Simultaneous measurement of wave and particle properties using modified Young's double-slit experiment

Kazufumi Sakai

TPORD(Optical Science)
Hoei-Haitu 1-11, Yabu-machi 74-11
Tosu-city, SAGA 841-0055 JAPAN

ksakai@phj.sakura.ne.jp

Abstract

The principle of complementarity is the foundation of quantum mechanics; its correctness has been verified by several studies. At present, the Englert – Greenberger duality relation is used for quantitative evaluations. We fabricated a new double slit experimental apparatus capable of simultaneously measuring the visibility and path-distinguishability, and measured the wave and particle properties. We thus obtained results in disagreement with the principle of complementarity.

Keywords: *complementarity. wave-particle properties, Interferometer, double slit*

1. Introduction

The principle of complementarity in Bohr's quantum mechanics states that a quantum system has particle and wave characteristics that are mutually exclusive[1]. It is famous due to the controversy over complementarity between Einstein and Bohr in the late 1920s. Furthermore, in February 1963, Feynman stated, "*No one has ever found a way around the uncertainty principle.*"[2] Many recent studies have focused on the question of whether the principle of complementarity is based on the uncertainty principle[3-6], and whether the view that the core of quantum mechanics is the principle of complementarity is correct. These are based on numerical evaluations of the Englert–Greenberger duality relation,

$$V^2 + D^2 \leq 1 \qquad (1)$$

where V is the visibility, which represents wave behavior, and D is the path-distinguishability, which represents particle behavior[7].

In recent years, Afshar[8,9] reported results disagreeing with the principle of complementarity using a double-slit interference experiment with thin wires. After a profound debate[10-14], various problems were pointed out and it was concluded that the principle of complementarity was satisfied. Experiments of this type require that (i) the wave property (interference) and the path information can be measured simultaneously, and (ii) the path information is uniquely determined from the beginning to the end within a series of experimental systems.

In this paper, we report a method to simultaneously measure the photon momentum and the interference intensity using an optical fiber-based device and its measurement results.

2. Experiments and results

A modified double-slit interferometer is shown in Fig. 1. Light emitted from the semiconductor laser (635 nm) is polarized in the direction of 45° by the Glan–Thompson polarizer-1 and is incident on a double slit (spacing = 400 μm, slit width = 20 μm). Polarizing plates in the horizontal and the vertical directions are attached to each slit of the double slit. The light waves diffracted by the double slit are separated into two paths according to their respective polarization directions by the Wollaston prism, and are incident on the cylindrical lens after passing through polarizer-2, polarized in the 45° direction. The distance between the light waves on the cylindrical lens is about 15 mm. The two light waves (path-A, path-B) overlap at a position about 250 mm from the cylindrical lens and produce interference fringes. The angle between path-A and path-B shown in Fig. 1 is about 3.5°. The interference fringes imaged by the CCD are shown in Fig. 2 (a laser of about 1 mW was used for the observation of these fringes). Since the phase difference is included in the two light waves (normal light and extraordinary light) emitted from the Wollaston prism, phase compensation is performed by rotating the cylindrical lens by

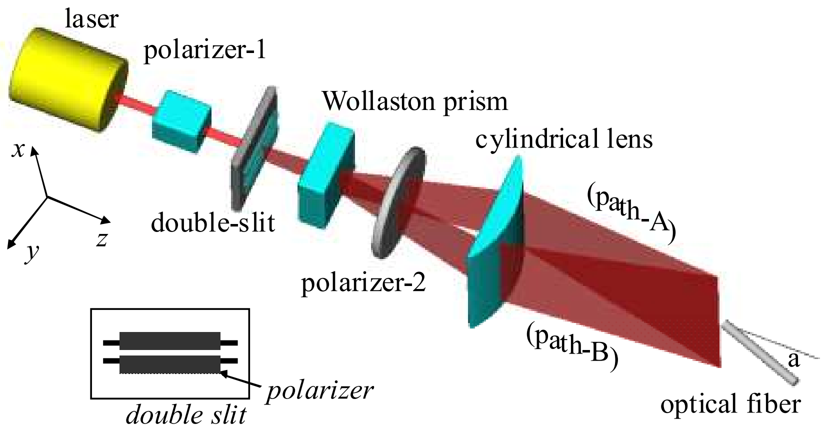

Fig. 1. Modified double-slit interferometer. Polarizing plates in the x- and the y-directions are attached to each slit of the double slit. Polarizers-1 and -2 are oriented at 45°. The optical fiber is on the yz-plane and is inclined at about 6° (denoted by "a") from the z-axis.

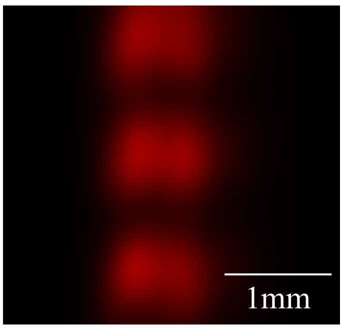

Fig. 2. Interference image obtained by placing a CCD at a location where path-A and path-B overlap.

about 10°. The interference fringe caused by the overlapping of path-A and path-B is measured by moving the optical fiber (NA = 0.22, core diameter = 50 μm), tilted by about 6° ("a" in Fig. 1). The light emitted from the optical fiber is amplified by the image intensifier, and its image is imaged by the CCD camera (IM-CCD image). Since the optical fiber is tilted, the incident angles of path-A and path-B waves are different (that is, the directions of the momenta of the photons are different). Therefore, the light emitted from the fiber forms an image of concentric circles of different radii. Fig. 3 (A) is an image of a concentric circle when both slits are opened, and Figs. 3 (B) and 3 (C) are images for when only path-A and path-B are incident, respectively. Figure 4 shows the interference intensity distribution obtained by moving the optical fiber in the x-direction (spacing = 20 μm). An interference intensity distribution similar to that of the interference fringe of Fig. 2 was obtained. It should be noted that similar experiments are possible using polarizing beam splitters instead of Wollaston prisms to separate them into path-A and path-B.

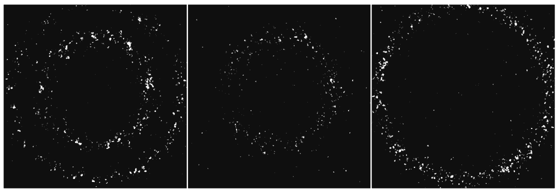

Fig. 3. (A) IM-CCD image of the light wave emitted from the fiber when path-A and path-B are opened, (B) and (C) are images when only either path-A or path-B is opened.

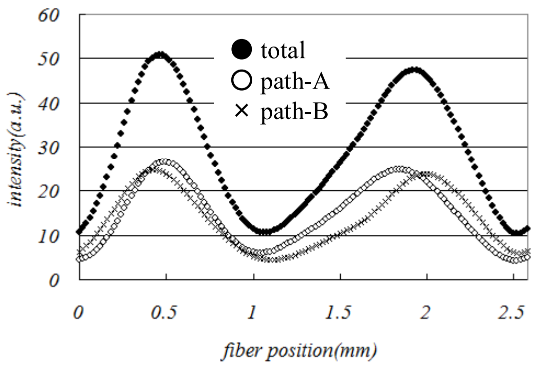

Fig. 4. Intensity distribution of the interference fringe obtained from intensity of the IM-CCD image on the fiber exit surface. The total intensity and the intensity distribution of each circle (path-A, path-B) are shown.

3. Measurement of wave and particle properties

In Fig. 1, the light wave emitted from the double slit has which-path information obtained from its polarization, but since the polarization direction is limited to 45° by polarizer-2, the path information is lost, and the interference fringes by path-A and path-B are recovered on the plane where these paths overlap. This is the same procedure as in the simple quantum eraser[15] experiment. In this experiment, path information in the polarization direction is lost, but it is obtained from the difference between the momentum vectors of path-A and path-B. Since the light wave incident on the fiber undergoes repeated reflections at the incident angle and is emitted from the fiber end, the angle of the emitted light depends on the incident angle, i.e., the outgoing angle corresponds to the momentum of the incident wave. Because the optical fiber is tilted, path-A has a smaller incident angle than path-B, and the outgoing light forms a circle with a smaller radius (see Fig. 3(B)). Therefore, circles with small radii correspond to path-A and large circles correspond to path-B. By using the conservation of momentum, we can know which path (A or B) the photon passed through, and then we can decide which slit the photon passed through.

When an image conduit (a bundle of fibers for image transfer bundling 12 μm fibers) is placed on the surface where path-A and path-B overlap, interference fringes similar to the incident surface are also observed on its output surface. The image conduit is composed of a large number of fibers, and it is understood that the energy (photon transmission) received by each fiber is propagated to the exit surface while preserving its position. The probability density on the surface of the image conduit propagates to the rear surface and observations similar to those for the screen used in the general double-slit interference experiment can be performed. In this way, interference fringes can be obtained from the intensity of the IM-CCD image at each point, and the which-path information can be obtained from the radius of the IM-CCD image, enabling the simultaneous measurement of wave and particle-like properties.

In the interpretation of quantum mechanics, it is widely known that it is impossible to simultaneously measure the wave behavior and particle property (momentum) in Young's double-slit experiment by the uncertainty principle (or complementarity). However, in recent years, the observation of the trajectory of a photon using weak measurements[16] (measurements of the positions and momenta of the photons) have been reported[17], and the uncertainty principle is attracting attention. In our experiment, the slit width Δx and the momentum uncertainty Δp_x are the same as in the previous experiments, and it is impossible to evaluate the wave motion and momentum at same time.

$$\Delta x \Delta p_x \geq h \qquad (2)$$

Therefore, we use the momentum in the y-direction to measure the particle-like properties.

$$\Delta y \Delta p_y \geq h \qquad (3)$$

Since Δy is large, Δp_y is small, and the momentum in the y-direction can be used for the measurement of the particle property. From Figs. 3 and 4, distinguishability $D \approx 0.9$ and visibility $V \approx 0.7$ are obtained, which does not satisfy eq. (1).

4. Conclusion

The modified double-slit interferometer succeeded in the simultaneous measurement of light wave and particle properties. The obtained visibility and distinguishability values did not satisfy the Englert–Greenberger duality relation. Complementarity is the fundamental principle of quantum mechanics, and thus a new interpretation of this experiment is necessary.

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