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The rotated diffraction grating - A laboratory experiment

James A. Lock

In most high school and college freshman physics labs, there is an experiment in which one measures the angular positions of the intensity maxima and minima for single-slit diffraction. There is also a similar experiment in which one measures the angular positions of the various order maxima for a diffraction grating. When such measurements are made, it is often said that one should measure the appropriate angles to each side of center and then average them in order to get a more accurate reading. It is claimed that this averaging procedure corrects for the fact that the plane of the single slit or diffraction grating may not be aligned exactly perpendicular to the direction of the incident light beam.

This procedure suggests a third experiment which demonstrates an interesting lesson about optics in particular and about physical phenomena in general. Let the incident direction of the light be fixed and let the diffraction grating be rotated counterclockwise from the perpendicular to the light beam. As the angle of rotation θ_0 increases there is an asymmetry between the behaviors of the right-hand side diffraction orders ($n > 0$) and the left-hand side diffraction orders ($n < 0$). This is qualitatively shown in Fig. 1. The positions of the right-hand side orders move steadily outward while the positions of the left-hand side orders move inward, stop, and then move back outward.

In general, if an independent variable is continually increased or decreased and an observed dependent quantity varies in one manner, stops, and then varies in the opposite manner, it is a signal that there are at least two competing effects working against each other to produce the turn-around. One of them dominates initially, then at some critical parameter their influence becomes equal, then the other dominates thereafter.

This is exactly what is happening in the present case. The two competing effects are suggested by the geometry of Fig. 2. When the light rays travel towards a diffraction grating with slit separation d and which has been rotated by the angle θ_0 , the wavefronts of the light ray encounter an effective grating spacing of $d \cos \theta_0$. This decreased effective

grating spacing causes the resulting interference maxima to occur further out symmetrically to the left and to the right. In addition, there is phase difference of $2\pi d \sin \theta_0 / \lambda$ in the light at adjacent slits of the grating at any time t . As a result, the light diffracted to the right of center has this phase difference subtracted from the extra path length accumulated after the light passes through the grating and the right-hand side maxima occur further out. The light diffracted to the left of center has this phase difference added to the extra path length accumulated after the light passes through the grating and the left-hand side maxima occur closer in. For small angles of rotation, $\sin \theta_0$ is small and $\cos \theta_0$ is large. So in this limit the phase difference effect dominates over the effective spacing effect. Then as is seen in Fig. 1, the negative orders are pulled in while the positive orders are pushed out. For larger θ_0 , $\sin \theta_0$ is larger, $\cos \theta_0$ is smaller, the effective spacing effect dominates, and both the positive and negative orders are pushed outward to larger θ .

The position of the n th-order diffraction maximum for the geometry of Fig. 2 is given by

$$n\lambda = d[\sin(\theta + \theta_0) - \sin \theta_0] \quad (1)$$

where the first term on the right-hand side represents the extra path length accumulated by the light going through

Fig. 1. The qualitative behavior of the first and second order diffraction maxima as the diffraction grating is rotated counterclockwise.

Fig. 2. The light beam/diffraction grating/viewing screen geometry.

Fig. 3. The angular positions of the first order diffraction maxima as a function of the rotation angle of the diffracting grating. The solid lines are the predictions of Eq. (3) and the dashed line is the average of the $n = +1$ and $n = -1$ predictions as is discussed in the first paragraph of the text.

Fig. 4. The angular positions of the second order diffraction maxima as a function of the rotation angle of the diffraction grating. The solid lines are the predictions of Eq. (3) and the dashed line is the average of the $n = +2$ and $n = -2$ predictions.

the upper aperture after the grating and the second term on the right-hand side represents the extra path length accumulated by the light going through the lower aperture in front of the grating.¹⁻² The fact that the two competing effects lead to the asymmetric behavior of the positive orders and negative orders can be more easily seen by rewriting Eq. (1) as

$$n\lambda = (d \cos \theta_0) \sin \theta - (d \sin \theta_0)(1 - \cos \theta) \quad (2)$$

The first term on the right-hand side of Eq. (2) is the effective slit separation contribution. It acquires no extra minus sign as one looks to the other side of center and simultaneously changes the signs of n and θ . It produces a symmetric behavior for the interference maxima. The second term on the right hand side of Eq. (2) is the phase difference contribution. It does acquire an extra minus sign as one looks to the other side of center and simultaneously changes the signs of n and θ . It then produces an asymmetric behavior for the interference maxima.

The asymmetry qualitatively observed in Fig. 1 may

be easily calculated if Eq. (1) is solved for θ to give

$$\theta = \arcsin\left(\frac{n\lambda}{d} + \sin \theta_0\right) - \theta_0 \quad (3)$$

and is then plotted for representative values of d and λ . This is done in Fig. 3 for $n = \pm 1$, $d = 1.667 \times 10^{-3}$ mm, and $\lambda = 6328$ Å. In Fig. 4, similar plots are shown for $n = \pm 2$ and for the same values of d and λ .

A test of this asymmetry was carried out using a Sargent-Welch grade A replica grating listed as having 600 grooves/mm ($d = 1.667 \times 10^{-3}$ mm) and a Spectra-Physics model 159-1 He-Ne laser which operates at a wavelength of 6328 Å. The grating was rotated by angles of up to 30° and the positions of the first and second order diffraction maxima were observed on a viewing screen roughly 1.5 m away from the grating. All rotation angles were measured to an accuracy of 1 min and all viewing screen positions were measured to an accuracy of 1 mm. The resulting data for the first order maxima are shown in Fig. 3 and the data for the second order maxima are shown in Fig. 4. The agree-

ment between the data points and the predicted asymmetry is encouraging. The systematic error between the data and the prediction can be accounted for if all the error is attributed to d and the grating actually has about 603 grooves/mm. The Sargent-Welch Company makes no quantitative determination of the grating spacing tolerance of their replica gratings. However a 0.5% increase in the number of grooves/mm is said to be qualitatively compatible with the degree of shrinkage expected of the replica material.

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bringing the occurrence of this diffraction order asymmetry to my attention. I also wish to thank Robert Van Dame of the Sargent-Welch Corp. for the information concerning the tolerances of their replica gratings.

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