WITHDRAWN: Curved, Expanded, Inclined and Mirror-Symmetric Diffraction Patterns of 2D-Cross-Grating— Rotating Grating Around Three Axes (2)

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Curved, Expanded, Inclined and Mirror-Symmetric Diffraction Patterns of 2D-Cross-Grating--- Rotating Grating Around Three Axes (2)

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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 introduced, which can rotate CW and CCW the 1D-double slit/2D-cross-double slit and 1D-grating/2D-cross-grating, respectively, 0^0-360^0 around three axes independently and sequentially. By this apparatus, the orientation-dependence of the diffraction patterns is systematically studied. The experiments are performed straightforwardly and intuitively. We show the mirror-symmetry of the diffraction patterns of the 2D-cross-grating for certain orientations. 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/cross-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, mirror-symmetry

Declaration: This article has no potential conflicts of interesting

Content

1. Introduction

The orientation-dependence, for certain orientations, of the conical diffraction patterns of the 1D-grating experiments have been studied theoretically and experimentally. J. E. Harvey and C. L. Vernold [1] discussed theoretically the conical diffraction pattern of the grating in terms of the direction cosines of the incident and diffracted angles, particularly for oblique incident angles and arbitrary grating orientation. The general grating equation for obliquely incident beams and arbitrarily oriented gratings was introduced. The "nonparaxial scalar diffraction theory" is used to predict the nonparaxial behavior. As an application of the conical diffraction, C. Braig, et al [2] introduced an alternative design for EUV beam-splitters.

Jetty et al [3] had introduced the experimental arrangement and the associated axis-system, with three axes, that is fixed to the grating. Then, they argued that to study the orientation-dependence of the diffraction patterns (hereafter, denoted as "pattern") of the grating, it is sufficient to rotate the grating around two axes out of the three axes, namely a total of ten orientations. They concluded that for an arbitrary orientation of the grating, the patterns have curved shapes. In their article, (1) the 1D-grating is used and rotated around two axes; (2) it is assumed that the clockwise rotation and counterclockwise rotation around the same axis create the same patterns; and (3) no expanded and inclined patterns are mentioned/shown; (4) no mirror-symmetry of the patterns is disclosed.

Based on energy- and momentum conservation, Georg Heuberger, et al [4] discussed the general case of off-plane diffraction geometries and derived the basic equations for the positions of the diffraction maxima for their angular dependence [4]. In their article, (1) the 1D-grating is used and rotated in two directions; (2) it is assumed that the clockwise rotation and counterclockwise rotation create the same patterns; and (3) no expanded and inclined patterns are mentioned/shown; (4) no mirror-symmetry of the patterns is mentioned/shown.

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 interference 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 patterns 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 cross-grating. However, the study only coves the orientations by rotating the cross-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 pattern and the curved 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 wave interpretation of the double slit/grating experiments, the wave-particle duality and the complementarity principle [15]. The particle nature of the light in the double slit/cross-double slit/grating experiments has been shown [16] [17] [18] [19].

To study the orientation-dependence completely, in this article, we use [19]: (1) the three-axis-rotation apparatus; and (2) a new coordinate system associated with 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. We show the mirror-symmetry of the patterns of the 2D-cross-grating for certain orientations. Note that, in this article of the series articles, we only show the orientation-dependence of the patterns of the 2D-transmission cross-grating rotating around two axes.

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

Note that the curved patterns of the grating and of the cross-grating in this article are different from that in References [1] [2] [3] [4].

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

2. Three-Axis-Rotation Apparatus: Rotating Cross-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 cross-grating. For this aim, we use the three-axis-rotation apparatus [19] that can rotate the double slit/cross-double slit and grating/cross-grating around 3 axes to reach desired orientations (Figure 1).

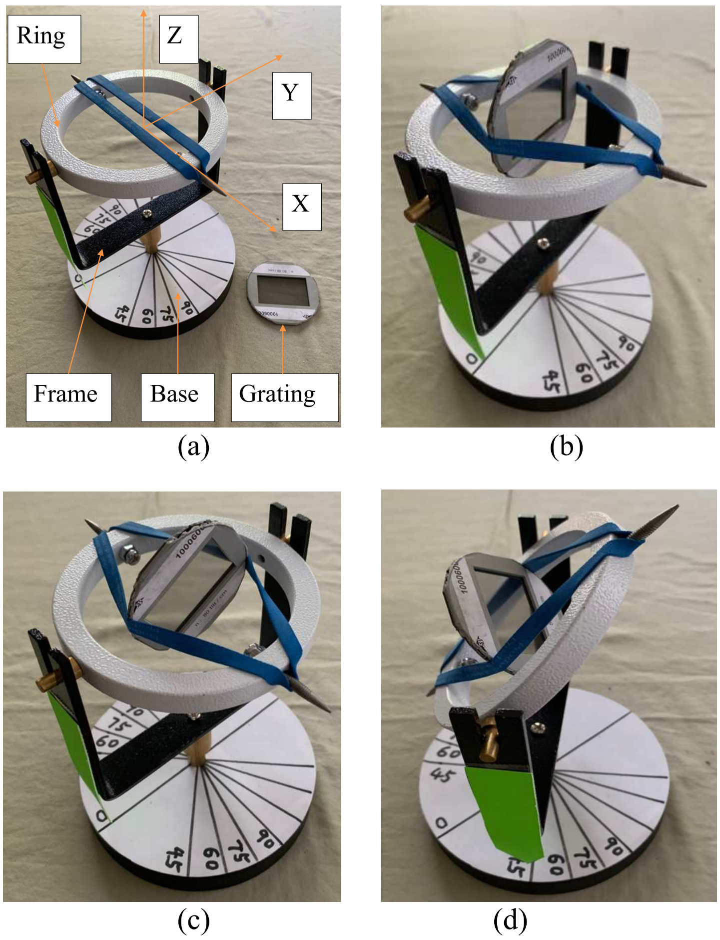


Figure 1. Experimental setup: the 3-axis-rotation apparatus:

the grating/ring/frame can rotate around Z axis; the grating/ring can rotate around Y axis;

the cross-grating can rotate around X axis.

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 the original orientation of the grating. Figure 2c shows that the grating rotates around the X axis. Figure 2d shows that the cross-grating, the ring/cross-grating, and the frame/ring/cross-grating rotate around the X axis, the Y axis and the Z axis respectively.

The shortcoming of the above apparatus 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 blockage. An alternative apparatus shown in Figure 2 is convenience to perform the experiments

Figure 2. The alternative 3-axis rotation apparatus

With those apparatuses, the orientation-dependence of the patterns of the cross-grating 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 cross-grating (Figure 1).

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

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 always. The laser beam points to the same direction always.

Original orientation of the cross-grating: At the original orientation, the X, Y and Z axes form the Cartesian coordinate system (Figure 3a), denoted it as the original coordinate system. The horizontal slits, denoted as S1, of the cross-grating are along the Y axis and creates the vertical pattern P1, while the vertical slits, denoted as S2, of the cross-grating are along the Z axis and create the horizontal pattern P2 (Figure 3b and 3c). The laser source is on the X axis, i.e., the light beam is normally incident on the plane of the cross-grating, referred it as the original orientation.

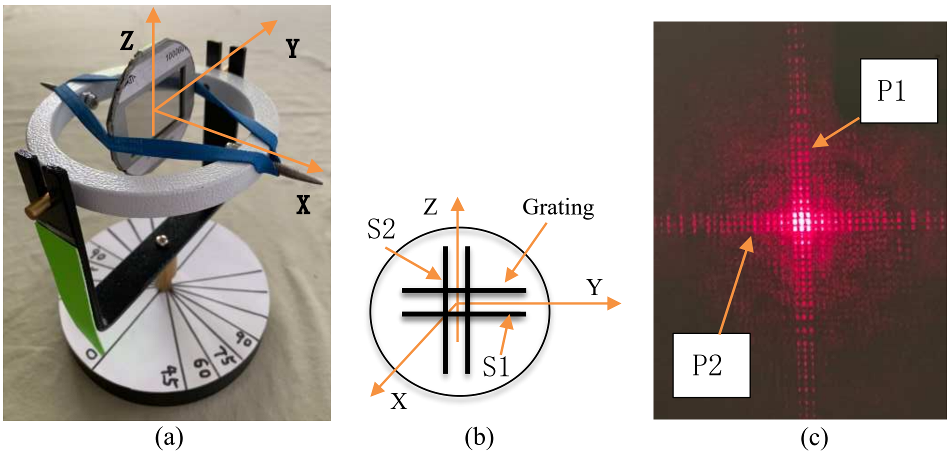


Figure 3. Apparatus/Coordinate (a), Cross-grating (b) and Pattern (c)

Direction of Rotation: to define the direction of the CW and CCW rotation, we introduce the right-hand rule that states 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 4).

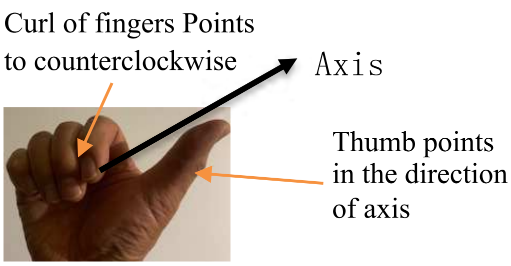


Figure 4. Right-hand rule for determining direction of rotation

2.3. Rotating Cross-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, the effects of the orientations on the patterns need to be considered when the following rotations are performed:

(A) Starting from the original orientation, then, rotating the cross-grating around one axis only:

(A1) Rotate the cross-grating around the X axis: CW α and CCW α, respectively

(A2) Rotate the cross-grating/ring around the Y axis: CW β and CCW β, respectively

(A3) Rotate the cross-grating/ring/frame around the Z axis: CW γ and CCW γ, respectively

(B) Starting from the original orientation, then, rotating the cross-grating around 2 axes, respectively:

(B1) Rotate (CW α and CCW α) the cross-grating around the X axis, then, rotate the cross-grating around the Y and Z axes, respectively,

X axis (CW α):	X axis (CCW α):
Y axis (CW β)	Y axis (CW β)
Y axis (CCW β)	Y axis (CCW β)
Z axis (CW γ)	Z axis (CW γ)
Z axis (CCW γ)	Z axis (CCW γ)

(B2) Rotate (CW β and CCW β) the cross-grating/ring around the Y axis, then, rotate the cross-grating around the Z and X axes, respectively,

Y axis (CW β):	Y axis (CCW β):
Z axis (CW γ)	Z axis (CW γ)
Z axis (CCW γ)	Z axis (CCW γ)
X axis (CW α)	X axis (CW α)
X axis (CCW α)	X axis (CCW α)

(B3) Rotate (CW γ and CCW γ) the cross-grating/ring/frame around the Z axis, then, rotate the cross-grating around the X and Y axes, respectively,

Z axis (CW γ):	Z axis (CCW γ):
X axis (CW α)	X axis (CW α)
X axis (CCW α)	X axis (CCW α)
Y axis (CW β)	Y axis (CW β)
Y axis (CCW β)	Y axis (CCW β)

(C) Starting from the original orientation, then, rotating the cross-grating around 3 axes respectively:

(C1) Rotate (CW α and CCW α) the cross-grating around the X axis, then, rotating the cross-grating around the Y axis + Z axis, and the Z axis + Y axis, respectively,

X axis (CW α):	X axis (CCW α):
Y axis (CW β) + Z axis (CW γ)	Y axis (CW β) + Z axis (CW γ)
Y axis (CW β) + Z axis (CCW γ)	Y axis (CW β) + Z axis (CCW γ)
Y axis (CCW β) + Z axis (CW γ)	Y axis (CCW β) + Z axis (CW γ)
Y axis (CCW β) + Z axis (CCW γ)	Y axis (CCW β) + Z axis (CCW γ)

Z axis (CW γ) + Y axis (CW β)	Z axis (CW γ) + Y axis (CW β)
Z axis (CW γ) + Y axis (CCW β)	Z axis (CW γ) + Y axis (CCW β)
Z axis (CCW γ) + Y axis (CW β)	Z axis (CCW γ) + Y axis (CW β)
Z axis (CCW γ) + Y axis (CCW β)	Z axis (CCW γ) + Y axis (CCW β)

(C2) Rotate (CW β and CCW β) the cross-grating/ring around the Y axis, then, rotating the cross-grating around the Z axis + X axis, and the X axis + Z axis, respectively,

Y axis (CW β):	Y axis (CCW β):
Z axis (CW γ) + X axis (CW α)	Z axis (CW γ) + X axis (CWα)
Z axis (CW γ) + X axis (CCW α)	Z axis (CW γ) + X axis (CCWα)
Z axis (CCW γ) + X axis (CW α)	Z axis (CCW γ) + X axis (CWα)
Z axis (CCW γ) + X axis (CCW α)	Z axis (CCW γ) + X axis (CCWα)
X axis (CW α) + Z axis (CW γ)	X axis (CW α) + Z axis (CW γ)
X axis (CW α) + Z axis (CCW γ)	X axis (CW α) + Z axis (CCW γ)
X axis (CCW α) + Z axis (CW γ)	X axis (CCW α) + Z axis (CW γ)
X axis (CCW α) + Z axis (CCW γ)	X axis (CCW α) + Z axis (CCW γ)

(C3) Rotate (CW γ and CCW γ) the cross-grating/ring/frame around the Z axis, then, rotating the cross-grating around the X axis + Y axis, and the Y axis + X axis, respectively,

Z axis (CW γ):	Z axis (CCW γ):
X axis (CW α) + Y axis (CW β)	X axis (CW α) + Y axis (CW β)
X axis (CW α) + Y axis (CCW β)	X axis (CW α) + Y axis (CCW β)
X axis (CCW α) + Y axis (CW β)	X axis (CCW α) + Y axis (CW β)
X axis (CCW α) + Y axis (CCW β)	X axis (CCW α) + Y axis (CCW β)
Y axis (CW β) + X axis (CW α)	Y axis (CW β) + X axis (CW α)
Y axis (CW β) + X axis (CCW α)	Y axis (CW β) + X axis (CCW α)
Y axis (CCW β) + X axis (CW α)	Y axis (CCW β) + X axis (CW α)
Y axis (CCW β) + X axis (CCW α)	Y axis (CCW β) + X axis (CCW α)

When rotate the cross-grating, the ring and the frame, we always rotate CCW and CW respectively. For rotating around one axis, rotating CW and CCW creates the mirror-symmetry patterns.

3. Experiments: Novel Phenomena of Cross-grating

3.1. Rotating Cross-grating Around One Axis

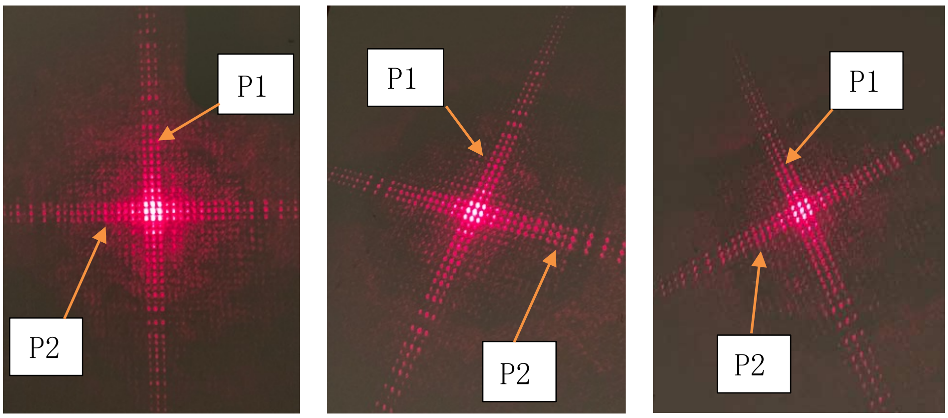
Let us start from the original orientation (Figure 3b). The horizontal slits of the cross-grating are along the Y direction, while the vertical slits are along the Z direction.

Then, rotating the 2D-cross-grating around one axis.

3.1.1. Rotating Cross-grating Around X axis

Experiment-A1: Rotating Cross-grating Around X axis:

Starting from the original orientation, i.e., the light beam is normally incident. When the cross-grating rotates CW and CCW around the X axis, the characteristics of the patterns remain the same. The patterns P1 and P2 rotate the same angles as that of the cross-grating.



(a) (b) (c)

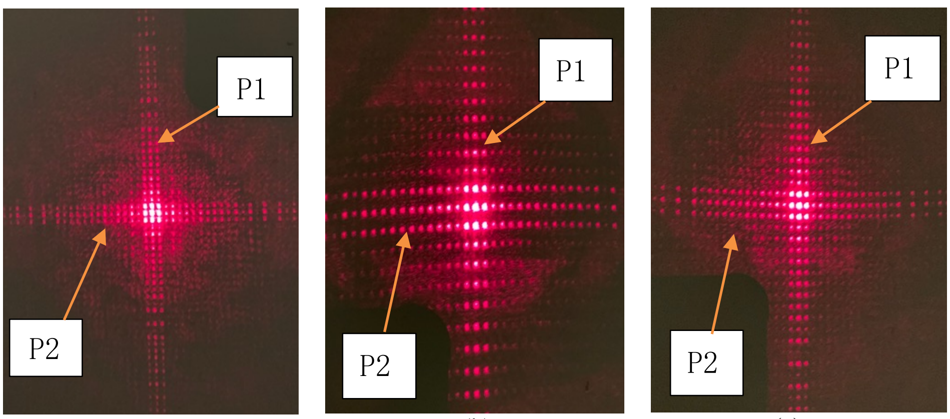
Figure 5. Cross-grating rotating around X axis: (a) shows the pattern of the cross-grating at the original orientation; (b) shows the pattern of cross-grating rotating CW 25^0; (c) CCW 25^0

Figure 5b and 5c show the pattern due to the CW and CCW rotations of the cross-grating, respectively.

3.1.2. Rotating Cross-grating Around Y axis

Experiment-A2: Rotating Cross-grating/Ring Around Y axis

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



(a) (b) (c)

Figure 6. Expanded and Curved Patterns:

Cross-grating/ring rotating around Y Axis CW $\beta = 70^0$ (b) and CCW $\beta = 60^0$ (c)

Figure 6a shows the pattern of the cross-grating at the original orientation. There are three primary vertical patterns P1, three primary horizontal patterns P2, and minor vertical patterns. Either CW rotation or CCW rotation of the cross-grating determine the direction of the patterns curved towards [9]. The primary pattern P2 is curved downwards due to the CW rotation (Figure 6b), which satisfy the right-hand rule. The primary pattern P2 is curved upwards due to the CCW rotation (Figure 6c), which satisfy the left-hand rule. The minor patterns are curved with the primary patterns. The vertical patterns P1 are expanded (Figure 6b and 6c). The larger the rotation angle, the larger the curvature and the larger the expansion. Note that the degrees of the expansions are independent whether the grating is rotation CW or CCW.

3.1.3. Rotating Cross-grating Around Z axis

Experiment-A3: Rotating Cross-grating/ring/frame Around Z axis

We observed that the vertical patterns (including primary and minor patterns) P1 curve, and the horizontal patterns (including primary and minor patterns) P2 expand (Figure 7b and 7c).

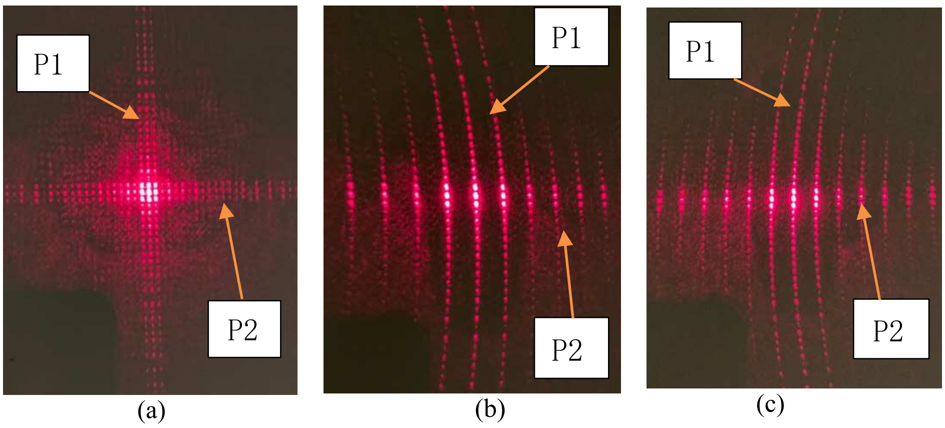


Figure 7. Curved patterns attribute to: CW rotation 70^0 (b) and CCW rotation 60^0 (c)

Figure 7a shows the pattern of the cross-grating at the original orientation. Figure 7b shows that the primary pattern P1 is curved towards the left due to the CW rotation, which satisfy the right-hand rule. Figure 7c shows that the primary pattern P1 is curved towards the right due to the CCW rotation, which satisfy the left-hand rule. The minor patterns are curved with the primary patterns. The horizontal patterns P2 are expanded (Figure 7b and 7c). The larger the rotation angle, the larger the curvature and the larger the expansion. The expansions are independent whether the grating is CW or CCW rotation.

3.2. Rotating Cross-grating Around Two Axes Sequentially

In this section, we perform the following experiments. Since the direction of the curved patterns is determined by the directions of the rotations, so in the following experiments, we rotate the cross-grating CW and CCW, respectively. The experiments are the following.

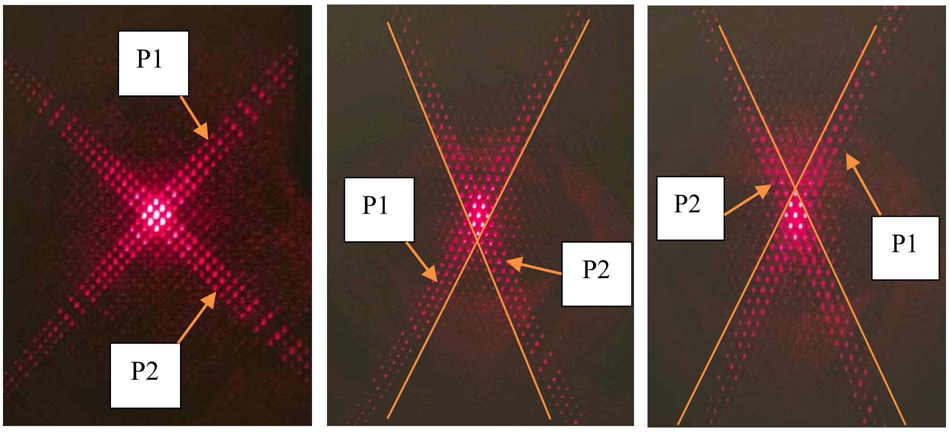
3.2.1. Rotating Cross-grating Around X+Y Axes and X+Z Axes

Experiment-B1: Rotate, CW and CCW, the cross-grating around the X axis first, then rotate, CW and CCW, the cross-grating around the Y axis and the Z axis, respectively.

Experiment-B1-1: Rotate the cross-grating CW around the X axis 45^0 (Figure 8a), then perform the following 4 experiments respectively.

Experiment-B1-1a: rotate the cross-grating/ring around Y axis 65^0 CW (Figure 8b)

Experiment-B1-1b: rotate the cross-grating/ring around Y axis 65^0 CCW (Figure 8c)



(a) (b) (c)

Figure 8. (a) shows the pattern of the original orientation; (b) and (c) show the curved (Shown by the orange lines) and expanded patterns, while the patterns inclined towards to the direction (the Z axis) that is perpendicular to the rotation axis (the Y axis)

Figure 8b and 8c show the curved, expanded and inclined patterns due to the rotation around the Y axis. The Y components of the slits of the grating create the expansion, while the Z components of the slits create the curved pattern. The slits as a whole tilting to the Y axis create the inclination of the patterns [5] [19]. The larger the rotation angle, the larger the curvature, the larger the expansion and inclined more. The different rotations, CW and CCW, cause the patterns curved toward to different directions.

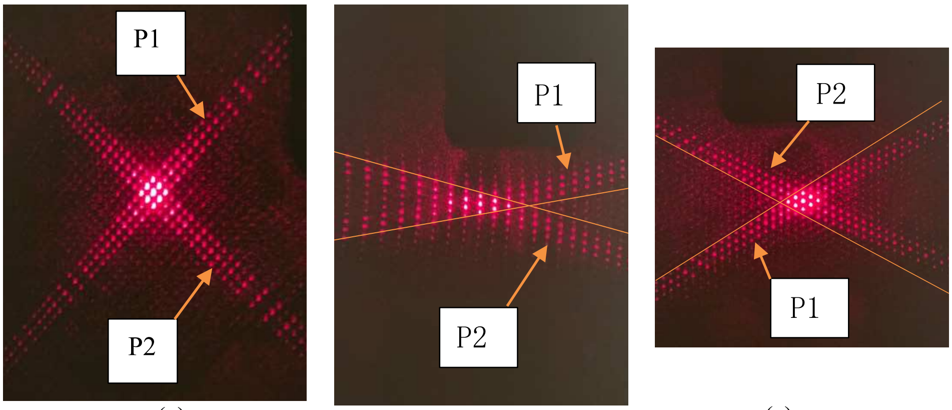
The behaviors of P1 are consistent with Figure 9 of Ref. [19]. The behaviors of P2 are consistent with Figure 13 of Ref. [19]

Experiment-B1-1c: rotate the cross-grating/ring/frame around the Z axis 75^0 CW (Figure 9b)

Experiment-B1-1d: rotate the cross-grating/ring/frame around the Z axis 65^0 CCW (Figure 9c)

Figure 9b and 9c show the curved, expanded and inclined patterns due to the rotation around the Z axis. The Y components of the slits of the grating curve the patterns, while the Z components of the slits expand the pattern. The slits as a whole tilting from the Z axis create the inclination of the patterns

[5] [19]. The larger the rotation angle, the larger the curvature, the larger the expansion and inclined more. The different rotation, CW and CCW, cause the patterns curved toward to different directions.



(a) (b) (c)

Figure 9. Cross-grating rotates CW around X axis at 45^0 (a), then: the grating rotates CW around Z axis 75^0 (b); the grating rotates CCW around the Z axis 65^0 (c)

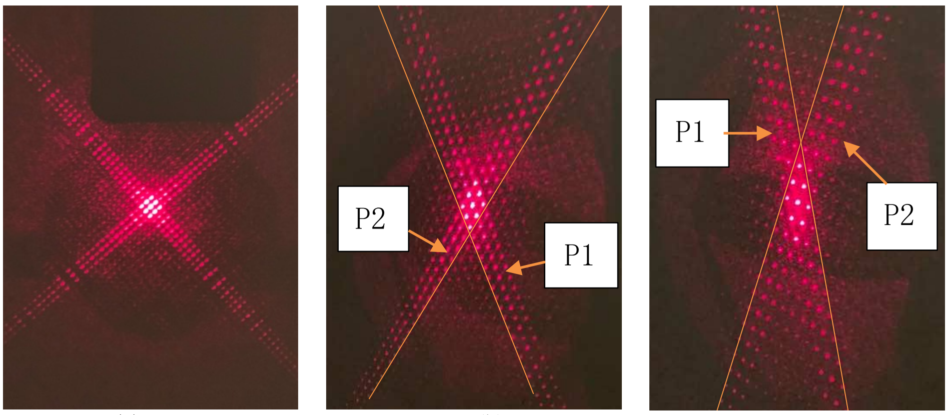
Since the grating rotating CCW 45^0 around the X axis and then, rotating CW 75^0 around the Z axis and CCW 65^0, respectively, the pattern due to the CW rotation is inclined more than the pattern due to the CCW rotation. P1 and P2 in both Figure 9b and 9c are curved and expanded the same.

The behaviors of P1 are consistent with Figure 10 of Ref. [19]. The behaviors of P2 are consistent with Figure 14 of Ref. [19]

Experiment-B1-2: Rotate the cross-grating around the X axis 45^0 CCW, then perform the following 4 experiments respectively.

Experiment-B1-2a: rotate the cross-grating/ring around Y axis 60^0 CW (Figure 10b).

Experiment-B1-2b: rotate the cross-grating/ring around Y axis 70^0 CCW (Figure 10c).



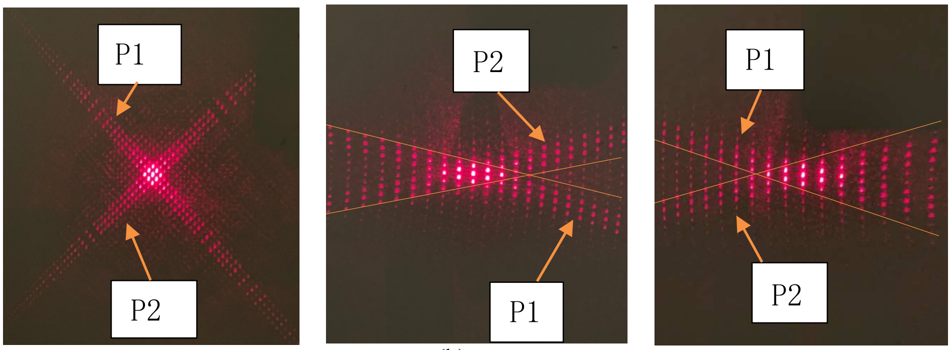
(a) (b) (c)

Figure 10. Grating rotating CCW 45^0 around X axis, then rotating grating around Y CW and CCW: P1 and P2 curve the same in (b), while P2 expands more than P1.

For the cross-grating rotating CCW 45^0 around the X axis, the Z-components of the slits S1 are the same as that of the slits S2, therefore the pattern P1 and P2 are curved, expanded and inclined the same.

Experiment-B1-2c: rotate CW 70^0 the cross-grating/ring/frame around the Z axis (Figure 11b)

Experiment-B1-2d: rotate CCW $70^0$the cross-grating/ring/frame around the Z axis (Figure 11c)



(a) (b) (c)

Figure 11. X CCW 45 then Z CW 70 and CCW 70

Figure 11b and 11c show the curved, expanded and inclined patterns due to the rotation around the Z axis. The Y components of the slits of the grating create the curve, while the Z components of the slits create the expanded pattern. The slits as a whole tilting to the Z axis create the inclination of the patterns [5] [19]. The larger the rotation angle, the larger the curvature, the larger the expansion and inclined more. The different rotation directions, CW and CCW, cause the patterns curved toward to different directions.

3.2.2. Rotating Cross-grating Around Y+Z Axes and Y+X Axes

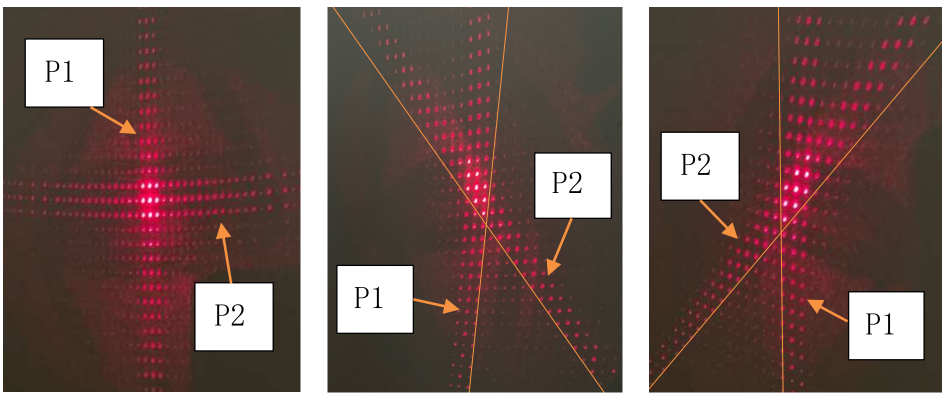
Second, let us rotate the cross-grating around the Y axis first.

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

Experiment-B2-1: Rotate the cross-grating/ring around the Y axis CW 60^0 (Figure 12a), then perform the following 4 experiments, respectively.

Experiment-B2-1a: rotate the cross-grating/ring/frame around the Z axis CW 45^0 (Figure 12b)

Experiment-B2-1b: rotate the cross-grating/ring/frame around the Z axis CCW 45^0 (Figure 12c)



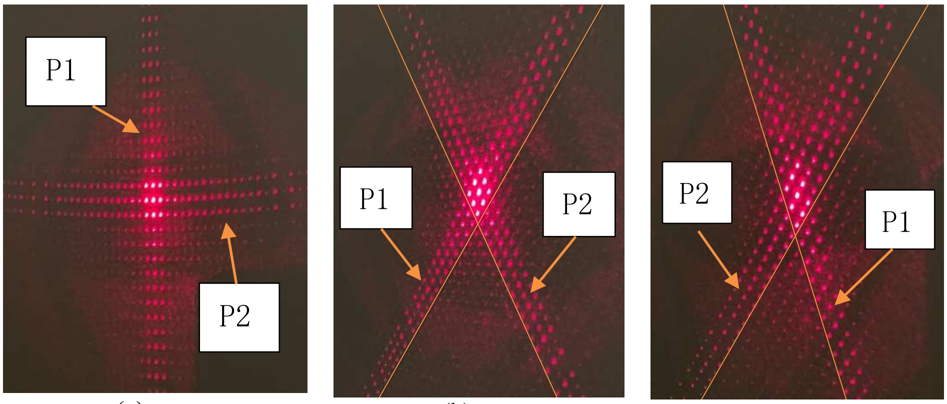
(a) (b) (c)

Figure 12. Curved pattern P2 in (a) is created by the rotation of cross-gratin around Y axis. Curved patterns P1s in (b) and (c) are created by rotation of cross-grating around Z axis, respectively.

When the cross-grating rotates CW around the Z axis, P1 curves towards the left, and P2 rotates CCW and less curve as shown in Figure 12 (b). When the cross-grating rotates CCW around the Z axis, P1 curves towards the right, and P2 rotates CW and less curve as shown in Figure 12(c). The curved P1 in Figure 12 b and 12c keep vertical.

Experiment-B2-1c: rotate the cross-grating around X axis CW 60^0 Figure 13(b)

Experiment-B2-1d: rotate the cross-grating around X axis CCW 60^0 Figure 13(c)



(a) (b) (c)

Figure 13. Curved pattern P2 in (a) is created by the rotation of cross-gratin around Y axis. Curved patterns P1s in (b) and (c) are created by rotation of cross-grating around Z axis, respectively.

When the cross-grating rotates CW around the X axis, P1 curves towards the left, and P2 rotates CCW and less curve as shown in Figure 13 (b). When the cross-grating rotates CCW around the X axis, P1 curves towards the right, and P2 rotates CW and less curve as shown in Figure 12(c). The curved P1 in Figure 13 b and 12c rotate CW and CCW, respectively.

Experiment-B2-2: Rotate the cross-grating/ring around the Y axis 60^0 *CCW* (Figure 14a), then perform the following 4 experiments respectively.

Experiment-B2-2a: rotate the cross-grating/ring/frame around the Z axis CW 45^0 (Figure 14b)

Experiment-B2-2b: rotate the cross-grating/ring/frame around the Z axis CCW 45^0 (Figure 14c)

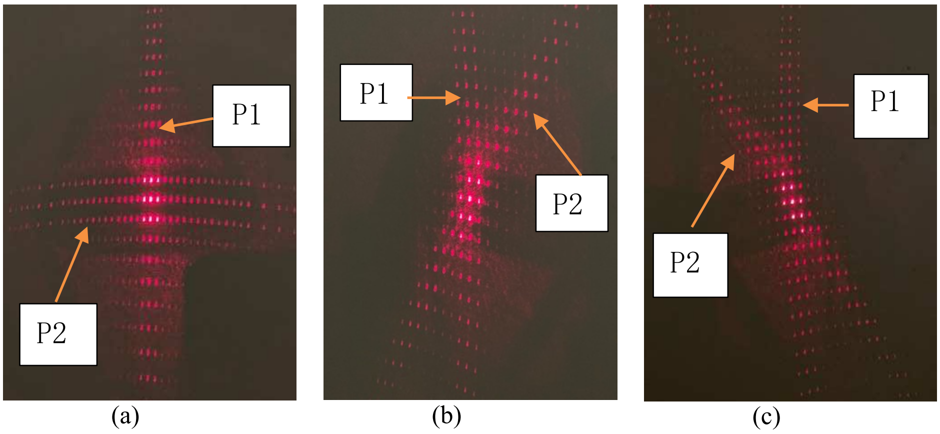


Figure 14. Curved pattern P2 in (a) is created by the rotation of cross-gratin around Y axis.

P1 patterns in (b) and (c) are vertical and curved,

which are due to rotations of cross-grating around Z axis

When the cross-grating rotates CW around the Z axis, P1 curves towards the left, and P2 rotates CCW and less curve as shown in Figure 14(b). When the cross-grating rotates CCW around the Z axis, P1 curves towards the right, and P2 rotates CW and less curve as shown in Figure 14(c).

Experiment-B2-2c: rotate the cross-grating around X axis CW 45^0 (Figure 15b)

Experiment-B2-2d: rotate the cross-grating around X axis CCW 45^0 (Figure 15c)

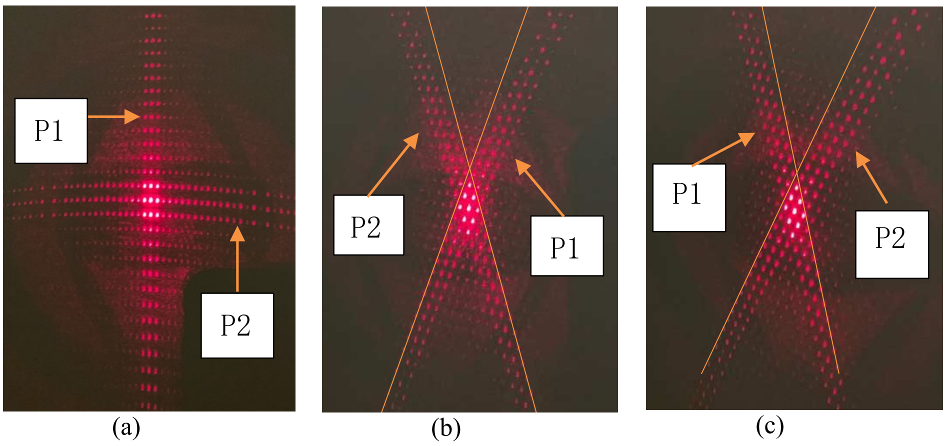


Figure 15. Curved pattern P2 in (a) is created by the rotation of cross-gratin around Y axis.

P1 patterns in (b) and (c) are curved *due to rotations of cross-grating around X axis*

Before rotating around the X axis, S1 has no Z component, thus, when rotate the cross-grating around the Y axis, P1 expanded only. After rotating CW or CCW around the X axis, S1 has Z component, thus, when rotate the cross-grating around the Y axis, P1 are not only expanded but also curved and inclined.

3.2.3. Rotating Cross-grating Around Z+X Axes and Z+Y Axes

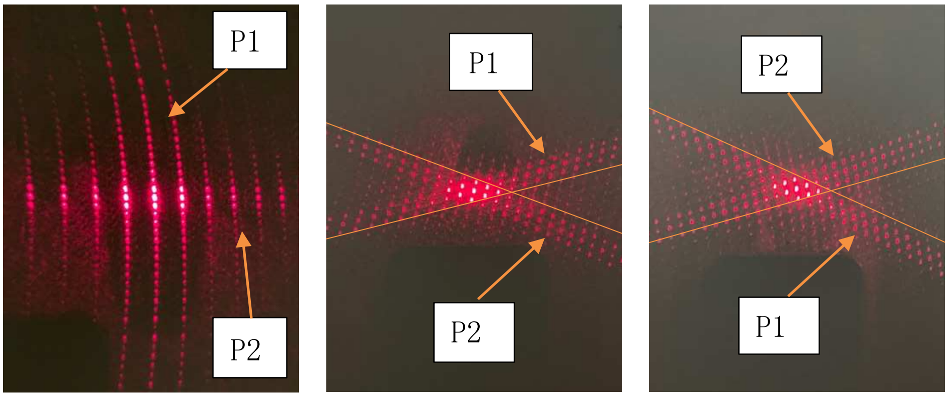
Third, let us rotate the cross-grating/ring/frame around the Z axis first.

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

Experiment-B3-1: Rotate the cross-grating/ring/frame around the Z axis CW 60^0 (Figure 16a), then perform the following 4 experiments respectively.

Experiment-B3-1a: rotate the cross-grating around X axis CW 45^0 (Figure 16b)

Experiment-B3-1b: rotate the cross-grating around X axis CCW 45^0 (Figure 16c)



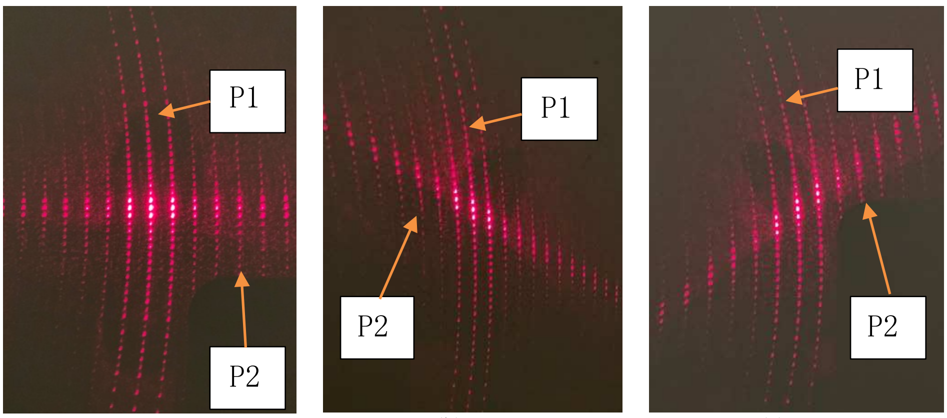
(a) (b) (c)

Figure 16. Curved pattern P1 and expanded pattern P2 in (a); (b) shows that P1 curved upwards, P2 curved downwards, while P1 and P2 inclined toward to the Y axis; (c) shows that P1 curved downwards, P2 curved upwards, while P1 and P2 inclined toward to the Y axis

Curved pattern P1 and expanded pattern P2 in (a) are created by rotating CW cross-gratin around Z axis. After rotating CW or CCW around the X axis, S1 gets Z component, thus, P1 are not only curved but also expanded and inclined; Also S2 gets Y component, thus, when rotate the cross-grating around the X axis, P2 are not only expanded but also curved and inclined;

Experiment-B3-1c: rotate the cross-grating/ring around the Y axis CW 45^0 (Figure 17b)

Experiment-B3-1d: rotate the cross-grating/ring around the Y axis CCW 45^0 (Figure 17c)



(a) (b) (c)

Figure 17. Curved pattern P1 and expanded pattern P2 in (a); (b) shows that P2 inclined toward to the Z axis; (c) shows that P2 inclined toward to the Z axis

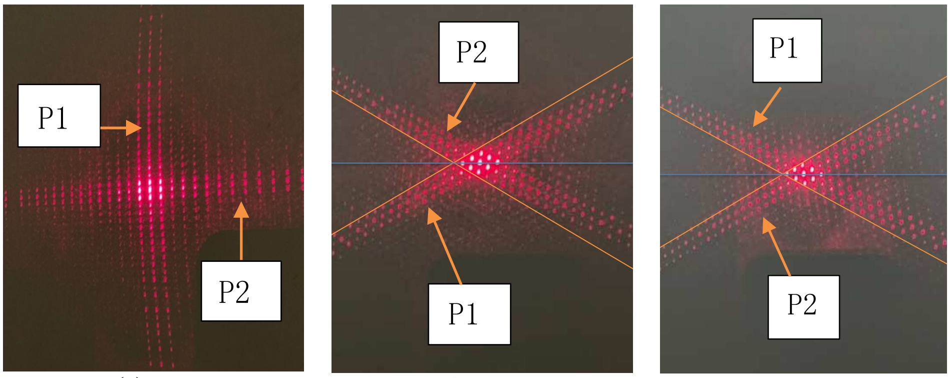
Curved patterns P1 in (a) (b) (c) are created by rotating CW cross-grating around Z axis. The expanded patterns P2 in (b) (c) are created by rotating CW cross-grating around Z and Y axes.

It is challenge to me to explain the behavior of P2 after rotating CW and CCW the cross-grating around the Y axis.

Experiment-B3-2: Rotate the cross-grating/ring/frame around the Z axis CCW 60^0, then perform the following 4 experiments respectively.

Experiment-B3-2a: rotate the cross-grating around X axis CW 45^0 (Figure 18b)

Experiment-B3-2b: rotate the cross-grating around X axis CCW 45^0 (Figure 18c)



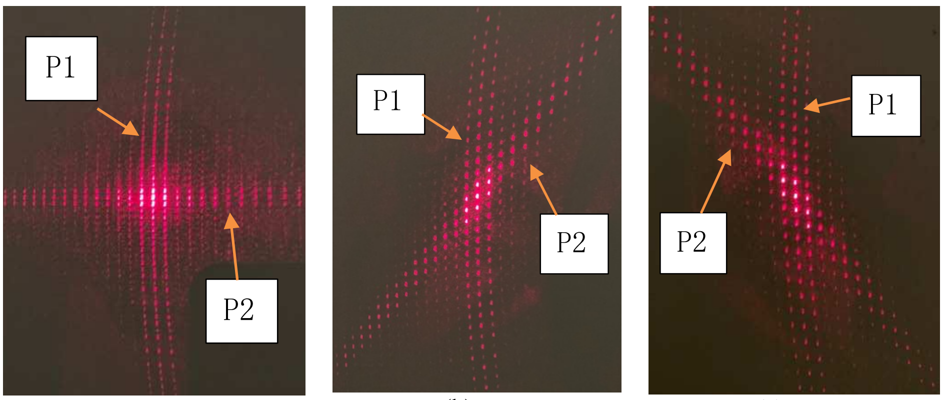
(a) (b) (c)

Figure 18. Curved pattern P1 and expanded pattern P2 in (a); (b) shows that P1 curved downwards, P2 curved upwnwards, while P1 and P2 inclined toward to the Y axis; (c) shows that P1 curved upwards, P2 curved downwards, while P1 and P2 inclined toward to the Y axis

Curved pattern P1 and expanded pattern P2 in (a) are created by rotating CCW cross-gratin around Z axis. After rotating CW or CCW around the X axis, S1 gets Z component, thus, P1 are not only curved but also expanded and inclined; Also S2 gets Y component, thus, when rotate the cross-grating around the X axis, P2 are not only expanded but also curved and inclined;

Experiment-B3-2c: rotate the cross-grating/ring around the Y axis CW (Figure 19b)

Experiment-B3-2d: rotate the cross-grating/ring around the Y axis CCW (Figure 19c)



(a) (b) (c)

Figure 19. Curved pattern P1 and expanded pattern P2 in (a); (b) shows that P2 curved upwards, while P2 inclined toward to the Z axis; (c) shows that P2 curved downwards, while P2 inclined toward to the Z axis

Curved patterns P1 in (a) (b) (c) are created by rotating CW cross-grating around Z axis. The expanded patterns P2 in (b) (c) are created by rotating CW cross-grating around Z axis.

It is challenge to me to explain the behavior of P2 after rotating CW and CCW the cross-grating around the Y axis.

4. Rotation Symmetry and Mirror Symmetry

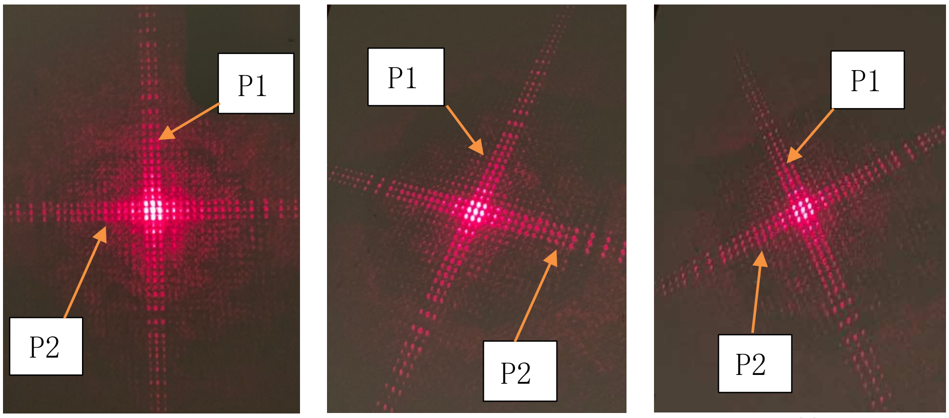
In this section, for convenience, we use the coordinate defined in Section 2.2 and introduce two terms:

Whole-Pattern: the pattern as a whole, for example, the pattern of Figure 6b, is denoted as "Whole-pattern".

Sub-Pattern: the patterns as a part of the whole pattern, for example, P1 (or P2) in Figure 6b, is denoted as "Sub-pattern".

4.1. Rotation symmetry

Starting from the original orientation, i.e., the light beam is normally incident, when the cross-grating rotates CW and CCW around the X axis, the patterns show the rotation symmetry.



(a) (b) (c)

Figure 5. Rotation symmetry: Cross-grating rotating around X axis:

(a) shows the pattern of the cross-grating at the original orientation;

(b) shows the pattern of cross-grating rotating CW 25^0; (c) CCW 25^0

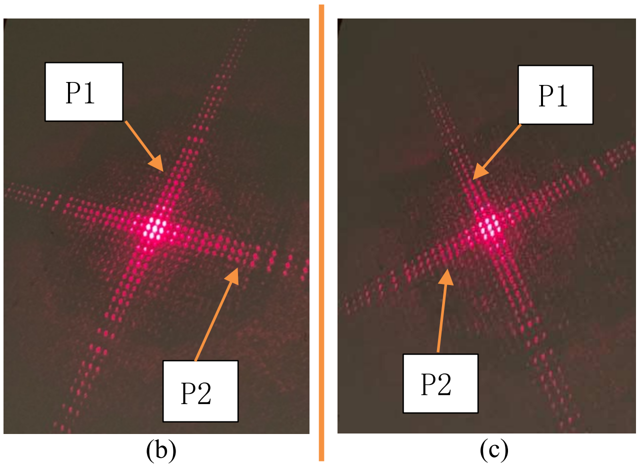
Figure 5b and Figure 5c show the pattern due to the CW and CCW rotations of the cross-grating, respectively. The patterns of the cross-grating have the rotation symmetry when the cross-grating rotates around the X axis and the laser beam is on the normal vector of the grating, the X axis.

When the cross grating rotates around the X axis, the whole patterns show the rotation symmetry (Figure 5).

4.2. Mirror-Symmetry Between Two Whole Patterns

4.2.1. Mirror-symmetry when grating rotates CW and CCW around X axis

Let us rotate the cross-grating CW (Figure 20b) and CCW (Figure 20c) respectively. When the CW rotation angle, α_{CW}, is equal to the CCW rotation angle, α_{CCW}, i.e., $\alpha_{CW} = \alpha_{CCW}$, the whole patterns have the mirror symemtry as show in Figure 20.



(b) (c)

Figure 20. Orange-colored bar representing “Mirror” shows the mirror-symmetry between whole-pattern (b) and whole-pattern (c)

The orange-colored bar between Figure 20b and 20c shows the mirror-symmetry between the whole pattern (b) and the whole pattern (c).

4.2.2. Mirror-symmetry when grating rotates CW and CCW around Y axis

Let us rotate the cross-grating CW and CCW around the Y axis, we observe the whole patterns, top-whole-pattern of Figure 21 and bottom-whole-pattern of Figure 21. When the CW rotation angle, β_{CW}, is equal to the CCW rotation angle, β_{CCW}, i.e., $\beta_{CW} = \beta_{CCW}$, the whole patterns have the mirror symemtry as show in Figure 21.

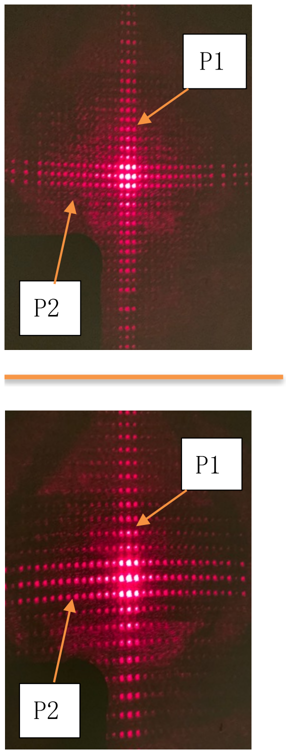
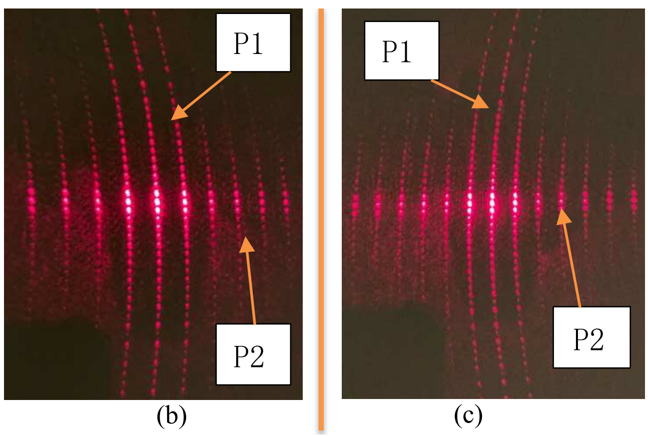


Figure 21. Orange-colored bar representing “mirror” shows the mirror-symmetry between top-whole-pattern and bottom-whole-pattern

The orange-colored bar between top-whole-pattern and bottom-whole-pattern shows the mirror-symmetry between the top-whole-pattern and the bottom-whole-pattern.

4.2.3. Mirror-symmetry when grating rotates CW and CCW around Z axis

Let us rotate the cross-grating CW and CCW around the Z axis, we observe the whole-patterns, shown in Figure 22b and Figure 22c. When the CW rotation angle, γ_{CW}, is equal to the CCW rotation angle, γ_{CCW}, i.e., $\gamma_{CW} = \gamma_{CCW}$, the whole patterns have the mirror symemtry as show in Figure 22.



(b) (c)

Figure 22. Orange-colored bar shows the mirror-symmetry between whole-pattern (b) and whole-pattern (c)

The orange-colored bar between Figure 22 b and 22c shows the mirror-symmetry between the whole-pattern of Figure 22b and the whole-pattern of Figure 22c.

4.3. Mirror-Symmetry of Sub-Patterns

For the special orientations of the cross-grating, we observe the phenomena of the mirror-symmetry of sub-patterns. To show this symmetry, first, rotating the cross-grating around the X axis CW 45^0, $\alpha = 45^0$ (Figure 23). Then, start from this special orientation, we rotate the tilt-cross-grating around the Y axis and the Z axis, respectively.

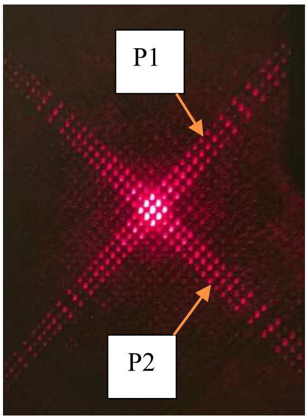


Figure 23. Cross-grating rotates CW around X axis

4.3.1. Mirror-Symmetry of Sub-Patterns: Rotating Grating Around Y Axis

Rotate the cross-grating/ring CW (Figure 24b) and CCW (Figure 24c) around Y axis 65^0, respectively.

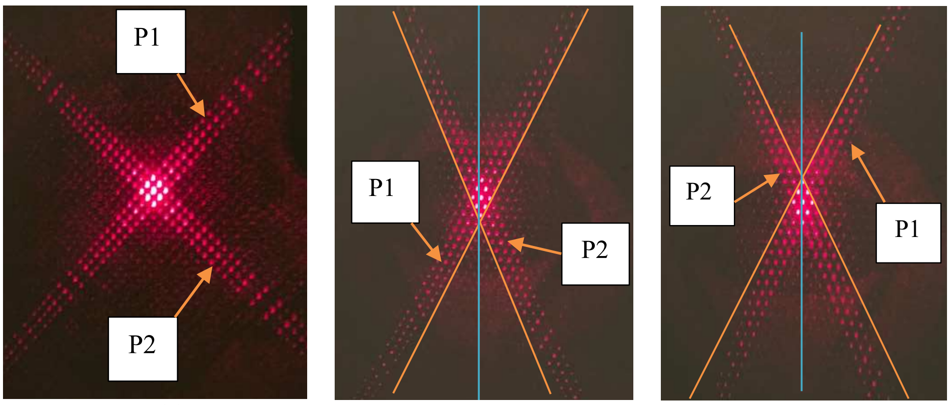


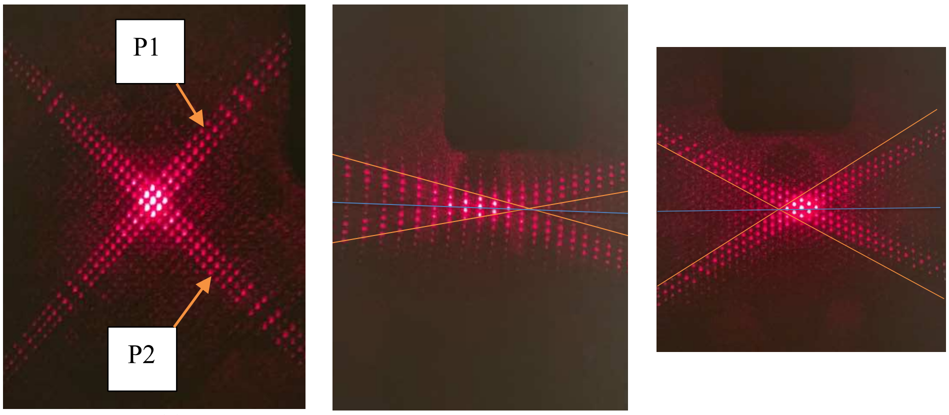
Figure 24. Blue-colored lines show the mirror-symmetry

between sub-patterns-pattern P1 and P2 (b) and (c)

The sub-pattern P1 in Figure 24b is the mirror-symmetry of the sub-pattern P2 (as shown by the blue line). The sub-pattern P1 in Figure 24c is the mirror-symmetry of the sub-pattern P2 (as shown by the blue line).

4.3.2. Mirror-Symmetry of Sub-Patterns: Rotating Grating Around Z Axis

We rotate the cross-grating CW 45^0 around the X axis first, then rotate it around the Z axis CW 75^0 (Figure 25b) and CCW 65^0 (Figure 25c) CCW respectively.



(a) (b) (c)

Figure 25. Cross-grating rotates CW around X axis at 45^0 then: the grating rotates CW around Z axis 75^0 (b); rotates CCW around the Z axis 60^0 (c)

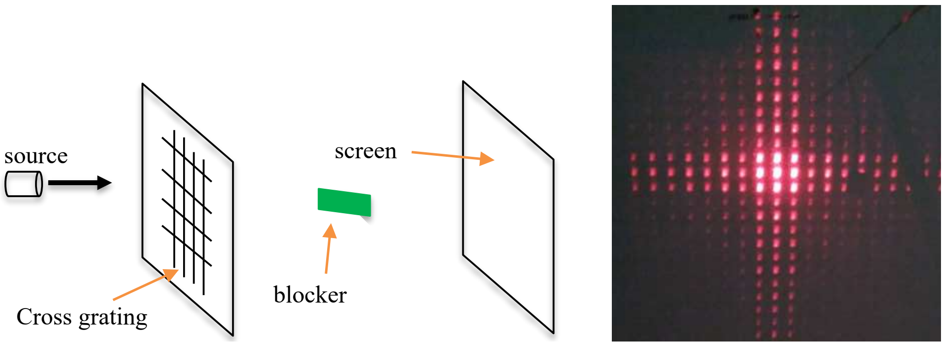
The P1 and P2 have the mirror-symmetry about the line (as shown by the blue line in Figure 25 b and 25c).

5. 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 [19].

Experiment-4: Placing a blocker between the cross-grating and the screen at different locations (Figure 26a).



(a) (b)

Figure 26. Schematic of Setup and Pattern of Cross-Cross-grating without Blocker

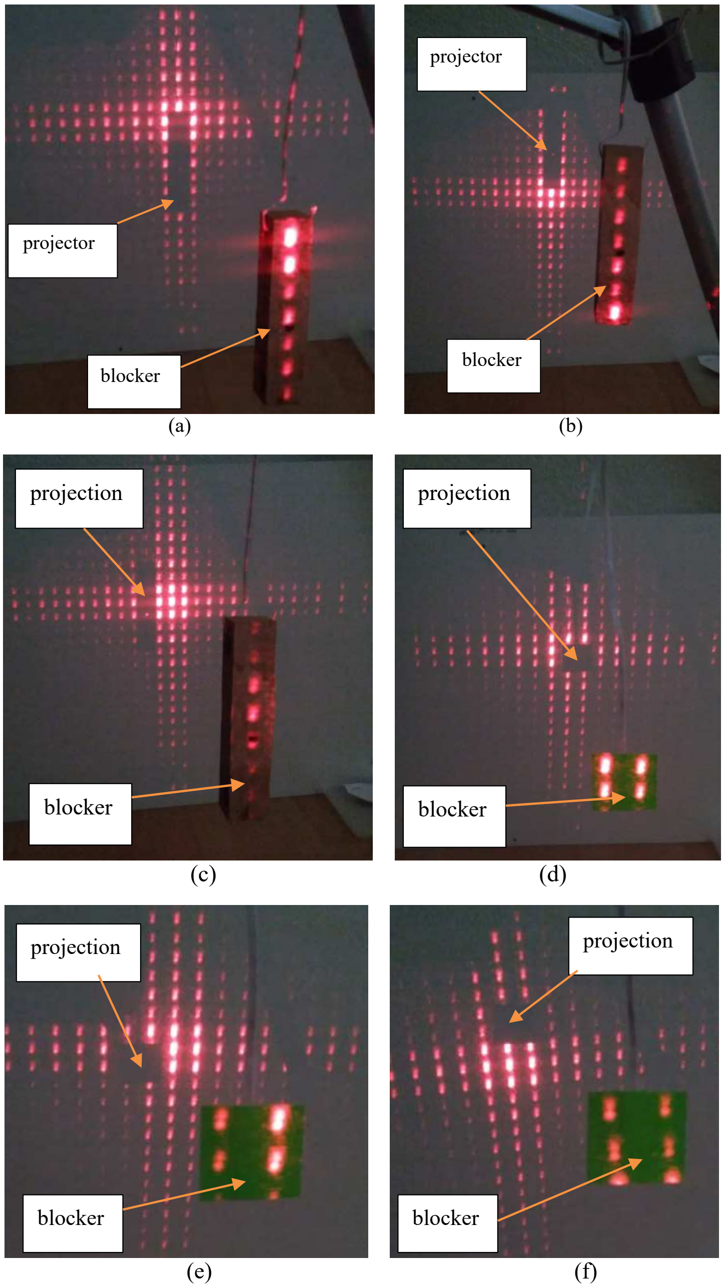


Figure 27. Blockers block partially patterns: blocks bottom portion of the vertical pattern (a); blocks top portion of the vertical pattern (b); blocks left portion of the horizontal pattern (c); blocks central portion of the pattern (d); blocks left center portion of the horizontal pattern (e); blocks 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.

6.Discussion and Conclusion

We have shown that the curved, expanded, inclined and mirror-symmetric patterns of the 2D-cross-grating are different from that in References [1] [2] [3] [4], not only because they only describe the 1D-grating.

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

The experiments show that the patterns are curved, expanded, inclined and mirror-symmetric differently, when the cross-grating is at different orientations. It is the challenge to explain the physical mechanism.

We suggest that a complete mathematical model should contains the rotation angles around three axes 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. Experiments of this article indicate that the patterns due to the rotations CW and CCW around the different axes are completely different. Those differences would guide us to understand the phenomena when the cross-grating rotating around 2 axes and 3 axes.

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

Appendix: Mathematic Description:

If the light beam is incident at an arbitrary angle β_i to the 1D-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 of 1D-grating violate the standard grating equation.

To describe the expanded patterns of the 1D-grating, we extend the standard grating equation to [19]:

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

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,

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

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

After rotating the 1D-grating around the X axis an angle α, the 1D-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) [19],

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

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) [19],

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

It is the challenge to describe the curved pattern.

Note that to describe the phenomena of a 2D-cross-grating, one can apply Eq. (3) (5) and (6) on S1 and S2 separately, since P1 and P2 are created independently.

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