Interference fringes caused by beams narrower than the fringe spacing

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Abstract
The interference of light has not only contributed to our understanding of natural laws, but it has also been used as a crucial foundational technology supporting modern industry. Both fundamental and applied aspects are being actively researched on interference. We've made an optical element that consists of a half-mirror and a mirror with an adjustable relative angle, and we're studying the fundamental characteristics of interference fringes. The fringe spacing can be altered by adjusting their relative angle. When light is incident on this device, numerous bright and dark lines appear, similar to thin-film interference or interference fringes of equal thickness. This report describes how the interference pattern and light intensity change as the width of the incident light beam is narrowed below the fringe spacing.

Keywords: interference fringes, fringe spacing, narrow beam, light intensity

1. Introduction

Since Young's double-slit experiment[1,2] demonstrated that light is a wave, interference effects have been used in discussions about the nature of matter[3,4]. Recently, interference experiments using atomic-scale slits[5] have been conducted, confirming the validity of quantum mechanics. Furthermore, interference effects are widely utilized in practical applications[6,7], making them one of the essential physical phenomena for modern industry. We are conducting fundamental research on optical interference [8-10]. In the present study, we made a device that allows the fringe spacing of interference patterns to be freely adjusted by stacking a mirror and a half-mirror and adjusting their relative angle. The changes in interference fringes when light beams of various widths are irradiated onto this device are being observed.

This paper reports on the observed interference fringes and changes in the total intensity of the interference light when light with a beam width narrower than the fringe spacing is irradiated. Figure 1 shows a schematic diagram of interference fringes when the incident beam width is varied. As shown in Fig. 1(a), when a uniform, wide beam is incident, numerous fringes are observed, and the average optical intensity is given by the average of the intensities of the bright and dark lines. Figure 1(b) is a schematic diagram showing a portion cut from the original fringes when the incident beam width is narrowed. In the experiment, a slit was used to narrow the beam width. Therefore, it is expected that diffraction waves generated at both ends of the slit will overlap with the interference waves, resulting in a complex image. A and B in Fig. 1(b) are schematic diagrams showing the positions of bright and dark lines when beams of the same width are incident at the positions. If the incident light is uniform, the total light intensity will be the same at A and B. Therefore, it is expected that the distribution of light will change such that the total intensity of light at points A and B matches due to the effects of diffraction. Consequently, it is anticipated that if a beam narrower than the fringe spacing is incident onto the interference device and this beam is scanned laterally, the interference fringes will disappear, yielding a uniform intensity distribution. To verify these predictions, the experimental apparatus shown below was constructed, and observations of the interference image and measurements of the intensity of the interference light were performed.

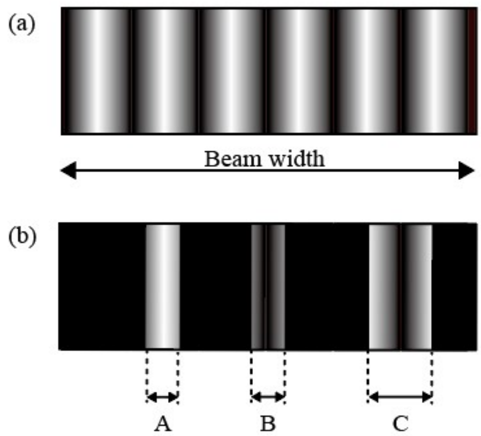

Fig. 1 Schematic diagrams of interference fringes for a wide incident beam (a) and a narrow incident beam (b) (diffraction effects are ignored). A and B are cropped images of (a) when the beam strikes the positions of the bright and dark lines. If the incident beam intensities are equal, the total light intensity at A and B must be equal.

2. Experiments and Results

Figure 2 shows the experimental apparatus. Laser light (532 nm, 2 mW) is expanded vertically by a cylindrical lens, passes through a variable slit, and is emitted after multiple reflections by a half-mirror (HM) and a mirror (M2). The position of the variable slit is controlled by a motorized stage placed beneath it. The fringe spacing is adjusted by the relative angle between the fixed HM and the angle-adjustable M2. The multiple-reflected light wave passes through a surfactant solution, and the scattered light is captured by a CCD camera to observe the interference pattern. The resulting interference fringes are shown in Fig. 3. Figures 3(a-1) and (a-2) show interference fringes obtained by varying the relative angle between HM and M2. As the relative angle narrows, the fringe spacing widens, as seen in (a-2). Figures 3(b-1), (b-2) and (b-3) show interference fringes as the slit width is gradually narrowed. Even when narrowing the width of the incident beam, no significant change is observed in the interference image. By adjusting the width of the incident beam, it is possible to isolate only one bright fringe of the interference pattern, as shown in Fig. 3(b-3). Light passing through the aqueous solution is focused by a 25 mm diameter lens and incident onto a photodetector (PD), where the total light intensity is measured. Figure 4(a) shows the simulated diffraction pattern (excluding interference from multiple reflections) at the PD position when the incident beam width is 0.3 mm. It can be seen that the lens diameter is sufficiently large compared to the spread of the diffraction wave. Figure 4(b) shows the vertical intensity distribution of the incident beam. Although asymmetrical, the difference between the maximum and minimum values within the scanning area used in the experiment (approximately 2 mm) is within 3%.

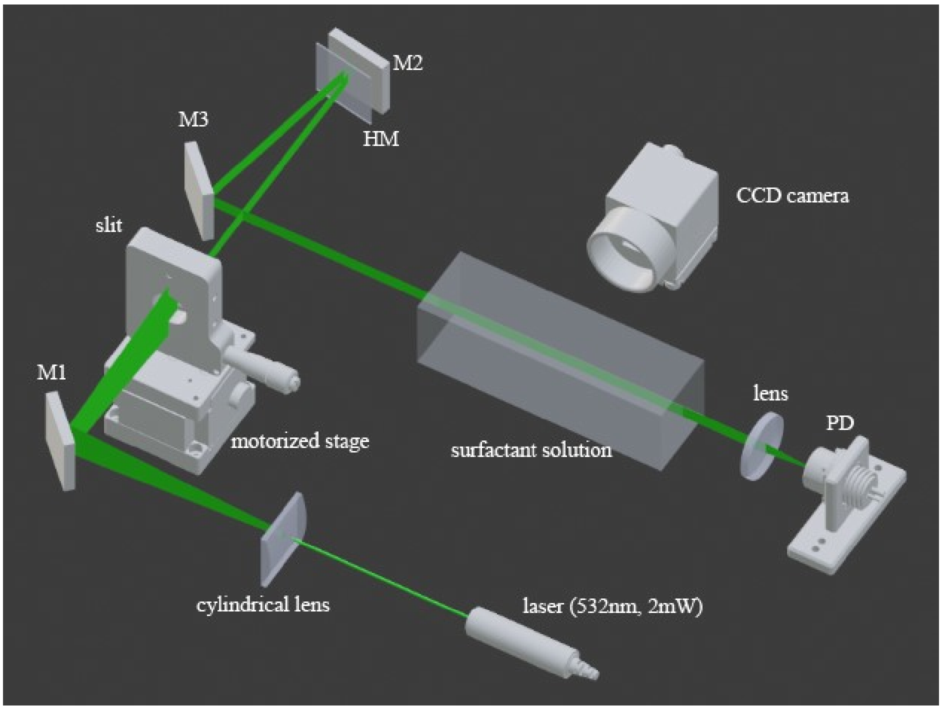

Fig.2 Schematic diagram of the experimental apparatus. Laser light (532 nm, 2 mW) is expanded vertically by the cylindrical lens, passes through the variable slit, and is incident onto the half-mirror (HM) and the mirror (M2). The HM was fixed, and the angle of M2 was adjusted to change the relative angle. Light undergoing multiple reflections between the HM and M2 passes through the surfactant solution, is focused by the lens, and the total light intensity is measured by the photodetector (PD). Light scattered in the aqueous solution was imaged by the CCD to obtain the interference patterns. The motorized stage was used to move the variable slit vertically.

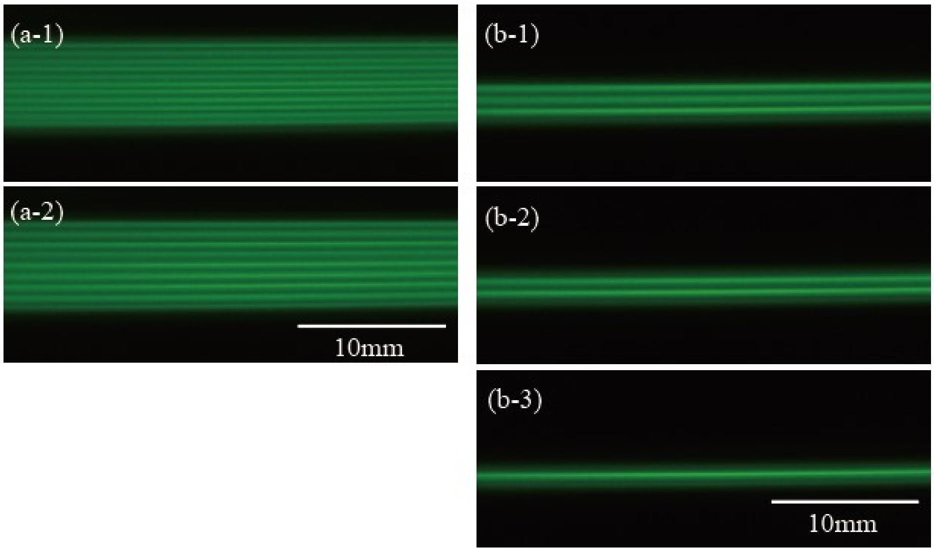

Fig.3 Interference patterns obtained by CCD. (a-1) and (a-2) are interference patterns when the relative angle between HM and M2 is varied. When the relative angle is small, the fringe spacing widens, as seen in (a-2). (b-1), (b-2) and (b-3) are interference fringes obtained by fixing the lower edge of the variable slit and moving its upper edge to gradually narrow the slit width. As seen in (b-3), it is possible to isolate a single bright line. Even when narrowing the width of the incident beam, no significant change is observed in the interference image.

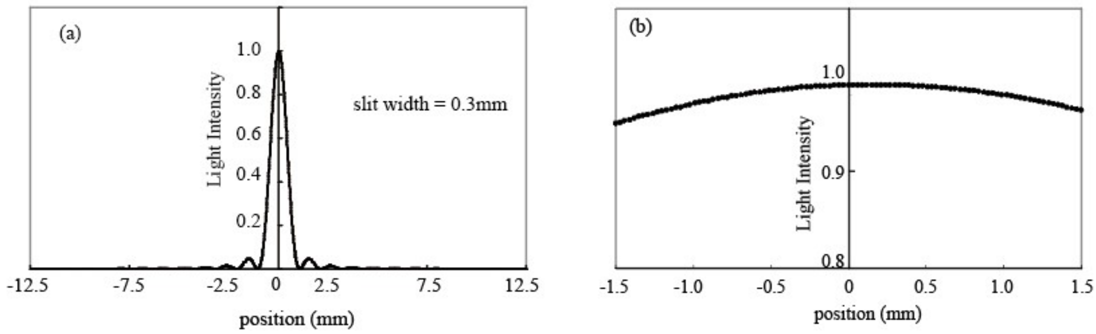

Fig.4 Simulation of the diffraction pattern at the PD position for the slit width of 0.3 mm (a). The lens diameter is 25 mm. It can be seen that the spread of the diffraction waves caused by the slit is sufficiently small compared to the lens diameter. (b) shows the vertical intensity profile of the incident beam. The region used for measurement is within ±1 mm from the center. Although asymmetrical, the difference between the maximum and minimum values in the measurement region is less than 3%.

Figure 5 shows the results of scanning the incident light with the fixed slit width. Figures 5(a) and (b) display the CCD image of the scanned interference fringes and the intensity profile along the scanning direction, respectively. The fringe spacing is approximately 0.6 mm. The approximately 2 mm width was scanned from bottom to top at 0.05 mm intervals. Figures 5(c) and (d) show the total light intensity obtained by PD for incident beam widths of 0.6 mm and 0.3 mm, respectively (values are averages of 10 measurements). When the beam width was 0.6 mm (roughly equal to the fringe spacing), the light intensity was randomly distributed around a value of approximately 50 μW. No correlation with the interference pattern was observed. In the case of the beam width of 0.3 mm (approximately half the fringe spacing), interference fringes similar to those in Figure 5(b) appeared.

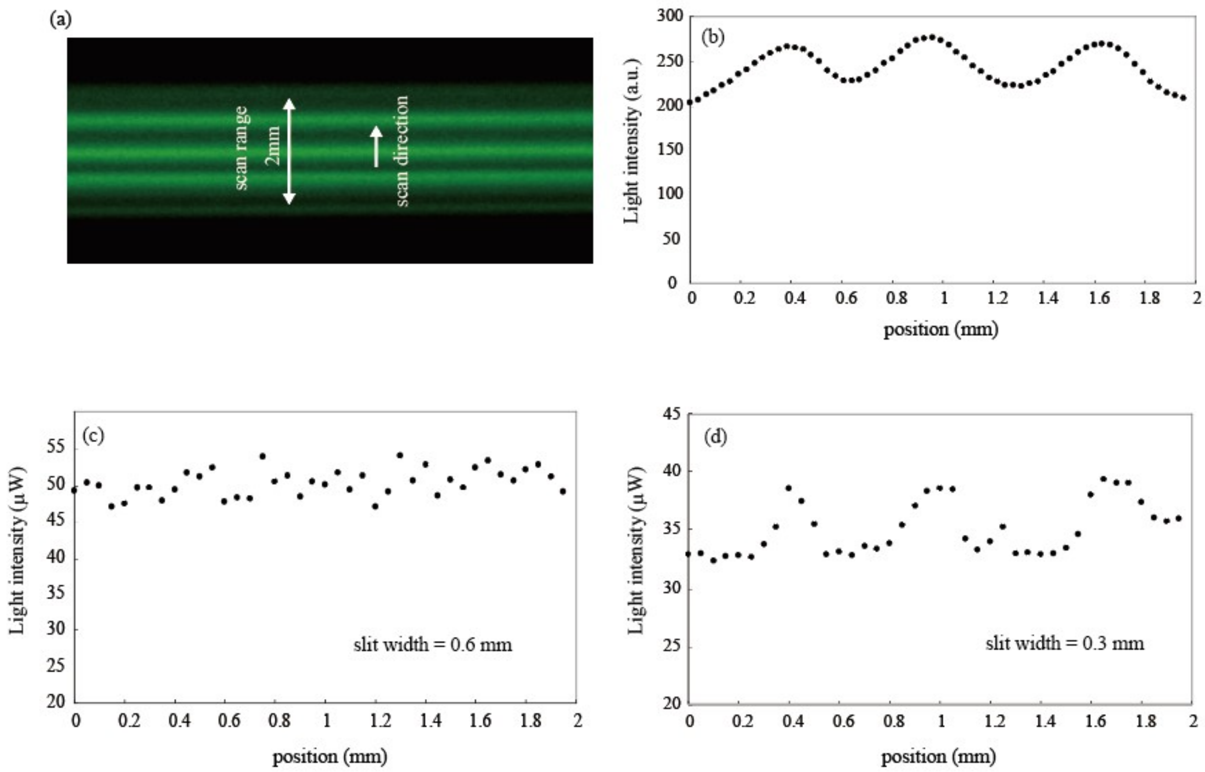

Fig.5 Measurements of total light intensity when scanning incident light with the fixed slit width. (a) and (b) show the CCD image of the scanned interference fringes and the intensity profile in the scanning direction, respectively. The fringe spacing is approximately 0.6 mm, and the measurement area is approximately 2 mm, scanned from bottom to top at 0.05 mm intervals. (c) and (d) show the change in total light intensity obtained by PD for incident beam widths of 0.6 mm and 0.3 mm, respectively (values are averages of 10 measurements).

3 . Conclusion

As shown in Fig. 5(c), when the incident beam width is nearly equal to the fringe spacing, one full cycle of interference fringes is integrated, so the detected light intensity remains nearly constant. Conversely, interference effects were observed when the incident beam width was narrower than the fringe spacing. As seen in Fig. 4(b), the incident light intensity is nearly constant, so we expected the output light to be nearly constant as well. However, we obtained the distribution similar to the interference fringe profile. This result contradicts our initial expectations, but the reasons remain unclear. We plan to continue our investigation.

References

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