REFLECTING POWER AND GRATING EFFICIENCY IN THE EXTREME ULTRAVIOLET

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ABSTRACT

A concave glass grating of one meter radius of curvature with 30,000 lines to the inch has been selected to make quantitative measurements of grating efficiencies and reflecting powers between 200A and 1,000A. A water-cooled vacuum spark between tungsten electrodes made an extremely intense and sufficiently constant source. Small plane gratings were crossed with the concave grating so that the efficiency of the small grating could be determined for several wave-lengths and all angles of incidence. The results show that gratings which are efficient at normal incidence are not at all suitable near grazing incidence. The reflecting powers of glass and gold mirrors at 388A and 770A have been measured for all angles of incidence. The values of the reflecting power of glass for several angles of incidence and wave-lengths from 50A to 4800A are given. The influence of reflecting power, groove form, and surface smoothness on the efficiency of a grating are discussed.

INTRODUCTION

THE ruled diffraction grating is at present the only means of obtaining the spectrum of wave-lengths between soft x-rays and the limit of transparency of fluorite. The most important factors affecting the efficiency of a grating are the form of the diffracting groove and the reflecting power of the grating surface. This reflecting power is determined by the smoothness of the surface as well as the optical properties of the substance. The ideal grating is one which will concentrate all of the incident energy into a single spectral order and is approximated by the echelette grating[1] for infrared wave-lengths. In the ultraviolet region reflecting powers are much lower than in the visible region, except near grazing incidence. This fact has been recognized by Thibaud,[2] Hoag,[3] Osgood[4] and others who have used gratings with the light incident near grazing incidence. Edlén and Ericson[5] in Siegbahn's laboratory have been very successful in obtaining spectra around 100A.

The use of gratings with the light incident near the normal to the surface has some advantages. Spectrographs for this arrangement are easier to construct and focus. These two arrangements are greatly different in dispersion, astigmatism, aberrations and the solid angle subtended by the grating. These factors which also govern the intensity of spectra are not discussed in this paper.

[1] R. W. Wood, Physical Optics, p. 227.
[2] J. Thibaud, Comptes Rendus **182,** 55 (1926).
[3] J. B. Hoag, Astrophys. J. **66,** 227 (1927).
[4] T. H. Osgood, Phys. Rev. Supp. **1,** 228 (1929).
[5] Edlén and Ericson, Zeits. f. Physik **59,** 656 (1930).

Apparatus

The vacuum spectrograph shown in Fig. 1a was similar to that described by McLennan[6] with the grating mounted at almost normal incidence. A Holweck molecular pump with an oil fore-pump made it possible to evacuate the spectrograph from atmospheric pressure to about 10^{-5} mm of mercury in an hour. This pressure was well below that required to prevent a parasitic discharge from extending into the body of the spectrograph and fogging the photographic plate. The pressures were observed by means of an ionization gauge connected to the center of the spectrograph. The molecular pump was connected to the end of the spectrograph and electrode chamber as shown in Fig. 1a, by an all metal tube system and a short flexible copper bellows of 2 cm bore and a total length of 20 cm. No mercury was present in the vacuum system and no liquid air traps were used.

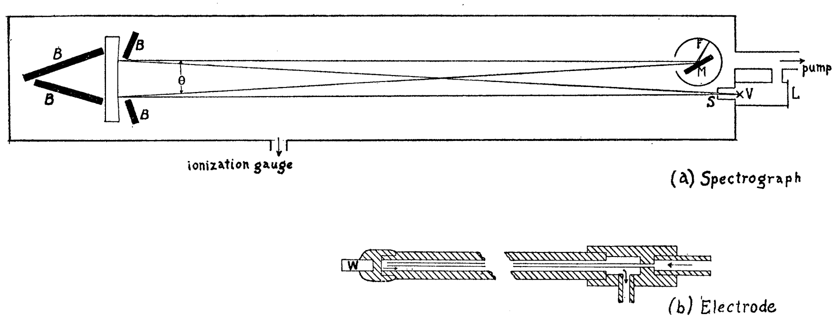

Fig. 1. Diagram of apparatus.

A 50,000 volt transformer drawing about 30 amperes at 115 volts was used to excite the vacuum spark. Across the secondary of the transformer was a 0.01 microfarad condenser consisting of aluminum plates separated by 2 cm of transformer oil in a glass battery jar. The external spark gap which was in series with the vacuum gap was cooled by a current of compressed air. The vacuum spark gap V (Fig. 1a) was about 4 cm from the slit S. The electrodes were about 3 mm in diameter and less than 0.5 mm apart. For the studies of the concave gratings copper electrodes were used, as the groups of copper lines in the region below 1000A are easily recognized. The water-cooled tungsten electrodes shown in Fig. 1b were more satisfactory for the quantitative measurements because the tungsten was less rapidly eaten away by the discharge. Tungsten rods about 6 mm long were welded into copper holders, the various parts of which were held together with silver solder. Water was circulated to within 2 mm of the base of the tungsten electrodes. With this cooling and the Holweck pump, it was possible to run the discharge continuously and not destroy the high vacuum. A few seconds of continuous operation without cooling would raise the electrodes to a red heat. For most of the experiments the spark was operated intermittently by a relay in the primary of the transformer at the rate of 15 times a minute with the discharge

[6] J. C. McLennan, Proc. Roy. Soc. London **98**, 114 (1920).

continuing about one-twentieth of the total time. Under these conditions the spark could be operated for periods as long as two or three hours before it was necessary to adjust the position of the electrodes. After about five minutes of continuous operation, enough tungsten was eaten away so that the spark gap was too large for the discharge to pass.

It is of particular importance in photometric measurements to reduce as much as possible the amount of scattered light which reaches the photographic plate. In order to study the sources of scattered light, the slit was illuminated by a carbon arc through the window L and a small mirror inserted in the position of the photographic plate so that the grating end of the spectrograph was visible. This intense illumination immediately showed that even the blackened metal surfaces, at the extreme end of the spectrograph, scattered an appreciable amount of light. Pieces of polished black glass B (Fig. 1a) were more effective than any blackened metal surfaces available, as there was no diffuse reflection and the regularly reflected light could be deflected from the photographic plate. With glass gratings the light transmitted by the grating was caught by a wedge of two pieces of black glass. The angle was made small enough so that any light returned through the grating had been reflected a great many times.

Schumann plates, from Adam Hilger and Company, which proved more sensitive than the oil coated plates, were used to study the short wave-length limit of the spectra and light scattered by each grating. Ordinary commercial films coated with one part Cenco pump oil in ten parts of amyl acetate were used for the photometric measurements. This particular concentration seemed to give the optimum sensitivity for Eastman Commercial safety films. Before developing, the films were washed in acetone.

Concave Gratings Examined

The spectra given at normal incidence by several gratings of one meter radius of curvature with 30,000 lines to the inch are shown in Fig. 2. The first four are of the copper spark on Schumann plates and the last of the tungsten spark on an oil sensitized film. The spectrum (a) is that given by a very light ruling on a soft glass whose refractive index in the visible is 1.617. On the original plate the group of lines extending to 200A was distinctly visible and there was very little scattered light present in the spectrum. The grating was then etched with hydrofluoric acid to produce maximum intensity of the visible spectrum by the method described by R. W. Wood.[7] The spectrum (b) given by the grating after etching shows the effect of the etching. No lines of wave-length less than 400A now appeared and only a very few of the group near 500A. The region on the plate between the central image and 200A showed a large amount of scattered light. The presence of the streaks across the spectrum caused by dirt on the slit showed that the grooves themselves were the scattering elements. This type of scattered light is very undesirable for it is focused along with the spectrum. The use of filters of glass quartz and

[7] R. W. Wood. Phil. Mag. 2, 310 (1926).

fluorite showed that this light was mostly of wave-lengths between 2000A and 1300A.

Five rulings on this same kind of glass of refractive index 1.617 were tested and the original rulings gave spectra extending to 200A and were comparatively free from scattered light. Etching with hydrofluoric acid in every instance was detrimental to the efficiency for wave-lengths less than 600A. The effect of a slight amount of etching was not as great as if the etching was continued for a longer time. The etching evidently enlarges the groove so that it is better able to diffract visible light but is roughened so that it scatters more light and fails to diffract the shortest wave-lengths.

A lightly ruled speculum grating gave the spectrum shown in Fig. 2c. With a prolonged exposure it was possible to detect the group at 150A, but so much scattered light was present that the photograph is not shown here. A heavily ruled grating on speculum showed very few lines below 500A. This is in agreement with the experience of others[8] with gratings of about 15,000 lines

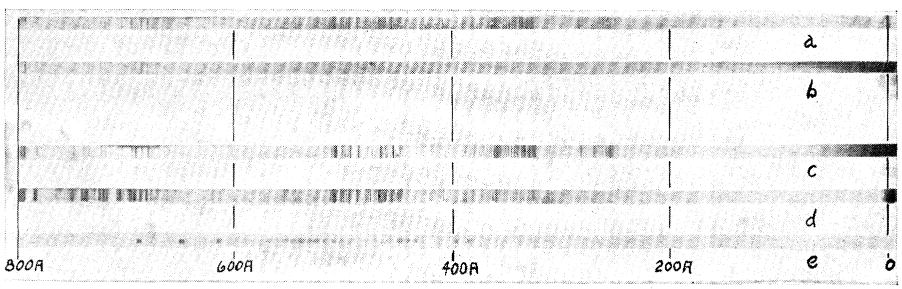

Fig. 2. Spectra from concave gratings.

per inch. The spectrum of a ruling on a "hard" glass of refractive index of 1.52 shown in Fig. 2d is like that in (a) but extends only to 250A instead of 200A with the other glass. As only one ruling was made on this "hard" glass, it is impossible to say whether this short wave-length limit of 250A was determined by the reflecting power of the glass or the type of ruling. On the soft glass, five rulings were tried and it appears that the short wave-length limit of 200A is determined by the reflecting power of this glass at normal incidence.

It is not possible to compare closely the efficiencies of glass and speculum gratings by this method. For normal incidence both lightly ruled glass and lightly ruled speculum are definitely superior to the etched glass or heavily ruled speculum for wave-lengths less than 600A. The durability and greater freedom from scattered light make the glass gratings more desirable for some kinds of work.

Crossed Gratings

Small trial plane gratings were inserted at M, Fig. 1a, so that the plane of the ruled surface coincided with the axis of the cylindrical film with the rulings parallel to this axis and perpendicular to the rulings of the concave grat-

[8] Millikan, Bowen and Sawyer, Astrophys. J. **53,** 150 (1921).

ing. The spectrum (Fig. 2e) used was that of the tungsten spark with the slit approximately 0.7 mm^2. These small gratings could be rotated through a ground joint from outside the spectrograph so that the spectrum of the concave grating was incident at any desired angle between grazing incidence and 10° from normal incidence. The spectra of these crossed gratings were photographed on a concentric oil sensitized film inside the cylinder at F. In order to interpret the intensities of the spectra a number of step exposures were made with the spectrum of the concave grating reflected from the second grating at 2° from grazing incidence. At this small angle no orders of the second grating were detectable and practically all light went into the central image. A recording Moll photometer was used to obtain the relative intensities of the spectra compared to the step exposures at grazing incidence.

In Fig. 3 are shown the spectra of the crossed gratings together with sketches of the possible groove forms of the small gratings. The wave-lengths are those of the spectrum formed by the concave grating and the numbers re-

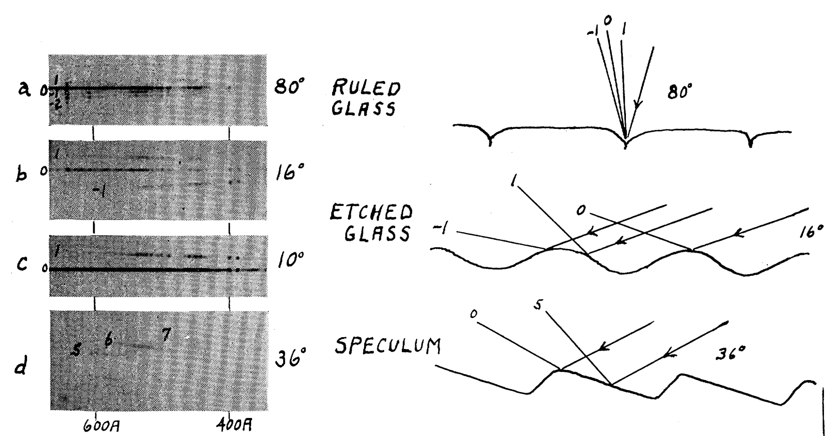

Fig. 3. Spectra of crossed gratings and shape of grooves.

fer to the spectral orders produced by the second grating. Inside orders, i.e., those between the central image and the tangent to grating are marked with a negative sign and the central image zero. The angles are those between the direction of the incident light and plane of the grating.

The spectra (a) were from a lightly ruled glass grating near normal incidence. At 650A, the central image contained about 4 percent of the total energy of this wave-length incident on the grating and the brighter first order about 1 percent. The intensities at 400A were too small to be measured. The orders on one side of the central image were much brighter than on the other, and this must be due to asymmetry in the groove form. At angles of incidence less than 30°, almost no spectra were obtained from the lightly ruled glass gratings. A possible form of the grooves of this type of grating is shown. The groove is apparently rather small, compared to the spacing for near grazing incidence the grating is more like a mirror, giving no spectra at any angle less than 20° from grazing incidence. Four gratings of this type gave spectra of about the same intensities. Sputtering these gratings with an almost opaque film of gold did not change the distribution of energy in the various orders which was characteristic of the ruled groove. The efficiency of the gratings was not changed by the gold film and later measurements of the reflecting powers of glass and gold showed the two were about equal near normal incidence. If the measurements of the reflecting powers of various substances are made at normal incidence it may be possible to find one which will increase considerably the efficiencies of gratings for the region between 400A and 2000A.

The spectra of an etched glass grating are shown in Fig. 3b and c. At 16° from grazing incidence and 400A the first inside order contained 6 percent of the total energy of this wave-length incident on the grating, the central image 5 percent and the first outside order 3 percent. At 10° the same grating gave an outside order of 10 percent. Several other etched gratings gave spectra of about the same intensities at these angles. The groove form for this type which is sketched is that suggested by Professor Wood as one produced from the ruled glass by the eating away of the surface at a constant rate in all directions by the hydrofluoric acid. The parts of the groove which may act as small mirrors concentrating the energy into the different spectral orders are indicated. The effective reflecting power for the inside orders is larger as these are reflected nearer grazing incidence and this factor will tend to increase the intensities of these orders. These etched gratings gave only extremely faint spectra at normal incidence as was found in the examination of the concave gratings. It is very probable that the hydrofluoric acid leaves a surface which is very rough to the shorter wave-lengths at normal incidence.

A small fragment of a speculum grating with 15,000 lines to the inch which gave a very bright first order and faint central image in the visible region, gave the spectra shown in Fig. 3d at 36° from grazing incidence. This bright visible first order indicates that the groove has one broad and rather flat side which makes an angle of about 10° with the grating surface as shown in the sketch. The fifth, sixth and seventh outside orders between 400A and 700A which are shown in the photograph coincide almost exactly with the direction of regular reflection from a plane mirror placed at an angle of 10° with the grating surface. In this instance the grating of 15,000 lines to the inch concentrates the ultraviolet wave-lengths in a few orders as the echelette concentrates visible light. This effect was found at other angles of incidence but not clearly enough to reproduce. The grating did not show spectra at normal incidence probably on account of the small reflecting power and the roughness of the groove surfaces at this angle.

Experiments with twelve gratings, of which three have been described in detail here, show that efficiency for normal and for grazing incidence requires gratings of quite different type. Near grazing incidence (less than 15°) the reflecting power of most substances will be 50 percent or more, and the choice of a material for a grating will be determined by physical properties which facilitate ruling. The ruled metal grating of the echelette type, modified to take advantage of the increase in reflecting power at small angles may become surprisingly efficient in the extreme ultraviolet and soft x-ray regions. Such gratings will be extremely difficult to rule, as it will be necessary to examine the trial rulings with ultraviolet light instead of visible light to obtain information regarding the shape of the groove formed by the ruling point. Although the examination of a ruling with short wave-lengths gives more information about the groove form than with longer wave-lengths, it is possible to predict partially the behavior of the ruling at 200A by examining it with 500A. The etched glass grating is particularly easy to rule as only a very light ruling is needed with the hydrofluoric acid forming the groove. This means less time spent in selecting the diamond point and less wear on the diamond.

It is probable that the results of these studies on the groove form and grating efficiency at 400A will be useful in ruling gratings for the soft x-ray region.

Reflecting Power

Preliminary determinations of the reflecting powers of glass and gold mirrors at various angles of incidence between 200A and 1000A were made with the hope of improving the efficiency of gratings in this region. The reflecting powers of these two substances proved to be of the same order of magnitude and not sufficiently different to make either greatly superior for a grating surface.

Selected pieces of plate glass 4 cm by 14 cm were inserted at M, Fig. 1a on the axis of the cylindrical film. The angle θ subtended by the beam from the grating surface was made about one degree to increase the "angular" resolving power of the reflection measurements. The dispersion on the photographic film was 8.6A per mm in one dimension and 0.78° per mm in the other. The intensities of the reflected spectra were compared with exposures reflected at $1\frac{1}{2}°$ from grazing incidence by a recording Moll photometer, and the fraction reflected calculated by use of the photographic reciprocity law. In order to obtain the comparison exposures, the mirror was set at $1\frac{1}{2}°$ and the photographic film rotated about its axis. To reduce any drift in intensity of the source, half of the reflected spectra were taken before the comparison exposures were made and the remainder afterwards.

Fig. 4a shows the experimental values of the reflecting power of gold at 388A between 0° and 40° compared to the reflecting power at $1\frac{1}{2}°$. These values were taken from four films using two sputtered gold mirrors. The variations in these experimental values are probably due to unsteadiness of the spark and variations of sensitivity of the photographic film. The extension of the curve to grazing incidence from $1\frac{1}{2}°$ indicates that only a small error would have been introduced by assuming 100% reflection at $1\frac{1}{2}°$. For the other curves the value at 0° has been obtained by extending the curve from $1\frac{1}{2}°$ and the entire curve expressed as fractions of this value. The reflecting powers of gold at 388A and 770A are shown in Fig. 4c and similar curves for glass in Fig. 4b.

At normal incidence both substances reflect 5 percent of 770A and give positive evidence of regular reflection at 388A. The effect of surface roughness is greater at this angle and wave-length than in any of the other values and may decrease the reflecting power considerably. It is known that gratings partially polarize the diffracted light to an extent which varies with the wave-length. The use of crossed gratings in the earlier part of this work showed that the ratio of intensities of the polarized components at 650A was less than five. The photographic laws whose validity have been assumed in computing the reflected intensities may introduce an error in the values reported. Harrison[9] has shown that the oil sensitized photographic plate is a well behaved combination and it is expected that the errors introduced by photographic laws are relatively small.

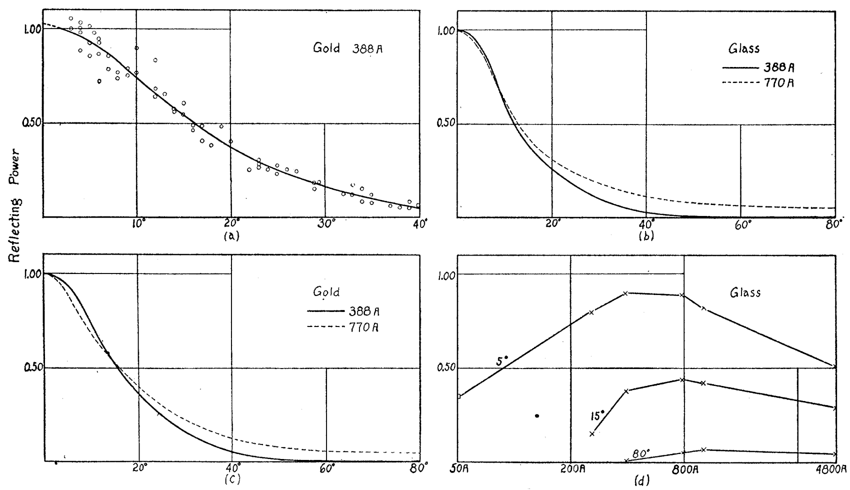

Fig. 4. Reflecting powers of glass and gold.

It is estimated that the probable experimental error is about 5 percent near grazing incidence, and 2 percent near normal incidence. At the present time, however, some of the sources of error mentioned above cannot be evaluated.

The reflecting powers of glass at 80°, 15°, and 5° for wave-lengths from the visible region to the $K\alpha$ line of carbon are shown in Fig. 4d. The values at 4800A are those for unpolarized light as computed by Fresnel's equations. The value at 50A is that given by Dershem[10] and the intermediate values as determined by the method described in this paper. The curve given by Gleason[11] for 45° incidence is in general agreement with those presented here. The shift of the maximum of reflecting power toward shorter wave-lengths as grazing incidence is approached cannot be entirely due to the decreasing influence of surface roughness.

Summary

Gratings of 15,000 and 30,000 lines per inch behave in the region below 1000A much like echelette gratings in the visible region. The intensity of the

[9] G. R. Harrison, Jour. Op. Soc. Am. **19,** 267 (1929).
[10] E. Dershem, Phys. Rev. **34,** 1015 (1929).
[11] P. R. Gleason, Proc. Nat. Acad. of Sci. **15,** 551 (1929).

spectra are largely determined by the reflecting power, shape of the groove and smoothness of the surface. In order to obtain a large reflecting power and smooth appearing groove surface for wave-lengths below 500A it is necessary to have the light incident at angles of less than 20° from grazing incidence. The reflecting power which is effective in determining the efficiency of a grating is that for half the angle by which the spectral order under consideration is deviated from the direction of the incidence light.

At present, for us near grazing incidence the etched glass grating is more suitable for it has an efficiency of the order of 8 percent at any angle near grazing incidence, and is readily ruled. The ruled metal grating will be more efficient but will be extremely difficult to rule and can only be used to great advantage at one definite angle of incidence. Near normal incidence either a lightly ruled glass or speculum grating will be satisfactory. Sputtering a glass grating with any substance with greater reflecting power should increase the efficiency.

These studies were suggested by Professor R. W. Wood and the gratings which were ruled on the Rowland engines were made available by him.

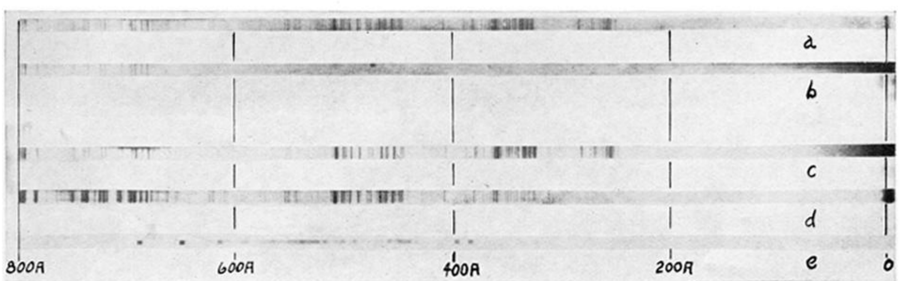

Fig. 2. Spectra from concave gratings.

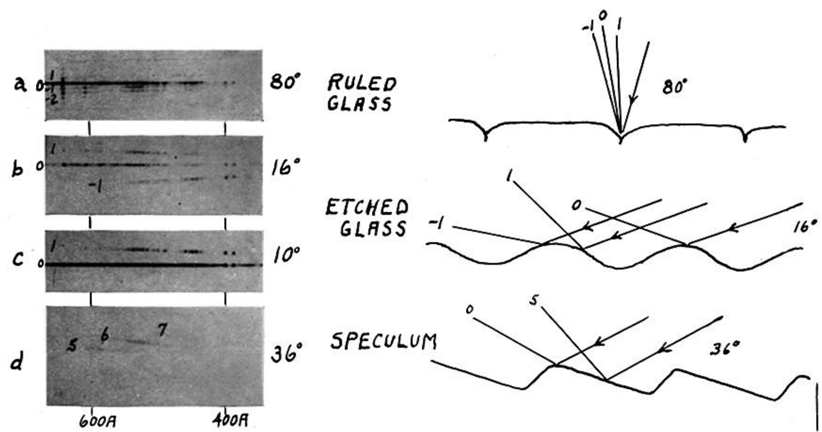

Fig. 3. Spectra of crossed gratings and shape of grooves.