Investigation of a Blazed Reflection Grating

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A reflection grating was studied via two different experimental measurement techniques. Initially, the diffractive properties of the grating were used to determine an average line spacing of 2401±6 L/mm. Atomic force microscopy was used to measure the same value. The average spacing as calculated through atomic force microscopy is 2351±51 L/mm. Both of these values are in near agreement with the accepted value of 2400 L/mm. In addition, the blaze angle of the grating was measured to be 12.4±0.4°. This value is also in near agreement with the calculated value of 17.5°.

INTRODUCTION & THEORY

The major scientific goal of this experiment was to better understand the surface topology of a reflection grating and its relationship to the optical diffractive properties of the grating.

Diffraction gratings have the unique property that they physically separate light of different wavelengths. In many regards they are similar to prisms, and in fact prisms were replaced by the more accurate gratings. Diffraction gratings are classified as either transmission or reflection, depending on whether they transmit or reflect light, respectively.

Diffraction gratings are useful in many different physical aspects. Most notably, gratings are used in the field of astronomy for analyzing light spectra produced by celestial objects. In other words, many objects of interest to astronomers are not within a reachable distance to study; thus, they are studied from Earth through the analysis of the light that they produce. In addition, the gratings may be manufactured in such a way as to produce an "antireflection surface." That is, nearly all incident light is transmitted, and hardly any is reflected. These surfaces would make ideal windows or car windshields that produce little to no glare. Also, maximum light absorption is desirable for solar cells in order to maximize the amount of power generated. Gratings are also used as polarization surfaces. Because they reflect or transmit light of a given wavelength in only a limited number of directions, they are ideal for polarization.[1]

There is a necessity to further study the relationship between surface topography and optical properties as studied here. Currently, the characteristics of a surface that may be deduced through optical measurement are few. If the relationship between optical properties and surface characteristics were better understood, perhaps more could be inferred about surface structure via optical measurement. This situation would be ideal considering the relatively small amount of time necessary for optical study compared to microscopic study.[2]

In addition, the combination of atomic force microscopy and optical diffraction could be used to further characterize other surfaces in general. Microscopy may be used to determine microscopic or local characteristics, whereas diffraction may be used to determine much larger, global characteristics.[3] For example, a grating could be studied optically to determine parameters such as line spacing. On the other hand, through the use of an AFM, local characteristics such as surface roughness and line spacing consistency can be characterized.

Line Spacing

In general for optical diffraction,

$$\sin(\theta_m) + \sin(\theta_{\text{in}}) = \frac{m \cdot \lambda}{d}, \tag{1}$$

must be satisfied for any integer m.[4] Equation (1) is known as the *grating equation*.

Using a spectrometer, it is possible to measure the incident angle as well as the angle of the diffracted maxima. If the wavlength of the incident light is known, then equation (1) may be solved for d, the average distance between lines on the grating. From d, the average line spacing may be calculated.

In addition, because atomic force microsopy gives a topographical view of a surface, it may also be used to determine the average line spacing of a grating. A section of grating may be scanned and a cross-section may be viewed using data analysis software such as Igor Pro Carbon v. 4.05. From this cross-section, the average distance between surface peaks may be calculated for both large and small cross-sectional areas. From this information, the average line spacing may be computed.

Blazing

Gratings may also be manufactured in such a way that they direct the majority of the light intensity into one order, typically the first. These types of gratings are known as "blazed gratings." Specifically, gratings with a blaze that directs light intensity into low orders are called "echellete gratings." [5]

Two prominent methods of manufacturing gratings are via either ruling or holographic techniques. In both cases, a very accurate "master" grating is made and then subsequent gratings are reproduced from this master template. Ruled gratings take on the form of a sawtooth, while holographic gratings more closely resemble sine waves. For a sawtooth grating, the angle between the long side of the ruled surface and the plane of the grating is known as the blaze angle. It is this angle that determines into which order the diffracted light will be directed. Holographic gratings, on the other hand, cannot be blazed as easily and therefore produce much lower efficiencies than ruled gratings. When the wavelength of the incident light, however, is on the order of the grating spacing, the efficiency increases to the point that it is comparable to that of a ruled grating. This wavelength of maximum efficiency is called the blaze wavelength. For the Oriel grating used in this experiment, the blaze wavelength is 250 nm.[6]

For a sinusoidally shaped holographic grating, the blaze angle is defined as the angle at which both the incident light hits the grating and the diffracted light is reflected, relative to the grating normal, when the incident light wavelength is equal to the blaze wavelength.[7] In other words, the blaze angle β is the angle that satisfies equation (1) for both θ_{in} and θ_m for $\lambda = \lambda_{\text{b}}$, and m is order of whichever maxima to which the light is directed. For the grating used in this experiment, the manufacturer has provided that the grating directs the majority of the light intensity into the first order and that $\lambda_{\text{b}} = 250$ nm. We may then calculate the blaze angle necessary to diffract the light intensity into the first order ($m = 1$), beginning with the grating equation:

$$\begin{aligned} \sin(\theta_m) + \sin(\theta_{\text{in}}) &= \frac{m \cdot \lambda}{d} \\ \sin(\beta) + \sin(\beta) &= \frac{1 \cdot \lambda_{\text{b}}}{d} \\ \beta &= \arcsin\left(\frac{\lambda_{\text{b}}}{2 \cdot d}\right). \end{aligned} \tag{2}$$

EXPERIMENT

This equipment used in this experiment included a Dimension 3100 AFM, an Oriel 77230 reflection grating, and an optical spectrometer. The Oriel reflection grating was first studied by atomic force microscopy. The AFM was tested using a wafer containing a grid of $5 \times 5\mu$m wells. The reflection grating was then scanned. Several scans were taken with sizes of both $5 \times 5\mu$m and $1 \times 1\mu$m. The grating had been previously used, and was therefore somewhat scratched. Care was taken not to scan an area that was exessively scratched. The AFM was controlled using the nanoscope software.

The gratings were scanned such that the tip movement was never parallel to the grating ruling. Data collected from these scans was then imported into the computer program Igor Pro Carbon v.4.05 for analysis.

The optical diffractive properties of the grating were then studied. A spectrometer was used in order to determine the angle of incidence and of diffraction for the grating to the nearest minute of arc. The light source was chosen to be a Mercury lamp, because it emits multiple discrete wavelengths of light. This way, multiple diffraction maxima were observed. The angles of the zeroth and first order diffraction maxima were recorded for multiple wavelengths of light. Five measurements were made for each maxima in order to ensure reproducibility. Each time, the spectrometer approached the peak from the right so as to minimize the possibility of systematic error.

RESULTS AND ANALYSIS

Line Spacing

Because the grating was produced by holography, its surface should be shaped as a sine wave. Thus, an average estimate of the frequency of oscillation may be determined by fitting a sine wave to the cross-sectional AFM data as shown in Figure 1. The cross section was chosen so that we look almost directly down the length of the grating lines. In other words, we "cut" perpendicular to the grating lines. Thus, local inconsistencies are averaged out of the data, and the average distance may be determined using the frequency of oscillation. This data is summarized in Table I.

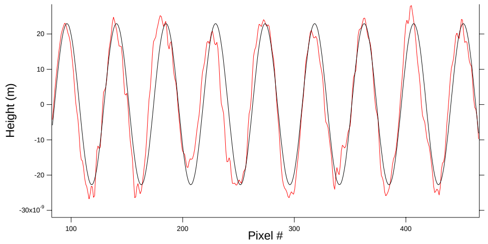

FIG. 1: A sine wave fitted to the cross section of a scan.

Using equation (1), the angles measured using the spectrometer may be used, along with the wavelengths of light emitted by the Hg lamp, to determine the distance between grating lines d and thus the lines spacing S. These results are summarized in Table II.

Blaze Angle

The grating studied here was fabricated such that there are 2400 lines/mm. This specification corresponds to a

TABLE I: Spacing data for the three reflection grating scan samples, as determined by sine wave fits.

Scan #	Spacing (Lines/mm)
1	2424 ± 4
2	2315 ± 2
3	2315 ± 2
Average	$2351 \pm 51(\sigma)$

TABLE II: Summary of line spacing as determined by optical diffraction.

Trial	Sspacing (Lines/mm)
1	2400 ± 6
2	2400 ± 6
3	2400 ± 6
4	2403 ± 6
5	2401 ± 6
Average	2401 ± 6

line spacing $d = 416.7$ nm. By plotting β as a function of λ_b, using equation (2) for $m = 1$, we obtain a way to determine the blaze angle from the manufacturer's blaze wavelength (Figure 2).

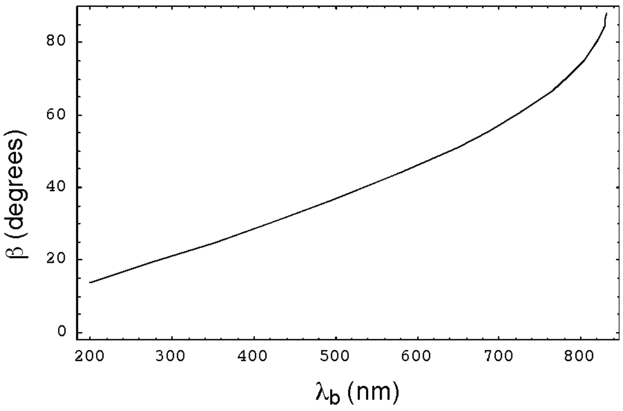

FIG. 2: A graph of blaze angle, β, versus blaze wavelength, λ_b.

By using the manufacturer's value for d and λ_b, we may solve equation (2) for the blaze angle β. For the grating used in this experiment, $\beta = 17.5°$.

As previously mentioned, for a ruled reflection grating, the blaze angle β which affects to which order light is directed is defined as the angle between the long face of the sawtooth-shaped surface and the plane of the grating. With a holographic grating, the surface is shaped as a sine wave. By using the definition of the blaze angle for a ruled grating, we may approximate the blaze angle for a holographic grating by assuming that the sine wave is approximately a triangular wave. As illustrated in Figure 3, if we make this assumption, calculation of the blaze angle becomes possible.

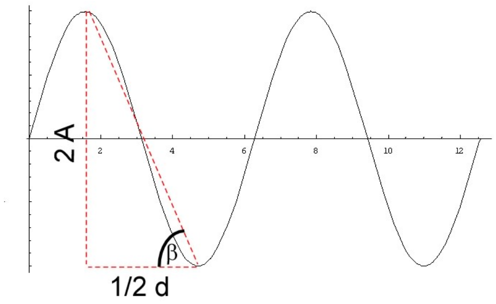

FIG. 3: Approximate blaze angle for a holographic grating.

If we assume that the height of the "triangle" is simply the height of the sine wave , then the vertical side of the triangle is simply twice the amplitude. Also, we may assume that the width of the triangle is one half of the period of the wave. Using geometry, we may calculate the approximate blaze angle:

$$\begin{aligned} \tan\beta &= \frac{2A}{d/2} \\ \beta &= \arctan\left(\frac{4A}{d}\right) \end{aligned} \qquad (3)$$

Using Equation (3) the aprroximate blaze angle was calculated for the best-fit sine waves generated previously to find the spacing d. These results are summarize in Table III

TABLE III: Spacing data for the reflection grating, as determined by a sine wave fit.

Scan Filename	β (degrees)
'refgrat2.004'	12.4 ± 0.1
'refgrat2.007'	12.8 ± 0.2
'refgrat2.009'	11.9 ± 0.2
Average	$12.4 \pm 0.4(\sigma)$

The calculated value of 17.5° is consistently larger than those approximated using atomic force microscopy. This difference could be caused by three sources. First, it is possible that some sort of systematic error was involved in the AFM measurement. The AFM was perhaps not calibrated properly. In addition, a second source of error could be the steepness of the grating lines. When the tip travels along the grating surface, it cannot accurately measure steep slopes. This type of error would result in the measured blaze angle to be slightly smaller than the calculated value, which is what we observe. Similarly, because we approximating a sine wave to be a trianle wave, a third source of error is introduced. Again, as seen in Figure 3, this error would cause the actual (calculated) angle to be greater than the measured angle.

DISCUSSION AND CONCLUSION

The average line spacing of a reflection grating was measured via both optical diffraction as well as atomic force microscopy. The average spacing as determined through optical diffraction is approximately 2401 ± 6 Lines/mm. This is, as expected, more accurate than the average measurement of 2351±51 Lines/mm as measured by the AFM. both of these values are near the accepted value of 2400 Lines/mm. In addition, the blaze angle β was approximated with the AFM data. The average blaze angle was determined to be 12.4±0.4°. This value is in approximate agreement with the calculated value of 17.5°. Overall the experiment was successful in the determination of the relationship between optical diffractive properties and surface topology. The measurement of the same property via two different methods gives insight into the vast difference in accuracy between optical measurement and atomic force microcopy.

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