Varied Line-Space Gratings: Past, Present and Future

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Abstract

A classically ruled diffraction grating consists of grooves which are equidistant, straight and parallel. Conversely the so-called "holographic" grating (formed by the interfering waves of coherent visible light) , although severely constrained by the recording wavelength and recording geometry, has grooves which are typically neither equidistant, straight nor parallel. In contrast a varied line-space (VLS) grating, in common nomenclature, is a design in which the groove positions are relatively unconstrained yet possess sufficient symmetry to permit mechanical ruling. Such seemingly exotic gratings are no longer only a theoretical curiosity, but have been ruled and used in a wide variety of applications. These include 1) aberration-corrected normal incidence concave gratings for Seya-Namioka monochromators and optical de-multiplexers, 2) flat-field grazing incidence concave gratings for plasma diagnostics, 3) aberration-corrected grazing incidence plane gratings for space-borne spectrometers, 4) focusing grazing incidence plane grating for synchrotron radiation monochromators, and 5) wavefront generators for visible interferometry of optical surfaces (particularly aspheres). Future prospects of VLS gratings as dispersing elements, wavefront correctors and beamsplitters appear promising. I discuss the history of VLS gratings, their present applications and their potential in the future.

Introduction

In the middle to late nineteenth century, when the imaging properties of the newly conceived concave grating were being discovered[1], attention was already being given to the effects of systematic variations in spacings between the grooves. The intent of these studies was primarily to explain anomalies observed in the spectra of imperfectly ruled gratings. For example, periodic spacing errors were found responsible for "ghost" lines and false images which dominated the spectra of the earliest gratings[2,3]. Indeed, much effort has since been concentrated into reducing such variations and their undesirable effects.

Cornu[4] also considered the focal properties of gratings ruled with slow non-periodic variations in groove spacings. By invoking a linear space variation (arising from an "error of run" inherent in early ruling engines), he was able to explain observed anomalies in the focal curves of concave gratings, and predicted some focusing ability of a plane grating if ruled with a large linear space variation. In referring to the distance between grooves, quotes from two of Cornu's papers read

> "J'ai en vue les erreurs systematiques qui produisent un changement de foyer sans alterer la nettete des images." (1875).

> "Elle effecte, suivant le rapport existant entre R et P, des formes tres diverses, qui derivent du type de la cissoide de Diocles a laquelle d'ailleurs elle se reduit lorsque la coubure de reseau devient nulle ($R=\infty$)." (1893).

Unfortunately, the engineering challenges inherent in the fabrication of even a conventional grating left such possibilities dormant for the next eighty years.

During this period, the diffraction grating found use in ever more demanding circumstances, driving the performance requirements to near perfection. Mechanical ruling[5-7] or optical interferometry[8-10] can now form finely spaced (up to 6000 g/mm) grooves on the surface of a large plane or curved surface, result in the retrieval of greater than 70% of the theoretical diffraction efficiency and with ghost line intensities negligible in most applications. Thus, we have reached the point where further engineering perfection of the basic plane or concave grating will yield limited return. Significant future enhancement in the performance of grating instruments requires that we now turn our attention to the use of new or unconventional geometric solutions to the problem of diffractive focusing.

Several recent technological events are seen as responsible for a growing interest in VLS gratings. First, the increased sophistication of ruling engines, which now routinely incorporate computer control, interferometric feedback and fine servo motions; all necessary ingredients to the construction of a VLS capability. Second, the realization that aberration-correction using mechanical ruling is optimal when the highest possible diffraction efficiency is crucial or when the reduction of certain aberrations (such as coma) requires a relatively unconstrained positioning of the grooves. Third, the use of gratings at increasingly shorter wavelengths, particularly in the soft x-ray with the availability of synchrotron and plasma radiation. The line-space variations available using visible or near UV interferometry do not closely approximate the large variations required for use at shorter wavelengths in grazing incidence. Varied line-spacing using mechanical ruling has emerged as a preferred method of aberration-correction in the far UV, extreme UV and soft x-ray bands. Fourth, spectrometers are now being designed and built for long duration space flights in astronomy. Requirements on physical compactness, efficiency and signal-to-noise are extreme, and are increasingly being met by exploiting the extra degree of freedom available with varied line-spacing. Such designs have revitalized the use of unconventional plane grating geometries in both astronomical spectrometers and laboratory monochromators. Fifth, the development of high-resolution photoelectric detectors (microchannel plates, imaging proportional counters, streak cameras, etc) for which the spectrum is imaged on a flat detecting surface. Varied spacings on a grazing incidence grating can be used to obtain such required flat-field imaging. Finally, the fabrication of precisely shaped aspheric surfaces (e.g. grazing incidence telescopes, toroids, normal incidence paraboloids) has precipitated the need for more exacting methods of surface metrology. VLS gratings, including the use of circular grooves, have been used to generate wavefronts suitable for the interferometric testing of figured optical surfaces. Thus, we see a broad range of needs have arisen in which VLS gratings are crucial elements.

In this paper, I have made an attempt to briefly review any work published on the subject of VLS gratings, survey their current applications, and speculate as to the future roles such devices may assume. The following sections discuss various relaxations of the classical constraints on grating design. First we consider gratings in which the grooves are straight and parallel, but not equidistant. Second we consider equally curved or concentrically curved grooves which may be either equally or unequally spaced. Lastly we discuss gratings in which the grooves are straight, but are not parallel and thus must also have space variations. In all three categories we find both plane grating and concave grating surfaces have been utilized.

Non-equidistant, straight and parallel rulings

Concave Surfaces

In the literal sense, a curved surface contains curved grooves. The phrase "straight and parallel rulings" refers to the conventional rectilinear motion of a mechanical ruling engine for which the grooves are formed at the intersection of the grating surface and a set of parallel planes in which the tool reciprocates. Any modern ruling engine can thus, in principle, be outfitted with means of specifying the location of individual grooves in this geometry. As such, these were the first VLS gratings studied and fabricated.

In a series of papers from 1875 to 1893, Cornu investigated in some detail the anomalous focal curves which result from linear space variations, i.e. $\sigma = \sigma_o + w\, d\sigma/dw$, where σ_o is the nominal spacing, w is the ruled width coordinate and the derivative $d\sigma/dw$ is a constant. He arrived at the following equation for the spectral (meridional) focal curve:

$$\rho = \cos^2\alpha \;/\; (\cos\alpha\,/R - \sin\alpha\,/P) \qquad (1)$$

where R is the grating radius of curvature, $P = \sigma_o/(d\sigma/dw)$, α is the angle of diffraction (or incidence) and ρ is the image distance measured from the grating center. A perfectly ruled classical concave grating has an infinite value for P, which from the above equation results in the Rowland circle $\rho = R\cos\alpha$. Small space variations mainly tilt the Rowland circle in the direction of larger groove spacings.
However, a significant space variation, for which

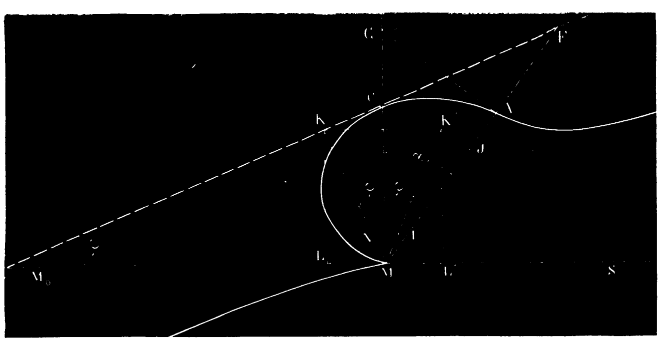

Fig. 1. Anomalous focal curve of Cornu (1893).

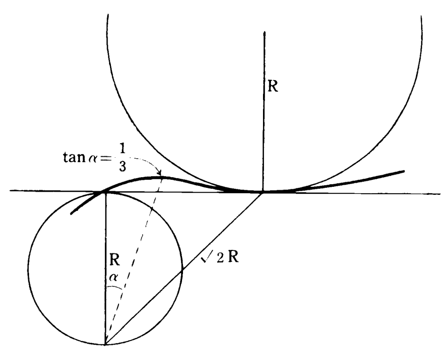

Fig. 2. Remuniscate of Sakayanagi (1967).

P is comparable to R, results in a non-closed focal surface reproduced in Fig. 1.

Apparently unaware of Cornu's work, Sakayanagi proposed in 1967 that a concave spherical grating be ruled with varied groove spacings[11]. Sakayanagi realized the potential of space variations in removing aberrations in the image*. With an approximately linear variation, defined by P=2R in eqn. 1, he generated a reminuscate meridional focal curve which would be tangent to the sagittal (secondary) focal plane at a point in whose vicinity astigmatism would be small (Fig. 2). The paper of Sakayanagi marks the beginning of an era when fabrication of VLS gratings became practical.

In 1970, Gerasimov et al[13, 14] devised a ruling engine capable of introducing fixed variations in the groove spacings. Their setup consisted of a grating interferometer within which was inserted a cam-driven screen which modulated the moire fringes according to the cam shape. Using a circular cam, they ruled several plane and concave gratings with linear space variations (of order 1%). In Fig. 3 are shown imaging tests of three concave gratings using a mercury light source and an entrance slit which was broken in height to test for astigmatism removal. The gratings had a radius of 1 meter and were mounted near normal incidence resulting in focal curves as illustrated below the spectra. The removal of astigmatism within a broad wavelength range centered at the intersection point of the distorted meridional curve and the sagittal plane was verified. Curve 4 in Fig. 3 shows the Rowland circle. It is historically interesting to note that this first demonstration of a mechanically ruled aberration-corrected grating occurred within the same time period in which holographic corrections were first demonstrated on photoresist gratings[15].

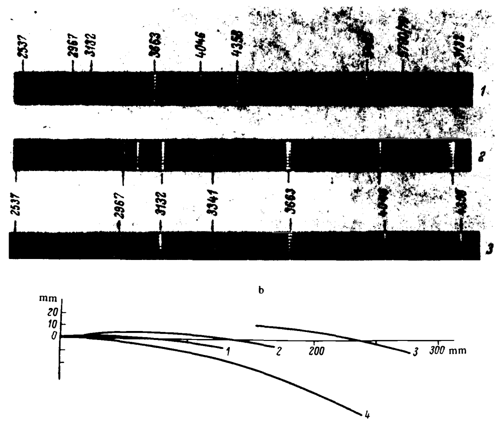

Fig. 3. Reduction of astigmatism demonstrated by Gerasimov(1970).

The first instrument which effectively used a VLS mechanically ruled grating appears to have been a far UV solar spectrograph flown on the Skylab space observatory in 1973[16]. The main grating of the spectrograph was preceded by a cross-disperser concave grating which decreased the level of focused stray light and extended the wavelength range by separating spectral orders 1 and 2 of the main grating. However another function of this predisperser was to correct for the astigmatism (2-3 mm) of the main grating. As shown in Fig. 4, the disperser was ruled in ten segments (multi-partite) across its ruled width, each segment having a discrete groove spacing. Although not continuous, this variation changed its meridional focal surface to approximate the sagittal plane (Sirk's position) of the main grating (POINT C). Astigmatism in the main spectrum was reduced a factor of three, and the recording speed of the spectrograph thereby increased. The segmented predisperser was ruled by B.W. Bach while at Bausch and Lomb. The instrument recorded 6400 spectra during its flight on Skylab (Fig.5).

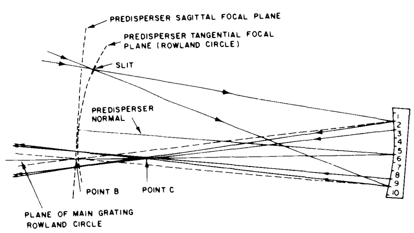

Fig.4. Bartoe segmented predisperser (1974).

The most significant advances in the engineering realization and practical use of the VLS concave grating have been made over the last decade by Harada and colleagues at Hitachi's Central Research Laboratory. They have constructed ruling engines capable of placing grooves according to essentially any desired input function continuously across the grating ruled width (Fig. 6)[17-19]. Their control system (Fig. 7) consists of a multi-reflection prism interferometer which can determine position of the grating blank to a small fraction of the laser wavelength. The desired space variation is input by microcomputer and used as a reference signal to correct the blank translation by means of a servo motor driven in pulsed steps of 0.2 Å. Harada has demonstrated systematic control of the groove positions to less than 1 Å in a coma-corrected VUV Seya-Namioka grating whose total required space variation was only 2 Å. This accuracy should be understood as a statistical uncertainty averaged over the number of grooves necessary to construct an interference pattern of the observed resolution.

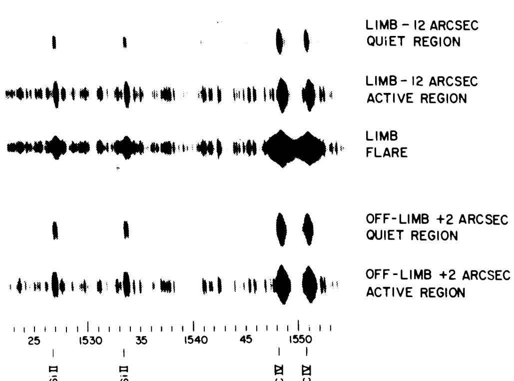

Fig.5. Skylab solar spectra, astigmatism 0.5 mm, $\lambda/\Delta\lambda \sim 15{,}000$. From Bartoe (1974).

*A thesis by Baumgardner[12] also investigated VLS gratings and found similar results.

Iwanaga and Oshio undertook a comprehensive analysis of the aberration-correction possible with mechanical ruling of a concave grating, and found that coma-type aberration can be reduced in addition to astigmatism for rotational mountings (e.g. Seya-Namioka) near normal incidence[20].

At grazing incidence, much larger space variations are required to effect useful deviations from the Rowland circle. The Hitachi group has designed, fabricated and tested a grazing incidence concave grating for which a 35% space variation constrained the focal surface to be approximately flat and normal to the diffracted beam[21], as illustrated in Fig. 8. In Fig. 9 is shown a scanning electron micrograph mosaic of different sections across the ruled width (50 mm) of a 1200 g/mm VLS concave grating ruled for flat-field use at grazing incidence from 50 to 300Å. This grating was measured in the extreme UV and found to retrieve over 70% of the theoretical efficiency expected from perfectly shaped grooves[22]. The level of stray light was also quite small in comparison to conventional gratings, an effect attributed to the necessarily small random errors in groove positions attained with the VLS numerically controlled ruling engine described above. Nakano et al have used two such flat-field gratings (10-50 Å and 50-300 Å) to analyze laser produced plasmas with photographic plates[23]. Flat-field focusing is even more crucial when electronic devices such as streak cameras are used to image the spectrum.

A second unique feature of the Hitachi VLS ruling engine is its ability to tilt the ruling plane a fixed angle from the grating normal, resulting in grooves which appear elliptically curved if projected in the plane tangent to the grating at its center. This tilt has been used to alter the sagittal focal curve and thus help reduce astigmatism in a Seya-Namioka monochromator[19]. Kita and Harada have also used this effect in the construction of a compact concave grating (lensless) optical de-multiplexer[24]. By a linear space variation in combination with a tilt of the ruling planes, both the meridional and sagittal focal curves were distorted, and a factor of twenty reduction in astigmatism was obtained over the 750-850Å spectral band. The coupling efficiency of the de-multiplexer thereby rose to 55%, which is a factor of six larger than attainable with a conventional concave grating. The instrument configuration is illustrated in Fig.10. The grating radius of curvature was only 50 mm, the nominal groove spacing was 1/300 mm, and the blaze angle was reset twice across the ruled width (tri-partite) to maintain high diffraction efficiency.

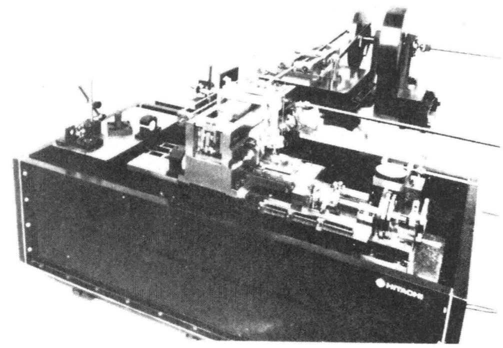

Fig. 6. Numerically controlled ruling engine. From Harada (1980).

Table I. Specifications of the Concave Gratings Ruled with the Numerically Controlled Ruling Engine

Nominal groove number	300–3000 g/mm
Min. radius of curvature	10 mm
Max. ruled area	150 (W) × 100 (L) mm^2
Max. aperture	F3
Min. space variation	0.02 nm
Grating surface	Spherical or toroidal

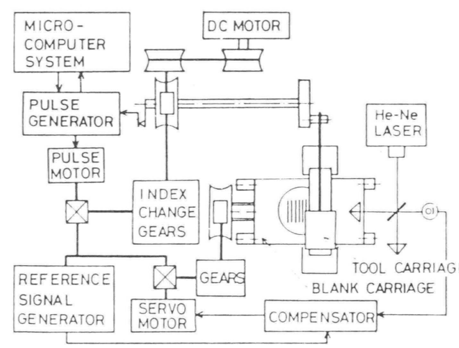

Fig. 7. Control system of Fig. 6.

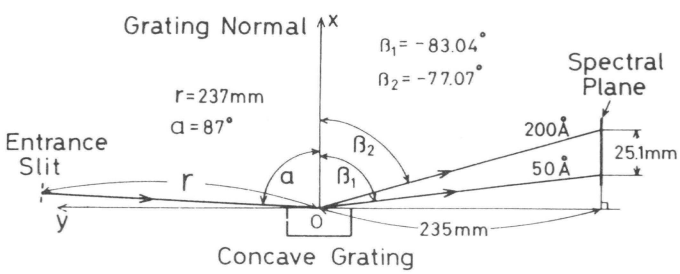

Fig. 8. Flat-field grazing incidence spectrograph using VLS grating. From Kita (1983).

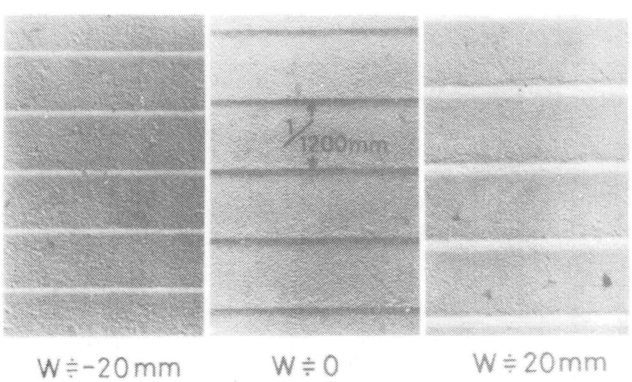

Fig. 9. Electron-micrographs of VLS grating for flat-field spectrograph (Harada, priv comm)

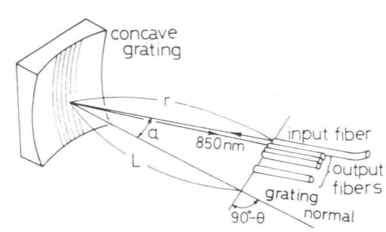

Fig. 10. Optical de-multiplexer using a VLS grating. From Kita & Harada (1983).

Aspnes has proposed a monochromator using a varied-space cylindrical grating design[25]. The surface curvature would provide sagittal focusing and the varied spacing would result in meridional focusing along the dispersion direction. As the grating accepts diverging incident light and is not curved along the direction of its ruled width, the required space variation is approximately an exponential function of the ruled width. Given practical constraints on the magnitude of the total space variation between opposite edges of the grating, this design is limited to applications requiring only a slowly diverging beam (e.g. synchrotron radiation). Interesting properties of such a monochromator are 1) almost no defocusing under a simple translational scanning motion of the grating, and 2) on-blaze diffraction efficiency at the central groove for all wavelengths accessible by the scan.

Plane Surfaces

In reference to Fig. 1, Cornu remarked[4]:

> "Enfin, passant a des conditions inverses, si le reseau est sensiblement plan et presente une progression systematique notable dans la distance des traits, le point C s'eloigne a l'infini, l'angle ϕ devient droit; la courbe focale principale devient une cissoide dont l'asymptote passe par M_o et est normale au plan du reseau. On retrouve alors la disposition des foyers des spectres que j'ai indiquee dans mes premieres recherches."

Despite such clues, the focusing properties of plane gratings received only intermittent and curious attention until recently. This reluctance has been with some justification, as the concave grating performs focusing and dispersion in a single optic, permitting use even at ultraviolet wavelengths where the number of reflections must be minimized. However, the single concave grating geometry does have some disadvantages, including the presence of significant astigmatism (which can degrade the ultimate sensitivity and hamper attempts to overlay a comparison spectrum), the need to obtain accurately curved and polished grating blanks, and its practical restriction to use in low spectral orders.

In 1928, Monk[26] proposed a spectrometer in which, following the idea suggested to him by the optician Pearson at the University of Chicago Ryerson Laboratory, a plane grating was illuminated by convergent light produced by a spherical mirror (Fig. 11). In 1949, Gillieson[27] re-invented this arrangement which has since been called the Monk-Gillieson mounting. Interestingly, a U.S. patent was issued in 1961 to Barnes and Collyer for a spectrometer using convergent light on a plane grating[28]. Monk himself deduced the meridional focal curve to be a lemniscate of the form:

$$S = \rho \cos^2\theta / \cos^2\iota \qquad (2)$$

where ι is the angle of incidence, θ is the angle of diffraction, ρ is the distance from the grating center to the (virtual) source located behind the grating, and S is the focal distance from the grating center to the image. If the incident and diffracted rays lie on opposite sides of the grating normal (e.g. zero order) then ι and θ are opposite in sign. In Fig. 11, the concave mirror C refocuses the light source s to the left of the diagram, and the plane grating G focuses various wavelengths along the lemniscate (dotted curve). The point I is the reflected zero order image, and is an equal distance from the grating as the virtual source. As the grating diffracts within its plane of reflection, it provides no focusing power in the image height direction, thus the point I contains no astigmatism. Although this zero order image is of no interest spectroscopically, the astigmatism is also absent at a second point on the opposite side of the grating normal, corresponding to the Littrow condition $\theta = \iota$. In 1962, Murty[29] used this normal incidence mounting (Fig. 12) and considered various methods of removing higher-order aberrations such as coma, the existence of which was first recognized by Richards, Thomas and Weinstein[30] and by Rosendahl[31]. By inspection of Fig. 12, where A is the virtual source, A' the spectral image and P a point on the grating, it was shown by Murty that point-

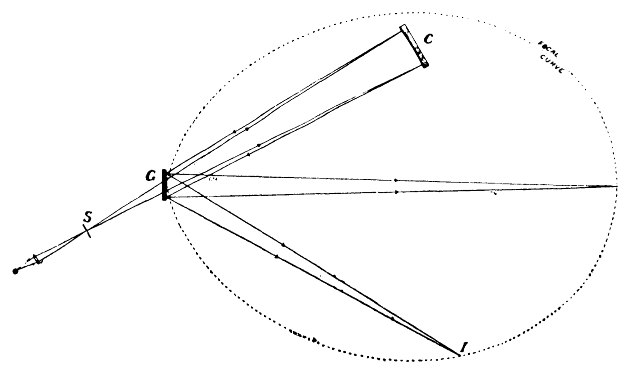

Fig. 11. Spectrometer consisting of a plane grating in convergent light (Monk 1928).

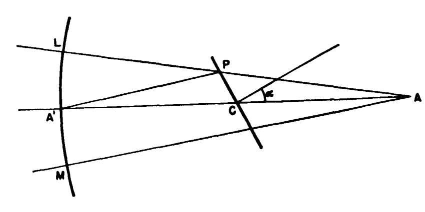

Fig. 12. Point-like focusing in Littrow Monk-Gillieson requires hyperbolic grooves (Murty 1962)

like focusing (stigmatism) at A' is achieved if the grooves coincide with hyperboloids of revolution about the AA' axis. This is the condition for which the distance AP - A'P is stationary for all P on the grating aperture. The groove curvature removes astigmatic coma and a quadratic space variation between the grooves removes the dominant meridional coma aberration. However, the unlikely prospect of ruling hyperbolic grooves led Murty and others[32-34] to consider less exotic means of reducing coma-type aberrations.

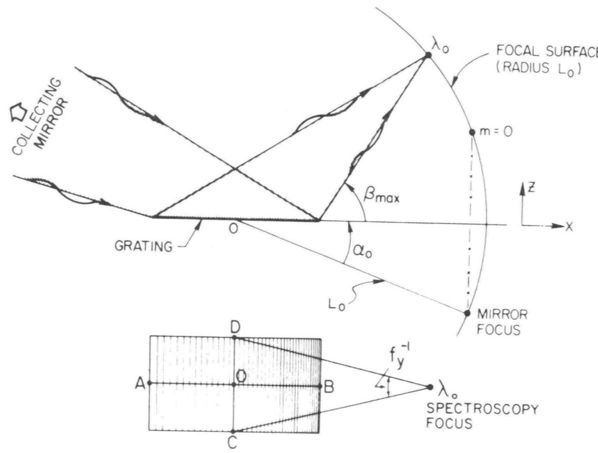

Fig. 13. VLS plane grating, corrected for astigmatism and coma. Figure is from Hettrick and Bowyer (1983).

At grazing incidence, the most debilitating aberration in moderate resolution applications is not coma, but astigmatism. Equation 2 states the focal distance S varies as the square of the ratio in cosines of the incident and diffracted angles. For angles approaching 90° (grazing incidence), the separation between the sagittal and meridional focal curves is even larger than for a spherical grating in diverging light, as in the later case the focal distance along the Rowland circle varies only linearly with the cosine of the angles. Such large astigmatism, combined with the aspherical focal surface illuminated at grazing incidence, has precluded the use of the Monk-Gillieson mounting for grazing incidence spectroscopy.

A solution to this problem has been given in a series of papers by Hettrick[35-37]. By use of straight parallel grooves whose spacing varies across the ruled width, the meridional focal curve is changed from a lemniscate to a curve which passes through the sagittal focal circle (Fig. 13) at a correction wavelength ($S=\rho$):

$$S = \rho \cos^2\theta \,/\, [c(\sin\theta + \sin\iota) + \cos^2\iota] \qquad (3)$$

where $c=(\cos^2\theta_o-\cos^2\iota)/(\sin\theta_o+\sin\iota)$, θ_o being the diffracted angle at the correction point. This not only removes astigmatism but also produces a normal incidence focal surface near the correction wavelength. Meridional coma is also eliminated by the choice of space variation. Because the incident focus (source) and spectral image are equidistant from the grating, sagittal coma is minimized, resulting in a resolution $\lambda/\Delta\lambda = 8\, f_y^2$, where f_y is the beam speed (e.g. 10) along the grooves.

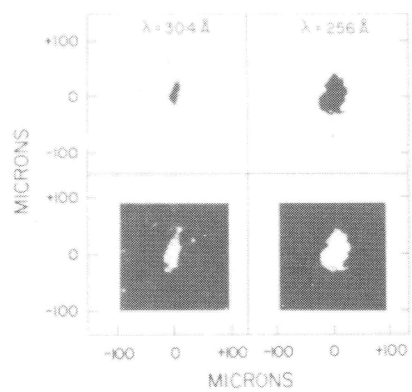

Fig. 14. Images from convergent beam test of VLS plane grating at grazing incidence (Hettrick 1985).

The use of varied spacing to alter the meridional focal surface and thus remove astigmatism has been realized for some time in the case of a concave grating (previous section). It is therefore interesting that the analogous improvement for a plane grating was not realized until 1983, nearly 100 years after the first theoretical work on the focusing properties of plane gratings. In part, this ignorance has probably been due to the requirement of convergent incident light in the plane grating case. It is generally assumed, though incorrectly, that use of other than divergent source light requires more reflections.

The realization that straight grooves could be used with small residual aberrations in a convergent beam led Hettrick to design a space observatory extreme UV spectrometer based on this principle. Given a pre-existing large aperture telescope which collected starlight, the primary goals of maximum sensitivity and a physically compact instrument were met by a slitless design using grazing incidence VLS gratings[37]. The gratings were fabricated by Harada and the performance results on a test sample reported by Hettrick et al[37]. Using a convergent beam provided in the laboratory, images were recorded on film as shown in Fig. 14. The elimination of astigmatism is verified over a wide spectral band near the correction wavelength. At the sagittal focal curve of a conventional grating, the image heights would still be approximately 50 microns, but the spectral resolution would be only 25%, corresponding to an image width of 15,000 microns (over 300 times as large as the image widths shown in Fig. 14). This grating was also measured to retrieve in excess of 80% of the diffraction efficiency expected from perfectly formed grooves, despite the 25% space variation across its aperture.

In 1966, Gale[38] studied the focal properties of VLS plane gratings illuminated by diverging light. Using a physical optics approach, Gale generated focal curves for two designs.

Harada has designed and fabricated a high resolution ($\lambda/\Delta\lambda = 10^3$-$10^4$) plane grating monochromator[39], using the focusing properties of varied spacing when the incident light is diverging. The instrument (Fig. 15) uses only plane surfaces (mirror and grating), which can be easily fabricated to high optical quality. As with the VLS grating monochromator proposed by Aspnes (above), the divergent incident light requires a large space variation and thus small acceptance angles. However, this is not a limitation when used with highly collimated synchrotron radiation, where the acceptance angle need be only 1 milliradian or less across the ruled width. The monochromator is currently becoming operational at Japan's Photon Factory synchrotron radiation light source, where it will be used to wavelengths as short as 5 Å. The flat mirror preceding the grating functions not only to keep the grating in focus through the wavelength scan, but also to reduce higher-order harmonic contamination and to partially compensate for the blaze shift in the grating diffraction efficiency as the grating scans. These properties are similar to those of the FLIPPER monochromator[40] used in synchrotron radiation beam lines, and result from the fact that both the pre-mirror and the grating are illuminated at larger graze angles as the scanned wavelength is increased. Yet, unlike the FLIPPER, the VLS plane grating monochromator of Harada does not require a curved re-focusing mirror after the grating.

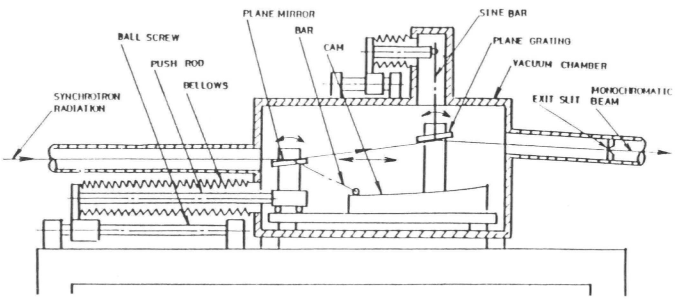

Fig. 15. VLS plane grating monochromator for synchrotron radiation. From Harada (1984).

The Perkin-Elmer Corporation has applied the technology of varied spacing on a plane grating to generate desired wavefronts in the diffracted beam[41,42]. The high optical quality attainable with a flat grating surface allows diffraction-limited wavefronts to be obtained. In the case of straight and parallel grooves, these wavefronts are cylindrical, and are used to interferometrically test the precise figure of cylindrical optics, as shown in Fig. 16. This is the only non-dispersive application in which mechanically-ruled VLS gratings have been used. Gomez and Hirst at the Perkin-Elmer Ruling Facility Instrument Group have set up a linear ruling engine "D" which uses interferometric control to emboss varied spaced straight and parallel grooves with frequencies of 1 to 3000 per millimeter across apertures as large as 175 x 175 mm^2. The freedom to place the grooves according to any desired functional form allows unique wavefronts to be generated which can match those of even non-circular cross-section cylinders.

When gratings are used for dispersing wavelengths, any unruled portion of the grating will simply lower the diffraction efficiency. This is a special consideration for a VLS grating, where a constant weight loading of the diamond tool cannot fully rule the groove depths required at the more coarsly ruled sections of the grating. If the grating is used at grazing incidence, this problem can be alleviated by use of a replica once removed from the master, where the imperfections are generally in the unilluminated bottom part of the grooves. However, in the case of a VLS grating to be used in optical interferometry, diffraction-limited performance demands use of the master ruling and the grating is illuminated at near-normal incidence; thus the unruled portions of the grooves are fully visible to the incident light at the groove tops. Although the resulting decrease in diffraction efficiency and shift in blaze wavelength are not crucial problems in this application, the unruled grating sections (duty cycle less than unity) result in phase disturbances in the diffracted wavefront[42] (Hirst, private communication). Therefore, Hirst has experimented with means of continuously varying the loading on the diamond tool to obtain a constant duty cycle for VLS gratings. Such conditions will also improve the efficiency of gratings used for dispersive functions.

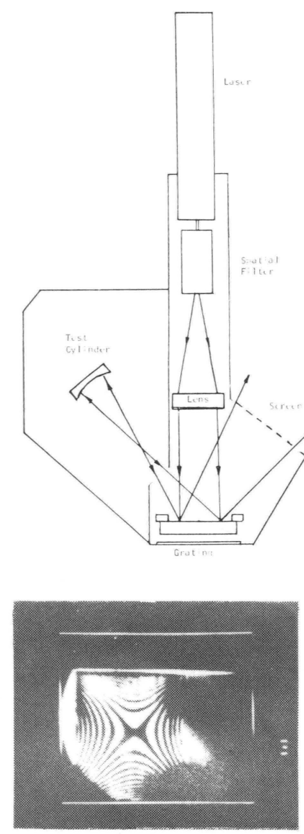

Fig. 16. Interferogram of test optic using VLS flat grating (Hirst 1985).

Non-linear rulings, equidistant or varied spaced

Concave Surfaces

Curved rulings are generally assumed to be impractical with mechanical ruling engines. It thus may be startling to uncover the work of Sakayanagi, who in 1954 designed[43], ruled

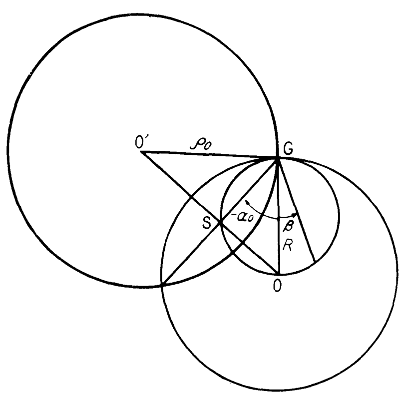

Fig. 17. Sakayanagi curved grating (1954).

and tested[44] a curved groove grating. Sakayanagi's "curved grating" design principle is shown in Fig. 17. The grating surface is a sphere with radius R and center of curvature at point O. If projected onto the plane O'G tangent to the grating, the grooves are circular with center at O'. The three dimensional groove is a circle with symmetry axis O'O on which astigmatism must vanish provided the image and source both lie on this line. This sagittal focal curve of the grating intersects the meridional focal curve (Rowland circle) at two points. If the source and image are located at these two points, in addition to no astigmatism, the image will be in focus spectrally and contain no coma aberration. At normal incidence (within 30° of the grating normal) Sakayanagi showed there will be a useful range in wavelength where the astigmatism remains small. Subsequent theoretical work[12,45,46], particularly that of Strezhnev and Shmidt[47] (and references cited therein) revealed that a curved groove spherical grating exhibits a broader region of astigmatism correction than would result from varied spacing alone or by use of aspherical (e.g. toroidal) surfaces. In the case of Sakayanagi's curved grating, the sagittal focal surface is altered, while the uniform spacings keep the meridional focal surface intact.

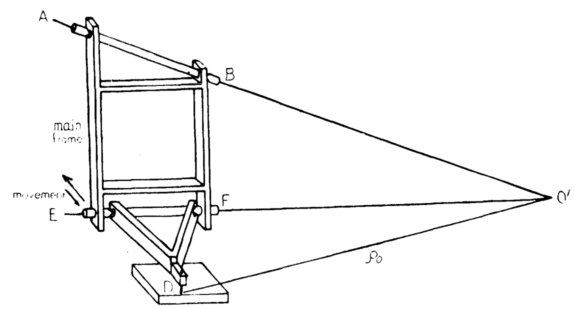

Fig. 18. Apparatus used by Sakayanagi to rule grooves of equal curvature on a sphere.

Sakayangi's ruling apparatus is shown in Fig. 18. This geometry constains the diamond D to move along a spherical surface with center O' and radius ρ_o. (As discussed above, Harada has more recently realized this curved groove constraint with a linear ruling motion by tilting the reciprocation plane to coincide with axis GS in Fig. 17. However, Sakayanagi's fabrication method provided a curved ruling motion even if the grating surface was flat.) A spherical grating blank of radius R=150 cm was used, and grooves of equal (not concentric) curvature ρ=315 cm were ruled with spacing 576 g/mm. The grating was illuminated with a Hg lamp and the spectra obtained (Fig. 19) compared to a conventional concave grating. Although the spectra suffered from a large amount of stray light, this work demonstrated clearly that astigmatism could be eliminated using curved grooves.

Murty[48] has proposed a spherical zone-plate diffraction grating in reflection or transmission (Fig. 20). The grating is aplanatic due to the choice of a coma-free surface PC (the circle of Apollonius) along which the magnification between object A and image A' is constant. Varied spacing is then required to remove spherical aberration. For example, if the object is at infinity, the grating surface is a sphere with center at the image. A mirror surface, of course, would have twice this radius of curvature; thus the groove densities on the grating must be quite high to remove spherical aberration, comparable to what is required for a planar zone plate. Murty showed that the grooves are at the intersection of parallel planes spaced equally in the horizontal direction of Fig. 20. Thus, if viewed from the grating normal, the grooves are concentric with spacings which vary inverse with their radii. Murty recently has proposed a tandem arrangement of two such gratings to construct a narrow-band filter.[49] While such gratings could be fabricated by holographic techniques, a mechanical ruling would provide much larger apertures and more easily attain the high groove densities desired.

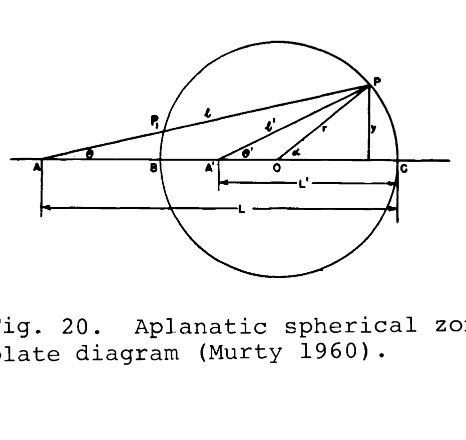

Fig. 20. Aplanatic spherical zone plate diagram (Murty 1960).

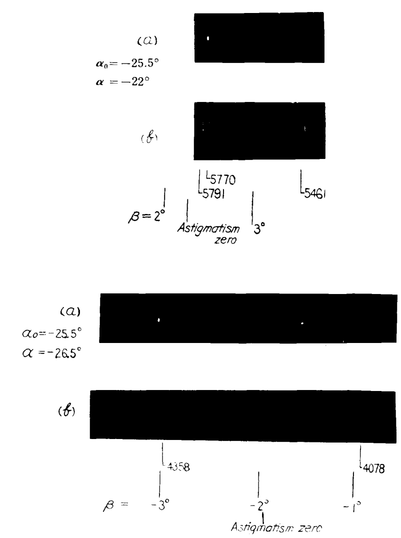

Fig. 19. Mercury spectra using 1 mm long entrance slit. (a) curved grating, (b) conventional grating. From Sakayanagi (1954).

Plane Surfaces

Encouraged by the prospect of mechanically-ruled curved grooves, a number of authors have proposed designs using plane grating surfaces and concentric grooves. Applications have ranged from use as fine-pitched rulers in surface metrology[50] to spectroscopy at grazing incidence[35,36,51] to interferometry at visible[52] or at grazing incidence in the extreme UV or soft x-ray[53]. However, until recently such gratings have not been attempted with a mechanical ruling engine. In 1982, the Perkin-Elmer Corporation constructed a prototype rotary ruling engine[41,42] for ruling single-start concentric grooves with varied spacings. As with their linear varied-spaced gratings, the concentric gratings have been used to generate desired wavefronts for the interferometric testing of curved surfaces - in this case spheres or aspheres. The grating behaves as a zone plate in reflection, focusing to a point image either incident parallel light (in first order diffraction) or a point source (second order diffraction). One such "paraboloid-sphere" is shown in Fig. 21, for which the focal length is 600 mm, corresponding to a groove density variation of approximately 50-150 g/mm for groove radii from approximately 20 to 60 mm. This grating has been used as a wavefront generator in interferometers to test spherical optics. Most recently, Hirst at Perkin-Elmer has, in addition to the prototype rotary engine, constructed an Advanced Circular Ruling Engine which is capable of providing VLS groove densities up to 1500 g/mm on ruled diameters as large as 500 mm (these proceedings[42]). A photograph of this new ruling engine is shown in Fig. 22.

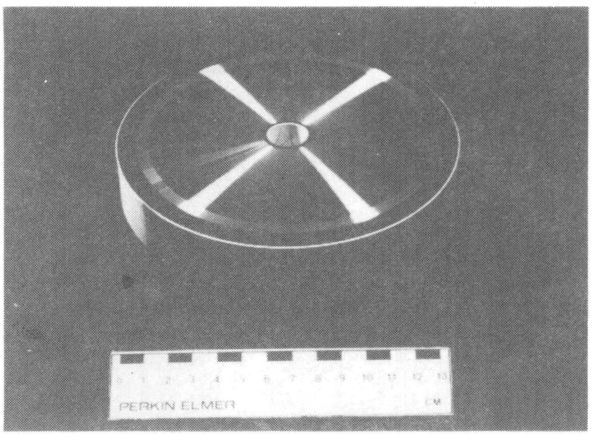

Fig. 21. Concentric groove VLS plane grating: "Paraboloid-sphere". Courtesy of G. Hirst, Perkin-Elmer Ruling Facility Instrument Group.

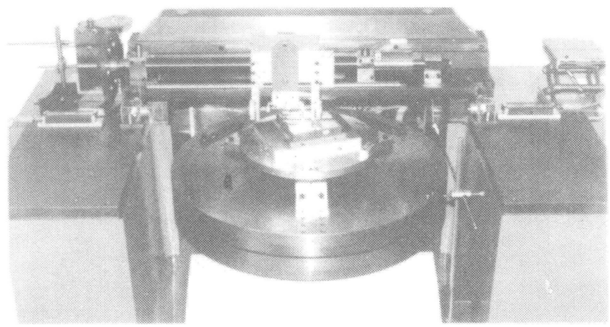

Fig. 22. Perkin-Elmer Advanced Circular Ruling Engine. Courtesy of G. Hirst, Perkin-Elmer Ruling Facility.

Hettrick has proposed a concentric groove plane VLS grating design which removes astigmatism at all wavelengths at grazing incidence, and thus provides an ideal means of low-dispersion order separation in a new echelle spectrometer[51]. One design variation of such a grazing incidence system is shown in Fig. 23, where the high-dispersion echelle grating is also a VLS grating (which will be discussed in the next section). A high-resolution spectrometer of this type, with the minimum number of reflections, was motivated by use in future astronomical missions. The focal length of the concentric groove grating in such applications is of order 2 meters, requiring large radii of the concentric grooves. In anticipation of spectroscopic use of concentric grooves, B.W. Bach[54] at Hyperfine Inc. has recently fabricated a grating with groove radii from 400 mm to 440 mm and, for initial test purposes, with a constant groove density of 600 g/mm. It should be noted that for use at grazing incidence, only a small sector of a groove circle is used to collect the incident light, unlike the situation for zone-plate normal incidence applications as described above.

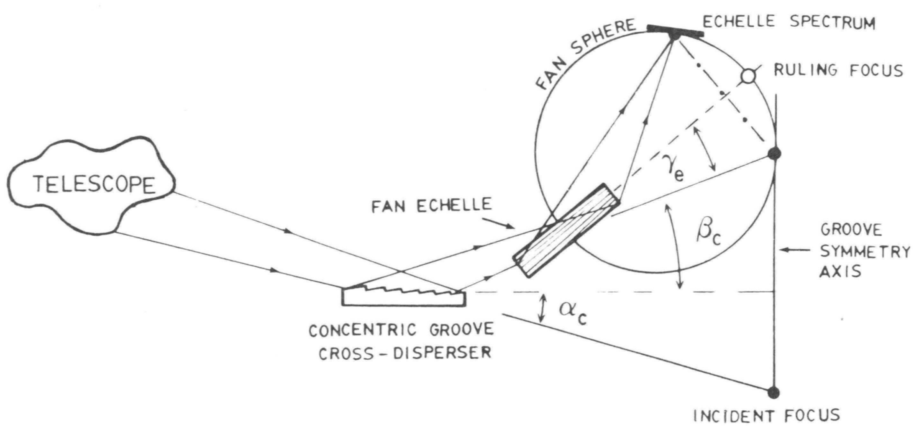

Fig. 23. VLS grazing incidence echelle spectrometer, using a concentric groove grating and fan grating (Hettrick 1985).

Non-parallel rulings

"Fan error", or successive non-parallelism, of grooves has been considered for some time to be one of the demons of ruling large gratings[55]. Uncontrolled fanning of grooves is, of course, undesirable and will degrade the resolution of a conventional grating whose grooves are assumed by the instrument designer to be perfectly parallel and straight. However, there are instances in which a controlled fanning of grooves can result in improved designs.

Concave Surfaces

In 1969, Baumgardner[12] briefly discussed a fan-type ruling pattern for the correction of image rotation from a concave grating when mounted for off-plane diffraction. This ruling pattern, where the grooves are straight but slanted towards the central ruling with various slopes, was shown by Baumgardner to remove first-order cross terms in the aberrant light-path function, and thus remove image distortion.

Plane Surfaces

Hettrick has proposed a "fan grating" for use at grazing incidence in convergent light, being the off-plane version of the plane grating geometry previously described. The imaging properties of these gratings, both in-plane and off-plane, were presented in several papers[35,36,51] by Hettrick. In the fan grating design (Fig. 24), the grooves converge to a common "ruling focus" and the diffracted wavelengths lie along a cone. This is a varied-space grating with the variation being in the direction along the groove lengths. This corrects for the linearly varying focal distance to the spectral image, which without the space variation would result in a large first-order cross term in the aberrant light-path function[36]. With fan grooves which converge to a ruling focus located behind the focal plane (and the virtual focus) by a distance

$$\Delta RF = L_o \sin\gamma_o \tan\gamma_o \, , \qquad (4)$$

Hettrick showed that this aberration is essentially cancelled at grazing incidence. In this equation, L_o is the nominal focal distance and γ_o the nominal graze angle. A single grating can therefore be used in-focus at any graze angle, provided the focal surface and incident virtual source lie on a circle (Fig. 23) of diameter $L_o/\cos\gamma_o$, which intersects the grating center, the virtual source, the spectral image and the ruling focus. By an additional space variation between the grooves, the next most significant aberration (meridional coma), can be removed, resulting in potentially high resolution at grazing incidence. However, due to the inherently low dispersion of an off-plane grating of a given groove density, high resolution in practice requires use of high spectral orders. This is feasible with the fan grating due to the absence of shadowing (thus high diffraction efficiency) at large blaze angles, and a unique by-product of the fan pattern being a nearly constant blaze wavelength across the grating aperture. Hettrick used these advantages of an echelle fan to design a class of grazing echelle spectrometer (Fig. 23).

Cash has also proposed use of fan-type rulings in low spectral order[56]. Adopting the nomenclature common in the opto-electronics industry[57] and in metrological applications using this pattern[10], Cash refers to this as the "radial groove grating."

A fan grating or "radial grating" was mechanically ruled by B.W. Bach at Hyperfine Inc. and subsequently tested in EUV and soft x-ray light by Windt[58]. The ruling of a fan groove pattern is extremely challenging, as the groove depth varies continuously along each groove, requiring a means of continuously varying the weight loading on a diamond tool. Combined with the requirement of large blaze angles to operate as an echelle in the desired high spectral orders, and the accompanying requirement of a second space variation between the grooves for high resolution, a spectroscopically useful fan grating is perhaps the most difficult of the VLS grating designs to fabricate.

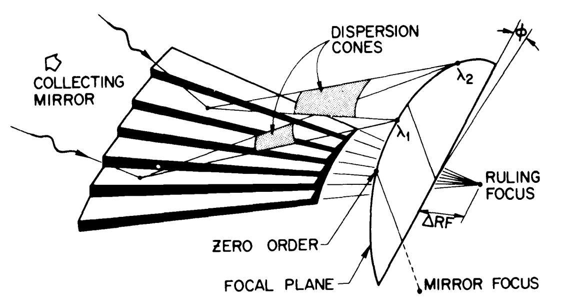

Fig. 24. Fan grating, mounted for conical diffraction at grazing incidence in a convergent beam. Figure for this plane grating from Hettrick and Bowyer (1983).

The future

The above review has inspired some speculation regarding the future direction in which VLS gratings may be headed. In addition to the plethora of proposed grating designs, a fraction of which have actually been ruled at present, the recent construction of ruling engines dedicated to varied-space capability has provided a forward momentum to the art.

The use of plane VLS gratings in converging or diverging light is a recently deomonstrated geometry, and as such it is likely to quickly find applications in a number of diverse fields. Its advantages in being used for large area moderate resolution astronomical spectrometers are currently being explored at shorter and shorter wavelengths[59]. In laboratory spectroscopy, such designs can be adapted to time-resolved streak cameras[60], providing a powerful method of plasma diagnostics. It may also be realistic to expect the stigmatic properties of VLS plane gratings to be used in extending interferometry to the soft x-ray region by use of grazing incidence. Interferometry at these energies will be made feasible by the development of intense coherent synchrotron radiation[61]. Further theoretical and experimental work on the properties of gratings with varied spacing may also permit even further simplification of dispersive systems, whereby all the optical functions required are performed in a single "monolithic" element.

A VLS concave grating design of tantalizing potential is the reflection zone plate, for which both coma and spherical aberration are absent. Such a grating should exhibit an exceptionally wide field of view, making it ideal for use as a camera or de-magnifying microprobe with loose alignment tolerances. Since such a grating is used at normal incidence, it would either be restricted to wavelengths longer than approximately 200 Å, or require multi-layer coatings which reflect only an interference-limited bandpass. A multilayered aplanatic zone plate would also have minimum achromatism, allowing its use in strong continuum light such as synchrotron radiation.

Varied spacing also permits higher resolution to be attained, particularly at grazing incidence. Applications to monochromator and spectrometer design are at an early stage, and likely to proceed with increased vigor given the increased availability of intense soft x-ray and extreme UV radiation.

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