

WITHDRAWN: Curved, Expanded and Inclined Diffraction Patterns of Grating–Rotating Grating Around Three Axes (1)

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Research Article

Keywords: grating experiment, cross-grating experiments, diffraction pattern, light bending, curved diffraction pattern, expanded diffraction pattern, inclined diffraction pattern

Posted Date: December 29th, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-1209507/v1>

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Curved, Expanded and Inclined Diffraction Patterns of Grating-- Rotating Grating Around Three Axes (1)

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Abstract The orientation-dependence of the interference/diffraction patterns of the 1D-double slit/1D-grating and 2D-cross-double slit/2D-cross-grating experiments have been studied experimentally and theoretically. However, the above experiments were limited to certain orientations, namely rotating around either one axis or two axes. In this article, the 3-axis-rotation apparatus is proposed/made, which can rotate the 1D-double slit/2D-cross-double slit and 1D-grating/2D-cross-grating, CW and CCW respectively, 0° - 360° around three axes independently and sequentially. By this apparatus, the orientation-dependence of the patterns is systematically studied. Moreover, the experiments can be performed easily. The complete phenomena of curved, expanded and inclined patterns are the orientation-dependent. Then we show that the photons, before landing on the detector/screen, behave as particles. The above observed phenomena provide the comprehensive information to theoretical study of the double slit/grating experiments. We suggest that the complete mathematical model should contain three rotation angles as parameters. Furthermore, the phenomena have potential applications.

Keywords: grating experiment, cross-grating experiments, diffraction pattern, light bending, curved diffraction pattern, expanded diffraction pattern, inclined diffraction pattern

Declaration: This article has no potential conflicts of interesting

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1. Introduction

The orientation-dependence, for certain orientations, of the conical diffraction patterns of the 1D-grating experiments have been studied theoretically and experimentally (see References [1] [2] [3] [4] and cited references within). The orientation-dependence, for certain orientations, of the interference patterns of the 1D-double slit and 2D-cross-double slit experiments have been studied experimentally and theoretically [5] [6] [7]. We have reported the novel phenomena that the interference patterns not only can be curved, but also can be expanded and inclined simultaneously and continuously, which are depended on the orientations of the 1D-double slit and 2D-cross-double. It is shown that the phenomena of the curved, expanded and inclined patterns are universal, namely, the same phenomena of the curved, expanded and inclined interference patterns emerge in the single slit, double slit, cross-double slit and triple slit experiments [8]. Theoretical analyses were presented: (1) Right-hand rule and Left-hand rule for determining the direction of the patterns curve toward are proposed [9]; (2) the mathematical formulars for describing the expansion [5] and the inclination [10] of the patterns are derived. However, in the above experiments, the diaphragm rotates around either one axis or two axes, i.e., the study of the orientation-dependence is not complete.

Recently, we have extended the orientation-dependence of the interference patterns of the 1D-double slit/2D-cross-double slit experiments to the 1D-grating and 2D-cross-grating experiments [11] [12] [13]. The phenomena of the simultaneously curved and expanded emerged in the 2D-cross-grating experiments, while the simultaneously curved, expanded and inclined patterns emerged in the tilt-2D-cross-grating experiments. The patterns are attributing to the different orientations of the 2D-cross-grating and, thus, are conveniently created and controlled. The new phenomena show that the characteristics of the patterns depend on the orientations of the grating. However, the study only covers the orientations by rotating the grating around two axes.

Also, it is shown that the dot-image of the laser source, which shows the particle nature of the laser beam, the straight diffraction pattern and the curved diffraction patterns of the 1D-grating can emerge in the same experiment [14]. The definition of the same experiment is that in an experiment, there is only one laser source and only one grating. Also, it is shown experimentally that when the light beam creates the curved pattern, the light beam behaves as particles, photons, before landing on the detector/screen, which challenge the standard interpretation of the double slit experiments, the wave-particle duality and the complementarity principle [15]. The particle nature of the light in the double slit/cross-double slit experiments has been shown [16] [17] [18].

To study the orientation-dependence completely, in this article, we introduce: (1) the three-axis-rotation apparatus; and (2) a new coordinate system to describe the new apparatus. By which, the systematic study of the orientation-dependence of the patterns is achieved intuitively. The diaphragms of the double slit and cross-double slit, gratings and cross-gratings are rotated around three axes sequentially and respectively. New phenomena are observed.

Note that in this article, we only show the orientation-dependence of the diffraction patterns of the 1D-transmission grating. However, the same three-axis-rotation apparatus can be utilized in the 1D-double slit, 2D-cross-double slit and 2D-cross-grating experiments (to be continued).

The novel phenomena of the continuously curved, expanded and inclined patterns provide the comprehensive data/information to theoretically study the double slit/grating experiments. The phenomena would provide the comprehensive information/data for theorists. We suggest that a complete mathematical model should contain three rotation angles as parameters and should be able to describe all phenomena of the orientation-dependence of the patterns consistently.

The concept of the orientation-dependence of the patterns is important for applications.

2. Three-Axis-Rotation Apparatus: Rotating Grating Around Three Axes

2.1. Three-Axis-Rotation Apparatus

To perform the experiments of studying the orientation-dependence of the patterns, it is practical convenience to keep the laser beam pointing to the same direction and rotate the grating. For this aim, we introduce the three-axis-rotation apparatus that can rotate the double slit/cross-double slit and grating/cross-grating around three axes to reach desired orientations (Figure 1).

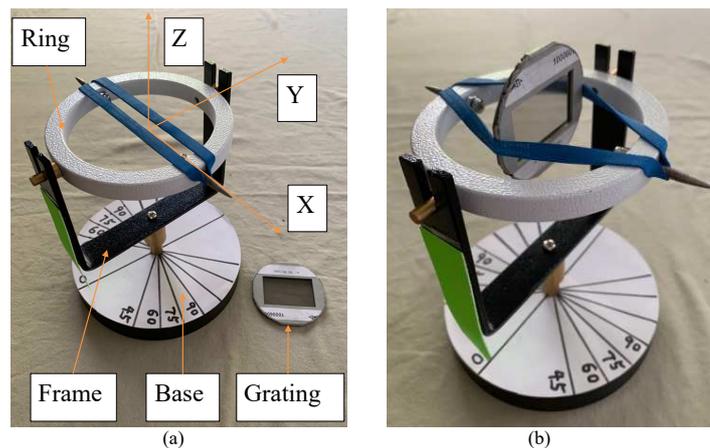


Figure 1. Schematic of the 3-axis-rotation apparatus: the frame rotates around Z axis, the ring rotates around Y axis, the round grating rotates around X axis.

The shortcoming is that the thick ring may block light beam for certain orientation. To avoid it, one can make the ring as thin as possible to minimize the blocking.

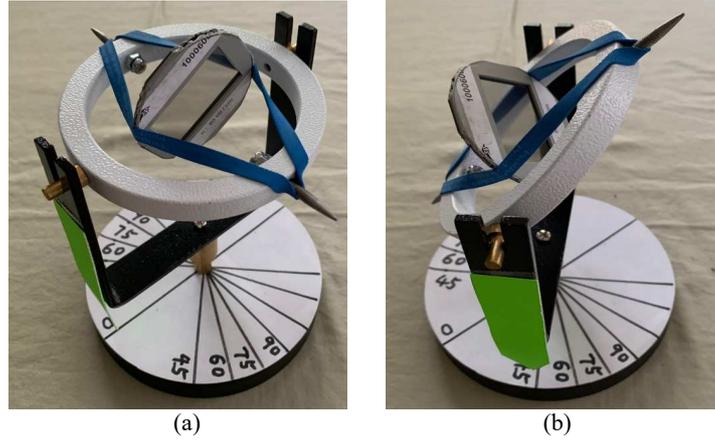


Figure 2. Rotation of the 3-axis-rotation apparatus: the grating rotates around X axis (a); the grating/ring rotate around Y axis (b); the grating/ring/frame rotate around Z axis (b).

The Y and Z axes are perpendicular to each other always; The Y and X axes are perpendicular to each other always. Figure 2b shows that the grating, the ring with grating, and the frame with ring and grating rotate around the X axis, the Y axis and the Z axis respectively.

With this apparatus, the orientation-dependence of the patterns can be studied thoroughly and conveniently, and novel phenomena are shown.

2.2. Coordinate System and Direction of Rotation

To study the orientation-dependence of the patterns, we introduce the coordinate system and the original orientation of the grating (Figure 1).

Coordinate System: The rotation axis of the frame defines the Z axis; the rotation angles are either “Clockwise γ ” (denoted as “CW γ ”) or “Counterclockwise γ ” (denoted as “CCW γ ”). The frame can be rotated around Z axis between $0^0 \leq \gamma \leq 360^0$ CW and CCW. The rotation axis of the ring defines the Y axis, the rotation angles are either “CW β ” or “CCW β ”. The ring can be rotated around Y axis between $0^0 \leq \beta \leq 360^0$ CW and CCW. The normal vector of the grating defines the X axis. The rotation angles are either “CW α ” or “CCW α ”. The grating can be rotated around X axis between $0^0 \leq \alpha \leq 360^0$ CW and CCW.

The X axis and the Y axis are always perpendicular to each other. The Y axis and the Z axis are always perpendicular to each other. The X axis changes its direction when the ring rotates around the Y axis and when the frame rotates around the Z axis. The Y axis changes its direction when the frame rotates around the Z axis. The Z axis keeps the same direction. The laser beam keeps the same direction.

Direction of Rotation: to define the direction of the CW and CCW rotation, we introduce the right-hand rule that the thumb of the right hand is pointed in the direction of the axis, the CCW rotation is given by the curl of the fingers (Figure 3).

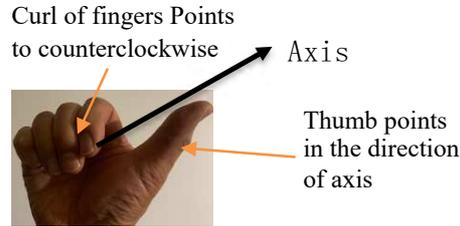


Figure 3. Right-hand rule for determining direction of rotation

Original orientation of the grating: At the original orientation, the X, Y and Z axes form the Cartesian coordinate system (Figure 4a), denoted it as the original coordinate system. The slits of the grating are along the Y axis (Figure 4b). The laser source is on the X axis, i.e., the light is normally incident on the plane of the grating, referred it as the original orientation.

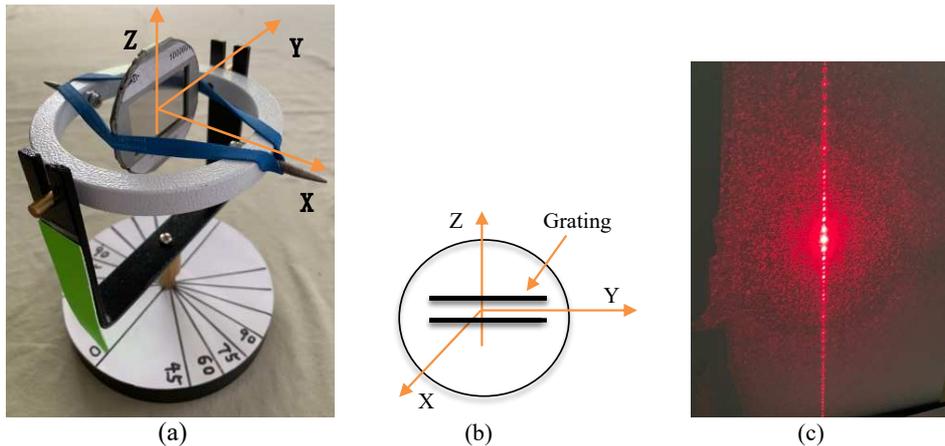


Figure 4. Apparatus/Coordinate (a), Grating (b) and Pattern (c)

2.3. Rotating Grating Around Three Axis

To study systematically the orientations-dependence of the interference patterns and diffraction patterns (hereafter denoted both as the “patterns”) of the 1D-double slit/2D-cross-double slit/1D-grating/2D-cross-grating (hereafter denoted as the “grating”), the effects of the orientations on the patterns need to be considered when the following rotations are performed:

(A) First, let us start from the original orientation, then, rotating the grating around one axis only:

- (A1) Rotate the grating around the X axis: CW α and CCW α , respectively
- (A2) Rotate the grating/ring around the Y axis: CW β and CCW β , respectively
- (A3) Rotate the grating/ring/frame around the Z axis: CW γ and CCW γ , respectively

- (B) Second, let us start from the original orientation, then, rotating grating around two axes sequentially:
- (B1) Rotate the grating around the X axis (CW α and CCW α , respectively), then, respectively,
- (B1-1) rotate the grating/ring around Y axis (CW β and CCW β , respectively)
- (B1-2) rotate the grating/ring/frame around the Z axis (CW γ and CCW γ , respectively)
- (B2) Rotate the grating/ring around the Y axis (CW β and CCW β , respectively), then, respectively,
- (B2-1) rotate the grating/ring/frame around the Z axis (CW γ and CCW γ , respectively)
- (B2-2) rotate the grating around X axis (CW α and CCW α , respectively)
- (B3) Rotate the grating/ring/frame around the Z axis (CW γ and CCW γ , respectively), then, respectively,
- (B3-1) rotate the grating around X axis (CW α and CCW α , respectively)
- (B3-2) rotate the grating/ring the Y axis (CW β and CCW β , respectively)
- (C) Third, let us start from the original orientation, then, rotating the grating around three axes sequentially:
- (C1) Rotate the grating around the X axis (CW α and CCW α), then, respectively,
- (C1-1) rotate the grating/ring around Y axis (CW β and CCW β), then rotate grating/ring/frame around Z axis (CW γ and CCW γ);
- (C1-2) rotate the grating/ring/frame around Z axis (CW γ and CCW γ), then rotate grating/ring around Y axis (CW β and CCW β)
- (C2) Rotate the grating/ring around the Y axis (CW β and CCW β), then, respectively,
- (C2-1) rotate the grating/ring/frame around Z axis (CW γ and CCW γ), then rotate grating around X axis (CW α and CCW α);
- (C2-2) rotate the grating around X axis (CW α and CCW α), then rotate grating/ring/frame around Z axis (CW γ and CCW γ).
- (C3) Rotate the grating/ring/frame around the Z axis (CW γ and CCW γ), then, respectively,
- (C3-1) rotate the grating around X axis (CW α and CCW α), then rotate grating/ring around Y axis (CW β or CCW β)
- (C3-2) rotate the grating/ring around Y axis (CW β and CCW β), then rotate grating around X axis (CW α and CCW α)

When rotate the grating, the ring and the frame, we always rotate CCW and CW respectively.

In this article, as the first one of a series-articles, we only report the observations of the grating experiments for the orientations of rotating the grating around one axis and around two axes.

3. Experiments: Novel Phenomena of Grating:

3.1. Rotating Grating Around One Axis

Let us start from the original orientation (Figure 4). The slits of the grating are along the Y direction. Then, rotating the 1D-grating around one axis.

Experiment-A1: Rotating Grating Around X axis

Figure 5a shows the pattern due to the CW rotation of the grating, while Figure 5b shows the pattern due to the CCW rotation. The patterns of the grating have the rotation symmetry when the grating rotates around the X axis and the laser beam is on the normal vector/the X axis.

Figure 5c shows the rotation symmetry of the patterns of the double slit/cross-double slit [19].

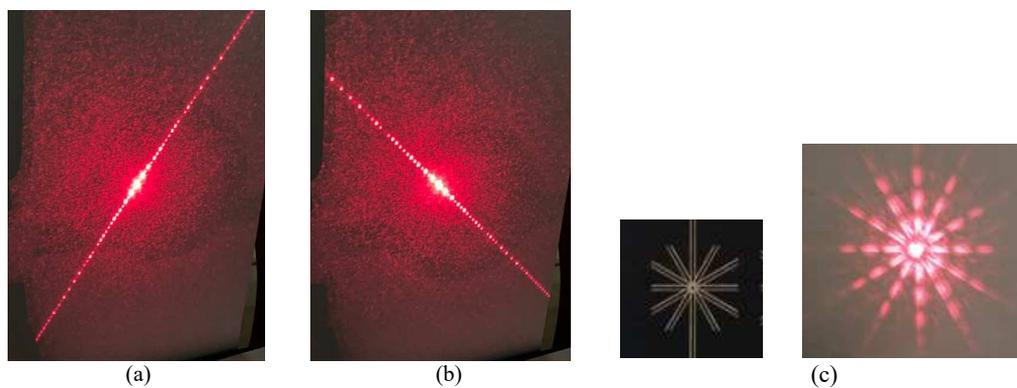


Figure 5. Rotation symmetry: Grating rotating around X axis:

Patterns due to CW rotation (a) and CCW rotation (b); Pattern of 2D-cross-double slit (c)

When the grating rotates around the X axis, the light is a normally incident beam. When the laser source is not on the normal vector of the grating, the rotation symmetry is no longer valid.

Experiment-A2: Rotating Grating/Ring Around Y axis

Figure 6a shows the pattern when the grating is at the original orientation.

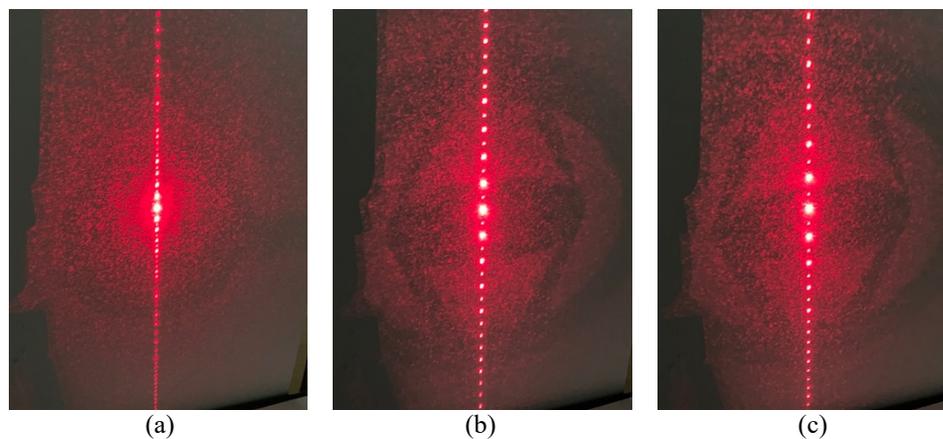


Figure 6. Expanded Patterns: Grating/ring rotating around Y Axis CW β (b) and CCW β (c)

We observed the expanded patterns: the larger the rotation angle, β , the larger the expansion.

When the slits of the grating are along the Y axis, The directions of rotating around Y axis, either CW or CCW, have no effects on the expansion of the patterns.

Experiment-A3: Rotating Grating/ring/frame Around Z axis

We observed the curved patterns. The directions of the curves are determined by the direction of the rotations: the CW rotation makes the pattern curves towards to the left, which satisfy the right-hand rule (Figure 7b), while the CCW rotation makes the pattern curves towards to the right, which satisfy the left-hand rule (Figure 7c) [9]. The larger the rotation angle the larger the curvature of the curved pattern.

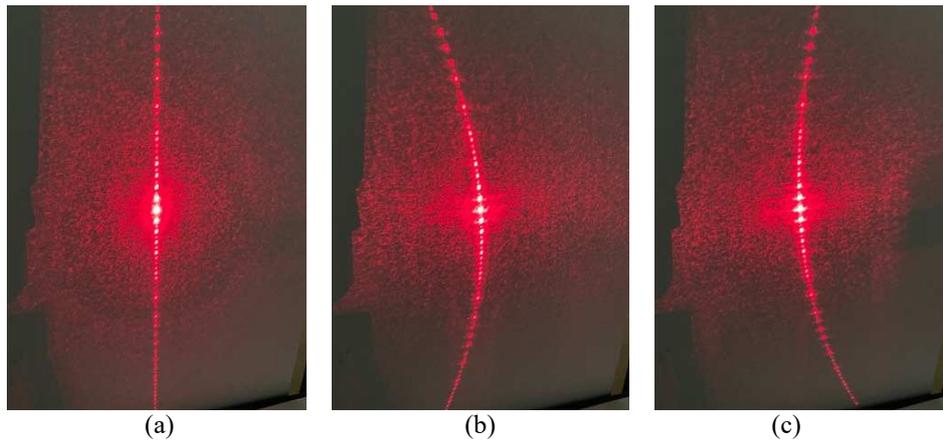


Figure 7. Curved patterns attribute to:

CW rotation (b) and CCW rotation (c) of grating respectively

Figure 7a shows the pattern of the grating at the original orientation. The directions of the rotations of the grating determine the direction of the curved patterns [9]. The patterns have no expansion.

Mathematic Description:

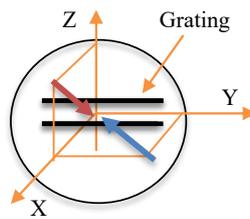


Figure 8. Incident Lights

In Experiment-A2, the incident light beam (Brown colored arrow in Figure 8) is in the X-Z plane with an incident angle β to the X axis, which create the expanded pattern. In Experiment-A3, the incident light beam (Blue colored arrow in Figure 8) is in the X-Y plane with an incident angle γ to the X axis, which created the curved pattern.

If the light beam in the X-Z plane is incident at an arbitrary angle β_i to the grating normal, the standard grating equation gives

$$\sin\beta_m = \frac{m\lambda}{d} + \sin\beta_i. \quad (1)$$

Where β_m is the diffraction angle, d is the spacing between two adjacent slits. The difference between two diffraction angles of two adjacent diffraction order is constant,

$$\sin\beta_{m+1} - \sin\beta_m = \frac{\lambda}{d}. \quad (2)$$

Namely the standard grating equation predicts the no-expansion patterns for the light beam with arbitrary incident angle.

The expanded patterns violate the grating equation.

To describe the expanded patterns of Experiment-A2, we extend the standard grating equation to:

$$\sin\beta_m = \frac{m\lambda}{d} L \sqrt{1 + (\tan\beta_i)^2} + \sin\beta_i. \quad (3)$$

Now the difference between two diffraction angles of two adjacent diffraction order is incident-angle-dependent, i.e., the larger the incident angle, the larger the spacing between diffraction orders,

$$\sin\beta_{m+1} - \sin\beta_m = \frac{\lambda}{d} L \sqrt{1 + (\tan\beta_i)^2}. \quad (4)$$

The term $(\tan\beta)^2$ shows that the expansions are independent with the directions, either CW β or CCW β , of the grating/ring's rotation.

Note that Equations (1) and (3) describe the patterns created by the oblique incident light beams that are in the X-Z plan (Figure 8) and thus, no pattern is curved. When the grating rotates around the Z axis, either CW or CCW, the different curved patterns are created as shown in Experiment-A3.

Experiment-A1, -A2 and -A3 indicate that the patterns due to the rotations around the different axes are completely different (Table 1). Those differences will guide us to understand the phenomena when the grating rotating around 2 axes and 3 axes.

Table 1. Characteristics of Patterns vs. Rotation Axis

Rotation	Change Direction	Rotation Symmetry	Expand	Curve
Around X Axis	Yes	yes		
Around Y Axis			Yes	
Around Z Axis				Yes

3.2. Rotating Grating Around Two Axes Sequentially

In this section, we perform the following experiments. Note that since the direction of the curved patterns is determined by the direction of the rotation, so in the following experiments, we rotate the grating CW and CCW respectively. The plan of the experiments is the following.

Experiment-B1: Rotate the grating around the X axis.

Experiment-B1-1: Rotate the grating around the X axis 30° CW, then perform the following 4 experiments respectively.

Experiment-B1-1a: rotate the grating/ring around Y axis 30° CW

Experiment-B1-1b: rotate the grating/ring around Y axis 30° CCW

Experiment-B1-1c: rotate the grating/ring/frame around the Z axis 30° CCW

Experiment-B1-1d: rotate the grating/ring/frame around the Z axis 30° CCW

Experiment-B1-2: Rotate the grating around the X axis 55° CW, then perform the following 4 experiments respectively.

Experiment-B1-2a: rotate the grating/ring around Y axis 60° CW

Experiment-B1-2b: rotate the grating/ring around Y axis 75° CCW

Experiment-B1-2c: rotate the grating/ring/frame around the Z axis 60° CW

Experiment-B1-2d: rotate the grating/ring/frame around the Z axis 70° CCW

Experiment-B1-3: Rotate the grating around the X axis 50° CCW, then perform the following 4 experiments respectively.

Experiment-B1-3a: rotate the grating/ring around Y axis 45° CW

Experiment-B1-3b: rotate the grating/ring around Y axis 75° CCW

Experiment-B1-3c: rotate the grating/ring/frame around the Z axis 60° CW

Experiment-B1-3d: rotate the grating/ring/frame around the Z axis 60° CCW

Experiment-B1-4: Rotate the grating around the X axis 80° CCW, then perform the following 4 experiments respectively.

Experiment-B1-4a: rotate the grating/ring around Y axis 75° CW

Experiment-B1-4b: rotate the grating/ring around Y axis 60° CCW

Experiment-B1-4c: rotate the grating/ring/frame around the Z axis 65° CW

Experiment-B1-4d: rotate the grating/ring/frame around the Z axis 75° CCW

Second, let us rotate the grating around the Y axis first.

Experiment-B2: Rotate the grating/ring around the Y axis.

Experiment-B2-1: Rotate the grating/ring around the Y axis 30° CW, then perform the following 4 experiments respectively.

Experiment-B2-1a: rotate the grating around X axis 45° CW

Experiment-B2-1b: rotate the grating around X axis 30° CCW

Experiment-B2-1c: rotate the grating/ring/frame around the Z axis CW

Experiment-B2-1d: rotate the grating/ring/frame around the Z axis CCW

Experiment-B2-2: Rotate the grating/ring around the Y axis 30° CCW, then perform the following 4 experiments respectively.

Experiment-B2-2a: rotate the grating around X axis CW

Experiment-B2-2b: rotate the grating around X axis CCW

Experiment-B2-2c: rotate the grating/ring/frame around the Z axis CW

Experiment-B2-2d: rotate the grating/ring/frame around the Z axis CCW

Third, let us rotate the grating/ring/frame around the Z axis.

Experiment-B3: Rotate the grating/ring/frame around the Z axis

Experiment-B3-1: Rotate the grating/ring/frame around the Z axis *CW*, then perform the following 4 experiments respectively.

Experiment-B3-1a: rotate the grating around X axis *CW*

Experiment-B3-1b: rotate the grating around X axis *CCW*

Experiment-B3-1c: rotate the grating/ring around the Y axis *CW*

Experiment-B3-1d: rotate the grating/ring around the Y axis *CCW*

Experiment-B3-2: Rotate the grating/ring/frame around the Z axis *CCW*, then perform the following 4 experiments respectively.

Experiment-B3-2a: rotate the grating around X axis *CW*

Experiment-B3-2b: rotate the grating around X axis *CCW*

Experiment-B3-2c: rotate the grating/ring around the Y axis *CW*

Experiment-B3-2d: rotate the grating/ring around the Y axis *CCW*

3.2.1. Grating Rotating Around X Axis *CW*, Then Rotating Around Y Axis and Z axis Respectively

Experiment-B1: Rotate the grating around the X axis

Experiment-B1-1: Rotate the grating around the X axis 30° *CW*, Figure 9a shows its pattern. Then perform the following 4 experiments respectively.

Experiment-B1-1a: rotate the grating/ring around Y axis 30° *CW* (Figure 9b)

Experiment-B1-1b: rotate the grating/ring around Y axis 30° *CCW* (Figure 9c)

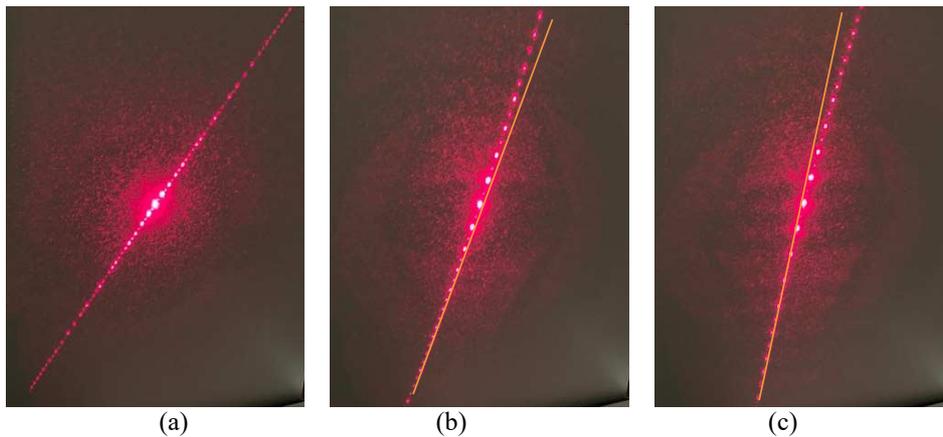


Figure 9. Grating rotates around X axis 30° *CW* (a), then rotates grating/ring around Y axis:
Patterns due to rotate *CW* (b) and rotate *CCW* (c)

Figure 9b shows that the patterns expanded, curved towards the left (shown by the orange straight line) and the whole pattern is inclined to the vertical direction. Figure 9c shows that the patterns expanded, curved towards the right (shown by the orange straight line) and the whole pattern is inclined to the vertical direction.

Experiment-B1-1c: rotate the grating/ring/frame around the Z axis 30° CW (Figure 10b)

Experiment-B1-1d: rotate the grating/ring/frame around the Z axis 30° CCW (Figure 10c)

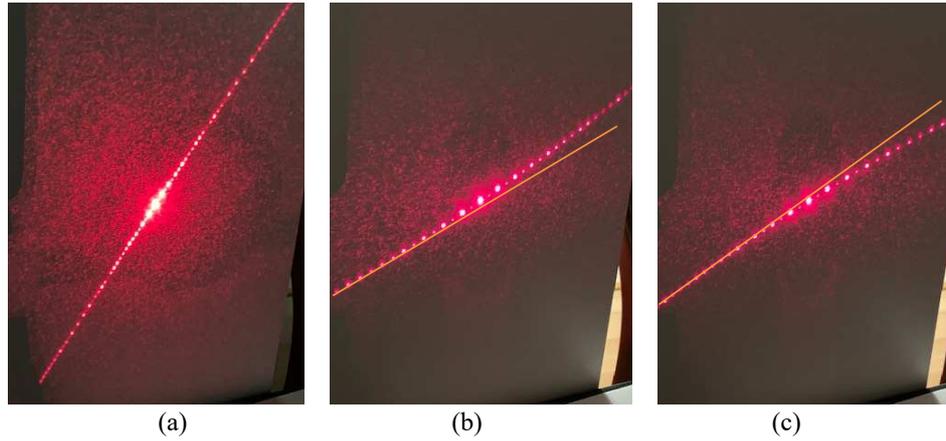


Figure 10. Grating rotates 30° CW around X axis (a), then rotates grating/ring/frame around Z axis: Patterns due to CW rotation (b) and CCW rotation (c)

Figure 10b shows that the patterns expanded, curved upwards (right-hand rule) (shown by the orange straight line) and the whole pattern is inclined to the horizontal direction. Figure 10c shows that the patterns expanded, curved downwards (left-hand rule) (shown by the orange straight line) and the whole pattern is inclined to the horizontal direction.

Mathematic Description: After rotating the grating around the X axis an angle α , the grating is tilt, and the slits of the grating have two components, the Y components and the Z components. If then, rotating the tilt-grating around the Y axis, the Y component create the expanded patterns, while the Z components create the curved patterns. If then, rotating the tilt-grating around the Z axis, the Z component create the expanded patterns, while the Y components create the curved patterns.

When rotating the tilt-grating around the Y axis an angle β_i , the mathematic equation describing the expansion of the pattern of the tilt-grating is the extension of Equation (3),

$$\sin\beta_m = \frac{m\lambda}{d} L\sqrt{1 + (\tan\beta_i)^2} \cos\alpha + \sin\beta_i. \quad (5)$$

When rotating the tilt-grating around the Z axis an angle γ_i , the mathematic equation describing the expansion of the pattern of the grating is the extension of Equation (3),

$$\sin\gamma_m = \frac{m\lambda}{d} L\sqrt{1 + (\tan\gamma_i)^2} \sin\alpha + \sin\gamma_i. \quad (6)$$

It is the challenge to describe the curved pattern.

Experiment-B1-2: Rotate the grating around the X axis 55° CW, Figure 11a shows its pattern. Then perform the following 4 experiments respectively.

Experiment-B1-2a: rotate the grating/ring around Y axis 60° CW (Figure 11b)

Experiment-B1-2b: rotate the grating/ring around Y axis 75° CCW (Figure 11c)

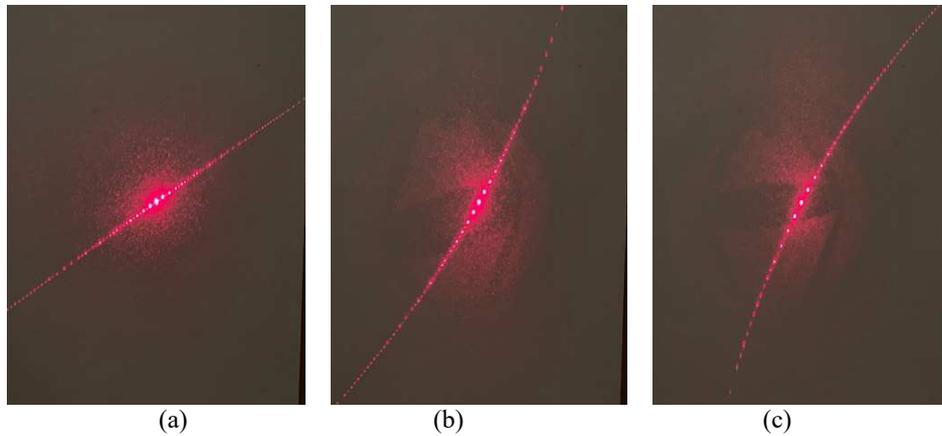


Figure 11. Grating rotates 55° CW around X axis (a), then rotates grating/ring around Y axis: Patterns due to 60° CW rotation (b) and 75° CCW rotation (c)

Figure 11b shows the patterns are curved towards the left, expanded and inclined towards the vertical axis. Figure 11c shows the patterns are curved towards the right, expanded and inclined towards the vertical axis.

Experiment-B1-2c: rotate the grating/ring around Z axis 60° CW (Figure 12b)

Experiment-B1-2d: rotate the grating/ring around Z axis 70° CCW (Figure 12c)

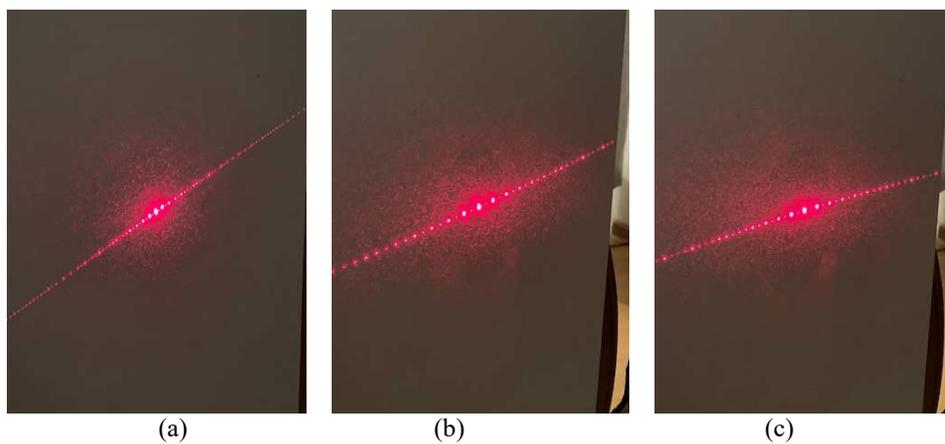


Figure 12. Grating rotates 55° CW around X axis (a), then rotates grating/ring/frame around Z axis: Patterns due to 60° CW rotation (b) and 75° CCW rotation (c)

Figure 12b shows the patterns are curved upwards, expanded and inclined towards the horizontal axis. Figure 12c shows the patterns are curved downwards, expanded and inclined towards the horizontal axis.

Conclusion: the patterns are different when the tilt-grating rotates around the Y axis and around the Z axis.

3.2.2. Rotating Grating Around X Axis *CCW*, Then Rotating Around Y Axis and Z axis respectively

Experiment-B1-3: Rotate the grating around the X axis 50° *CCW* (Figure 13a), then perform the following 4 experiments respectively.

Experiment-B1-3a: rotate the grating/ring around Y axis 45° *CW* (Figure 13b)

Experiment-B1-3b: rotate the grating/ring around Y axis 75° *CCW* (Figure 13c)

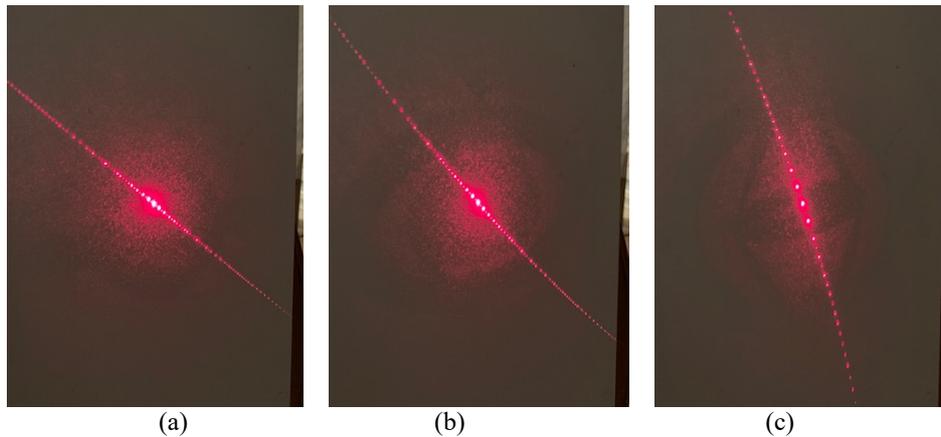


Figure 13. Grating rotates 50° *CCW* around X axis (a), then rotates grating/ring around Y axis: Patterns due to 45° *CW* rotation (b) and 75° *CCW* rotation (c)

Figure 13b shows the patterns are curved towards the left, expanded and inclined towards the vertical axis. Figure 13c shows the patterns are curved towards the left, expanded and inclined towards the vertical axis.

Experiment-B1-3c: rotate the grating/ring/frame around Z axis 60° *CW* (Figure 14b)

Experiment-B1-3d: rotate the grating/ring/frame around Z axis 60° *CCW* (Figure 14c)

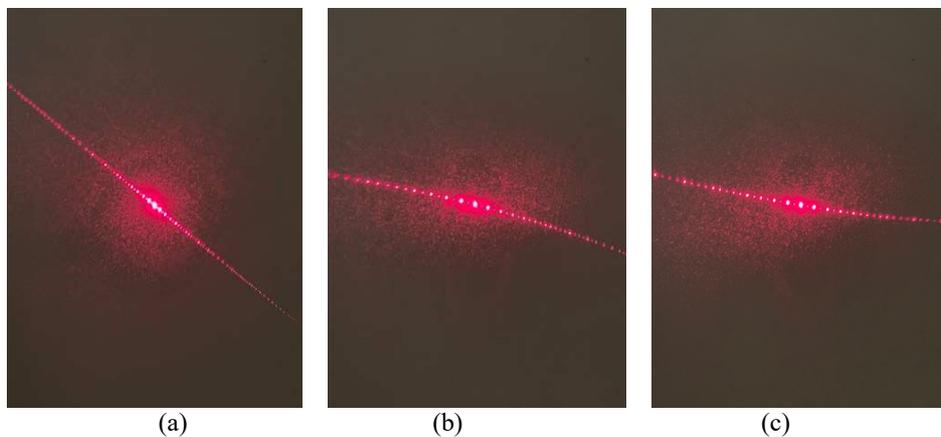


Figure 14. Grating rotates 50° *CW* around X axis (a), then rotates grating/ring/frame around Z axis:

Patterns due to 60° CW rotation (b) and 60° CCW rotation (c)

The patterns expanded, curved and inclined to the horizontal direction.

Experiment-B1-4: Rotate the grating around the X axis 80° CCW (Figure 15a), then perform the following 4 experiments respectively.

Experiment-B1-4a: rotate the grating/ring around Y axis CW 75° (Figure 15b)

Experiment-B1-4b: rotate the grating/ring around Y axis CCW 60° (Figure 15c)

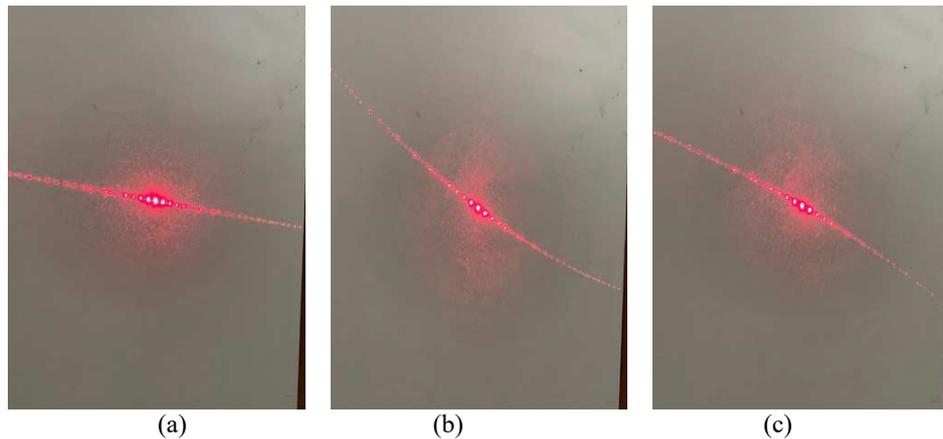


Figure 15. Grating rotates 80° CCW around X axis (a), then rotates grating/ring/frame around Y axis:

Patterns due to 75° CW rotation (b) and 60° CCW rotation (c)

Figure 15b shows the patterns are curved upwards, expanded and inclined towards the vertical axis.

Figure 15c shows the patterns are curved downwards, expanded and inclined towards the vertical axis.

Experiment-B1-4c: rotate the grating/ring/frame around the Z axis 65° CW (Figure 16b)

Experiment-B1-4d: rotate the grating/ring/frame around the Z axis 75° CCW (Figure 16c)

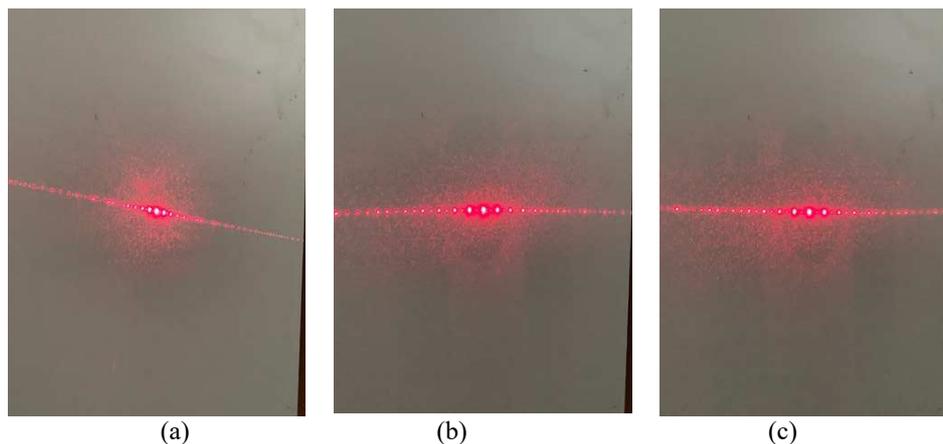


Figure 16. Grating rotates 80° CCW around X axis (a), then rotates grating/ring/frame around Z axis:

Patterns due to 65° CW rotation (b) and 75° CCW rotation (c)

Figure 16b shows the patterns are curved downwards, expanded and inclined towards the horizontal axis.

Figure 16c shows the patterns are curved upwards, expanded and inclined towards the horizontal axis.

3.2.3. Rotating Grating/ring Around Y Axis CW, Then Rotating Around X Axis and Z axis respectively

Experiment-B2: Rotate the grating/ring around the Y axis

Experiment-B2-1: Rotate the grating/ring around the Y axis 60° CW *first*, the pattern is expanded (Figure 17a). Then perform the following 4 experiments respectively.

Experiment-B2-1a: rotate the grating around X 45° axis CW (Figure 17b)

Experiment-B2-1b: rotate the grating around X axis 30° CCW (Figure 17c)

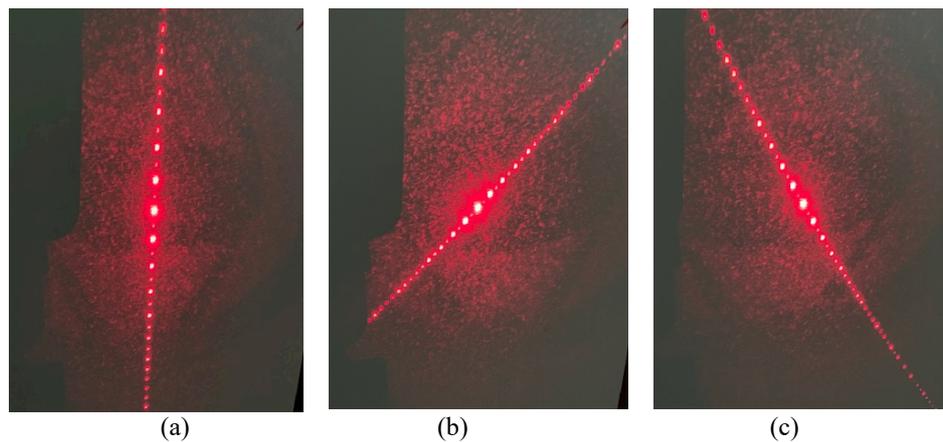


Figure 17. Grating/ring rotates around Y axis 60° CW (a), then rotates around X axis 45° CW (b) and around X axis 30° CCW (c)

We observe that the patterns are curved after the grating rotates around the X axis, which indicates a novel phenomenon that since the grating rotates around Y axis first, the grating has no longer the symmetry when it rotates around the X axis either CW or CCW.

It is the challenge to explain why the patterns (Figure 17b and 17c) are curved.

Experiment-B2-1c: rotate the grating/ring/frame around Z axis CW (Figure 18a)

Experiment-B2-1d: rotate the grating/ring/frame around Z axis CCW (Figure 18b)

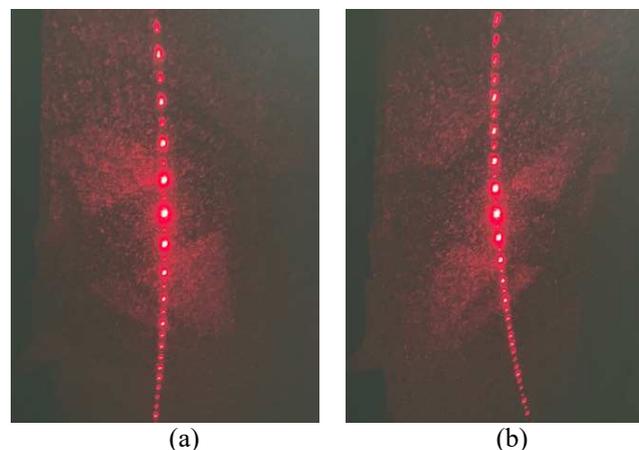


Figure 18. Grating/ring rotates around the Y axis CW, then rotates

grating/ring/frame around Z axis CW (a) and CCW (b)

We observe that the patterns are expanded (due to the rotating around Y axis) and curved (due to the rotating around Z axis).

It is the challenge to describe mathematically the curvatures of the patterns (Figure 18b and 18c).

3.2.4. Rotating Grating/ring Around Y Axis CCW, Then Rotating Around X Axis and Z axis respectively

Experiment-B2-2: Rotate the grating/ring around the Y axis 60° CCW first (Figure 19a), then perform the following 4 experiments respectively.

Experiment-B2-2a: rotate the grating around X axis CW (Figure 19b)

Experiment-B2-2b: rotate the grating around X axis CCW (Figure 19c)

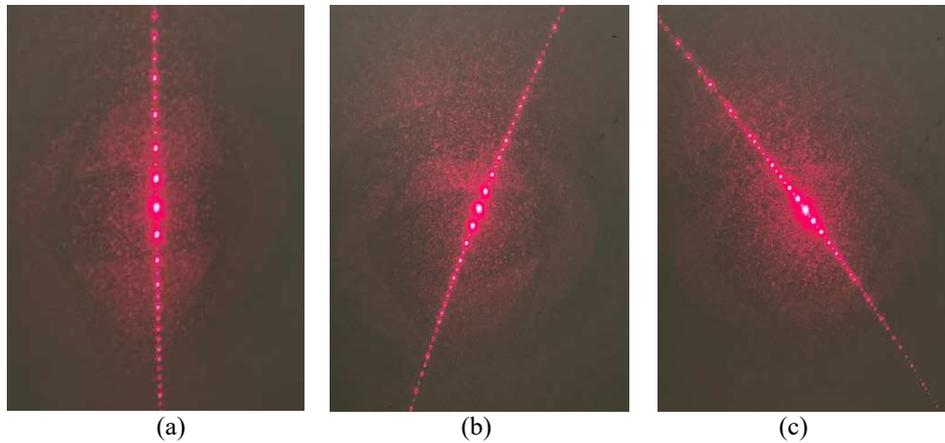


Figure 19. Rotate Grating/ring around Y axis CCW (a), then Rotating Grating around X axis CW (b) and CCW (c)

We observe that the patterns are curved after the grating rotates around the X axis.

Experiment-B2-2c: rotate the grating/ring/frame around the Z axis CW (Figure 20b)

Experiment-B2-2d: rotate the grating/ring/frame around the Z axis CCW (Figure 20c)

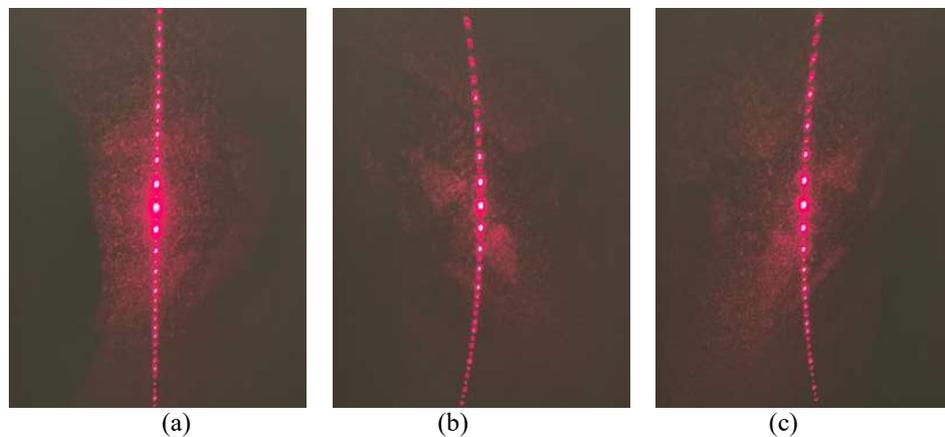


Figure 20. Rotate Grating/ring around Y axis CCW (a), then

Rotating grating/ring/frame around Z axis CW (b) and CCW (c)

It is the challenge to describe the curvature of the patterns.

3.2.5. Rotating Grating/ring/frame Around Z Axis CW, Then Rotating Around X Axis and Y axis respectively

Experiment-B3: Rotate the grating/ring/frame around the Z axis first

Experiment-B3-1: Rotate the grating/ring/frame around the Z axis CW (Figure 21a), then perform the following 4 experiments respectively.

Experiment-B3-1a: rotate the grating around X axis CW (Figure 21b)

Experiment-B3-1b: rotate the grating around X axis CCW (Figure 21c)

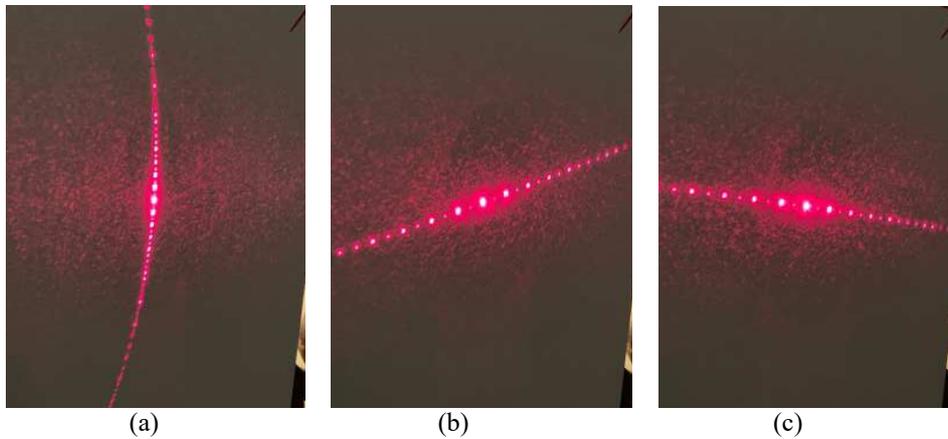


Figure 21. Rotating grating/ring/frame around Z axis CW:

Patterns due to rotating grating around X axis CW (b) and CCW (c)

The rotation of the grating/ring/frame around the Z axis makes the pattern curve (Figure 21a). After rotating the grating around the X axis, the Z component of the grating still makes the curved pattern but less curved, while the Y component of the grating makes the expanded patterns.

Experiment-B3-1c: rotate the grating/ring around the Y axis CW (Figure 22b)

Experiment-B3-1d: rotate the grating/ring around the Y axis CCW (Figure 22c)

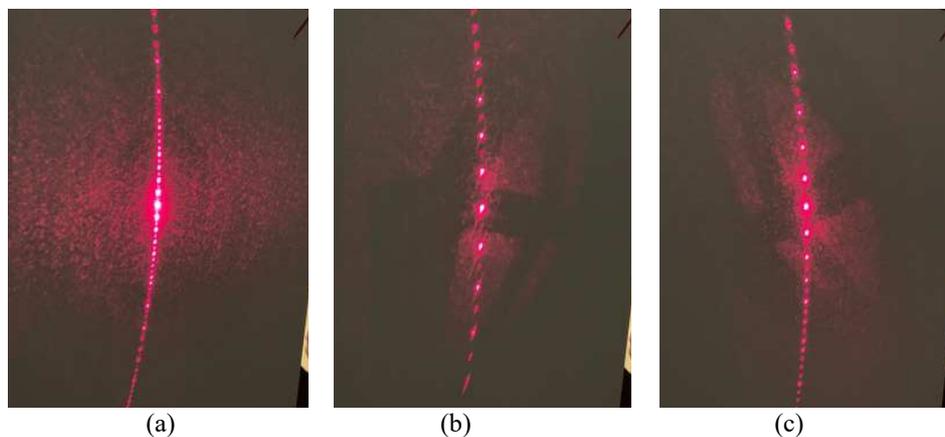


Figure 22. Rotating grating/ring/frame around Z axis CW: Patterns due to rotating grating/ring around Y axis CW (b) and CCW (c)

The rotation of the grating/ring/frame around the Z axis makes the pattern curve (Figure 18a). After rotating the grating/ring around the Y axis, the Z component of the grating still makes the curved pattern but less curved, while the Y component of the grating makes the expanded patterns.

3.2.6. Rotating Grating/ring/frame Around Z Axis CCW, Then Rotating Around X Axis and Y axis respectively

Experiment-B3-2: Rotate the grating/ring/frame around the Z axis *CCW* (Figure 23a), then perform the following 4 experiments respectively.

Experiment-B3-2a: rotate the grating around X axis CW (Figure 23b)

Experiment-B3-2b: rotate the grating around X axis CCW (Figure 23c)

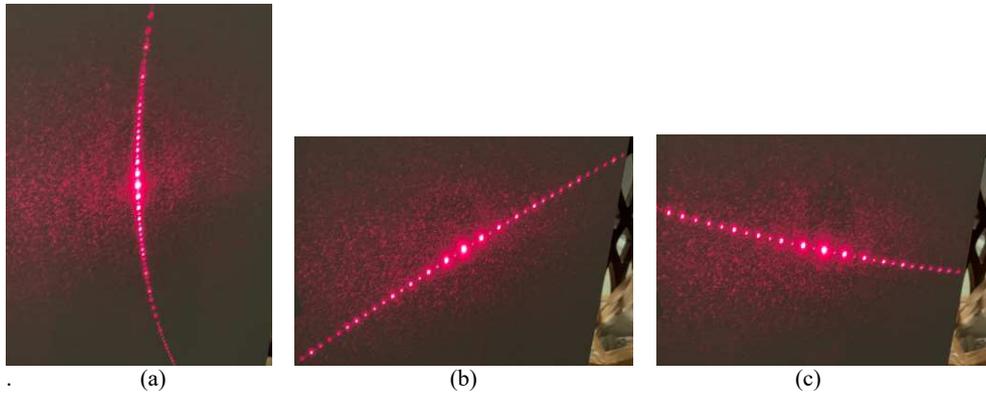


Figure 23. Rotating grating/ring/frame around the Z axis *CCW* (a): then rotating Grating around X axis CW (b) and rotating grating around X axis *CCW* (c)

We observed that, due to the rotation around the X axis, the curvatures become smaller, while the patterns expanded.

Experiment-B3-2c: rotate the grating/ring around the Y axis CW (Figure 24b)

Experiment-B3-2d: rotate the grating/ring around the Y axis *CCW* (Figure 24c)

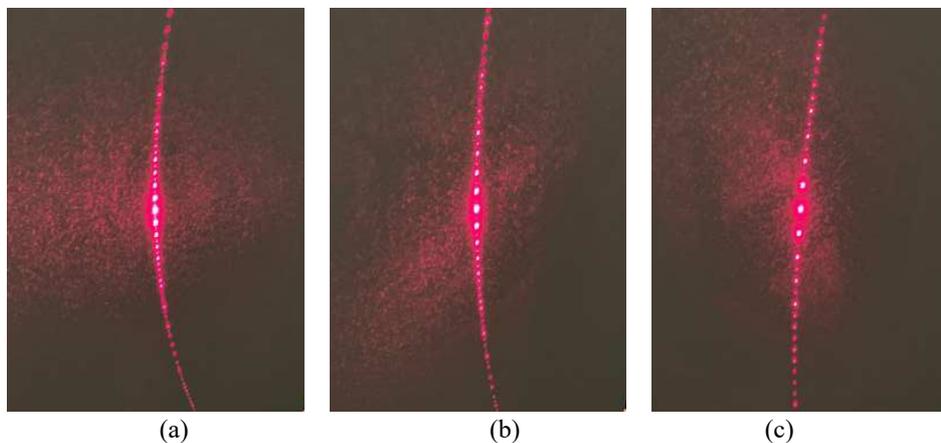


Figure 24. Rotate the grating/ring/frame around the Z axis CCW (Figure 20a), then rotate grating/ring around Y axis CW (b) and CCW (c)

Figure 24 shows that the rotation of the grating/ring around the Y axis expands the patterns and reduces the curvature of the curved pattern.

4. Patterns of 2D-Cross-Grating Are Created by Photons that Behave as Particle

We have shown that the patterns of the double slit/cross-double slit/1D-grating experiments are formed by photons behaving as particle, but not as waves [16] [15].

Let us show that the curved, expanded and inclined patterns observed in the cross-grating experiments are created by the photons that behave as particle, but not as waves.

Experiment-4: Placing a blocker between the cross-grating and the screen at different locations (Figure 25a).

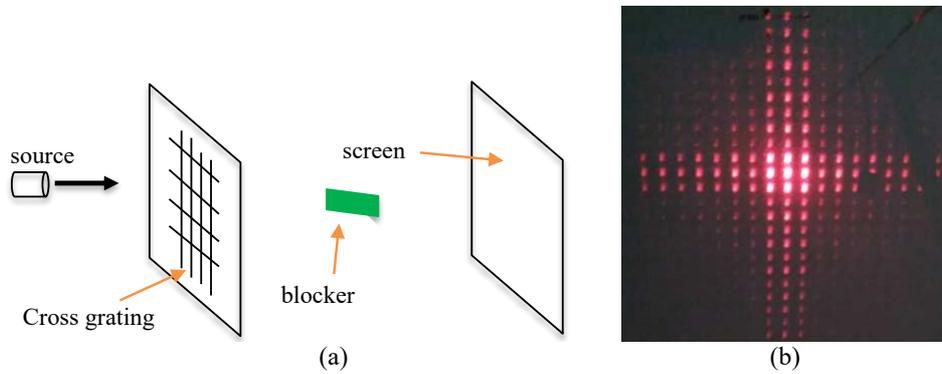
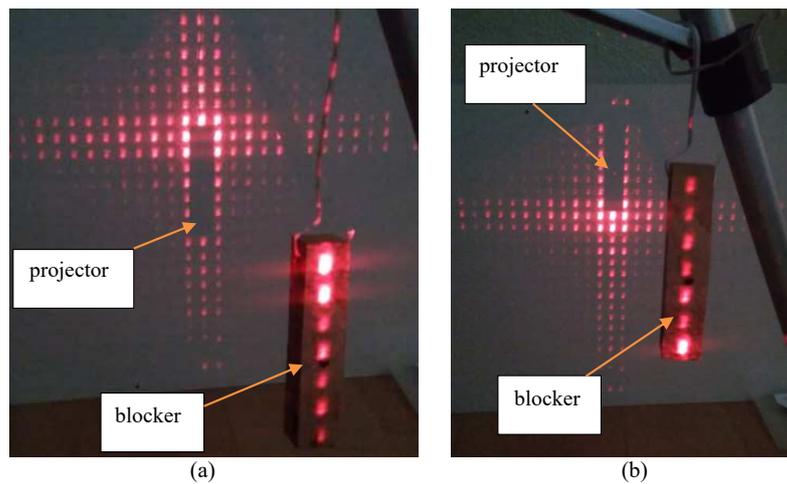


Figure 25. Schematic of Setup and Pattern of Cross-Grating without Blocker



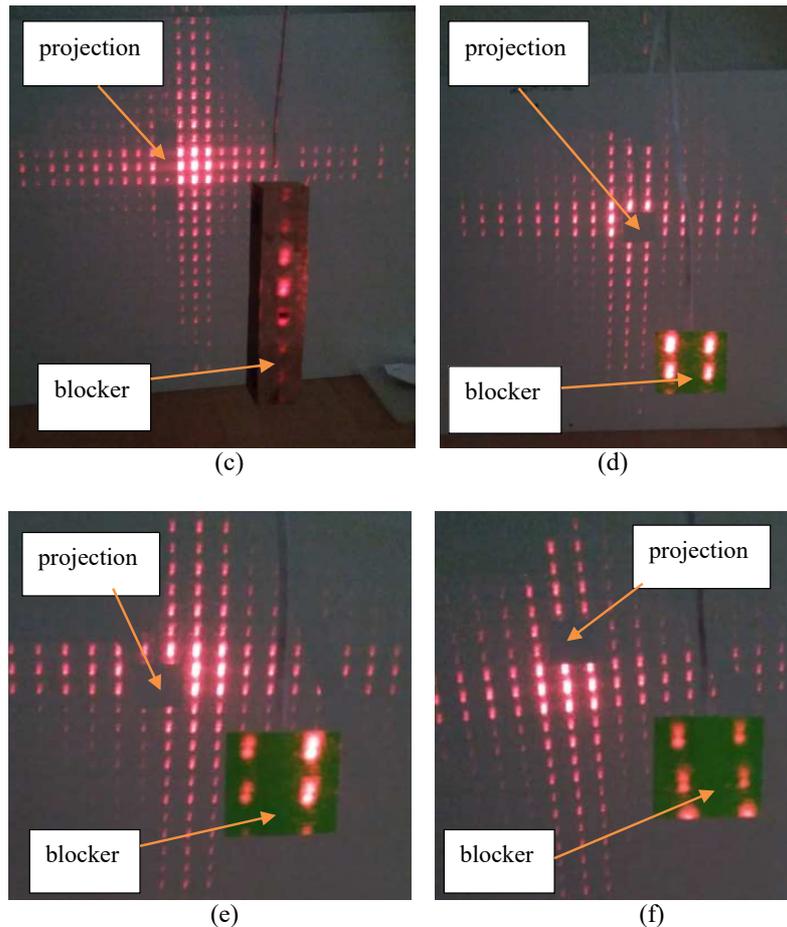


Figure 26. Blockers block partially patterns: blocks bottom portion of the vertical pattern (a); blocks top portion of the vertical pattern (b); blocks left portion of the horizontal pattern (c); blocks central portion of the pattern (d); blocks left center portion of the horizontal pattern (e); blocks top center portion of the vertical pattern (f)

Only propagation of particles can explain the above patterns. Namely the light propagates and creates the patterns as particles, but not as wave.

5. Discussion and Conclusion

We introduce the 3-axis-rotation apparatus, and associated coordinate system, that can rotate the double slit/cross-double slit/ grating/cross-grating to desired orientations. The apparatus makes it is possible to thoroughly study the orientation-dependence of the patterns of the grating without difficulty.

The experiments show that the patterns are curved, expanded and inclined differently, when the grating is at different orientations.

We suggest that a complete mathematical model should contain three rotation angles as parameters and should be able to describe all phenomena of the orientation-dependence of the patterns consistently. The phenomena would provide the comprehensive information/data for theorists.

The effects of the orientations on the patterns may be utilized in the applications.

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