Vol. X—No. 3 September, 1965

The SPEX Speaker

INDUSTRIES, INC. · 3880 PARK AVENUE · METUCHEN, N.J. · 201-549-7144

THE DIFFRACTION GRATING

Customarily an article on diffraction gratings begins by introducing the human hair for comparison. Somehow, its diameter (50-100 μ) has become solidly entrenched as the fundamental unit of measurement to which all minute linear distances must be related. With no desire to belittle the importance of the hair in these days of Beatles and beards, I thought it might be almost as appropriate to relate the miniscule displacements and tolerances entailed in ruling a grating within their own microcosm of tools, devices and measuring instruments.

Let's first see what kind of numbers are involved. Bausch & Lomb has just undertaken to supply several gratings with the smallest ruling constant yet, 0.2μ, 4800 grooves/mm. To achieve a grating acceptable by today's standards, the placement accuracy of each groove must be in the order of 0.01μ. That is to say, the separation error between two successive grooves or *between the first and last groove must* not exceed 0.01μ. Table I shows how these figures fit into present-day technology of measurement schemes.

TABLE I: MEASUREMENT LIMITS

Instrument	*Microns*
Vernier caliper	30
Micrometer accuracy	3
High-resolution photographic plate	0.7
Visible light microscope	0.5
Ultraviolet microscope	0.2
Linear transformer	0.3
Jo-blocks (flatness)	0.1
Optical interferometry	0.01
Electron microscope	0.001

It becomes immediately apparent that grating production measurements must utilize electron microscopy and optical interferometry. Above 1200 grooves/mm gratings appear hopelessly unresolved when examined under even the best optical miscroscope.

The principle of the diffraction grating was discovered in the late 18th Century. The dual requirements for fine ruling (or wire lattice spacing practiced by some of the pioneers) as well as a large total number of lines were formidable and the history of the grating can almost be told by plotting these against time. In 1785, Rittenhouse ruled 53 grooves in 1/2 inch; in 1823 Fraunhofer ruled 4000 grooves in 1/2 inch; in 1846, Norbert ran up 6000 grooves in 1 inch; L. M. Rutherford, a New York lawyer by profession but an amateur astronomer at heart, ruled 35,000 grooves on a speculum mirror 2 inches wide in 1870. By this time, the advantages of a reflection grating were appreciated.

The total number of grooves and fineness of spacing establish theoretical resolving power and dispersion, respectively. To attain a practical resolution near theoretical and to reduce bothersome ghosts resulting from periodic errors in ruling, the spacing accuracy had to be improved. H. A. Rowland took up this torch and, over the first half of the 20th Century, his laboratory at Johns Hopkins University became the focal point for the finest quality gratings in the world. By around 1900, Rowland had already ruled 100,000 grooves over 6 inches to achieve a resolution in excess of 150,000. By 1916 the laboratory had produced gratings with a resolution of 350,000. This magic number now approaches 400,000, close to the maximum theoretical resolving power for that width. Within the past decade Harrison has produced a number of 10-inch plane gratings on the large interferometically-controlled ruling engine built at MIT. These have a resolution of 800,000 within a whisper of the theoretical 900,000 (1).

Scattered throughout this article the words "resolution" and "resolving power" appear. Because spectroscopists tend to use them interchangeably, they should be defined. Resolving power is a theoretical term denoting the wavelength divided by the difference in wavelength of two equally intense lines "just" resolved.

$$R = \lambda/\Delta\lambda = mN$$

where m is the order and N the number of lines on the grating.

The hitch is the word "just" which, by the Rayleigh criterion, is interpreted in such a way that, given two lines of equal intensity, the intensity dip between them would be about 19% under conditions where the two lines appear separated. Neglecting to point out how to obtain two lines of equal intensity the difference between which could be adjusted with the turn of a knob, Rayleigh did not, in fact, offer a convenient method of measuring "resolution." Artificial doublets can be painfully produced with a Rochon prism (2), or by Zeeman splitting a laser line as suggested by D. H. Rank of Pennsylvania State University. But fortunately there is a better way of approximating resolution: measuring the width of a line at half intensity. With modern linear photomultipliers and strip-chart recorders, half-widths are readily measured and, if not exactly equal to a figure obtainable on a strict Rayleigh criterion basis, are incontrovertibly objective.

Objectivity, however, is unfortunately not sufficient. The half-width of spectral lines produced from two gratings may be exactly similar yet one of the gratings can be decidedly inferior. Ideally, the contour of a spectral line should be without inflections or shoulders. In practice, often a grating will produce a characteristic "shoulder" at one or both sides of a line; since this shoulder is beneath the position where the half-width is measured, it will escape notice. Such a shoulder will obscure a weak line in proximity to a strong one and is therefore quite meaningful. To include it, one proposal currently before ASTM is to measure both the half-intensity and the tenth-intensity of a line as an assay of the "practical resolution" of a particular grating.

While unquestionably a step in the right direction, even 1/10-intensity measurements are not sufficient to define the resolution of a grating completely. Under high resolution conditions, the shoulder emerges as a number of closely-spaced satellites or "grass." Down at a level as far as 1/1000 of the parent intensity, these satellites can obscure, say, a line of an isotope at low concentration. Intensity of most satellites increases, like that of ghosts, roughly by the square of the order. This is probably why most gratings show a decrease in resolution at high orders.

From its definition, the theoretical resolving power of a grating could be increased indefinitely by increasing the number of total lines in a given width. But combining the resolving power definition with the grating equation,

$$m\lambda = W/N\ (\sin\alpha \pm \sin\beta),$$

where W is the width of the grating; α and β are the angles of incidence and diffraction, respectively, Michelson showed early in this century that the maximum resolving power was limited by the width of the grating and the wavelength. Since $\sin\alpha + \sin\beta$ can have a maximum value of 2, the maximum resolving power at any wavelength turns out to equal $2W/\lambda$. At 5000A the maximum resolving power of a 6″ grating is around 600,000 regardless of the diffraction order or the number of grooves.

It was this figure that Michelson was shooting for with his "University of Chicago" engine, an engine that, with several new handles and blades, is even now one of the two main producers of gratings at Bausch & Lomb, Inc., in Rochester, N. Y. A. A. Michelson, who earlier collaborated with E. W. Morley in the famous speed-of-light experiments where unsuccessful attempts were made to find the elusive "ether" of interplanetary space, described the difficulty of ruling gratings in an article written in 1912 (3):

"One comes to regard the machine as having a personality —I had almost said feminine personality—requiring humoring, coaxing, cajoling, even threatening! But finally one realizes that the personality is that of an alert and skillful player in an intricate but fascinating game who will take immediate advantage of the mistakes of his opponent, who "springs" the most disconcerting surprises but who nevertheless plays fair, in strict accordance with the rules of the game.

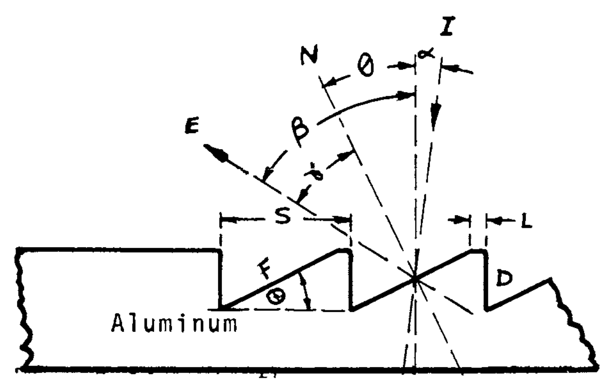
"When the accumulation of difficulties seems to be insurmountable, a perfect grating is produced—and the event celebrated with much rejoicing, only to find the next trial a failure."

These conditions, described with so much humility and respect for a simple yet awesome machine, are no less true today. Yet within the span of this half-century, technological advances have helped the ruling art significantly. Air-conditioning, permitting the control of temperature to an almost unbelievable 0.001°; the development of dimensionally stable alloys, of lubricants the viscosity and friction of which do not change in time, of superior bearing materials, of interferometric control and measuring tools including the electron microscope, of vacuum aluminizing to permit the diamond to plow through a relatively soft material with little wear—all these have contributed to the elevation of the grating to a position of equality with, and in many instances dominance over, the prism as a means of dispersing light.

Bausch & Lomb, Inc. is the foremost manufacturer of gratings today. From its inventory of over 500 masters, it "pulls" thousands of replicas a year for distribution throughout the world and outer space surrounding it. Some 18 years ago, David Richardson was engaged to organize a grating-ruling operation at B&L and he is considered one of the leading experts on the subject. I had the privilege of interviewing him recently to obtain a general picture of how gratings are produced and tested at B&L.

According to Richardson, one of the early correct decisions was to use BSC-2 glass for the blanks rather than other borosilicate glasses which, because they have coefficients of expansion only half as large, might have been a more logical choice. BSC-2 is a material which can be baked for curing the epoxy replicating material and sawed without introducing strains and without distortion. It is bubble-free and so can be ground and polished with no danger of breaking into a crater. After being polished to a flatness of better than 1/4 wave, the glass is vacuum-coated with aluminum or gold to a thickness approximately equal to the first-order blazed wavelength. For gratings blazed for the XUV, the coating thickness may be as little as 1000A. At the present time, the thickest coating of aluminum that can be made to adhere properly to the blank limits the ruling of gratings for the infrared to those blazed for 45μ. Many of the so-called ruled Echelles having blaze angles of 60° or more are designed for high-order work. The coarsest have 20 grooves/mm.*

Although aluminizing itself might seem to be one of the easiest steps in the complex production of a diffraction grating, even this is an art hounded with provoking, interacting and critical variables not all of which are thoroughly understood nor controllable. Among these are the pressures in the evaporator, purity of the aluminum, depth and speed of its deposition, cleaning treatment of the base glass, geometry of boat or filament, presence and strength of an electric field. All influence the "rulability" of the aluminum and only a test ruling can tell whether the surface of the blazed face is proper for the production of a grating of acceptable quality.



D	Depth of ruling
S	Groove spacing
L	Unruled land
α	Angle of incidence
β	Angle of diffraction
γ	Angle of reflection
θ	Blaze angle
F	Groove face
N	Normal to face

Fig. 1. Blazed groove profile. The aluminum thickness is generally equal to the blaze wavelength; the depth of the groove to about half of that. The dimensions shown approximate the relative shape of a grating ruled with 1200 grooves/mm, blazed at 7500A. (Courtesy B&L.)

*Burnishing an aluminized coating is not practical for groove spacings in excess of 50μ. To prepare far infrared gratings B&L has a special engine which cuts steps in aluminum alloy blanks. Fitted with both English and metric components, the engine may produce a wide variety of spacings. The nominal 8/mm grating, for example, is actually ruled 200/inch. As few as 1 groove per 2 mm rulings can be cut on this engine.

BLAZE

The word "blaze" denotes considerably more than just the angle that the ruling diamond presents to the face of the aluminum. It represents the profile of each and every groove along its entire length. On this profile depends the efficiency of the grating: the percent of light diffracted at a stated wavelength as compared with the reflectance of aluminum at the same wavelength.* The efficiency is, in turn, inversely related to the scattered light characteristics of a grating. A portion of the light is reflected specularly by the grating and forms the so-called zeroth order or direct image. Another portion of the incident light may be reflected elsewhere. All of the light not diffracted is unwanted; it may reflect off surfaces inside of the spectrograph to appear as scattered light.

Actually, blaze connotes the shape of the groove which, in turn, determines the distribution of energy into different orders and wavelengths as well as the maximum efficiency at the blaze wavelength and the overall scattered light.

Fig. 1 depicts an idealized profile of two successive grooves in which θ is the blaze angle itself. Ideally, L, the unruled land surface should be completely absent to prevent the grating from acting as a simple mirror. As indicated earlier, a grating of high efficiency should have a weak direct image. Ideally, too, the groove face should be perfectly flat, free from any irregularities. The blaze wavelength is defined as that wavelength for which the angle of reflectance of the groove face and the angle of diffraction are identical when the angle of incidence and the angle of diffraction are equal. Referring to Fig. 1, $(\theta + \alpha)$ is the angle of incidence to the grating face equalling the angle of reflectance. Intuitively, it may be seen that incoming light along I will be diffracted at optimum intensity along E which also represents the reflection path.

When α and β are unequal, a correction must be applied to determine the actual blaze wavelength as follows:

$$\lambda' \beta = \lambda \beta \cos (\alpha - \beta)/2.$$

This correction is needed most at grazing incidence where the angle of incidence may be as high as 88°. Here a 1200 groove/mm grating, nominally blazed at 1200A, will actually be blazed at 126A.

In the Spex side-by-side, symmetrical Czerny-Turner spectrometers, although the two angles are unequal, their difference is a constant 14°. Cos 7° is 0.99, so close to unity that the actual blaze wavelength is virtually identical with that calculated for $\alpha = \beta$.

One question often raised relates to the useful wavelength range of a blazed grating. Peaking at a single diffraction angle, does the efficiency of the grating drop off at the low and high wavelength ends in a predictable fashion? A second question concerns the relative efficiency of the grating in successive orders. If a grating has an efficiency of unity in the first order at 6000A, what is its efficiency in the second order at 3000A and the third at 2000A. While no exact laws apply to either question, some rules of thumb have been found applicable and are illustrated in Table 2. In the first order the efficiency of a grating usually drops more rapidly on the low wavelength side than on the high. The span corresponding to half-intensity starts at a wavelength of around 2/3 the blaze wavelength and extends to around twice that. In the second order, the grating intensity curve tends to be more balanced in that the upper wavelength of the half-intensity curve crosses at around 3/2 of the blaze. In the third, the high wavelength drops still faster. Table 2 also furnishes approximations concerning the efficiency in subsequent orders, 80-90% of Order I.

Table 2 is presented with trepidation. Although it serves as a convenient rule of thumb, the efficiency curves of individual gratings may be expected to depart significantly from the typical figures given.

TABLE 2

TYPICAL EFFICIENCY OF B & L PLANE GRATINGS

Order	*Nominal Blaze W.L., A*	*Efficiency %*	*Half-Intensity Range, A*
I	10,000	70	6666 to 20,000
II	5,000	56	3333 to 7,500
III	3333	56	2200 to <5.000

It will be seen from Table 2 that the half-intensities of subsequent orders overlap. If, therefore, it is desired to cover a wide range of spectra with a single grating, it is best to choose one with a high wavelength blaze. B&L gratings usually reflect only about 5% of the oncoming light into the direct image which, not only accounts for their high efficiency but also for the low scattered light.

A paradoxical question concerning blaze refers to a grating blazed for a lower wavelength than the illuminating light. In such an instance where does the light go? The answer is simple and readily demonstrated. Under such conditions, the light is mostly reflected instead of diffracted. Thus a grating blazed for 1500A appears to be merely a mirror. One of the simplest visual tests of a grating blazed for the visible and higher is to examine a reflected image in it. If it appears bright and clear, the grating will probably have poor efficiency. Checking visually for the blaze direction is done almost as simply by reflecting a beam of sunlight and examining the visible spectra appearing on both sides of the direct image.

What has been said thus far pertains to plane gratings. When a concave grating is ruled, the spacing between grooves is equalized for the chord rather than the arc of the surface. The blaze angle therefore changes continuously as the diamond rules from one side through the center to the other. In fact, with gratings of short focal length and low blaze angle it is possible for the heel of the diamond to dig into the aluminum as it moves uphill during the final ruling stage. To prevent this and, at the same time, improve the blaze characteristics of the grating, so-called tripartite gratings are made. The diamond is set to achieve the desired blaze angle on the downhill side, readjusted for the center section and once again for the uphill section. Although ideally, the diamond angle should be readjusted after each stroke, tripartite gratings provide a good deal more intensity than ones ruled in a single pass. Incidentally, it is not necessary to rule the three areas exactly in phase; two discontinuities have little practical significance.*

How well the groove shape is controlled by B&L is depicted in Fig. 2, an electron micrograph of a terminal groove of a grating blazed for the XUV. The technique for getting the electron micrograph is unusual (4). Natural asbestos fibers, tubes with a diameter of around 0.1 μ, are strewn on a thin, transparent replica. The asbestos fibers are shadowed obliquely with platinum and on to the entire grating is evapo-

*Efficiency is thus defined in terms of an aluminized standard reflector. In the vacuum ultraviolet where the reflectivity of aluminum drops, efficiency is measured in absolute terms against an unreflected monochromatic beam.

*B&L is planning to rule an interesting "Bipartite" grating in which the main ruling will have 4800 grooves/mm and be blazed at the helium 303A line. A small section will be ruled at 266.3 grooves/mm and be blazed at 5461A to permit visual alignment with a convenient Hg lamp.

rated a layer of carbon to render it translucent to the electron beam after the original replica has been dissolved.

If one is lucky, just the right length fiber will have landed exactly perpendicular to and straddling the terminal groove as shown by the black rod running diagonally across Fig. 2. On the right is the unplowed aluminum, its texture characteristic of the deposition. The riser of the first groove is followed by the 4°35′ slope of the groove face and then by a second riser for the next groove 1/600 mm away. The bottom of the white shadow is an image of the groove profile. Knowing the shadowing angle and the thickness of the fiber, the blaze angle and step height (here nominally 1380A) can be measured. Irregularities along the shadow line clearly show how the pock-marked base material has been burnished by the diamond. The groove face is straight, without evidence of flat land which, as mentioned earlier sends light to the direct image.

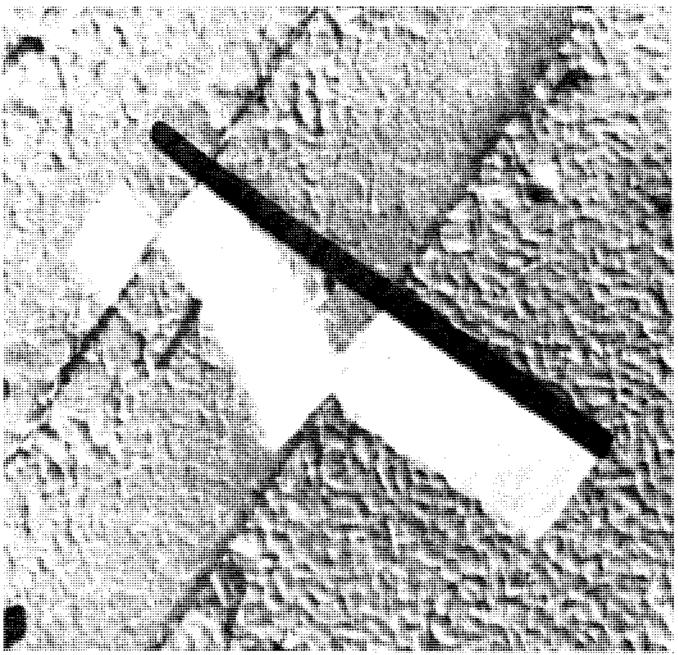


Fig. 2. An electron micrograph of a terminal groove of a grating blazed for the XUV (Courtesy B&L.)

Even more of a workhorse than the electron microscope in determining groove and diamond shape is the interference microscope. Monochromatic light is directed through a beam splitter. One part is reflected from the grating, the other from a plane mirror. When the two beams remerge an interference pattern is produced which depicts the groove shape. Although the interpretation of tbe pattern is in itself an art, the interference microscope furnishes information about the grooves that to an ordinary light microscope is undefinable.

Although it is beyond the scope of this article to pursue the techniques further, electron and interference light microscopes have proved to be "right hand" tools for diagnosing and correcting such things as diamond bounce on a rough surface, incomplete burnishing, defects and wear in the diamond surface, and pile-up of debris along the groove. They have proved invaluable in measuring the diamond face and its angle of contact with the surface.

The importance of proper blaze in a grating is now well established and beyond controversy for the region above 500A. In the extreme ultraviolet (XUV), however, where grazing incidence is a necessity, there remain two diverse schools of thought. One, represented by B&L, insists that blazed (1-3°) gratings are preferable here, too. The other is that of Siegbahn in Sweden who maintains that such gratings should be scratched very lightly on glass with a symmetrically pointed tool. The profile of his gratings is characterized by a long flat land separated by fine, shallow troughs. This differs markedly from the sawtooth rulings of a blazed grating which leave no land surface parallel to the base material. Intuitively, it appears obvious that the land of the Siegbahn grating will direct maximum energy into the reflected beam while the blazed grating will reflect maximum energy into a predetermined wavelength. A comparison between the two approaches that is free of variables and prejudice is eagerly awaited.

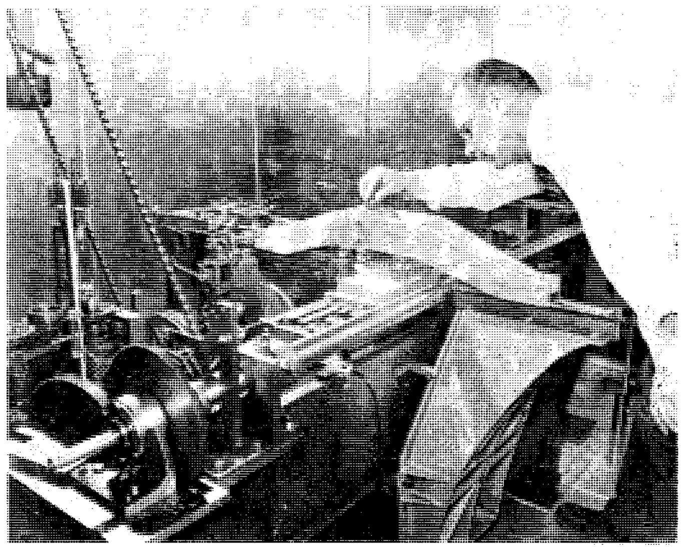


Fig. 3. R. S. Wiley is adjusting the diamond during the 8 to 60 setting up hours on the Chicago engine at B & L. To the left of the lead screw, just before the large spur gear is the cylindrical cam on which a follower rests. Prepared interferometrically, this cam corrects for errors in diamond placement to reduce ghost intensity. The gears may be so combined that almost any spacing can be achieved. (Courtesy B&L.)

REPLICATION

A grating is ruled at a rate of about 10 strokes/min. A 1200 groove/mm grating 100 mm wide thus takes nearly eight days to rule. Finer gratings take more than this time proportionally because the load on the diamond must be reduced to a point where chatter becomes a problem unless the stroke speed is slowed. Some large gratings take weeks to rule during which time temperature must be maintained to 0.01°, the diamond must not develop signs of wear and the operator's growing temptation to peek must be successfully restrained.

Were it not for the process of replication in which 30-50 gratings can be "pulled" from a single master, the cost of gratings would be prohibitive and the delivery time would range from months to never. Barring accidents as many as ten sub-masters may be obtained from the original. From these are produced the second and third generation replicas that are normally sold.

Fig. 4 depicts the steps in the replication process. After a layer of aluminum is deposited on the glass, the master ruling completed and tested, a layer of proprietary material is evaporated over the surface as a parting agent. On this surface a second layer of aluminum is deposited. Removed from the bell-jar, the coated master is sandwiched to what will become the replica, a thin coating of epoxy cementing the two together. After curing, the replica is pulled from the master, the separation occurring at the parting layer. The last block in Fig.

4 shows how a transmission grating is obtained from the reflection replica by dissolving the aluminum away in dilute caustic.

SPECIAL TREATMENT

Fast coating with aluminum is known to produce surfaces with high reflectance in the ultraviolet but this falls off precipitously below around 2000A. For the region from around 500A upwards, gratings are overcoated with MgF_2 to boost the reflectance to around 70% at 1216A. This rises to 90% above 2000A. For a typical Czerny-Turner mount in which the light must bounce off three surfaces, the overall reflectance thus drops to around 35% at 1216A setting the natural limit here for much spectroscopic work with sources of "normal" intensity. In the region from 500 to 1216A, concave grating instruments are generally preferred since they eliminate two reflecting surfaces.

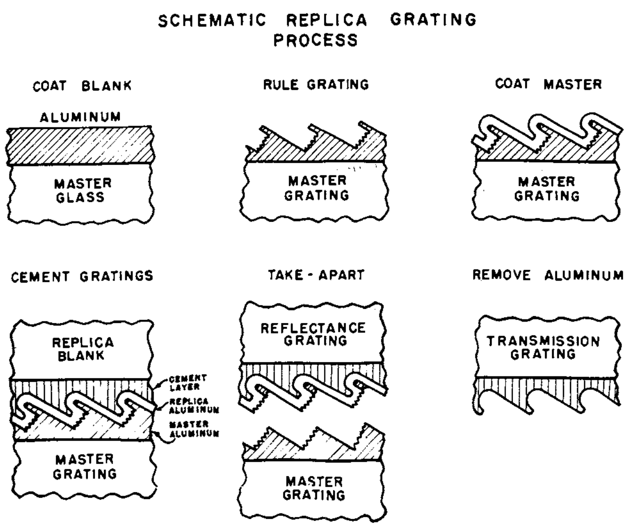


Fig. 4. The replication process for gratings. Here the long face is that blazed. Replication removes the overhanging burr which is seen to intercept a portion of the incoming light to the original. The result is an improvement of efficiency often in the order of 100%. (Courtesy B&L.)

Below 500A is the largely unexplored grazing incidence or XUV. Theory indicates that platinum or gold surfaces are preferable to aluminum. With the former, the critical angle of total reflectance for a particular wavelength is smaller than for aluminum. Because astigmatism and polarization rise rapidly with increasing incidence angle, it is usually held as small as possible. The presently suggested method of preparing gratings for this region is to overcoat them with platinum. A research program at B&L has shown originals ruled in gold and gold-germanium alloys to be promising.

GHOSTS AND SATELLITES

The word describing bothersome, spurious lines produced by gratings was aptly chosen. For line ghosts are as unwelcome as their metaphysical namesakes. Spectroscopists early distinguished between two types of ghosts. Rowland ghosts are those close to and symmetrically positioned (although not necessarily of matching intensity) on both sides of a strong line. The other type, Lyman ghosts, are weaker and far removed from the parent: a green spittin' image of the parent might eerily poke out of the invisible ultraviolet.

Until recently the origin of the two types of ghosts was thought to differ. Rowland ghosts were found to be caused by periodic errors in the ruling. Once per revolution, a slightly bowed lead screw will cause a shift from a rising to a falling wavelength error. Repeated every 0.5 mm in a lead screw of that pitch, the error will result in an extraneous line the wavelength of which is easily calculated. The many ruling engine gears and linkages introduce periodic errors corresponding to their periods of oscillation or rotation. Interaction among them gives rise to further ghosts. Seventeen ghosts in all have been found with careful scrutiny of gratings by B&L under conditions so severe that they would normally never be encountered in laboratory experiments. With sources having few strong lines, three or four ghosts are about as many as one is likely to encounter. Among these, the most prominent will generally have an intensity no greater than 0.1% in the first order, the others considerably weaker.

Because Lyman ghosts are displaced by large distances from their parents, their origin was understandably puzzling. Positions of these ghost lines, generally found at small fractions of the parent such as 2/5, 3/5, 4/5, 6/5 etc. were thought to be caused by superposition of two periodic errors. In early gratings Lyman ghosts were more bothersome than Rowland ghosts because of the danger in assuming the former to be real. The photographic plate does not, of course, distinguish a displaced line from one that belongs there unless the plate is insensitive to the wavelength of the ghost. Many lines erroneously reported in the literature may actually have been Lyman ghosts. In modern gratings, the intensity of Lyman ghosts is so weak (0.001% of parent or less) as to be inconsequential.

Meticulous searching will reveal exceedingly weak Lyman ghosts 4/9 and 5/9 of the parent wavelength with gratings from 1 B&L engine. Their origin is now clear and as straightforward as Rowland ghosts. They have been found to be periodic with a worm gear which rotates slowly in contact with a spur gear. Between the time when one tooth of the worm releases contact with the mating spur tooth and the next tooth of the worm makes contact, a momentary reduction of tangential pressure against the spur occurs. This is enough to displace the groove being ruled and produce what B&L has nicknamed a "Worm" ghost. Because the worm turns so many fewer revolutions than the lead screw, the number of grooves displaced is correspondingly small and the resulting ghost intensity gratifyingly weak.

Generally speaking, the smaller the number of grooves/mm, the weaker will be the Rowland ghosts. Attempting to apply a covering specification, ASTM set a limit of 0.1% for the maximum ghost intensity of a grating with 600 grooves/mm in the first order. This has proved to be inadequate because it does not limit the number of ghosts. Presumably, all 17 of the ghosts B&L has unearthed could each have an intensity of less than 0.1% and still meet these specifications. Were it not for the fact that an instance similar to this was reported (the grating was not one of B&L's), the problem would be thought insignificant. Perhaps a more realistic specification should be formulated based on the summational intensity of all of the ghosts in addition to the maximum of any one ghost.

Ghost intensity increases roughly with the square of the sine of the diffraction angle or with the square of the order. When seeking very weak lines at high resolution, the spectroscopist tries to set his grating to the maximum order. To his dismay, a ghost intensity of 0.1% will have increased to 10% in the tenth order. Fortunately, gratings of very low ghost intensity are now being manufactured to cope with such research. Interferometric control of spacing has reduced ghost levels by several orders of magnitude.

Realizing that ghost intensity seemed to have leveled off to the point where conventional means of improving the mechanical accuracy of engines seemed improbable, Dr. G. R. Harrison of MIT conceived a way of correcting for mechanical errors by interferometric measurements and servo control of the placement of the diamond tool. A series of articles by Harrison and his colleagues describes his steady progress in the decade starting in 1949 (5). One of the remarkable gratings ruled on this engine recently, from which B&L makes replicas in sizes up to 5″ x 10″, has 300 grooves/mm and, though not sharply blazed, shows an efficiency of 45-50% in the region 5400-6400A in the 9th, 10th and 11th orders. In the 11th order of Hg 5460A, the ghost intensity is a remarkable 0.05% calculating to an almost undetectable, unbelievable 0.0004% in the first order.

Satellites, in sharp contrast with ghosts, are ordinarily unseen, confined as they usually are within the bandpass of the spectral line. Only with very fine slit settings and in high orders are they detectable. No one has fully explained their origin although they are known to consist of areas on a grating where the spacing is different from that in the main portions. R. S. Wiley of B&L believes satellites are due to horizontal shifts of the carriage during ruling, shifts of such high frequency that they escape correction by present interferometer controls. When properly functioning, a well designed engine need not produce satellites of objectionable intensity, according to Wiley. The interferometer should be responsible only for the correction of lower frequency displacement errors. Dean Harrison feels that in his engine satellites are due to tilting of the carriage during ruling so that, although the interferometer mirror is correctly controlled, the part of the blank being ruled is not.

The famous MIT grating shows both low ghost as well as low satellite structure and so can be set to orders as high as the 110th to achieve remarkable resolution and freedom from interferences. The resolution has been shown to approach theoretical in typical long-path, low-aperture instruments.

The present ruling engine at MIT is one of the most remarkable mechanical achievements of man. To maintain constant friction in the system, the lead screw turns continuously as the diamond is drawn across the grating blank. Most other engines employ a mechanically simpler stop-and-go approach. The continuous movement would result in a non-constant velocity of the ruling diamond analagous to that of a person getting on and leaving an escalator. In the MIT engine appropriate cams are provided to provide constant velocity of the diamond. The interferometer control is so devised that correction is achieved during the entire stroke rather than only at the beginning. Lissajous figures on an oscilloscope screen monitoring the stroke, tell the operator at a glance how much of a correction is being made from one end to the other of the diamond path. Depending on an invariant light beam, the interferometer was initially set up with a Hg-198 light source. Recently a special wavelength stabilized helium-neon laser was substituted. The wavelength of its output is 6328A $\pm$ 5 megacycles or about 1 part in 10^8. Although temperature in the engine room is controlled, barometric pressure is not. A three-dimensional cam that looks like a drooping Dali surface corrects the interferometer for what otherwise would be a significant change in the refractive index of its air path.

ERROR OF RUN

If the ruling spacing does not remain constant but progressively changes across the grating face, a so-called "error of run" results. With the extreme pains taken to control temperature in modern grating engine rooms, this error has been reduced dramatically but is still something to be aware of. The easiest way of checking for it with a plane grating instrument is to find best focus for a strong line in the first order and then determine whether the focus changes for subsequent orders. The effect of error of run is most pronounced in higher orders.

Small errors of run are not too hard to live with if all they do is upset the focus. Spacing errors other than progressive, are more troublesome. In an extreme case, sections of a grating may be found to have discreet but different ruling constants. Of course, these limit the resolution. They can be tested for by systematic masking of portions of the grating. Theory to the contrary, it is often possible to improve the resolution of a particular spectrometer markedly by this procedure, particularly if the grating was ruled several years ago.

How modern diffraction gratings compare with theory is still quite an individual matter. Not only are there wide differences in performance from one manufacturer to the next but every master ruled winds up with a unique test report in which many of the properties show wide divergence. To be sure, the ultimate user would like to purchase a ghost—and satellite—free grating, with perfect efficiency in the region of his experiments, with resolution approaching theory, cosmetically perfect and with all parts of the grating contributing equally to the imaging of spectral lines. Upon further thought, however, the investigator may actually want to achieve the optimum in one property at the possible expense of another. Suppose his experiments are light-limited and the lines he seeks are not overly sharp as in fluorescence measurements. Obviously, ghost intensity and resolution are not nearly so important as is speed. A grating blazed at the wavelength of interest with an efficiency of 90% would be far more worthwhile for such an experiment than one with 40% efficiency showing half the ghost intensity.

Considerations such as this have prompted us to amass the information shown in Table 3. Going through the certificates for our current stock of gratings, we have abstracted the pertinent specifications. More than any other way, the table will permit the prospective user to determine what range of characteristics he can expect in a particular grating. Needless to say, the information presented is subject to continual change as new masters are introduced and old ones retired.

EXTRAPOLATION

The need for still larger gratings with still smaller groove spacing is still with us. As long as astronomers reach ever further into the heavens for their stars, there will be a need for ever larger gratings to concentrate the light and so boost the speed of their spectrographs. Studies of hyperfine structure and detection of weak isotopes are hampered by gratings of insufficient resolution. Raman spectroscopy, having found a new excitation source in the laser, is now thwarted by scattered light from gratings interfering with the detection of lines close to the exciting line.

MIT may soon be preparing gratings with a resolution even better than the 1.25 million already achieved when their new engine is completed. Dean Harrison is designing and supervising the construction of an engine which, it is hoped, will be capable of ruling gratings twice as large as the present one. To double the ruling speed, dual diamonds, each on an independent monorail and interferometrically controlled, will travel simultaneously.

Horsfield (6) has just described a radically new approach toward attaining spacing perfection, a hydraulically-actuated system in which the lead screw is notably absent and from which gratings completely devoid of ghosts will presumably be produced.

Table 3. Characteristics of Typical Current B & L Gratings

Ruling Const., grooves/mm	*Resolution, %*	*Blaze W.L., A*	*Efficiency, % at W.L. in Order shown*	*Ghost Intensity, % of 5461A in Order shown*
150	75	60,000	73-5461-XI	0.16-XI
150	85	40,000	67-5461-VII	0.21-VII
300	80	20,000	83-6438-III	0.054-III
300	75	30,000	80-4047-VIII	0.49-VI
300*	90+	.....	49-5461-XI	0.05-XI
600	85	7,500	77-3650-II	0.016-I
600	90	5,000	70-4047-I	0.072-I
600	75	16,000	46-5461-III	0.026-I
600	90	16,000	74-5461-III	0.071-III
600	70	10,000	61-5086-V	0.49-V
600	70	25,000	65-4047-VI	0.49-V
1200	75	3,000	65-3650-I	0.17-I
1200	75	1,500	36-2224-I**	0.06-I
1200	95	3,000	62-2967-I**	0.054-I
1200	80	5,000	89-5461-I	0.08-I
1200	90	5,000	83-5461-I	0.033-I
1200	95	7,500	73-4047-II	0.067-I
2160	93	3,000	69-4047-I	0.14-I

*This MIT grating shows a resolution beyond the capacity of the standard test method.
**MgF_2 overcoated.

Only time will tell whether this fresh approach will prove superior to that of Merton (7) who 15 years ago attempted to rule gratings on a continuous cylinder like the old Edison phonograph records. Although the ruling seemed fine, no method has yet been devised to slit the cylinder, open it up flat, cement it to a suitable optical flat, and wind up with a grating acceptable by today's high standards.

ACKNOWLEDGMENTS

I wish to convey my thanks to David Richardson and C. F. Mooney of B&L and Stephen Thompson of MIT, each of whom spent patient hours trying to transfuse the information he had acquired over years of hard, frustrating, but certainly rewarding work.

—A.J.M.

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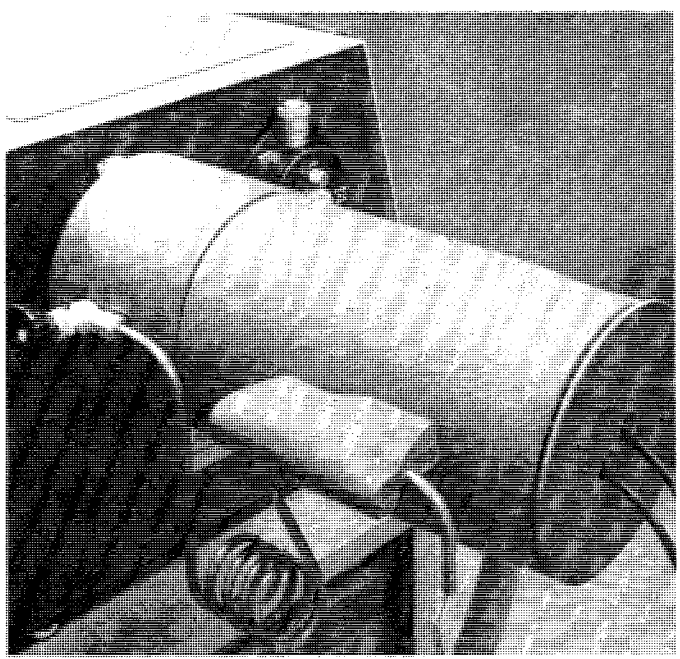

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OPTIMIZING ACCURACY IN EMISSION SPECTROCHEMICAL ANALYSIS

In the last issue of the SPEAKER we invited criticism and addenda to the article on accuracy. An error of reversal with regard to alpha and gamma forms of alumina was reported by A. L. Hannam of Carborundum Company, Niagara Falls, N. Y. and R. H. Black, Aluminum Laboratories Limited, Arvida, Quebec. Dr. Black, who also discussed a significant source of error of which we were not at all aware, writes:

"The first paragraph on page 5 compares intensity ratios in 'the low-temperature alpha alumina' with those in 'gamma-alumina, the form obtained by firing in a higher temperature atmosphere' and offers the rather pat explanation that the 'heat of the dc arc simply excites the aluminum in the low-temperature alpha material to a greater degree than the aluminum in the gamma form.'

"As has probably been pointed out to you by now, the term gamma actually designates a relatively low-temperature form of alumina, and alpha is generally not produced much below 1100°C. Hence the explanation should read 'the arc excites the aluminum in the high-temperature alpha material to a greater degree . . .' I do not know if this is more plausible than the original statement. In any event the change by a factor of two is not surprising; we have noted even five-fold variations when sparking different forms of alumina supported on cellulose tape. Our published 'mineralized calcination' treatment greatly reduces such structural effects.

"Your concluding paragraph invites mention of additional sources of error. Several come to mind which, in my opinion, have received far too little attention. As we have been wedded to direct readers for 18 years, the following comments apply primarily to photoelectric detection. When a simple quartz lens (or lens system) is used to image the source of light on to a grating, the position and size of the image vary tremendously with wavelength; therefore, not only does light from various regions of the source reach different areas of the grating, but the area reached depends also on wavelength (and may even lie outside the ruled area). Hence there is no nice one-to-one correspondence between points in the source and points on the grating, except possibly for the particular wavelength at which focusing of one on the other occurs. Even with a perfect grating, then, any movement of the discharge column leads to imprecision. Focusing the source on the entrance slit presents similar difficulties.

"We would, though, expect two orders of the same spectral line to behave the same optically up to the point where diffraction occurs, and a perfect grating should afford near-perfect precision. Alas! gratings are far from perfect and we have observed variations of 30% in the intensity ratio (Al 2568 x 2)/(Al 2568) when we covered the left, right, top, or bottom halves of a grating. In actual reproducibility tests the coefficient of variation obtainable is around 1%, but this is an order of magnitude worse than an incandescent lamp affords.

"Still another source of error (in direct readers) is non-uniformity in photo-cathode surfaces. It is common practice to focus either the exit slit or the grating on to a small area in the detector; but obviously, the smaller the area, the greater the risk that a small movement of the light spot relative to the phototube (or vice versa) will alter the output current."