Surprising Results from Experiments of a Longitudinally Separated Slit

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For the first time, the paper reports the experimental results of a longitudinal separated single slit. The asymmetric diffraction pattern in the experiments cannot be explained by either the wave theory of light or quantum electrodynamics, and thus calls for a theoretical breakthrough. The paper also upgrades the slit diffraction formula to include the longitudinal separation distance and the formula fits the experimental data well. However, the absolute value of the fitted parameter differs for the left and right fringe patterns and for different experimental setting, suggesting potential role of factors other than slit width, light frequency, and longitudinal separation.

1 Introduction

The studies on light diffraction and interference have a long history and have dramatic impact on our understanding of the nature of light. The effect of light diffraction were carefully observed by Francesco Grimaldi before 1660 [1]. Christiaan Huygens studied diffraction phenomenon in great details and established his wave theory of light [2] which, however, was suppressed by Newton's corpuscles theory of light [3]. The famous double-slit experiment of Thomas Young [4] reinvigorated Huygens' theory and Fresnel [5, 6] did further experimental studies and landed support for the wave theory of light. Later, the wave theory was again challenged by Einstein [7], who showed the particle nature of light. Eventually, Bohr [8] and de Broglie [9] suggested the wave-particle duality for light and for mass particles. With the ascendance of quantum mechanics, Feynman [10] invented the path integral method which was applied to study the quantum nature of light diffraction and interference. Now the quantum theory is used to explain not only the diffraction and interference of light but also of massive particles such as electrons, photoelectrons, neutrons, atoms and molecules [11–22].

It seems that the experiments of light diffraction from slits have examined all possible factors such as slit widths, light frequencies, slit shapes, and the number of slits, but all experiments so far have adhered strictly to the traditional definition of a slit: the closely placed barriers to restrict the passage of light or particles. This paper reports on an innovative single slit experiment that breaks the definition of slit. In the experiment, the barriers of a traditional slit are broken into two to form two half slits which can be placed at different positions along the light propagation direction.

2 Predictions from existing theories

Before we proceed to the experiments, we briefly discuss the expected experimental results based on the currently main theories related to light diffraction: the wave theory of light and the quantum electrodynamics. The diffraction patterns predicted by the wave theory of light is illustrated in Fig. 1.

When a laser beam hits the half-slit A, the wave theory

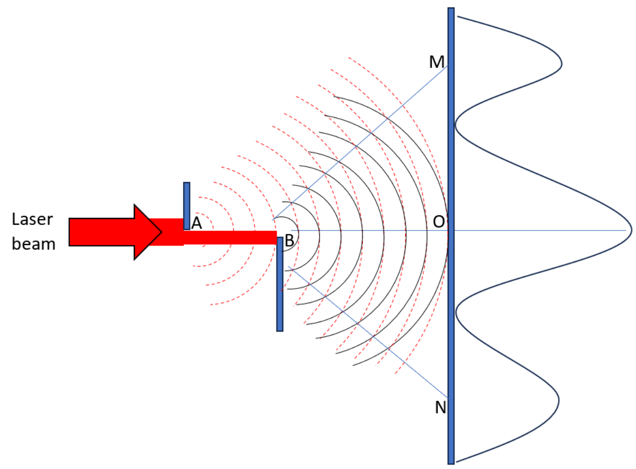


Fig. 1: Wave explanation of light diffraction from a longitudinally separated slit.

suggests that the diffraction occurs because the light at A acts as a point source of light waves illustrated by the spherical red dashed curves (the diffraction angle is exaggerated for clearer illustration). Similarly, the light at half slit B acts as a point source of light waves shown as the solid black curves. Since the light waves from both A and B interfere with each other, the interference pattern will form at the observer plane MN. Due to the nature of spherical wave propagation, the interference pattern on the observing plane should be symmetric, i.e. OM=ON, a result similar to the normal single slit interference pattern.

In the above discussion considering only two wave sources at point A and B, it may be argued that this is an oversimplification because Huygens' principle indicates that light at any point between A and B can act as a source of light waves. With the aid of Fig. 2, we can show that using n wave sources give the same result.

In a traditional way we use the n coherent oscillators to indicate n wave sources. In a traditional slit A_0B, n oscillators are evenly positioned on the dashed line between A_0 and B.

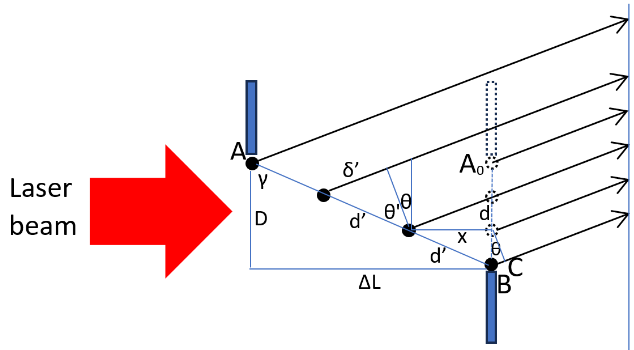


Fig. 2: Wavelets explanation of light diffraction from a longitudinally separated slit.

A textbook derivation (e.g. [23]) gives the following intensity of the diffraction pattern at the observer plane:

$$I = I_0 \frac{\sin^2(N\delta/2)}{\sin^2(\delta/2)} \tag{1}$$

where I and I_0 are light intensity at the observer plane and at the source respectively; $\delta = kd \sin\theta$ is the phase difference of neighbouring coherent oscillators, k the wave vector, and θ the diffraction angle; $d \sin\theta$ is the length difference of neighbouring propagation paths, as shown as BC in Fig. 2. The principal maxima of the fringes occur at $\delta = kd \sin\theta = 2m\pi$, where $m = 0, \pm1, \pm2, \ldots$. This gives the diffraction formula:

$$d \sin\theta = m\lambda\,. \tag{2}$$

In the case of longitudinally separated slit AB, the n wave sources should be equally positioned between A and B. As shown in Fig. 2, the phase difference of neighbouring coherent oscillators δ should be calculated as $\delta' = kd' \sin\theta'$, with $d' = \sqrt{x^2 + d^2}$. We can also add a fixed initial phase difference ϕ between neighbouring oscillators and upgrade δ' to $\delta' = kd' \sin\theta' + \phi$. One may worry about applying to the current case the wave amplitude approximation used in the traditional derivation. As the longitudinal separation between A and B is much smaller than their distance to the observer plane, the longitudinal separation hardly affects the light intensity at the observer plane and the approximation condition for deriving the diffraction pattern holds.

For the setting shown in Fig. 2, half-slit A is at the left of half-slit B, we have $\Delta L < 0, \gamma < 0$, and $\theta' < 0$, so we can relate the diffraction angle θ to θ' by:

$$\theta = -(\gamma - \theta') = \arctan(\Delta L/D) + \theta'\,. \tag{3}$$

As such, the traditional derivation should give the same formula as (1). The only difference is that we need replace δ with δ'. Consequently, the diffraction formula for the longitudinal separated slit should be: $kd' \sin\theta' + \phi = 2m\pi$, or $d' \sin\theta' = (m - \phi/2\pi)\lambda$. Solving for θ' and substituting into (3), we have:

$$\theta = -(\gamma - \theta') = \arctan(\Delta L/D) + \arcsin[(m - \phi/2\pi)\lambda/d']\,. \tag{4}$$

From this formula, it is apparent that the width of fringes indicated by θ is different from that in (2), but the fringe width should be almost equally spaced just as in the case of normal single slit.

The wave-theory explanation of knife-edge diffraction is also relevant here but it is unable to predict the pattern diffraction from a longitudinally separated slit. Based on Fresnel's integrals and Kirchoff's scalar diffraction theory, Sommerfeld [24, 25] provided a rigorous solution to knife edge diffraction pattern, which explained the fringe pattern of diffraction on the unrestricted side of a knife edge and the decay of the diffracted light intensity (with no fringe) in the shadow area. While the energy losses in the shadow areas due to single and multiple knife-edge diffraction are intensively studied and modelled, so far there is no study on the diffraction pattern from knife edges that are placed on opposite sides. An apparent reason is that the diffraction pattern in Summerfeld's solution is hard to be generalized to oppositely placed knife edges.

The explanation from quantum electrodynamics (QED) also gives rise to a symmetric diffraction pattern for longitudinally separated slits. In the view of QED, the single-slit diffraction pattern results from the momentum distribution of the diffracted particles, and the probability of the momentum distribution can be calculated by the square of amplitudes of momentum-space wavefunction [26–29]. When a photon passes through a slit, the real-space wavefunction of the photon is constrained by the slit width. A Fourier transformation of the constrained real-space wavefunction into the momentum-space wavefunction gives the probability amplitude and thus the diffraction pattern.

The real-space wave function can be expressed as [28]:

$$\Psi(y, w) = \begin{pmatrix} 1/\sqrt{w}\,, & \text{for } -w/2 \le y \le w/2 \\ 0\,, & \text{otherwise} \end{pmatrix}$$

where w is the transverse width of the slit, y the transverse distance from the centre of the slit.

A Fourier transform of this wave function into the momentum space gives the following momentum wave function:

$$\Phi(p_y, w) = \int_{-w/2}^{w/2} \frac{1}{\sqrt{2\pi\hbar}} \exp\left(-\frac{ip_y y}{\hbar}\right) \frac{1}{\sqrt{w}}\, dy = \sqrt{\frac{2\hbar}{\pi w}}\, \frac{\sin\frac{p_y w}{2\hbar}}{p_y}\,.$$

The diffraction pattern is given by the square of the amplitude of the momentum wave function $|\Phi(p_y, w)|^2$. Apparently, the fringe minimals occur at $\frac{p_y w}{2\hbar} = \pm n\pi$. This gives a symmetric pattern for both sides of the central maximum. It has

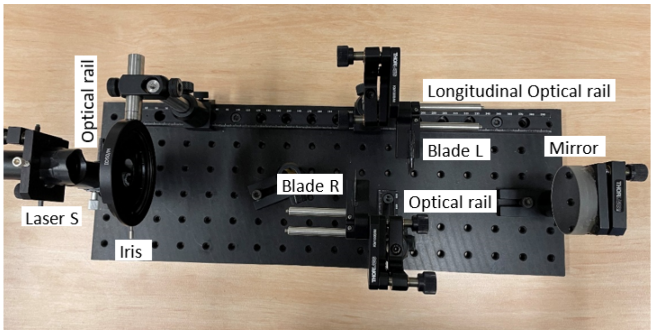


Fig. 3: Experimental setup.

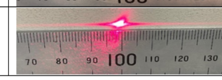
Scenario	Position of Blade L (mm)	Position of Blade R (mm)	Longitude Separation (mm)	Fringe patterns
1	160	200	-40	
2	190	200	-10	
3	200	200	0	
4	213	200	13	
5	220	200	20	
6	N/A	200	N/A	

Table 1: Selected experiment measurement.

been showed that Feynman's path integral method also gives the same results [26, 30, 31].

Since our longitudinally separated slit maintains the same transverse slit width w, the constraint on the real-space wavefunction (as well as on Feynman path integral) is unchanged, so the wave function in both real and momentum space should be the same as those for a traditional single slit. Consequently, a QED explanation should also give a symmetric diffraction pattern as in the case of normal single slit experiments.

3 Experimental setup and results

To test the prediction from both the wave theory of light and QED, an experiment of a longitudinal movable slit is designed. The simple experimental setup is shown in Fig. 3.

The laser source S is a common red laser pointer of wavelength of 532 ± 10 nm. The razor blade R is movable transversely so as to change slit width while the blade L can move along the longitudinal optical rail to change longitudinal separation. Since the transverse width of the slit (i.e. the transverse distance between two blades) is small and crucial to the interference pattern, it is important that this width has minimum variation when the blade L is moving along the rail. As such, it is important to align the laser beam to be parallel to the longitudinal optical rail. This is achieved by centering the laser beam on the centre of the adjustable iris when moving it along the rail. To be sure that the laser beam is parallel to the longitudinal when the laser source moves along a transversely placed optical rail, a reflection mirror is employed to confirm the overlapping of the retro-reflected light with incident light. The mirror is removed during the fringe pattern measurement. By putting the two blades in the same plane to form a normal single slit and measuring the total length of two blades, the transverse width of the slit is measured indirectly by subtracting the length of each blade from the length of two blades at the normal single slit position.

The typical experimental results are shown in Table 1. Scenario 3 shows the case of zero longitudinal separation, i.e. the normal single slit case. The fringe pattern is, as expected, symmetric. However, the fringe patterns in other scenarios are not expected. In scenarios 1 and 2 where the blade L on the left side is closer to the light source (and thus farther away from the observer plane), the left side of fringe patterns have smaller width while the right side of the fringe patterns have much larger width. The larger longitude separation is, the greater difference in fringe widths of both sides are. In scenarios 4 and 5, where the blade L on the left side is closer to the observing plane, it is the opposite story – the left-hand side of fringes have larger widths. Qualitatively, this experimental result is not consistent with the Huygens-Fresnel principle or the prediction of QED.

One may argue that the pattern may be related to the Fresnel diffraction of the single blade or due to possible changes in the transverse width of the slit as it moves along the rail. Regarding the first argument, we display a diffraction pattern caused by the edge of one blade in the last row of Table 1. The diffraction from one blade does agree with knife-edge diffraction theory – there is no fringes in the shadow area but fringes appear on the other side. However, the fringe width is very small and can be observed directly, but cannot be observed from the photo due to resolution limitation. As explained earlier, how this fringe pattern affects the fringes after the second blade is still a mystery. For the second argument, we admit that there is a nonzero possibility of a change in transverse width of the slit, but this would affect equally the fringe width of both sides, and thus its impact should also be symmetric. As a result, these factors can be ruled out as the cause of asymmetric fringe pattern.

Asymmetric diffraction patterns are not rare phenomena, but all asymmetric patterns must have contributing factors and mechanisms. The light diffraction patterns in our daily life are often asymmetric or even have weird shapes, e.g. the diffraction pattern from a spider web, skin hairs, spilt oil surface. These kinds of uncontrolled natural experiments have many contributing factors which are hard to disentangle. The asymmetry in the diffraction pattern of a grating can rise due to periodic errors [32]. The Bragg diffraction on thick grating involves multi-wave interference [33]. Asymmetric diffraction in a periodic potential can be generated by phase gradients and randomness [34, 35]. In the present paper, the asymmetric pattern is clearly caused by longitudinal separation, but how the longitudinal distance affects the fringe pattern is still a mystery.

In order to examine the relationship between the longitudinal distance and the fringe pattern, the left and right fringe widths are measured for a given longitudinal position of blade L. The measurement of fringe width is limited by the 1 mm accuracy of the ruler. However, this accuracy can be improved by further measuring the width of the magnified images. For the case of multiple fringe spots on one side, the measurement accuracy can be improved by measuring the average width of many spots. The measurement of longitudinal distance is also limited by the 1 mm accuracy of the optical rail, but this limit can be offset partially by the large distance between the observer plane and the fixed half-slit. This distance is L=1600 mm in our experiment. The measured transverse width of the slit is D=0.26 mm for theabove results, which is consistent with the calibration based on the diffraction formula together with the measured fringe width and known wavelength. To reduce the chance of possible change in transverse width of slit when longitudinal distance changes, the laser beam is aligned carefully and the position of the left half-slit is locked properly after each movement.

4 An empirical formula explaining experimental results

Our target is to develop an empirical formula for fringe width for the longitudinally separated slit. Since the experiments show that both longitudinal distance and transverse width affect fringe width, we assume that longitudinal separation ΔL has a similar role to the transverse width D, so we can modify the formula for normal slits slightly for our longitudinally-separated slit:

$$\sin\theta = \frac{\lambda}{D + A\,\Delta L} \qquad (5)$$

where $\sin\theta$ indicates fringe width, λ the wavelength of light, D the transverse width of the slit, ΔL the longitudinal separation. A is the parameter to be calibrated.

Because $D \gg \lambda$ in our experiments, the diffraction angle θ is very small, so we can use an approximation $\sin\theta \approx \Delta y/L$ for the above diffraction formula, where L is the distance between the observer plane and the fixed half-slit, and Δy the fringe width. A brief inspection reveals that the formula can produce results that qualitatively agree with experiment results. Namely, when $\Delta L < 0$, i.e. the left half-slit is farther away from the observer plane, the formula with a positive parameter A will produce a larger width for the right fringe. Conversely, when $\Delta L > 0$, the left half-slit is closer to the observer plane, the formula with a positive parameter A produces a smaller width for the right fringe. For left fringes, the formula should also work well if parameter A takes a negative value.

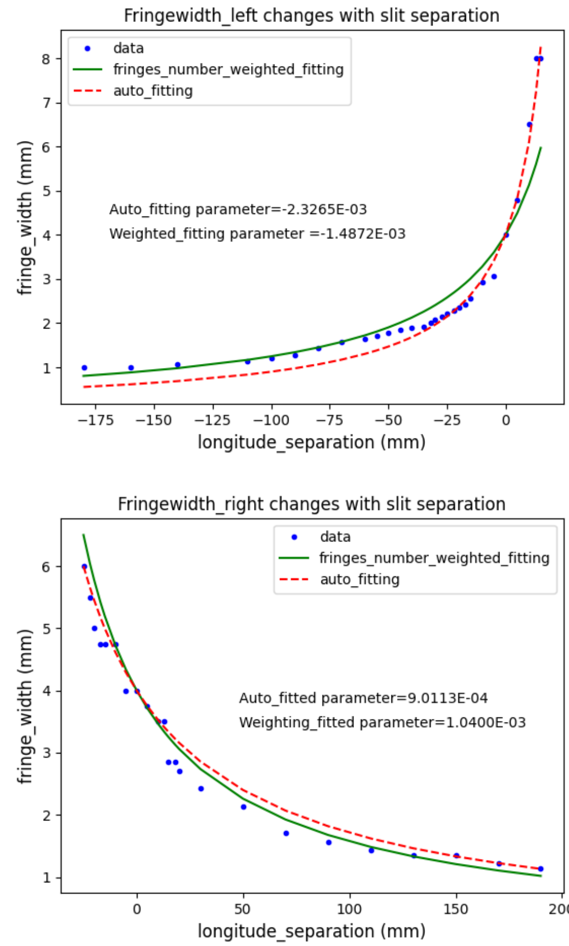


Fig. 4: Fitting of experimental data with the proposed formula.

However, experimenting with different transverse width of slit shows that the impact of ΔL on Δy is very sensitive to this width. A smaller transverse width D' (with λ and L unchanged) corresponds to a significantly larger $\Delta y'$ and dramatically smaller $\Delta L'$, suggesting that the impact of ΔL on Δy is inversely constrained by width D. Considering this as well as the approximation for a small θ, we upgrade the formula to:

$$\Delta y = \frac{L\lambda}{D + A\,\Delta L/D}\,. \qquad (6)$$

Next, we confront this formula with data. With experimental measurements of D, L, ΔL and Δy, as well as known λ, we can fit the data with the above formula. The fitting results are shown in Fig. 4.

The red dash curves are the automatic fitting based on the least squares method. Overall, this fitting is pretty good, and the fitted parameter A has the expected sign: negative value for the left fringes and positive value for right fringes. However, the absolute values of the two fitted parameters differ considerably by about 2.5 times.

The automatic fitting fits the data especially well for the parts of high fringe width. However, the measurement for high fringe width is relatively less reliable for two reasons. One is that only one or very few fringes are visible so the method of reducing measurement error by averaging a number of fringe widths is not applicable. The other reason is that the sizes of the first and the last fringes differ considerably in some cases (see rows 4 and 5 in Table 1). Considering these factors, we can improve the fitting by giving more weights to smaller fringe widths, which are obtained by averaging a number of fringes at a given longitudinal separation. The weighted fittings are shown in green solid curves, which fit much better the data at small widths.

The parameter values of weighed fitting for the left and right fringes are closer compared with the auto fitted values. Although the absolute parameter values for left and right fringes data are of the same magnitude, they still differ by 50 percent. Since the fitting for both left and right fringes is based on the same value of L, D, ΔL, λ, the significant difference in fitted parameter values for both sides suggest that some other factors may also affect fringe width.

5 Conclusion

Performing the same experiments with slits of different transverse widths and with light of different wavelengths, we find that the experiment data fit well with the proposed formula. However, the fitted parameter values are quite different, suggesting other factors may play a significant role. Future experiments may find missing variables and fit a constant parameter for experiments of all settings.

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References

1. Brewster D. A Treatise on Optics.. London: Longman, Rees, Orme, Brown & Green and John Taylor, 1831.
2. Huygens C. Traité de la Lumière. Leyden: Van der Aa, 1690.
3. Newton I. Opticks: or, a treatise of the reflexions, refractions, infexions and colours of light. London, 1704.
4. Young T. The Bakerian Lecture: experiments and calculations relative to physical optics. *Philosophical Transactions of the Royal Society of London*, 1804, v. 94, 1–16.
5. Fresnel A. Mémoire sur la diffraction de la lumière (Memoir on the diffraction of light). *Annales de Chimie et de Physique*, 1816, v. 1, 239–281.
6. Fresnel A. Mémoire sur la diffraction de la lumière (Memoir on the diffraction of light). 1818, in Mémoires de l'Académie Royale des Sciences de l'Institut de France, vol. V (for 1821 & 1822, printed 1826)
7. Einstein A. On a heuristic point of view concerning the production and transformation of light. *Annalen der Physik*, 1905, v. 17, 132–148.
8. Bohr N. The Quantum postulate and the recent development of atomic theory. *Nature*,, 1928, v. 121, 580–590.
9. de Broglie L. Waves and quanta. *Nature*, 1923, v. 112, 540.
10. Feynman R. P. Space-time approach to non-relativistic quantum mechanics. *Review of Modern Physics*, 1948, v. 20, 367–387.
11. Davisson C., Germer L. The scattering of electrons by a single crystal of nickle. *Nature*, 1927, v. 119 558–560.
12. Estermann I. E., Stern O. Beugung von Molekularstrahlen. *Zeitschrift für Physik*, 1930, v. 61, 95–125.
13. Gahler R., Zeilinger A. Wave-optical experiments with very cold neutrons. *American Journal of Physics*, 1991, v. 59, 316–324.
14. Jonsson C. Electron diffraction atmultile slits. *American Journal of Physics*, 1974, v. 42, 4–11.
15. Zeilinger A., Gahler R., Shull C. G., Treimer W., Mampe, W. Single and double-slit diffraction of neutrons. *Review of Modern Physics*, 1988, v. 60, 1067–1073.
16. Carnal O., Mlynek J. Young's double-slit experiment with atoms: a simple atom interferometer. *Physical Review Letters*, 1991, v. 66, 2689–2692.
17. Schollkopf W., Toennies J. Nondestuctive mass selection of small van der Waals clusters. *Science*, 1996, v. 266, 1345–1348.
18. Borde C., Courtier N., Burck F. D. Goncharov A., Gorlicki, M. Molecular interferometry experiments. *Physics Letters A*, 1994, v. 188, 187–197.
19. Arndt M., Nairz O., Vos-Andreae J., Keller C., van der Zouw G., Zeilinger A. Wave-particle duality of C(60) molecules. *Nature*, 1999, v. 401, 680.
20. Eibenberger S., Gerlich S., Arndt M., Mayor M., Tuxen J. Matter–wave interference of particles selected from a molecular library with masses exceeding 10 000 amu. *Physical Chemistry Chemical Physics*, 2013, v. 15, 14696.
21. Pursehouse J., Murray A. J., Watzel J., Berakdar J. Dynamic double-slit experiment in a single atom. *Physical Review Letters*, 2019, v. 122, 053204.
22. Zhou H., Perreault W., Mukherjee N., Zare R. N. Quantum mechanical double slit for molecular scattering. *Science*, 2021, v. 274, 960–964.
23. Hecht E. Optics, 5th ed. Pearson Education Limited. 2017.
24. Sommerfeld A. Mathematische Theorie der diffraction. *Mathematische Annalen*, 1896, v. 47, 317–374.
25. Sommerfeld A. Optics: Lectures on Theoretical Physics. Acedamic Press, New York, 1954.
26. Marcella T. V. Quantum interference with slits. *European Journal of Physics*, 2002, v. 23, 615–621.
27. Muino P. L. Introducing the uncertainty principle using diffraction of light waves. *Journal of Chemistry Education*, 2000, v. 77, 1025–1027.
28. Rioux F. Calculating diffraction patterns. *European Journal of Physics*, 2003, v. 24, N1–N3.
29. Wu X., Zhang B., Yang J., Chi L., Liu X., Wu Y., Wang Q., Wang Y., Li J., Guo Y. Quantum theory of light diffraction. *Journal of Modern Optics*, 2010, v. 57 (20), 2082–2091.
30. Stöhr J. Diffraction without waves: emergence of the quantum substructure of light. arXiv: quant-ph/2003.14217.
31. Stöhr J. Overcoming the diffraction limit by multi-photon interference: a tutorial. *Advances in Optics and Photonics*, 2019, opg.optica.org/aop/fulltext.cfm?uri=aop-11-1-215&id=407746.
32. Preston R. C. Asymmetry in the diffraction pattern of a grating due to periodic errors. *Optica Ata*, 1970, v. 17 (11), 857–867.
33. Cronin A. D., Schmiedmayer J., Oritchard D. E. Optics and interferometry with atoms and molecules. *Review of Modern Physics*, 1957, v. 81 (3), 1051.
34. Zhou S., Groswasser D., Keil M., Japha Y., Folman R. Robust spatial coherence 5 um from a room-temperature atom chip. *Physical Review A*, 2016, v. 93, 063615.
35. Liu Y., Xiang Y., Mohammed A. A. Asymmetric diffraction grating via optical vortex light in a tunneling quantum dot molecule. *Laser Physics letters*, 2022, v. 19, 095205.