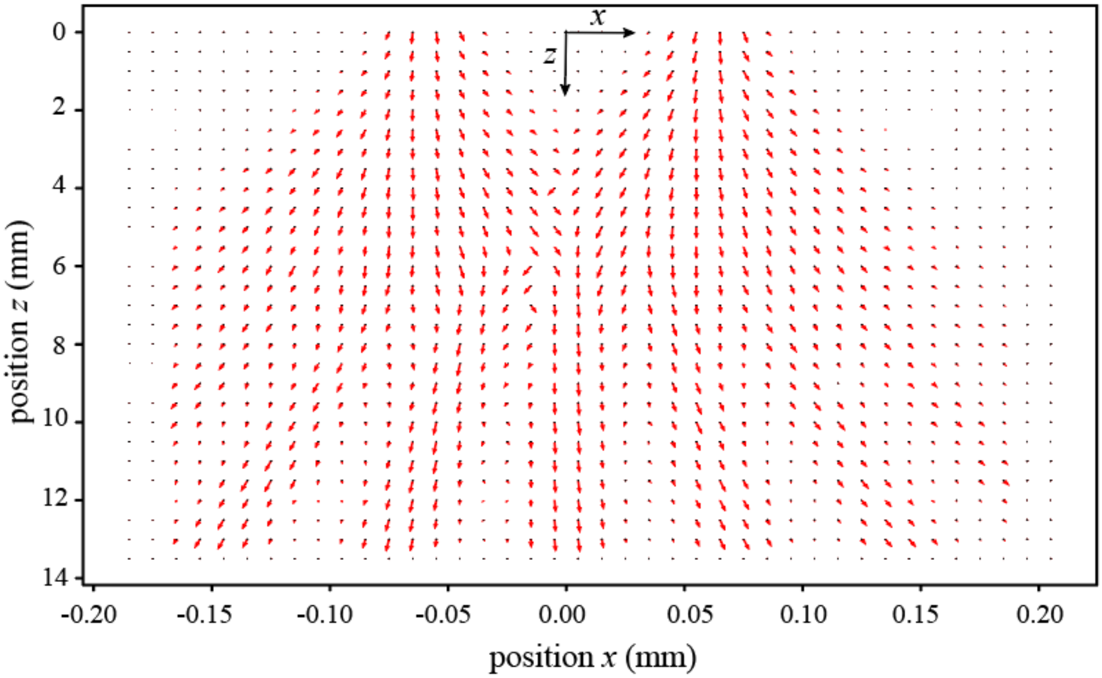

Fig. 2. Two-dimensional map of photon movement. When multiple vectors are measured, only the vector of maximum intensity is displayed. The length of the vector is normalized with data in each row.

3. Correlation between the change in photon motion and the electric field

Figure 3(a) shows a method of calculating the angle change $\Delta\theta$ of the vector. The intersections of the dotted line are the measurement points, Δx and Δz are the measurement intervals, and the vectors $\boldsymbol{V}_0$, $\boldsymbol{V}_\mathrm{A}$, and $\boldsymbol{V}_\mathrm{B}$ are the measured vectors. By extending $\boldsymbol{V}_0$, the intersection point P with the horizontal dotted line and the lengths a and b are obtained, and $\boldsymbol{V}_0'$ is calculated by the following equation:

$$2.\quad \boldsymbol{V}_0' = \frac{b\boldsymbol{V}_A + a\boldsymbol{V}_B}{a+b} \qquad (1)$$

The angle change $\Delta\theta$ is obtained using the following equation:

$$3.\quad \Delta\theta = \angle\boldsymbol{V}_0' - \angle\boldsymbol{V}_0 \qquad (2)$$

In Fig. 3(b), $\Delta\theta$ at each point is shown by the brightness of the red dot. They are concentrated in the area where the light waves emitted from both slits intersect (the upper center of Fig. 3(b)) and in the vicinity of the dark line of the interference fringes.

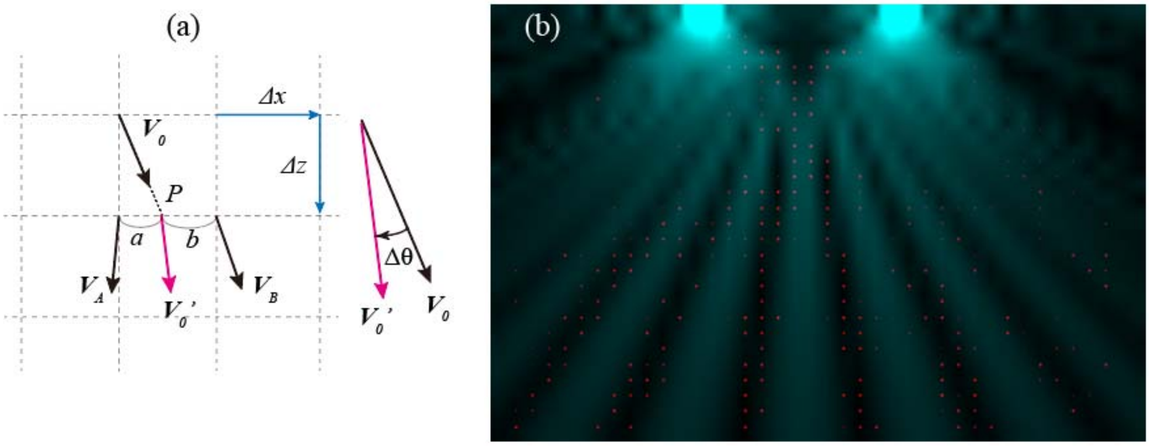

Fig. 3. Angle change of photon motion. (a) Method of calculating angle change $\Delta\theta$ using measured vectors $\boldsymbol{V}_0$, $\boldsymbol{V}_\mathrm{A}$, and $\boldsymbol{V}_\mathrm{B}$ (Δx and Δz are measurement intervals).
(b) Two-dimensional distribution of $\Delta\theta$ (indicated by red dots).

Figure 4 shows the correlation between the angle θ of the vector and the angle change $\Delta\theta$ at each point. Since the maximum error of the angle measurement in this experiment is 0.0053rad, only the data in which $\Delta\theta$ is 0.0050rad (about 0.28°) or more is used. The measurement points that satisfy this condition are the red dots near the center bright line in Fig. 3(b). Further discussion will be limited to this area. Angle θ exists continuously in the range of −0.03 to 0.03rad (−1.72° to 1.72°), and when θ is positive (negative), $\Delta\theta$ is always negative (positive), which means that the photon changes its direction of motion so that it bends inward. The line linearized by the least-squares method in Fig. 4 was obtained using the following equation:

4. $$\Delta\theta \approx -0.90\theta \tag{3}$$

This equation shows that $\Delta\theta$ is uniquely determined by θ. Considering θ □ π ,

5. $$\frac{\theta}{\theta+\Delta\theta} \approx \frac{\sin\theta}{\sin(\theta+\Delta\theta)} \approx 10 \ . \tag{4}$$

This is equivalent to the refraction of light incident on the interface with a refractive index ratio of 10. The angular displacement according to Eq. (4) occurs near the dark lines of the interference fringes, as shown in Fig. 3(b), but at many other positions, the photons travel in a straight line.

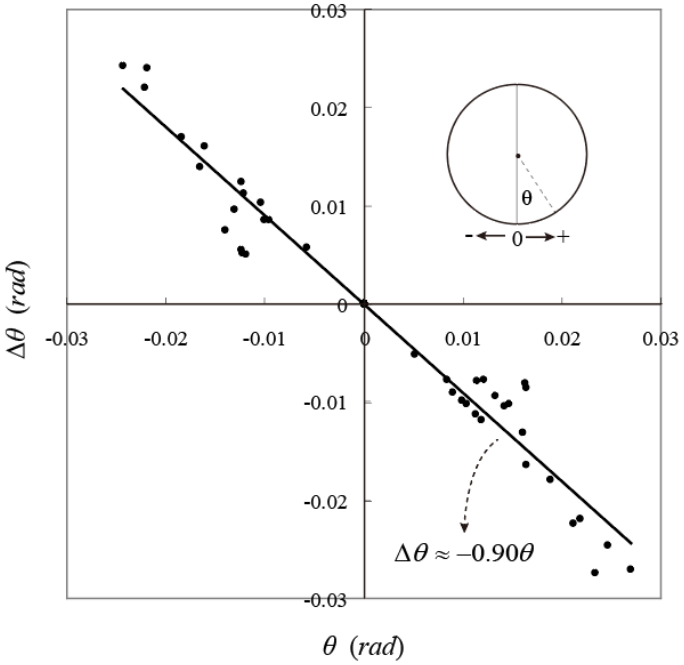

Fig. 4 Correlation between the moving direction θ of the photon and the angle change $\Delta\theta$ (only $|\Delta\theta| > 0.005$rad is displayed).

Next, the relationship between the angle change $\Delta\theta$ and the electric field ***E*** will be considered. Figure 5 shows the correlation between the second derivative of the electric field in the x-direction and $\Delta\theta$. The data points are the same as those used in Fig. 4. The derivative of the electric field is obtained using the calculated numerical value of the electric field at each measurement point x and $x \pm dx = x \pm 0.1\mu$m. Figure 4 shows that the absolute value of the second derivative of the electric field divided by the electric field is proportional to $\Delta\theta$. If we let C_1 and C_2 be the proportional coefficients for $\Delta\theta>0$ and $\Delta\theta<0$, respectively,

$$|\Delta\theta| \approx \frac{|C_1|+|C_2|}{2}\left|\frac{1}{E}\frac{\partial^2 E}{\partial x^2}\right| = C\left|\frac{1}{E}\frac{\partial^2 E}{\partial x^2}\right| \quad . \tag{5}$$

By substituting Eq. (5) into Eq. (3), we obtain:

$$\left|\Delta\theta\right| = \left|0.9\theta\right| \approx C\left|\frac{1}{E}\frac{\partial^2 E}{\partial x^2}\right| \tag{6}$$

Equation (6) represents a conditional expression that changes the motion of photons moving in the θ direction. At the position where this condition holds, the photon changes its direction; otherwise, the photon travels in a straight line.

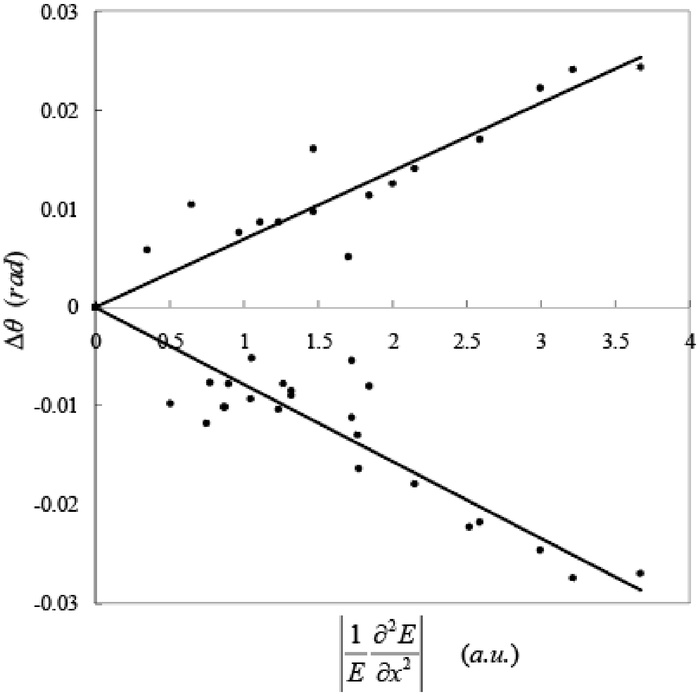

Fig. 5. Correlation between the second derivative of the electric field and the angle change $\Delta\theta$ (the data of $|\Delta\theta| > 0.005$rad is displayed).

We experimentally showed in the previous paper [9] that particle and wave properties are independent, but how photons change their direction of motion in the process of forming interference fringes remained uncertain. From the results of this experiment, it seems that the photons emitted from the slit travel straight in the interfering electric field and change their direction at the position where the condition of Eq. (6) is satisfied.

The change $\Delta\theta$ on the left side of Eq. (6) corresponds to the time variation in the velocity vector of the photon. If we consider the right side of Eq. (6) as "*force*", we can say that Eq. (6) corresponds to "*photon's motion equation*". Further, since the direction of the wave-vector and the electric field are always orthogonal to each other, $\Delta\theta$ also corresponds to the time variation in the electric field. A link with Maxwell's equation is suggested. Further study of Eq. (6) will also be necessary.

In this experiment, only the motion of photons near the center of the interference fringes was examined. This is because there is a limit to the accuracy of angle measurement using a multimode optical fiber. We plan to improve the measurement accuracy (considering the convolution integral etc.) and verify Eq. (6)'s applicability to a wide area.

REFERENCES

[1] W. Rueckner, "A lecture demonstration of single photon interference", Am. J. Phys. **64**, 184 (1996).

[2] R. Shankar, *Principles of Quantum Mechanics* , Springer (1994).

[3] F. Giacosa, "On Unitary Evolution and Collapse in Quantum Mechanics", Quanta. **3**, 156(2014).

[4] D. Bohm, "A Suggested Interpretation of the Quantum Theory in Terms "Hidden" Variables. I", Phys. Rev. **85**, 166(1952).

[5] D. Bohm, "A Suggested Interpretation of the Quantum Theory in Terms of "Hidden" Variables. II", Phys. Rev. **85**, 180(1952).

[6] C.R. Leavens, "Timing quantum particles from the perspective of Bohmian mechanics" Superlattices Microstruct. **23**, 795(1998).

[7] D. Bohm, B. J. Hiley and P. N. Kaloyerou, "An ontological basis for the Quantum theory", Phys. Reports **144**, 321 (1987).

[8] S. Kocsis, B. Braverman, S. Ravets, M. J. Stevens, R. P. Mirin, L. K. Shalm, A. M. Steinberg, ”Observing the Average Trajectories of Single Photons in a Two-Slit Interferometer”, Science **332**, 1170(2011).

[9] K. Sakai, “Simultaneous measurement of wave and particle properties using modified Young's double-slit experiment”, Journal for Foundations and Applications of Physics **5**, 49 (2018).

[10] K. Sakai, “Observation of photon movement near Young’s double-slit”, Journal for Foundations and Applications of Physics **7**, 1 (2020).